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SEGMAG MACHINES FOR MARINE ELECTRICAL PROPULSION SYSTEMS

Final Report Submitted to Office of Naval Research

R. A. Feranchak, R. B. Powell, H. W. Miller, T. H. Putman, F. J. Prines, D. L. Greene, W. P. Welch, A. Abbondanti, W. W. Hickey, R. D. Schultz, T. J. Heathcote

September 13, 1978

Westinghouse R&D Center
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Contract N00014-77-C-0307

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This report describes the application of segmented magnet (SEGMAG) electrical generators and motors for ship propulsion drives. It encompasses the conceptual design of a 40,000 horsepower per shaft, two shaft, drive system for a destroyer type vessel and a 20,000 horsepower per shaft, two shaft, drive system for a hydrofoil type vessel. It also includes a detail design and initiated construction of a 3,000 horsepower per shaft, two shaft, prototype drive system for a land based demonstration. All three drive systems utilize gas turbines for prime movers. In addition to the main propulsion machinery → over

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designs, the auxiliaries required for the systems are also described.

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VOLUME A - DESTROYER TYPE SHIP

SECTION 1

INTRODUCTION

This report is submitted in partial fulfillment of the requirements under Contract N00014-77-C-0307 with the Office of Naval Research. This contract encompasses three major endeavors:

1. The conceptual and preliminary design of electric propulsion systems for two representative naval ship types with the intent of providing feasibility and performance demonstrations of the segmented magnet (SEGMAG) machine concept.

2. The preliminary and detail design and initiation of construction of a 3000 hp/shaft twin drive test system.

3. The construction of a 3000 hp motor and generator originally designed under a companion research contract.*

The two naval ship types referred to in (1) above are a displacement vessel typified by an 8000-ton-class destroyer and an ocean-going hydrofoil craft. In order to clarify this report, it is divided into two major volumes: "A" relating to the displacement ship and "B" relating to the hydrofoil craft. Both volumes follow the same outline, and in most cases, the corresponding sections are identical. Thus, in order to eliminate needless duplication, these identical sections are omitted from volume "B" and reference is made to the identical corresponding section in Volume "A".

The principal objective of conducting conceptual and preliminary designs of SEGMAG machine propulsion systems for naval ship types was to

*ONR Contract N00014-76-C-0619

test the hypothesis that SEGMAG machinery would provide a lightweight and efficient drive system, with the inherent arrangement flexibility and reversibility associated with electric systems. To meet this objective, designs of the system components and their interconnections were conducted, and the operation of the system was tested by computer simulation. This process was, of course, iterative, in that some of the system component characteristics were derived from the simulation.

One of the first tasks to be initiated during this study was to determine the optimum designs in terms of weight, volume, and efficiency of the SEGMAG machines and their auxiliaries. After a preliminary sizing of the principal drive components was accomplished, the next logical step was to determine the required components and their operating characteristics both individually and as a combined system. An analog simulation study was then initiated to determine the types of control systems that would be required and their response during maneuvering. One of the immediate problems to be determined during the system simulation was the method of absorbing the regenerative energy during ship reversal. This became an area of substantial effort in the study, since many of the system features were dictated by this maneuver. The source of regenerative energy, of course, is in the mass of the moving ship, and it is transmitted through the propeller and shaft to the motor. The motor now desires to function as a generator which would transmit this energy to the generator and drive turbine, if means are not taken to prevent it. Various arrangements and types of equipment were simulated, including mechanical brakes and dynamic braking resistors. The simulation study permitted evaluation of the equipment schemes tested and fixed the main components of the drive system and their interconnection. It also demonstrated that the basic control loop responded favorably to various levels of output power.

1.1 Summary

The low power density inherent in the design of SEGMAG machines is their most salient characteristic. Exploitation of this advantage directs one to marine propulsion systems not only because shipboard volume is valuable but also because dc electrical systems provide equally important advantages in control and arrangement flexibility. Although the arrangement advantages were not utilized to their fullest possible extent in this study of the application of SEGMAG machines to the destroyer type displacement ship, their potential is clearly evident. Table 1.1 itemizes all the components of the electrical propulsion system for the destroyer type ship and lists their volume and weight. A comparison with a geared/CRP design is also presented, assuming a direct substitution without rearrangement. Using a typical 352 hour mission profile, the penalties in pounds for utilizing the ship's service electrical system and the seawater cooling system are tabulated in Section 2. The actual hardware weight of the basic electrical propulsion system and bedplate that would be substituted for the gear unit (and some of its eliminated auxiliaries) is lower than the gear unit and its bedplate. Further segregation of the requirements of each system's components increases the weight difference even more. In addition, the increased efficiency of the electrical system would reflect in weight savings in fuel and ship's service requirements. Thus, on a one-for-one substitution, the electrical propulsion system weight is an improvement over that of the geared drive. As stated earlier, locating the motors nearer the propellers would reduce weight even more by saving shafting weight.

In terms of performance, however, the electric drive projects a headreach of less than three ship lengths from the full ahead condition and even less from the one-quarter power condition. The performance, as determined from the system simulation, not only showed that the crash-reversal maneuver is accomplished quite quickly but also showed the drive system to be stable under all conditions and modes of operation. Through this simulation, the control system components evolved to satisfactorily function under all instantaneous demands of torque and possible operating states of the ship. The versatility of the electric propulsion system in interconnecting power sources and loads is clearly more advantageous than the straight-through geared turbine drive. This

TABLE 1.1 - DRY WEIGHTS FOR TWIN SHAFT DESTROYER PROPULSION SYSTEM

- IN METRIC TONS (1 metric ton = 0.984 long tons)

	Electric Drive			Geared/CRP Propeller		
	No. Units Per Ship	Unit Weight	Total Wt. For Ship	No. Units Per Ship	Unit Weight	Total Wt. for Ship
Gas Turbines	4	20.64	82.56	4	20.64	82.56
Propulsion Bedplates	2	18.14	36.29	2	27.22	54.43
Turbine Aux. Systems	(Weight Not Included)			(Weight Not Included)		
Propellers	2	17.01	34.02	2	23.81	47.63
Propeller Subsystems	-	-	-	2	3.90	7.80
Shafting and Bearings	2		166.79	2		166.79
L.O. Systems Plus Oil	2		13.61	2		31.75
SUB-TOTAL			333.27			390.96
Motors	2	53.84	107.69	Reduction Gears		
Generators	4	10.73	42.91	2	72.58	145.15
Exciters/Engine Room	2	3.40	6.80			
Cooling Water Systems	2	4.71	9.44			
Cover Gas Systems	2	0.23	0.45			
Dynamic Brake Sys.	2	2.02	4.04			
Electric Cables & Lines	1		10.43			
Setup Switches	1		.91			
Control	2	1.50	3.00			
SUB-TOTAL			185.67			145.15
GRAND TOTAL			518.94			536.11

is particularly true in the ability of the electric drive system to drive two motors from any one generator, which is achieved by energizing a crossover bus, and the variable reduction ratio which permits operation of the gas turbine at its most economical speed for any power level.

In addition to the machines designed for the 40,000 hp/shaft system, a 3000 horsepower motor and generator were designed to demonstrate the SEGMAG technical objectives. These machines and their control system will be tested in a later phase of this program. The characteristics of these machines are discussed in Section 4 of this report.

1.2 Exceptions

The original goals established for the system specified that the peak reverse torque to be supplied by the motor during one method of reversal should not exceed 150% of normal full load torque. It is not clear that this applies to all methods of ship reversal, however, the amount of reverse torque required to stop the propeller is a function of ship's speed and, hence, how fast the maneuver is accomplished. The ability of the motor to supply this required torque is a function of the design of the machine, primarily in its current carrying capacity and its method of heat dissipation. Most dc machines are capable of overloads for short periods of time, the shorter the period the larger the tolerable overload. For example, the machine should tolerate a 5% overload for approximately one hour, while a 50% overload can be tolerated for about 5 minutes. The simulation showed that the motor current required to develop optimal reverse torque was approximately 175% for a period of a few seconds. This should be well within the tolerable range of the machine. Thus, the 150% torque limitation is without foundation as long as the machine's temperature rise is within the permissible range. The important criteria is not the magnitude of developed torque but rather the permissible temperature rise due to the absorbed energy.

1.3 Development Risks

The major area of development required for the electric drive system is that of circuit and machine protection. In particular, the desired circuit breakers as presently conceived are not commercially available. A method of quickly reducing the generator field to establish zero armature current has been considered in lieu of circuit breakers. However, this concept impacts the field coil design and in particular its insulation level. To enable the field to force the armature current to zero requires a field forcing voltage of approximately ten times normal. This can be accomplished at the expense of increased field insulation. Thus, it might be prudent to investigate the cost trade-off between this field forcing method in the development of a high voltage and current dc circuit breaker. At present, the outlook for development of such a breaker is an extension of the present state-of-the-art. Manufacturers of such breakers state that the unavailability of them is due primarily to lack of demand rather than a technological impossibility.

SECTION 2

SYSTEM DESCRIPTION

The electric propulsion system was specified in the work directive to drive a twin screw displacement vessel of a destroyer type. The ship was defined to have a displacement of 7800 tons, a top speed of 32 knots at a propeller speed of 168 rpm and the propeller characteristics, that is, the torque and thrust coefficients, were to be taken as propeller #18 from the date of Miniovich.* Cruise speed was to correspond to a propeller speed of 100 rpm. Table 2.1 lists the other data used to define the baseline propulsion system.

The gas turbine specified as the prime mover was the G.E., LM2500 whose principal characteristics are tabulated on Table 2.2 For the baseline case, the full load output of each of the two turbines per shaft is nominally 20,000 HP, although to meet the ship's full load condition only 19,450 HP is required from each turbine. Since two turbines per shaft are required for the full load condition, the drive is usually referred to as the 40,000 HP system. The one-half load configuration is defined as utilizing only one turbine per shaft operating at the same horsepower output from the turbine as in the full power configuration. The quarter power configuration is defined as operating the two shaft motors from one generator whose turbine output is the same as it was under full load conditions.

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*Naval Ship Research and Development Center, Marine Engineering Lab Technical Note 202/67, "Representation of Propeller Thrust and Torque Characteristics for Simulations", Appendix C, D. W. Baker and C. L. Patterson.

TABLE 2.1

BASELINE PROPULSION SYSTEM FOR DESTROYER TYPE SHIP

Ship Data

Ship displacement = 7800 tons

Ship speed, V_s = 32 knots = 54.01 fps

Propeller diameter = 16.2 ft

Propeller data, #18 from Miniovich data

Ship drag, 183 V_s^2

Propeller speed = 168 rpm @ full power

Propeller speed = 100 rpm @ cruise power

Propeller inertia = 34,300 lb ft sec^2 (includes shafting and entrained H_2O)

TABLE 2.2

BASELINE PROPULSION SYSTEM FOR DESTROYER TYPE SHIP

Gas Turbine Data

Type GE - LM2500

Power Turbine Inertia = 57.4 lb ft sec^2

Fuel rate at idle = 800 lbs/hr (@ 2000 rpm)

Fuel rate at 19,450 HP = 8,364 lbs/hr (@ 3,264 rpm)

Idle fuel rate = 800 lb/hr

Maximum fuel rate = 9,030 lb/hr

Maximum increase of fuel rate = 750 lb/hr-sec

Topping Governor speed trip = 3,744 rpm

Power turbine overspeed trip = 3,960 rpm

The baseline data for the generator is given on Table 2.3, which lists the primary electrical and mechanical design parameters. Table 2.4 lists similar data for the propulsion motor.

The circuit reconfiguration required to change from full, to one-half, to one quarter power levels are accommodated by closing or opening the appropriate circuit set-up switches. These switches have the capacity of conducting the required current for the various configurations, however, they have little or no load interrupting capacity of which more will be discussed later.

For each configuration and power output, there is a ship's speed which corresponds to a balance between the thrust developed by the propellers and the drag on the ship produced by the water. These balanced ship's speeds also reflect back to different propeller speeds and torques and consequently shaft horsepower. The required speed and torque of the propulsion motor demands a different voltage and current from the generator(s) which is achieved by generator field variation. For the full power configuration, which is shown in Figure 2.1, two generators are operated in parallel powering the port motor, while the two starboard generators are paralleled to power the starboard motor. The one-half power configuration is shown in Figure 2.2, where one generator powers the corresponding shaft motor, still in the split plant configuration. The quarter power configuration is shown in Figure 2.3 and demonstrates the cross-connect capability of the drive system. Here, one generator is powering both the starboard and port motors connected in series. The cruise configuration is normally used cross-connected with only one generator as shown in Figure 2.4 but in some instances, is operated in the split plant mode as shown on Figure 2.5

2.1 Physical Description

One of the major advantages of an electric propulsion drive is the freedom in arrangement of the major components. Turbine generators can be mounted without any particular physical relationship

TABLE 2.3

BASELINE PROPULSION SYSTEM FOR DESTROYER TYPE SHIP

Generator Data

Nominal Electrical Characteristics:

2,000 volts

9,800 amps

19,600 kilowatts

3,600 rpm

4 poles

1.755 milli ohm armature resistance

40 microhenry armature inductance

17.61 ohms, field resistance

5.21 henries, field inductance

1,000 volts, field voltage at full voltage

56.8 amps, field current at full voltage

Nominal Mechanical Characteristics: (Preliminary Layout 1289J27)

Dimensions:

Stator OD = 45.2 inches

Rotor OD = 24.0 inches

Rotor ID = 11.0 inches

Length between brgs. = 100 inches

Weight:

Stator = 17,075 lbs

Rotor = 6,570 lbs

Rotor Inertia = 36.23 lb ft sec^2

TABLE 2.4

BASELINE PROPULSION SYSTEM FOR DESTROYER TYPE SHIP

Motor Data

Nominal Electrical Characteristics: (Computer Output 5/31/77)

2,000 volts

15,000 amps

40,000 HP

168 rpm

18 poles

2.36 milli ohm, armature resistance

75 microhenry, armature inductance

11.53 milli ohm, field resistance

16.20 millihenry, field inductance

234 field voltage at full voltage

957 field current at full voltage

Nominal Mechanical Characteristics: (Preliminary Layout 1289J30)

Dimensions:

Stator OD = 127 inches

Rotor OD = 104.265 inches

Rotor ID = 90.5 inches

Length between Brg ℄ 's = 87 inches

Weight:

Stator = 60,525 lbs

Rotor = 58,150 lbs

Rotor inertia = 20,000 lb ft sec^2

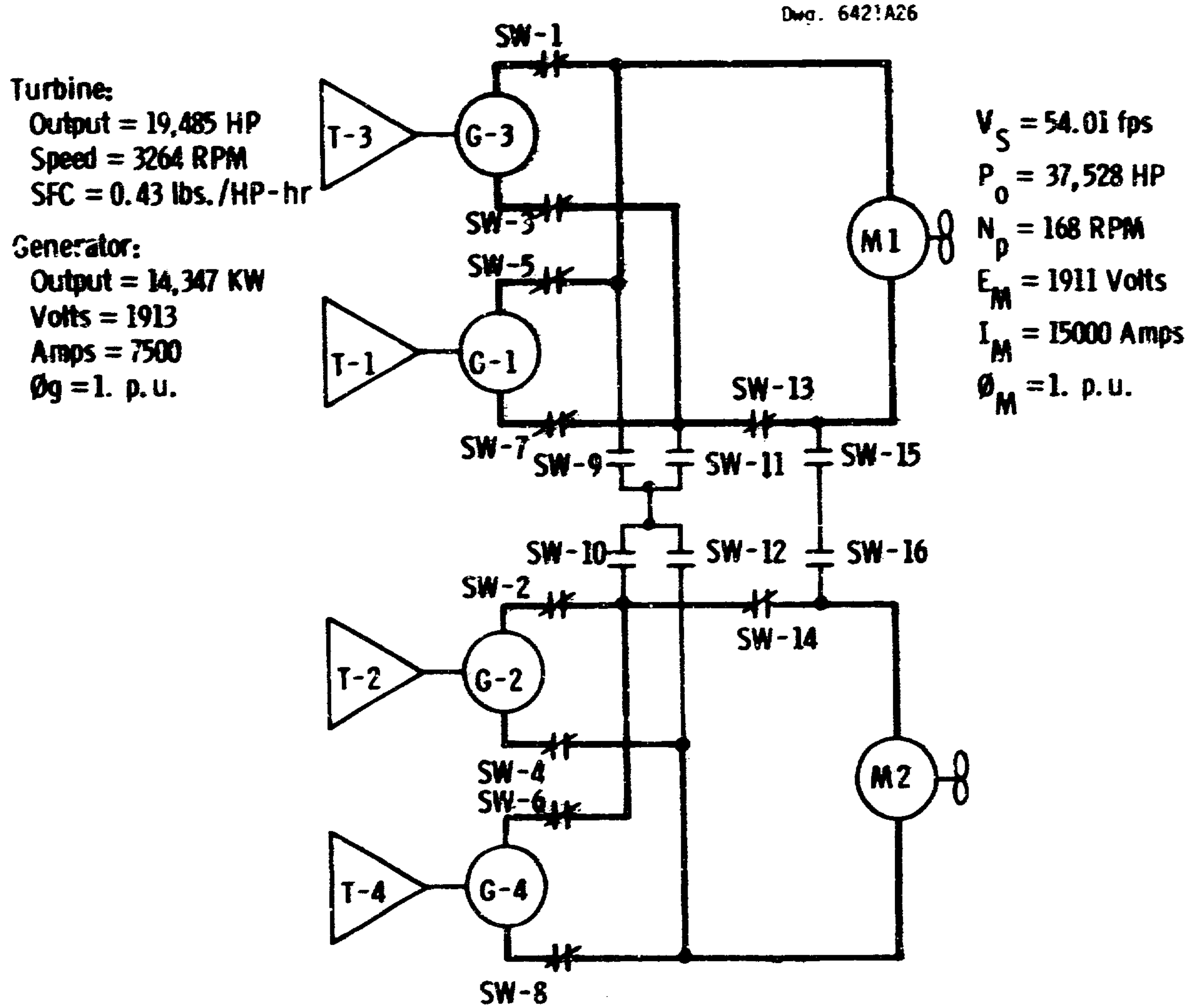

Figure 2.1. Full Power Configuration

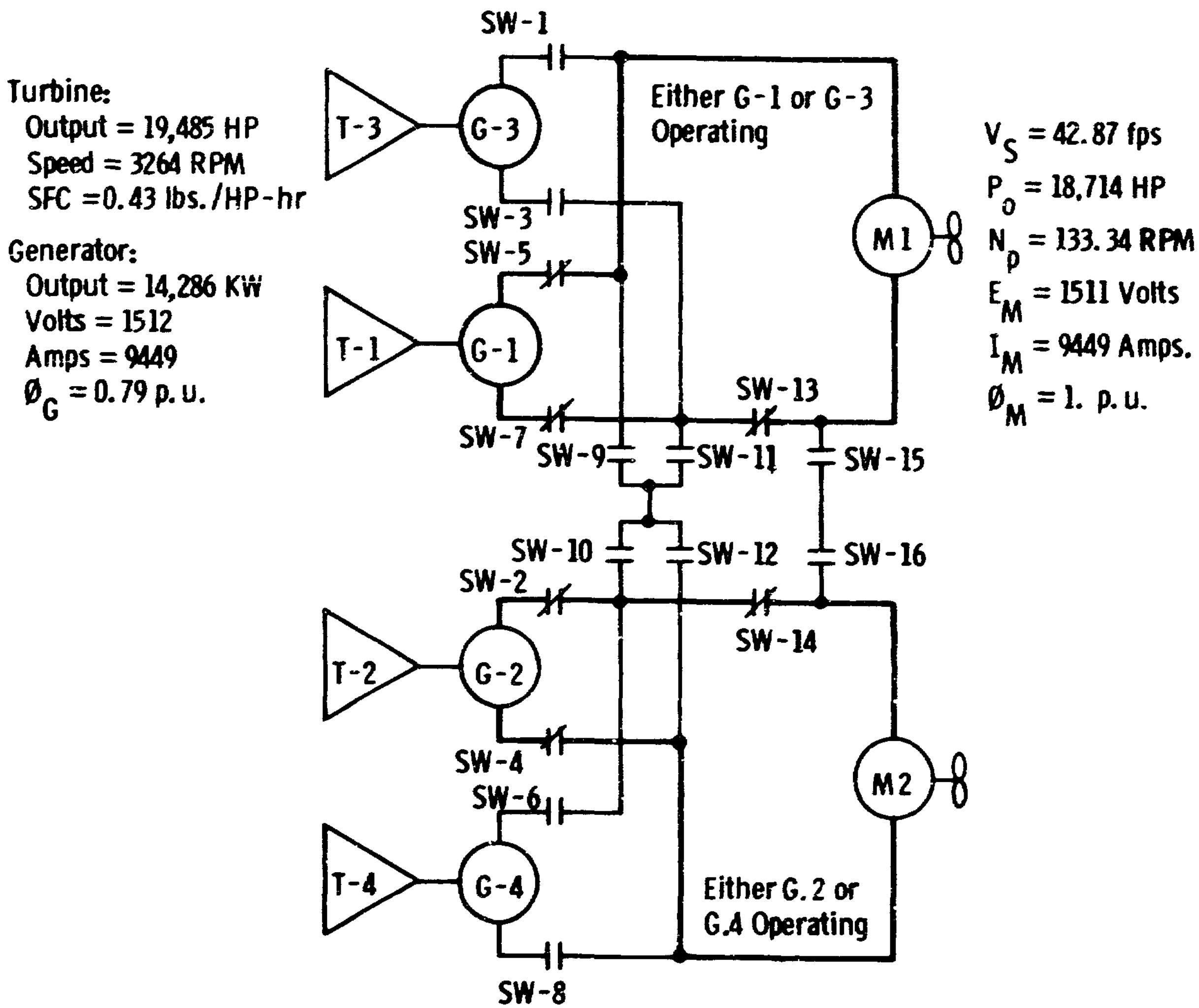

Figure 2.2. One Half Power Configuration

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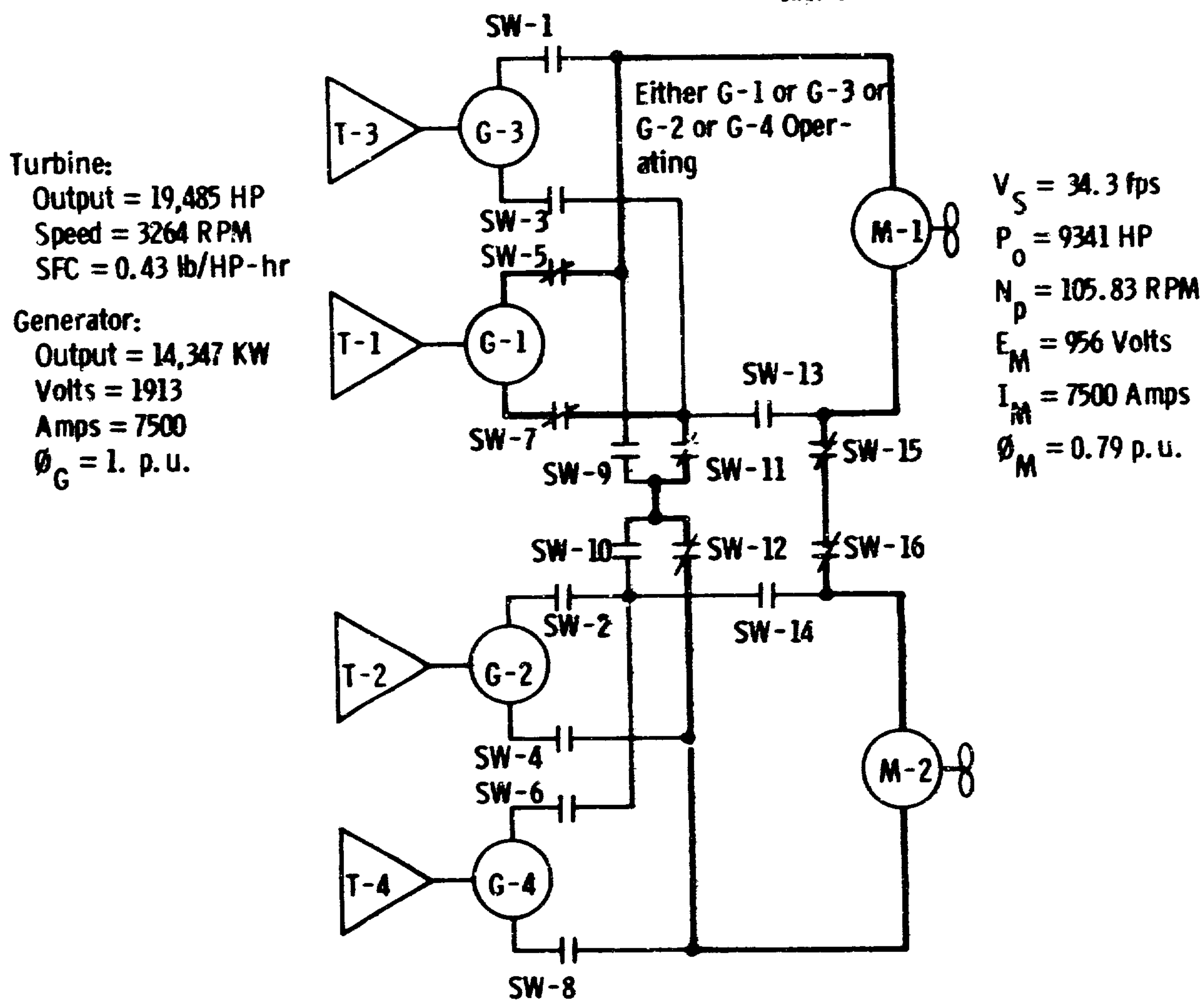


Figure 2.3. One Quarter Power Configuration

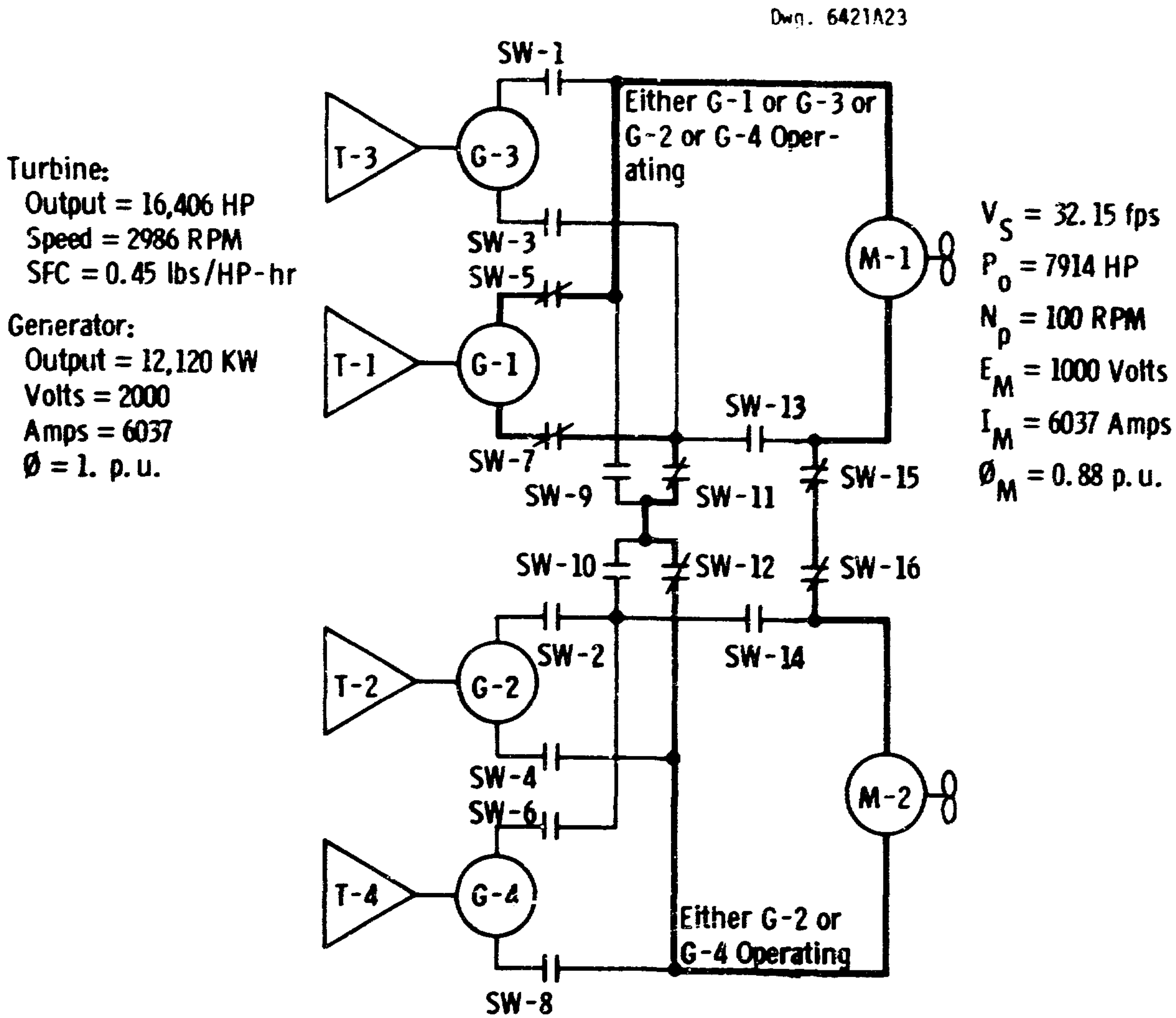


Figure 2.4. Cruise Power Configuration (Cross-connected)

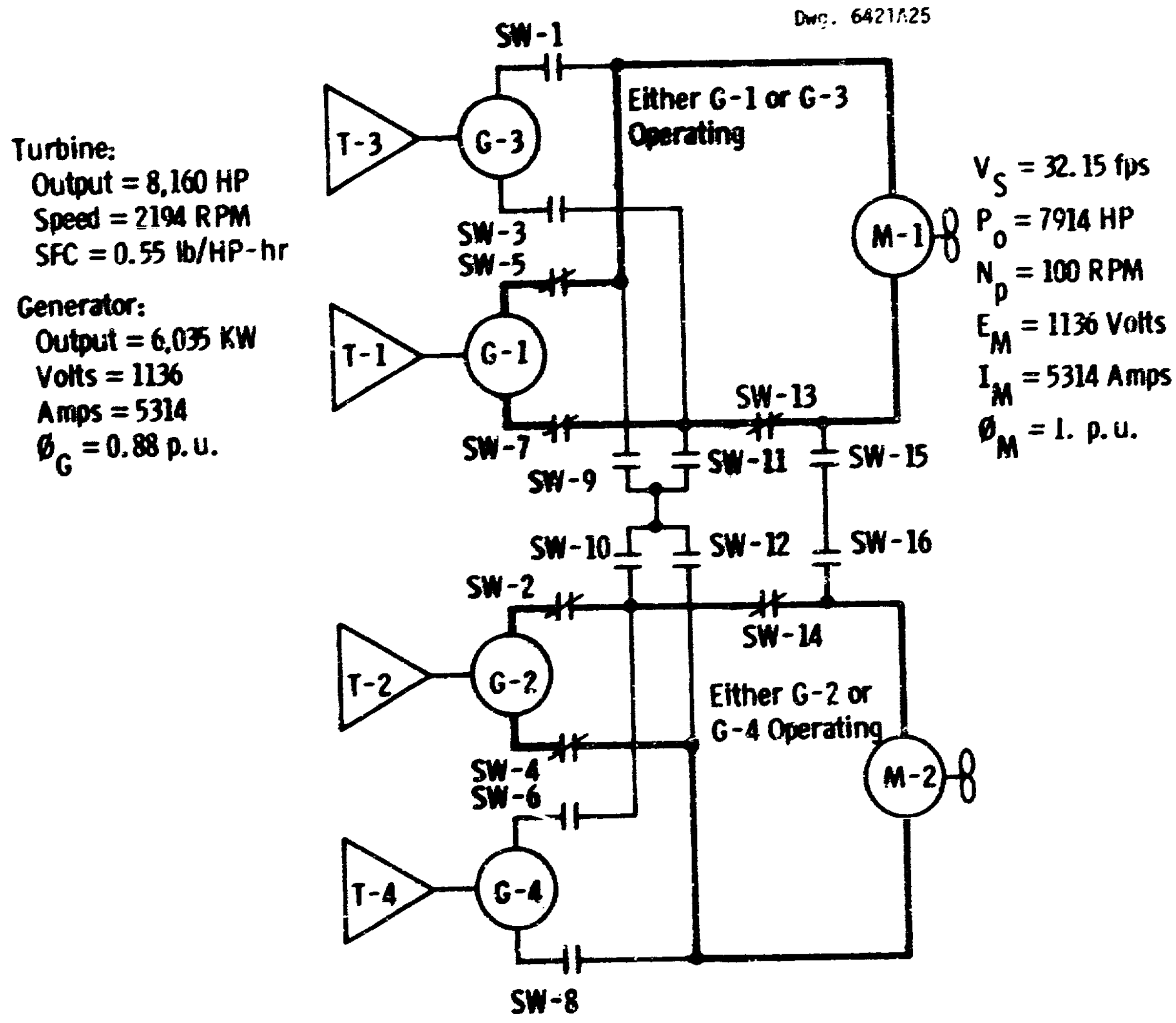


Figure 2.5. Cruise Power Configuration (Split Flant)

to the drive motor, as power is transmitted through relatively flexible electrical leads. Thus, the turbines can be mounted on higher decks with shorter intake and discharge ducts than in mechanical drives where the turbine output shafts must be properly aligned with the reduction gear and drive shaft. To achieve proper balance, the marine architect may move the T-G sets up or down, fore or aft or athwartships with relative freedom. A big advantage is that the drive motor can be located quite close to the aft end of the ship while the generators can be located in the engine room closer to mid-ships and separated by several water-tight bulkheads. This physical separation improves the reliability of the power drive system making it less vulnerable to damage and, operationally, more viable under combat conditions. This arrangement also has the advantage of saving a significant amount of weight by reducing line shafting and bearings.

Despite these obvious advantages, it was felt that a simple replacement of the reduction gear in a DD963 class destroyer with the electrical generators and motors would be the most convincing scenario of the application of an electric drive system to a modern ship. By not utilizing one of the electric drive's major advantages, that is, its weight saving arrangement flexibility, and yet show a favorable weight comparison would positively demonstrate its adaptability of application.

2.1.1 System Layouts

Since the 40 KHP twin shaft plant is intended to power a modern destroyer, the Spruance Class destroyer hull seemed an appropriate choice for the arrangement study. The DD963 machinery arrangement drawings as updated for DD993 were used for the scaled layouts of SEGMAG propulsion machinery in a typical modern destroyer. In addition, the gas turbine, type LM-2500 installed in this ship, is the prime mover used for the system study and the layouts.

The replacement of the main reduction gear and CRP propeller with generators, motor and a fixed blade propeller offers certain self-evident arrangement advantages. The gas turbine drive shafting no longer need be parallel with the ship's lineshafting, nor in fixed relation thereto. The two gas turbines likewise need no special geometrical spacing, and may be located high or low, level or non-level.

The propulsion motors may have any location along the line of shafting, subject to the need for clearance above the tank top. The horizontal rake of the shafts may be selected strictly on the basis of propulsive effort rather than for reasons of lateral clearance for machinery. Motor foundations can be simple, strong and rigid. The thrust bearing may be located at any selected station along the inboard shafting, as it may be with other forms of propulsion units.

2.1.1.1 Forward Engine Room

The arrangement studies we have made show up best in the layout sketches Figures 2.6 to 2.14. The legend for the components shown on these figures is given on Table 2.5. The first three relate to the forward machinery room, which drives the port lineshaft and propeller. Here the SEGMAG generators and motor have been arranged in the present DD963 space with relatively no rearrangement of existing other components except as may be required for the auxiliary systems.

As may be seen in elevation (Figure 2.6), the generators are supported from the motor barrel structure, the combination of the two generators and one motor occupying approximately the same space as the DD963 reduction gear. In order to accommodate the intervening foundation structure, the shaft has been moved downward one foot at the lineshaft coupling, thus reducing the rake of the shaft line.

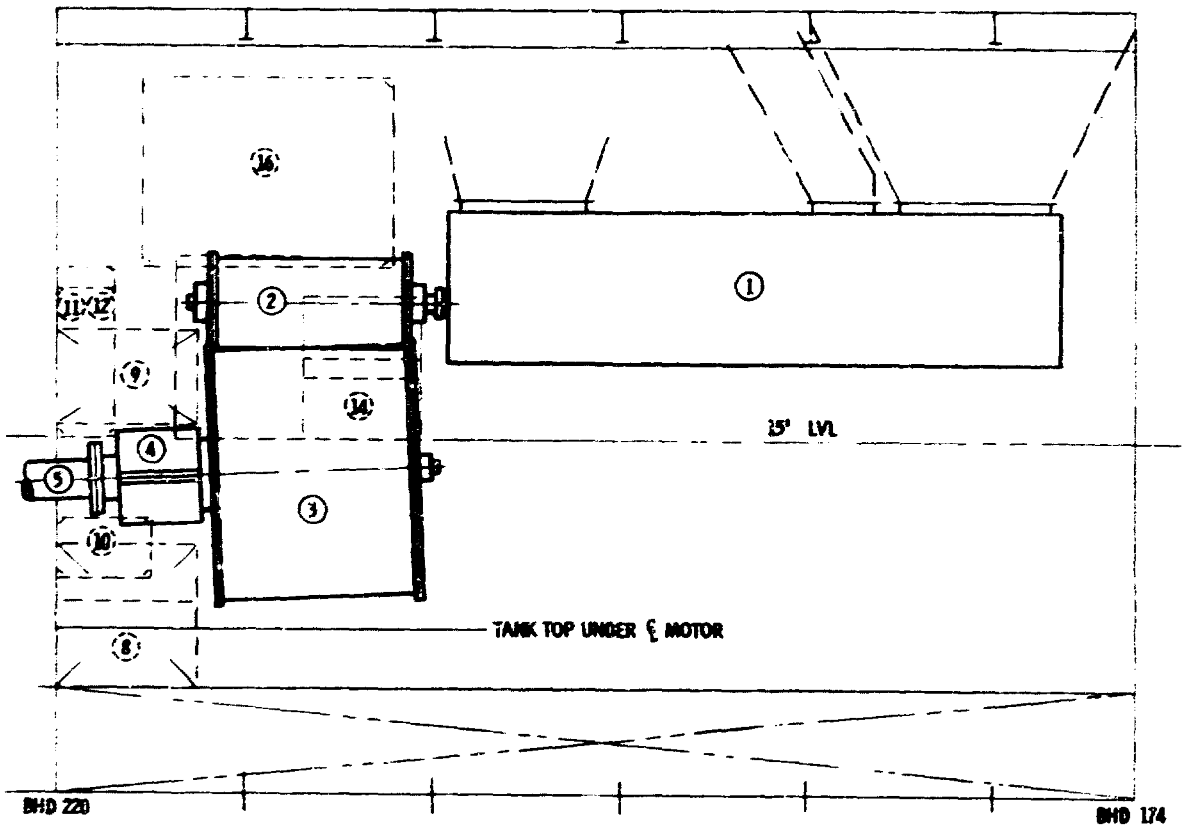
Since there is no requirement for parallelism of turbine and shaft centerlines, the gas turbine-generator modules have been positioned level. The 963 turbine subbase structure has been simplified and essentially the same foundation for the turbines has been retained. The turbine air and exhaust ductings have not been altered except in a

TABLE 2.5

LEGEND FOR FIGURES 2.6-2.14

PROPULSION SYSTEM COMPONENTS AND SUBSYSTEMS

ITEM	NAME
1	Propulsion gas turbine
2	Propulsion generator
3	Propulsion motor
4	Thrust bearing
5	Lineshaft, port side
6	Lineshaft, starboard side
7	Lineshaft bearing
8	Lubricating oil system
9	Cooling water system for motor and generators
10	Brush atmosphere system
11	Generator exciters and control
12	Motor exciter and control
13	Dynamic braking resistors, solid state switches and contactor
14	Control console with logic boards and supervisory control
15	Interface relay cabinet
16	Switchgear



FWD ENGINE ROOM ELEVATION ℄ TO PORT

Figure 2.6. Machinery Arrangement in Destroyer Forward Engine Room, Elevation

minor way for leveling the turbines. The present high misalignment turbine flexible coupling is required to allow the large excursions of the turbine on its shock mounts. The generators and motor are solidly mounted on a foundation from the ship's hull structure, requiring no shock mounts.

The thrust bearing is located just aft of the motor with the bearing collar or runner an integral part of the motor shaft. Replaceable collar liners are provided per usual NAVSEC practice.

Because of the need for cooling water rotary transfer seals at the motor forward end, provision must be made along the lineshaft for the radial introduction of Prairie Masker air, if needed. No CRP control fluid is required since the propeller has fixed blades.

The essential details of the mounting structure between generator and motor are shown in Figure 2.7. Each generator has four feet by means of which alignment to the turbine is achieved with fitted shocks and fitted bolts. Two side support pads are located near the generator centerline and, after alignment is completed, shocks are fitted between the side pads and the athwartship support structure which is integral with the motor frame at the top. Here clearance bolts will be used.

As may be readily seen, the generator support scheme is strong and rigid with inherent good shock resistance. The motor is supported and is aligned to the line shaft by four 18" by 30" feet located 24" below the shaft centerline. This arrangement permits a non-complex, strong and rigid foundation to be placed between the motor and the hull structure.

Although good alignment between motor and lineshaft should be achieved in accordance with established shipbuilding practice, the motor is much less sensitive to misalignment than is a reduction gear where concern is present for the disturbance of uniform gear tooth contact by shaft misalignment.

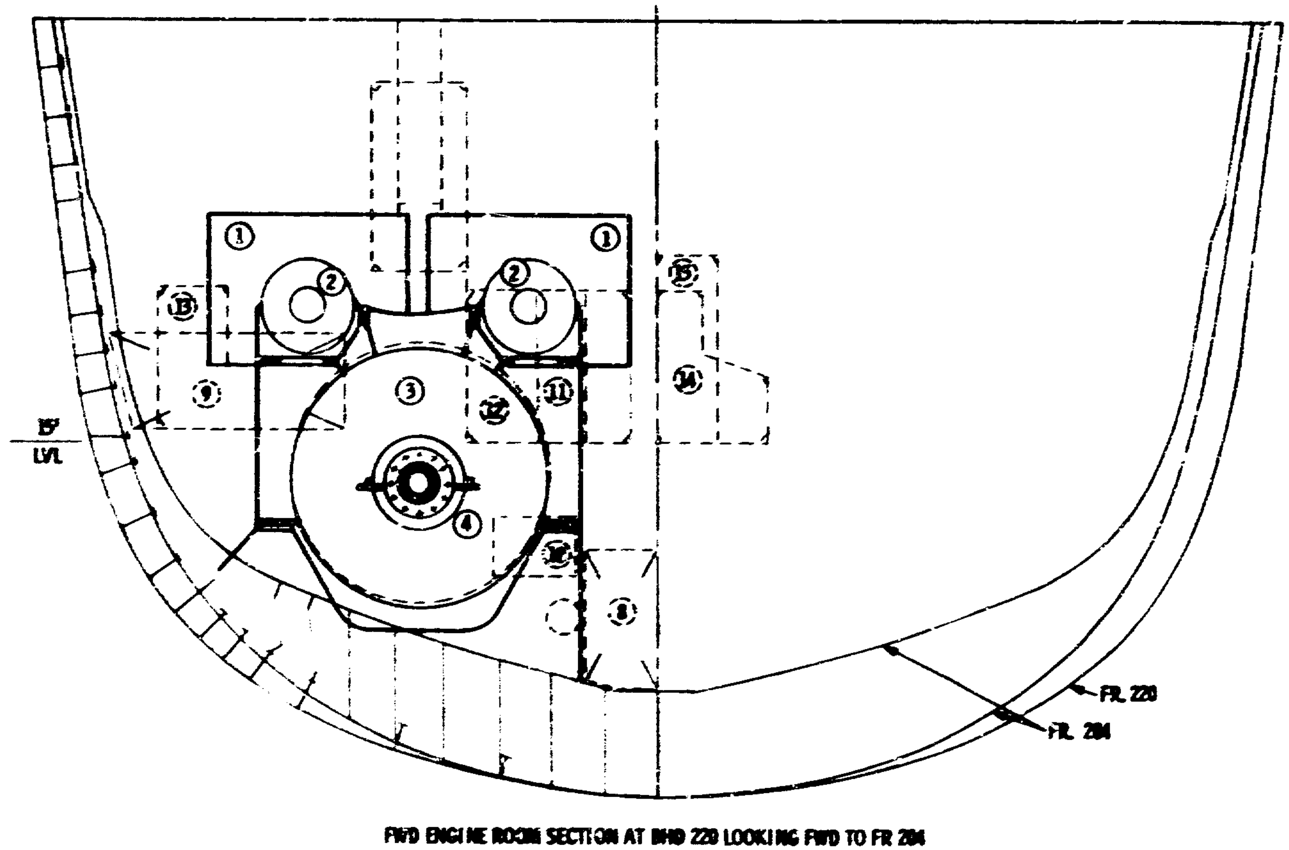


Figure 2.7. Machinery Arrangement in Destroyer Forward Engine Room, Section

Shown on the sketches Figures 2.6 to 2.9 are the approximate space required for the subsystems for the electric drive, these being:

Control and supervisory system
Switchgear with protective elements
Excitation systems
Dynamic braking resistors and switches
Cooling system - deionized water
Lubrication system - oil
Brush atmosphere system

These subsystems have been arbitrarily located on the layouts, and may be moved about as the arrangement requires, except for certain restrictions. For example, the lube oil sump must be at a level below the lowest bearings of the machines and properly designed for ship static and dynamic inclinations.

The space shown occupied by each of the subsystems is based on reasonably accurate estimates.

2.1.1.2 Aft Engine Room

In the Aft Engine Room (which drives the starboard shaft), a different approach has been taken to accomplish the arrangement of the motor and generators. In this space, the layout has been formulated to illustrate the flexible features of the SEGMAG machinery to accommodate variations in arrangements as would be desired during the planning stages of a new ship.

The propulsion motor has been located as far aft in the space as the length of the motor will allow (Figure 2.10). In order to accommodate the motor external dimensions over the tank top a shaft height of about 6 ft above the tank is required. For this reason the shaft elevation at the motor has been increased by 18 inches. This increases the shaft vertical rake from the value of 0.88 inches per foot (on DD963) to 1.0 inch per foot. Some of this increase may

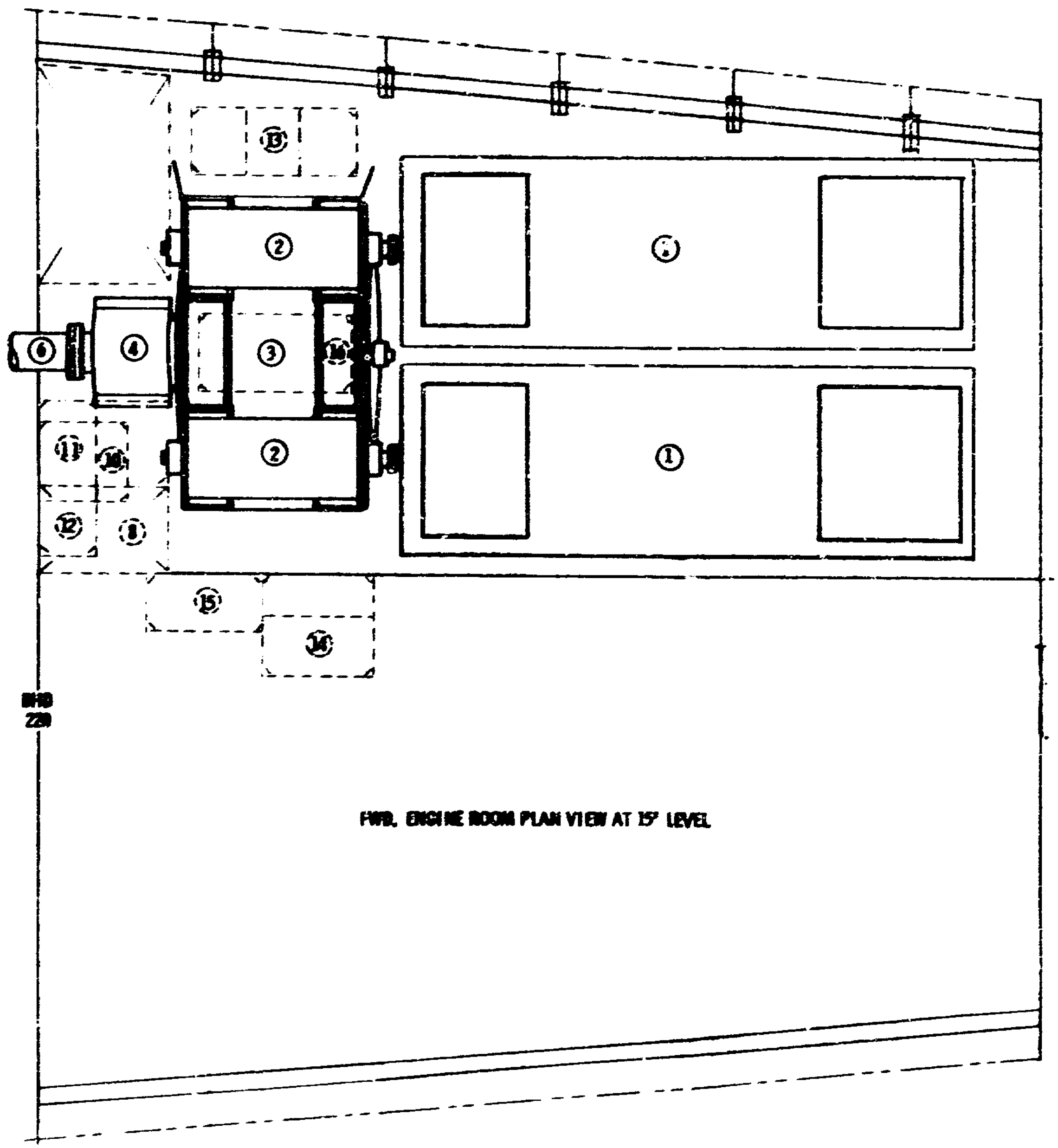


Figure 2.8. Machinery Arrangement in Destroyer Forward Engine Room, Plan

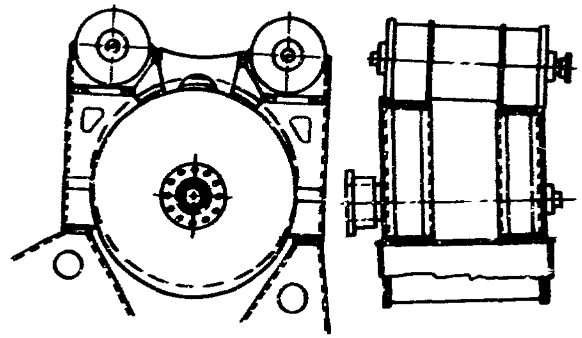


Figure 2.9. Generator and Motor Foundation, Forward Engine Room

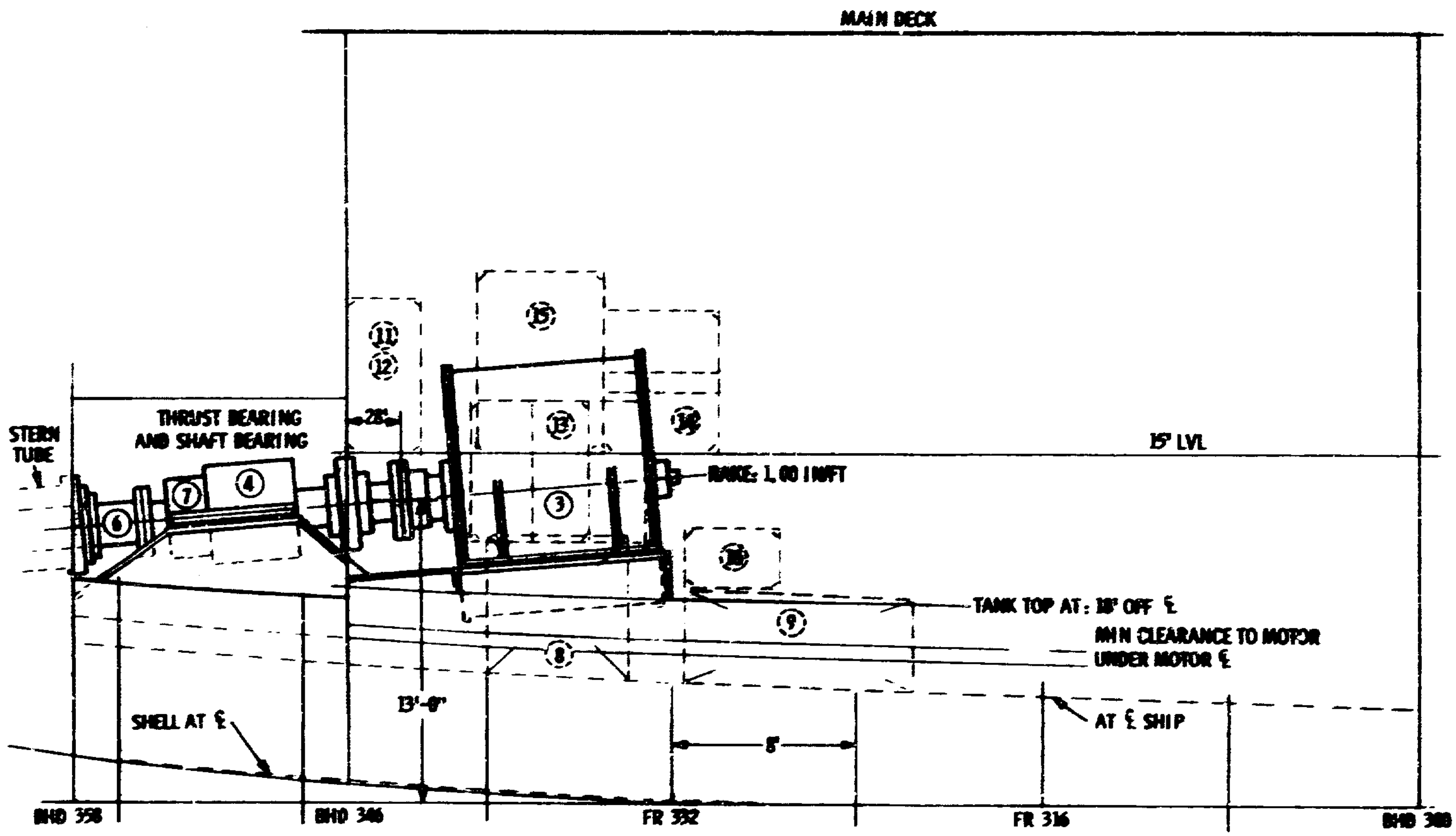


Figure 2.10. Machinery Arrangement in Destroyer, Aft Engine Room, Elevation

be recovered if the smaller diameter fixed blade propeller were to be located at a higher elevation relative to the baseplane of the ship, probably desirable from a draft reduction point-of-view.

The thrust bearing is shown located in the compartment just aft of the engine room, Figure 2.10, as close to the stern tube as practicable. In many ship shafting arrangements this is the preferred location for the thrust bearing since the greatest overall thrust block stiffness can be attained here with a foundation of optimum rigidity. If the bearing location in the machinery room is preferred, an arrangement similar to Figure 2.6 can be achieved by moving the motor forward about 3 feet.

To show the flexibility in arrangement inherent with electric propulsion, the gas turbine-generator modules have been positioned on the port side and at an elevation convenient for the inlet and exhaust ducting, Figures 2.11 and 2.12. Although the generators are arranged aft of the turbines in order to shorten the cabling to the switchgear and motor, there is no other reason why the inverse arrangement (as now used on DD963) could not be used.

Different from the plan used in Forward Engine Room, the generators are mounted on an extension of the gas turbine module bedplate, or subbase. This bedplate supports two gas turbines and two generators, Figures 2.11 and 2.12, and in turn rests on a machinery foundation not shown.

Unfortunately, all the good features possible in such an arrangement are not fully utilized on account of the necessity to retain the high misalignment coupling between generator and turbine, this being required on account of the large-motion shock mounts on the LM-2500 gas turbine. Despite this aspect, the inclusion of the generator within the power module structure takes full advantage of the mutual disassociation of generators and motors inherent with electric drive. Moreover, there is no reason of necessity to have two gas turbine-generator units mounted on a single bedplate and it

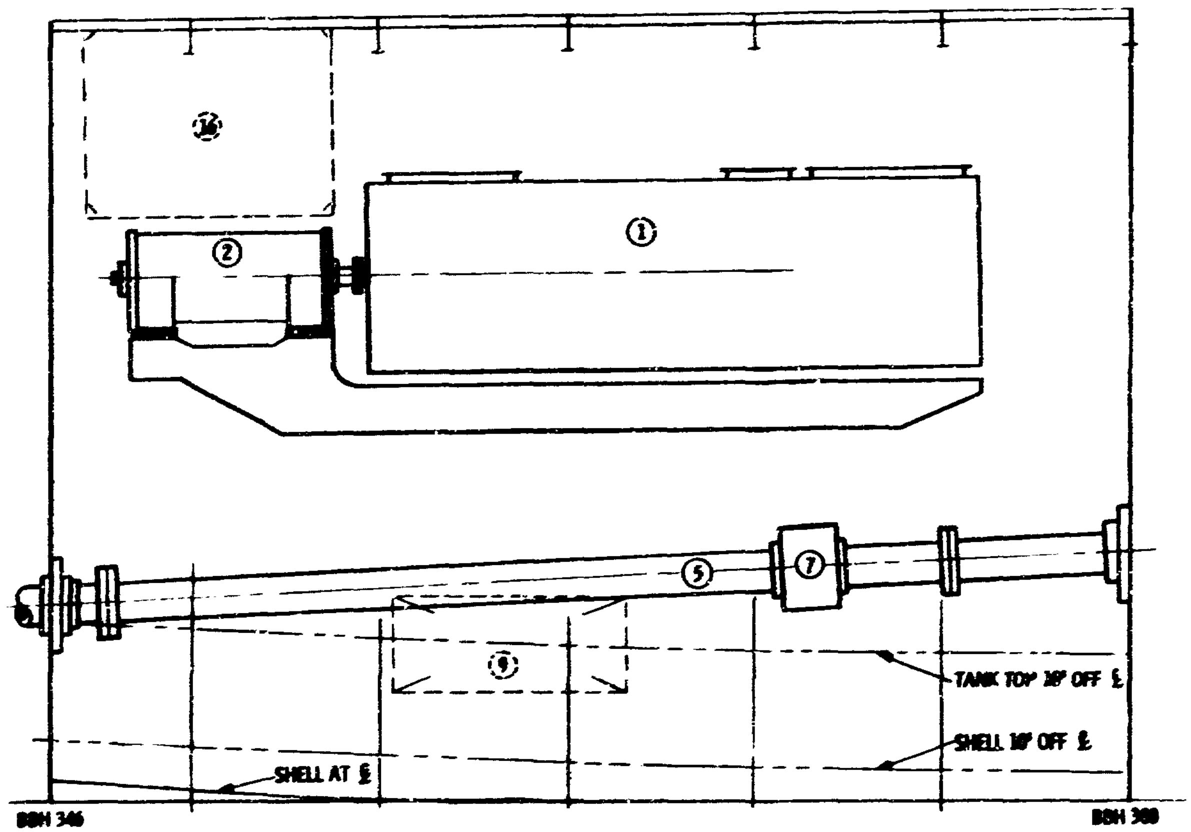


Figure 2.11. Machinery Arrangement in Destroyer
Aft Engine Room, Elevation

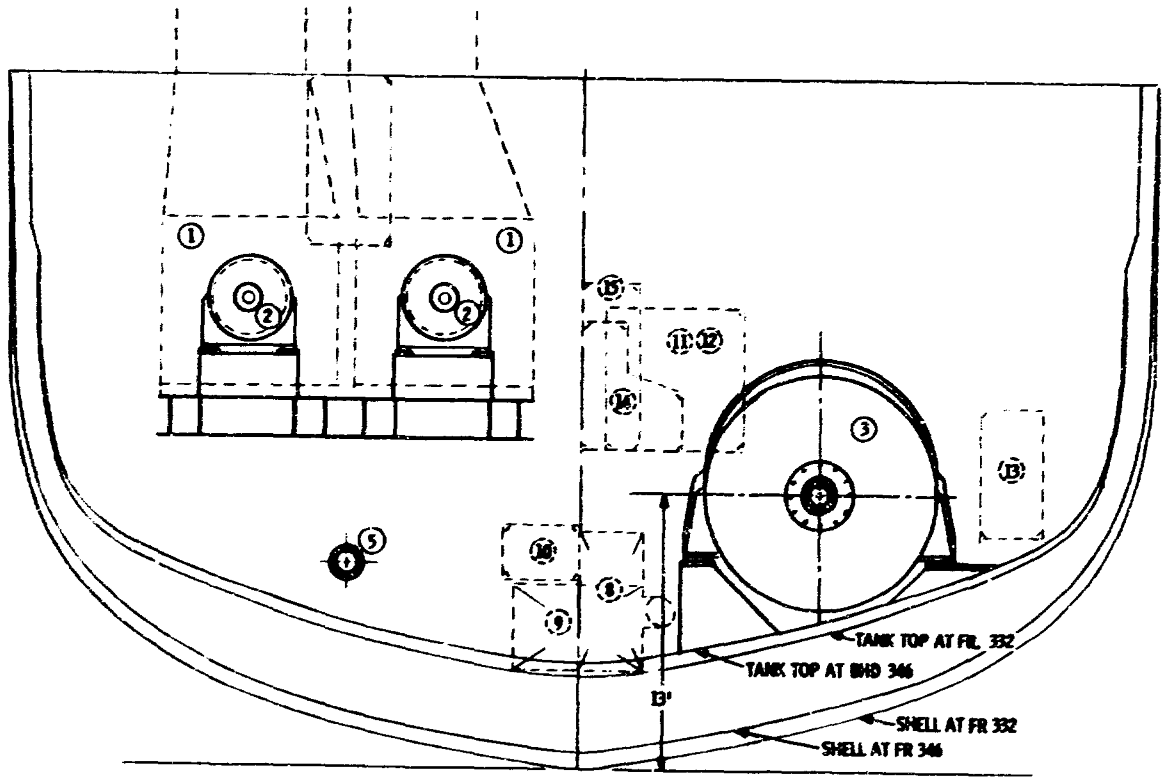


Figure 2.12. Machinery Arrangement in Destroyer, Aft Engine Room, Section

is obvious that many ship arrangements will call for separate modules for each unit. Considerations of damage protection may lead to an arrangement with each of the four turbine-generators in a separate space.

Shown also on the layouts of the Aft Engine Room are the spaces required for the subsystems as previously described for the forward engine room.

2.1.1.3 Alternate Machinery Arrangements

The twin shaft electric drive system offers opportunities for various arrangements not available to other propulsion systems, since the motors and generators may be located in separate spaces either close by or well removed from each other. Several options may be chosen during the preliminary design stage of a ship system and evaluated for desirable and improved characteristics. These could be lesser weight, better weight distribution, improved accessibility, better gas turbine ducting arrangements, or enhanced survivability or damage control effectiveness.

The conventional two main machinery space arrangement is depicted in Figures 2.6 to 2.13 and is modeled after the DD963 layout.

Figure 2.14 shows two alternate arrangements, each being four compartment layouts, with the gas turbine-generators retained in paired groupings and in different spaces from the propulsion motors. These are only two of the many possibilities, since the complete system has a total of six generators and motors, so that combinations with as many as five or six separate spaces may be studied.

Although the sketches shown imply location of turbine generators and motors without significant vertical separation, there is no reason other than adverse weight distribution why the turbine generators could not be placed in separate compartments higher or lower in the ship than indicated in the arrangements shown.

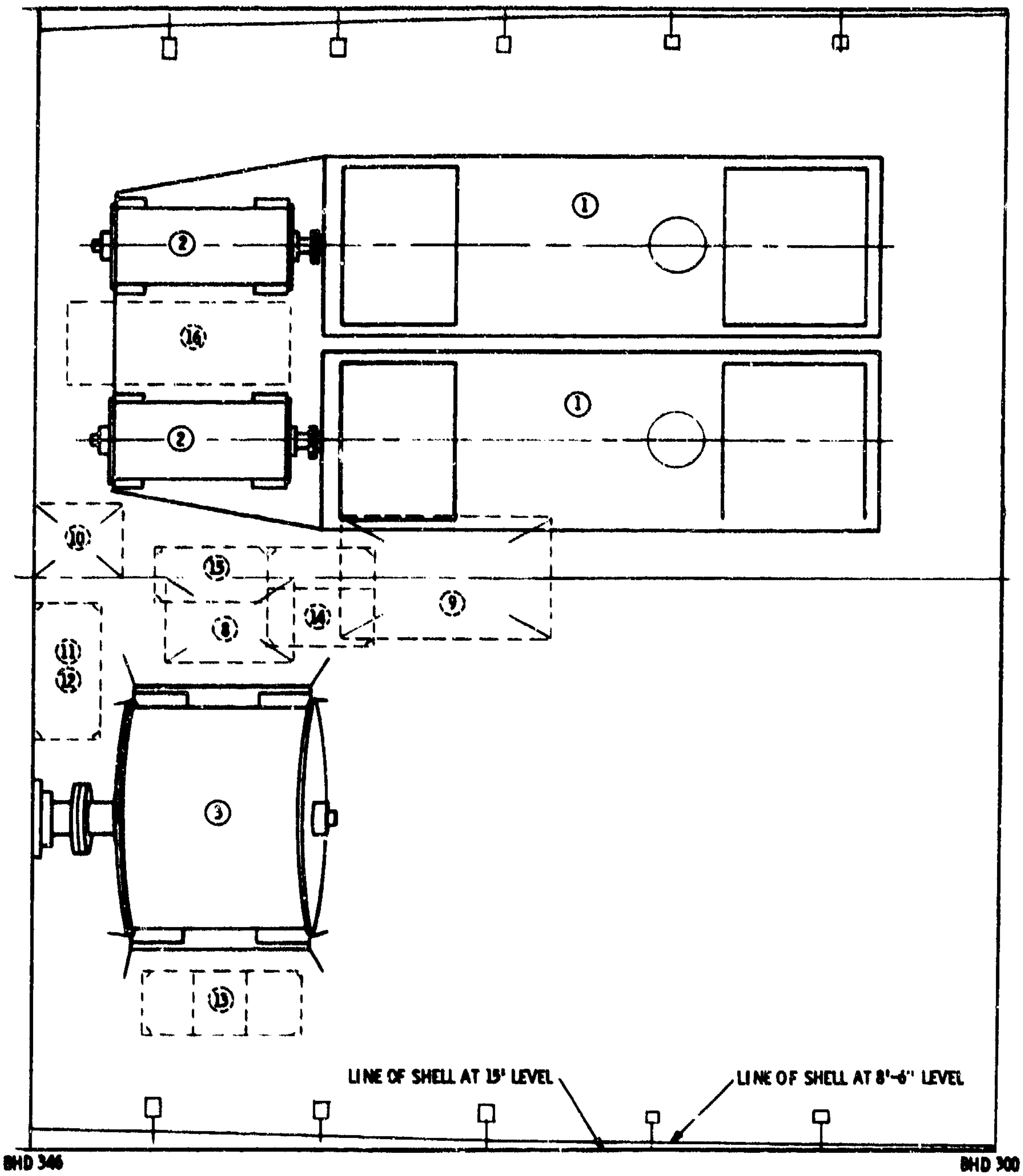


Figure 2.13. Machinery Arrangement in Destroyer
Aft Engine Room, Plan

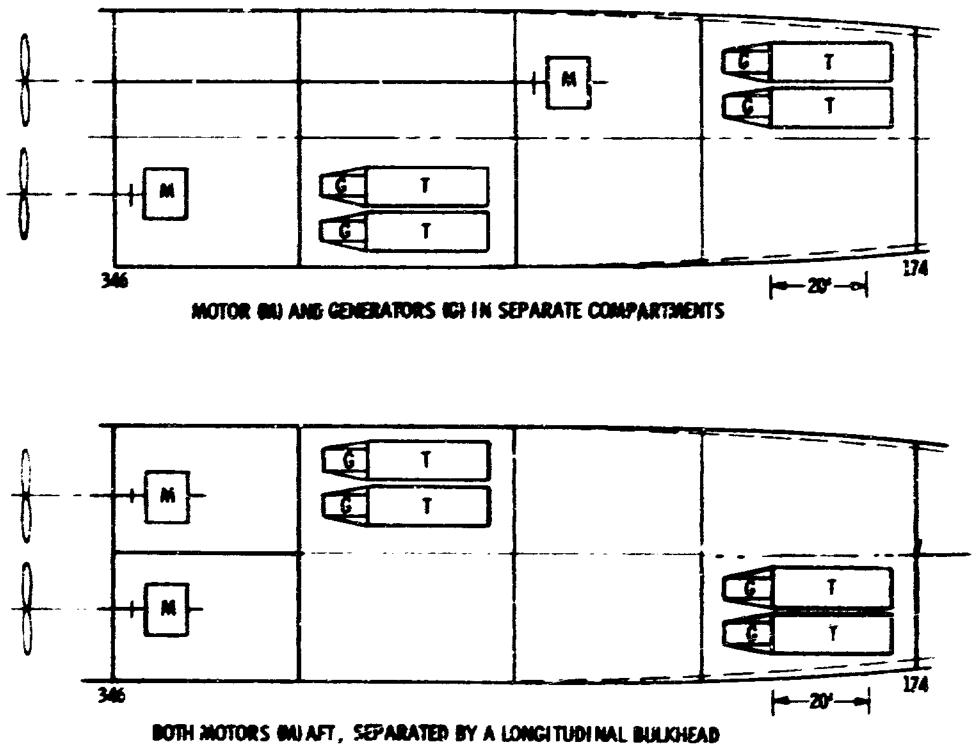


Figure 2.14. Two 4 Space Machinery Arrangement

2.1.2 Summary of Weight, Volume, and Ship's Service Requirements

The propulsion drive components and their estimated weights and volumes are tabulated on Table 2.6. In addition, the cost, in weight, for ship's service electrical and seawater requirements are also shown on this figure. The mission used was that specified in the work directive for the SWATH 352 hour mission. Where definitive effort is required on components yet to be developed, an estimate is given of what we believe is attainable and realistic. Breakdown of the individual weights can be found in the specific sections describing these components.

2.2 System Block Diagrams

The electric propulsion power distribution block diagrams have previously been shown as Figures 2.1 to 2.5 for the various power configurations, full, half, quarter, and cruise (both cross-connected and split plant).

The control system block diagram is shown on Figure 2.15 which indicates the dynamic, upper level and lower level of the control system. Also shown on this figure are the feedback parameters and the sensed variables that are to be indicated or recorded.

The ship's service electrical distribution for the starboard side is shown on Figure 2.16. A similar system exists for the port side. The spare ship's service generator would have provisions for paralleling with either generator. Interconnections would also be supplied to feed both sides of the ship from one generator.

The lube oil schematic for one side of the ship is shown on Figure 2.17. A description of the lube system is given in Section 3.7 of this report.

Figure 2.18 is the schematic flow diagram for the dionized cooling water system, again for only one side of the ship. The cross-connect line is shown dotted for those configurations where one coolant system is used for both sides.

TABLE 2.6

SUMMARY OF COMPONENTS WEIGHT, VOLUME AND SHIP'S SERVICE REQUIREMENTS FOR BASELINE of DESTROYER PROPULSION SYSTEM

Propulsion Components				Required Ship's Service for 352 Hr Mission					
				Electrical			Seawater		
					Cost (Lb)			Cost (Lb)	
Description	Quantity Per Ship	Shipset Volume (Cu Ft)	Shipset Weight (Lbs)	KW	Hardware	Fuel	GPM	Hardware	Fuel
40 KHP Motor	2	1,276	237,350	75	3,000	13,600	540	2,160	2,960
20 MW Gen.	4	372	94,580				480	1,920	2,630
Motor Exciters	2	82	3,400	500	20,000	82,800	30	120	164
Gen. Exciters	4	92	4,000	300	12,000	17,400	40	160	219
Transmission Line	1	60	19,200				5	20	27
Switchgear	1	750**	6,000**						
Control	1	110**	1,800**	10	400	3,500			
Cover Gas System	6	48	1,050	5	200	1,760	5	20	27
Braking System	2	26	800				60	240	329
Lube Oil System	2	72	4,500	45	1,800	3,750	40	160	219
TOTAL		2,888	372,680	935	37,400	122,810	1,200	4,800	6,575

**Estimated

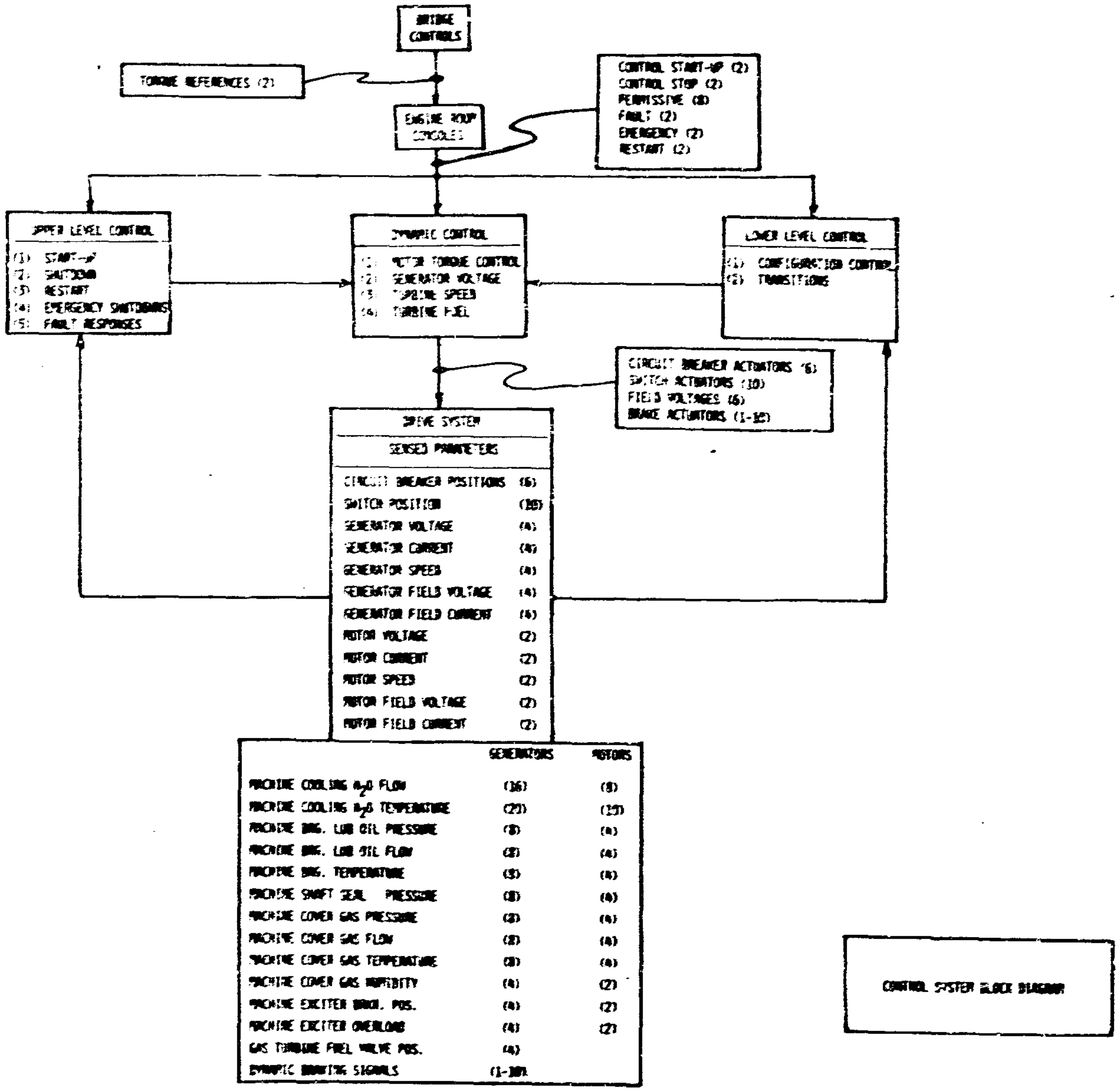


Figure 2.15. Control System Block Diagram

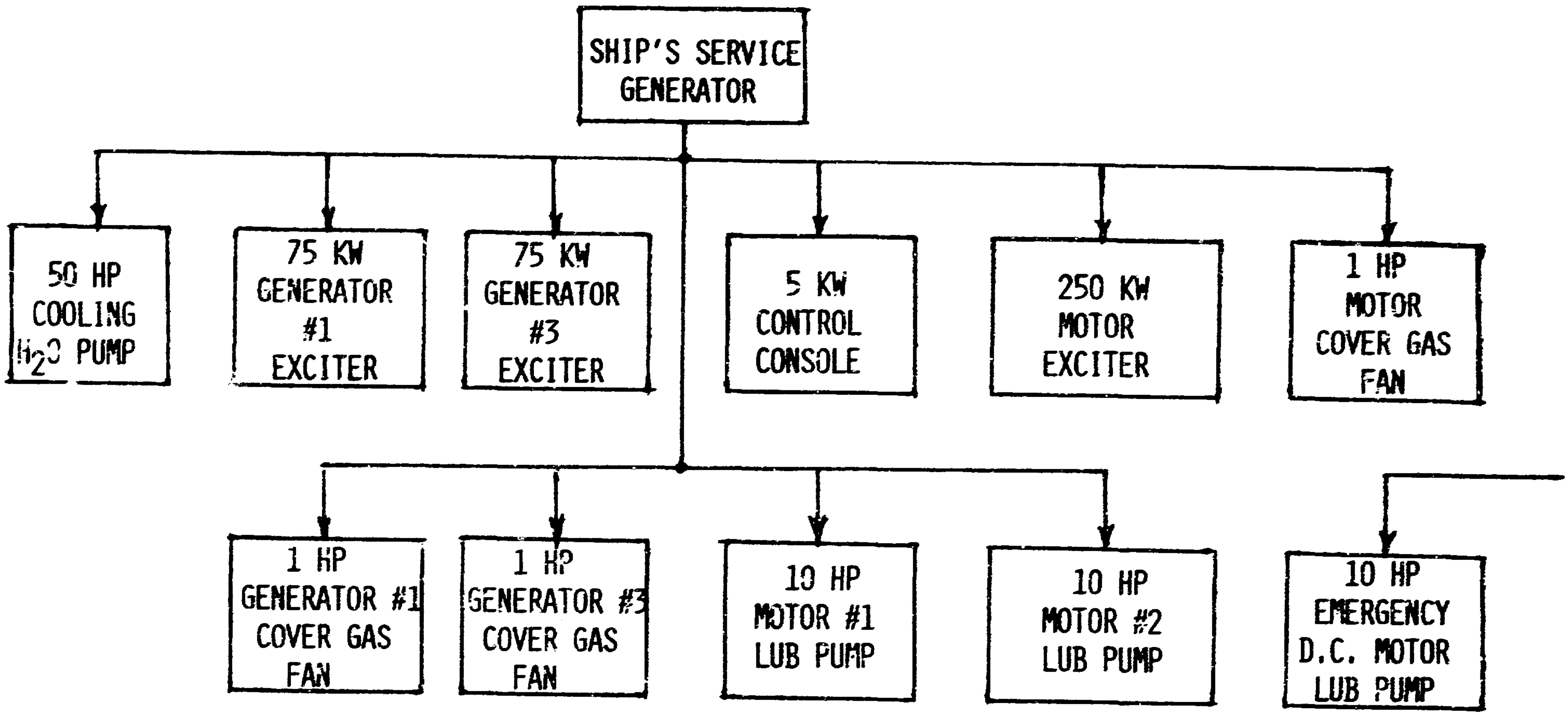


Figure 2.16. Ship's Service Electrical System

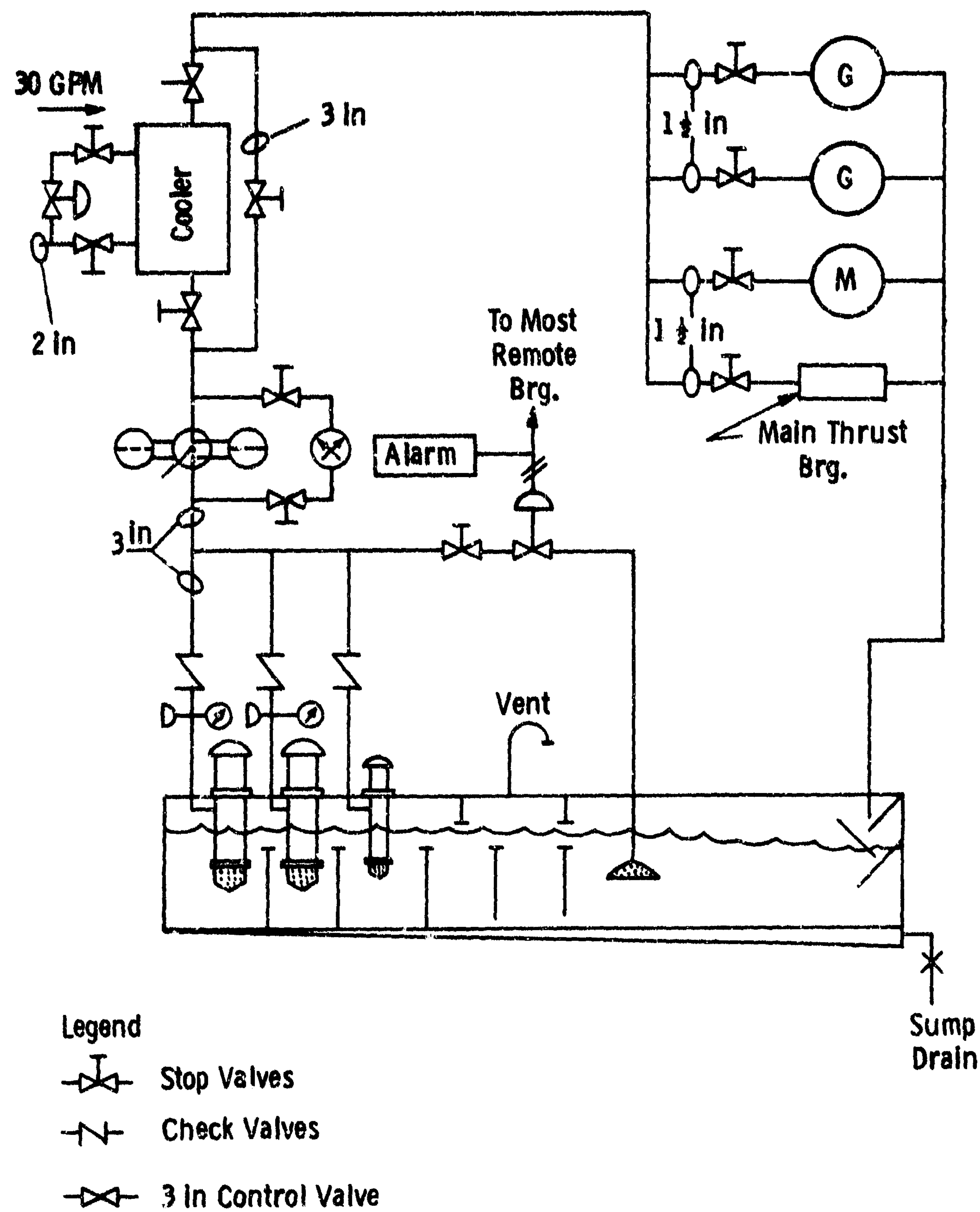


Figure 2-17. Lube Oil Schematic

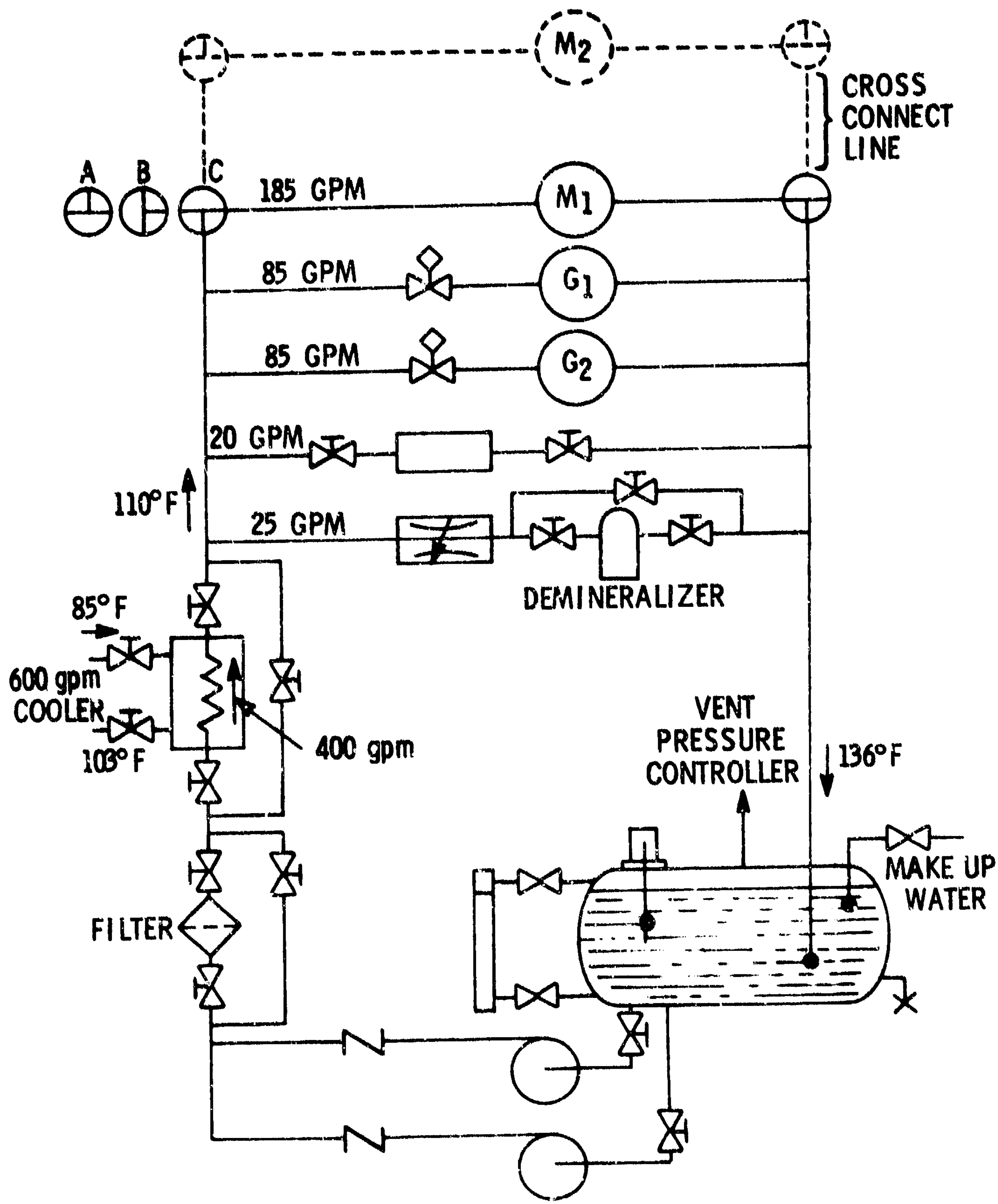


Figure 2.18. Deionized Cooling Water Schematic

A typical cover gas schematic is shown on Figure 2.19 for a SEGMAG machine. Each of the six machines will have a similar system.

2.3 System Operation

2.3.1 Normal Operation

This section describes normal operation and is divided into three major parts which are highlighted below.

- Electrical Diagrams

  A propulsion system power schematic is presented which shows the location of the switches used to configure the system. A description is given of the various configurations which allow operator selection of the number of generators used to power the motors.

- Steady State System Performance

  The methods and assumptions used to determine the system operating characteristics are given. Generator and motor voltages, currents, speeds, powers, and efficiencies are tabulated and presented graphically. Ship service fuel costs are detailed and the total system fuel consumption as a function of propeller speed is given.

- Representative Mission

  The propulsion system performance evaluation for a representative mission is given both on a summary basis and on a mission step by step basis.

2.3.1.1 Electrical Diagrams

2.3.1.1.1 Propulsion System Power Schematic

The propulsion system power schematic shown in Figures 2.1 to 2.5 is described in the following paragraphs.

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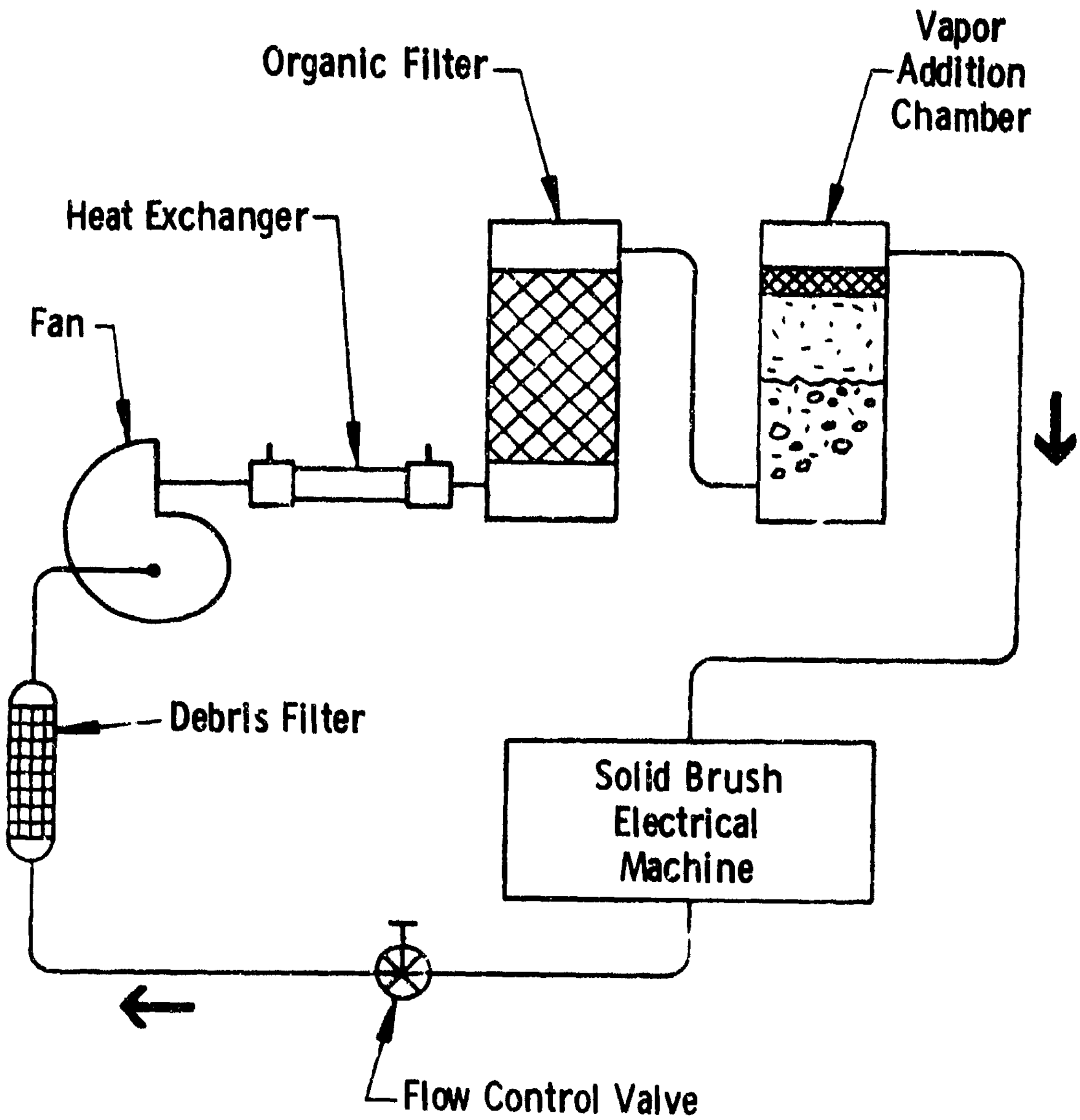

Figure 2.19. Cover Gas Schematic

Each SEGMAG dc generator (G1 through G4) is driven directly by a LM-2500 gas turbine (GT1 through GT4). The nominal rating for these units is 15 MW (20,000 hp). Each propeller shaft of the twin-screw ship is coupled directly to a 30 MW (40,000 hp) SEGMAG dc motor.

The power electrical transmission lines between the SEGMAG machines are shown including the sixteen switches (S1 through S16) used to configure the system. Each engine room contains two generator/gas turbines and one motor. Besides the transmission lines within each engine room, a cross connect line allows for electrical power transfer between the two sides.

By setting the switches in appropriate positions, the motors may be powered by one, two, or four generators. These arrangements are referred to as the quarter, half, and full power configurations respectively.

Due to the discrepant rotational speeds of the power turbine (nominal 3600 rev/min max) and propeller (nominal 168 rev/min max), the drive system functions as an electrical gear box. Further, by using separately excited machines, the "gear ratio" is adjusted to optimize the performance of the system. That is, for a given load the speed of each generator/power turbine is adjusted to minimize the gas turbine SFC (specific fuel consumption).

2.3.1.1.2 System Configurations

Five basic propulsion system configurations are used. When the ship is to be driven, either the quarter power, half power, or full power configuration may be selected by the operator. When the ship is not to be driven, the operator may select the idle configuration which minimizes the auxiliary power loads while still allowing the gas turbines to remain running. The zero power configuration is called for by the control system when performing transitions between the idle, quarter power, and half power configurations.

The electrical connection diagram for the full power configuration is shown in Figure 2.1. Each motor is driven by two generators connected in parallel. The sides are not connected electrically and thus there are two separate electrical power circuits. This split plant mode allows maximum operating flexibility since each motor is controlled independently of the other.

A typical half power configuration is shown in Figure 2.2. This is also a split plant mode. On each side one generator supplies power to the motor in its own engine room.

In the quarter power configuration there is only one power circuit. The cross connect line must be used in order to connect the two motors and any one of the generators in series. Figure 2.3 shows the case where generator 1 is powering the two motors.

In the quarter power configuration, differential motor torques are accomplished through motor field control. Torque ratios up to 2:1 are attainable which allows for reasonable operating flexibility.

In the zero power and idle configurations, all of the switches are open and thus there is no power transfer between the generators and motors.

2.3.1.1.3 Transitions Between Configurations

The allowable transitions between the five configurations, idle, zero power, quarter power, half power, and full power, and the necessary conditions are illustrated in Figure 2.20. The power configuration is plotted against available generators, i.e., generators which are operating in the system or are ready to operate in the system (gas turbine at idle).

In both the idle and zero power configurations, the propulsion system is de-energized, i.e., all sixteen switches are open, and therefore, power is not transferred between the SEGMAG machines. In order to transition from the idle to the zero power configuration, the cooling

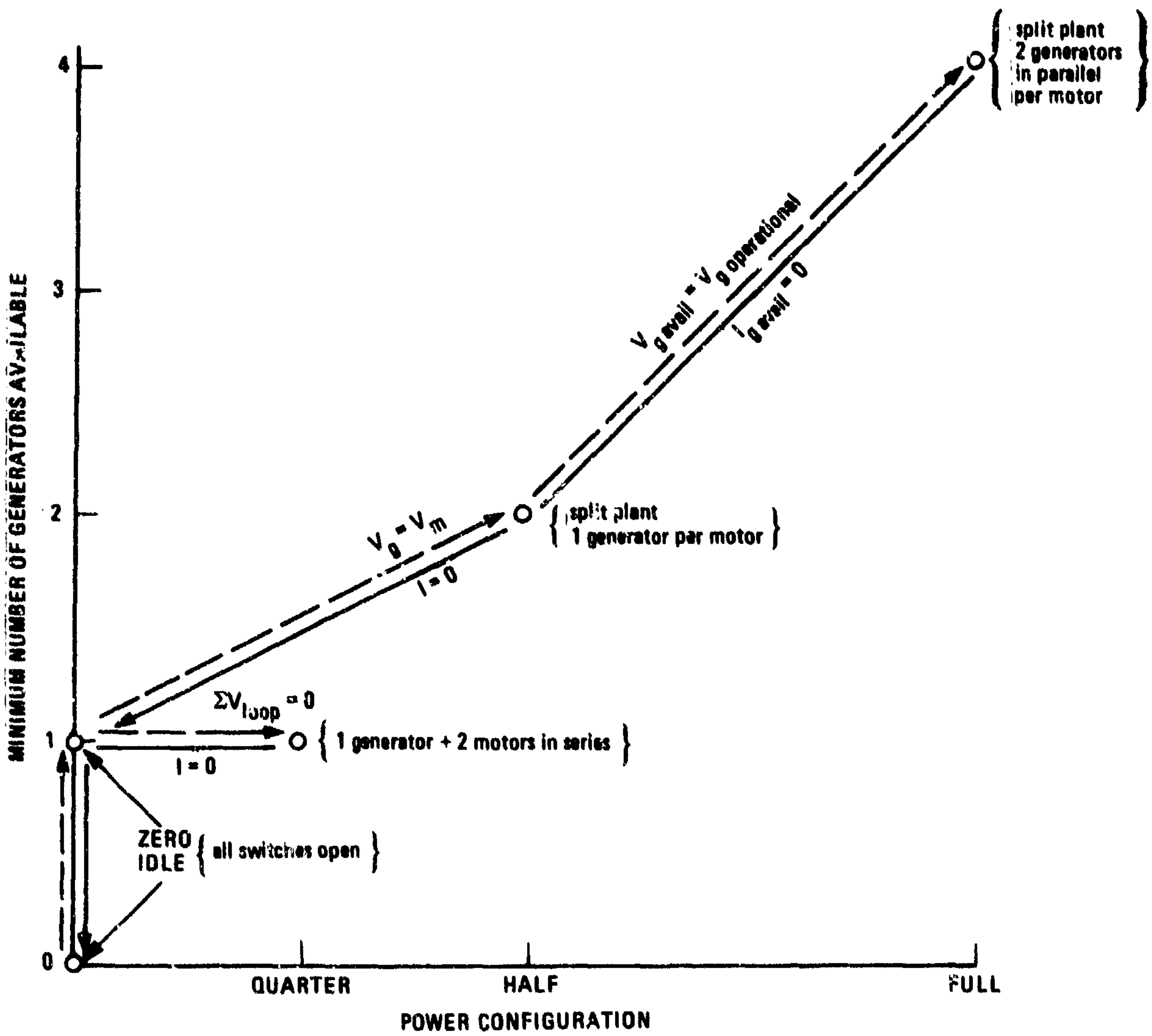

Figure 2.20. Allowable Transitions Between Configurations

water systems must be operating and the motor fields are energized to their rated values. In the reverse transition, each exciter is commanded to produce zero field current and the cooling water systems may be turned off.

The current must be approximately zero before opening the switches in transitioning from either the quarter or half power configuration to the zero power configuration. In carrying out the reverse transitions, the sum of the voltages around the circuit(s) must be approximately zero before closing the switches. The zero power configuration serves as an intermediary between the quarter and the half power configurations, i.e., the system must first be de-energized before reconfiguring from the quarter to half power configuration or vice versa.

The transition between the half and full power configurations can be performed without de-energizing the system because the generators are connected in parallel. When transitioning from the half to the full power configuration, the voltage of the available generator must be approximately equal to the voltage of the operating generator before closing the appropriate switches. In the reverse transition, the current must be approximately zero in the generator which is to be taken off the line before the appropriate switches may be opened.

In principal, transitions between the zero and full power configurations could be made. However, this would entail additional control complexity with little or nothing to be gained, since the transitions between the half and full power configurations can be made without power interruption.

When a transition is called for, the control system performs the task of making the transition. This is accomplished by controlling the machine fields to meet the necessary conditions (e.g., zero armature current) and then commanding the appropriate switches to open or close.

2.3.1.2 Steady State System Performance

Before proceeding with a detailed description of the system performance, a few pertinent explanatory notes are given in the following paragraphs.

- Design Point

  At the system design point the ship speed is 16.46 m/s (32 knots) and the propeller speed is 168 rev/min. This point is hereinafter referred to as the full power operating point.

- Ship Drag

  The ship drag is proportional to ship speed squared, i.e., the drag coefficient is assumed to be a constant. At the full power operating point the total ship drag is 2.37457 MN (533,826 lb).

- Propeller

  The propeller characteristics are based upon the data for propeller number 18 from the work of I. Ya. Miniovich (see Appendix No. 2). A propeller diameter of 4.9378 m (16.2 ft) was selected such that the thrust balances the drag at the full power operating point.

- Gas Turbine

  The gas turbine performance is based upon estimated average performance data for the LM-2500 (see Appendix No. 2).

- Cruise

  At the cruise operating point, the propeller speed is 100 rev/min and the propulsion system is in the quarter power configuration.

2.3.1.2.1 System Operating Characteristics

For a given configuration and load (i.e., propeller speed and torque), the system operating characteristics may be altered over a wide range by changing the machine fields. It is therefore appropriate to first describe the manner in which the machine fields will be adjusted by the control system.

Steady state system operating characteristics including the machine field currents are shown in Figure 2.21 plotted against motor speed. The motor field current is held constant at its rated value of 1391 A in the full and half power configurations.

In the quarter power configuration, the motor field is held constant over most of the motor speed range at 70 percent of its rated value. At motor speeds above 102 rev/min the motor field is increased slightly in order to limit the armature current, I, to a value of 7500 A. Note that when unequal motor torques are called for, the motor fields must be set at different values due to the series connection in the quarter power configuration.

For all three configurations, the generator field is controlled in such a manner that the generator/power turbine speed results in minimum gas turbine SFC (specific fuel consumption). The generator speed plots show the very strong variable gear ratio characteristics of the electrical drive.

Also shown in Figure 2.21 are the terminal voltage and armature current characteristics for a single machine. With a constant motor field, the motor terminal voltage is very nearly proportional to motor speed. Since the transmission line voltage drop is very small the generator voltage is almost the same as the motor voltage in the full and half power configurations. In the quarter power configuration, the generator voltage is twice that of a single motor due to the series connection.

Under steady state conditions with balanced propeller torques, the torque varies as the square of the propeller speed. Since the motor torque is proportional to armature current under fixed motor field conditions, the armature current also varies as the square of the motor speed. An exception, mentioned earlier, is the small upper speed region

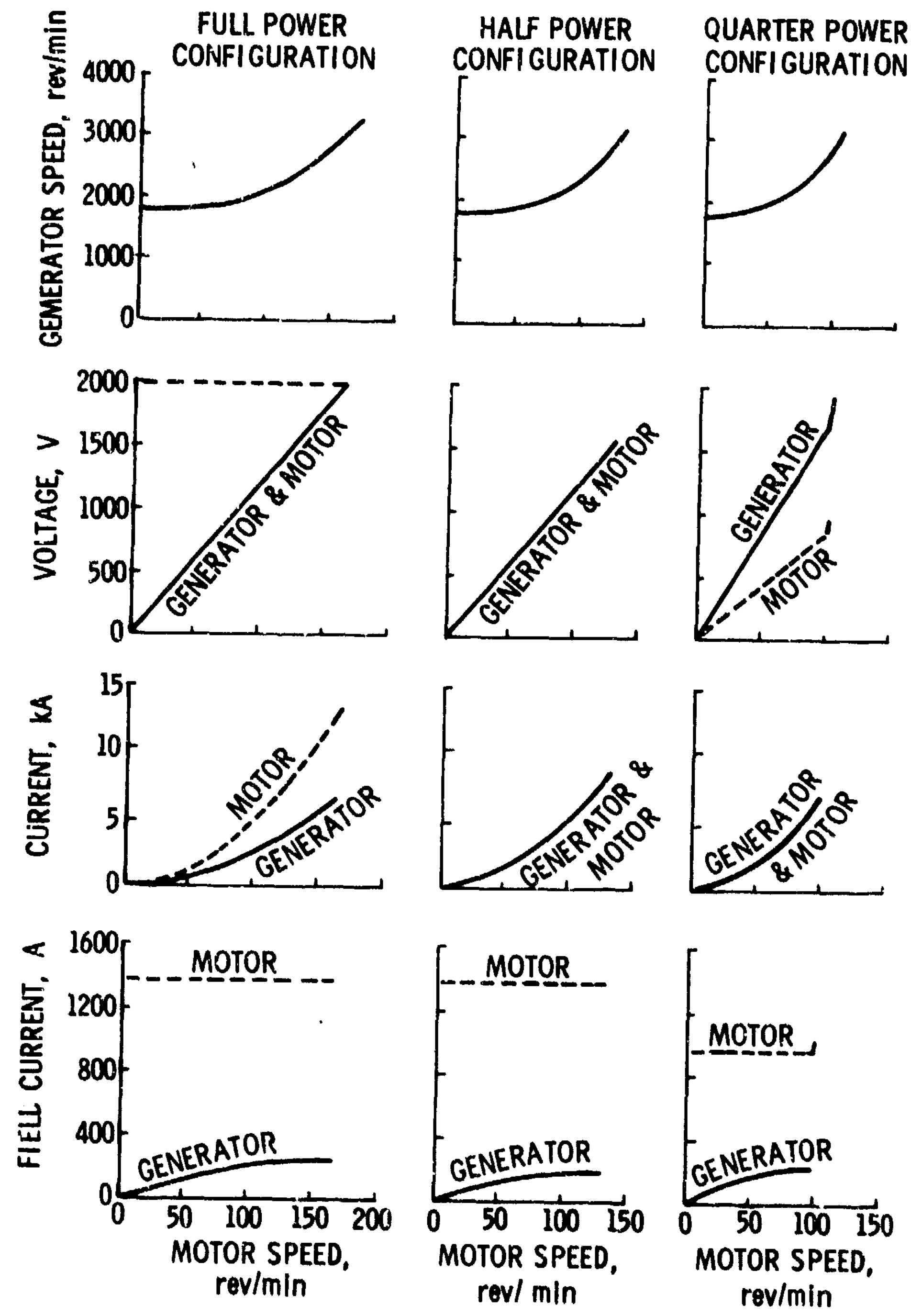

Figure 2.21. System Operating Characteristics

in the quarter power configuration where the armature current is limited to 7500 A by increasing the motor fields.

The generator and motor currents are identical except in the full power configuration. Due to the arrangement of two generators in parallel, driving one motor, the current through a single generator is half that of the current through a motor.

Table 2.7 lists the system operating characteristics for four points. The first three columns show operating values at rated conditions for the full, half, and quarter power configurations. The last column lists the cruise point conditions. The values shown are for a single machine.

2.3.1.2.2 Power Flow

The power flow from the power turbine to the propeller is illustrated in Figure 2.22. Mechanical power is input to the generator through the shaft connected to the power turbine. There may of course be up to four gas turbine/generators operating depending upon the power configuration.

In converting mechanical power to electrical power, the generator incurs machine losses which comprise such factors as stator copper losses, rotor copper losses, brush friction, etc. (see Section 3 for a detailed breakdown).

The electrical power is transferred to the motor via the transmission line. In the processes there is a small line loss.

In reconverting the electrical power to mechanical power, the motor also incurs machine losses. The motor power output drives the propeller shaft directly.

The power input, losses, and power output for four points are listed in Table 2.8. The values listed are on a total system basis. For instance, in the full power configuration, the machine losses for a single generator would be one-quarter of the value shown.

TABLE 2.7

PROPULSION SYSTEM OPERATING CHARACTERISTICS

Power Configuration Operating Point	Full Full	Half Half	Quarter Quarter	Quarter Cruise
Gas Turbine				
Specific Fuel Consumption, kg/kW-hr	0.249	0.249	0.249	0.258
(lb/hp-hr)	(0.409)	(0.409)	(0.409)	(0.424)
Generator Input				
Power, kW	14440	14440	14440	12311
(hp)	(19365)	(19365)	(19365)	(16510)
Speed, rev/min	3193	3193	3193	2988
Torque, kNm	43.18	43.18	43.18	39.34
(10^3 lb-ft)	(31.85)	(31.85)	(31.85)	(29.02)
Generator Output				
Power, kW	14261	14221	14254	12144
Voltage, V	1998.8	1583.9	1900.6	1679.7
Current, A	7135	8978	7500	7230
Generator Field				
Current, A	252	200	240	227
Motor Input				
Power, kW	28514	14216	7178	6063
Voltage, V	1998.3	1583.4	949.0	838.6
Current, A	14269	8978	7500	7230
Motor Output				
Power, kW	27904	13926	6924	5885
(hp)	(37420)	(18674)	(9285)	(7892)
Speed, rev/min	168.0	133.3	105.6	100.0
Torque, kNm	1586	998	626	561
(10^3 lb-ft)	(1170)	(736)	(462)	(414)
Motor Field				
Current, A	1391	1391	1046	974

Note: Values given are for a single machine.

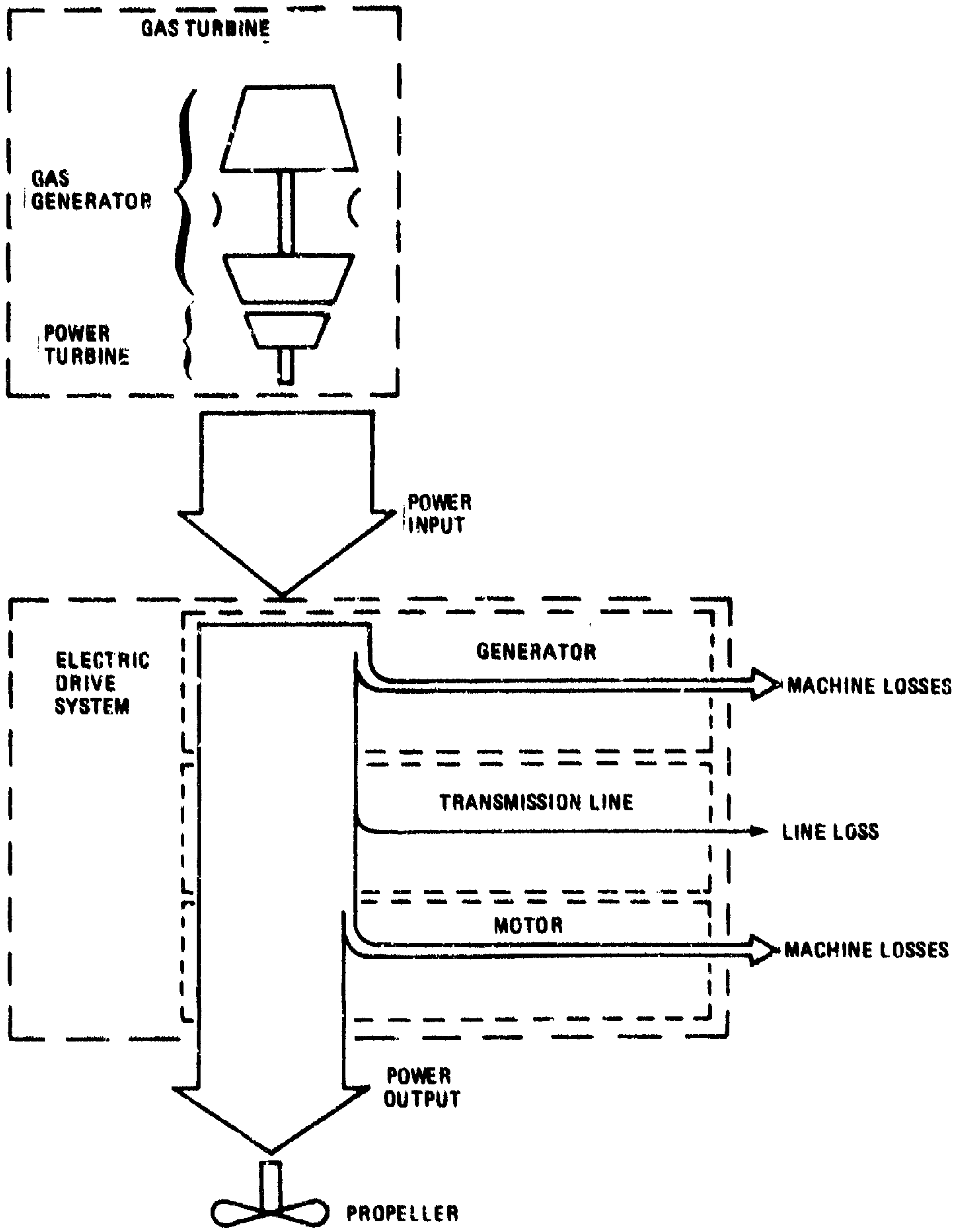

Figure 2.22. Power Flow Diagram

TABLE 2.8

PROPULSION SYSTEM POWER FLOW

Power Configuration Operating Point	Full Full	Half Half	Quarter Quarter	Quarter Cruise
Generator Input Power, kW	57761	28880	14440	12311
(hp)	(77458)	(38729)	(19364)	(16510)
Generator Machine Losses, kW	718	439	186	167
Transmission Line Losses, kW	16	9	19	18
Motor Machine Losses, kW	1219	581	387	356
Motor Output Power, kW	55808	27851	13848	11770
(hp)	(74840)	(37349)	(18571)	(15784)

Note: Values given are summed for each component type.

2.3.1.2.3 Efficiency

The generator, transmission line, motor, and system efficiency formulas are given below:

$$\eta_{gen} = \frac{\text{(armature) electrical power output}}{\text{mechanical power input}}$$

$$\eta_{tran\ line} = \frac{\text{electrical power output}}{\text{electrical power input}}$$

$$\eta_{mot} = \frac{\text{mechanical power output}}{\text{(armature) electrical power input}}$$

$$\eta_{sys} = \eta_{gen}\ \eta_{tran\ line}\ \eta_{mot}$$

$$= \frac{\text{power delivered to the propellers}}{\text{power supplied by the gas turbines}}$$

Table 2.9 lists the above efficiencies for four points and the system efficiency is shown plotted against motor speed in Figure 2.23. At high power levels, the system efficiency is on the order of 0.96.

TABLE 2.9

COMPONENT AND SYSTEM EFFICIENCIES

Power Configuration Operating Point	Full Full	Half Half	Quarter Quarter	Quarter Cruise
Efficiency				
Generator	0.9876	0.9848	0.9871	0.9865
Transmission Line	0.9997	0.9997	0.9986	0.9985
Motor	0.9786	0.9796	0.9728	0.9706
System	0.9662	0.9644	0.9590	0.9560

2.3.1.2.4 Fuel Cost Breakdown

In addition to the fuel supplied to the gas turbines, fuel costs are also assessed for ship services as follows:

- Auxiliary Electric $0.454 \frac{kg}{kW\text{-}hr}$ $\left(1.0 \frac{lb}{kW\text{-}hr}\right)$
- Sea Water $0.00359 \frac{kg/hr}{liter/min}$ $\left(0.03 \frac{lb/hr}{gpm}\right)$

As illustrated in Figure 2.24, sea water is used as the cold fluid for heat exchangers and auxiliary electrical power is required to drive pumps and to provide field excitation.

A fuel cost breakdown, summed for each component type or item, is shown for four points in Table 2.10. By far, the largest portion of the fuel goes to the gas turbines. At the full power and cruise points, the gas turbines take 97 and 95 percent respectively of the fuel consumed by the total propulsion system. This shows the merit in adjusting the gear ratio to minimize the turbine SFC.

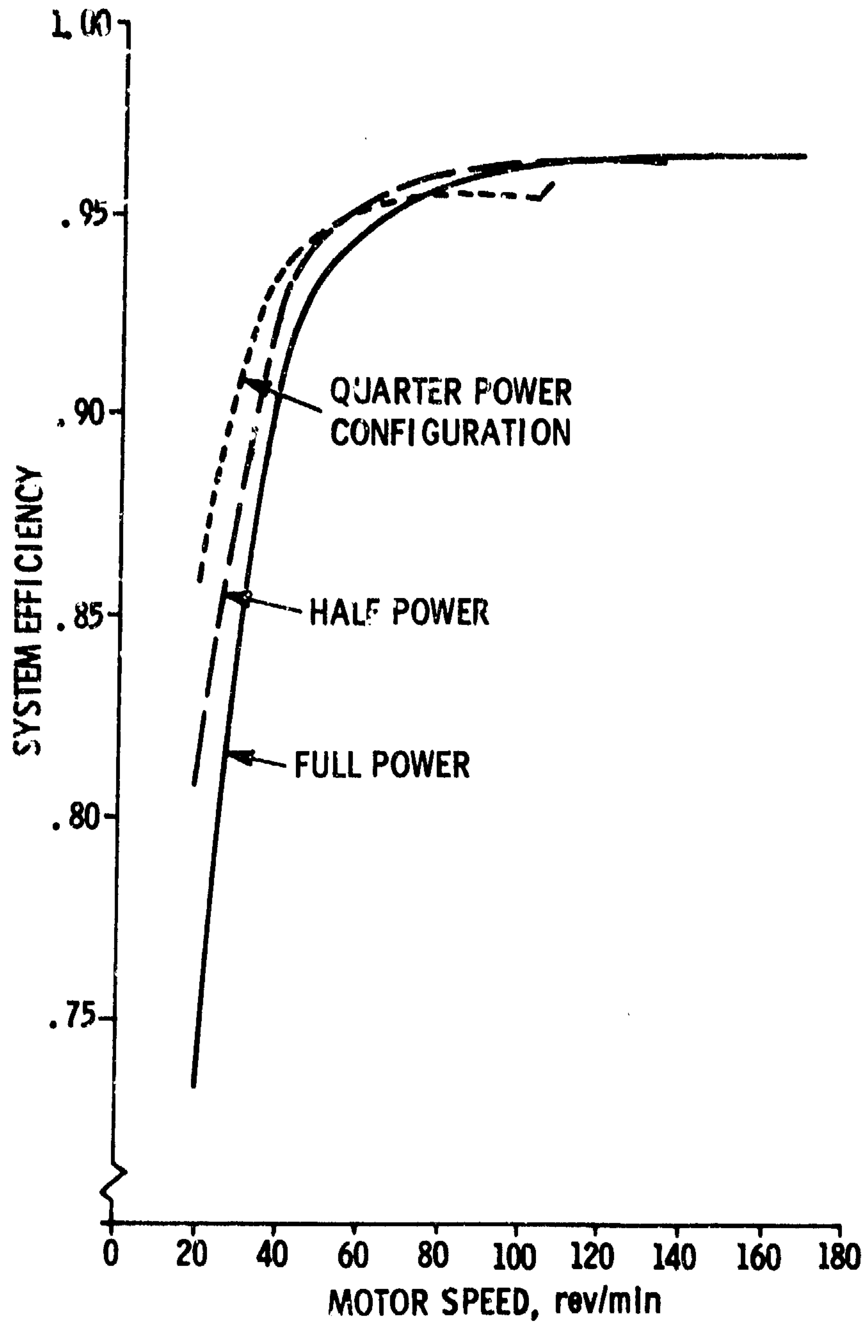

Figure 2.23. System Efficiency

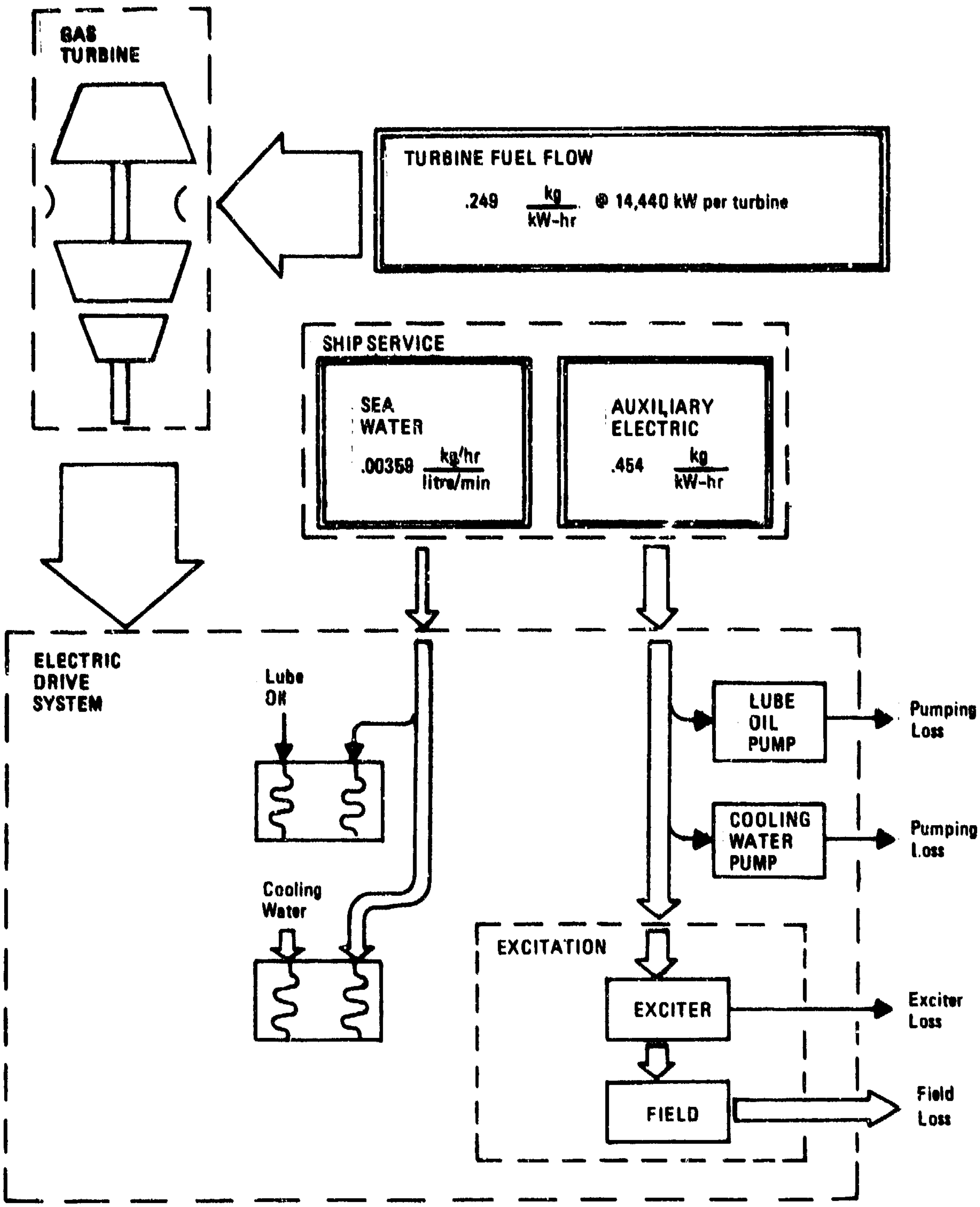

Figure 2.24. Fuel Cost Diagram

TABLE 2.10

FUEL COST BREAKDOWN

Power Configuration Operating Point	Full Full	Half Half	Quarter Quarter	Quarter Cruise
Gas Turbines				
Fuel Consumption, kg/hr	14370	7185	3593	3174
(lb/hr)	(31682)	(15841)	(7920)	(6997)
Auxiliary Electric				
Power Consumption				
Generator Excitation, kW	291	94	68	61
Motor Excitation, KW	531	531	303	264
Lube Oil Pumps, kW	11	11	11	11
Cooling Water Pumps, kW	56	56	28	28
Total, kW	888	691	410	363
Total Fuel Cost, kg/hr	403	313	186	165
(lb/hr)	(888)	(691)	(410)	(363)
Sea Water				
Flow Rate				
Lube Oil Systems, liter/min	227	227	227	227
Cooling Water Systems, liter/min	4542	4542	2271	2271
Total, liter/min	4770	4770	2498	2498
(gpm)	(1260)	(1260)	(660)	(660)
Total Fuel Cost, kg/hr	17	17	9	9
(lb/hr)	(38)	(38)	(20)	(20)
System				
Total Fuel Cost, kg/hr	14791	7516	3787	3348
(lb/hr)	(32608)	(16569)	(8350)	(7380)

In the following, details are given of the assumptions and calculation methods used to establish the various fuel costs.

- Gas Turbine

  The gas turbine SFC is shown plotted against propeller speed in Figure 2.25. Curves are shown for the quarter, half, and full power configurations. The curves are based upon estimated average performance data and assume that for a given power requirement the power turbine/generator speed is optimized to achieve a minimum SFC. For a given propeller speed, the SFC varies widely with the power configuration being highest for the full power and lowest for the quarter power.

  For a given operating point the fuel consumed by the gas turbines is the product of the SFC and the sum of the mechanical power delivered to the generators. At a fixed propeller speed, the sum of the power delivered to the electrical drive system by the gas turbines is very nearly independent of the configuration. For instance, at a propeller speed of 100 rev/min, this power is 12311 kw, 12205 kw, and 12210 kw respectively for the quarter, half, and full power configurations. Therefore, it is of considerable advantage to operate with the minimum number of gas turbine/generators required to power the motors due to the SFC characteristics.

- Excitation

  The electrical power for field excitation makes up for the field losses and exciter losses. Following a description of these losses, a sample tabulation is given.

  Field Losses

  The field loss for a machine is calculated by taking the product of the field resistance and the square of

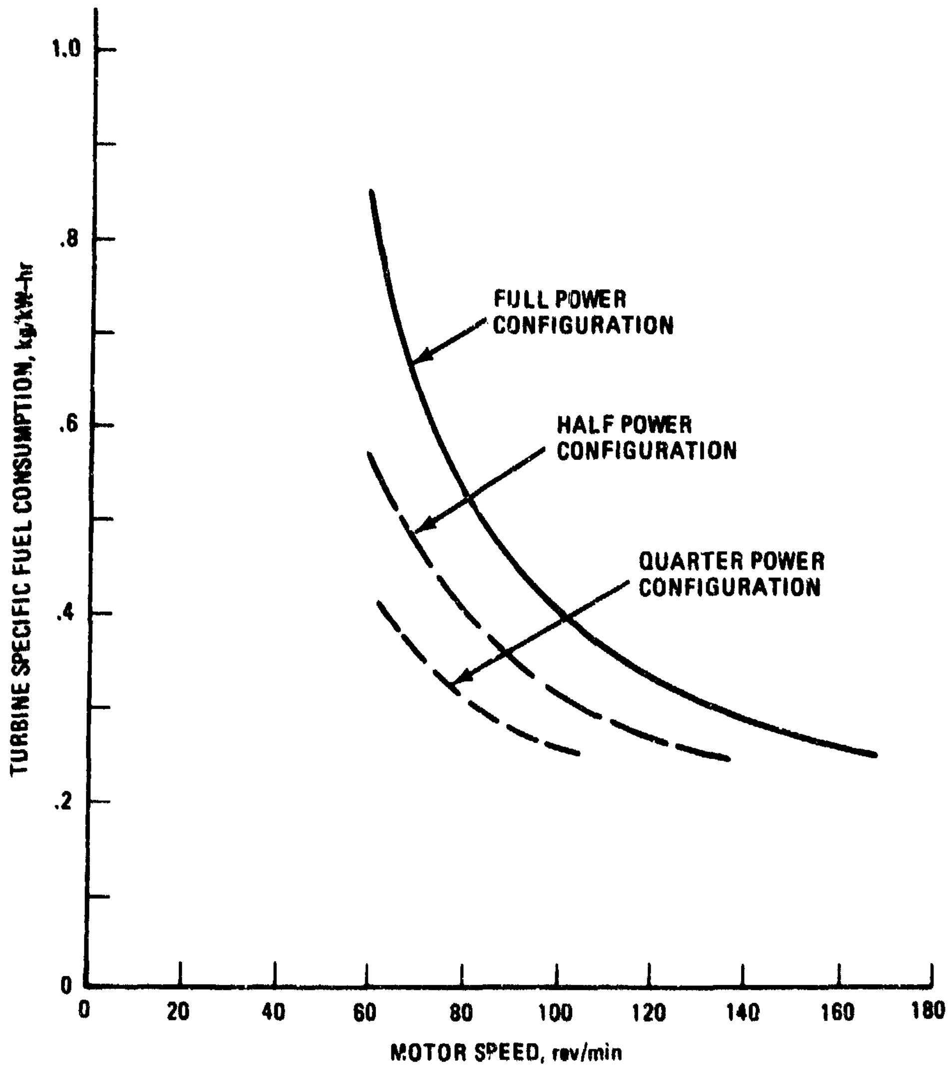

Figure 2.25. Specific Fuel Consumption

the field current. For the generators and motors, the values of the field resistances are 1.115 and 0.133 ohm respectively.

At the generator design point, the field loss is 56 kW at a field current of 224 A. For the motor, the field loss is 257 kW at 1391 A.

The simplified model for a machine field exciter consists of a transformer with fixed and variable losses and a solid state PDR (phase delayed rectifier) with a constant voltage drop of 2 V. The design point values in the preceeding paragraph are used here as the base current and power for the exciters.

The fixed losses are assumed to be approximately 1 percent of the base power, being 0.6 kW for the generator and 2.6 kW for the motor. These losses are present whenever the exciter is energized, i.e., whenever the transformer primary is connected to the ship service 3 phase electrical power supply.

The transformer variable losses are proportional to the square of the field current. At base current, these losses are assumed to be the same as the fixed losses.

At the base conditions, the loss for a single generator exciter is 1.7 kW and for a single motor exciter it is 8.0 kW.

Table 2.11 lists the field and exciter losses at the full power operating point. The total excitation fuel cost is 373 kg/hr (822 lb/hr). Approximately 35 percent of the fuel cost is for excitation of the four generators, the remaining 65 percent being for excitation of the two motors.

TABLE 2.11

EXCITATION AT THE FULL POWER POINT

Machine	Generator	Motor
Field Current, A	252.1	1391.0
Field Loss, kW	70.89	257.34
Exciter Loss, kW		
Transformer, Fixed	0.60	2.60
Transformer, Variable units	0.76	2.60
PDR	0.50	2.78
Total	1.87	7.98
Field+Exciter Losses, kW	72.76	265.32
Number energized	4	2
Total Excitation, kW	291.03	530.64
Total Fuel Cost, kg/hr (lb/hr)	132.01 (291.03)	240.69 (530.64)

- Lube Oil Systems

  Each engine room contains an independent lube oil system which requires 5.33 kW of auxiliary electrical power for a pump and 114 liter/min (30 gpm) of sea water for cooling the lube oil. The fuel cost for the two systems is fixed at 5.7 kg/hr (12.5 lb/hr), i.e., that is not a function of the power level or configuration.

- Cooling Water Systems

  A cooling water system is located in each engine room. When operating, the ship services required for a single system are 28 kW of electrical power for the pump and 2271 liter/min (600 gpm) of sea water for the heat exchanger.

In the full and half power configurations, both systems are used with a total fuel cost of 42 kg/hr (92 lb/hr). In the quarter power configuration, one system suffices and the fuel cost is thus reduced to 21 kg/hr (46 lb/hr).

In the idle configuration, both cooling systems may be shut down. This, however, requires that the brushes be lifted on any generator which is turning at (gas turbine) idle speed.

- Items Not Accounted For

  Due to the very low power requirements, certain items have not been included in the fuel cost calculations. These include the control system, CO_2 systems, and switch actuators.

2.3.1.2.5 Fuel Consumption

The total system fuel cost for three configurations is shown in Figure 2.26 plotted against motor speed. From the viewpoint of fuel consumption, the system should be operated in the minimum power configuration commensurate with the power requirements. This improvement in fuel consumption is due primarily to the SFC characteristics which are discussed in the preceeding section. At a motor speed of 100 rev/min, as compared to the quarter power configuration, the half and full power configurations have increased fuel consumptions of 23 and 60 percent respectively.

At low motor speeds, the total fuel consumption does not go towards zero, but rather it levels off due primarily to maintaining a minimum flow rate to the gas turbine(s) and supplying auxiliary electrical power to make up the motor field losses. For instance, at zero motor speed in the quarter power configuration, the total system fuel consumption of 512 kg/hr (1129 lb/hr) is broken down approximately as follows: 75 percent for the turbine, 20 percent for motor field excitation and 5 percent for the lube oil and cooling water systems.

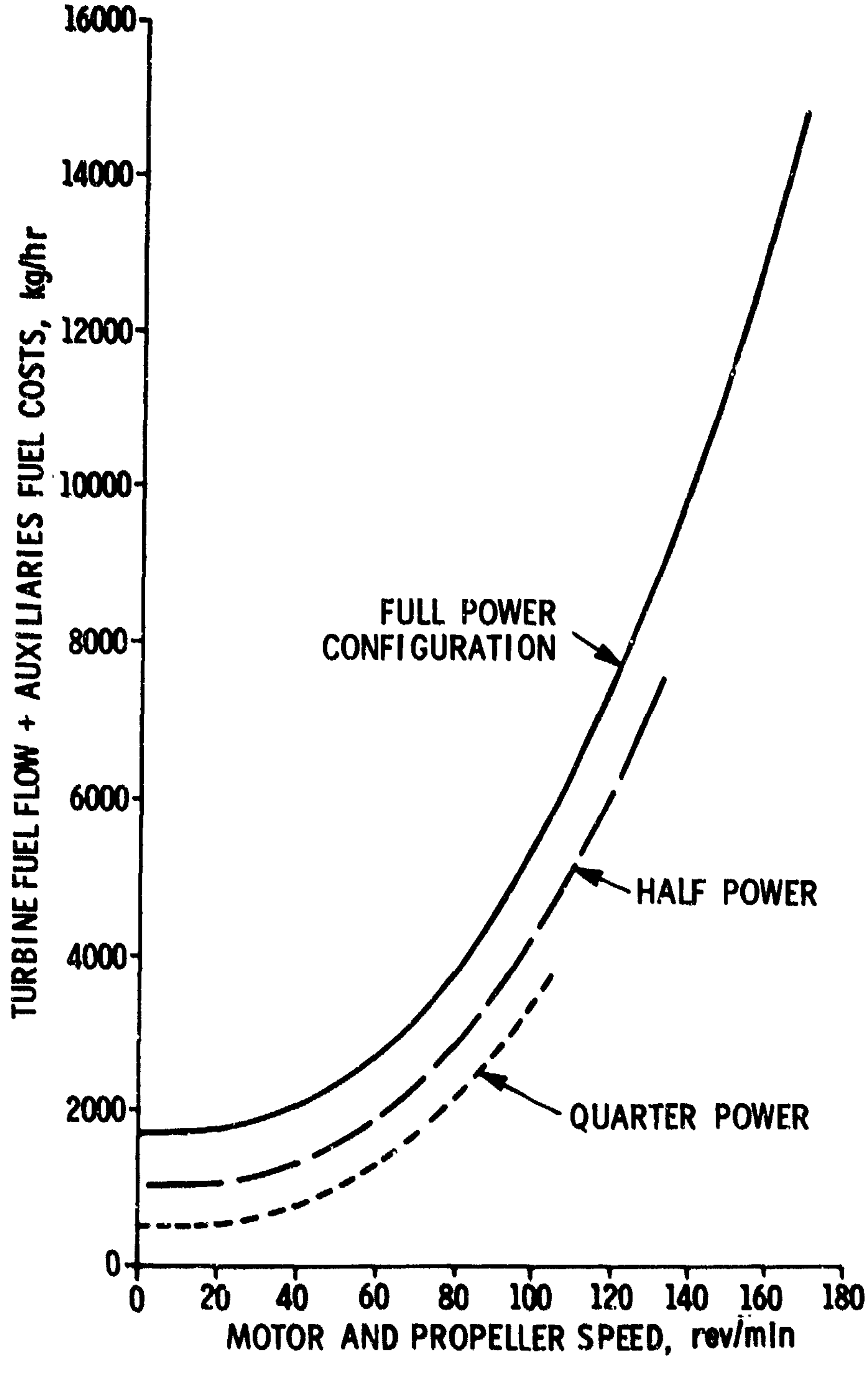

Figure 2.26. Total System Fuel Consumption

The range to fuel consumed ratio is shown in Figure 2.27 plotted as a function of the motor speed and ship speed. The three curves, one each for the quarter, half, and full power configurations, show maximums at about 45 to 60 rev/min (8.6 to 11.4 knots). For each configuration, the range can be doubled for a given quantity of fuel when operating at the curve maxima as compared to operating at the rated power point. At low motor speeds, the ratio drops off going to zero at zero speed.

Compared to the full power operating point (motor speed = 168 rev/min), for a given quantity of fuel the range may be increased about 160 percent if the propulsion system is operated at the cruise point (quarter power configuration, motor speed = 100 rev/min). If the ship were driven in the quarter power configuration at a motor speed of 45 rev/min, the range increase would be approximately 375 percent.

2.3.1.3 Representative Mission

2.3.1.3.1 Mission Profile

The mission profile given in the DTNSRDC Work Directive is for a SWATH ship. The propulsion motor speeds were ratioed by the factor 168/180 in order to apply the profile to the destroyer type ship under consideration here. In addition, the cruise patrol motor speed was set at 100 rev/min. The resulting 352 hour mission profile is tabulated in Table 2.12 and the (average) motor speed is shown graphically in Figure 2.28.

2.3.1.3.2 Integrated Mission Performance

Pertinent steady state system operating characteristics for each step of the profile were integrated over the complete 352 hour mission. The makeup of the fuel consumed is shown in Table 2.13. Broken down on a percentage basis, the turbine, auxiliary electric, and sea water consume 95.15, 4.60, and 0.25 percent of the total.

Step		Operation	Power Configuration	Generators Available		Motors			
						Starboard		Port	
				Idle	Operating in System	Speed, rev/min	Torque, kNm	Speed, rev/min	Torque, kNm
1	-A	Dockside	(Shut Down)	0	0	0	0	0	0
2	0	Dockside	Idle	0	0	0	0	0	0
3	0-0.1	Dockside	Idle	2	0	0	0	0	0
4	0.1-0.11	Dockside Man'g	Half	0	2	8	11	-8	-11
5	0.11-1.0	Harbor Man'g	Half	0	2	42	99	42	99
6	1.0-200	Cruise/Patrol	Quarter	0	1	100	561	100	561
7	200-300	Cruise/Patrol	Idle	1	0	0	0	0	0
8	300-300.1	Cruise/Patrol	Idle	4	0	0	0	0	0
9	300-1.305	High Speed	Full	0	4	145	1181	145	1181
10	305-305.1	High Speed	Full	0	4	145	1181	145	1181
11	305.1-310	High Speed	Full	0	4	168	1586	168	1586
12	310-310.01	Crash Back	Full	0	4	Variable	Variable	Variable	Variable
13	310.01-330	Cruise	Quarter	0	1	103	597	103	597
14	330-350	Cruise	Quarter	0	1	98	508	103	613
15	350-350.1	Cruise	Quarter	1	1	98	508	103	613
16	350.1-352	Harbor Man'g	Half	0	2	37	77	37	77
17	352- +B	Dockside	(Shut Down)	0	0	0	0	0	0

Table 2.12. Mission Profile

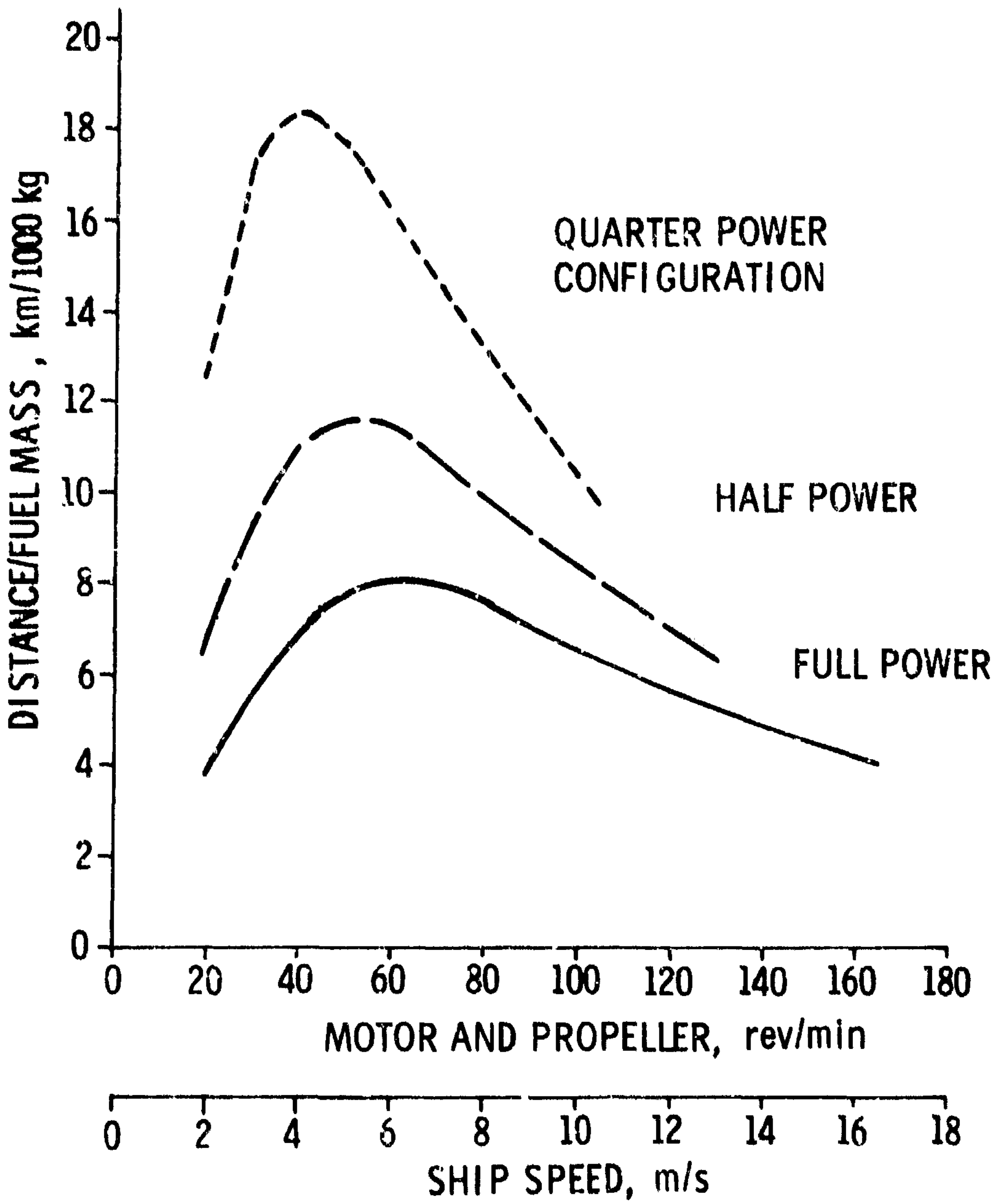

Figure 2.27. Range to Fuel Consumed Ratio

TABLE 2.13

FUEL CONSUMED DURING MISSION

Item	Fuel Consumed, kg	(lb)
Turbines	926907	(2043481)
Motor Excitation	31851	(70220)
Generator Excitation	8061	(17772)
Lube Oil Systems	1702	(3752)
Cooling Water Systems	3357	(7401)
Total	44971	(99145)
Sea Water		
Lube Oil Systems	288	(634)
Cooling Water Systems	2160	(4761)
Total	2447	(5395)
System Total	974326	(2148021)

A summary of the mission performance is shown in Table 2.14. The mission fuel consumption is calculated by taking the total fuel consumed by the propulsion system and dividing by the mission duration of 352 hours.

TABLE 2.14

SUMMARY OF INTEGRATED MISSION PERFORMANCE

Mission Fuel Consumption, kg/hr (lb/hr)	2768 (6102)
Specific Fuel Consumption, kg/kW-hr (lb/hp-hr)	0.269 (0.443)
Mission Efficiency	0.9573

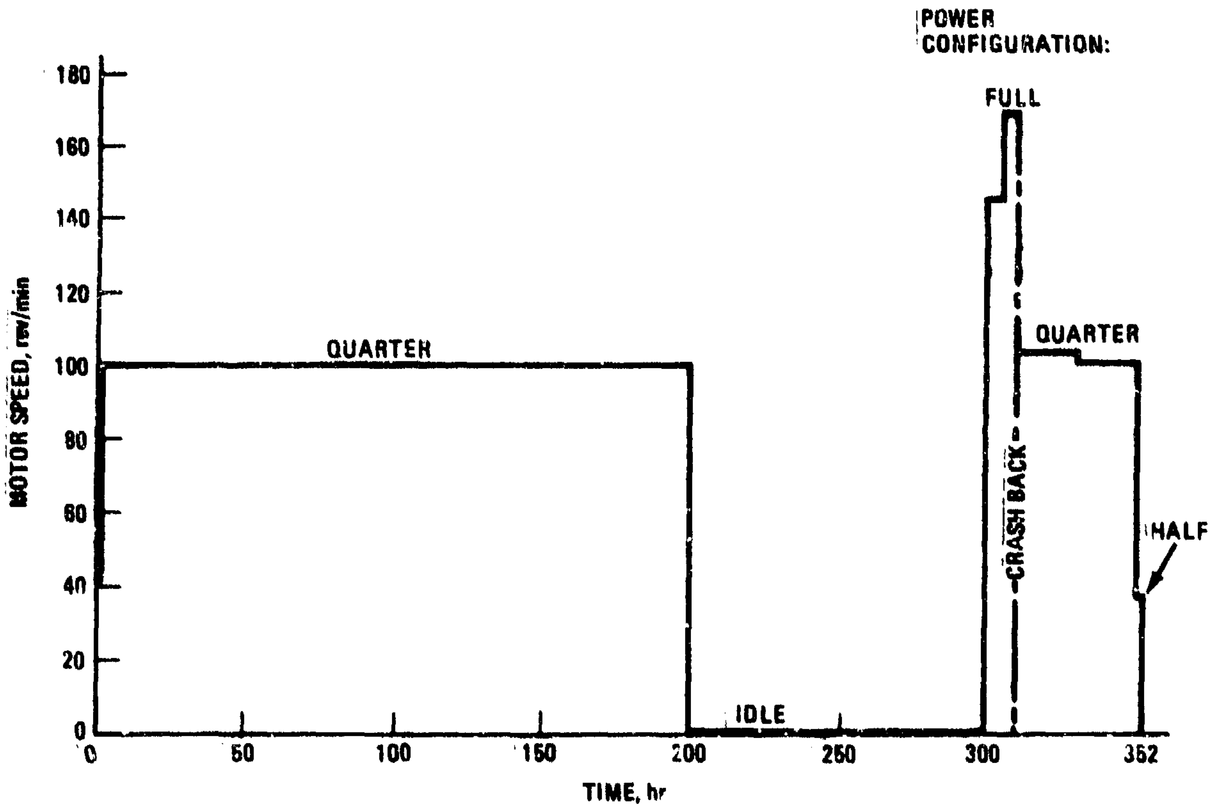

Figure 2.28. Motor Speed Profile for Representative Mission

The specific fuel consumption for the mission is obtained by taking the total fuel consumed by the gas turbines and dividing by the total energy supplied by the gas turbines to the generators.

The mission efficiency is the total energy delivered to the propellers divided by the total energy supplied by the gas turbines. This corresponds to the system efficiency as defined in Section 2.3.1.2.3.

2.3.1.3.3 Operation During Representative Mission

The following outline describes the sequence of events which occur for each step of the mission profile.

Step 1: Time, -0 hr Operation, dockside

a. Control system off.
b. All auxiliaries off.
c. All switches (S1 through S16) open.
d. Turbines not running.

Step 2: Time, 0 hr Operation, dockside

a. Control system energized.
b. Configuration selection idle.
c. Lube oil systems on.
d. Exciters energized. (Note: all field currents zero)
e. CO_2 systems on

Step 3: Time, 0 to 0.1 hr Operation, dockside

a. Lift brushes G1 and G2.
b. Schedule G1 and G2 to idle.

Step 4: Time, 01-0.11 hr Operation, dockside maneuvering

a. Configuration selection half power.
b. Cooling systems on.
c. Lower brushes G1 and G2.
d. Motor fields at 1391 A.
e. Switches S1, S5, S13, S2, S6, and S14 close.
f. Torque reference commands result in +8 rev/min on M1 and -8 rev/min on M2.

Step 5: Time 0.11-1.0 hr Operation, harbor maneuvering

a. Torque reference commands result in M1 and M2 turning at 42 rev/min.

Step 6: Time 1.0-200 hr Operation, cruise/patrol

a. Configuration selection quarter power.
b. Switches S1, S5, S13, S2, S6, and S14 open.
c. Switches S1, S5, S9, S12, S15, and S16 close.
d. Schedule G3 to shut down.
e. After G3 shut down, engine room 2 cooling water system off. (Note: engine room 1 cooling water system cools G1, M1, cross connect line and M2)
f. Torque reference commands result in M1 and M2 turning at 100 rev/min.

Step 7: Time 200-300 hr Operation, cruise/patrol

a. Configuration selection idle.
b. Switches S1, S5, S9, S12, S15, and S16 open.
c. G1 at idle.
d. Lift brushes G1.
e. Engine room 1 cooling water system off.
f. Motor fields and generator fields at zero current.

Step 8: Time 300-300.1 hr Operation, cruise/patrol

a. Lift brushes G2, G3, G4
b. Schedule G2, G3, and G4 to idle.

Step 9 and 10: Time 300.1-305.1 hr Operation, high speed

a. Configuration selection full power.
b. Cooling water systems on.
c. Lower brushes G1, G2, G3, and G4.
d. Motor fields at 1391 A.
e. Switches S1, S5, S13, S2, S6, and S14 close.
f. Switches S3, S7, S4, and S8 close.
g. Torque reference commands result in M1 and M2 turning at 145 rev/min.

Step 11: Time 305.1-310 hr Operation, high speed

a. Torque reference commands result in M1 and M2 turning at 168 rev/min.

Step 12: Time 310-01 hr Operation, crash back

See Section 2.3.3 for a description of the crash back maneuver.

Step 13: Time 310.01-330 hr Operation, cruise

a. Configuration selection quarter power.
b. Switches S3, S7, S4, and S8 open.
c. Switches S1, S5, S13, S2, S6, and S24 open.
d. Switches S1, S5, S9, S12, S15, and S16 close.
e. Schedule G2, G3, and G4 to shut down.
f. After G2, G3, and G4 shut down, engine room 2 cooling water system off.
g. Torque reference commands result in M1 and M2 turning at 103 rev/min.

Step 14: Time 330-350 Operation, cruise

a. Torque reference commands result in M1 and M2 turning at 98 rev/min and 103 rev/min respectively.

Step 15: Time 350-350.1 hr Operation, cruise

a. Lift brushes G2.
b. Schedule G2 to idle.

Step 16: Time 350.1-352 hr Operation, harbor maneuvering

a. Switches S1, S5, S9, S12, S15, and S16 open.
b. Engine room 2 cooling water system on.
c. Lower brushes G2.
d. Motor fields at 1391 A.
e. Switches S1, S5, S13, S2, S6, and S14 close.
f. Torque reference commands result in M1 and M2 turning at 37 rev/min.

Step 17: Time 352- +8 hr Operation, dockside

a. Propulsion system commanded to stop.
b. Switches S1, S5, S13, S2, S6, and S14 open.
c. Motor and generator fields to zero current.
d. G1 and G2 shut down.
e. Cooling water and CO_2 systems off.
f. Exciters deenergized.
g. Lube oil systems off.
h. Control system deenergized.

2.3.1.3.4 Mission Steady State Operating Values

The steady state system operating characteristics for Steps 2 through 16 of the mission profile are shown in Table 2.15. The manner in which transitions from one configuration to another are carried out by the control system are detailed in Section 3.6.

2.3.2 Abnormal Operation

2.3.2.1 Loss of Ships Service Power

The following propulsion subsystems are supplied from the ships service power:

- Generator field exciters
- Motor field exciters
- Deionized cooling water pump motors
- Lubricating oil pump motors
- SEGMAG propulsion system control console
- Motor driven configuration switches

The loss of ships service power to any of the generator or motor field exciters will be critical and will require immediate and automatic shutdown of these systems and their attendant machines. Should any of the affected machines be on line at the time of the casualty, the control system will be required to command an emergency shutdown of the propulsion plant. Because of the absolute dependence upon maintaining power to the exciters, these systems should be supplied from a high reliability buss.

TABLE 2.15

MISSION STEADY STATE SYSTEM PERFORMANCE

Mission Profile Step	2. Dockside
Turbine Power, Total	0 KW (0 hp)
Motor Power, Total	0 KW (0 hp)
System Efficiency (Motor Power/Turbine Power)	
Total System Fuel Consumption	9 kg/hr (20 lb/hr)

Ship Services

Auxiliary Electric

Generator Excitation	2	kW
Motor Excitation	5	kW
Lube Oil Pumps	11	kW
Cooling Water Pumps	0	kW
Total	18	kW

Sea Water

Lube Oil Systems	227	liter/min
Cooling Water Systems	0	liter/min
Total	227	liter/min

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr				
Fuel Consumption, kg/hr	0	0	0	0
Generator				
Input Power, kW				
Speed, rev/min				
Output Power, kW				
Output Voltage, V				
Output Current, A				
Field Current, A	0	0	0	0
Motor				
Input Power, kW				
Input Voltage, V				
Input Current, A				
Output Power, kW				
Speed, rev/min				
Field Current, A	0		0	

TABLE 2.15 (Cont)

Mission Profile Step 3. Dockside
Turbine Power, Total 10 KW (13 hp)
Motor Power, Total 0 KW (0 hp)
System Efficiency (Motor Power/Turbine Power) ---
Total System Fuel Consumption 774 kg/hr (1706 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	2 kW	Lube Oil Systems	227 liter/min
Motor Excitation	5 kW	Cooling Water Systems	0 liter/min
Lube Oil Pumps	11 kW	Total	227 liter/min
Cooling Water Pumps	0 kW		
Total	18 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	77.645		77.645	
Fuel Consumption, kg/hr	382	0	382	0
Generator				
Input Power, kW	5		5	
Speed, rev/min	1800		1800	
Output Power, kW	0		0	
Output Voltage, V	0		0	
Output Current, A	0		0	
Field Current, A	0	0	0	0
Motor				
Input Power, kW				
Input Voltage, V				
Input Current, A				
Output Power, kW				
Speed, rev/min				
Field Current, A	0		0	

TABLE 2.15 (Cont)

Mission Profile Step 4. Dockside Maneuvering
Turbine Power, Total 33 KW (45 hp)
Motor Power, Total 19 KW (25 hp)
System Efficiency (Motor Power/Turbine Power) 0.5700
Total System Fuel Consumption 1061 kg/hr (2339 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	3 kW	Lube Oil Systems	227 liter/min
Motor Excitation	531 kW	Cooling Water Systems	4542 liter/min
Lube Oil Pumps	11 kW	Total	4770 liter/min
Cooling Water Pumps	56 kW		
Total	601 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	22.990		22.990	
Fuel Consumption, kg/hr	336	0	386	0
Generator				
Input Power, kW	17		17	
Speed, rev/min	1802		1802	
Output Power, kW	11		11	
Output Voltage, V	108.1		-108.2	
Output Current, A	103		-101	
Field Current, A	25	0	-25	0
Motor				
Input Power, kW	11		11	
Input Voltage, V	108.1		-108.2	
Input Current, A	103		-101	
Output Power, kW	10		9	
Speed, rev/min	8		-8	
Field Current, A	1391		1391	

TABLE 2.15 (Cont)

Mission Profile Step	5. Harbor Maneuvering
Turbine Power, Total	933 KW (1251 hp)
Motor Power, Total	872 KW (1169 hp)
System Efficiency (Motor Power/Turbine Power)	0.9349
Total System Fuel Consumption	1332 kg/hr (2936 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	29 kW	Lube Oil Systems	227 liter/min
Motor Excitation	531 kW	Cooling Water Systems	4542 liter/min
Lube Oil Pumps	11 kW	Total	4770 liter/min
Cooling Water Pumps	56 kW		
Total	638 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	1.105		1.105	
Fuel Consumption, kg/hr	515	0	515	0
Generator				
Input Power, kW	466		466	
Speed, rev/min	1845		1845	
Output Power, kW	452		452	
Output Voltage, V	506.5		506.5	
Output Current, A	893		893	
Field Current, A	111	0	111	0
Motor				
Input Power, kW	452		452	
Input Voltage, V	506.5		506.5	
Input Current, A	893		893	
Output Power, kW	436		436	
Speed, rev/min	42		42	
Field Current, A	1391		1391	

TABLE 2.15 (Cont)

Mission Profile Step	6. Cruise/Patrol	
Turbine Power, Total	12311 KW	(16510 hp)
Motor Power, Total	11770 KW	(15784 hp)
System Efficiency (Motor Power/Turbine Power)	0.9560	
Total System Fuel Consumption	3348 kg/hr	(7380 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	61 kW	Lube Oil Systems	227 liter/min
Motor Excitation	264 kW	Cooling Water Systems	2271 liter/min
Lube Oil Pumps	11 kW	Total	2498 liter/min
Cooling Water Pumps	23 kW		
Total	363 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	0.258			
Fuel Consumption, kg/hr	3174	0	0	0
Generator				
Input Power, kW	12311			
Speed, rev/min	2988			
Output Power, kW	12145			
Output Voltage, V	1679.7			
Output Current, A	7230			
Field Current, A	227	0	0	0
Motor				
Input Power, kW	6063		6063	
Input Voltage, V	838.6		838.6	
Input Current, A	7230		7230	
Output Power, kW	5885		5885	
Speed, rev/min	100		100	
Field Current, A	974		974	

TABLE 2.15 (Cont)

Mission Profile Step	7. Cruise/Patrol		
Turbine Power, Total	5 KW	(7 hp)	
Motor Power, Total	0 KW	(0 hp)	
System Efficiency (Motor Power/Turbine Power)			
Total System Fuel Consumption	391 kg/hr	(863 lb/hr)	

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	2 kW	Lube Oil Systems	227 liter/min
Motor Excitation	5 kW	Cooling Water Systems	0 liter/min
Lube Oil Pumps	11 kW	Total	227 liter/min
Cooling Water Pumps	0 kW		
Total	18 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	77.645			
Fuel Consumption, kg/hr	382	0	0	0
Generator				
Input Power, kW	5			
Speed, rev/min	1800			
Output Power, kW	0			
Output Voltage, V	0			
Output Current, A	0			
Field Current, A	0	0	0	0
Motor				
Input Power, kW				
Input Voltage, V				
Input Current, A				
Output Power, kW				
Speed, rev/min				
Field Current, A	0		0	

TABLE 2.15 (Cont)

Mission Profile Step: 8. Cruise/Patrol
Turbine Power, Total: 20 KW (27 hp)
Motor Power, Total: 0 KW (0 hp)
System Efficiency (Motor Power/Turbine Power): ______
Total System Fuel Consumption: 1539 kg/hr (3392 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	2 kW	Lube Oil Systems	227 liter/min
Motor Excitation	5 kW	Cooling Water Systems	0 liter/min
Lube Oil Pumps	11 kW	Total	227 liter/min
Cooling Water Pumps	0 kW		
Total	18 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	77.645	77.645	77.645	77.645
Fuel Consumption, kg/hr	382	382	382	382
Generator				
Input Power, kW	5	5	5	5
Speed, rev/min	1800	1800	1800	1800
Output Power, kW	0	0	0	0
Output Voltage, V	0	0	0	0
Output Current, A	0	0	0	0
Field Current, A	0	0	0	0
Motor				
Input Power, kW				
Input Voltage, V				
Input Current, A				
Output Power, kW				
Speed, rev/min				
Field Current, A	0		0	

TABLE 2.15 (Cont)

Mission Profile Step 9. and 10. High Speed
Turbine Power, Total 37118 KW (49776 hp)
Motor Power, Total 35882 KW (48118 hp)
System Efficiency (Motor Power/Turbine Power 0.9667
Total System Fuel Consumption 10726 kg/hr (23646 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	305 kW	Lube Oil Systems	liter/min
Motor Excitation	531 kW	Cooling Water Systems	liter/min
Lube Oil Pumps	11 kW	Total	liter/min
Cooling Water Pumps	56 kW		
Total	902 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	0.277	0.277	0.277	0.277
Fuel Consumption, kg/hr	2575	2575	2575	2575
Generator				
Input Power, kW	9280	9280	9280	9280
Speed, rev/min	2696	2696	2697	2696
Output Power, kW	9162	9162	9162	9162
Output Voltage, V	1723.8	1723.8	1723.8	1723.8
Output Current, A	5315	5315	5315	5315
Field Current, A	258	258	258	258
Motor				
Input Power, kW	18319		18319	
Input Voltage, V	1723.4		1723.4	
Input Current, A	10630		10630	
Output Power, kW	17941		17941	
Speed, rev/min	145		145	
Field Current, A	1391		1391	

TABLE 2.15 (Cont)

Mission Profile Step 11. High Speed
Turbine Power, Total 57761 KW (77458 hp)
Motor Power, Total 55808 KW (74840 hp)
System Efficiency (Motor Power/Turbine Power) 0.9662
Total System Fuel Consumption 14791 kg/hr (32608 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	291 kW	Lube Oil Systems	227 liter/min
Motor Excitation	531 kW	Cooling Water Systems	4642 liter/min
Lube Oil Pumps	11 kW	Total	4770 liter/min
Cooling Water Pumps	56 kW		
Total	888 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	0.249	0.249	0.249	0.249
Fuel Consumption, kg/hr	3592	3592	3592	2593
Generator				
Input Power, kW	14440	14440	14440	14440
Speed, rev/min	3193	3193	3193	3193
Output Power, kW	14261	14261	14261	14261
Output Voltage, V	1998.8	1998.8	1998.8	1998.8
Output Current, A	7135	7135	7135	7135
Field Current, A	252	252	252	252
Motor				
Input Power, kW	28514		28514	
Input Voltage, V	1998.3		1998.3	
Input Current, A	14269		14269	
Output Power, kW	27904		27904	
Speed, rev/min	168		168	
Field Current, A	1391		1391	

TABLE 2.15 (Cont)

Mission Profile Step 12. Crash Back

The time dependent system operating characteristics are described in Section 2.3.3. For the purposes of calculating the mission performance, the steady state conditions of step 11 were used as an approximation for step 12.

TABLE 2.15 (Cont)

Mission Profile Step	13. Cruise
Turbine Power, Total	13440 KW (18024 hp)
Motor Power, Total	12861 KW (17247 hp)
System Efficiency (Motor Power/Turbine Power)	0.9569
Total System Fuel Consumption	3576 kg/hr (7884 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
General Excitation	69 kW	Lube Oil Systems	227 liter/min
Motor Excitation	276 kW	Cooling Water Systems	2271 liter/min
Lube Oil PUmps	11 kW	Total	2498 liter/min
Cooling Water Pumps	28 kW		
Total	378 kW		

	Starboard			Port
Turbine				
Specific Fuel Consumption, kg/kW-hr	0.252			
Fuel Consumption, kg/hr	3396	0	0	0
Generator				
Input Power, kW	13440			
Speed, rev/min	3097			
Output Power, kW	13261			
Output Voltage, V	1768.2			
Output Current, A	7500			
Field Current, A	230	0	0	0
Motor				
Input Power, kW	6621		6621	
Input Voltage, V	882.8		882.8	
Input Current, A	7500		7500	
Output Power, kW	6431		6431	
Speed, rev/min	103		103	
Field Current, A	996		996	

TABLE 2.15 (Cont)

Mission Profile Step 14. Cruise
Turbine Power, Total 12404 KW (16635 hp)
Motor Power, Total 11838 KW (15875 hp)
System Efficiency (Motor Power/Turbine Power) 0.9543
Total System Fuel Consumption 3356 kg/hr (7399 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	57 kW	Lube Oil Systems	liter/min
Motor Excitation	247 kW	Cooling Water Systems	liter/min
Lube Oil Pumps	11 kW	Total	liter/min
Cooling Water Pumps	28 kW		
Total	343 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	0.257			
Fuel Consumption, kg/hr	3191	0	0	0
Generator				
Input Power, kW	12404			
Speed, rev/min	2997			
Output Power, kW	12232			
Output Voltage, V	1630.9			
Output Current, A	7500			
Field Current, A	219	0	0	0
Motor				
Input Power, kW	5407		6805	
Input Voltage, V	721.0		907.4	
Input Current, A	7500		7500	
Output Power, kW	5223		6614	
Speed, rev/min	98		103	
Field Current, A	850		1024	

TABLE 2.15 (Cont)

Mission Profile Step 15. Cruise
Turbine Power, Total 12409 KW (16614 hp)
Motor Power, Total 11838 KW (15875 hp)
System Efficiency (Motor Power/Turbine Power) 0.9539
Total System Fuel Consumption 3739 kg/hr (8242 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	57 kW	Lube Oil Systems	227 liter/min
Motor Excitation	247 kW	Cooling Water Systems	2271 liter/min
Lube Oil Pumps	11 kW	Total	2498 liter/min
Cooling Water Pumps	28 kW		
Total	343 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	0.257		77.645	
Fuel Consumption, kg/hr	3191	0	382	
Generator				
Input Power, kW	12404		5	
Speed, rev/min	2997		1800	
Output Power, kW	12232		0	
Output Voltage, V	1631		0	
Output Current, A	7500		0	
Field Current, A	219	0	0	0
Motor				
Input Power, kW	5407		6805	
Input Voltage, V	721.0		907.4	
Input Current, A	7500		7500	
Output Power, kW	5223		6614	
Speed, rev/min	98		103	
Field Current, A	850		1024	

TABLE 2.15 (Cont)

Mission Profile Step	16. Harbor Maneuvering
Turbine Power, Total	645 KW (865 hp)
Motor Power, Total	596 KW (799 hp)
System Efficiency (Motor Power/Turbine Power)	0.9241
Total System Fuel Consumption	1247 kg/hr (2750 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	25 kW	Lube Oil Systems	227 liter/min
Motor Excitation	531 kW	Cooling Water Systems	4542 liter/min
Lube Oil Pumps	11 kW	Total	4770 liter/min
Cooling Water Pumps	56 kW		
Total	622 kW		

	Starboard		Port	
Turbine				
Specific Fuel Consumption, kg/kW-hr	1.469		1.469	
Fuel Consumption, kg/hr	474	0	474	0
Generator				
Input Power, kW	323		323	
Speed, rev/min	1831		1831	
Output Power, kW	311		311	
Output Voltage, V	448.4		448.4	
Output Current, A	693		693	
Field Current, A	99	0	99	0
Motor				
Input Power, kW	311		311	
Input Voltage, V	448.3		448.3	
Input Current, A	693		693	
Output Power, kW	298		298	
Speed, rev/min	37		37	
Field Current, A	1391		1391	

Failure of the ships service power to the deionized cooling water pumps will cause a failure of the cooling water system and will require machinery shutdown. This shutdown may follow normal shutdown procedures by relying upon the thermal inertia of the machinery to store the losses generated during the normal shutdown period. For reliability, both a main and a standby AC motor driven pump (both fully rated) are supplied to provide protection against service interruptions resulting from pump or motor failure. This redundancy, however, will not protect against loss of ships service power. Consideration was given to providing an emergency pump supplied from an uninterruptable power source, however, this was not included since loss of ships service power will cause shutdown due to loss of the machine exciters.

The lubricating oil system has been provided with two redundant AC motor driven supply pumps and is backed up by a DC motor driven emergency oil pump. This DC pump can either be supplied from an available DC bus, or from a separate storage battery bank. The system, therefore, can operate for a sufficient period of time following loss of ships service power to allow casualty control measures to either restore the normal service bus or provide an alternate power source.

In order to maintain continuity of control during ships service power outages, the control consoles will be arranged to be powered from two alternate high reliability power sources so that failure of one source will not cause system shutdown. Because of the extensive use of solid state circuitry, the power requirements will be low and, therefore, suitable for backup by a non-interruptable power system.

The loss of ships service power to the motor driven configuration switches prevents remote control of the switches, but will not otherwise affect continued operation of the propulsion plant in the existing mode. If operating mode changes are required prior to restoration of the service power, they can be accomplished by operating the switches in the manual mode.

The system configuration switches which serve to open and close the armature circuit during emergency reversal maneuvering must be given special consideration. Loss of function of these devices will inhibit the ability to rapidly slow the ship. Thus, the operators for these switches must be provided with alternate power sources or else changed to a type that can employ energy storage for opening such as compressed springs, pressurized gas or hydraulic fluid system and/or a DC electrical system for closures. The specific method of providing increased availability for these devices is left for selection later.

2.3.2.2 Loss of Seawater Cooling

Since the main deionized cooling water system relies on seawater for heat rejection, the total loss of seawater cooling would drastically reduce the power output of the system. There is, of course, a time factor involved here, in that a momentary loss of seawater would have very little effect on the system due to the large quantity of stored cooled deionized water. However, for a prolonged outage of seawater, the deionized water temperature would rise to an unacceptable level which would limit the operation of all equipment cooled by deionized water system. This equipment includes not only the main propulsion machinery but also the lube oil system, the cover gas system, the machine excitation systems, ships service power, the main propulsion transmission busses, and its associated switchgear.

Depending on ambient temperature at the time of loss of seawater, a small amount of the heat generated in the above systems could be rejected to ventilating air, however, this amount would be very low and propulsion power output would have to be drastically reduced to that level that could be sustained by whatever cooling seawater was available, assuming that the seawater cooling system is not confined to a single source as would most probably be the case. Partial loss of seawater cooling would normally reduce main power output to a level depending on the type or cause of loss, however, temporary re-routing of flow from other seawater loops and expedient reduction of flows to some equipment could restore main propulsion power to significant output levels.

2.3.2.3 Loss of Switch or Breaker

Three switch failure modes have been considered:

A. Failure of a switch to open

B. Failure of a switch to close

C. Failure of a switch in an intermediate position (incomplete operation)

The function of the switches used in the armature circuits are grouped into two categories and identified as category (1) or (2) as follows:

Category

(1) Those used for system configuration changes only.

(2) Those used for emergency maneuvering (emergency reversal) service.

Refer to Section 3.4 for a detailed description of the functional differences between these services. The severity of a switch casualty will depend upon which of the functional categories the switch belongs and the maneuvering situation at the time of the casualty.

Switch position changes are only required when making mode changes or when performing an emergency reversal maneuver. Thus for function category (1) switches, the three failure modes will most probably occur or be discovered when making mode changes under steady state conditions. For functional category (2) switches, failure can occur during emergency maneuvering switching when the system is in a dynamic operating condition.

For functional category (1) switches, either an A, B or C casualty will prevent automatic mode changes from taking place in the sequence commanded by the control logic. When a mode change is commanded which involves the malfunctioning switch, the control system lower level supervisory logic will detect the failure of the switch to respond and will then control the system to the "start" condition. When in the start configuration all switches are open, the motor and generator fields are de-energized.

With the system in the "start" condition, corrective action can be taken to either return the switch to service, to operate it in the manual mode or to isolate it from the system. Because the system is controlled to current zero during switching, it is expected that failures of this type would not cause consequential damage.

For functional category (2) switches, a type "A" failure will prevent the initiation of the dynamic braking cycle during an emergency reversal maneuver. This is a critical failure as it subsequently prevents braking of the propeller and allows it to continue in the windmill condition. This results in a failure to perform the reversal maneuver.

A type "B" failure would most probably occur following the dynamic braking cycle and would prevent the system from being powered in the reverse direction. This would keep the dynamic resistors and initiating thyristors in the circuit longer than their rated time and would probably result in damage to these devices. This failure would terminate the reversal maneuver at some intermediate reach and would be a partial failure of the ship to perform the reversal maneuver.

The effects resulting from a type "C" failure will depend upon the point in the maneuver at which the malfunction occurred. If the switch malfunctioned during the opening cycle, it causes the same effect as a type "A" failure. If the switch malfunctions during the closing portion of the reversal cycle, it exposes both the switch and the thyristor to possible damage by the reverse power current. The severity of the resulting damage and the amount by which the reversing maneuver is compromised is dependent upon the switch failure mode.

2.3.2.4 Loss of Brush Atmosphere

The loss of cover gas flow through the machine is not critical if the loss is temporary. The effects of the cover gas are stated in Section 2.1.2.4. In the event of gas flow loss, the gas contained inside the machine would still possess the proper additive for lubrication and the proper gas for arc suppression. Even though the internal pressure may fall to atmospheric pressure, the effective gas properties would be essentially unaffected. The effects of the loss of gas flow must be monitored during the prototype machine tests to establish realistic time limits for continual operation. The result of an investigation of lost gas flow would be to determine the following parameters as a function of time:

- Reduced machine power output due to lower arc suppression capability
- Reduced brush life
- Higher brush electrical loss
- Lower brush frictional loss

There are, however, other abnormalities associated with the cover gas (debris removal) system that are critical. Since the loss of cover gas flow for short periods is not expected to cause adverse effects, the remedy for the other abnormalities is to terminate gas flow by stopping the fan. The following abnormalities would be typical causes for termination of gas flows:

- Loss of cooling water causing the gas temperature leaving the cooler to rise above the desired level.
- Loss of vapor addition
- Loss of water flow
- Loss of fan power

In addition to stopping the fan, an alarm should be activated so that the problem can be corrected.

2.3.2.5 Loss of Machine Coolant

There are several elements of the machines requiring coolant, and each will have different effects if coolant is lost. There are water tubes cooling the stator iron, the field winding, the brushes, and the rotor bars. Brush performance is highly dependent on maintaining the proper operating temperature, and therefore maintaining coolant to the brushes is very critical to machine operation. The other cooled elements are limited by their Class B insulation rating; if coolant is lost, the current in them must be reduced to the point where a hot spot temperature of 130°C is not exceeded.

Loss of coolant to the field winding will be least disruptive to machine operation. The field winding has relatively thin insulation, and is in close proximity to the stator steel, which is cooled. Thus, field loss could be removed by conduction to the stator iron, and thence to the water cooling tube. Pending a thermal analysis, a rough estimate of field current possible under this condition is one-half of full field. If a motor has lost field coolant, about 70% propeller speed could be maintained, and about 35% power. If a generator has lost field coolant, it could still maintain about half its rated power output.

Loss of coolant to the stator iron would be somewhat more serious, since there is no other convenient cooling tube through which the stator bar losses could be removed. However, some of these losses could still be removed by conduction through the machine frame, and radiation from the outside of the machine. Since these loss removing mechanisms would be considerably less effective than the water cooling tube, it would be unlikely to be able to maintain more than 20% of armature current under this condition. This means that if stator coolant is lost to a motor, no more than half propeller speed could be maintained, and 10% power. A generator with a loss of stator coolant could maintain 20% output power.

The rotor bars are very well insulated from possible sources of heat removal, other than their cooling tubes. Therefore, if rotor bar cooling was lost, only a small fraction of armature current could be maintained, and the machine would have to be shut down. Likewise, as stated previously, brush coolant is critical to machine operation, and loss of brush coolant would require machine shutdown.

2.3.2.6 Emergency Connections

The eighteen configuration control switches provide the capability of connecting one or two generators per side to their corresponding motor, while operating in the split plant configuration; they also provide for interconnecting any one generator with both of the motors, connected in series, for the quarter power configuration which interconnects the two engine rooms. There is, however, a possibility that one engine room could be totally disabled while the other is still intact, which would make it desirable to connect these two functioning generators with both motors for operation at the half power level. This could be accomplished by the present switch configuration by connecting both motors and both generators in parallel, however, two of the motor switches and interconnecting busses would have to be installed with additional current carrying capacity since single motor demand is approximately 9000 amps while at present the interconnecting lines and switches are rated at 7500 amps. Thus, a trade-off would have to be considered between flexibility and additional cost. The four machines could also all be connected in series, again by increasing the capacity of the interconnecting busses, plus the inclusion of two removable bus links. This removal would be accomplished manually while at a de-energized state. In both cases, slight modifications would have to be made in the control system to properly supply the correct torque and feedback signals. Either or both of these schemes could be accommodated if the desired flexibility outweighs the additional cost.

2.3.2.7 Damage Considerations

For the best protection against loss of propulsion power due to flooding, fire or explosion, a first reaction may lead to the conclusion that separation of components by compartmentalization is beneficial and desirable. However, further generalized reasoning leads to a contradiction of this conclusion, and instead that the arrangement with all of the propulsion machinery for one shaft located in a single space (as on DD963) is the best arrangement from a damage control point-of-view. This latter conclusion derives from (1) the fact that a set consisting of one motor and at least one generator is required to drive the ship, and (2) each set should be disposed so as to present the least target cross-section to the anticipated hazard. This optimum disposition is apparently achieved in the two machinery space layout of Figures 2.6 to 2.14.

The generalized reasoning above overlooks the possibility of reducing the target cross-section of the motor space by shortening its length, plus taking advantage of the redundancy of generators. A more exact probability analysis is required to adequately assess the improvement in damage control protection. The analysis has been done for five different arrangements of spaces, including the original two compartment layout which we call the "baseline" arrangement. The cases are:

I. Two compartments, each with two generators and one motor. Designated "Baseline"

II. Two motor rooms, 2 generator rooms

III. Two motor rooms, 3 generator rooms

IV. Two motor rooms, 4 generator rooms

V. One motor room, 4 generator rooms

The probability analysis seeks the probability that the propulsion system will be totally disabled by flooding, fire, projectile impact or some causes other than conventional breakdowns. A length of the ship called a zone length Z is defined as about the very minimum space into which a propulsion motor could be fitted (approximately 15 feet). Due to the length of the gas turbine-generator module, a generator room length of 3Z is required if the unit is disposed with shaft axes fore and aft. A practical length of motor room is 1.5Z.

The probability of a single hit or damaging event on a space of length Z is taken to be "p". On a space nZ long, the probability of one or more hits is: $1 - (1-p)^n$.

Implicit is the assumption that the target cross-section has a constant height so that the area varies only with the length (of the space). A further premise is that the occurrence of one hit does not reduce the probability of a second hit, and so on.

The analysis has been done for a range of values of the single hit probability "p", with full realization that probability values much in excess of 0.1 represent inordinately high values.

The results are presented by the curves of Figures 2.29 and 2.30, where the vertical scale is the "Probability of the Ship Propulsion System being Inoperative". These of course require as a minimum either disablement of both motors or disablement of all generators.

The first curve set (Figure 2.29) is for a practical motor room length of 1.5Z and a turbine-generator space length of 3Z. The horizontal scale is "p", the "Probability of Hitting a Zone (of length Z)". Representative values from the two-compartment "Baseline" case are:

"p"	Inoperative Probability
0.01	0.00088
0.05	0.020
0.10	0.073

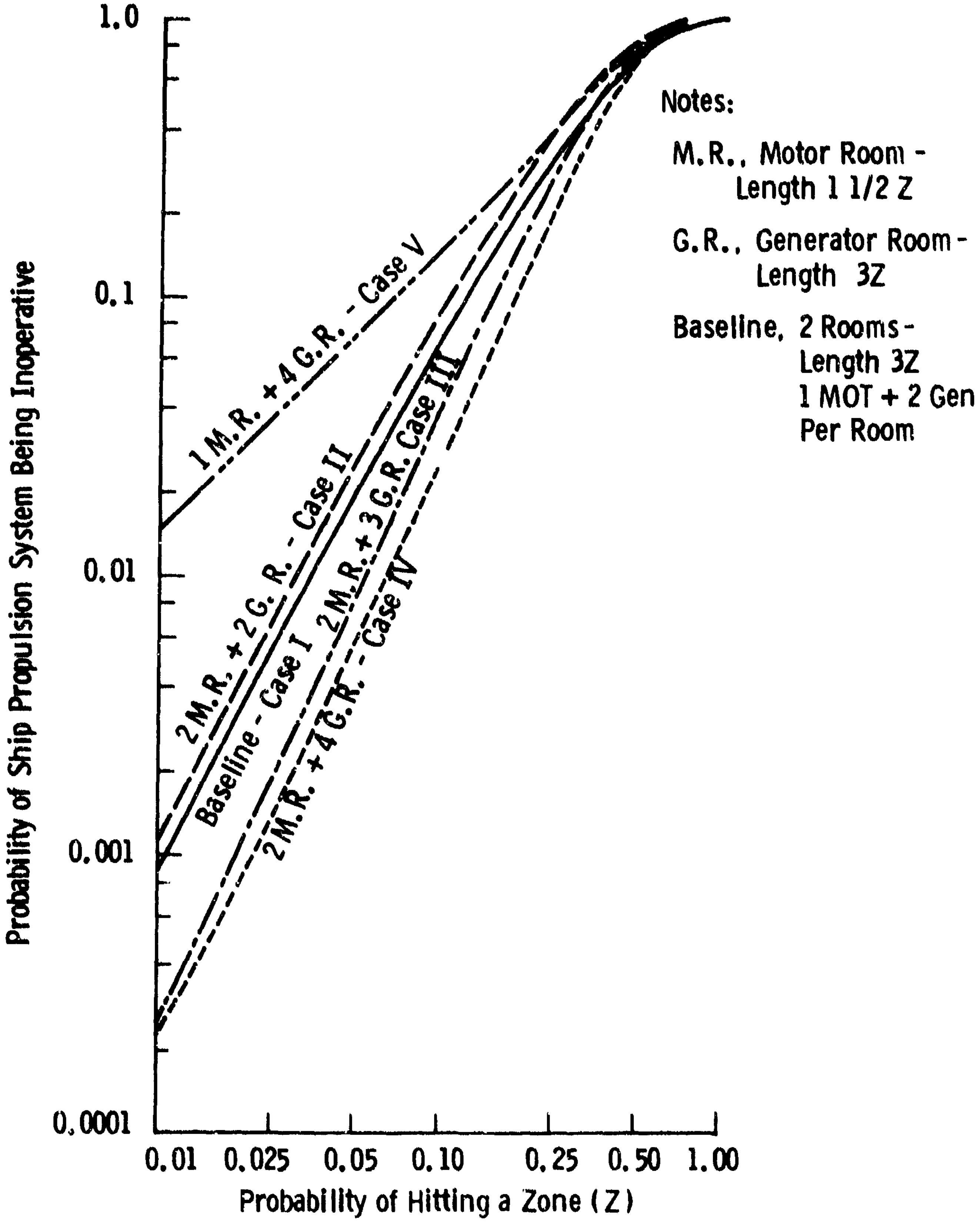

Figure 2.29. Probability of Disabling Propulsion System by Zone Hit

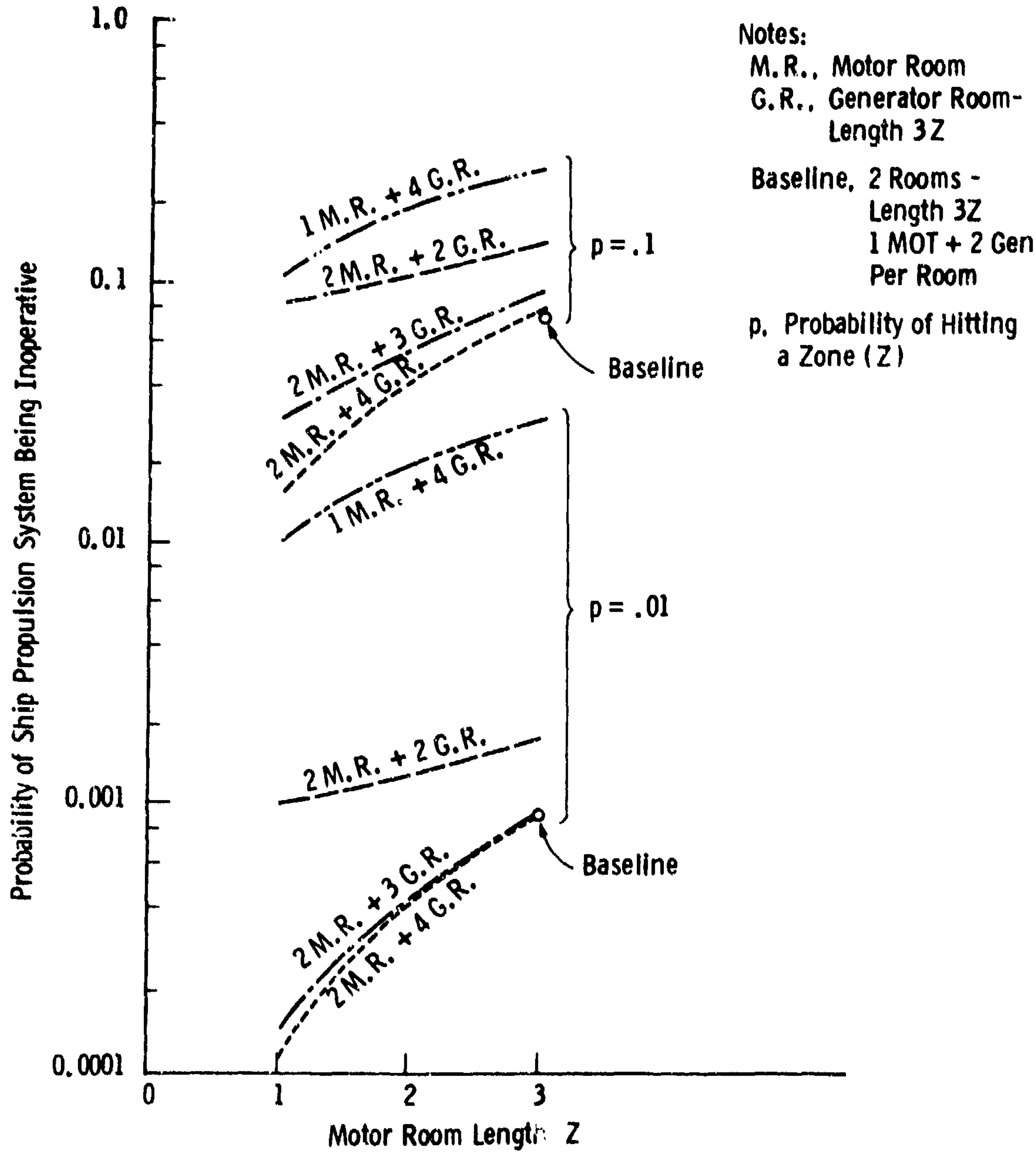

Figure 2.30. Probability of Disabling Propulsion System Vs Engine Room Length

First it is seen immediately that separating the T-G units in pairs to separate rooms, Case II on Figure 2.29, increases the overall probability of disablement - as generalized reasoning may deduce from target cross-sections considerations alone.

Next we see that further separating the turbine-generator units into 3 or even 4 separate spaces, Case III and Case IV, provides a marked increase in damage control protection, as basic intuition may initially conclude. Extension of the previous tabulation illustrates the results with numbers:

PROBABILITY OF TOTAL LOSS OF PROPULSION

p	NUMBER OF SPACES		
	2	5	6
0.01	0.00088	0.00025	0.00022
(Ratio)	1.0	0.28	0.25
0.05	0.020	0.0084	0.0059
(Ratio)	1.0	0.42	0.30
0.10	0.073	0.041	0.027
(Ratio)	1.0	0.56	0.37

The ratios in the table show clearly that a 4:1 improvement (in event p = 0.01) can be achieved with a 6 compartment arrangement and motor room lengths of 1.5Z (22.5 ft).

The high probability of being inoperative for Case IV, the single motor room arrangement, shows the obvious folly of placing both motors in a single space.

Figure 2.30 gives an extension of the results of the analysis where the length of motor room is varied from Z to 3Z, and shows the profound influence of target length on the results. This curve group is discussed in the Appendix No. 1 where also the complete probability analysis is given.

In conclusion we may see from these results that the versatility in arrangement afforded by the multi-unit electric drive system offers diverse opportunities for design improvements, especially in a naval warship.

2.3.3 Maneuvering Simulation

2.3.3.1 Description of Maneuvering Simulation

The system simulation incorporated the components shown on Figure 2.1 and described in Section 2 of this report. Briefly, it consisted of four gas turbines, each driving an electrical dc generator, two such generators power a dc motor per shaft which drive fixed pitch propellers. In addition to these major components, several methods of braking the propeller shaft were simulated; mechanical brakes and electrical braking resistors. The machine exciters and armature switching were also simulated, as was the propeller and ship's drag.

For lower power configurations that entail the use of less than four generators, the same input signals, albeit different values, are utilized as those for the full power configuration. It was thus possible to simulate the various multi-machine configurations by changing the base quantities without resorting to multiple simulations of machines on the analog computer.

The basic control is a motor torque control which can easily be attained by operating the motors with fixed field current and controlling the armature current by varying the generator field current. This control is well suited to the ship drive for several reasons.

First, it brings under direct control two critical physical parameters: the armature-circuit current and the shaft torque. Armature current is important to control not only because of the thermal limitations of the machines but also because of potentially destructive torques and forces which could result if the propeller were to become entangled with some foreign object. The alternative to torque control is motor speed control. With speed control, in the event of a propeller entanglement, the system would increase the generator field current and thereby the armature current and torque. Special means would have to be provided to sense and limit the armature current. On the other hand, if one were to lose a propeller or otherwise lose propeller torque, the speed control will limit the motor speed which is an advantage. However, under the loss of propeller condition, with the torque control system, the generator field will increase (assuming field control is used) until saturation or other limiting occurs at which time the motor speed will no longer increase. Of course, in both systems, protective circuitry would have to be provided to protect the machinery, under the torque control system a self-limiting action results without additional expense. By considering these two extreme cases, it is evident that armature current control is more advantageous than speed control.

One of the first tasks to be initiated during this study was to determine the configuration of the systems and the design parameters in terms of weight, volume, and efficiency of the SEGMAG machines and their auxiliaries. After a preliminary sizing of the principal drive components was accomplished, the next logical step was to determine the optimum arrangement of the components and their operating characteristics both individually and as a combined system. The analog simulation study was then initiated to determine the number and types of control systems of the inner loops that would be required and their responses during maneuvering. One of the immediate problems to surface during the system simulation was the method of absorbing the regenerative energy during ship reversal. The source of this energy of course is in the mass of the moving ship and is transmitted through the propeller and shaft to the motor. The motor now desires to function as a generator which would transmit this energy to the generator and drive turbine, if means are not taken to prevent it. Various arrangements of equipment were simulated, the most obvious is to put a mechanical brake on the motor shaft and thus absorb the energy as heat. A mechanical brake could also be installed on the generator to absorb the energy. Due to the versatility of the simulation program, both of these arrangements were analyzed. However, both mechanical brake schemes were abandoned after an analysis of the brake requirements indicated that the simultaneous fulfillment of both the energy capacity and power rating verged on the edge of the present state-of-the-art.

Electrically, the stored energy of the moving ship can be dissipated in resistors that can be inserted into the circuit when the motor begins to regenerate energy. The usual method employed is to control the generator field to lower the generated voltage to that of the regenerative motor thus producing zero current in the armature circuit, which can now be opened. The dynamic braking resistors are then inserted into the motor circuit, the first resistor having a value such as to circulate approximately 150% of full load motor current. This load on the motor, of course, decelerates it and the motor current drops to a lower value at which time another resistor is inserted into the circuit to again raise the current and, hence, the retarding torque to 150% of rating. The process continues until the motor is slowed to near zero speed and the dynamic braking resistance approaches zero. The armature circuit resistance then consists mostly of the motor and generator resistance and the dynamic braking resistors can then be shorted out. The generator can then be controlled to reverse the motor and accelerate in the reverse direction. The use of dynamic braking resistors was simulated and proved very effective in reversing the drive system.

The simulation study thus fixed the main components of the drive system and their interconnection. It also demonstrated that the basic control loop responded favorably to various levels of output power.

2.3.3.2 Model and Simulation Features

The propulsion system was divided into 23 functional blocks so that the blocks could be interconnected into the several arrangements that were tried. Not all 23 blocks of course are used at any one time, for example, block 14 (generator friction brake) and block 17 (armature relay controls) are the mechanical and electrical methods of accepting regenerative power and are used independently of each other. These blocks are described in detail in the Appendix No. 4 of this report which encompasses the complete simulation study performed for the 40 KHP system under consideration. It includes the model equations and the logic circuitry.

2.3.3.3 Circuit Schematics

As stated previously, the circuit schematics for the components and the control system are included in the Appendix No. 4 of this report.

2.3.3.4 Analogue Traces

The simulation study exercised the system not only in the methods of control but also for the various power levels required of the system. The results of these investigations in the form of analogue tracers of the responses of the system to input torque demands are disclosed in the report of the study included in the Appendix No. 4.

2.4 Environmental Considerations

The environmental requirements specified in the work directive relate to externally imposed environmental conditions and system generated environmental requirements. These requirements are listed on Table 2.16 and further expanded in the following paragraphs.

2.4.1 Temperature

All materials used in the machines are Class B materials or better. Therefore, the thermal designs of the machines will be to maintain all hot spot temperatures below the Class B limit, 130°C.

All the water cooling circuits are designed for a maximum of 90°F inlet temperature.

TABLE 2.16

ENVIRONMENTAL REQUIREMENTS

Operating Temperature	0° to 50°C
Relative Humidity	0 to 95% (w/5 ppm salt)
Ships Motion	Inclined 15° from the vertical
Roll	±45° at a 9 second period
Pitch	±30° at a 6 second period
Shock (Hull Mounted)	$1000/\sqrt[3]{w}$ g's acceleration for 2 ms
(Deck Mounted)	$500/\sqrt[3]{w}$ g's acceleration for 2 ms
Shaft Torque Capacity	3 x full ahead
Magnetic Field	$<$100 gauss at 6" away
Surface Temperature	$4 < T_S < 60°C$

2.4.2 Humidity

Since the machines are sealed systems, ambient humidity is irrelevant to their operation. Ventilated or semi-enclosed spaces will be provided with space heaters to prevent condensation. For humidity requirements in the cover gas within the machine environment, see Section 2.1.2.

2.4.3 Ship Motion

The specified roll and pitch requirements were considered in the design of the machines and their supports. The main thrust bearing for the shaft and propeller were retained from the direct drive arrangement so that only the additionally imposed thrust from the motor had to be accommodated. The machine supports for both the rotor and stator of the motor will be designed for the specified ship roll. Drains for the cooling water and lube oil will be designed to insure proper drainage for both the specified pitch and roll requirements.

2.4.4 Design for Shock Resistance

The systems designs that are developed in this program will be examined for compliance with the requirements tabulated on Table 2.16.

The systems developed in the program comprise generators, motors, controls, current handling subsystems, and auxiliary systems. Only the generators and motors are examined in this section for shock resistance. The remaining equipments either are not developed to a stage where analysis is practical or are of conventional design requiring only routine development for shock resistance.

The motors and generator would be classed as hull mounted, being normally supported by a strong and rigid foundation landed on the hull structure of the ship. The following tabulation gives the shock input g-level as computed by the formula 1000 $W^{-1/3}$, W being the weight of the machine in pounds, for hull mounted equipment:

TABLE 2.17

SHOCK g-LEVELS FOR DESIGN

Rating KHP	Machine	Speed rpm	Weight lbs	g-level (a_o)
20	Generator	3600	26,650	35
40	Motor	168	119,000	20
20	Motor	1200	33,750	31

The wording of the work statement, "the machines.... will be required to withstand the equivalent of.... 1000 $W^{-1/3}$ g forces.... applied for 2 ms", does not lend itself to an exact interpretation. The literal meaning would be that all inertial forces throughout the machines would be increased by the g-level factors shown in the last column of the above table, and the loads sustained for 2 milliseconds, a difficult interpretation to utilize.

Another interpretation is that the shock is described by a square wave acceleration input at the mounting plane or seating of the machine, having an amplitude a_o equal to the tabulated G-levels and a time duration of 2 ms, applied in any of the three directions. It is this interpretation that we have elected to utilize, and in the following paragraphs the dynamic influences of the shock pulse on the machine's subsystems and components are examined. The concept of the "shock response spectrum" will be used to approximate the response of each normal mode of vibration of the machine and its subassemblies.

The prescribed shock input is as shown in Figure 2.31, having a stepwise, very steep, change in acceleration at the start and the end of the pulse. Steep wave fronts give large initial response (up to a magnification of 2) due to the instantaneously applied excitation. Since this magnification occurs initially there is no amelioration of the shock effect as the subsystems become more and more rigid. This does not seem to be consistent with reality, since one would expect a high frequency system to follow a low frequency shock pulse without appreciable dynamic magnification.

In Figure 2.32 is shown in dashed lines the response spectrum to the square wave acceleration input shock.* The vertical scale is the ratio of peak acceleration to the input acceleration peak, a_o. The horizontal scale is the natural frequency of the machine component or subassembly. It is seen that all higher frequency components (above 250 Hz) are subjected to an acceleration magnification of 2. This result seems to be not consistent with experience.

Medium and low frequency components (below 90 Hz) are exposed to no amplification of shock (i.e., the a/a_o ratio is unity or less) and moreover show a diminished response proportional to the component's natural frequency. For example a 45 Hz component has a response factor of approximately 0.5.

A more realistic shock input pulse would have a sloping wave front at the beginning and at the end. A displaced cosine curve

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*Reference should be made to "Shock and Vibration Handbook," McGraw Hill, 1961, v. 1, Chapter 8 and Figure 8.18 for the Development of the REsults of Figure B.

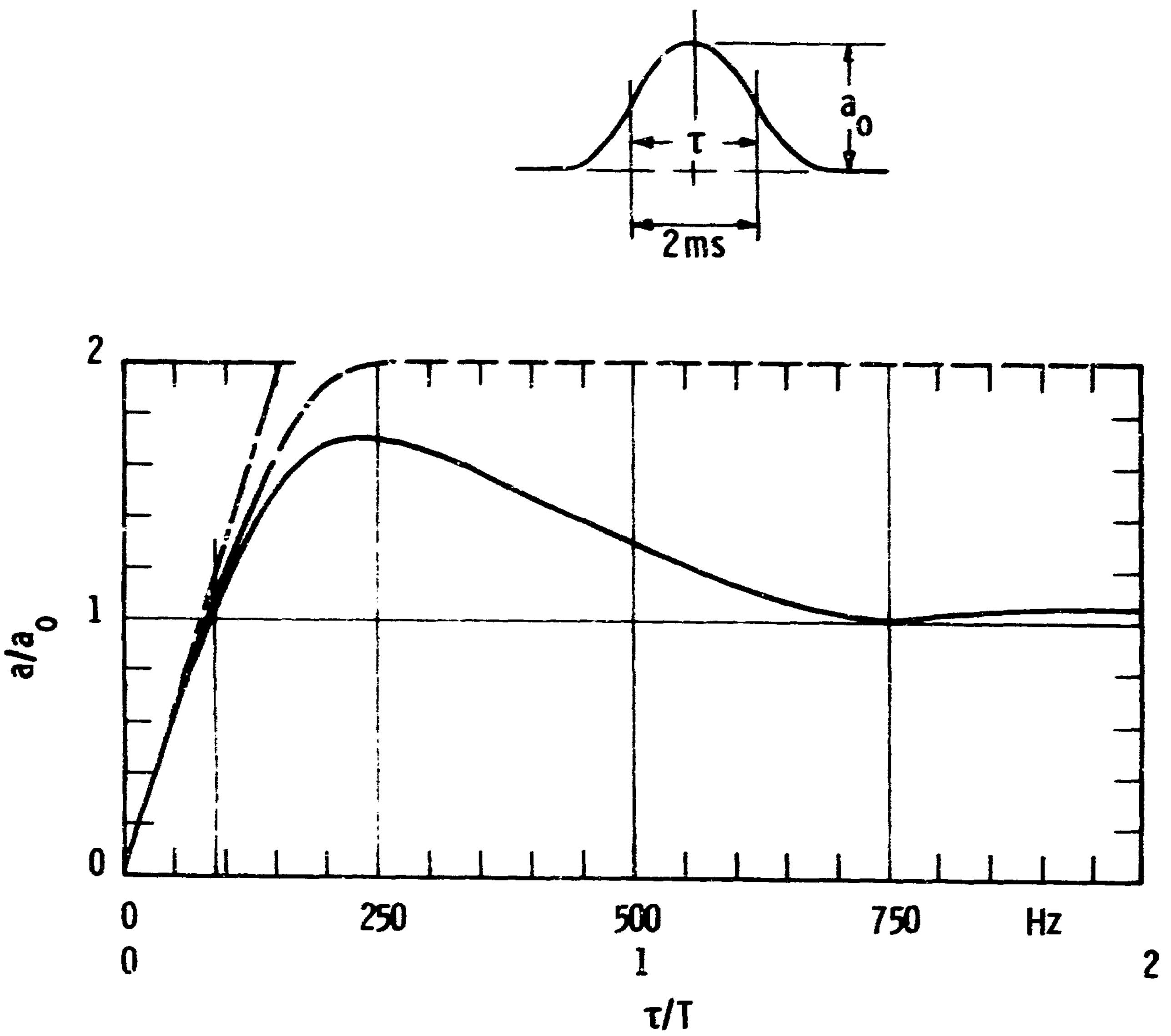

FIGURE 2-32. Shock response curve for (a) square wave acceleration input of Fig. 2-31 (dashed line) and (b) shock input having same amplitude and area but with versed sign wave fronts (solid line) per sketch.

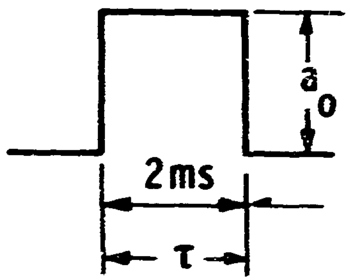

Fig. 2-31
Square Wave Shock Input

(a "versine curve") has been used to form the pulse whose response is shown by the solid line in Figure 2.32. At component frequencies up to 90 Hz the response curve is virtually the same as that for the square wave pulse. This is the frequency range over which the component response is identical to that resulting from a suddenly applied velocity at the seating, equal to $a \cdot dt$ of the acceleration pulse, and is independent of the pulse shape, being only dependent on its area.

From 90 to 250 Hz the solid line curve is progressively lower than the dashed line curve and peaks at a value of $a/a_o = 1.7$ at 225 Hz. At higher frequencies there is a steady decline in response to a value of 1.0 at 750 Hz, with but minor increases above 1.0 for higher frequencies.

Considering the flexibilities or compliances of the structures between the machine and the outer hull of the ship, at which location the shock forces would be applied, the use of a shock pulse with modified wave fronts such as shown in Figure 2.32 appears to be a reasonably equivalent approach for evaluating the dynamic response of the machines during initial design. Hence the shock response curve shown by the solid line in Figure 2.32 will be used for design evaluation of the generator and motors. Values of the acceleration input amplitude a_o for each machine are given in the tabulation presented earlier in this section (Table 2.17).

The curves of Figure 2.32 are based on an input pulse length of 0.002 second measured from the mid-height points of the wave fronts at the start and ending of the pulse, as shown by the sketch and designated as τ. T is the natural period of vibration of any selected subsystem or component of the machine, the inverse of the natural frequency f_n in Hz. Values of the ratio τ/T are given on the abscissa scale in addition to the frequencies.

For preliminary design procedures the g-factors of Table 2.18 should be used for the machine's components, so as to avoid the requirement of reading the curve of Figure 2.32 for every component.

TABLE 2.18

DYNAMIC FACTORS FROM RESPONSE SPECTRUM

Component Natural Frequency, fn - Hz	Design g-factor
0 to 90	$\frac{fn}{90} \cdot a_o$
90 to 700	Use 1.7 a_o for initial stress check. If component fails to verify, use a/a_o factor from Figure 2.32
700 up	a_o

Body loads equal to the weight of each component part times the g-factor should be applied successively in each of the three directions. Resulting stresses should not exceed the material's 0.2% yield strength and deflections should be of acceptable values.

The design of the generator and motors has developed to the stage where the rotors, stators and bearings are sized but many details remain to be done. Four areas are evaluated for shock resistance at this preliminary stage.

Mounting feet and bolts: These have not been designed to date. When this is accomplished, the feet and bolts should be sized to the basic g-factors shown by a_o in Table 2.17, for vertical and horizontal shock. The multiplier of $a/a_o = 1$ is here used since it is unlikely that the fundamental natural frequency of a machine on its foundation will exceed 90 Hz and yet will not be low. There should be no appreciable difficulties in satisfying these requirements.

Shock Deflection of Rotor in Air Gap

The static deflection diagrams for the generator and motors are computed as a first step in the critical speed analysis.

The ordinates of this are multiplied by the a_o value for each for each machine as given in the tabulation earlier in the section. The ordinates are then modified by the dynamic factor in the second table $\frac{fn}{90}$, where f_n is the rigid bearing critical speed in Hz.

Results of these calculations are shown in the final table and are compared with the design value of air gap clearance.

TABLE 2.19

SHOCK DEFLECTION OF ROTORS

Machine	g-level	Maximum Static Deflection (in.)	X g-level (in.)	Rigid Brg Critical (Hz)	$\frac{fn}{90}$	Resultant Shock Max Defl- (in.)	Air Gap (in.)
20 KHP generator	35	$6.4 * 10^{-3}$	0.224	42.2	0.47	0.105	0.150
40 KHP motor	20	$2.1 * 10^{-5}$	0.00042	684	1.7	0.0007	0.125
20 KHP motor	31	$7.3 * 10^{-4}$	0.023	112	1.7	0.039	0.150

Loading of Bearings Under Shock

Shock loading of sleeve bearings is first calculated by the product of a_o with the weight of the rotor, divided proportionally between the bearings and then divided by the projected area of each bearing. Results of this computation are given in Table 2.20, and are compared with the maximum allowable shock loading for sleeve bearings permitted by the propulsion turbine military specification MIL-T-17600D.

It is seen that all bearing shock loads are well below the allowable maximum of 22,000 psi as established by the military specification for steam main propulsion machinery.

TABLE 2.20

BEARING SHOCK LOADS

	Estimated Rotor Wt. lbs	g-level a_o	Brg. Size	Shock Unit load-psi	Allowable shock unit load-psi
20 KHP generator	6600	35	8 x 8	1804	22,000
40 KHP motor	58200	20	24 x 10	2425	22,000
20 KHP motor	13200	31	10.25 x 10	1996	22,000

Bouncing of Brushes due to Shock

This aspect of the design evaluation is the most difficult of those to be reviewed. Only the generator configuration will be considered here, the motor arrangements being similar. Each brush holder module consists of four clusters of brushes, each having four brushes, with each cluster fitting in its separate rectangular slot and loaded with two constant-force springs.

The conceptual design is shown on Figure 2.33. The four brush clusters are held in a single casting supported at the bearing end by an insulating structure. The end adjacent the armature core is shown positoned but not supported by an insulated shield.

Data on the brushes and current collector are given in Table 2.21.

The predominantly important question is: "Will the brushes lift from the current collector surface under shock conditions?"

If the anser is "yes", then the electrical circuitry will have to be tolerant of brush lifting, or the brush system will have to be redesigned and developed to minimize or avoid all momentary brush lifting.

The analysis of this question is not straightforward. Figure 2.34 is a schematic sketch of the principal features of the brush holder. The sixteen brushes are forced down onto the current collector by constant force springs, one to each four brushes, producing a unit pressure of 7 psi.

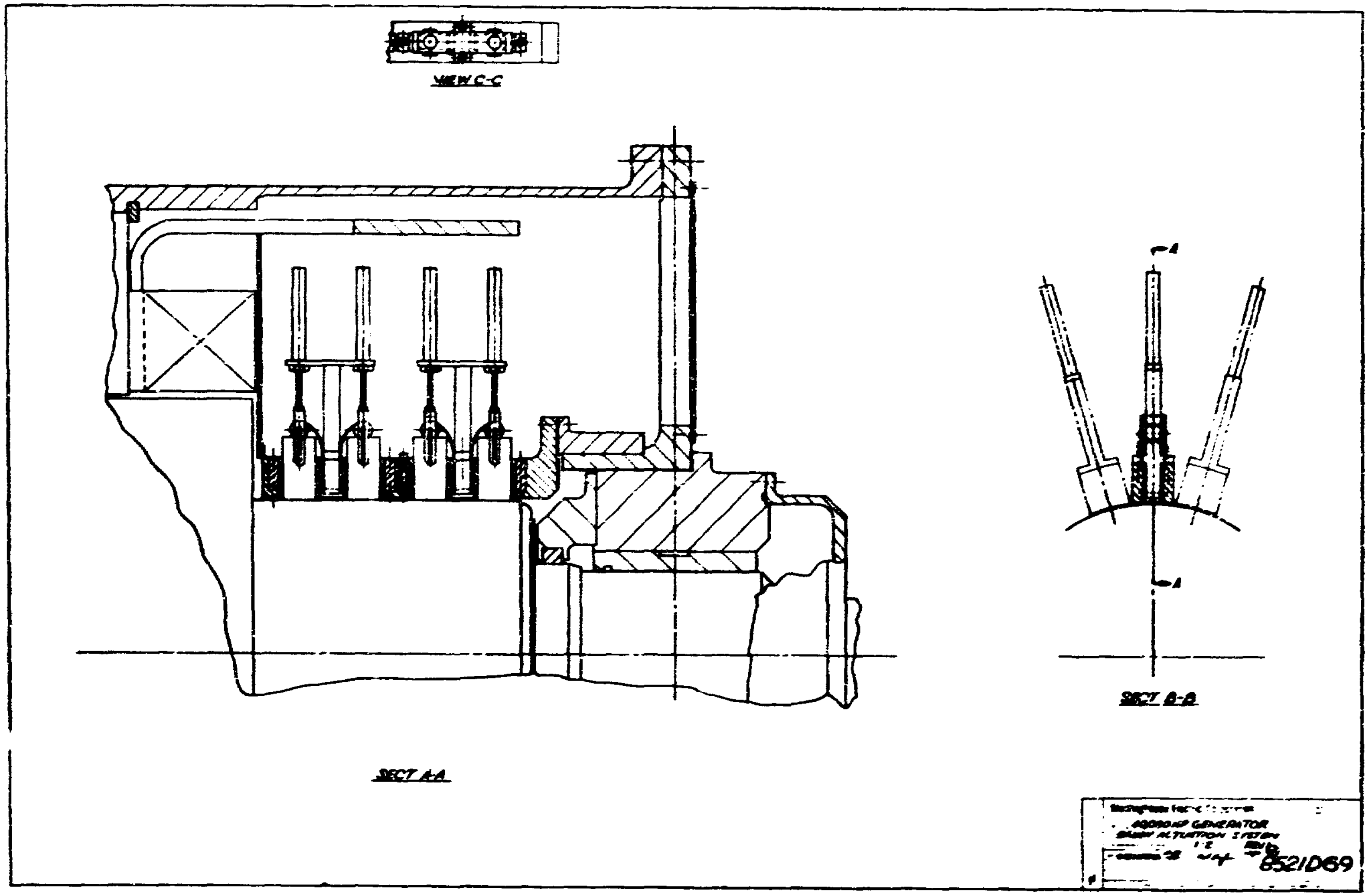

Figure 2.33. Concept Design of Brush Holder, for 20 KHP Generator

TABLE 2.21

CURRENT COLLECTOR DATA FOR 20 KHP GENERATOR

Collector diameter = 14.85 in.
Speed = 3600 rev/min.

No. of brushes per cluster = 4
No. of clusters per brush holder = 4

Cluster width = 1.64", Thickness = 1.06"

Brush width = 0.82", Thickness = 0.53"

Pressure at collector surface = 7 psi

Force for 1 brush (0.82 x 0.53) = 3.05 lb

Brush length = 2"
Density = 0.18 lb/cu in.
Modulus E = 5,000,000 psi

Weight of 1 brush = 0.156 lb

The force per brush is slightly over 3 pounds. When divided by the brush weight a value of 20 is obtained, corresponding to the steady value of g required to lift the brushes, far short of the value a_o = 35 g for the prescribed shock input for the generator. Treatment of this deficiency must await further design investigation and analysis.

The schematic model shown in Figure 2.34 should be analyzed as a next step in the design process of shock design. Looking at the details of the model, the brush holder casting may be considered as rigid so that only its mass distribution need be considered. The main support is at the bearing end where an insulated structure forms the base connection for the cantilevered brush holder. This support is stiff in shear and moderately flexible in rotation and may be modelled as an elastic hinge of stiffness K_θ.

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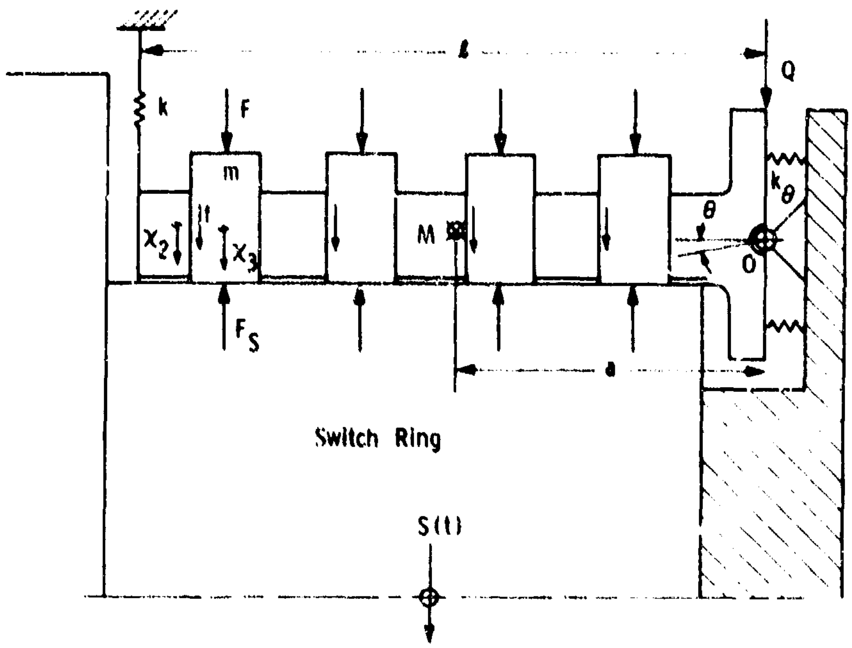

Equations of Motion of Brush and Holder

X_2 = Motion of Holder at Brush ℄

X_3 = Motion of Brush

P = Lateral Force in Holder on Brush

$f = \pm \mu P$. + for $\dot{X}_2 - \dot{X}_3$ +

− for $\dot{X}_2 - X_3$ −

μ = Coef. of Friction

$Ma\ddot{\theta} + k\ell\theta = Q - M\ddot{S} - kS$
$\frac{I_0}{g}\ \ddot{\theta} + (k_\theta + k\ell^2) = -k\ell S$ } For Holder

$m\frac{d^2X_3}{dt^2} = F - F_S + f,\ X_3 = X_2.$ Before Separation

$= F - 0 + f,\ X_3 = X_2.$ After Separation

M = Mass of Holder, m = Mass of Brush

θ = Angular Deflection

I_0 = Moment of Inertia of Holder About "O"

S (t) = Shock Motion of Frame

Figure 2.34. Schematic of Brush Rigging for Analysis with Equations of Motion

The presently shown configuration is almost certainly excessively flexible, and will have to be redesigned. In order to determine the stiffness K_θ a partial full scale model test will undoubtedly have to be performed.

The only other brush holder support is at the armature core end and is represented by the spring constant k. By redesign this should be made much stiffer than it now is, for otherwise the fundamental natural frequency of the brush holder on its supports will be low.

Each brush cluster may be considered as being held in position by the surface of the switch ring, the guiding of the brush holder slot and the force of 12.2 lbs per cluster provided by the constant force spring - whose force at the brush will not change due to vibratory motions of the brush pair.

Lateral forces exist in the brush holder slot in order to provide contact pressure on the current shunt finger connectors. These forces produce friction that opposes the sliding of the brush in the holder. In general this friction increases the duty of the constant force spring in holding the brush in contact with the collector.

The evaluation of this brush holder friction force will be done by test on a prototype assembly so that the upward and downward values will be determined for a range of lateral forces. This force is designated "f" in Figure 2.34.

The equations of motion of the brush and holder are non-linear due to the characteristics of "f" and the fact that the brush may lift off of the switch ring surface. The equations are given on the lower half of Figure 2.34 and have to be solved by stepwise integration. The shock input motion, s(t) is as determined by the square wave acceleration shock pulse of amplitude a_o and 2 ms time duration. For the system shown, a satisfactory approximation to s(t) is a suddently applied velocity of 0.002 $a_o g$ inches per second.

The outcome of the analysis will show if the brushes are lifting from the switch ring. No analysis is being performed at the present time, first, due to lack of data on K_θ and f, and, second, since the design shown in Figure 2.33 does not appear to be adequately stiff to prevent brush lifting problems.

2.4.5 Design for Vibration

2.4.5.1 Critical Speed and Vibration of the 19.6 MW Generator

The undamped-rigid lateral natural frequency of the 19.6 MW generator rotor is approximately 2530 RPM (N_o).

The oil lubricated bearings are of the partial-arc, hydrodynamic type. One 0.203 m (8 in.) dia. bearing is at each end of the rotor. Bearing to bearing length is 2.565 (101 in.). The oil film spring damping properties calculated were 0.525 GN/m (3×10^6 lb_f/in.) and 0.35 GN/m (2×10^6 lb_f/in.), respectively.

The dynamic model Figure 2.35 includes the stiffness of the torque tube only. The punchings, rotor bars and banding are included in the weight circulation.

The damped-flexible lateral natural frequency is 2326 RPM. These calculations use the above oil film properties and a pedestal stiffness of 2.627 GN/m (15×10^6 lb_f/in.).

The specification critical speed is defined as:

$$N_C = N_o \times 1.10 \times 1.25$$

= operating speed x turbine overspeed criteria x safety factor

$$= 3600 \times 1.10 \times 1.25 = 4950 \text{ rpm}$$

Since $N_C > 2326$ RPM, this machine is supercritical. Other multiples of the exciting frequency would be 0.5 N_o (1800 RPM); 2 N_o (7200 RPM), and 3 N_o (10,800 RPM).

The damped-flexible second lateral natural frequency is 9592 RPM using the above bearing and pedestal properties.

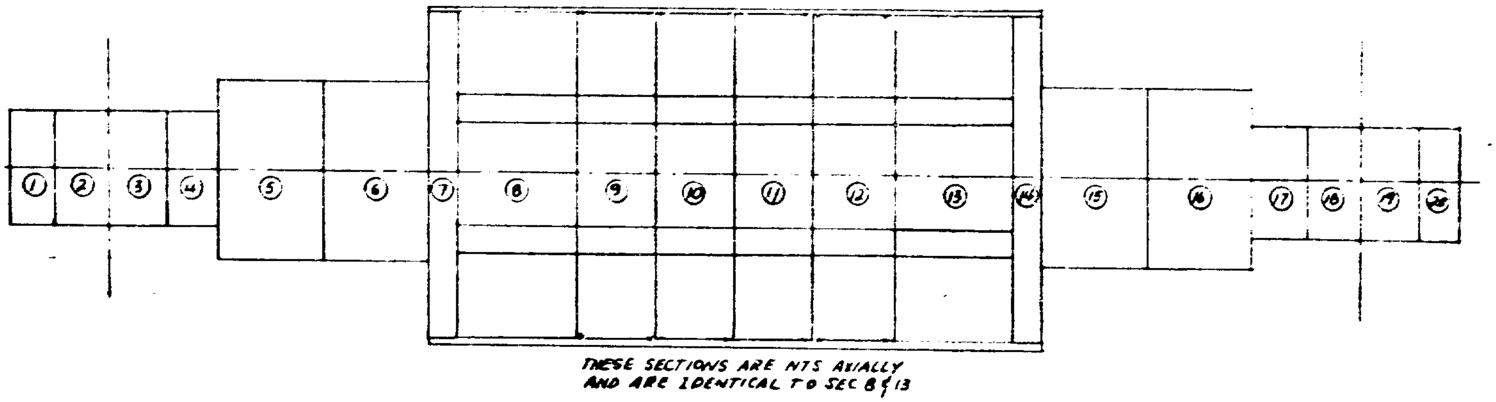

Figure 2.35. Dynamic Model of 19.6MW Generator Rotor

The rotor length was increased to reduce the lateral natural frequency below the minimum operating speed of 1800 RPM. The brush section lengths were changed to increase the overall length from 2.921 m (115 in.) to 3.632 m (143 in.). The lateral natural frequency decreased from 2326 RPM to 1618 RPM. Figure 2.36 shows the vibration of the rotor at the brush sites is 5 to 8 x 10^{-6} inches (single amplitude) at the normal operating speed of 3600 RPM.

The rotor will be rough balanced at several stages of the fabrication sequence. This should take the rotor final balance a small precision balance or just a check balance. The prototype instrumentation will allow orbit studies at operating conditions.

2.4.5.2 Critical Speed and Vibration of 40 k HP Motor

The operating speed (N_o) of the 40 k HP motor is 168 RPM. Dwg. 1289J30 shows the bearing to bearing length is 2.210 m (87 in.) and the torque tube punching support diameter is 2.299 m (90.5 in.). Since the operating speed is low, the bearing to bearing length is long and the shaft stiffness high, the ROTCO computer program was not used to calculate the rotating undamped-rigid or the damped-flexible lateral frequencies. The mid-span deflection of a constant beam is:

$$y = \frac{5}{334}\frac{w\,L^4}{E\,I}$$

The beam was assumed to extend the total bearing to bearing length. Only the torque tube was used in the calculation for shaft stiffness, although the weight of both the rotor punchings and the torque tube was included, which is a conservative calculation.

The non-rotating fundamental beam frequency with rigid supports is

$$N_C = \frac{187.7}{\sqrt{y}} = 41057 \text{ RPM}$$

Since $N_C >>> N_o$; this machine will operate below the first lateral natural frequency.

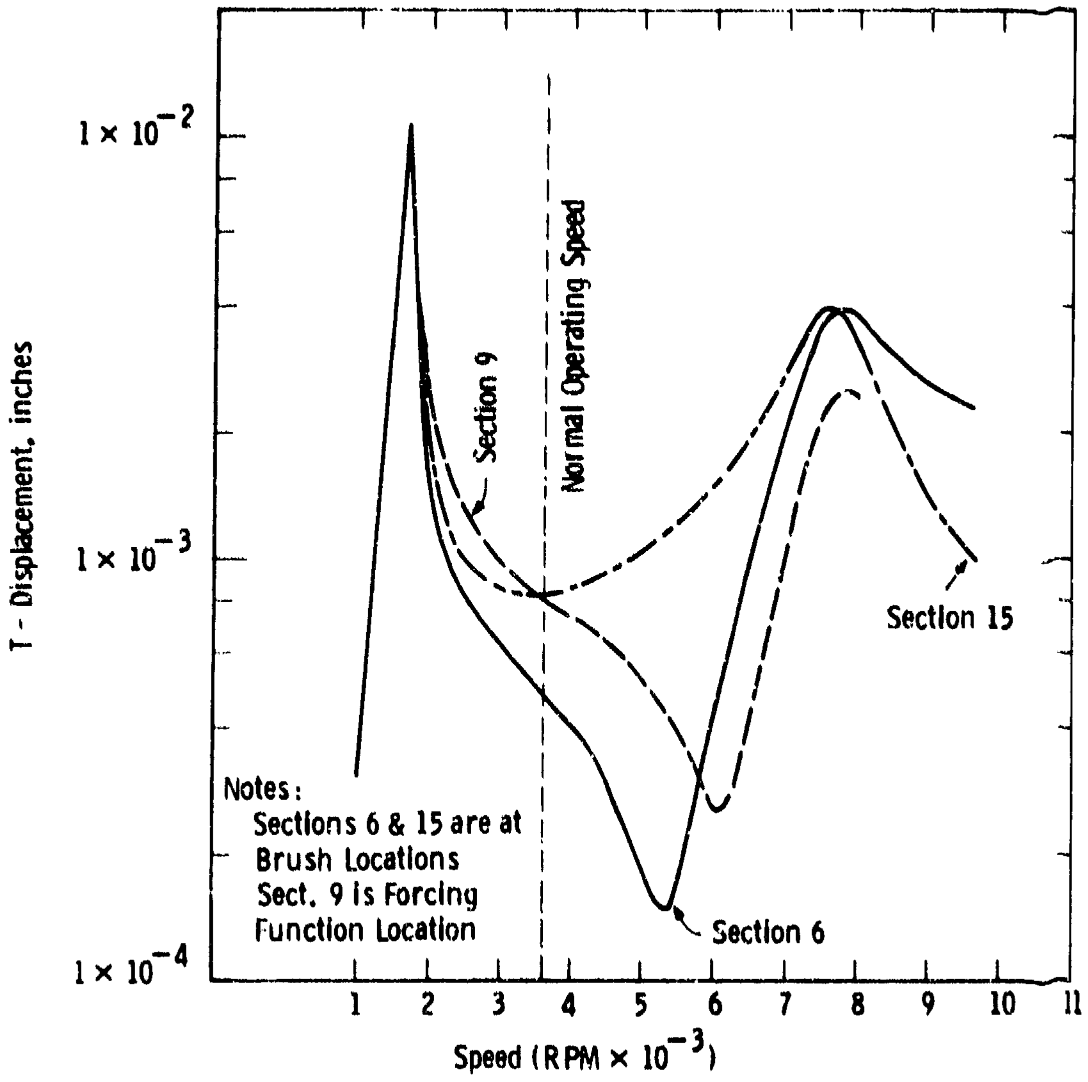

Figure 2.36. Displacement Vs Speed of Brush Vibration

The rotor will be rough balanced at several stages of the fabrication sequence. This should make the final balance a small precision balance or just a check balance. The prototype instrumentation will allow orbit studies at operating conditions.

2.4.6 Grounding

Specification MIL-E-9170 requires that the "design and construction of the equipment shall be such that all exposed parts or panels of metal or other electrically conductive material are at ground (ship's hull) potential at all times". Ground straps will be provided where necessary to conform with this specification.

2.4.7 Magnetic Fields

The work directive requires that a magnetic field no greater than 100 gauss shall occur at a distance of 6 inches from the surface of the equipment. The magnetic field calculations performed on the machines indicate that this requirement is satisfied.

2.4.8 Electromagnetic Interference

The armature current in the rotor bars of the machines is switched on as the bar comes under the brush and is switched off as it leaves the brush. This switching action will give rise to electromagnetic fields. The brushes, however, are enclosed inside of a steel end structure. This end structure must be tight to contain the brush atmosphere and since it is metal, it will act as an electromagnetic shield. It is expected, therefore, that fields external to the machine will be of little consequence.

2.5 Operability Considerations

2.5.1 Rotor Removal Procedures for Maintenance

A preliminary study has been made on the steps that are necessary to remove the rotors from the ship on the destroyer application. This study does not encompass the design details of the first part of the process, that of disassembling the rotor from the frame and stator of the machine. The machines will be designed so as to facilitate this first stage of disassembly, beginning with the unbolting of the drive coupling and ending with the rotor positioned on supports adjacent to the non-drive end bearing housing (in the case of the generator).

This is position "1" on Figure 2.37, a plan view of the aft engine room of the destroyer, showing the outboard generator rotor removed from its frame. As will be seen from this layout an opening in the forward bulkhead must be provided to accept the generator rotor in this position, along with provision for rotor set down space in the adjacent compartment.

The rotor may then be moved into position "2", from which removal from the ship may be accomplished through an access hole cut through the starboard shell plating, or, alternatively, the rotor may be removed vertically through an access opening in the main deck. The weight of the generator rotor is 6600 lbs.

The process of removal of the motor rotor is more elaborate because of its size (8'-8" dia.) and its weight (58,000 lb) and the presence of the main thrust bearing and line shafting. Removal of the rotor axially in the direction of the gas turbines is not considered practical on account of the space occupied by the turbines, although if the turbines were to be removed for other reasons this mode of rotor removal should be studied.

The first stage, namely the disassembly of the rotor from the motor frame, is not detailed here, since this procedure will be developed during the final design of the motor. In any event, to complete the rotor removal process, first the thrust bearing and the forward section of line shafting must be moved from their positions of interference.

Next a thru hole must be provided in the engine room bulkhead. Figure 2.38 shows the forward engine room on the destroyer and in this case the transfer hole must be provided through Bulkhead 220, the aft bulkhead in the engine room. The motor rotor, 8'-8" dia. and 8' long with

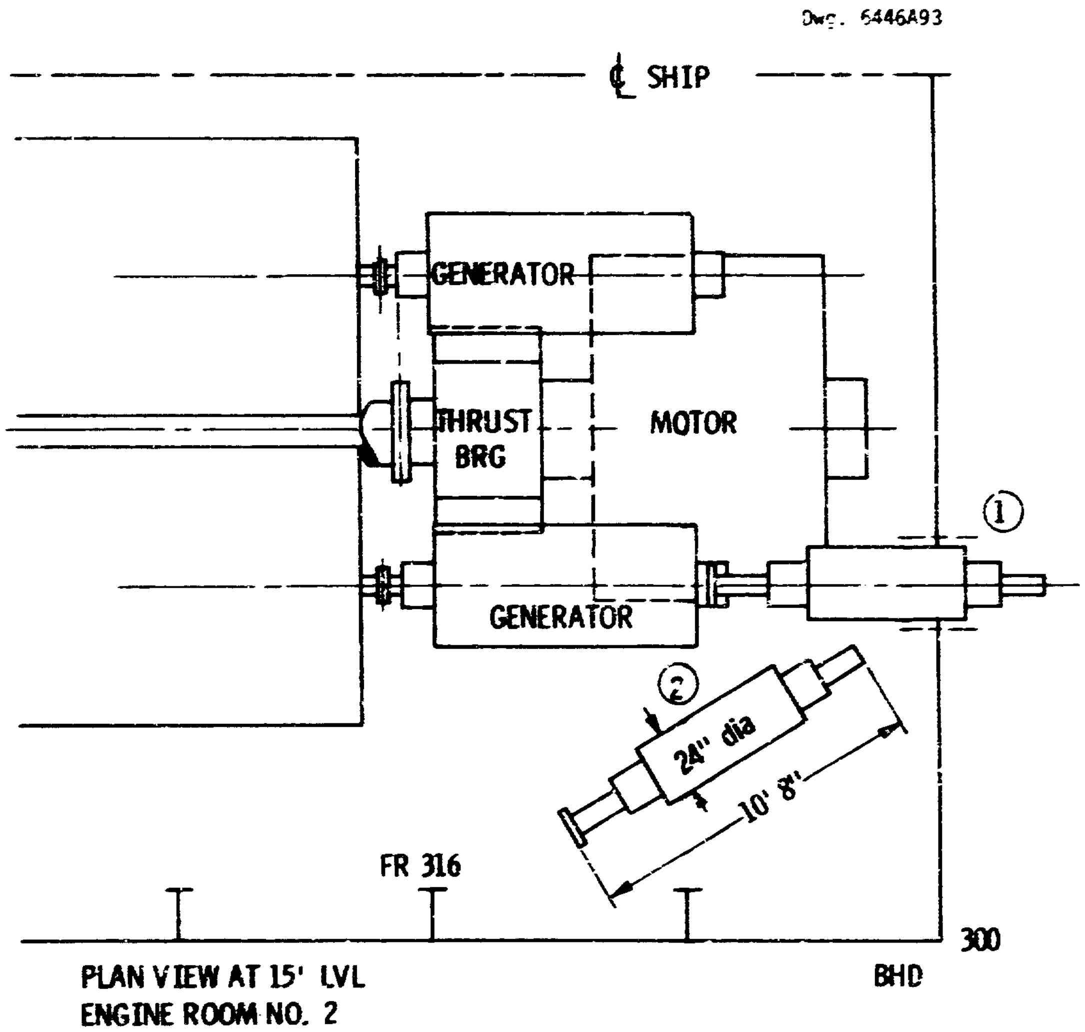

Figure 2.37. Removal of Generator Rotor

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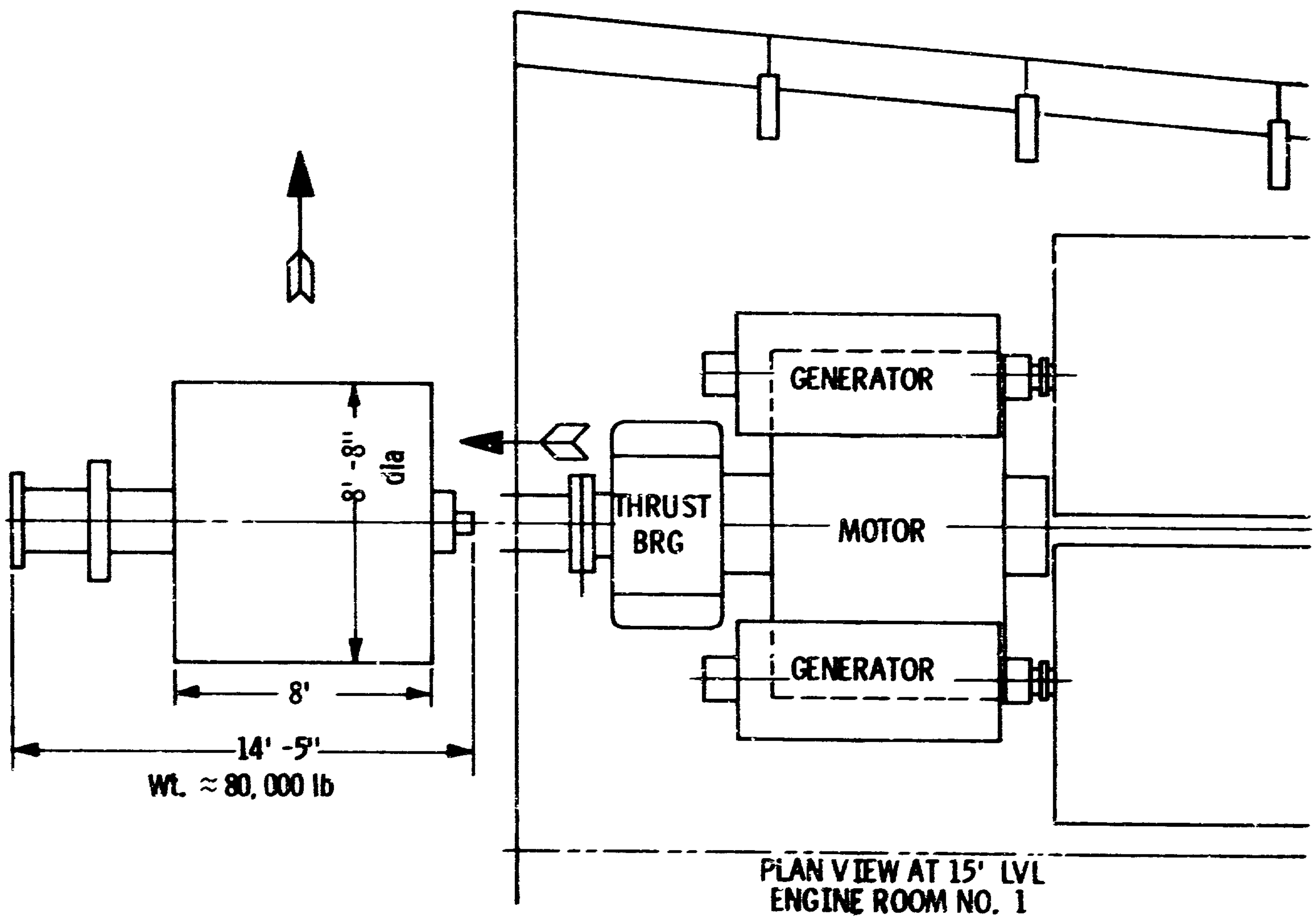


Figure 2.38. Removal of Motor Rotor

extended shaft 14'-5" long is shown moved into the space aft of the forward engine room, being the forward auxiliary machinery room on the present destroyers.

From this position, the rotor is removed from the ship through either an access hole cut into the ship's port side or vertically through openings in the main deck and deckhouse overhead.

process, that of disassembling.

2.5.2 Corrective Maintenance Concepts

In general, each electrical machine can be maintained in situ for most tasks such as bearing replacement, brush removal, seal replacement and switch-ring undercutting and smoothing. Most of the water cooling and lube system is readily available for cleanout without having to remove the machines from their foundations. For major maintenance or replacement of damaged machines, the motors or generators would have to be removed, as was described for the machines in the previous section. The excellent record of electrical propulsion machinery, in terms of high reliability, utilized in marine propulsion systems indicates that major maintenance requiring removal of the machines would seldom have to be performed in the lifetime of the ship. Of the other major components, modular construction is used whenever possible so that these devices can be maintained quite readily by simple replacement of modulus in case of damage requiring repair.

2.5.3 Caution and Safety Alarms

As contemplated, the 40 KHP system would have in addition to the programmed computer logic control system, a data logging and alarm system. This would most likely be supplied as an additional separate computer that not only logs the pertinent data but would also determine if the sensed variable was within its normal limits. If it was not, it would alarm the operator so that corrective action may be initiated. In some cases, where immediate action is demanded, these anomalous indications will automatically initiate the proper corrective action.

This will minimize damage to the principle components and considerably shorten the time that a component is subjected to high temperature, pressure or stress.

2.5.4 Safety and Hazardous Materials

There are no hazardous materials that are utilized in this electrical propulsion system that are not now presently aboard ship. The most hazardous material of course is the ship's fuel which for the purpose of this analysis is excluded since it is common to all gas-turbine powered ships. The next most hazardous material would be the lube oil, which is present on all ships in various amounts and in which most personnel are usually well trained in its handling and safe use. Additionally most are trained in preventing fires of this substance and how to combat fires if they should accidently occur. The remaining substance that is used (in small amounts) in this system is the CO_2 used in the cover gas system. The inherent hazard is in handling the storage bottles and preventing leakage of the gas into a confined unvented space in which personnel may be present which could result in suffocation. This substance is used in many fire extinguishers typically found aboard ships, and most personnel are trained in its handling and use. It is thus a familiar substance to which most personnel have become accustomed to handling safely.

2.5.5 Logistics

The logistics of providing spare and replacement parts are considered of a secondary nature. The amount of expendable materials used in the system have been kept to a minimum. Probably the most important of these consumables are the electrical brushes used in the machines. Since they are utilized conservatively, the estimated wear rates would necessitate the aboard storage of only one complete set for a generator and motor to be used at periodic replacements if these inspections were not performed in part prior to departing. The same can be said of the filters used in the lube and cover gas systems.

The amount of CO_2 needed for the cover gas system is very small and is a function of seal wear. With proper maintenance of these seals very little CO_2 will escape and therefore only a few extra bottles would be required for gas replacement. However, since opening any of the machines for inspection or maintenance would release the cover gas, at least one spare bottle per machine should be aboard as this procedure would account for most of the required replacement gas.

2.5.6 Test Equipment and Personnel Training

After manufacturer's tests are completed and the machines are installed, they will not require any special equipment beyond what would normally be aboard ship for servicing these machines. Electronic technicians familiar with volt, amp and ohmeters and capable of servicing electronic equipment will be able to properly attend this equipment. An electronic technician capable of operating an oscilloscope should be able to service the solid state control system as it will be designed on a modular basis with replacement circuit boards and modules. Thus very little additional training will be required in order to service the electrical equipment. The mechanical servicing of the electrical equipment will pose no additional barriers to personnel familiar with normal shipboard equipment.

SECTION 3

MAJOR SUBSYSTEMS

3.1 19.6 MW Generator

This section describes the generator which is to be employed in the destroyer type ship and the large hydrofoil application. The generator is a dc machine, with a nominal rating of 2000V and 9800 amps at 3600 rpm. It is intended to operate in a unidirectional mode powered by a gas turbine. The destroyer utilizes four of these generators, and the hydrofoil employs two. The basic configuration of the generator conforms to that described in Appendix 5. The principal features of this machine include a circumferentially segmented magnetic circuit, an armature winding which is mounted on the surface of the rotor iron, direct water cooling of the electrical conductors and solid brushes operating at very high current densities. Figure 3.1 illustrates the basic electromagnetic geometry of the machines under consideration for this systems analysis effort.

Parametric studies were undertaken to determine the effect of variations in the design parameters on the weight and efficiency of the machines. The parameters studied were: the number of poles, the number of series circuits, the rotor diameter, the rotor and field current densities, the air gap flux density, and the pole face to pole pitch ratio. The effects of varying these parameters are discussed in Appendix 5.

3.1.1 Exceptions

No exceptions to Work Directive requirements are required.

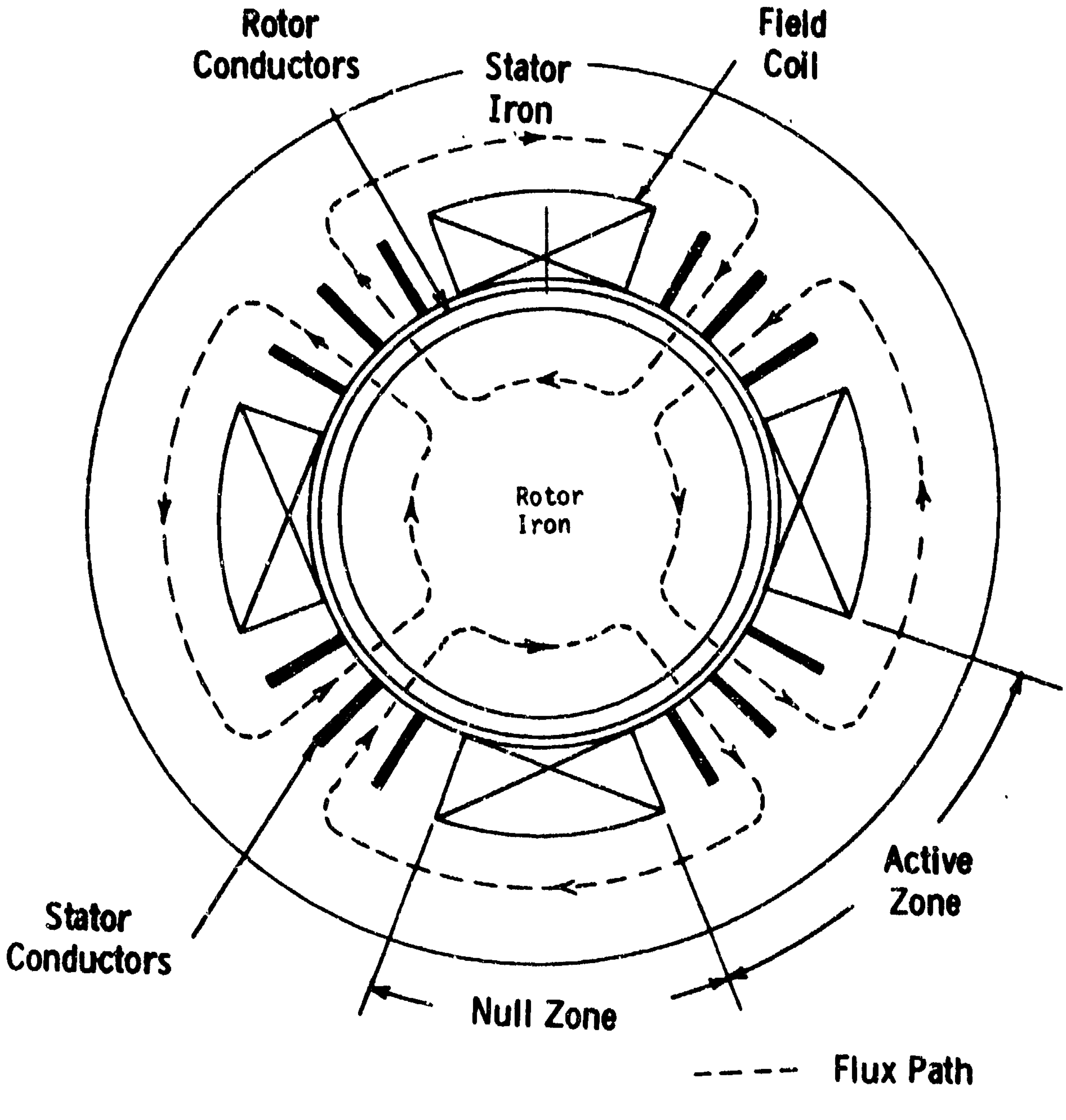


Figure 3.1. SEGMAG II Geometry

3.1.2 Technical Summary

The 19.6 megawatt generator is rated at 2000 volts, 9800 amperes, and 3600 RPM. The major design characteristics for the preliminary design of this machine are given in Table 3.1. Figure 3.2 is a flux plot of the machine. Tables 3.2, 3.3 and 3.4 present the estimated losses and efficiency at the rated, full system load and cruise conditions. Figure 3.3 is a connection diagram for this machine.

3.1.3 Generator Physical Description

The preliminary design layout of the 19.6 megawatt generator is shown in Figure 3-4. The machine is designed to class B insulation specifications. Because of the high power density, both the rotor and stator are water cooled.

There are four circumferential magnetic segments, resulting in the winding diagram schematically that of Figure 3.3. The end region of the machine contains the switching and brushes which provide the switching mechanism to move armature current from one rotor bar to the next, as bars enter and leave the active zone of each segment.

As a rotor conductor moves into the active zone of the machine, it is contacted at both ends by brushes. The conductor now forms one-half of an electrical turn. The other half turn is provided by the stator conductor, which also serves to provide a compensating flux in the airgap to counter the armature current reaction field. The rotor conductor stays in contact with the brushes until it enters the null zone, and the current flowing in the conductor produces the machine torque (or voltage) while it is in the active field region. Because the rotor conductors and any other conducting rotor material will see a variation in field during rotation, losses will be induced in them. These losses are kept to an acceptable level by laminating the iron portions and stranding and transposing the rotor conductors. The rotor conductor strands will be 0.508 mm (0.02 inches) in diameter and fully transposed in the active length.

TABLE 3.1

MAJOR DESIGN CHARACTERISTICS FOR THE 19.6 MEGAWATT GENERATOR

Rated Voltage		2000 Volts	
Rated Current		9800 Amps	
Rated Speed		3600 RPM	
Number of Poles		4	
Number of Circuits per Pole		3	
Pole Face to Pole Pitch Ratio		0.6	
Gap Flux Density		1.3 Tesla	
Nominal Iron Flux Density in Stator Back Iron		1.8 Tesla	
Nominal Iron Flux Density in Rotor		1.6 Tesla	
Current Densities - Rotor Bars	11.04 M Amps/m^2	(7122 Amps/in^2)	RMS
	7.66 M Amps/m^2	(4940 Amps/in^2)	Peak
- Risers	5.76 M Amps/m^2	(3714 Amps/in^2)	RMS
	12.07 M Amps/m^2	(7790 Amps/in^2)	Peak
- Stator End Rings	4.65 M Amps/m^2	(3000 Amps/in^2)	
- Stator Bars	5.72 M Amps/m^2	(3690 Amps/in^2)	
- Field Winding	4.65 M Amps/m^2	(3000 Amps/in^2)	

Major Dimensions

Rotor OD	0.610 m (24.00 inches)
Rotor Iron ID	0.280 m (11.00 inches)
Stator OD	1.149 m (45.25 inches)
Stator ID	0.635 m (25.00 inches)
Mechanical gap	0.381 m (0.15 inches)
Rotor Bar Thickness	14.7 mm (0.58 inches)
Banding Thickness	8.9 mm (0.35 inches)
Stator Active Length	1.18 m (46.5 inches)
Rotor Lamination Length	1.28 m (50.5 inches)
Bearing - Length	2.54 m (100.0 inches)
Bearing Diameter	0.203 m (8.00 inches)
Current Collector OD	0.376 m (14.80 inches)
Machine Weight	10,725 kg (23,645 lb)

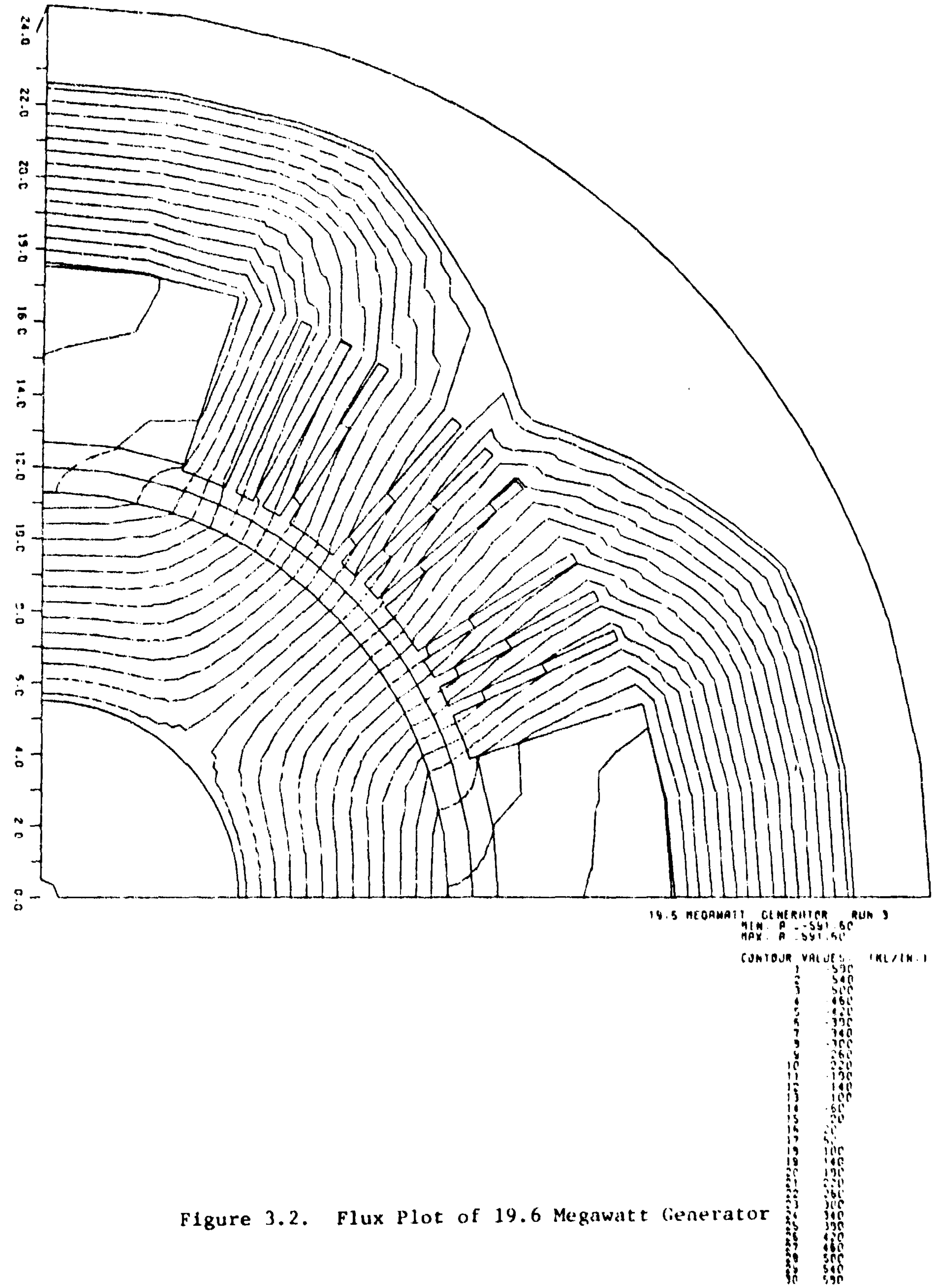


Figure 3.2. Flux Plot of 19.6 Megawatt Generator

TABLE 3.2

GENERATOR LOSSES - MACHINE RATING

(Losses in Kilowatts)

I^2R	- Rotor bars	80.4
	- Stator bars	16.7
	- End Connections	21.7
	- Field Windings	56.1
Brushes	- Friction	37.0
	- Contact & Ohmic	24.9
	- Shunt Contact	4.7
Eddy Currents	- Main Flux	10.5
	- Tooth Ripple	10.2
	- Risers	30.6
	- End Plates	46.2
	- Collector Bars	18.7
	- Core Loss	15.9
Bearing		24.1
Windage		3.3
		401.0
Efficiency at 19.6 Megawatts		98.0%

TABLE 3.3

GENERATOR LOSSES - SYSTEM FULL LOAD

I_L = 76.1% Rated

I_F = 100% Rated 25% of brushes are lifted

Speed = 100% Rated

I^2R	- Rotor Bars	46.6
	- Stator Bars	9.7
	- End Connections	12.6
	- Field Winding	56.1
Brushes	- Friction	28.0
	- Contact & Ohmic	18.9
	- Shunt Contact	3.6
Eddy Currents	- Main Flux	10.5
	- Tooth ripple	10.2
	- Risers	30.6
	- End Plates	46.2
	- Collector Bars	18.7
	- Core Loss	15.9
Bearing		24.1
Windage		3.3
		335.0
Efficiency at 14,910 KW	=	97.80%

TABLE 3.4

GENERATOR LOSSES - CRUISE CONDITION (IN KILOWATTS)

I_L = 73.37% Rated

I_F = 100% Rated 25% of Brushes are lifted

Speed = 77.8% Rated

I^2R	- Rotor Bars	43.3
	- Stator Bars	9.0
	- End Connects	11.7
	- Field Winding	56.1
Brushes	- Friction	28.0
	- Contact & Ohmic	18.3
	- Shunt Contact	3.4
Eddy Currents	- Main Flux	6.4
	- Tooth ripple	6.2
	- Risers	18.5
	- End Plate	28.0
	- Collector Bars	11.3
	- Core Loss	12.3
Bearings		14.6
Windage		2.0
		269.1

Efficiency at 11,180 KW = 97.65%

Dwg. 6429A54

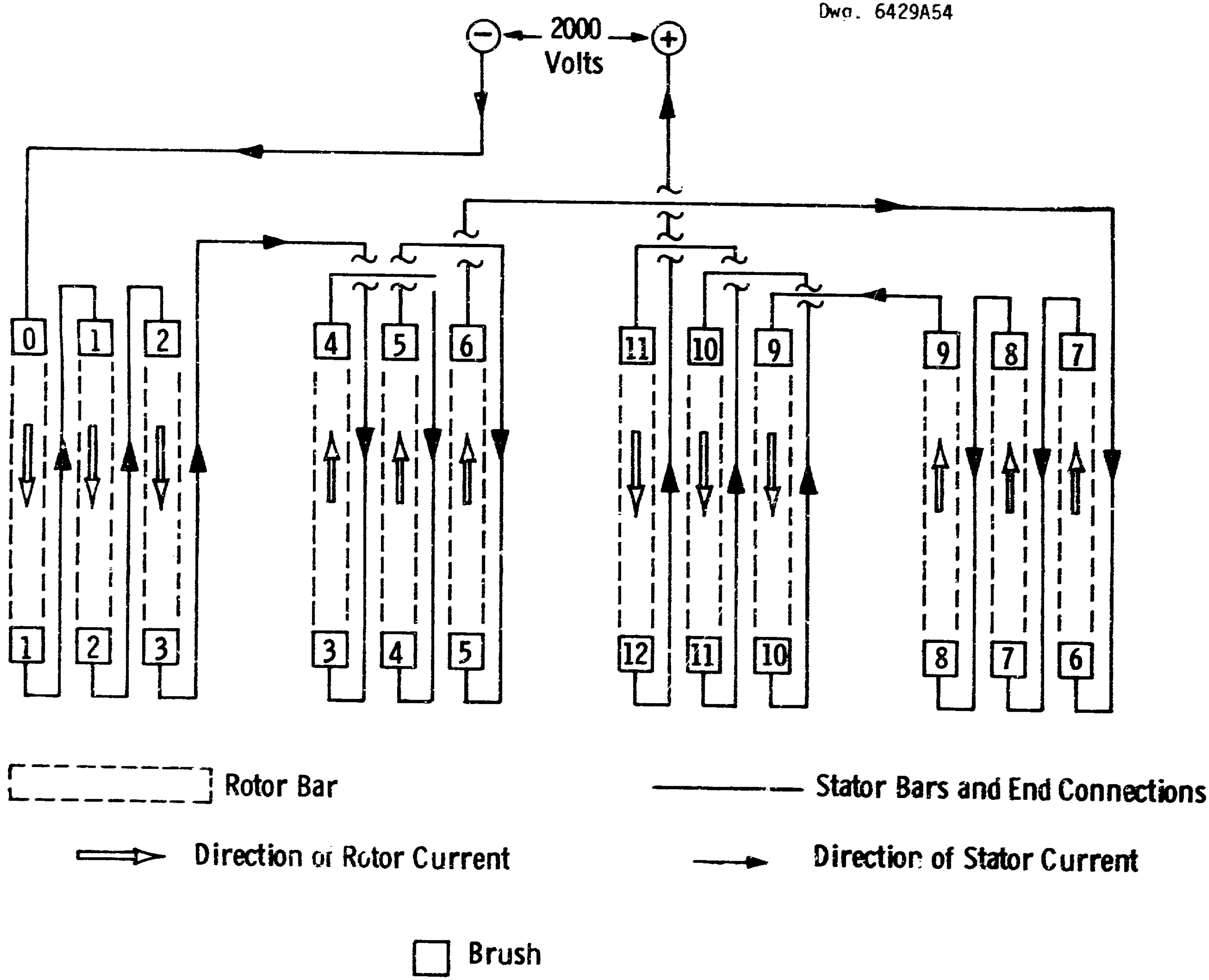


Figure 3.3. Rotor and Stator Bar Interconnection Diagram

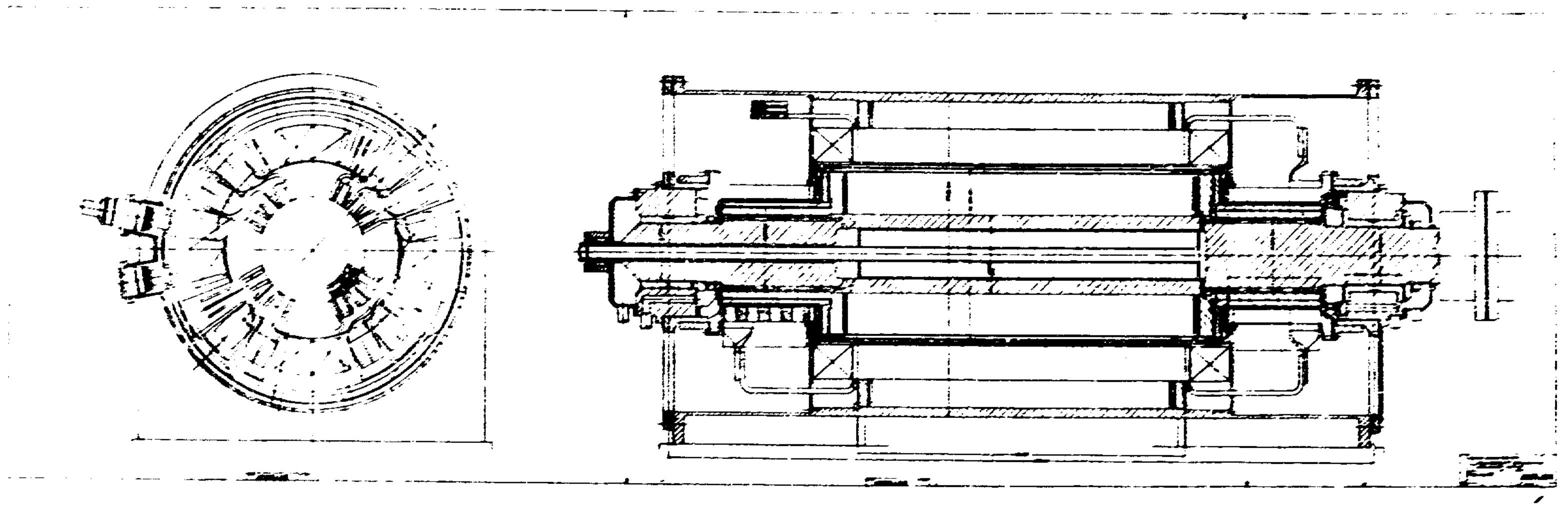


Figure 3.4. 19.6 MW Generator Preliminary Design Layout

The current collection function which is performed at both ends of the machine is accomplished by brushes sliding on a segmented slipring.

The solid current collector bars are connected to the rotor bars through radial risers. The current passes from the rotor through metal graphite brushes and multi-contact shunts to the brush holders, shown isometrically in Figure 3.5, and then to the stator circuit. The collector bars and brush holders are water cooled to remove the current collection losses. The parameters for the current collection system are as follows:

Brush contact drop	0.1 volt
Shunt contact drop	0.02 volts
Brush loading pressure	48.0 kPa (7 lbs/in^2)
Brush current density	2.33 M $Amps/m^2$ (1500 $Amps/in^2$)
Brush material resistivity	17.0 nΩ-m (6.8 x 10^{-6} Ω-in.)
Brush coefficient of friction	0.1
Total brush area	0.101 m^2 (156.8 in^2)
Volts/in. on collector surface	6.55 V/m (258 V/in. max.)

Brush lifters will lift 25% of the brushes when the machine is operated at system full load or at the cruise condition.

The generator rotor consists of a central shaft, which is hollow to accommodate a cooling water path for removing heat from the magnetic core. The rotor laminations are pressed on the rotor shaft, and the rotor conductors rest on the laminations, insulated from the laminations and retained in place by a fiberglass band. The pretension of the band (approximately 310 MPa, or 45,000 psi) is selected to prevent any motion of the bars, even under overspeed conditions. Also on the rotor shaft ends are the switching structures, connected to the rotor bars by risers. The second rotor cooling circuit comprises the switchrings, risers and rotor bars, with the switchrings contributing the largest heat flux. Water is introduced to and removed from the rotor in a rotating union waterbox with integral seals. The rotor is projected to be stainless steel for corrosion and non-magnetic properties.

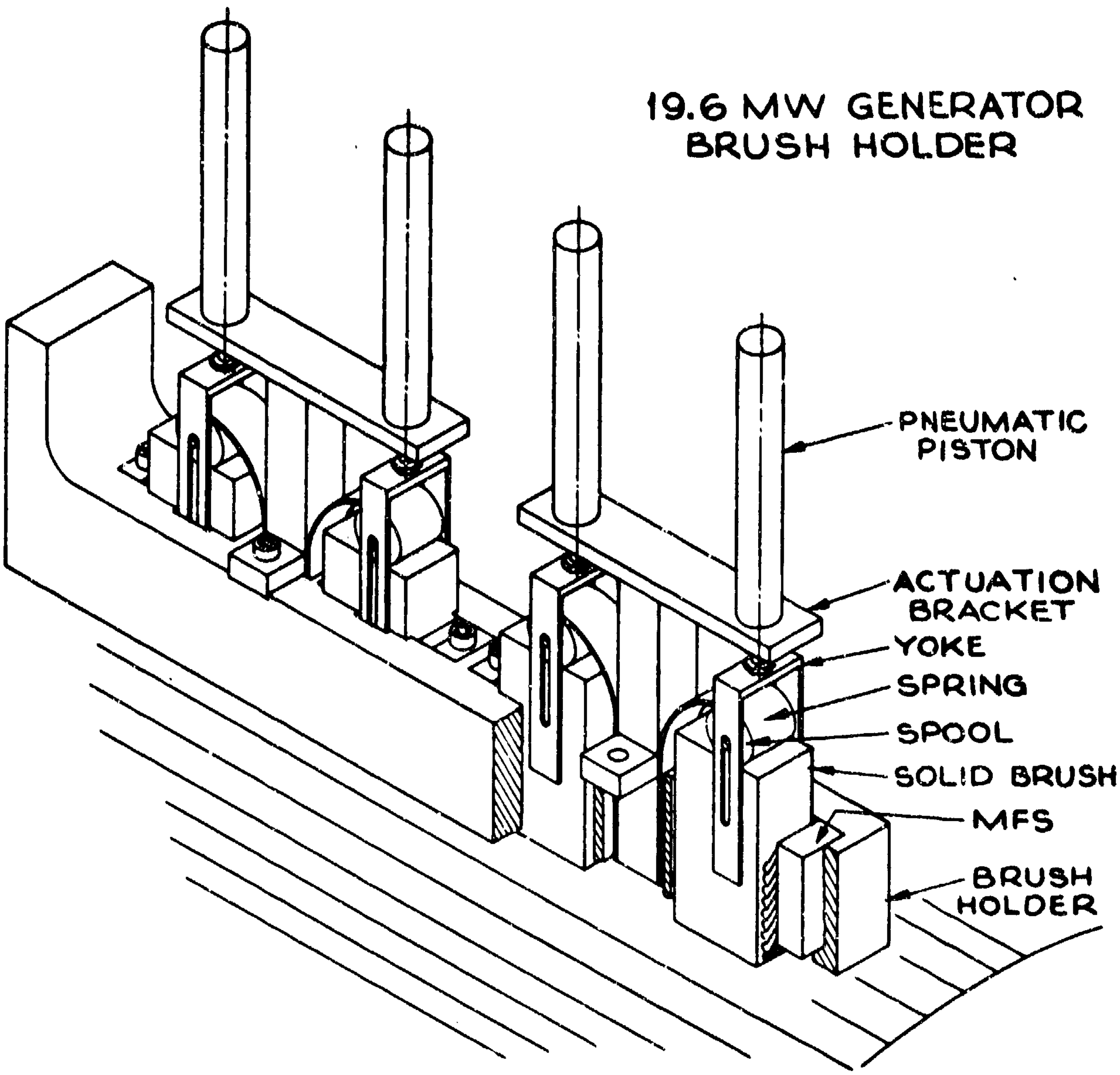


Figure 3.5. Brush Holder Isometric

The stator of the machine consists of the outer core, the field coils, the stator conductors and end connections, an outer shell, end covers, bearings and seals, brush holders and the machine terminals. The stator core is a set of laminated segments containing the solid stator conductors and their coolant paths. The segments are keyed together and arch-bound by the outer shell. The segment construction permits the insertion of formed field coils during stator assembly, allowing full utilization of the null zone of Figure 3.1 for field structure. The field coils have coolant paths in direct contact with the conductors to improve the heat rejection capability. Each field coil is composed of 159 turns, and the field current is 224 amps. The bearings are shown as plain journal bearings, with adequate thrust capacity to support the dynamic pitch requirements of the rotor. The double seals will prevent migration of oil into the electrical region of the generator. Gas pressure inside the machine will be maintained at 34 kPa (5 psi), the space between seals near atmospheric pressure and the oil will be provided at 103-140 kPa (15-20 psi). Connection of the generator to the gas turbine will be through a flexible coupling.

3.1.4 Operation During Representative Mission

Generator performance at other than the full load condition is described in Section 2, which includes the loss distributions at the various steps in the mission profile.

3.1.5 Environmental Considerations

Of particular concern are the generator shock response and the stray magnetic fields present around the machine. Shock response is discussed in Section 2.4. Figure 3.2 shows the flux plot for the generator and indicates that virtually all flux is contained within the machine. In the end region, a flux shunt under the field coils prevents any leakage flux from reaching the bearings or the exterior of the machine. Figure 3.6 illustrates the arrangement of the machine end region and the flux shunt.

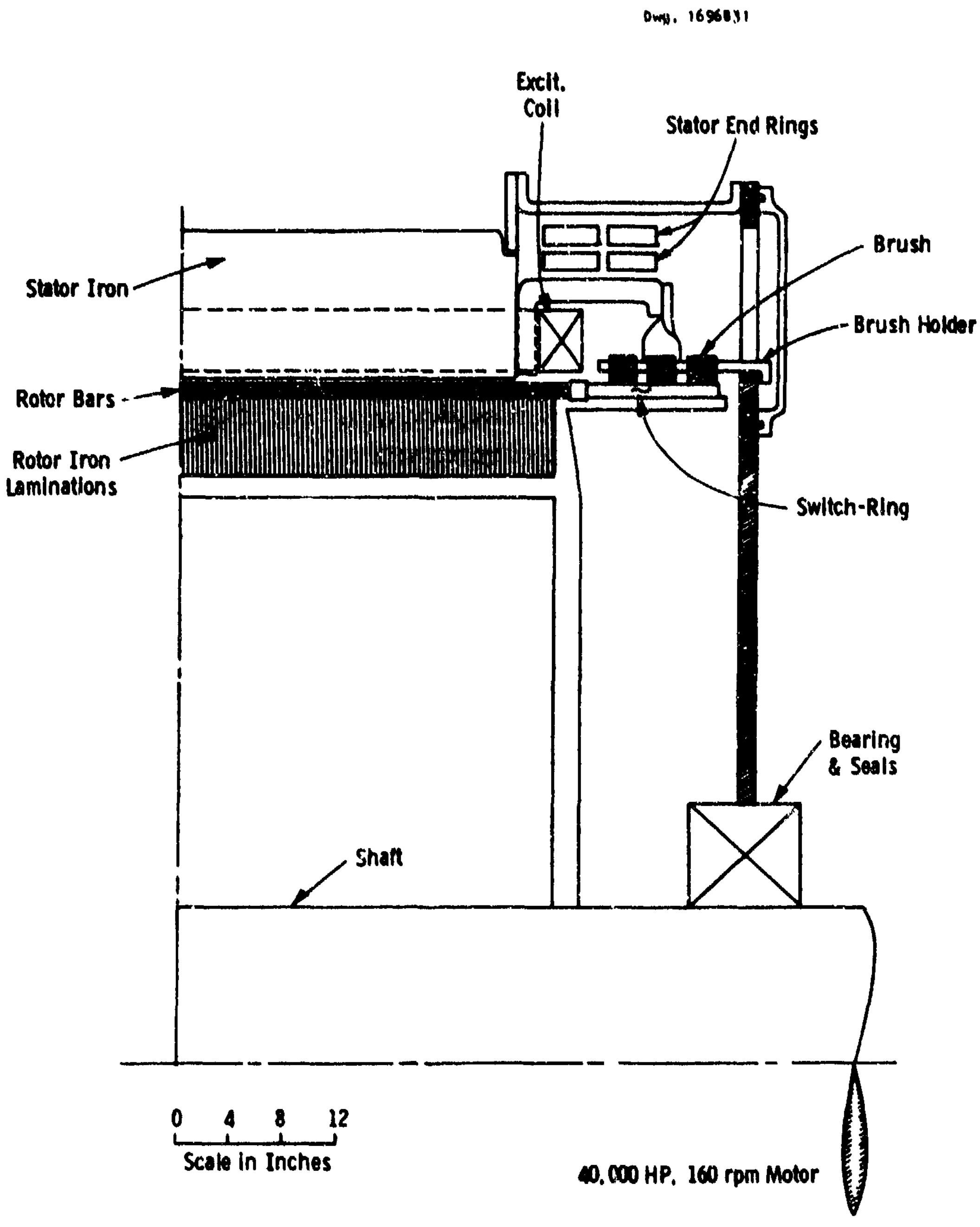


Figure 3.6. 19.6 MW Generator End Region Arrangement

3.1.6 Reliability

It is anticipated that standard electrical machine reliability can be attributed to the generator, except for the following areas, where the generator may be more susceptible to failure:

a. Loss of machine cooling water: a partial drop in cooling water pressure would be accompanied by a rise in machine operating temperatures. Specific guidance for operation at increased temperature could only be developed after machine prototype testing, however, only a complete loss of primary cooling water to the generator would result in loss of all capability.

b. Loss of internal cover gas: the loss of cover gas pressure would result in the possible introduction of oxygen or oil vapor in the machine. In such a case the wear rate of the brushes would be accelerated, but loss of machine operating capability would not be expected.

As with conventional machines the following failure modes could also produce casualties:

a. Loss of lubricating oil: following standard shipboard practice, loss of lube oil pressure at the generator bearings will be accompanied by an audible annunciator which should produce a normal or automatic system shutdown. Failure to immediately secure the affected unit will result in loss of the bearings and possible damage to the machine internals, particularly the rotor windings, if bearing damage was severe.

b. Loss of excitation power: a failure of the exciters to deliver full field current would limit the generator voltage output proportionately. An increase in generator speed could be employed to offset the loss; however, this could only be a small and temporary improvement. Complete loss of exciter power would cause a loss of the machine to the system.

3.1.7 Maintainability

The principal area of distinction between this and conventional dc machines, from a maintenance standpoint, is the expected life of the brushes. The goal for brush development is 3150 hrs/cm (8000 hrs/in.) of lineal wear at full power. This would easily permit a brush change-out on an annual basis. Access to the brushes is facilitated by end covers which are removable, permitting simple extraction of the old, and insertion of new, brushes. The brushes are retained by constant force springs and shunted by finger contacts, which would also simplify brush change-out.

Routine preventative maintenance measures are foreseen, in addition to brush replacment, in the areas of bearing clearance measurements, lubricating oil sampling and testing, vibration measurements, insulation resistance tests, and visual examinations. It is envisioned that all maintenance actions could be easily incorporated in the engineering PMS package.

3.1.8 Safety

Standard electrical safety requirements would exist with the generator, and no additional constraints have been identified.

3.2 30 MW Motor

The motor to be used in the destroyer-type propulsion system is a 30 MW (40,000 HP), 168 RPM machine rated at 2000 volts and 15,000 amperes. Unlike the generators for this application, the motors must be bi-directional and capable of regenerative operation. The motor which was selected by an extensive parametric analysis is an 18-pole machine with a basic electrical configuration similar to that of the generator described in Section 3.1.

3.2.1 Exceptions

No exceptions to the Work Directive requirements have been identified.

3.2.2 Technical Summary

The configuration of the motor was determined by using the parametric analysis techniques described in Reference 3.1. The parameters which were varied within the constraints of the circumferentially segmented geometry were: the number of poles, the number of series circuits, the rotor diameter, the rotor and field current densities, the air gap flux density, and the pole face to pole pitch ratio. This parametric analysis resulted in a motor preliminary design with the principal characteristics shown in Table 3.5. The preliminary design layout for the motor is shown in Figure 3.7. Using the loss evaluation techniques described in Reference 3.1, the full load and cruise condition losses are determined and are presented in Tables 3.6 and 3.7.

One notable difference between the generator and the motor, apart from the difference in the number of poles, is the fact that the generator has two turns per pole, while the motor has three. For the motor, two configurations for the stator end ring connectors were considered. One minimized the voltage gradient in the segmented collector ring which resulted in 38 volts per inch. The second configuration increased the voltage gradient to 66 volts per inch (maximum), but this reduced the total length of end rings to about half. Since 66 volts per inch is well within conventional practice, this configurration was chosen. The resulting circuit arrangement is shown in Figure 3.8.

TABLE 3.5

40,000 HP MOTOR CHARACTERISTICS

Rated Power	29,840 KW (40,000 HP)
Rated Speed	168 RPM
Rated Voltage	2000 Volts
Rated Current	15,000 Amperes
Number of Poles	18
Number of Turns in Series/Pole	3
Number of Rotor Bars in Parallel/Turn	3
Dimensions - Outside Diameter	3.23 m (127 in.)
Rotor Diameter	2.64 m (104 in.)
Air Gap Radial Clearance	0.15 cm (0.06 in.)
Rotor Steel Inside Diameter	2.29 m (90 in.)
Active Length	1.26 m (49.5 in.)
Brg.-Brg. Length	2.13 m (84 in.)
Switch Ring Length	20.8 cm (8.2 in.)
Current Densities (in the copper) -	
Rotor Bars	542 A/cm^2 (3500 A/in^2/RMS
Stator Bars	516 A/cm^2 (3330 A/in^2)
Stator End Rings	341 A/cm^2 (2200 A/in^2)
Field Winding	399 A/cm^2 (2580 A/in^2)
Flux Densities -	
Air Gap	1.3 Tesla
Rotor Steel	1.5 Tesla
Stator Steel	1.7 Tesla
Machine Weight -	
Rotor	18,045 Kg (39,700 lb)
Stator	35,898 Kg (78,975 lb)
Total	53,943 Kg (118,675 lb)

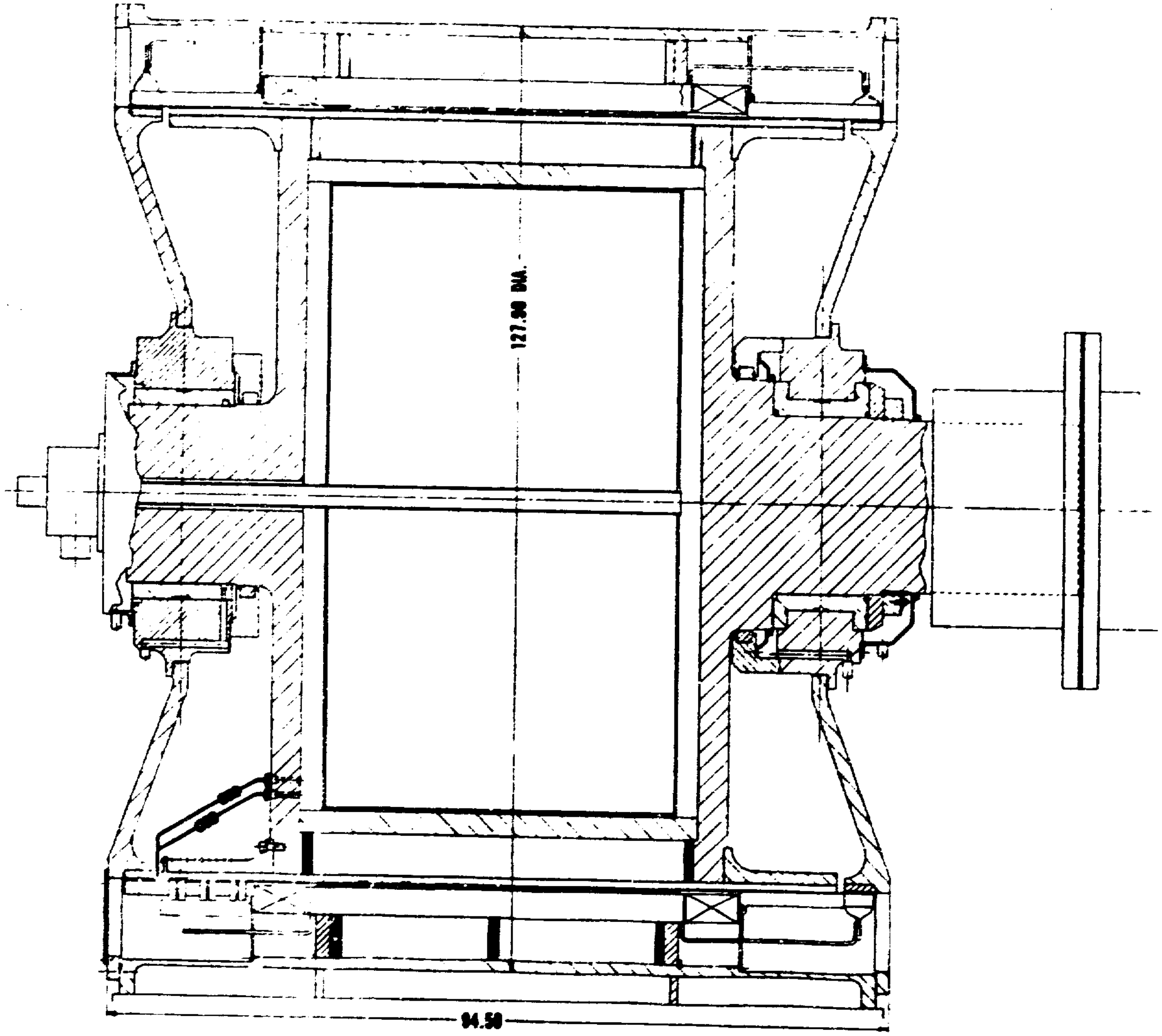


Figure 3.7. 30 MW, 168 RPM Motor Preliminary Design Layout

TABLE 3.6

SEGMAG II Efficiency Chart

Rating: 40,000 HP, 168 RPM, 18 Pole

I^2R Loss -	Rotor Bars.	249.1	
	Stator Bars	97.4	
	Brush Holders	9.0	
	Stator End Rings. . . .	76.9	
	Bolted Connections. . .	1.7	
	Field Winding	253.6	687.7
Brushes -	Friction.	68.7	
	Slip Ring Contact . . .	80.6	
	Ohmic	6.5	
	Shunt Contact	16.2	
	Radial Field.	----	172.0
"Eddy Currents" -	Main Flux	37.2	
	Tooth Ripple.	2.6	
	Risers.	----	
	End Plates.	----	
	Cooling Tubes	< .1	
	Circulating Current . .	----	
	Core Loss	14.3	54.1
Mechanical -	Seals		
	Bearings.		9
	Windage		
	TOTAL.		972.8
	EFFICIENCY.		97.00%

TABLE 3.7

SEGMAG II Efficiency Chart

Rating: Cruise; 7900 HP, 100 RPM

I^2R –	Rotor Bars	53.2	
	Stator Bars	20.6	
	Brush Holders	2.0	
	Stator End Rings	16.0	
	Bolted Connections	0.8	
	Field Winding	62.8	155.4
Brushes* –	Friction	30.7	
	Slip Ring Contact	23.4	
	Ohmic	1.9	
	Shunt Contact	4.7	
	Radial Field	----	60.7
"Eddy Currents" –	Main Flux	6.9	
	Tooth ripple	0.5	
	Risers	----	
	End Plates	----	
	Cooling Tubes	----	
	Circulating Current	----	
	Core Loss	2.6	10.0
Mechanical –	Seals		
	Bearings		3.5
	Windage		
		TOTAL	229.6
		EFFICIENCY	3.5

*Assumes 25% of brushes are lifted.

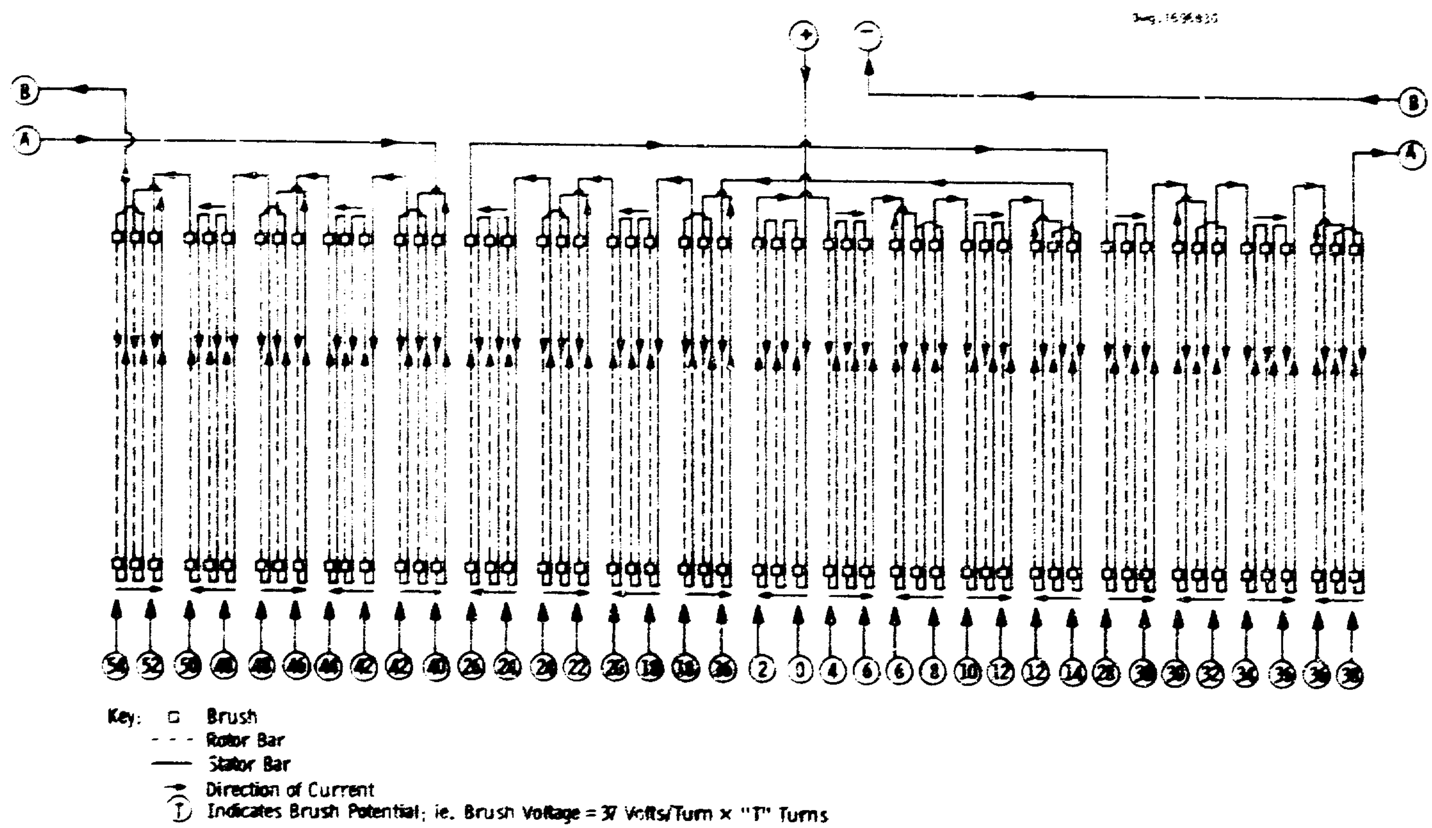


Figure 3.8. Motor Rotor and Stator Bar Interconnection Diagram

The brush holders carry the current, at a density of 1000 amperes/square inch, to the stator end connections. Water cooling is provided to the brush holders to remove the current collection losses.

There are three turns per pole and 18 poles in this machine. Therefore, there are 54 current collection assemblies on each switch ring. Since the rated 15,000 amperes must be carried by each assembly, 7.5 square inches of brush area are required. The total brush area in the motor is thus 810 square inches.

3.2.3 Stator

Because the stator is subject only to dc fields, the stator steel need not be laminated, and the stator bars can be solid copper. There may be an economic or manufacturing advantage to using laminated poles, but no technical necessity. The pole faces will be shaped to tailor the air gap flux density wave form for optimum switching.

The stator bars will be in slots in the pole face. The slots will be semi-closed for minimum ripple in the air gap flux density wave form. The bars will be wrapped with 0.03 inch of ground wall insulation. The stator bar ohmic losses will be removed by conduction to the stator steel, where water cooling will be provided.

3.2.4 Motor Physical Description

The 30 MW (40,000 HP) motor is similar in configuration and construction to the 19.6 MW generator, with differences associated with the rotational speed and power rating. The motor is characterized by extensive use of water cooling on the rotor and stator. The water cooling, the use of high current density brushes and the novel electromagnetic geometry combine to make the motor very efficient and power-dense. The motor is capable of bi-directional operation and of regenerative operation during rapid reversal maneuvers.

3.2.4.1 Motor Rotor

As with the generator, the motor rotor is a hollow structure, consisting of a non-magnetic stainless steel tube on which are mounted the rotor laminations. Inside the stainless steel tube a thin steel shell provides a water coolant path for removal of core loss heat from the laminations. The laminations are 0.36 mm (0.014 in.) thick, with a packing factor of 95% to allow for interlaminar insulation. The lamination material is ASTM 677-36F145 steel, which has excellent core loss characteristics. It is estimated that the loss at the induced frequency of 25 hz (motor full speed) with a 1.5 Tesla peak field will be 1.1 watts per kilogram (0.5 W/lb). The laminations will be restrained by non-magnetic end plates for minimum loss.

The rotor conductors are located on the outer periphery of the laminations and retained on the stack by glass fiber banding. The banding is pretensioned, as in the generator, to prevent movement of the rotor conductors away from the laminations, even at overspeed conditions. The ground wall insulation under the conductors is 0.75 mm (0.03 in.) of mica tape, while the insulation between rotor conductors is 0.25 mm (0.01 in.). The rotor conductors are stranded and transposed to minimize eddy current losses. The 1.25 mm (0.05 in.) strands are transposed and compressed to form a monolithic structure which is 95% copper. Internal to the stranded conductor is a stainless steel cooling tube which will provide water cooling. Thermal analysis shows that the maximum conductor temperature will be 100°C at continuous full load operation, well within the Class B limit of 130°C. This temperature assumes a flow velocity of 1.7 M/S (5 ft/sec) and a machine cooling water inlet temperature of 32°C.

The rotor bars are connected to the current collector segments directly, since the collector bars are at the same radius. The collector bars are water cooled to maintain a brush operating temperature in the 65-80°C range. The current collector segments are insulated with aluminum oxide electrostatically impregnated with a polyamide resin to protect against pin-holes. The collector segments are retained on a stainless steel ring by bolts pretensioned to prevent radial movements. Current is collected from the collector segments by metal graphite brushes and passed through multi-contact shunts to the brush holders. The end region arrangement is shown schematically in Figure 3.9. The full load operating parameters of the brush/collector ring system are the following:

Brush/shunt contact drop	0.01 volts
Brush loading pressure	10 psi
Brush current density	2000 A/in^2
Brush material resistivity	10^{-7} Ω-m
Brush/switch ring contact drop	0.05 volts
Coefficient of friction	0.08
Switch ring voltage gradient	66 volts/inch max.

The values for contact drop and coefficient of friction represent the goals of a current collection research program (ONR Contract N00014-76-C-0683) which seeks to minimize interface losses in sliding electrical contracts. If the machines were constructed with brushes which have been demonstrated at a contact drop of 0.1 volt and a friction factor of 0.16, the full load efficiency would be reduced by approximately 1/2%. The brush holders carry the current at a density of 155 A/cm^2 (1000 A/in^2) to the stator end connections.

The basic stator structure is of laminated poles and back iron, contained in a non-magnetic shell. The laminations on the stator are only required to improve the field response of the motor and to reduce the construction cost; there is no impact on losses due to laminating this portion. Similarly, because the stator is subject only to dc fields, the stator bars can be solid copper. The stator loss will be in slots in the pole face, and the slots will be semi-closed for minimum ripple in the air gap flux density wave form. The bars will be wrapped with 0.75 mm (0.03 in.) ground wall insulation. The stator bar ohmic losses will be removed by conduction to the stator steel, where cooling is provided by water in stainless steel tubes.

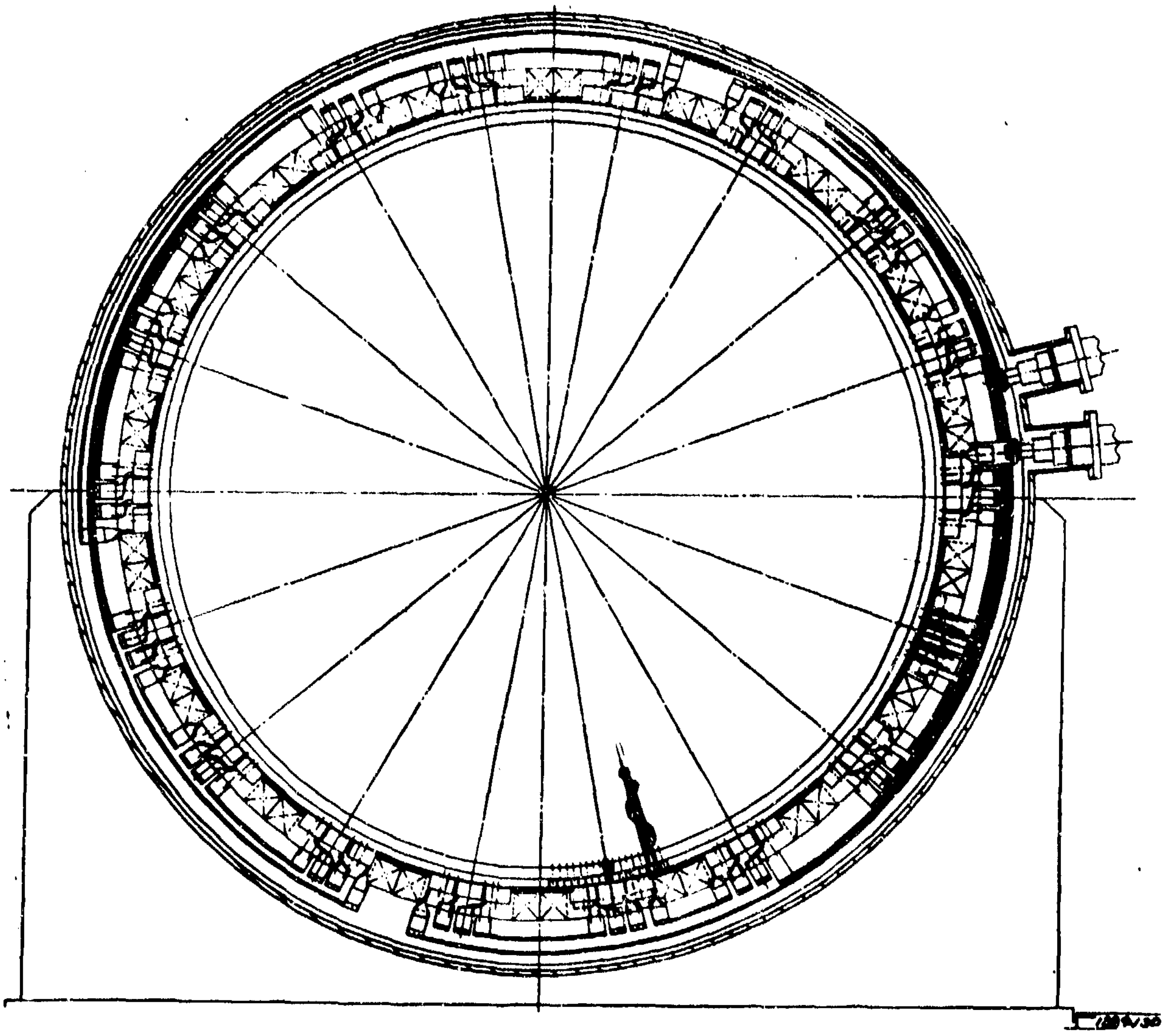


Figure 3.9. Motor End Region Arrangement

Since there are 54 turns in series in the machine, there must be 54 sets of stator bars, each capable of carrying the rated 15,000 amperes. At the ends of the active length, each set of stator bars is connected, in parallel, to the stator end rings and end connections. These have a cross-section of 7 square inches, in order to limit the current density to under 2200 amperes per square inch.

The field winding is also placed in slots in the stator. It is provided with 0.02 inch of ground wall insulation, and 0.005 inch of turn insulation. One water cooling duct is provided in each field winding slot. A total of 47,500 ampere turns per pole is provided by 34 turns carrying 1400 amperes; the copper current density is 2580 amperes per square inch. The 18 coils are connected in series, and have a rated terminal voltage of 185 volts.

As with the generator, the motor bearings will be forced lubricated, plain journal bearings, with thrust capability adequate to support the dynamic pitch requirements. The motor will drive the propeller shaft through a flexible coupling, and the shaft thrust will be taken in a separate thrust bearing. The internal gas atmosphere of the motor will be non-oxidizing, humidified gas at a pressure of 34 kPa and a dew point between 0 and 20°C. This pressure will be maintained by a double seal arrangement.

3.2.5 Operation During Representative Mission

Motor performance at other than the full load condition is described in Section 2, which includes the loss distributions at the various steps in the mission profile.

3.2.6 Environmental Considerations

As with the generator, shock response and stray magnetic fields are of greatest concern when considering external influences. Machine shock response is discussed in Section 2.4.4. Figure 3.10 shows

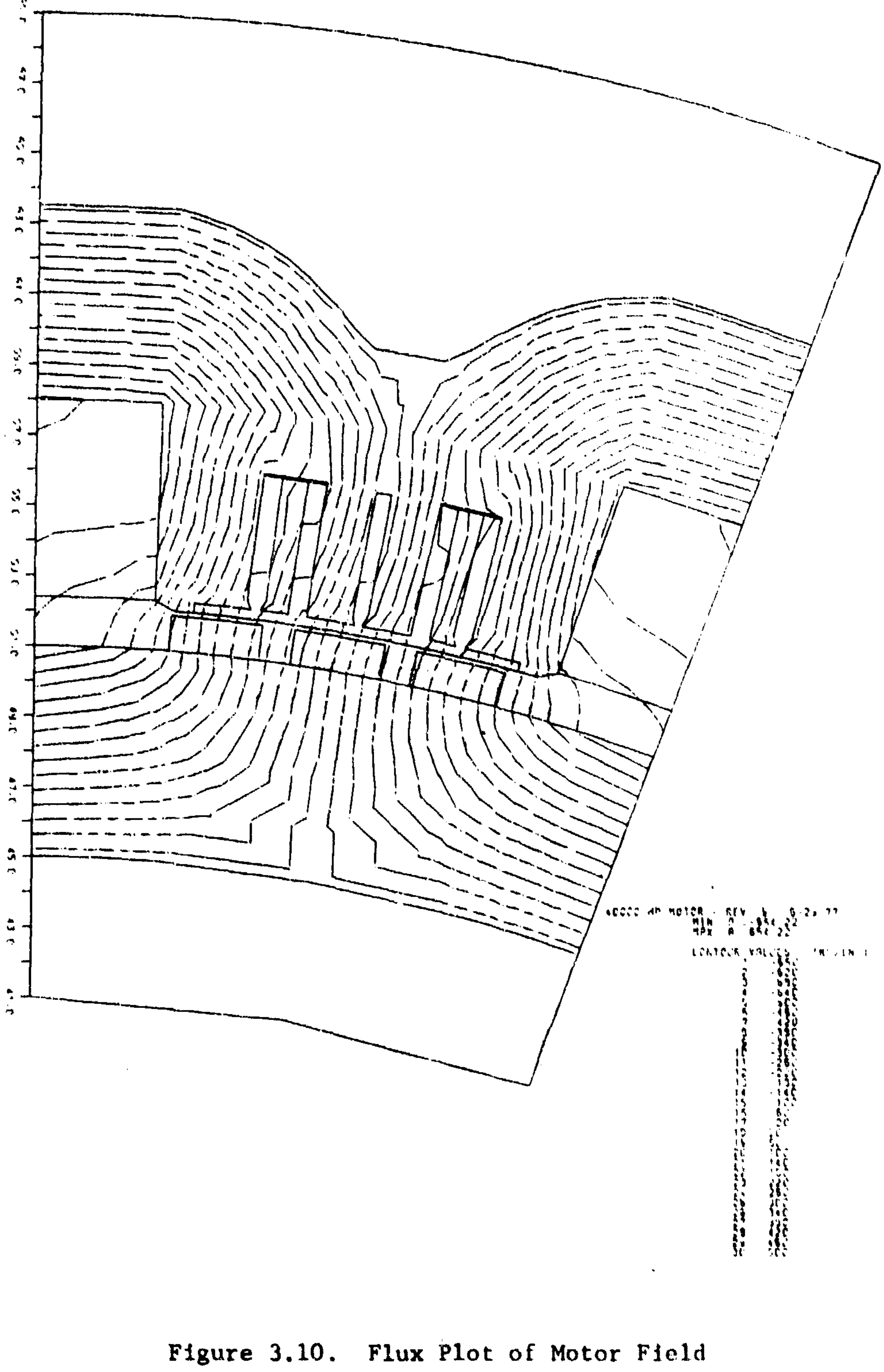


Figure 3.10. Flux Plot of Motor Field

a flux plot for the motor which shows that virtually all flux is contained within the machine. End region flux is likewise negligible.

3.2.7 Reliability

The comments regarding generator reliability in Section 3.1.6 are applicable to the motor, except that loss of motor field must be accompanied by a control system action to limit current and motor overspeed.

3.2.8 Maintainability

The comments regarding generator maintainability in Section 3.1.7 are applicable to the motor.

3.2.9 Safety

As with the generator, the motor requires observance of standard electrical safety precautions; however, no additional constraints have been identified.

3.3 Transmission Lines

The transmission lines are envisioned to be made up of two types of conductors. The first consists of copper bus work which, along with switches, provides the armature power connections between the machines within each engine room. The second type is the cross connect line which utilizes cables to transmit electrical power from one engine room to another.

This description on transmission lines concentrates on the second type since the first type would utilize conventional and well known practices and, thus, does not warrant special attention at this time.

3.3.1 Arrangement

It is assumed that in each engine room two generators will be in close proximity to the propulsion motor, thus, minimizing transmission line losses in the full power and half power modes. It is envisioned that the sixteen switches used to configurate the system will be located in the bus work. For study purposes, a bus length of 4.57m (15 ft) is assigned per machine terminal which is to allow for leads and interconnections between generators, motors and switches.

The cross connect line which connects the two engine room is estimated to have a one way length of 36.58m (120 ft). This line provides both sending and return paths for the armature current.

Due to the preliminary nature of the machinery layouts, detail design of the bus work has not been made.

3.3.2 Bus Description (Type 1)

The bus work is made up of separated copper bars to allow for natural convection cooling. The busses are sized for a current density of 1550 kA/m^2 (1000 A/in^2) at estimated maximum currents of 9800 A and 15000 A for the generators and motors respectively.

As a conservative estimate, the copper temperature is assumed to be 100°C which gives a resistivity of 0.02347 μΩm. The resistance per unit length are 3.712 μΩ/m for the generator busses and 2.425 μΩ/m for the motor busses.

3.3.3 Cross Connect Line Description (Type 2)

The cross connect line is designed for continuous operation at a current of 7500 A and voltage of 1000 vdc between the plus and minus conductors. Two identical bundles form the 36.58m (120 ft) long line which is used to connect the two engine rooms.

Figure 3.11 shows the cross-section of a bundle which comprises an aluminum cooling support tube in the center surrounded by six cables. Lashing around the cable tube assembly would be employed to keep the cables firmly in place. The direction of the current flow alternates in adjacent cables resulting in low inductance and a very small magnetic field.

In the two bundles, the cooling water flows in opposite directions, providing a complete water path between the two engine rooms.

3.3.3.1 Cable

A description of the Navy cable selected for the cross connect line is given in Table 3.8.

TABLE 3.8

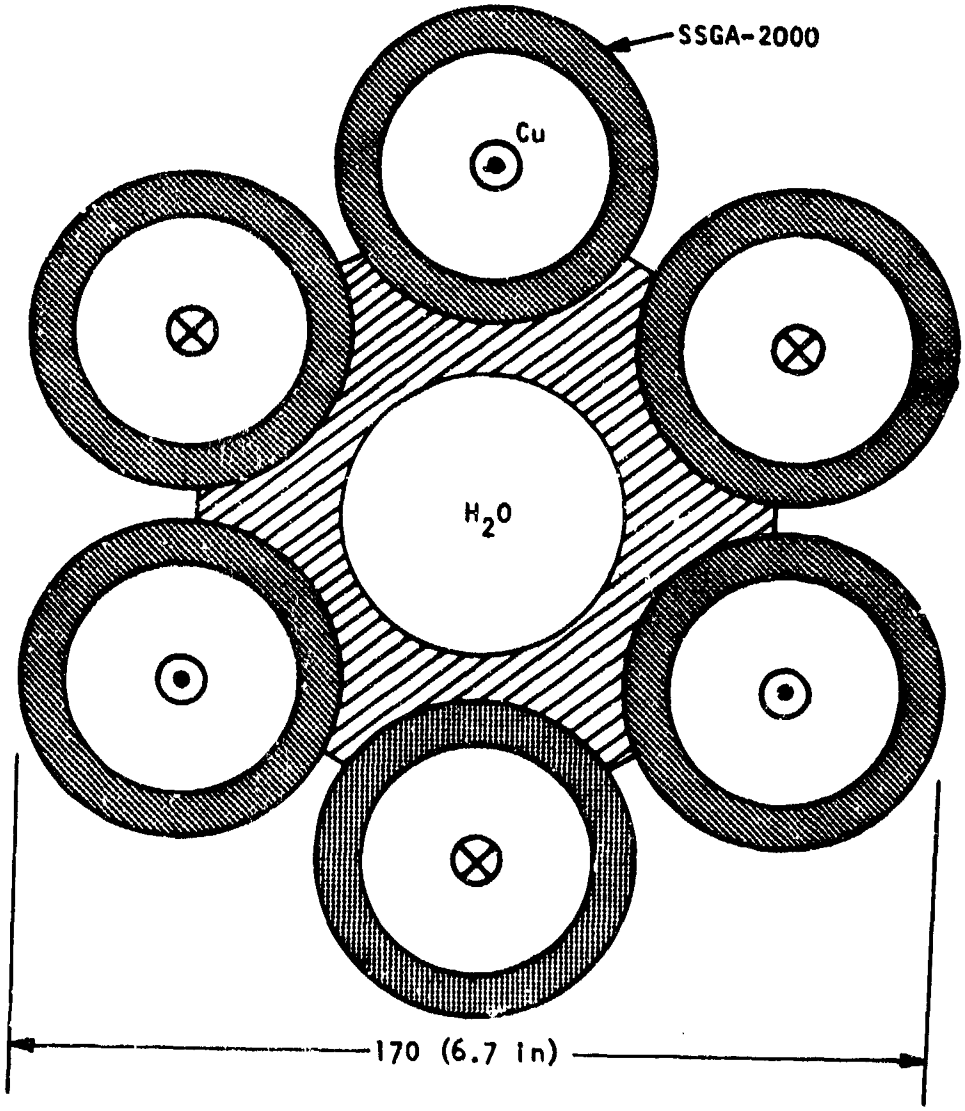
CABLE SPECIFICATIONS

Type and Size	SSGA-2000, single conductor, 127 strands
Copper Area	0.001063 m^2 (2097000 circular mils)
Cable O.D.	0.0574m (2.26 in.)
Current Rating @ 40°C Ambient	1440 A
Maximum Voltage	1000 V
Est. Weight/Length	11.21 kg/m (7.53 lb/ft)

At a total current of 7500 A, the current per cable is 1250 A which results in a current density of 1176 kA/m^2 (759 A/in^2).

3.3.3.2 Resistance Per Unit Length

The copper temperature is assumed to be 95°C which gives a resistance per unit length of 21.75 μΩ/m for a single cable. For the line, the one way value is 3.625 μΩ/m.



Note: Two bundles form the cross connect line.

Figure 3.11. Transmission Line Bundle Cross Section

3.3.3.3 Inductance

The inductance per unit length for a single bundle including sending and return paths is 0.125 μH/m. For the complete cross connect line, the inductance is 2.342 μH.

3.3.3.4 Magnetic Field

At a distance of 0.154m (6 in.) from the bundle surface, the magnetic field is less than 0.0001 T (1 gauss) at a line current of 7500 A.

3.3.3.5 Center Tube

The center tube provides a large nesting surface for each cable which not only provides support but also serves as a cold " plate" to conduct heat away from the cables. The cooling water flowing through the 0.051m (2 in.) diameter hole maintains the tube at a moderate temperature.

The aluminum cross-sectional area is $0.0037m^2$ which gives a weight per unit length of 10.03 kg/m (6.74 lb/ft).

3.3.3.6 Shock

A preliminary investigation of the effects of shock indicate that supports should be placed at 1.43m increments. This is based upon the following assumptions:

- 6061-T6 aluminum tube material with a yield strength of 276 MPa (40 kpsi)
- Vertical (static) load of 75G
- Maximum stress equals the yield strength

3.3.4 Weight

The bus, cross connect line, and (total) transmission line weights are listed in Table 3.9. The values shown for the busses are the bare copper weights only, however, for the cross connect line, the cable insulation and center tube weights are included.

TABLE 3.9

WEIGHTS

	Total Weights kg	(lb)
Generator Busses	2068	(4558)
Motor Busses	1582	(3488)
Cross Connect Line	5652	(12461)
Transmission Lines	9302	(20507)

3.3.5 Resistance

The bus and line resistances are listed in Table 3.10. The assumed copper temperatures are 100°C for the busses and 95°C for the cross connect line.

TABLE 3.10

RESISTANCES

	Resistance
Generator Bus, per Machine	33.90 μΩ
Motor Bus, per Machine	22.18 μΩ
Cross Connect Line, Total	265.27 μΩ

3.3.6 Performance

The transmission line performance for four operating points is shown in Table 3.11. The bus and cross connect line losses are tabulated and the transmission line efficiency is given.

TABLE 3.11

TRANSMISSION LINE PERFORMANCE

Power Configuration	Full	Half	Quarter	Quarter
Operating Point	Full	Half	Quarter	Quarter
Generator Power Output - Total, kW	57760	28880	14440	12311
Generator Current, A	7135	8978	7500	7230
Motor Current, A	14269	8978	7500	7230
Power Loss - Total, kW				
Generator Bus (ses)	6.90	5.46	1.91	1.77
Motor Busses	9.03	3.58	2.50	2.32
Cross Connect Line	--	--	14.92	13.87
Transmission Line	15.94	9.04	19.32	17.96
Transmission Line Efficiency	0.9997	0.9997	0.9987	0.9985

3.4 Switchgear

The discussion in this section is limited to the armature loop switching devices. Devices in other systems are not unique and are not included as a part of this discussion.

3.4.1 System Requirements

The armature loop switching devices are grouped into two categories depending on the function they perform in the system. These categories are as follows:

1. Switches used for changing circuit configuration and for machine isolation.
2. Switches used in conjunction with the dynamic braking assembly during the emergency reversal maneuver.

The principle functions performed by the category (1) switchgear are:

a. Provide the capability to connect or remove selected machines in the propulsion system armature loop within each engine room.

b. Provide for cross-connecting the motor in either engine room into the armature current loop in the opposite machinery room.

c. Provide for electrical isolation of selected machines for maintenance or repair.

Figure 3.12 shows elementary armature loop diagrams for each of the normal operating modes and shows the maximum normal steady state (continuous) loop current and system operating voltage for each arrangement. The switches must be rated to carry the maximum current shown and must operate at up to 2000 volts as indicated on Table 3.12. The operating sequence of the category (1) switches is described in the control Section 3.6 of this report.

Switches 1 through 16 are the category (1) switches and switches 17 and 18 are the category (2) switches.

The principle functions performed by the category (2) switchgear are:

a. Open the operating armature current loop near the beginning of an emergency reversal maneuver for insertion of dynamic braking resistors.

b. Reclose the operating armature current loop at the end of a dynamic braking cycle to reestablish the initial armature current loop and allow reverse power operation.

The fundamental difference in operational requirements for the two classes of switches are that the category (1) switches will be operated during steady state controlled system conditions where current zero switching is available. The category (2) switches, however, will be operated under dynamic conditions and will be required to "make" appreciable current at the termination of the dynamic braking cycle.

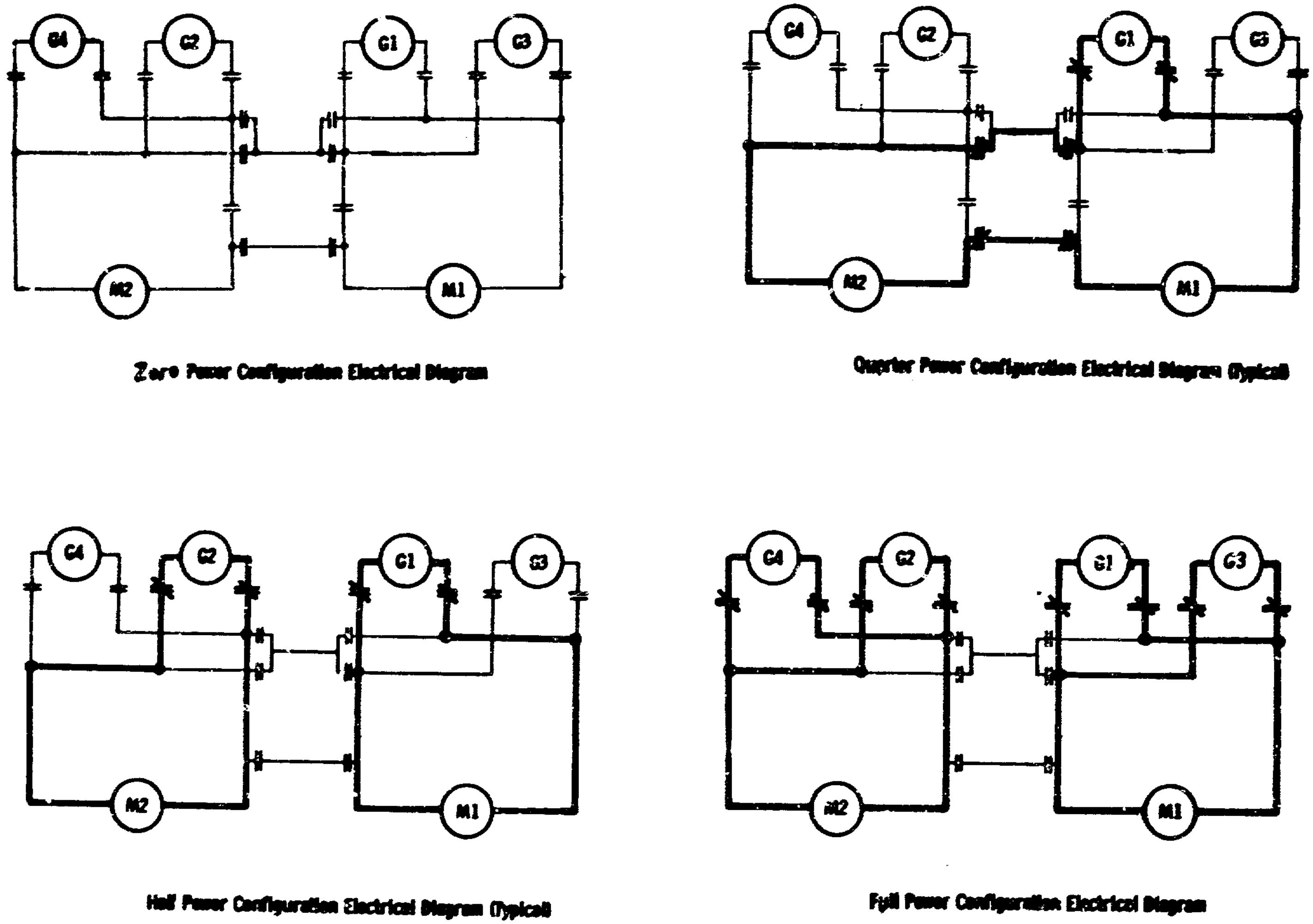


FIGURE 3.12. Armature loop connections for zero, quarter, half, and full power.

TABLE 3.12

SWITCH CURRENTS FOR FULL, HALF AND QUARTER POWER CONFIGURATIONS

	Maximum Continuous Amperes		
Switch Identification	Full Power	Half Power	Quarter Power
S1 thru S8	7500	9500	7500
S9 thru S12, S15 and S16	Open	Open	7500
S13 and S14	15000	9500	Open
S17 and S18	15000	9500	7500

3.4.2 Device Availability

A survey was conducted of switchgear manufacturers for available switches for these system requirements. No existing equipments were found that met these requirements which would be directly applicable in this system for either category (1) or category (2) service. The survey revealed that one company (Multilam Corporation) offered designs of motor operated disconnect switches in ratings up to 20 KA at 2 KV continuous duty. The designs offered were for commercial use and would require modification for Navy service. The switches are identified by the Multilam Corporation as model STR-1200-2 (rated 10 KA) and model STR-1300-2 (rated 20 KA). Although these switch designs have adeqeate continuous current and voltage ratings, they are limited in having no current making or interrupting rating in their present form. Modified switches of this design have been considered for application in this system as follows.

3.4.3 Switch Application

In order to accommodate the switching limitations of the Multilam switch, logic has been provided in the control system to control the armature loop currents and voltages to suitable conditions prior to switch operation. The armature loop current will be controlled to zero before opening a closed switch and the voltage across an open switch will be controlled to zero before closing the switch. This approach appears feasible during normal maneuvering when time is available for zeroing the loop currents and for switch operation. However, it is not feasible for category (2) switches which must reclose the circuit at the end of the emergency reversal maneuver dynamic braking cycle without reducing the circuit voltages to zero.

During this maneuver, a fast closing switch will be required that is capable of making up to 22.5 KA (surge) and carrying a 30% current overload for the remainder of the maneuver. Following the maneuver, the switch must again carry 100% continuous current. For this service, a combination switch consisting of two paralleled switches will be employed. One switch which carries the continuous duty current is the 20 KA Multilam switch previously described. This switch would be paralleled with a conventionally constructed DC contactor which has a short time current rating sufficient to make and carry the reversing current for the time required to close the Multilam disconnect switch, approximately 5 seconds. These two devices would be mechanically interlocked so that the Multilam switch could not be closed unless the closing contactor were first closed.

3.4.4 Fault Current Protection

Two methods of controlling fault current in the armature circuits were considered:

1. Opening the armature loop circuits
2. Rapidly collapsing (field forcing) the machine fields to zero.

The first method will require some form of circuit interrupting device that can carry full load continuous current and which can interrupt the system fault currents. Two fundamental types of devices commonly in use for this service are:

1. fuses
2. circuit breakers

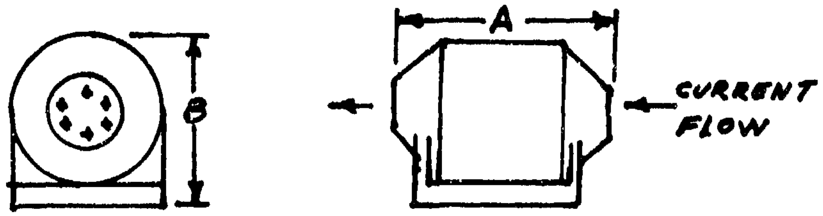
Fuses

There are no known single fuses available with large enough ratings to meet the system continuous current requirements. However, a fuse bank consisting of individual fuses connected in parallel appeared feasible and was investigated. This approach would provide each machine with a bank of fuses in a suitable enclosure and located at the machine terminals.

Preliminary features of fuse banks rated at 10 KA and for one rated at 20 KA (2000 volts) are given in Table 3.13. The fuses considered for this application were Chase-Shawmut Catalog #A200P600. These are current limiting type, silver sand, non-expulsion type fuses rated at 600 amps continuous 100,000 amps (RMS) interrupting 2000 volts. The continuous current rating of fuses are derated by a factor of 0.75 to account for imperfect load current division and to minimize damage from current spikes during dynamic braking.

TABLE 3.13

FUSE BANK CHARACTERISTICS



	A	B	Volume	Estimated Wt.	Power Loss	No. of Fuses
10 KA	40"	30"	20 ft^3	3500	8 KW	23
20 KA	40"	50"	42 ft^3	5500	16 KW	46

The advantages of this approach are that:

1. It uses available devices.
2. Fuses can function independently from the remainder of the circuit.

The use of fuses for circuit protection has several disadvantages. Some of these disadvantages are:

1. The fuses dissipate power thereby reducing circuit efficiency and thus must be provided with cooling. Refer to Table 3.13.
2. Fuses exhibit a premature unpredictable failure mode which may cause them to blow at levels below their threshold.

3. There is no convenient or reliable method of determing the condition of the installed fuses.

4. Fuses must be replaced after functioning.

Because of these disadvantages the fuse approach is not recommended for this application.

Circuit Breakers

A survey of switchgear manufacturers was conducted for available armature circuit interrupting equipment (circuit breakers) for use in this system. No equipment manufacturer was found who offered equipment which could meet the system requirements. Commercial high speed dc circuit breakers are available for stationary service in ratings up to 12000 amps at 1500 volts, however, these designs do not appear suitable for modification to the increased rating required nor for modification for Navy service.

The feasibility of developing a suitable Navy qualified circuit breaker has been explored within the Westinghouse R&D Division and with the development group of an outside independent circuit breaker manufacturer, I.T.E. Gould, Inc. Both of these development groups believe that it is entirely feasible to develop a breaker for this system which meets the circuit requirements and can be shock hardened to Navy requirements.

It would be required that work be initiated on a development program for increased rating dc circuit breakers which would proceed in parallel with the development of high powered dc machinery.

The second method of fault current control to be considered was to rapidly collapse the machine fields. This method of control has the following advantages:

1. This method can be designed to use existing exciter components.

2. This method provides protection against internal machine faults in addition to external faults.

3. There is minimal increase in weight and volume requirements over the other two methods.

4. The armature winding and switch ring are not exposed to the arc voltage of an interrupting device.

This method, however, will have the following disadvantages:

1. The fault currents will not be limited as quickly as by circuit interruption.

2. The machine field insulation levels will have to be raised to accommodate higher field forcing voltages.

3.5 Excitation

3.5.1 Exceptions

None.

3.5.2 Technical Summary

The propulsion generators and motors are separately excited machines and require a variable power supply to provide a controlled field current. A six pulse thyristor converter offers a reliable and rugged means of rapidly controlling the magnitude of current in the machine field. A basic six-pulse converter is shown in Figure 3.13. The converter input is connected to the ship's 440, 60 Hz supply by a three phase transformer. The transformer provides isolation, power matching to improve the steady state power factor and additional impedance that reduces line interference. The output voltage of the converter, when operated into an inductive load supplying a continuous current, is

Curve 695414-A

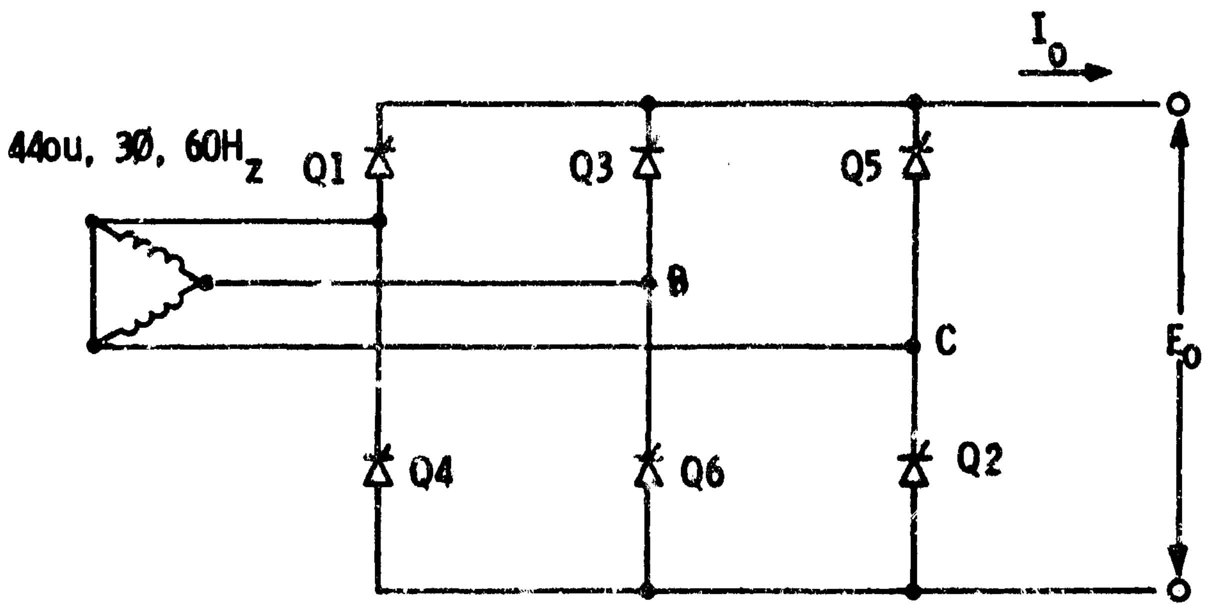


Figure 3.13. Basic Six-Pulse Converter

related to the thyristor firing angle as shown in Figure 3.14. For firing angles from 0° to 90° the converter operates in the rectification mode supplying a positive voltage and positive current. Beyond the 90° firing angle the converter operates in an inversion mode and develops a negative voltage at the output terminals. Since the thyristors are unidirectional current devices a negative current cannot exist. However, the negative voltage developed in the inversion interval may be used to rapidly force the inductive current in the field to zero.

In the proposed application of a ship's propulsion system it is required that the field flux of the generator be reversed. Also, the field flux of all generators and motors must be made zero during certain operating intervals. Reducing the field current to zero may not result in a zero flux condition due to the magnetic hysterisis present in the field core. Thus, the converter must be capable of providing a negative field current to reduce field flux to zero. In Figure 3.15 is shown a dual converter capable of supplying both polarities of voltage and current. Thyristors Q_1 thru Q_6 comprise a positive converter and thyristors Q_7 thru Q_{12} comprise a negative converter. The per unit output voltage of the dual converter versus thyristor firing angle is shown in Figure 3.16. When supplying the load with a positive current, only the thyristors in the positive converter are activated. When supplying negative current, only the negative converter thyristors are fired. Reversing the polarity of the field current requires that the field current must be held at zero for several milliseconds before activating the other converter. This action prevents a converter fault by ensuring all thyristor have regained a blocking state before gating the other set of thristors.

The armature current in the propulsion machines are controlled by controlling the machine field currents. A sudden increase in armature current, due to an abnormal event, may be controlled by field excitation only if the response of the field circuit is comparable to the rate of change of armature current. Although the time constant of the field is much greater than the armature, the response of the field may be improved by field forcing. Field forcing is the application of a voltage to a

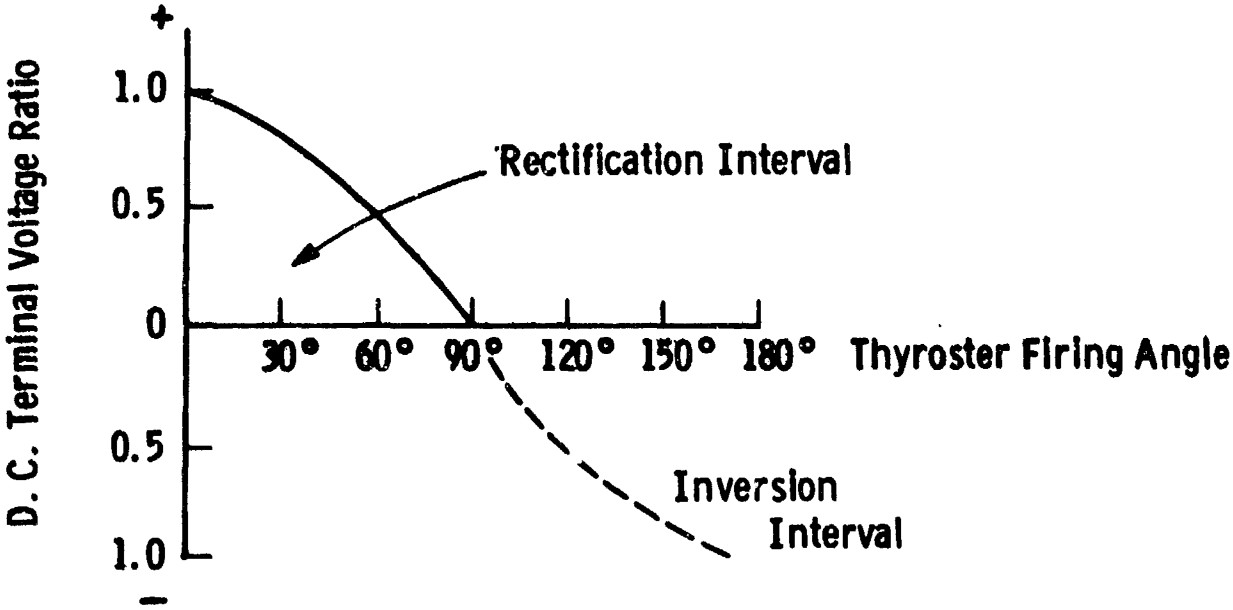


Figure 3.14. Converter Output Voltage vs Firing Angle

Dwg. 1696B68

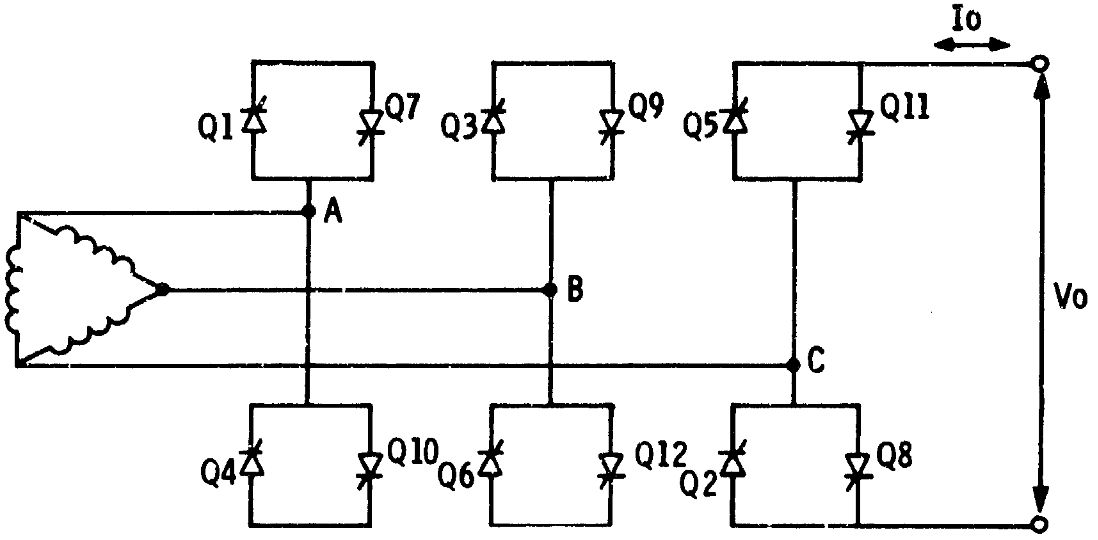


Figure 3.15. Basic Dual Converter

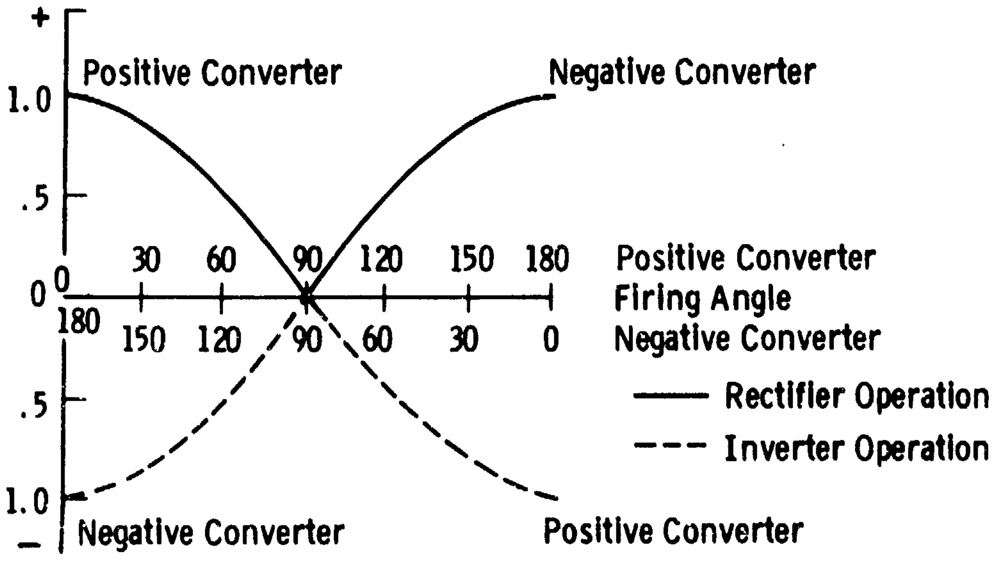


Figure 3.16. Dual Converter Output Voltage vs Firing Angle

field that is greater than the steady state value. In Figure 3.17 is shown the reverse field voltage required to force the field current to zero in a given time for the SEGMAG machines. Forcing the field current to zero in 30 milliseconds would require a forcing voltage of 10 kV. The field winding insulation must be designed to withstand this voltage and the exciter must be capable of developing this level of voltage. If a single set of transformer windings is used to develop both the rated field voltage and the forcing voltage the resulting input power factor would be poor (0.02 pf) at rated load and the transformer kVA rating and size would be greatly increased. Improved power factor and reasonable transformer size may be achieved with the exciter circuit shown in Figure 3.18. A low voltage dual converter controls the field current during normal operation supplying up to two times rated forcing voltage. During this period the thyristor gate drives in the high voltage converter are held off with the exception of Q_{5a} and Q_{2a} when supplying positive field currents and devices Q_{8a} and Q_{11a} when supplying a negative field current. In Figure 3.19 is shown the negative field forcing voltage that may be developed when forcing a positive field current to zero. The dotted curves show the available voltage from each converter and the heavy line indicates the maximum forcing voltage that could be generated as the firing angle increases through the inversion interval.

3.5.2.1 Exciter Internal Control

Each exciter unit contains a control circuit that protects the unit against device overcurrents and ensure proper operation. A block diagram of the control circuit is shown in Figure 3.20. The converters are energized from the ship's 440 V, 3ϕ, 60 Hz supply by means of a three phase transformer containing two sets of secondary windings. The converter thyristors are activated by thyristor gate drive circuits that generate a train of gate pulses throughout the gate firing interval. The appropriate gating signals to the high voltage converter are inhibited by an external signal. The gate director circuit selects which bank of

Curve 695367-B

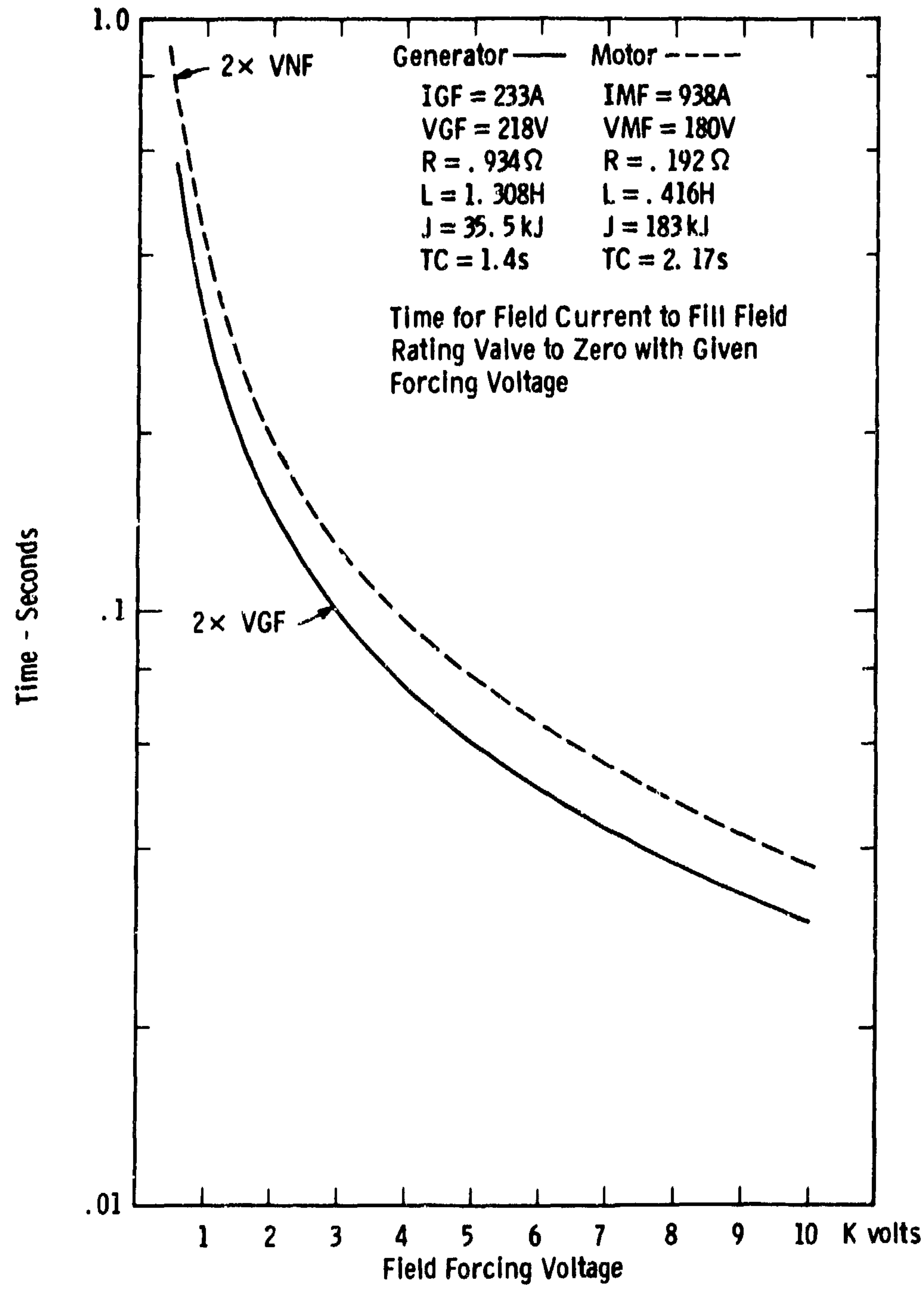


Figure 3.17. Relationship Between Field Forcing Voltage and Field Response Time

Dwg. 6435A18

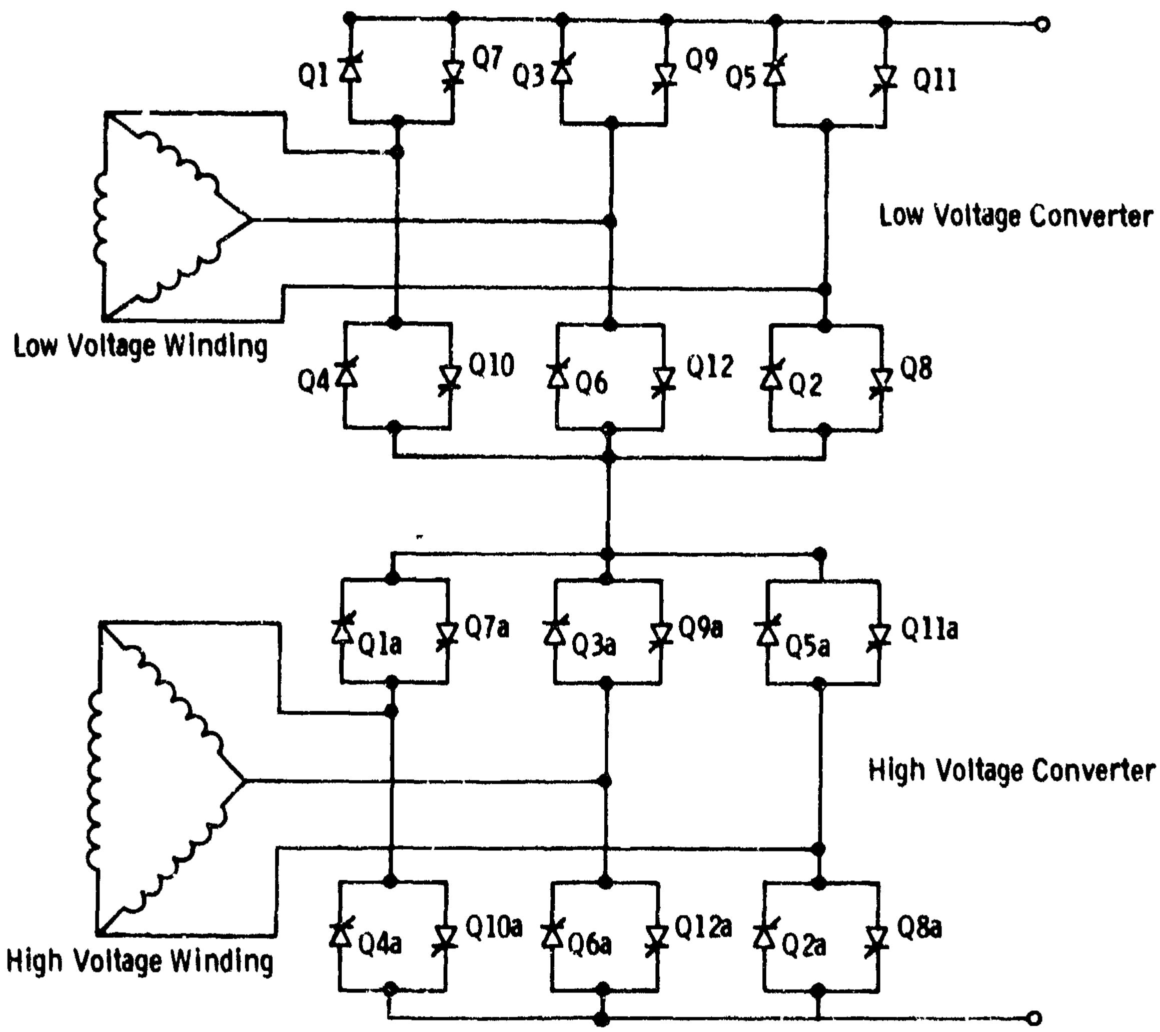


Figure 3.18. Field Exciter with an Auxiliary Field Forcing Converter.

Curve 695365-A

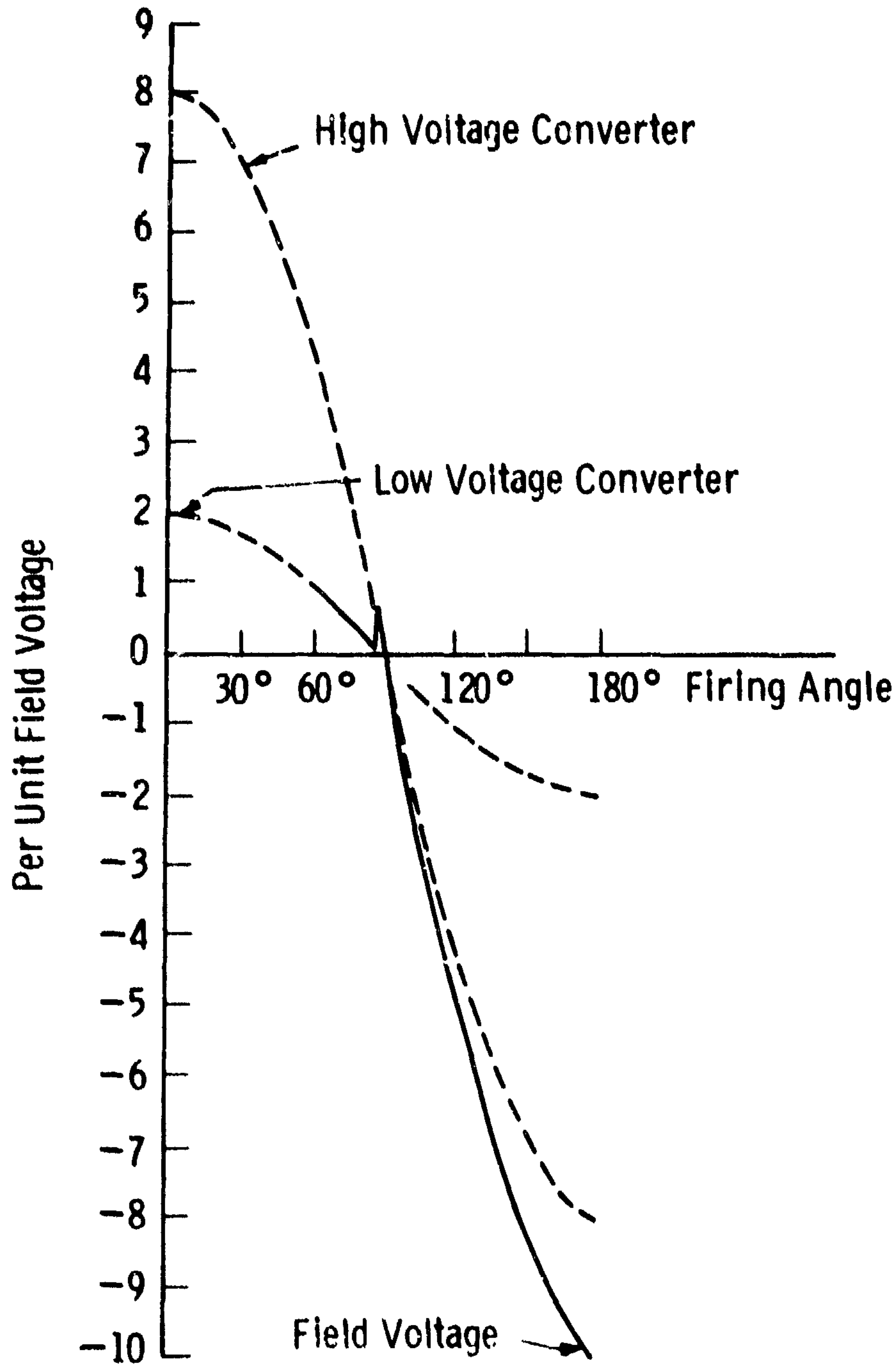


Figure 3.19. Field Forcing Voltage Versus Firing Angle

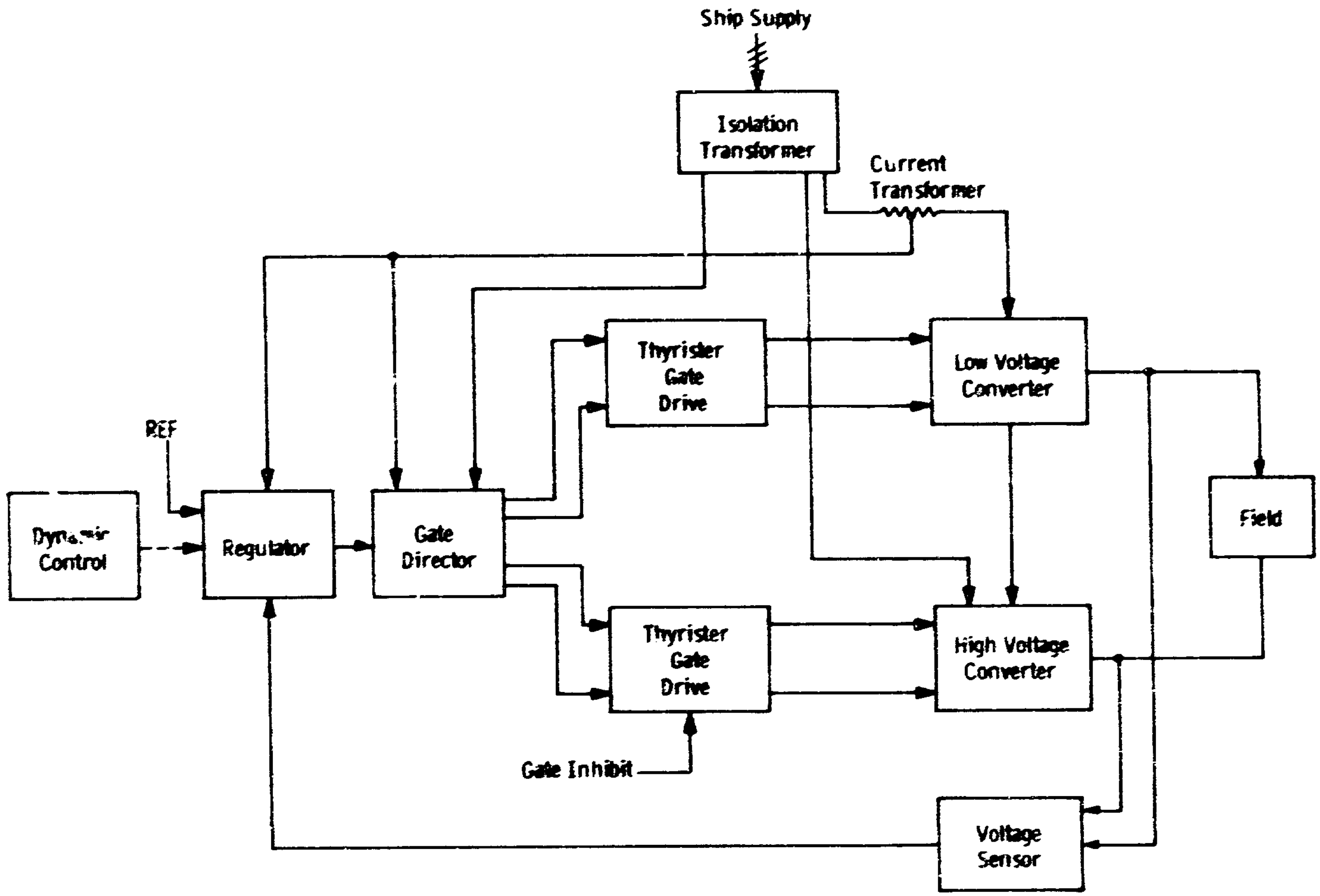


Figure 3.20. Exciter Internal Control Diagram

thyristors within each converter may be gated, detects a current zero condition before permitting a reverse current operation, synchronizes the generation of gate pulses and varies the firing angle of the gate pulse in response to the regulator. The regulator circuit provides an internal control loop to limit the current output of the exciter. An exciter output voltage control loop is also made available. The exciter also responds to external control loops that are developed by the dynamic control section of the master control unit and are the primary control means within the limitations imposed by the exciter internal controls.

3.5.3 Physical Description

The exciters will be housed within a cabinet that will contain the isolation power transformer, converters, internal controls, input breaker and fuses, meters and indicator light showing the status of the exciter. Each exciter will be located in the vicinity of its respective machine. The power transformer and the control module will be forced air cooled. The converter thyristors will be water cooled to reduce cabinet size and ensure safe operating temperatures. The control circuit will be placed on plug-in cards. The thyristor heat sink assembly will be designed to ease the removal of a single leg of the converter bridge or an entire bridge panel. The weight and size of the exciters is given in Section 2.1.

3.5.4 Environmental Considerations

The exciters are constructed of solid state components and should have no difficulties in meeting the environmental requirements of salty humidity and ambient temperature in this application. Particular consideration shall be given to the suppression of electro-magnetic interference normally generated by this type of equipment.

3.5.5 Reliability

Thyristors are solid state power switching devices and when used in a converter circuit offer one of the most reliable applications of this device. Device reliability is enhanced by proper cooling of the device and protection against overvoltage and overcurrents. In addition, all power and control components of the exciter system will be required to meet the appropriate Navy MIL Standards.

3.5.6 Maintainability

The exciter components will be mounted within the cabinet to permit ease of identification and removal without the need of special tools. Where practical, components will be assembled in a modular form. Test points will be available to assist in troubleshooting defective components.

3.5.7 Safety

The exciter will be designed to protect personnel from electrical, mechanical, or thermal safety hazards.

3.6 Controls

3.6.1 Exceptions

No exceptions apply to the propulsion control system and related hardware.

3.6.2 Technical Summary

3.6.2.1 General

This section outlines in broad lines the organization and implementation aspects of a control system executing the functions and strategies described in Section 5 of the Appendix. The intent of this description is to illustrate the feasibility of the proposed control philosophy and to provide a tentative indication of the amount of hardware involved in the propulsion system controller.

The general block diagram of the controller is shown on Figure 3.21. The meaning of the functional blocks and the signals exchanged between blocks will become apparent in the following sections, as drawings detailing the functions of most blocks are described.

Briefly, the Electrical Propulsion System includes four dc generators whose shafts are driven by four gas turbines in block H. The generators' outputs are applied to two propulsion motors in D. Motors' and generators' fields are controlled by exciters in C. Feedback control of the machines' dynamic condition is achieved through a Primary Sensor System E, which acquires signals such as machine voltage, current, torque, speed, etc. and feeds them back to the dynamic controllers in C and to a supervisory controller in B. This unit receives manual input signals from a control console in A and initiates startup and shutdown functions, as well as the changes in power configuration of the drive system dictated by console-originated torque commands. To this effect, the supervisory controller decides the modes of operation of the dynamic controllers in C and modifies sequentially these modes to orderly perform the configuration transitions. The supervisory controller in B also receives auxiliary feedback signals from an Auxiliary Function Monitor F, which determines drive auxiliary parameters such as status of lube system, cooling system, etc. From this information, the supervisory controller in B can initiate if needed a shutdown cycle for protection purposes in case of abnormal conditions. A Dynamic Brake Unit G is used to dissipate energy from the motors in case of crash reversal, thus preventing regenerative action on the turbines. The supervisory controller determines the need of activating the braking unit and controls its dynamics. Finally, the supervisory controller generates the turbine speed reference signals to block H in order to maintain in any condition the optimum turbine speed resulting in minimum fuel consumption.

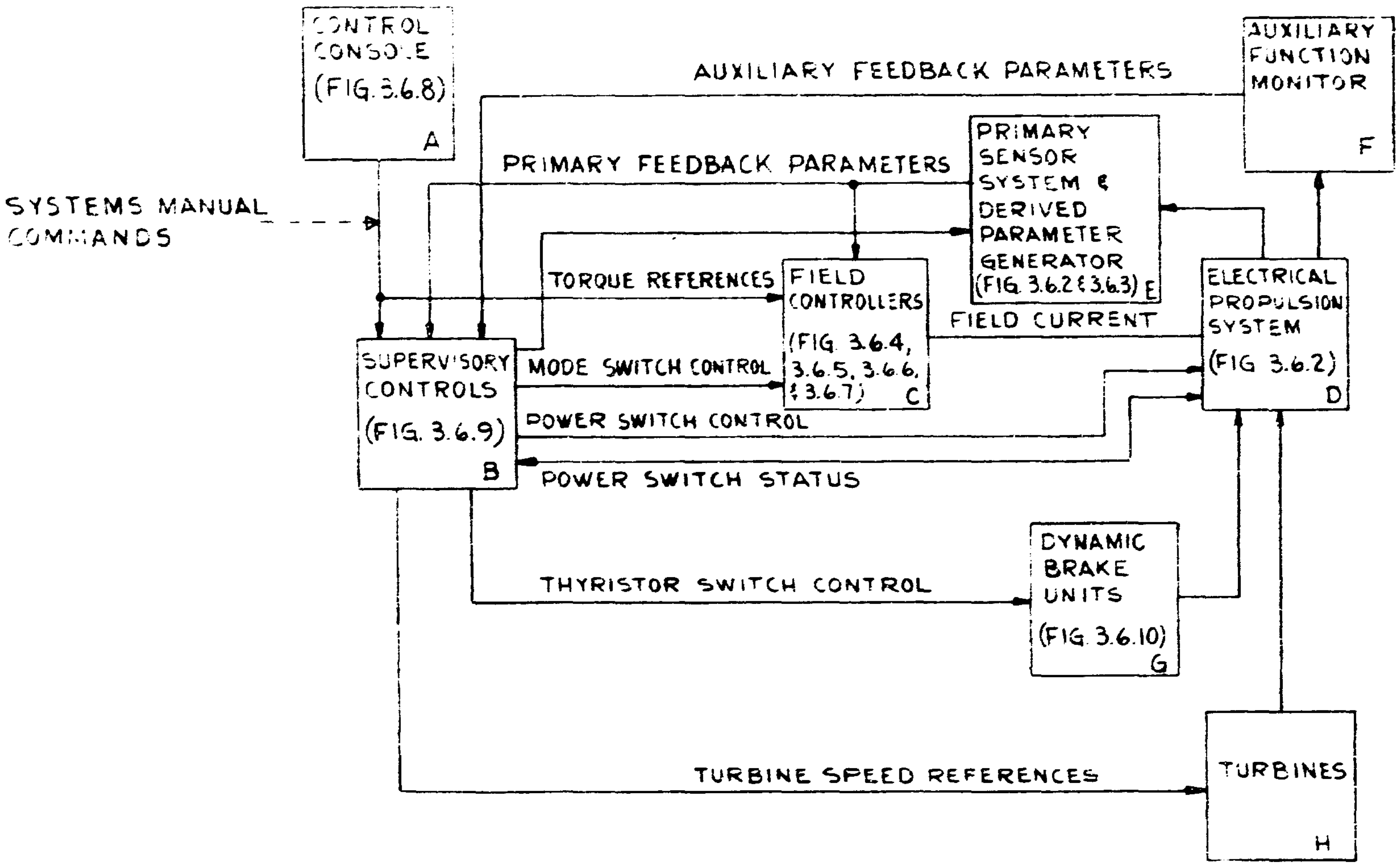


Figure 3.21. Propulsion Control System General Block Diagram

3.6.2.2 Microcomputer-Based Design

A circuit design based on the use of amicrocomputer system is considered. The microcomputer is built around an 8-bit microprocessor. A INTEL 8085 unit has been assumed for reference, although other similar 8-bit machines could be used. Some of the advantages of using microprocessor techniques in the present application are as follows:

1. For systems of the size and complexity such as considered here, there is a substantial reduction in the amount of circuitry required, due to the ability of microprocessors to execute a variety of different complex tasks with the same investment of hardware. This results in an improvement of the system's reliability as a consequence of a lower component count and associated lower failure probability.

2. A further improvement in reliability can be obtained by exploiting the ability of microprocessor systems to perform self-checking functions without increasing the overall system complexity.

3. The use of microprocessors greatly improves the flexibility of the design, i.e., the ability of implementing unforeseen operational changes after installation of the equipment. This is a direct consequence of the programmability of microprocessor systems, in which radical alterations of system behavior can be accomplished by merely modifying the software.

4. The presence of a microprocessor in the system facilitates the tasks of testing, troubleshooting, and fault diagnosis by building-in testing aids and testing routines at almost no increase of complexity.

3.6.2.3 Analog Circuitry Section

In the present state of development, readily available microprocessors such as the 8085 discussed here and its competitive equivalents presently on the market are unsuitable for some of the functions in the propulsion system. These functions are those associated with the close-loop servo control of the machines, and in particular, the tasks of deriving feedback parameters and error signals, amplifying them, performing the integration and differentiation operations necessary for lead-lag error signal compensation, notching out mechanical resonances, etc. Previous experience with the use of microprocessors in implementing proportional-integral-derivative regulator functions show that the sampling rate limitations inherent in these systems result in response delays generally incompatible with stability requirements and/or servo bandwidth requirements. Progress in microprocessor performance, in particular in the direction of higher clock frequencies will almost certainly eliminate these limitations in the near future. However, since it is difficult to anticipate the properties of these advanced microprocessors, the areas of servo regulation are considered, in the present study, as best implemented through traditional analog circuits. There is thus a core of analog circuitry, embedded in the microprocessor system and interfacing with it at the level of the reference signals to the controllers. Generally, the areas identified as "dynamic controls" in the conceptual study are implemented with analog circuits (Block C, Figure 3.21) whereas the areas identified as "upper level supervisory control" and "lower level supervisory controls" are implemented via microprocessor (Block B, Figure 3.21).

3.6.2.4 Primary Sensor System and Feedback Signals

A system of analog transducers and sensors is provided to supply signals proportional to the electrical quantities describing the condition of the propulsion machines. The transducers and sensors as well as their conditioning or scaling amplifiers are represented in functional diagram form on Figure 3.22. The 18 electrical parameters sensed consist of generator armature current I_{gx}, armature voltage V_{gx} and field current I_{fgx} (with gx = g1 or g^2 or g^3 or g^4) and motor armature current I_{mx}, armature voltage V_{mx} and field current I_{fmx}

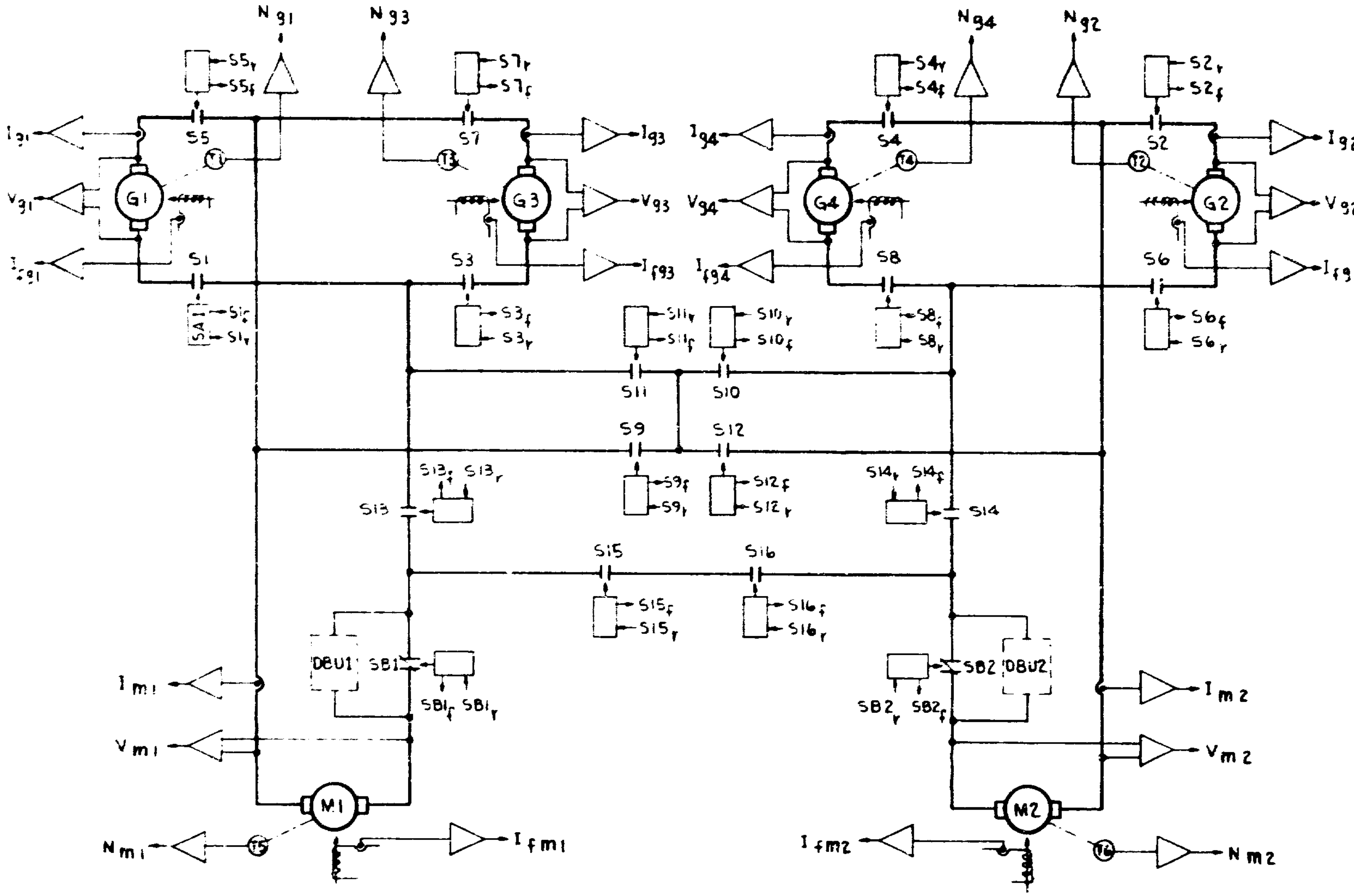


Figure 3.22. Primary Sensor and Switch Actuator System Functional Block Diagram

(with mx = m1 or m2). In addition, through shaft-mounted tach-generators T1 through T6, six mechanical parameters, namely the generators' and motors' rates of rotation N_{gx} and N_{mx} are supplied. The figure also shows 18 switch actuator units such as (typically) SA_1, which in response to input logic signal $S1_r$ causes switch S1 to acquire its ON or OFF state. Each switch actuator unit outputs a status feedback signal such as $S1_f$, which indicates the state of the switch. The 18 switch actuator units shown control the condition of the 16 power switches used to implement the various power configurations, as well as the condition of two auxiliary switches SB1 and SB2 used during dynamic braking operations, when dynamic braking units DBU1 and DBU2 (see also Figure 3.30) are active.

Part of the feedback signals developed on Figure 3.22 are used as is. Other signals undergo some processing to produce desired feedback parameters as illustrated on Figure 3.23. This figure shows how signals τ_{m1} and τ_{m2}, representative of the motors' electromagnetic torques, are derived from the motors' armature and field current information from Figure 3.22, through analog multiplier modules M1 and M2. Also, derived parameters y_1 through y_4 are evolved from generator armature current and voltage information in analog subunits Y1 through Y4, each containing a comparator and two analog switches. These subunits implement a derivation described on Figure 3-16 of the "Conceptual Supervisory Controls" report, at the $t = t_3$ step. The bottom part of Figure 3.23 illustrates the derivation of parameters I_r, α'_{m1} and α'_{m2} used in controlling the generator's armature current and the motor field current in the quarter power configuration. The shown analog circuits execute the operations described in Figures 3-9a, 3-9b and 3-9c (revised) of the "Conceptual Supervisory Control" report. The input quantities to this analog processor subunit are the torque error signals $\Delta\tau_1$ and $\Delta\tau_2$ from Figure 3.24 and 3.25, the generator armature voltage from Figure 3.22 and logic signals TQ, $\overline{TQ}$, Q_1, Q_2, Q_3, Q_4, XAF1, XAF2 and AF_1, discussed later (Figure 3.29).

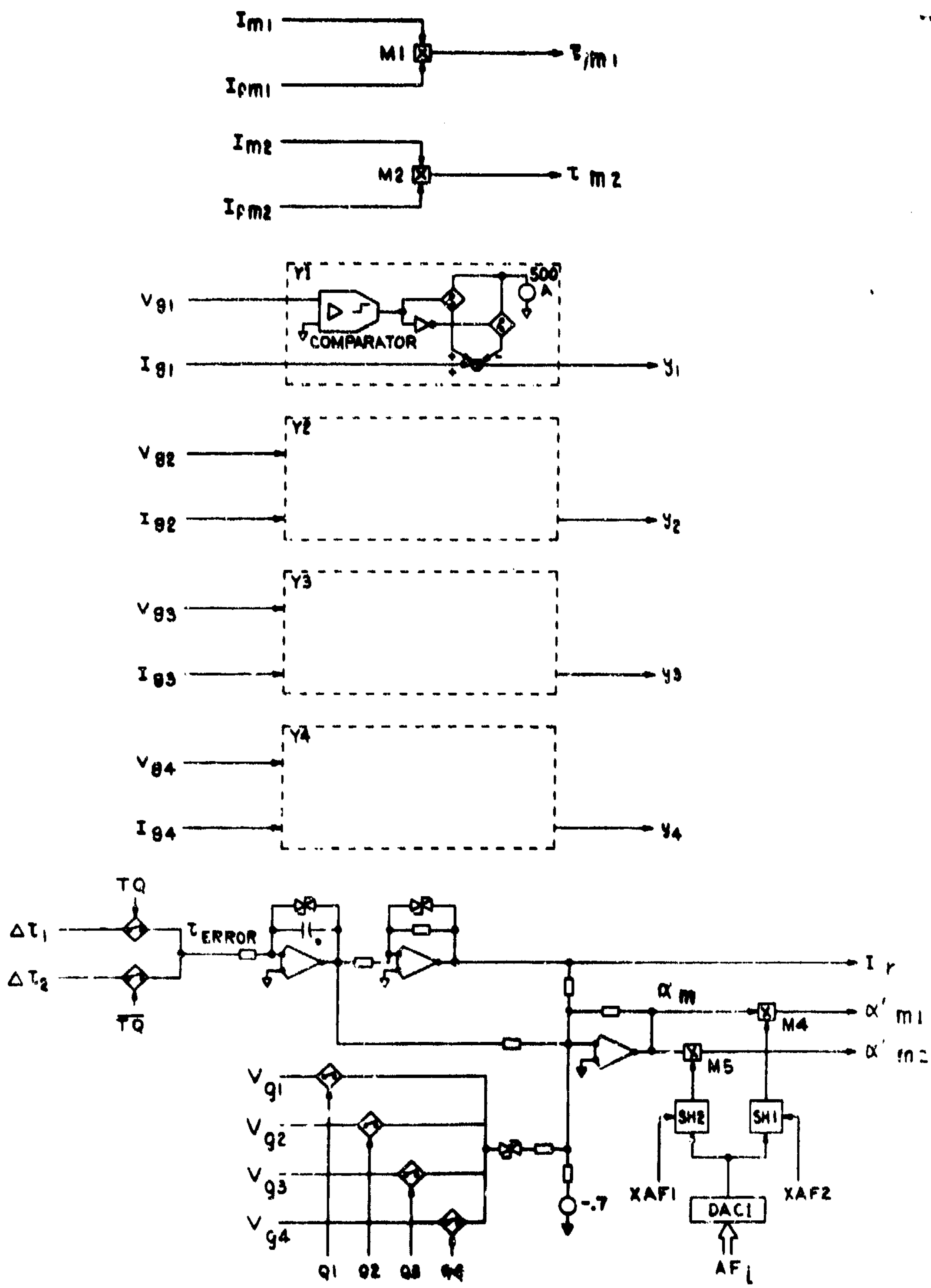


Figure 3.23. Derived Parameters Generation

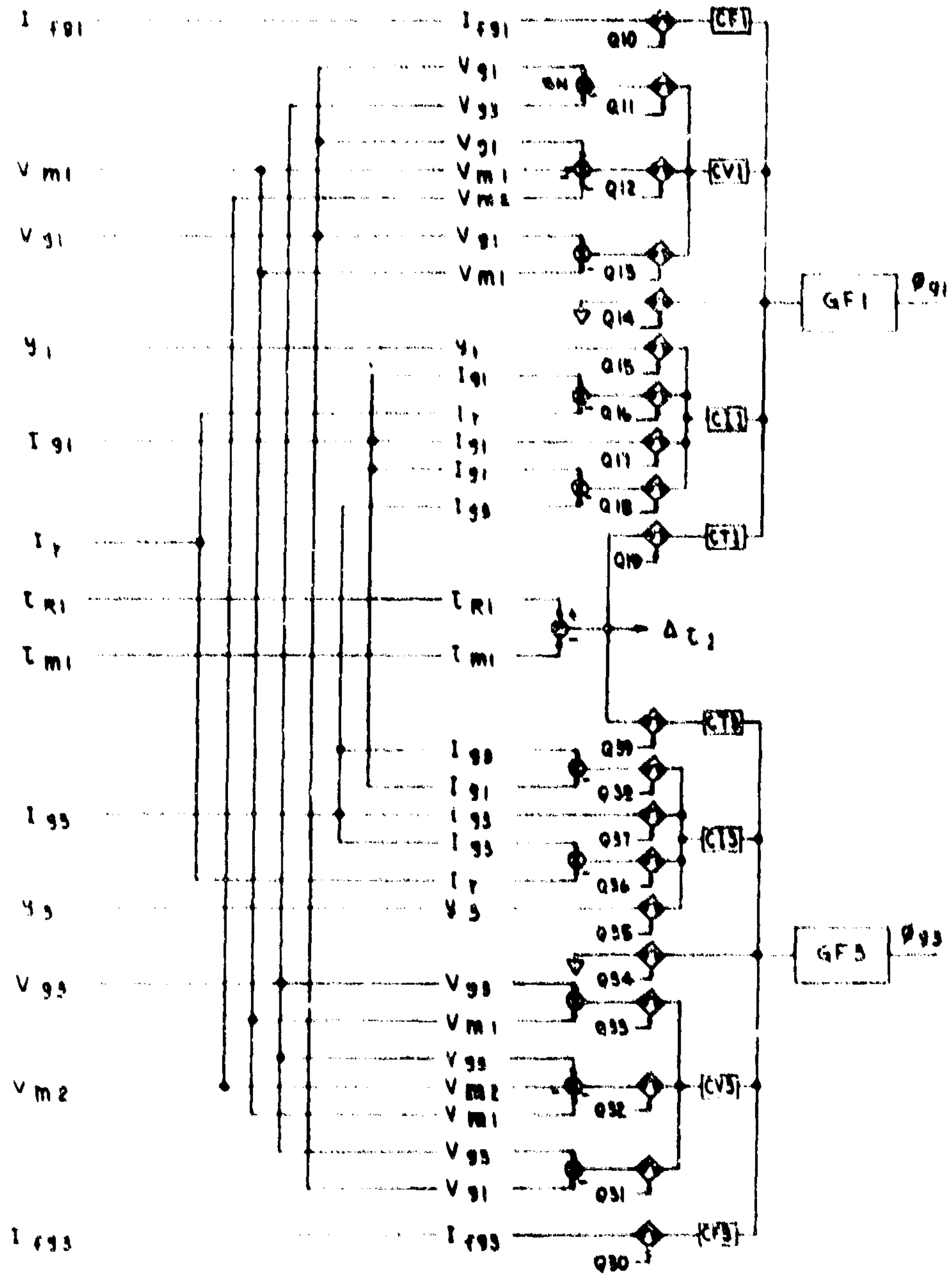


Figure 3.24. Generator Field Controllers and Mode Switches (Side 1) Functional Block Diagram

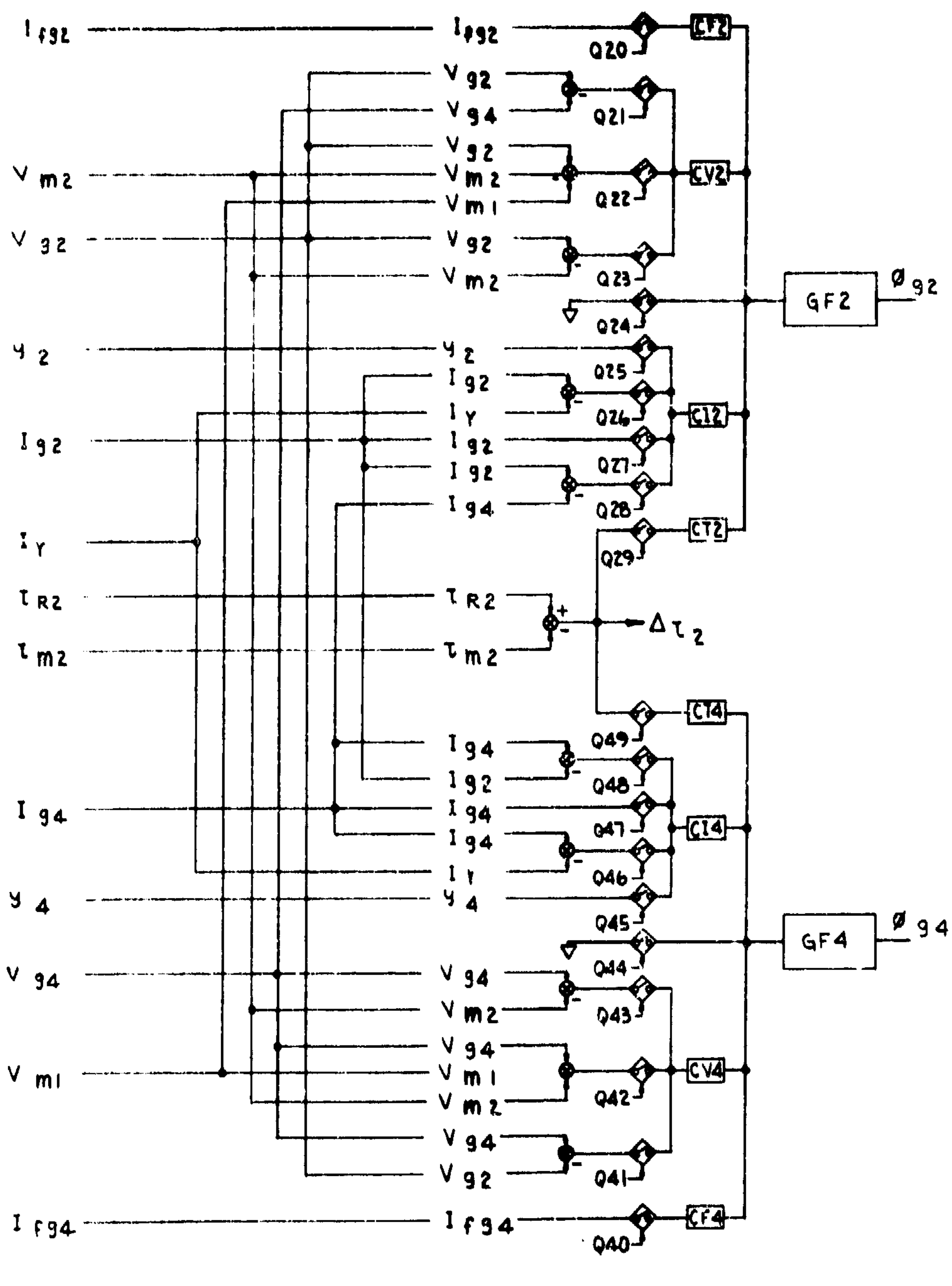


Figure 3.25. Generator Field Controllers and Mode Switches (Side 2) Functional Block Diagram

3.6.2.5 Mode Switches and Controlled Parameters

Most feedback parameters from Figure 3.22 and derived parameters from Figure 3.23 are routed to the machine field controllers (Block C, Figure 3.21) via an array of analog "mode" switches shown on Figures 3.24, 3.25 and 3.26. The mode switches allow applying a variety of possible error signals to the generator field controllers GF1 through GF4 and to the motor field controllers MF1 and MF2. The error signals consist of feedback parameters from Figure 3.22 or derived parameters from Figure 3.23 or sums and differences between pairs of such parameters. Signals τ_{R1} and τ_{R2} are propeller torque request signals, "manually" originated at the ship's control console (Figure 3.28). Summing modes such as SN, Figure 3.24, represent operational amplifiers, performing the sum or difference of applied signals. The mode switches are low-level, solid state analog switches, controlled by logic signals such as Q_{10}, Figure 3.24. When one of the mode switches associated with a given field controller is turned ON by bringing its controlling logic signal to the true state, a particular mode of regulation is implemented by which the control action on the field drives a selected parameter to assume a desired value. For instance, activation of Q_{19} results in a control action on the field of generator G1 aimed at compelling the electromagnetic torque of motor M1 to track the torque request τ_{R1} as set at the ship's control console. This implements the control diagram of GF1 stipulated on Figure 3-7 of the "Conceptual Supervisory Controls" report.

Similarly, the control diagram of GF3 on the same Figure 3-7 is implemented by activating Q_{38}. In this manner, activation of a selected group of mode switches brings about the control situation required to operate the propulsion system in any one of the possible power configurations or sets the machines in any one of the transitory states stipulated at the various steps of execution of a transition routine, such as envisioned in Figures 3-11 to 3-16 in "Conceptual Supervisory Controls".

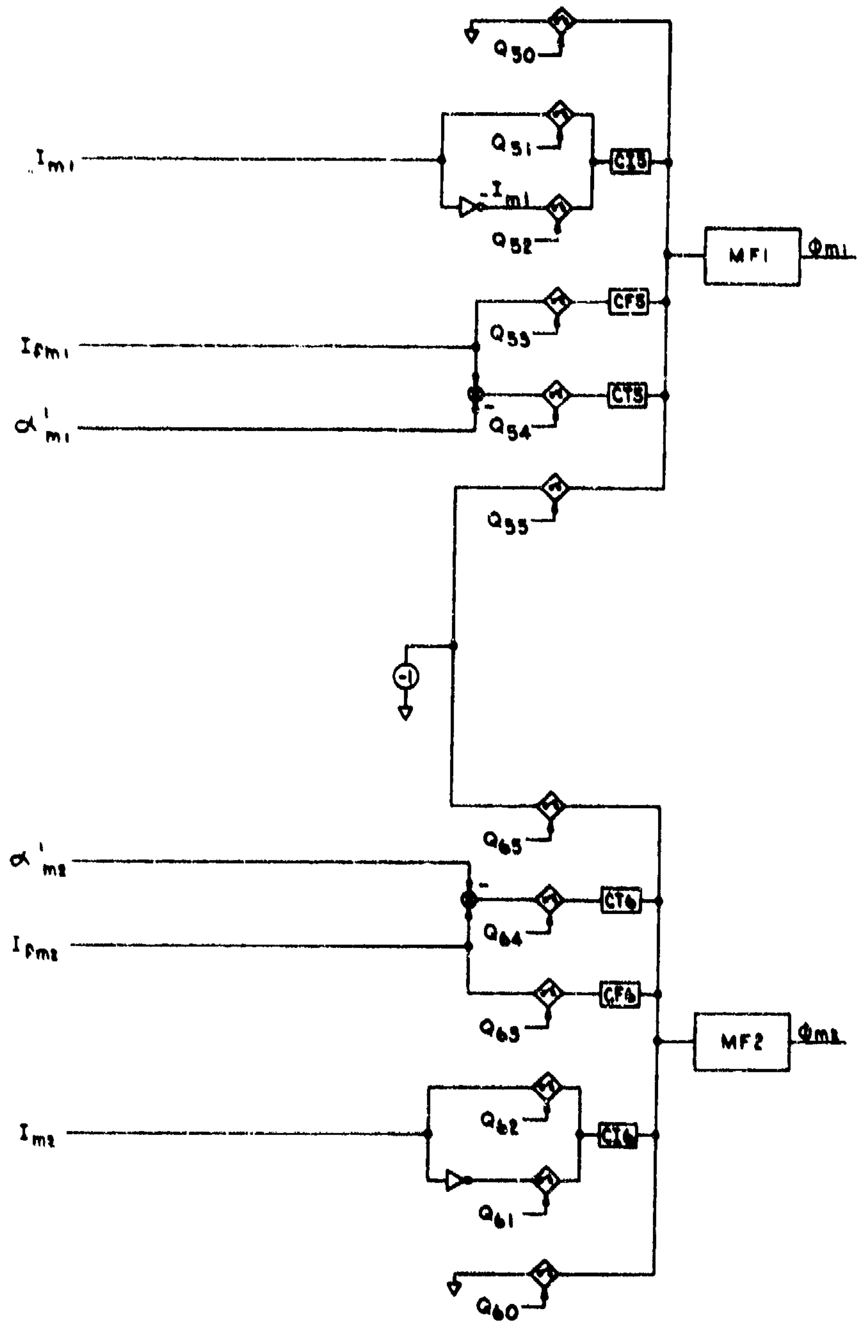


Figure 3.26. Motor Field Controllers and Mode Switches (Sides 1 and 2) Functional Diagram

The mode switch control signals Q_{10} through Q_{65} represent the controlled parameters of the supervisory control system, together with the switch actuator signals $S1_r$ through $S18_r$ on Figure 3.22. For any given set of states assigned to these controlled parameters by the microprocessor-based supervisory control, a situation exists in which the actual instantaneous value of the machine electrical quantities is governed by the circuitry of the analog dynamic controllers. These consist of compensation networks such as CF1, CV1, CI1, etc., (Figure 3.24) and the field controller circuitry, such as GF1, GF3, etc. The compensation networks are necessary to offset the fact that the various feedback loops implemented by activating the mode switches possess widely varying characteristics of gain, bandwidth requirements, transfer functions, linear range, etc. Each category of loops thus needs a particular compensation network setting the loop gain and shaping the frequency response. Figure 3.27 tentatively outlines the typical aspect of such compensation networks, used on Figure 3.24, 3.25 and 3.26, at all locations showing a compensation functional block such as CF1, with varying values of components.

Not shown on Figure 3.27a, but included in some of the compensation networks, is an arrangement to vary the gain of the network as a function of the generators' speed. This circuit which could consist of an analog divider controlled by one of the N_{gx} signals from Figure 3.26, is necessary to compensate for the fact that the transfer function of a generator in which the armature voltage or current is regulated through field control is speed-dependent.

The detail of the circuitry in the field controller functional blocks GF1 through GF4, MF1 and MF2 is tentatively outlined on Figure 3.27b for reference. There is an integrator amplifier to provide integral control action, driven by a clipping stage to achieve rate limiting. The integrator output is fed to the exciter unit, a thyristor dual converter which rectifies the incoming ac power and drives the machine excitation winding (see Section 3.5). The exciter incorporates its own internal feedback circuits, including a current limit provision for protection purposes.

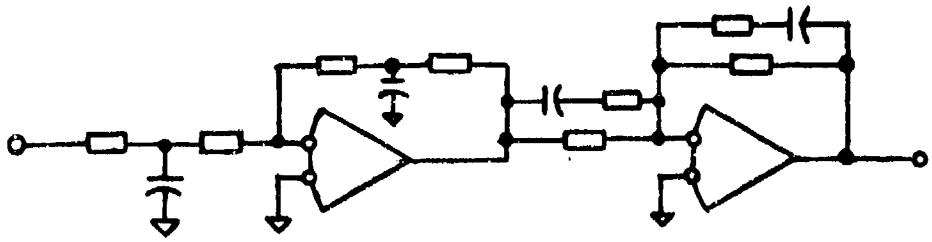


Figure 3.27a. Typical Content of a Compensation Functional Block such as CF1 in Figure 3.23.

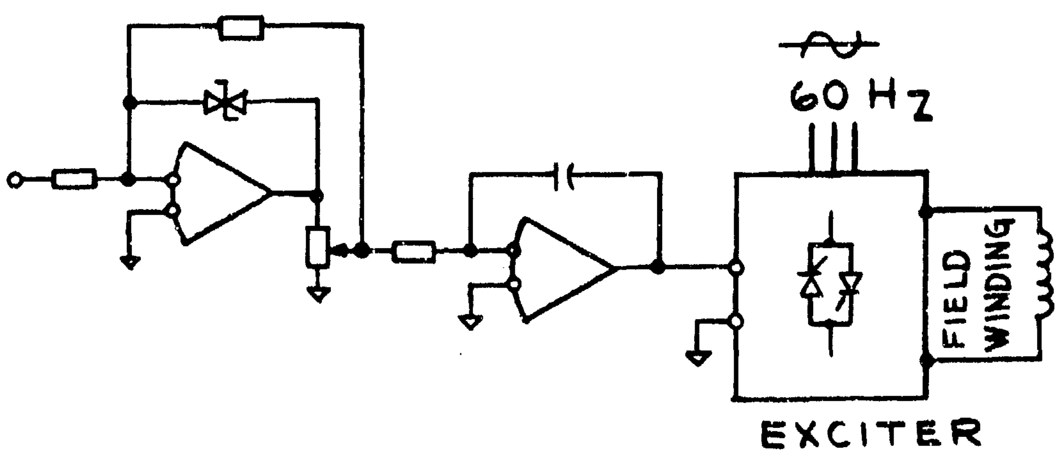


Figure 3.27b. Typical Content of a Field Controller Functional Block such as GF1 in Figure 3.24

3.6.2.6 Console-Originated Signals

Figure 3.28 shows the principal signals originated at the ship's control console (Block A, Figure 3.6.1) which are of interest in the present discussion. Two such signals are the propeller reference torques controlled by two levers coupled to potentiometers. Other signals are generated by system control pushbuttons and buffer logic assemblies such as BL1, containing anti-bounce circuits. Four system control pushbuttons are shown for reference, but their number in a fully designed system may be higher. A set of 4 switches is used to generate the permissive signals by which a given turbine-generator can be made available for inclusion in the power configuration. A manually set configuration selector is provided, by which the logic levels of 2 signal lines can be controlled to encode into 4 possible values of the requested power configuration parameter C_S.

Other signals not shown on Figure 3.28 are part of the interface operator-propulsion system and are brought to or from the console. Some of these signals, for instance, are provided for monitoring the propulsion system status, for announcing malfunctions, for displaying critical parameters, etc. Because these signals play only a secondary role in the control strategy of the propulsion system, they are not part of this conceptual discussion.

3.6.2.7 Microcomputer Hardware

Figure 3.29 shows the functional block diagram of the microcomputer system implementing the supervisory control functions of Block B, Figure 3.21. Each functional block on the figure corresponds in fact to one LSI chip or one module. The central role is played by block M which represents an 8085 microprocessor, which includes its own clock generator (3 MHz), governed by an external crystal CY. The microprocessor interfaces with external memory and input/output (I/O) ports through 3 groups of logic signal lines or "busses". There is an 8-bit "upper" address bus, carrying the most significant 8 bits of the

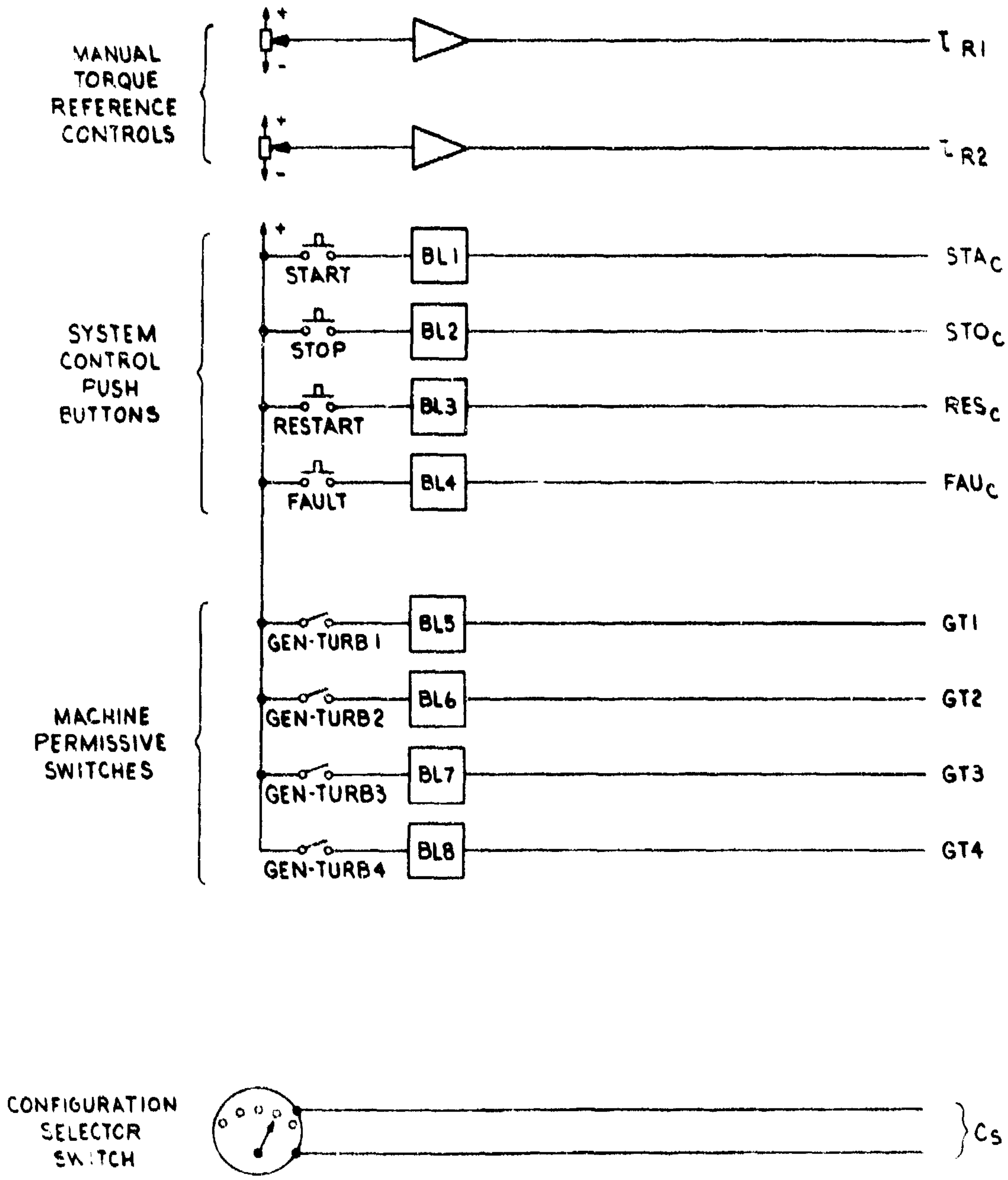


Figure 3.28. Ship's Motion Control Console Principal Signals

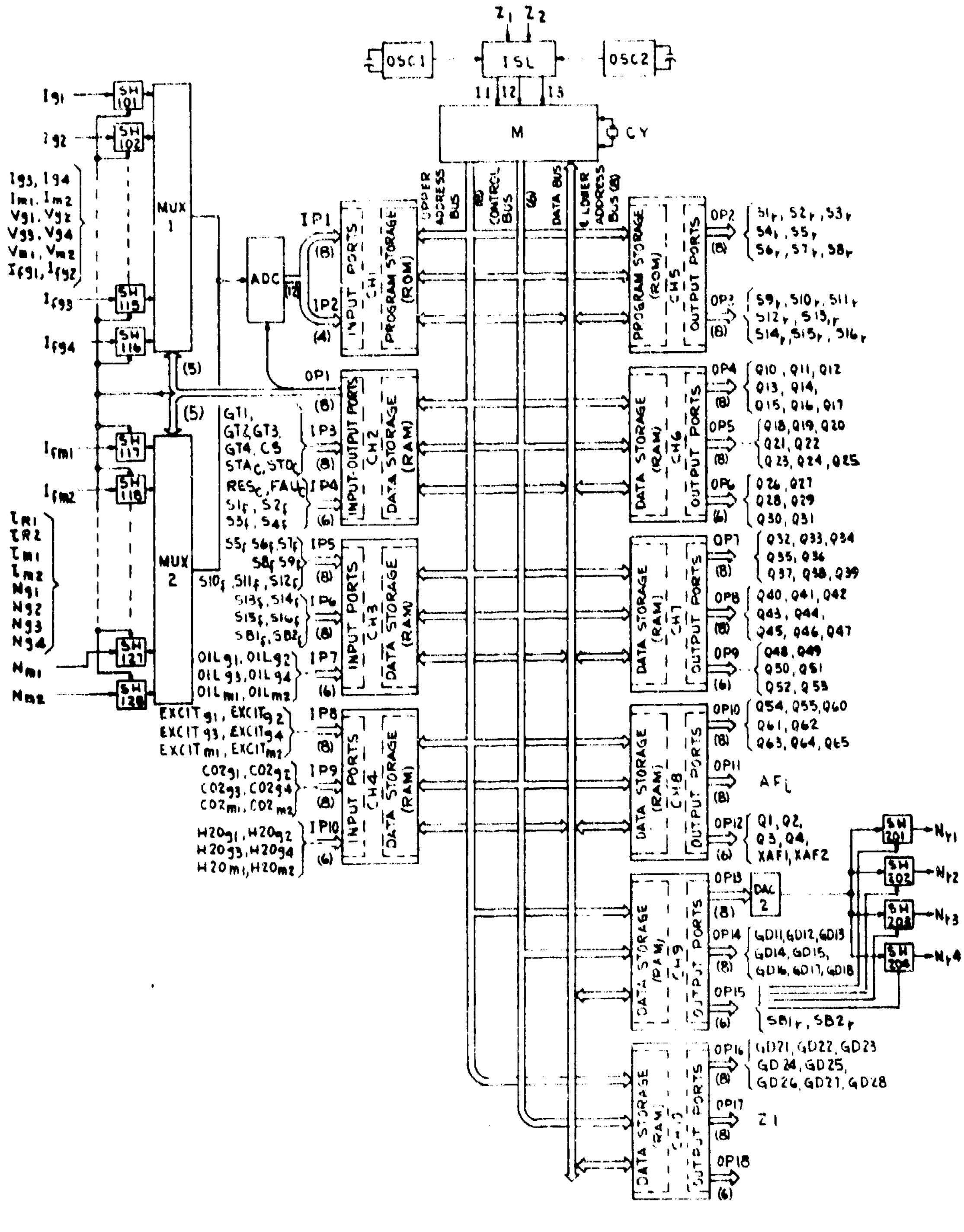


Figure 3.29. Microcomputer-Based Supervisory Control Functional Block Diagram

memory address or the bits of I/O address. A 6-bit control bus supplies synchronization and enabling signals to the peripheral chips. An 8-bit multiplexed address/data bus supplies at times the least significant 8 bits of memory address ("lower" address) and at times is used for data transfer between the microprocessor and the memory or the I/O ports.

Memory and I/O functions are provided by chips CH1 through CH10. Chips CH1 and CH5 are 8755 Programmable Read Only Memories (PROMs), each providing 2048 words of program storage. In addition, each chip contains two 80bit I/O ports that can be programmed as input or output by the microprocessor itself. Chips CH2 through CH4 and CH6 through CH10 are 8155 Random Access Memories (RAMs), each supplying 256 words of data storage, plus two 8-bit and one 6-bit I/O ports each programmable as input or as output. These chips also include one programmable timer each (not shown). The ports on CH5 through CH10 are programmed as output ports OP2 through OP18. The ports on CH1 through CH4 are programmed as input ports IP1 through IP10, except OP1 on CH2, which is programmed as output. Expansion of the system's size in terms of ROM, RAM or I/O capacity can readily be accomplished by simply connecting more 8755 or 8155 chips to the three machine busses up to the limit dictated by the 16 bits of addressing capacity of the 8085 microprocessor.

In order to feed to the microcomputer a digital representation of the analog signals provided by the sensor system, an analog-to-digital data conversion arrangement is provided. This makes use of the 12 bit analog-to-digital converter module ADC, which is time-shared by the numerous analog channels through the use of a multiplexing scheme, made up of MUX1 and MUX2, which are two 16 channels multiplexer chips. To ensure signal stability during conversion and guarantee that all processed variables are sampled simultaneously, a set of sample-and-hold modules (SH10) through SH128) are provided, each storing the instantaneous value of one of the analog input signals such as presented to the microcomputer system at a common sampling instant.

Means for data conversion from digital form to analog form are also provided, through digital-to-analog converter module DAC2, shared by 4 analog output channels through sample-and-hold modules SH201 through SH204, which each store the analog level present at the output of DAC2 at 4 different sampling instants.

The operation of the microprocessor is governed by a set of three external signals I1, I2 and I3, applied to "interrupt" inputs. Signal I1 is a train of short pulses at a frequency of about 50 Hz, generated by pulse generator OSC1 and routed through interrupt selector logic ISL. Signals I2 and I3 are also trains of narrow pulses at about 1 KHz, generated by pulse generator OSC2 and routed through ISL. Only one of the three interrupt lines I1, I2 or I3 is energized at any given time, according to the level of the mode selector signals Z_1 and Z_2.

3.6.2.8 Input/Output Assignments

Input ports IP1 and IP2 on Figure 3.29 are used to feed the microcomputer system the digitized values of the feedback parameters generated by the sensor system of Figure 3.22. The torque references τ_{R1} and τ_{R2} from Figure 3.28 and the motor electromagnetic torques τ_{m1} and τ_{m2} from Figure 3.23 and 3.24 follow the same route. The digitized quantities have the form of 12 bit words, as dictated by the resolution requirements of the system. The eight most significant bits are fed to IP1 and the four least significant bits are applied to IP2. Output port OP1 is used to direct the digitization operations, by timely activating the sample-and hold modules, addressing the multiplexer and triggering the conversions in ADC.

Inputs ports IP3 and IP4 are used to read-in the console-originated signals from Figure 3.28. Input ports IP5 and IP6, as well as part of IP4 serve for acquisition of the power switches status feedback signals. Input ports IP7 through IP10 deliver to the micro-computer the signals from the Auxiliary Function Monitor System (Block F, Figure 3.21, i.e., logic signals representative of the status in each machine of the lube oil system (OIL_x) the field exciters ($EXCIT_x$), the CO_2 system ($CO2_x$) and the cooling water system ($H2O_x$).

Output ports OP2 and OP3 generate the logic reference signals for control of the power switch actuators on Figure 3.22, whereas output ports OP4 through OP10 supply the control lines for the mode switches governing the field controller units of Figure 3.24 through 3.26. Output port OP11 feeds to the Derived Parameter Generator on Figure 3.23, an 8-bit word AF_1 which is converted to analog form by digital-to-analog converter DAC1 on said figure. The output of DAC1 is stored in sample-and-hold circuits SH1 and SH2, activated by signals XAF1 and XAF2 from port OP12 of the microcomputer. The stored analog levels are applied to analog multipliers M4 and M5, Figure 3.23, to achieve the imbalance in motor field references required in the quarter power configuration, as envisioned on Figure 3-9c (revised) of the "Conceptual Supervisory Control" report. The degree of imbalance is dependent upon the value of AF_1, which is generated by the micro-computer as a function of the ratio of the torque request signals τ_{R1} and τ_{R2} from the control console.

Output port OP12 provides other signals to the circuitry of Figure 3.23, namely the switch control lines Q1 through A4 which select the proper generator voltage feedback to be used in the quarter power configuration, according to the information in which of the four generators is active. Output port OP13 generates sequentially the speed reference levels to the turbines. These are calculated by the microcomputer as predicated on Figure 3-5b of the "Conceptual Supervisory Controls" report, in order to minimize the fuel consumption when feasible. The four digital values of the speed references are converted into analog form by DAC2 and stored by sample-and-hold modules SH201 through SH204, timely activated by signals from output port OP15.

Other signals from OP15 control the braking switches SB1 and SB2, Figure 3.22. Signal Z_1, from OP17, becomes true whenever the need of an anti-regeneration cycle is detected by the microcomputer Z_1 then steers the system into a particular mode through the logic in ISL, and this results in the generation of thyristor control signals at ports OP14 and OP16. These signals, applied to the Dynamic Braking Units on Figure 3.30, control the solid state switches that sequentially insert the braking resistors in the armature circuits of the motors.

In addition to the I/O ports discussed so far and shown on Figure 3.29, numerous other ports may be necessary in a fully developed controller, to provide monitoring and display functions of drive status parameters, to generate diagnostic messages, to accept interlock and permissive signals, etc. These functions are not included in this conceptual discussion.

3.6.2.9 Programming Concepts

3.6.2.9.1 Scanning Modes

What follows is a succinct description of the programming philosophy of the microcomputer system envisioned in order to implement the control strategies conceptually formulated in the "Conceptual Supervisory Controls" report. Some of the steps of the attached flow charts (Figure 3.31 through 3.33) have been developed in detail to verify feasibility with the proposed microprocessor. However, fully developed flow charts and the programming details are deleted here for the sake of simplicity.

The microprocessor operates in the proposed system in a so-called scanning mode, by which it cyclically checks all inputs of the system and determines the course of action to be taken based on whatever input modification has occurred between two successive scan cycles.

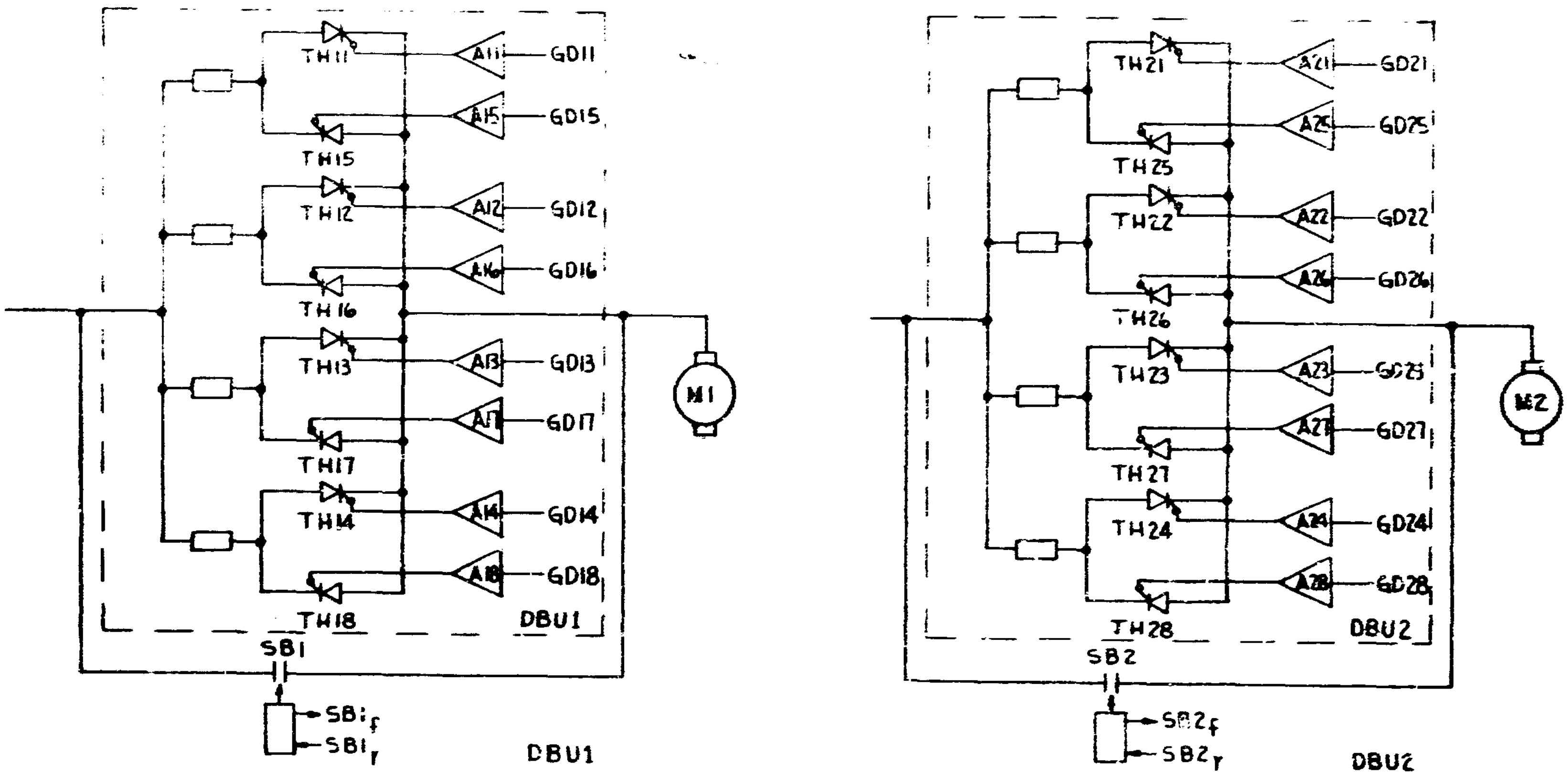


Figure 3.30. Dynamic Brake Units Functional Block Diagram and Control Signals

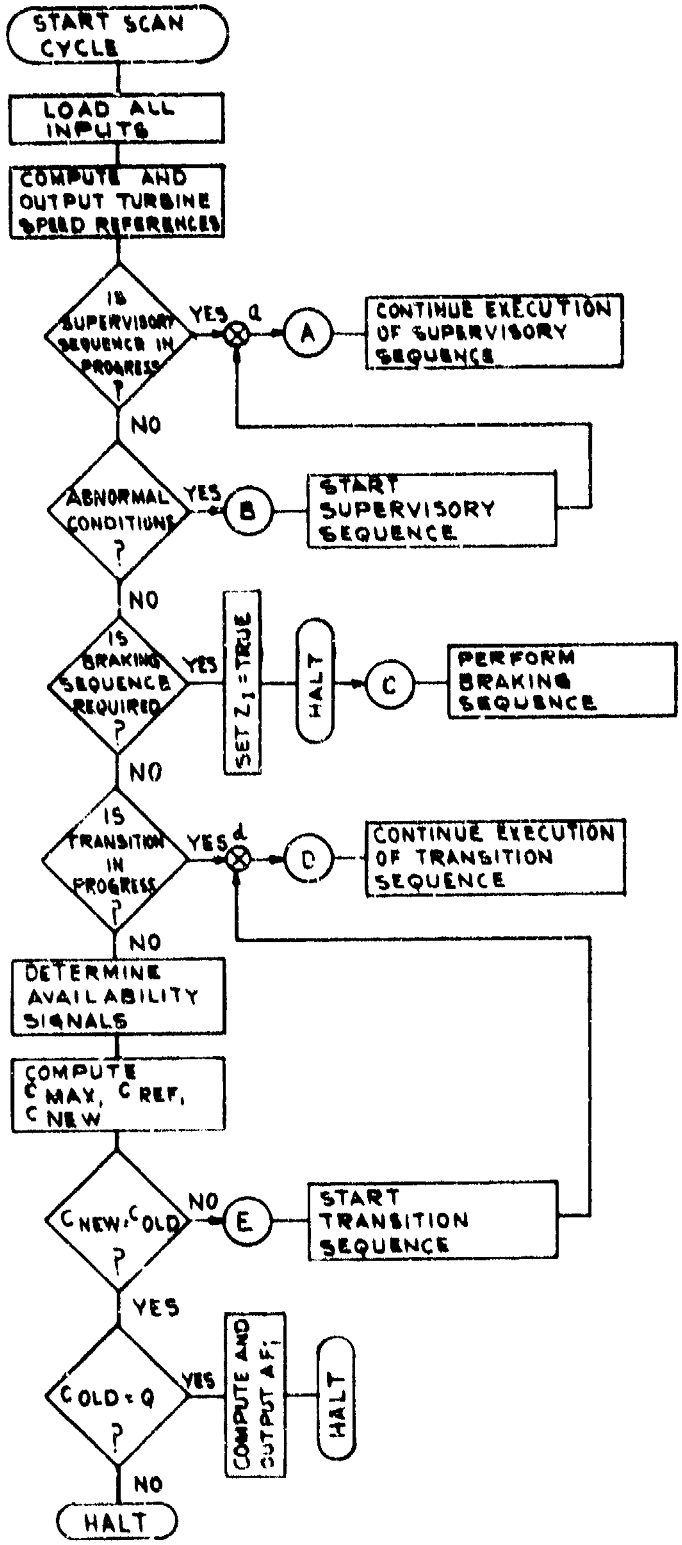


Figure 3.31. Simplified Flow Chart of Basic Supervisory Control Program

It is proposed to use one basic scan mode and two accelerated scan modes. The basic scan mode is used most of the time. The accelerated scan modes are initiated either when a dynamic braking operation is needed or an overcurrent fault condition develops. With the Z_1 and Z_2 signals at the input of ILS (Figure 3.29) in their false state, the basic scan mode is in effect. This means that pulses from OSC1, at about 50 Hz rate, are applied through line I_1 to one of the "external interrupt" inputs of the microprocessor M.

Just before a given I_1 pulse, the microprocessor is in a HALT condition, i.e., is inactive as a result of the last instruction received in the former scan cycle. The arrival of a I_1 pulse resets the program counter at a given predetermined count corresponding to the address in ROM where the first instruction of the basic scan period is written. This initiates the scan cycle, which is therefore performed 50 times per second. During a scan cycle, the program counter is incremented at the normal machine rate governed by the microprocessor internal clock and the scan cycle routine programmed in the ROM is executed, until a HALT introduction is encountered, whereupon the system turns inactive again until next I_1 pulse.

3.6.2.9.2 Basic Program

Figure 3.31 gives a simplified flow chart of the basic scanning cycle program. The cycle starts at an incoming I_1 pulse and the first operation consists of loading all input data into RAM locations. The analog quantities are all sampled at the same instant by activating simultaneously all sample-and-hold modules SH101 through SH128, Figure 3.29, then the signals are digitized in sequence and moved from input port to memory. All other non-analog input ports are similarly read into memory.

Next the system computes the turbine speed references, applying the algorithm indicated and retrieving as input variables the values of armature voltages and currents and field currents just stored at the start of the cycle. The calculated speed reference values are immediately outputted and sample-and-hold modules SH201 through SH204 updated.

At this point, means exist to indicate if the current scan cycle happens to be in the middle of a supervisory sequence. By supervisory sequence, it is meant an operation such as a START cycle, a STOP cycle, a RESTART cycle or a FAULT cycle, i.e., sequences under control of "Upper Level" supervisory logic. If a supervisory sequence is being performed, the program branches to subroutine A, which allows it to proceed with the current supervisory sequence.

If no supervisory sequence is in course of execution, selected stored data are checked to verify whether or not abnormal conditions exist to justify the start of a supervisory sequence. These conditions could be for instance that one or more speed parameter exceeds a preset limit, or one or more of the auxiliary feedback parameters (e.g., OIL_x or $H2O_x$) are false, etc. The presence of a console pushbutton signal commanding, for instance, START is also considered an abnormal condition.

In presence of an abnormal condition, subroutine B is called, which starts the proper supervisory sequence. In absence of such conditions, the program proceeds to verify if a situation exists requiring the use of one of the dynamic braking units. For this purpose, the condition

$$\left[(\tau_{R1} > 0) \cdot (N_{m1} < 0)\right] + \left[(\tau_{R1} > 0) \cdot (N_{m1} > 0)\right] = \text{TRUE}$$

is checked, as well as its correspondent for the port side. If one of the braking conditions is verified, subroutine C is started, initiating a braking sequence. If no braking condition is verified, the program proceeds to next step.

At this point, the system enters in the phase of execution of "lower level" supervisory functions, after the absence of commitments to higher priority "upper level" supervisory functions has been ascertained.

A verification is conducted to check if the current scan cycle happens to be in the middle of a transition sequence, i.e., the succession of steps leading from one power configuration to another. If such is the case, the program branches to subroutine D, which carries on the execution of the transition sequence.

If no transition sequence is in course of execution, the system proceeds with the configuration control logic, along the algorithms outlined on Figure 3-4a and 4-4b (revised) of "Conceptual Supervisory Controls". From the stored state of the permissive signals from the console (GT1 through GT4) and the stored state of the auxiliary feedback variables at ports IP7 through IP10, the availability signals A_{g1} through A_{g4} (shown on Figure 3-4a of "Conceptual Supervisory Controls") are determined. From these C_{max} is evolved and from the configuration request C_s and C_{max}, C_{ref} is calculated. Finally, the stored value of C_{old} from the previous scan cycle is combined with C_{ref} to produce C_{new}.

C_{new} is now compared to C_{old}. In case of inequality, subroutine E is called, starting a transition sequence. In case of equality, the scan cycle is concluded by executing a HALT instruction, unless the current configuration happens to be a quarter power configuration. In this case, prior to entering the HALT state, the quantity AF_1 (port OP11) is calculated and outputted, and sample-and-hold modules SH1 and SH2 (Figure 3.23) are updated, to supply the signals for torque imbalance control.

3.6.2.9.3 Principal Subroutines

This section gives a few more details on the subroutines A, B, D, E referred to on Figure 3.31.

Subroutine B (Figure 3.32) starts by setting a bit in a register (flag) signalling that a supervisory sequence is in progress, so that in subsequent scan cycles, the program will automatically branch to subroutine A. Next, the nature of the required supervisory

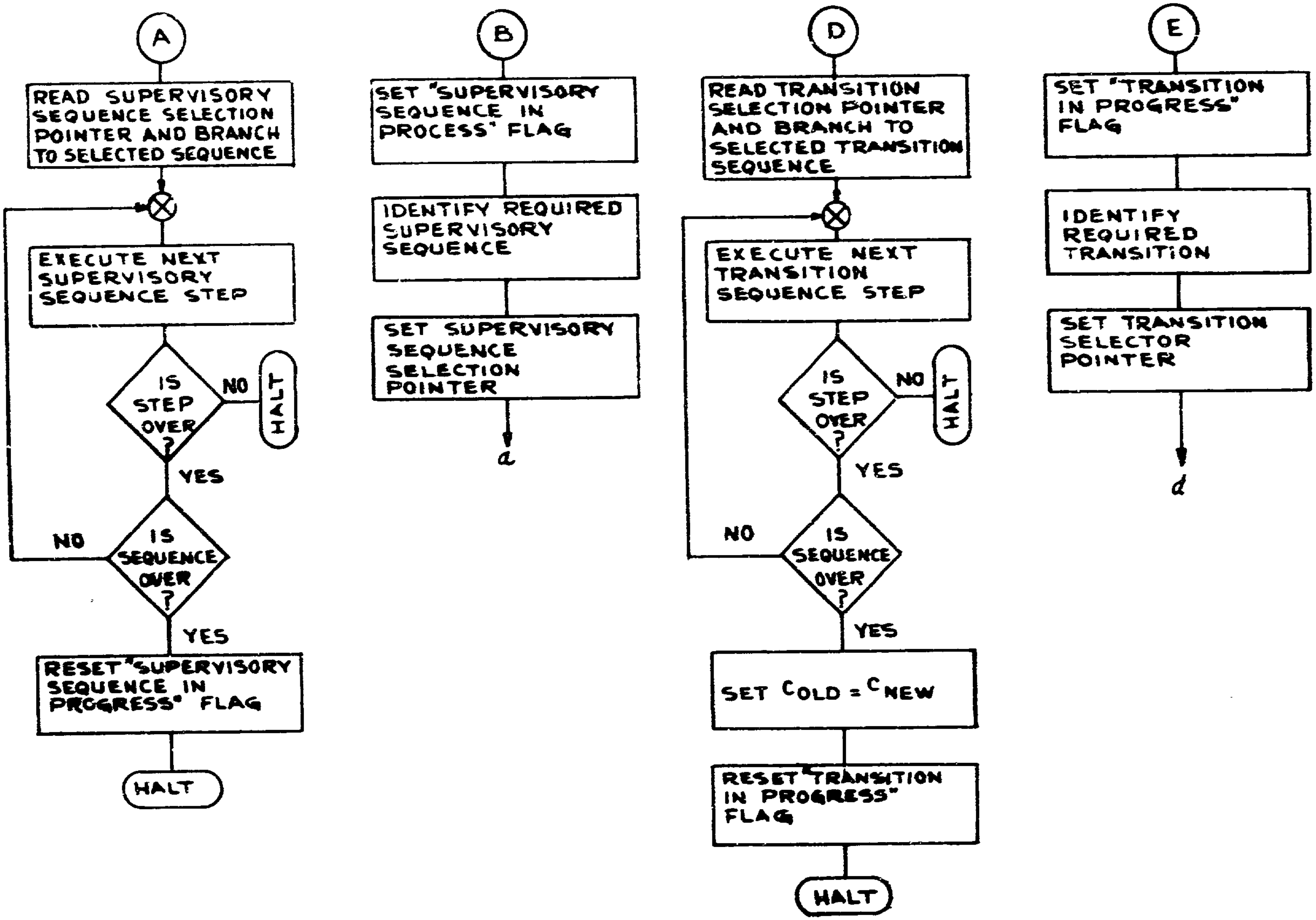


Figure 3.32. Principle Subroutines in Basic Supervisory Control Program

sequence is identified (either START, STOP, FAULT, etc.) and the side or machine affected is recognized by performing checks on the stored console signals or stored auxiliary feedback parameters. This allows singling out the required sequence among the many possible. This required sequence has its program written starting at a particular location in memory. A register (sequence selector pointer) is loaded with the address of this start location. The program then branches to node "a" on Figure 3.31, for execution of subroutine A,

Subroutine A starts by reading the supervisory sequence selector pointer and starting execution of the selected sequence. The various steps may include modifying the state of mode switch control signals at output ports OP4 through OP10, waiting for machine electrical quantities to decay or rise at present levels, activation or deactivation of power configuration switches through output ports OP2 or OP3, waiting for power switch status signals to input ports IP4 through IP6, starting timers and waiting for delays, etc. Each step may take numerous scan cycles to be executed. At each scan cycle, if a given step is not completed, the microprocessor goes in the HALT state and waits until the next cycle to check again for completion. At the last step of the sequence, the flag signalling that the supervisory sequence is in progress is reset.

Subroutine E is very similar to A in its principle. A flag is set signalling that a transition is in progress, so that the program can automatically branch to D during the subsequent passes. From the stored value of C_{old} and C_{new} and from machine availability signals, the nature of the requested transition is determined and a pointer locating the starting instruction of the proper transition sequence is loaded. The program then branches to node "d" on Figure 3.31 for execution of subroutine D.

The description of subroutine D reads identical to that of subroutine A, except that the selection process applies now to the many possible transition sequences, such as those described on Figure 3-11 through 3-16 of "Conceptual Supervisory Controls", plus their correspondents for the port side. Each of these sequences has been programmed in ROM and the proper one is retrieved through the transition selector pointer. After the last step of the sequence has been executed, C_{old} is set equal to the stored C_{new} value and the "transition in progress" flag is reset.

3.6.2.9.4 Accelerated Scan Modes

Subroutine C is distinct from the other subroutines, in that it involves a change in the mode of operation of the microprocessor. As Z_1 (port OP17) is set true just before branching to C on Figure 3.31 the interrupt selector logic ISL on Figure 3.29 becomes programmed to route towards line I_2 the pulses from source OSC2, whereas the pulses from source OSC1 are inhibited. Source OSC2 starts delivering to the microprocessor pulses at 1 KH_z, i.e., 20 times more frequent than the I_1 pulses. Thus, the microprocessor operates now in an accelerated scan mode. At each I_2 pulse, the program counter is reset at a location where the first statement of subroutine C is written.

An accelerated scan mode is needed for dynamic braking control because the 50 Hz sampling rate imposed by the basic scan mode is too slow to execute the thyristor firing steps. The decisions of firing several thyristors in sequence may have to be taken in a few tenths of a second. Since the basic scan rate of 50 Hz is dictated by the large number of variables to be loaded in memory in the basic mode and the numerous program steps to perform in the worst case, the braking operations cannot be conveniently controlled as part of the basic program. The solution adopted consists of abandoning execution of the basic program whenever a braking sequence is required and switching to an auxiliary scan program, which because it is exclusively dedicated to the braking routine, contains fewer steps and requires acquisition of less inputs, and thus can be executed at a faster rate. After the braking sequence, which is expected to last a few seconds, the basic scan mode is resumed.

Figure 3.33 shows the flow chart of the braking subroutine C. The program starts by causing the microprocessor to load input data, as in the basic scan mode. However the loading operations involve fewer variables than in the general case. Basically, only motor currents and speeds, generator voltages and torque signals are loaded. The program then proceeds in a way that allows execution of the braking sequence for one motor while monitoring the condition that could require a braking sequence for the other motor, and if needed, carrying out braking sequences for both sides.

At the first scan cycle in case of starboard braking, the program path is through blocks a-b-c-d-e. In d, the required braking sequence is identified, based on the polarity of the motor's current and the extent power configuration. A pointer is loaded so that the program can be steered to the proper sequence at next scan cycle, which will follow the path a-b-f-g. When the program arrives at node ND, a check is run on the condition of the port motor to verify if braking is required. If it turns out that the port side does not need braking, the program continues along the path j-k-n for all subsequent scan cycles until the sequence is over. In this case, the path is h-i-t. In block t, the conditions corresponding to the end of the regeneration cycle are checked. For the starboard side, this condition is:

$$\left[(N_{m1} = 0) \cdot (\tau_{R1} > \tau_{m1}) \cdot (\tau_{R1} > 0)\right] + \left[(N_{m1} = 0) \cdot (\tau_{m1} > \tau_{R1}) \cdot \right.$$

$$\left. \cdot (\tau_{R1} < 0)\right] = \text{TRUE}$$

A similar condition exists for the port side.

If both conditions are verified, Z_1 is set false, which returns the system to the basic scan mode.

If at block j it is found that the port side needs to enter a braking sequence, the program proceeds along j-k-l-m for one cycle and then along j-o-p until the end of the sequence.

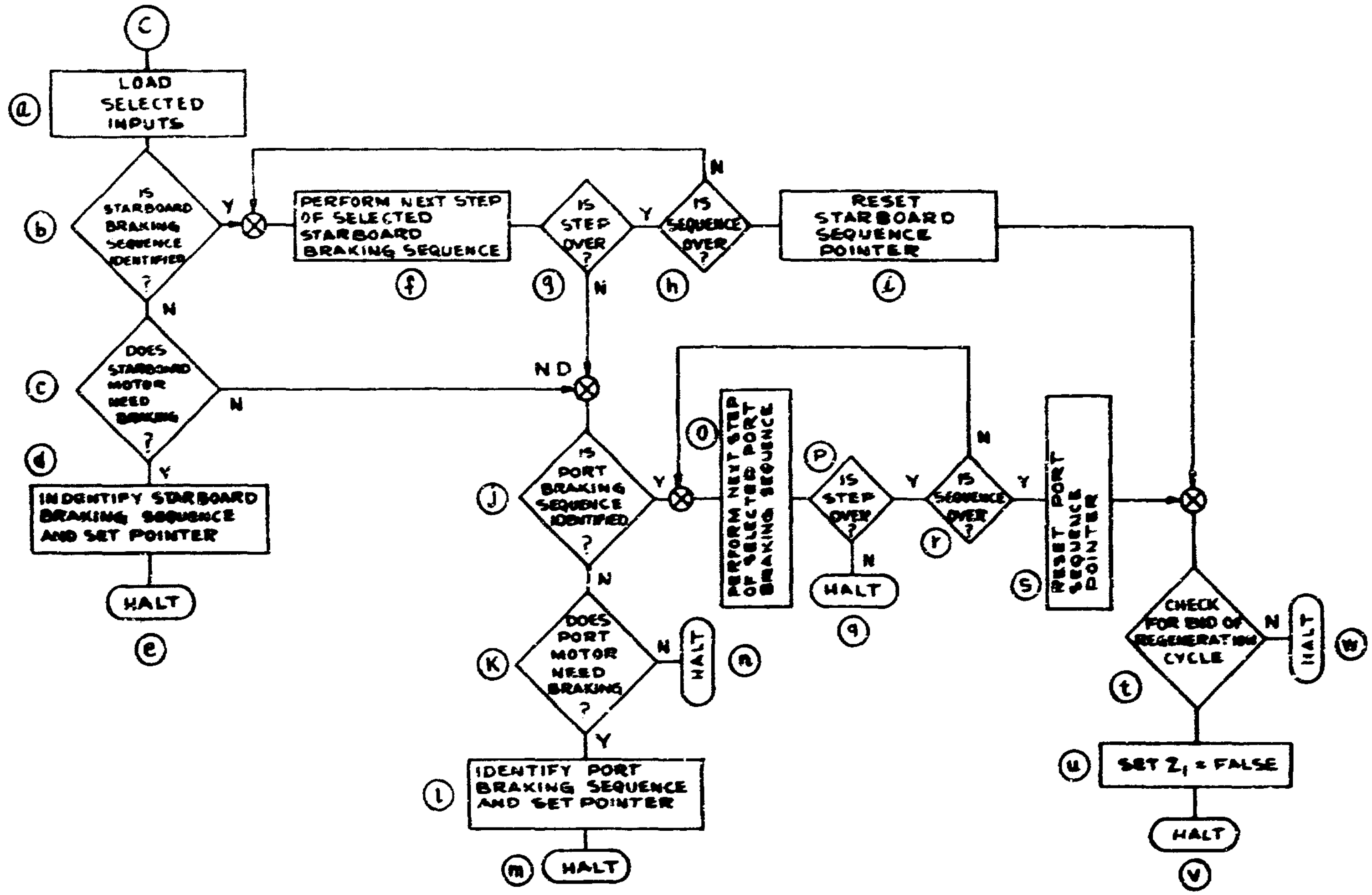


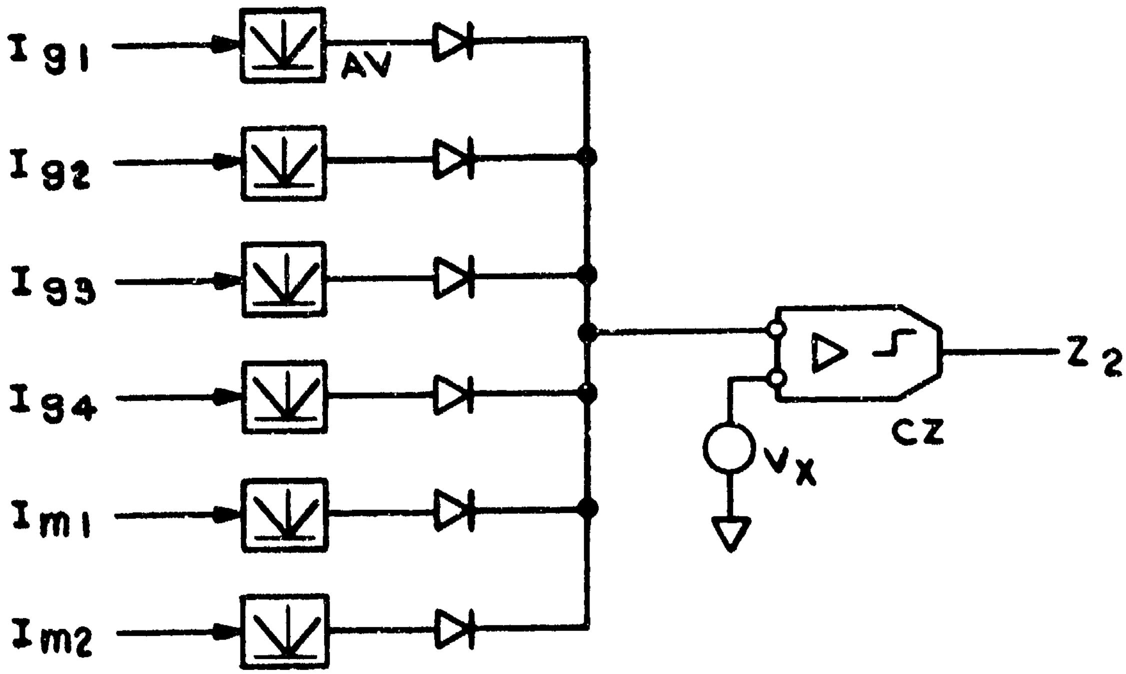
Figure 3.33. Dynamic Braking Subroutine

The braking sequences involve: (1) commanding a reduction to zero of generator armature current by action on mode switches on Figure 3.24 and 3.25 via ports OP4 through OP9 (Figure 3.29); (2) opening power switches SB1 or SB2 (Figure 3.22) via port OP15; (3) commanding a reduction to zero of generator voltage by action on mode switches; (4) firing the thyristors in the braking units (Figure 3.30) through ports OP14 and OP16. (The thristors are fired in a predetermined order, whenever the motor current reaches preset values, which depend on the power configuration in use. The array of thyristors to be fired depends on the current polarity); (5) closing power switches SB1 or SB2.

Another accelerated scan mode is foreseen, by which 1 KH_z pulses will be routed to interrupt input I_3 (Figure 3.29). This mode is started when input Z_2 becomes true and is intended to handle a fault situation triggered by excessive current in one of the machines. Emergency shutdown will be commanded in this case, with measures to reduce machine current as fast as possible to prevent damage. The exact means of current reduction has not been identified at this point of the study. They could consist of either a set of armature circuit breakers or of special circuitry for fast field collapse. The control of such means will have to be executed at a fast rate and thus the routines should be part of an accelerated scan mode. Such routines have not been defined at this stage. Figure 3.34 shows schematically how the parameter Z_2 would be generated through analog means external to the microcomputer system for reasons of speed.

3.6.3 Physical Description

The control system will consist of two principal subunits, namely a remote control console and a control hardware cabinet.



AV : ABSOLUTE VALUE CIRCUIT
C Z : COMPARATOR
Vx : REFERENCE LEVEL

Figure 3.34. Analog Arrangement for Fast Detection of Overcurrent Condition

The control console provides the means for interfacing the operator with the propulsion system, i.e., equipment for applying commands to the system and equipment for readout and monitoring of the system's parameters. Machine and subsystem status will be displayed at the control console through visual indicators.

The control hardware cabinet will contain the microcomputer elements and the analog control circuits on printed circuit modules. It will be located in the proximity of the exciter cabinets and the machines, to minimize imput/output interface problems.

3.6.4 Environmental Considerations

It is expected that no particular difficulties will be encountered in designing the control system so that it will meet the environmental requirements of this application. Ambient temperature constraints are projected to be such that an adequate design margin can easily be achieved. Both packaging and component selection will take into account the influence of the salty humidity in the operating environment.

Particular consideration shall be given to the control of electromagnetic interferences generated by the control system and to the shielding of the control system from the effects of externally generated interferences. No major problems are presently anticipated in implementing adequate interference control.

3.6.5 Reliability

The proposed choice of a control system implementation approach based on a microcomputer system is aimed at achieving inherent reliability through minimization of the component count. The following design guidelines will be applied to further increase the reliability level of the control system:

Component Selection

Whenever feasible, only parts meeting Navy MIL standards will be used. Circuit design will be performed to accommodate these parts and Navy standard modules. When nonstandard parts will have to be included, MIL-STD-749 will be applied in requesting approval to the Navy.

Failure Analysis

Worst case studies will be performed on possible failure modes to determine the required derating levels of component stress, the applicability of redundancy, the tradeoffs between alternative approaches and the minimization of single point failure modes, with the objective of enhancing reliability and obtaining a minimum projected MTBF figure.

Self-Check Features

The versatility of the microcomputer approach will be exploited to built-in self-check routines in the system's programming and the ability of displaying diagnostic messages in case of incipient malfunction.

3.6.6 Maintainability

The following ground rules will be applied in an effort to minimize the control system's maintainability requirements:

- Use of modularity in packaging
- Provide standardication of modules and interchangeability between identical modules
- Limit to a minimum module diversity
- Design for maximum accessibility to subunits
- Provide buffered test points avilable to automatic test equipment

In addition, the built-in diagnostic capability of a microcomputer system will be put to use to provide diagnostic message display as an aid in fault detection procedures.

3.6.7 Safety

The control system will be designed in application of the pertinent personnel safety requirements of MIL-STD-454. In particular, all external cabinet and console walls, control panels and displays, and all accessible components will be grounded; isolation transformers will be used in power supplies; all test points and input/output lines will be buffered and capable of withstanding a reasonable level of power transients. Adequate protection of the electrical parts in the control system, will be ensured through monitoring and alarm provisions capable of detecting conditions of abnormal temperature, impaired cooling, supply line under- and over-voltage and abnormal status of critical parameters. Audio and visual alarms will be used to signal the malfunction. Protective automatic shutdown of failing equipment will be applied to prevent fault propagation. Other safety provisions will have to be determined through a detailed safety hazard analysis of the system to be performed in future development efforts.

3.7 Auxiliaries

3.7.1 Exceptions

No exceptions apply to the auxiliaries required for this sytem.

3.7.2 Technical Summary

This section describes the principal auxiliary equipment and subsystems required for this propulsion system, the deionized cooling water system, the lube oil system, and the cover gas system.

3.7.2.1 Coolant Distribution

Figure 3.35 shows a schematic diagram of the deionized cooling water supply for the SEGMAG propulsion machinery. There would be one (1) cooling water system in each engine room providing two (2) cooling systems total aboard ship. Each cooling water system is designed to provide cooling for two (2) generators, one (1) motor and one (1) dynamic braking assembly when operating in the full power mode. In addition, when operating in the quarter power mode, the system piping is reconfigured by valves to provide service to one (1) generator and one (1) motor in the prime engine room and to one (10 motor in the secondary engine room. In this mode, the cooling water is circulated between engine rooms through the cooling duct in the cross connect transmission lines thus providing cooling for the cross connect lines.

The deionized cooling water system will operate as an unregulated variable pressure system without automatic temperature regulation. The system will have main and secondary pumps both rated to supply full cooling water flow in the full power mode. The main and secondary pumps will be of the centrifugal type which have been selected to have low shut off heads thus limiting the system over-pressure during periods of low cooling water flow.

The deionized cooling water system maintains the quality of the water by recirculating approximately 10% of the pump output back to the water storage reservoir through a mixed bed resin column. The quantity of water recirculating is regulated by a constant flow orifice which is adjusted to match the system requirements to maintain the resistivity of the water in the storage reservoir in the range of 1 to 2 megohm-centimeters. Table 3.14 lists some of the parameters of the cooling water system.

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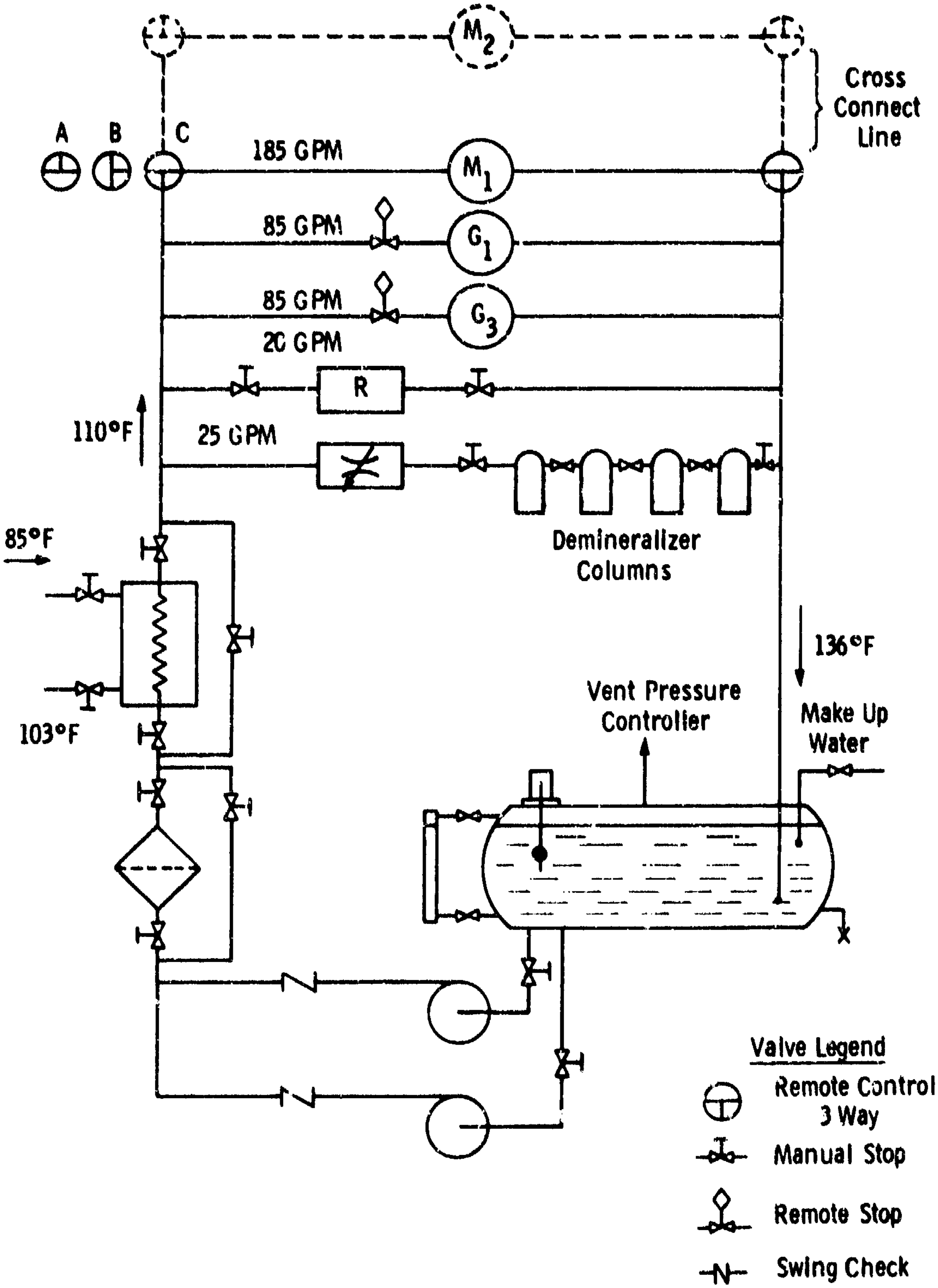

Figure 3.35. Deionized Cooling Water Schematic

TABLE 3.14

SEGMAG COOLING WATER SYSTEM SUMMARY

Item	Capacity	Wt. Dry	Wt. Wet	Vol.	Ref. Source
Storage Tank 4' Dia x 10' Long	800 Gal H_2O = 2 x pump Rate	2000 lb	8700 lb	175 cu ft	Mg Est.
Pump and Motor	30 HP 400 GPM ΔP = 70	1100 lb ea.	2200 lb total for (2)	6 cu ft ea.	ETA-80-400 + MTR and B&D
Filter (1)	ΔP = 10	400 lb	800 lb	6 cu ft	Pall # ME-1048
Cooler	5.2×10^6 Btu/hr 140°F in 110°F out	1600lb	2100 lb	18 cu ft	Young RC-1309
Valves 4" stop 8	150 lb Stainless Steel Est. 110 lb ea.	880 lb	880 lb	--	Crane API
Valves 4' Check	150 lb Stainless Est. 100 lb eac.	200 lb	200 lb	---	Crane #147
Valves 5" Stop (2)	150 lb Seawater Est. 150 lb ea.	300 lb	300 lb	--	Crane API
Stainless Steel Tube + Fittings	Est.	1000 lb	1000 lb	--	Est.

TABLE 3.14 (CONT)

Item	Capacity	Wt. Dry	Wt. Wet	Vol.	Ref. Source
Remote 3" Stop Valves (2)	150 lb Stainless Steel Est. 200 lb	400 lb	400 lb	--	Crane Model 27F + Remote Actuator
3 Way Remote Control (2)	150 lb Stainless Est. 250 ea.	500 lb	500 lb	--	Jamesbury Type 3 TR
Demin-eralizer Columns (4)		400 lb	400 lb	8 cu ft	Aqua - Media
Motor Control Size 3 (2)		300 lb	300 lb	8 cu ft	C-H #6862
Totals		10380 lb	18130 lb		

SEGMAG cooling water system features.

(A) 2 centrifugal pumps rated 400 gpm, 70 psi requiring 30 hp motors.

(B) Tank has 2 minute storage capacity.

(C) When operating in 1/4 power condition, 3 way valve allows cooling water system to engine room service motor in opposite engine room after remote control valves secure one of the generators.

(D) Expected required seawater flow = 600 gpm.

(E) Not shown are protective instruments as follows:

(1) Minimum ΔP alarm across each motor and generator.

(2) Maximum temperature out of each machine.

(3) Maximum conductivity of water leaving cooler and also H_2O

(4) Low level alarm on tank level.

(5) High fresh water temperature leaving cooler.

(F) NOTE: When in 1/4 power mode, (one generator and two motors) the motor in opposite engine rooms only gets 100 gpm -- this shows to be sufficient since losses in motor at that mode is only 317.2 kw compared to 825.4 kw at full power. Gross temperature rise through motor at the 1/4 power mode is then approximately 21.64°F while normal rise through motor at full load and 185 gpm - 30.43°F. Water, however, will pick up some heat from transmission line prior to arriving at motor -- thus if H_2O out of cooler = 110°F (normal design value), then it would rise 0.51°F before it reaches the motor. You will probably want to check that at 100 gpm, (est. ΔP = 10.23 vs normal ΔP = 35 @ 185 gpm), that the heat distribution is not seriously distorted from that seen at full load.

Salient Features:

Fresh Water = 400 gpm @ 35 psi across machines
110°F Supply
140°F Return

Sea Water = 600 gpm @ 23 psi drop
85°F Supply
105°F Return

When running at 1/4 power mode condition, only one cooling water system would be running but both lube oil systems must be in operation.

3.7.2.2 Lube Oil System

The schematic of the lube oil system is shown on Figure 3.36 and the component flow requirements and losses are tabulated on Table 3.15.

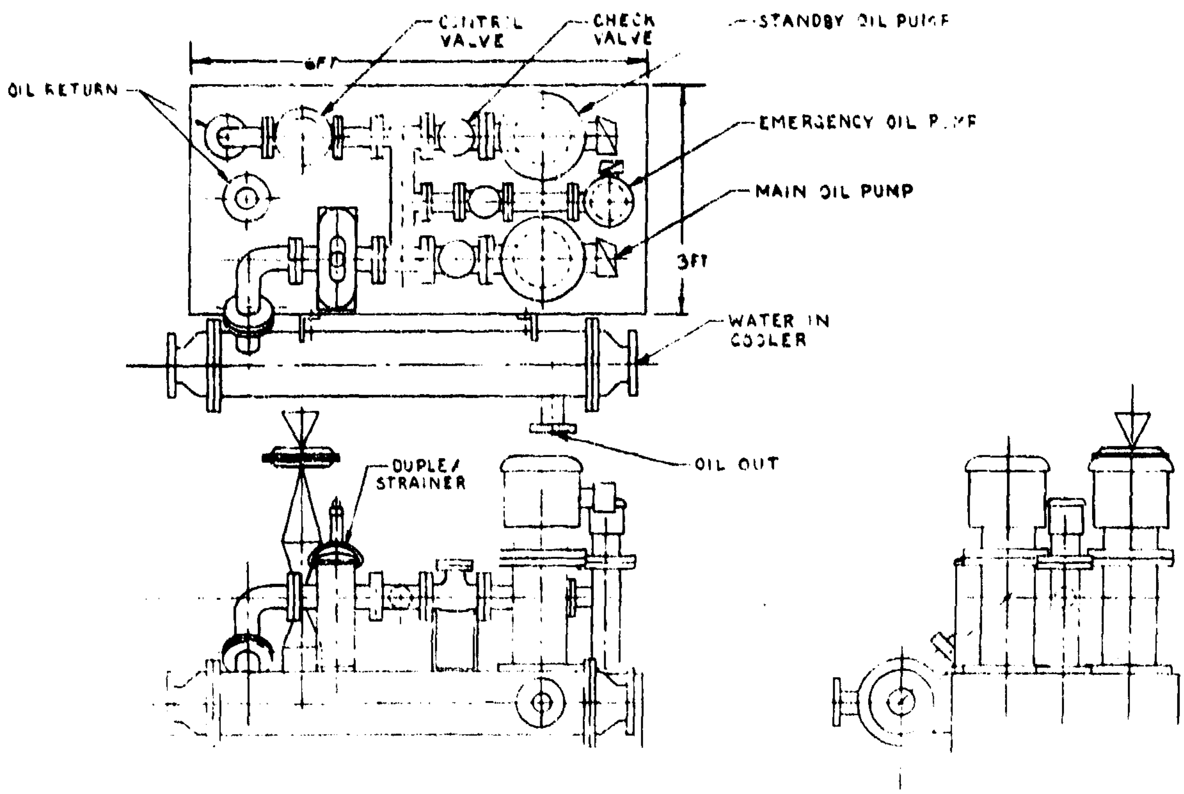

Figure 3.36. Lube Ol System Arrangement

TABLE 3.15

SUMMARY OF SEGMAG LUBE OIL REQUIREMENTS

Bearing Ident.	GPM Brg.	Total GPM/Mach.	KW/Brg.	Total KW/Mach.	Δt (°F)
#1 Gen. Radial Bearing	4.98	9.96	9.25	18.5	30°
#1 Gen. Thrust Bearing	8.0	8.0	11.4	11.4	23.02°
#1 Gen. Brake	--	--	--	--	--
#2 Gen. Radial Bearing	4.98	9.96	9.25	18.5	30°
#2 Gen. Thrust Bearing	8.0	8.0	11.4	11.4	23.02°
Motor Radial	4.3	8.62	4.0	8.0	15°
Thrust Bearing	22.0	22.0	16.4	16.4	12.05°
Total for System		64.53		84.20	21.86°

Each engine room has one (1) lube oil system to service only those machines within the engine room. There are a total of two (2) systems aboard the ship. Each system is designed to provide lube oil to the two (2) generators, one (1) motor and the main thrust bearing.

The lube oil system consists of a baffled rectangular storage reservoir which has a storage volume equal to 3 minutes of lube oil demand. The tank is provided with two (2) positive displacement, AC motor driven, submerged suction screw pumps. Both pumps are rated 15% above the system demand. These two pumps are backed up by a third, DC motor driven emergency coast down pump which is rated at 50% of the system demand. The DC motor takes power from the ship's DC system if available or else from a dedicated battery bank with sufficient ampere-hour capacity to operate for 1 hour. Each pump motor is protected by an integral pressure relief valve.

The bearing pressure is regulated by a relief valve which senses system pressure at the most remote bearing.

A 40 micron duplex oil strainer with differential pressure gages is supplied ahead of the lube oil cooler. The cooler is rated for a maximum of 85°F ships service cooling water.

The lube oil will be distributed to the serviced machines through a lube oil header which has flow control orifices before the entrance to the bearings.

The weight summary for the lube oil system are shown in Table 3.16.

DESIGN RULES FOR SEGMAG LUBE OIL SYSTEM

1. Provide pressure system.

2. Provide two AC motor driven positive displacement pumps both rated 1.25 x lube oil demand.

3. Provide one DC emergency pump rated @ 50% of demand.

4. Provide sump tank with minimum oil level = 4X GPM demand.

5. Provide pressure regulating valve ahead of filter and cooler sufficient to regulate pressure at most remote bearing to 15 psig.

6. Provide duplex strainer (100 mesh) with non-interrupting change over valve.

7. Provide one cooler with bypass valve. Provide temperature control by regulating cooling water. Tubes shall be suitable for cleaning.

8. Provide 0.25 sq ft of free surface of oil per GPM demand.

9. Provide sufficient excess tank volume to allow rundown of system without overflowing tank.

10. Provide following instrument gages and alarms:

    a. Low sump level alarm

    b. Sump dip stick

    c. Auto shutdown at 10 psi pressure @ most remote bearing.

    d. Differential strainer pressure and alarm

    e. Cooling outlet temperature and alarm indicator.

    f. EWEC Alarms

        (1) Standby motor running

        (2) Emergency motor running

    g. Auto shutdown when emergency motor running

11. Provide DC motor controller with charger and storage batteries sufficient to power DC motor for 10 minutes of emergency lube oil pump operation.

TABLE 3.16

SEGMAG LUBE OIL WEIGHT SUMMARY

Item	Capacity	Wt. Dry	Wt. Dry	Vol.	Ref.
Tank 6 x 3 x	300 Gal.	1600 lb	4100 lb	72 cu ft	Mink
IMD Pumps (3)	(2) - 75 GPM (1) - 40 GPM 1 MO 313-187	1200 lb	1200 lb	Inch in tank	1 MO
3 Motors	(2) - 10 Hp AC (1) - 2 Hp DC 1/2 hr rated	750 lb	750 lb	6 cu ft	Westinghouse + Est.
Strainer		300 lb	350 lb	2 cu ft	Andale 104 B
Cooler	157 sq ft	350 lb	500 lb	5 cu ft	Young 809
Stop and Check Valves	+ Piping	450 lb	450 lb	Incl	Est.
AC MTR Control Size 1 (2)		200 lb	200 lb	4 cu ft	C-H
DC Motor Controller + 10 min. Battery		600 lb	600 lb	30 cu ft	Galbraith Pilot Marine PM-BC-19-00
Totals		5450 lb	8150 lb	121 cu ft	

3.7.2.3 Gas Atmosphere

The gas atmosphere control system for a machine will be designed in consideration of the following parameters:

- Desired gas and pressure which establishes the propensity for arc suppression
- Desired vapor additive which reduces brush friction and ennances brush life
- Desired gas exchange rate which controls brush debris and off-gassing products.

At present, the most probable machine cover gas is carbon dioxide with water vapor added as a lubricant. Other cover gas possibilities include nitrogen and argon with additives of water vapor and/or hydrocarbon vapors. The cover gas will be used to transport the airborne brush debris out of the machine. Particles too large to be suspended by the gas will fall to the bottom of the machine where the insulation inhibits electrical short circuits.

A schematic of the debris removal system is shown in Figure 3.37. The gas stream existing from the machine first flows through a valve that controls the amount of flow through the machine. The gas is then passed through a filter that removes the debris particles. Following the filter, the gas flows through a centrifugal blower that pressurizes the gas to overcome the circuit flow resistance. A heat exchanger is used to cool the gas since the machine as well as the blower add heat to the gas. The gas then passes through a filtering bed of activated charcoal that will filter out unwanted organic vapors. The vapor additive is then restored to a desired level in the vapor addition chamber. The gas is then returned to the machine.

The gas pressure inside the machine will be maintained at approximately 5 psig. The volume flow of gas through the machine will be approximately 2 scfh. The system schematically shown in Figure 3.37 is presently being tested on a laboratory test vehicle that simulates

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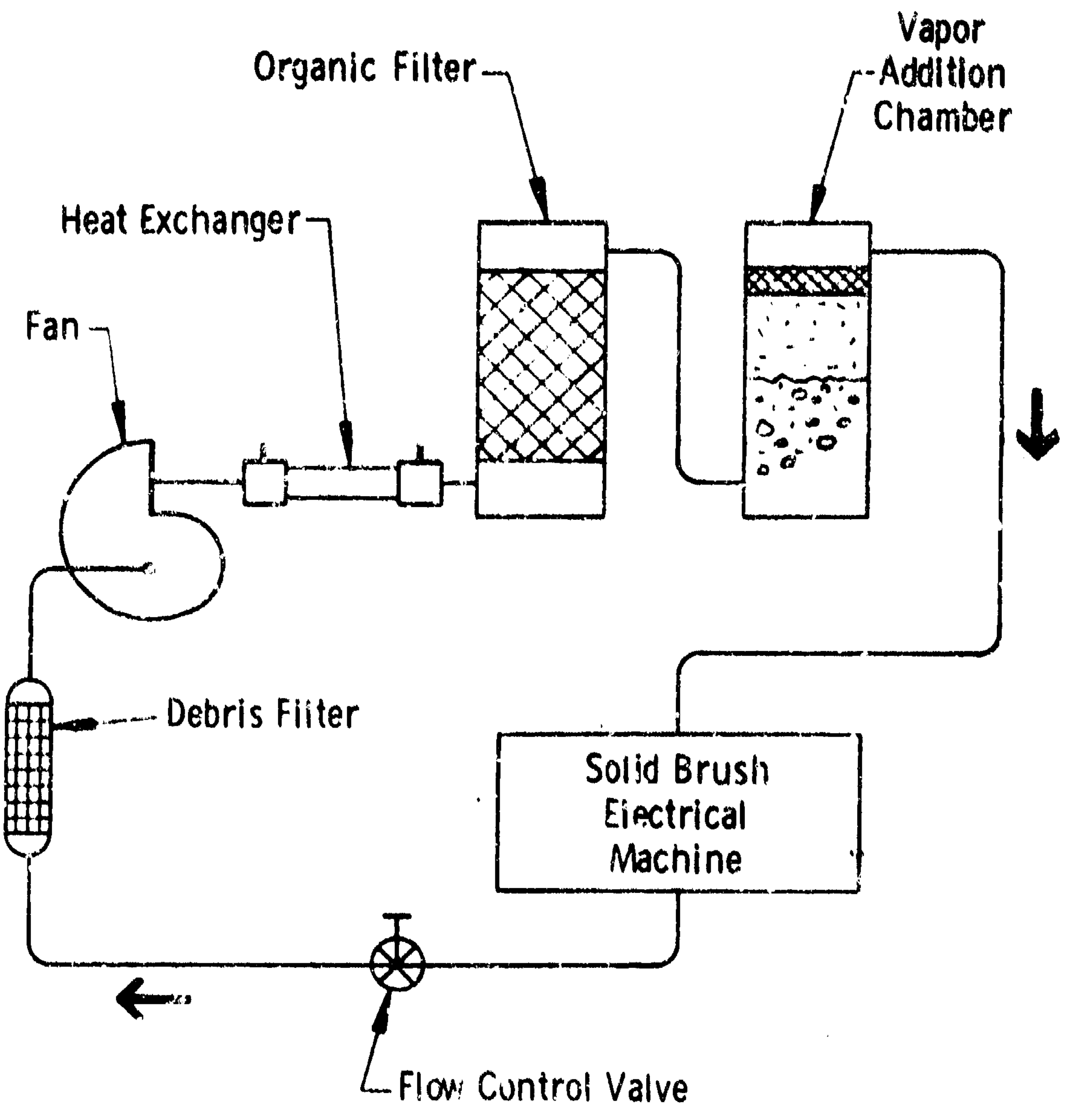

Debris removal system

Figure 3.37. Cover Gas System Schematic

a typical machine environment. This particular system is expected to be typical of a 3000 horsepower machine application. The volume flow rate of the experimental apparatus can be varied over a range of 1 to 100 ft^3/hr.

Shown in Figure 3.38 is a view of a brush holder module showing a more complex system. Here the gas is drawn out of the machine through axial slots along the trailing underside of the brush holder. Gas could also be injected in a similar fashion along the leading underside of the brushholder.

3.8 Dynamic Braking

3.8.1 Technical Summary

During a crash reversal operation of the ship's propulsion system, it is required that the propeller rotation be reduced to zero speed and driven in the reverse direction so that the ship may be quickly reversed. To accomplish this objective, it is necessary to provide a reverse torque on the propeller greater than the water torque applied to the propeller due to the ship's speed. The time required to reduce the propeller speed to nearly zero RPM is dependent on how rapidly the energy stored in the rotational mass of the motor armature, shaft and prop is dissipated. By operating the motor as a generator during the braking interval, a reverse torque is applied to the prop that is proportional to the product of the motor armature current and motor field flux. Although several methods may be used to dissipate the stored energy, this section of the report is concerned only with dissipating the energy into resistors that are placed in series with the motor armature circuit. To maintain the motor armature current to the desired level as the motor RPM and EMF lowers, the braking resistor value is reduced by switching in additional parallel resistors. In this application, the resistors are switched in by solid-state thyristors rather than electromechanical contactors. The basic

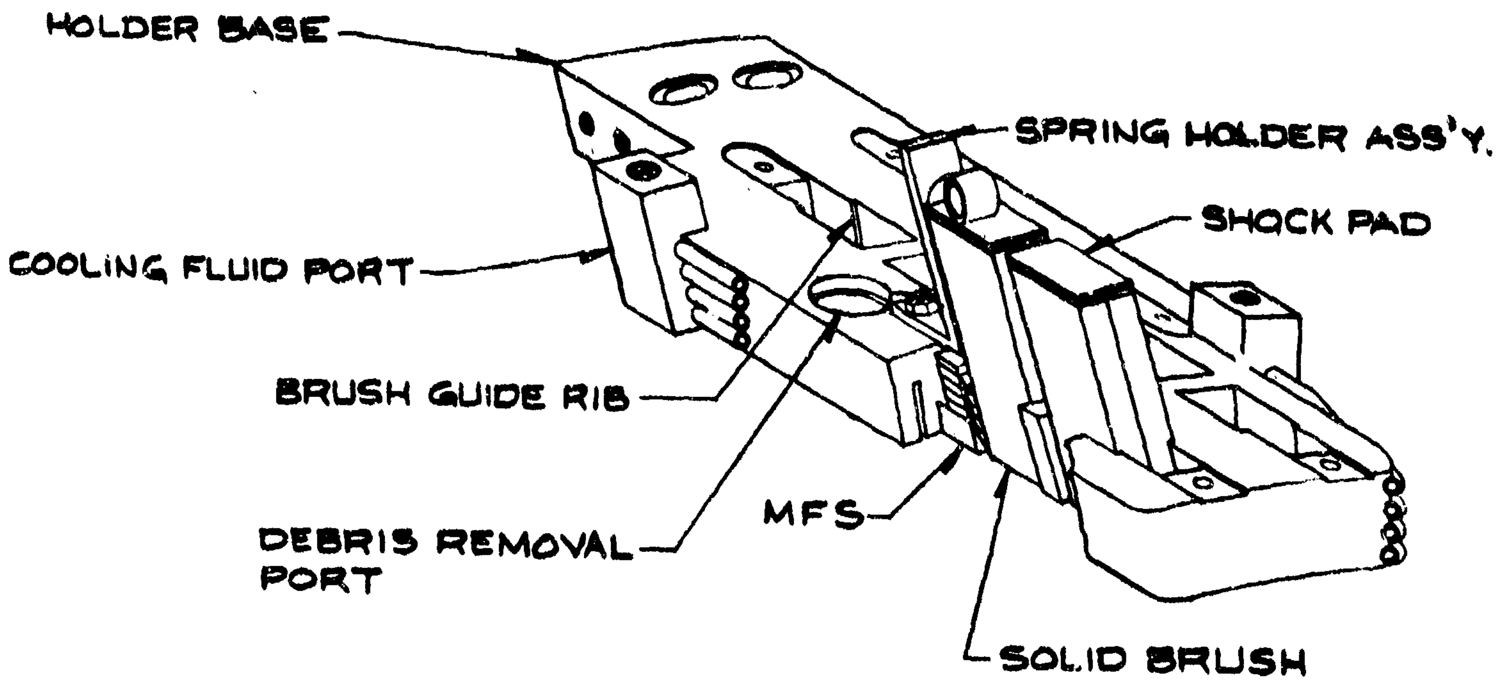

Figure 3.38. Gas Flow Around Brush Holder

thyristor-resistor braking circuit is shown in Figure 3.39. The system is placed in a braking mode in the following manner. When a motor reversal command is generated, the dynamic control intiates a braking sequence. The generator field current is adjusted such that the generator and motor armature current is zero. Switch S_B is opened and the generator field current is reduced until the generator voltage is zero. Although substantial motor voltage is present and switch S_A may be closed, no armature current exists since switch S_B is opened and all thyristors (T_1-T_4) are non-conducting.

The maximum value of reverse torque required to stop the propeller increases with ship speed. The maximum reverse torque that may be safely developed by the motor at maximum motor field flux is limited by the armature current rating and the configuration of the machines. If the maximum torque required to stop the propeller is greater than the maximum torque that may be developed by the motor then the braking interval is delayed. When the ship's speed has reduced to a value where a reverse motor torque is greater than the expected propeller torque, the braking sequence is continued by gating on thyristor T_1. At this point, the braking sequence may not be interrupted by commands from the control console.

When thyristor T_1 is gated on, a reverse current is initiated in the armature circuit causing the motor to develop a reverse torque and power dissipation in the circuit resistances. These actions cause the motor speed, voltage and current to decrease. When the motor current falls below a preselected value, the next thyristor (T_2) is gated on. The circuit resistance is thus reduced and the current rises to a maximum value again. The resulting torque and power dissipation further reduces the motor speed and voltages. As the current falls to a given value, the next thyristor is gated on. This process is continued until the last switch S_B is reclosed and the motor speed is nearly zero. At this time, the braking interval is completed and either the propeller reversing action may be continued or the motor reaccelerated with the same rotation.

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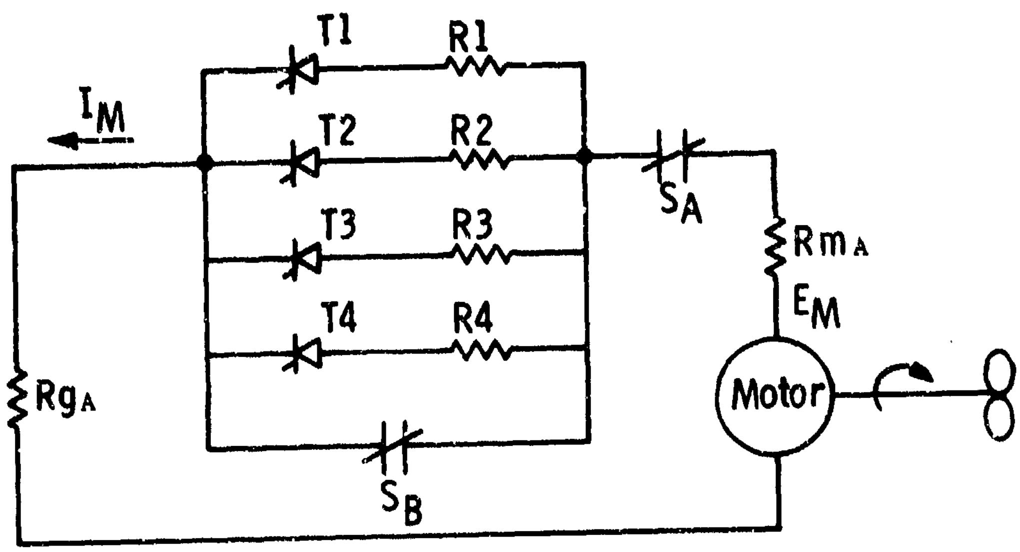

Figure 3.39. Simplified Thyristor-Resistor Braking Circuit

Figure 3.40 shows simplified motor voltage and current waveforms while braking with a constant motor field flux. The one per unit motor voltage is the voltage developed by the motor at rated field flux at the start of the braking interval. The E_{min} value of motor voltage is that value which produces an armature current of I_{max} when limited by the armature resistances only. I_{max} is the maximum value of armature current permitted during braking and is usually greater than the rated current of the machines. I_{min} is the lowest value of armature current permitted during braking to ensure adequate braking torque. The number of resistor branches needed to brake the propeller is dependent on the ratios of E_{min}/E_{max} and I_{min}/I_{max} and may be determined by the expression

$$N_R = \log (E_{min}/E_{max})/\log(I_{min}/I_{max})$$

In Figure 3.8-2, the number of resistor branches $N_R = \log 0.05/\log 0.6 =$ 5.86 or 6 branches. It would be desirable to reduce the number of braking resistor branches required so that the braking circuit and control may be simplified. This may be done by controlling the motor field flux during the first braking step as shown in Figure 3.41. In this example, the values of I_{max}, I_{min}, E_{min} and E_{max} at one per unit field flux are the same. However, the actual value of E_{max} is reduced to 0.3 per unit by reducing the field flux. Thus the number of resistor branches required is

$$N_R = (\log 0.05/0.03)/\log 0.6 = 3.5$$

or four branches. During the interval that the first resistor is placed in the circuit, the motor field current is controlled for a fixed value of motor current I_{max}. When one per unit field is reached, motor voltage and current will fall. At I_{min}, the next resistor branch is closed and the braking continues as with the constant field scheme. Another advantage of the variable field braking method is the thyristor voltage rating may be reduced due to the lower motor voltages.

Curve 695364-A

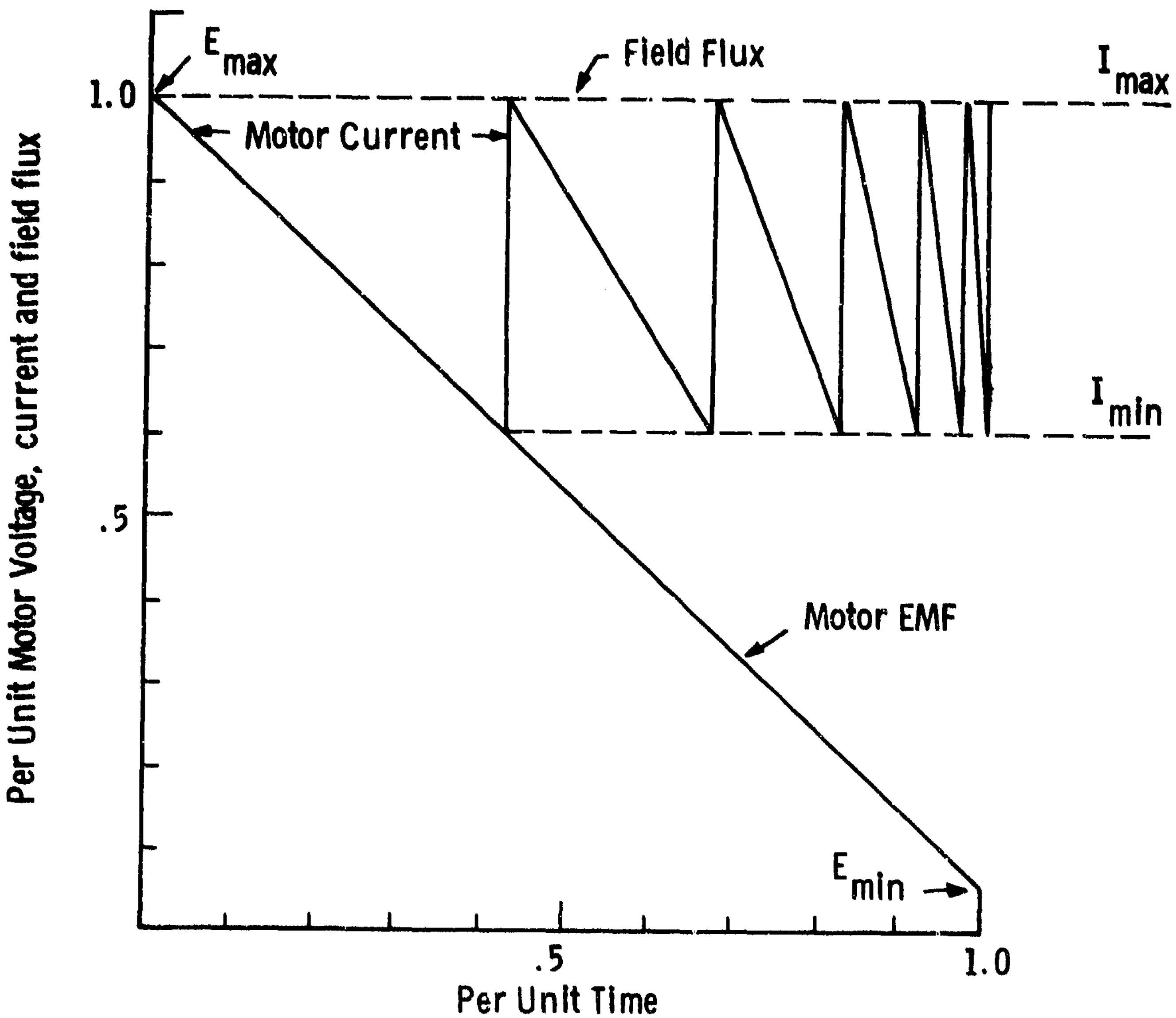

Figure 3.40. Simplified Motor Current and Voltage for a Constant Field Flux

Curve 695366-A

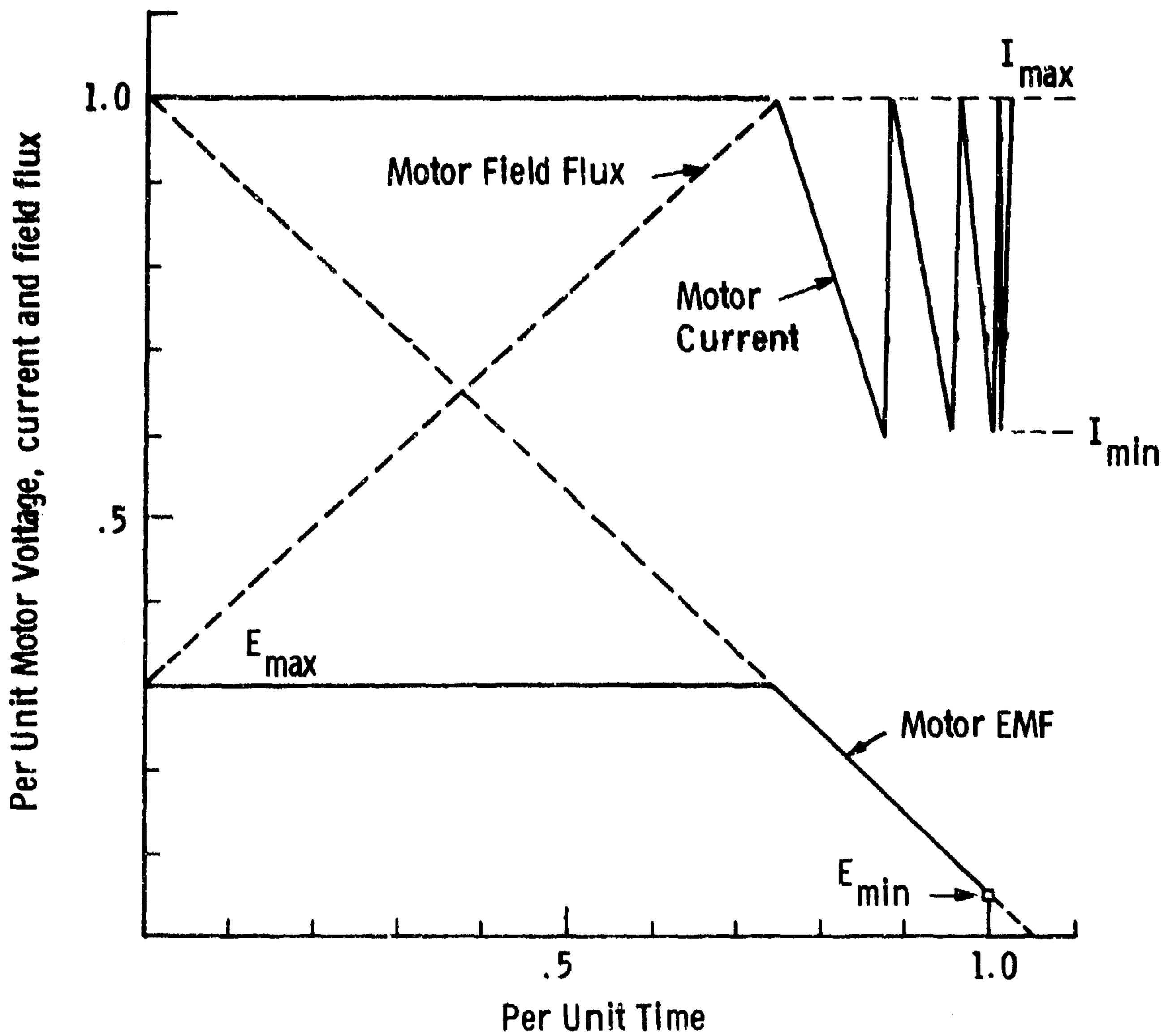

Figure 3.41. Simplified Motor Current and Voltage for a Variable Field Flux

Disadvantages of variable field braking are increased braking times due to reduced values of torque and peak power developed during the first braking interval. However the braking period is very short (about one second) and the braking torque at low motor speeds are equivalent to the constant field method. The resulting reduced performance may be acceptable and will be given further consideration in the final design of the dynamic brake circuit.

Another simplification may be made by eliminating the thyristors (T_1) in the first braking resistor branch. (See Figure 3.39.) This would require that switch S_A be opened at the start of the braking interval when the armature current is made zero. The brake resistor switching sequence would then be initiated by reclosing switch S_A. This would require that the switch be capable of closing the circuit to resistor R_1 at the maximum braking current and motor voltage selected. The adoption of motor field control during the braking interval would reduce the closing requirements of the switch. This will also be given further consideration.

The thyristor resistor braking unit presently considered is shown on Figure 3.42. Each thyristor position contains a pair of devices connected in anti-parallel. This enables the brake unit to control bi-directional currents. The additional thyristors could be eliminated by ensuring only a unidirectional current would exist in the armature circuit. This would require that the motor field flux be reversed when a motor reversal is undertaken. To accomplish a rapid reversal of the motor field, a four quadrant field exciter is required that has a large field forcing capability. This would add a greater cost and circuit complexity with no improvement in braking performance. Therefore a bi-directional braking unit is proposed. Further consideration will be given to the alternate braking method when the 3000 hp test bed data is evaluated.

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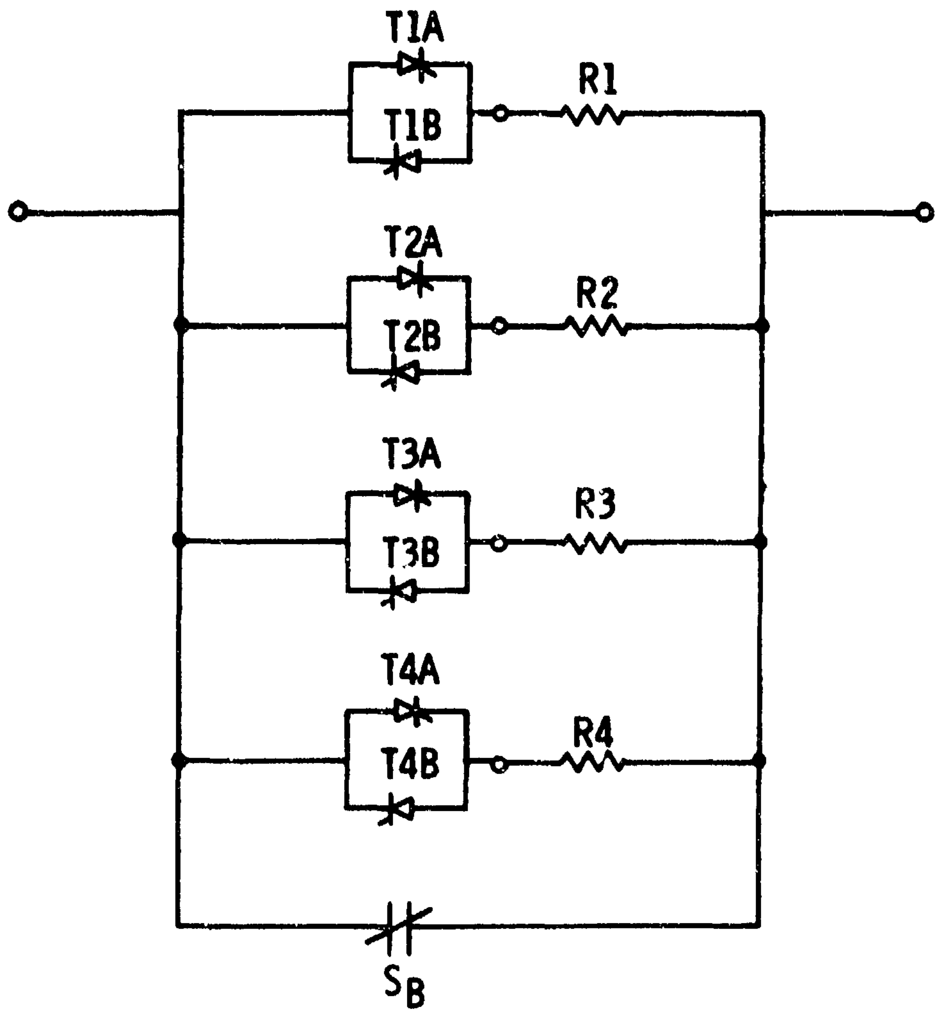


Figure 3.42. A Bidirectional Thyristor-Resistor Braking Unit

3.8.2 Physical Description

The bi-directional thyristor-resistor braking unit will be assembled in two adjoining cabinets. One cabinet will house the water cooled resistors and the other will contain the thyristors and associated thyristor gate firing circuits. From the results of a computer simulation of the 40,000 hp system a four branch thyristor-resistor braking unit is required as shown in Figure 3-42. The current in each branch is much greater than the current ratings of the largest available thyristor. Several water-cooled thyristors are placed in parallel to meet the current switch requirements of each branch. In Figure 3.43 is shown the thyristor circuit for the first braking resistor branch. Two thyristors (Switches T1A-1 and T1B-1) are mounted on a water cooled assembly. Each assembly will also contain an RC snubber circuit and possibly a current sharing resistor (RS1) if required. All "A" directional thyristors are switched on by transformer coupling to the "A" gate drive circuit. The "B" directional thyristors are turned on by the "B" gate drive circuit. The output of the thyristor switch circuit is connected in series with an appropriate braking resistor in the adjoining cabinet. The remaining three branches of the braking unit employ a similar thyristor switch circuit with fewer thyristors. The second branch contains five thyristor assemblies and the third and fourth branch contain four assemblies. The entire thyristor assembly will be mounted on panels and enclosed in a cabinet. The dimensions of the cabinet will be approximately 30 inches by 24 inches by 72 inches high and weigh approximately 700 pounds.

3.8.3 Environmental Considerations

The use of solid-state thyristors as switching components should have no difficulty in meeting the salty humidity and ambient temperature requirements in this application. The control circuits will be protected against the salty environment.

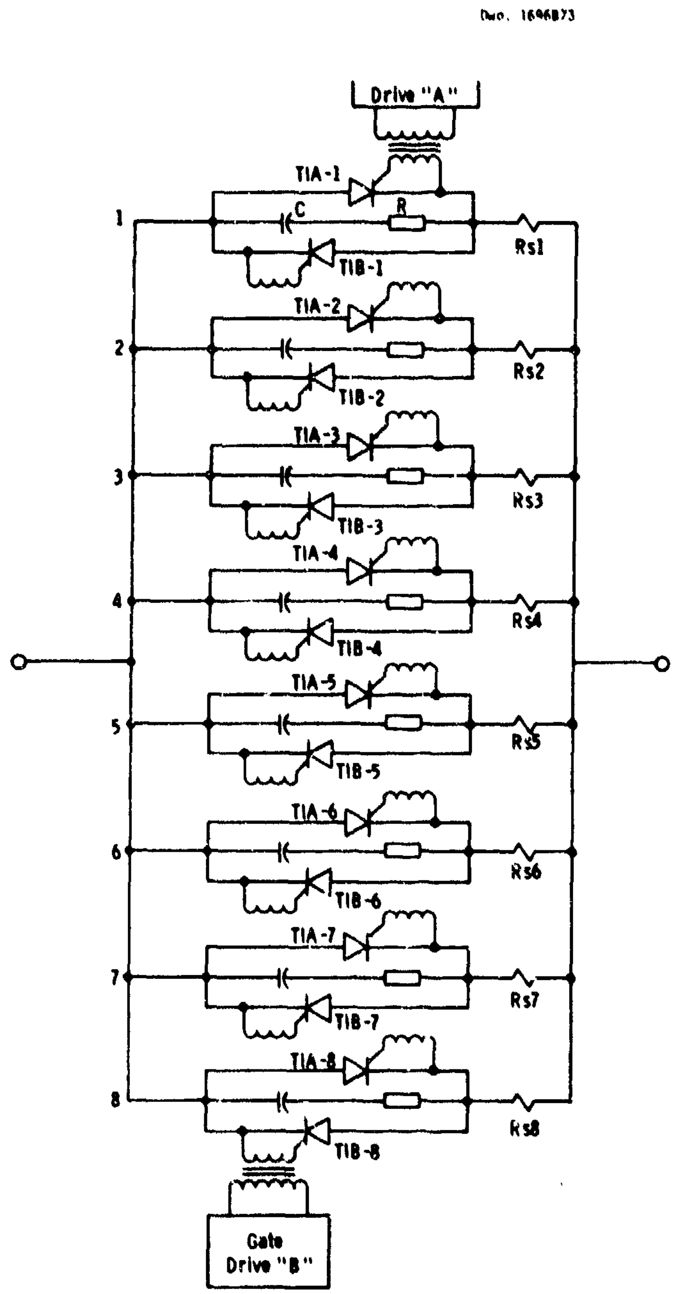


Figure 3.43. Thyristor Switch Circuit for 1st Branch of Dynamic Brake Unit

3.8.4 Reliability

In this application, the thyristors are required to conduct current for only one second. A sufficient number of devices are paralleled to carry the maximum current for at least two seconds. In addition, the devices are water cooled to ensure an initial thyristor junction temperature of less than 40°C. Particular consideration will be given in the design and test of this circuit to obtain equal current sharing between devices of the same branch.

3.8.5 Maintainability

The braking thyristors will be mounted within the cabinet to permit ease of identification and removal without the need of special tools. Gate control circuits will be assembled on plug-in cords. Test points will be available to assist in circuit troubleshooting.

3.8.6 Safety

The thyristor braking unit will be designed to protect personnel from electrical, mechanical or thermal safety hazards.

3.9 Instrumentation

It is anticipated to specify the instrumentation required for the 40 RHP propulsion system during final design. This specification would list the type, number, range, location and function of all the instrumentation sensors and indicators used in the system. A partial list per machine of these sensed parameters would include, but not limited to, the following:

- Bearing Oil Flow
- Bearing Temperature
- Shaft Speed
- Shaft Torque
- Armature Voltage
- Armature Current
- Field Voltage
- Field Current

- Field Coil Temperature
- Cooling Water Inlet Manifold Pressure
- Cooling Water Outlet Manifold Pressure
- Rotor Bar Hot Spot Temperatures
- Collector Bar Temperature
- Stator Bar Hot Spot Temperature
- Brush Lifter
- Position Indicators

Depending on final machine designs and configuration the number, capacity and range of these sensors will vary from those specified for the 3000 hp machines (See Section 4.3.9). As a minimum, all pertinent data presently recorded aboard ships of this type will also be provided in the 40 KHP electrical drive system. These sensors will be connected into a data logger for a permanent record of these variations, and these utilized for control purposes will interconnect with the master control unit.

SECTION 4

3000 HP SYSTEM TEST BED INTRODUCTION

One of the major long term objectives of the SEGMAG program is to develop high powered electrical propulsion systems for ship drives.

Early in this program it was recognized that it would be both economical and prudent to confirm the validity of the present design approach prior to committing to the construction of full scale technical equipment.

With this intent in mind, it was decided to construct and operate a reduced power land based test system that could serve as a test vehicle to establish confidence in the program direction and to confirm the present design levels. This test vehicle could also be used to investigate alternatives which could not be resolved at the preliminary design stage.

The power level chosen for the test system machines is 3000 HP. This power level was deemed high enough to provide a significant test of the SEGMAG II motor and generator concept at an acceptable overall system cost.

Because overall system performance is as dependent upon the control system design approach as it is upon machinery performance, two shafts of propulsion machinery are needed to substantiate the satisfactory operation of the control system philosophy as applied to the SEGMAG machines. Two shafts of machinery are considered the minimum necessary to investigate operation in the three principle powered modes of operation and to investigate automatic transitions between modes.

Several methods of removing power from the system when operating in the regenerative region are investigated in the 40,000 SHP conceptual system study. Of these, the electrical dynamic braking resistor method was selected for use in the 3000 HP test stand as it was one of the most promising of the full scale methods studied and was the most economical to implement on the 3000 HP test stand.

Various auxiliary supporting subsystems will be required to service the system under test, however, development of these subsystems is not the main objective of the test stand.

The following sections will describe the test system and will present the testing philosophy followed in the development of this 3000 HP SEGMAG test stand.

4.1 System Summary

The 3000 HP system test bed consists of two SEGMAG II generators, two SEGMAG II motors and a solid state control system. In addition, various subsystems required to operate the system as an isolated independent twin shaft propulsion drive train, have been included. The prime movers and load absorbing devices necessary to drive the system and to load the system for testing are not supplied as part of the system. The system will require nominal electrical power and a cooling water heat sink as services to the auxiliary support subsystems.

In addition, the system will be provided with a data acquisition and recording logger to record normal shipboard data.

Figure 4.1 is a block diagram of the test system showing the interrelationships of the following subsystems.

a. Two (2) SEGMAG II generators.

b. Two (2) SEGMAG II motors.

c. Master system control.

d. Motor and generator field exciters.

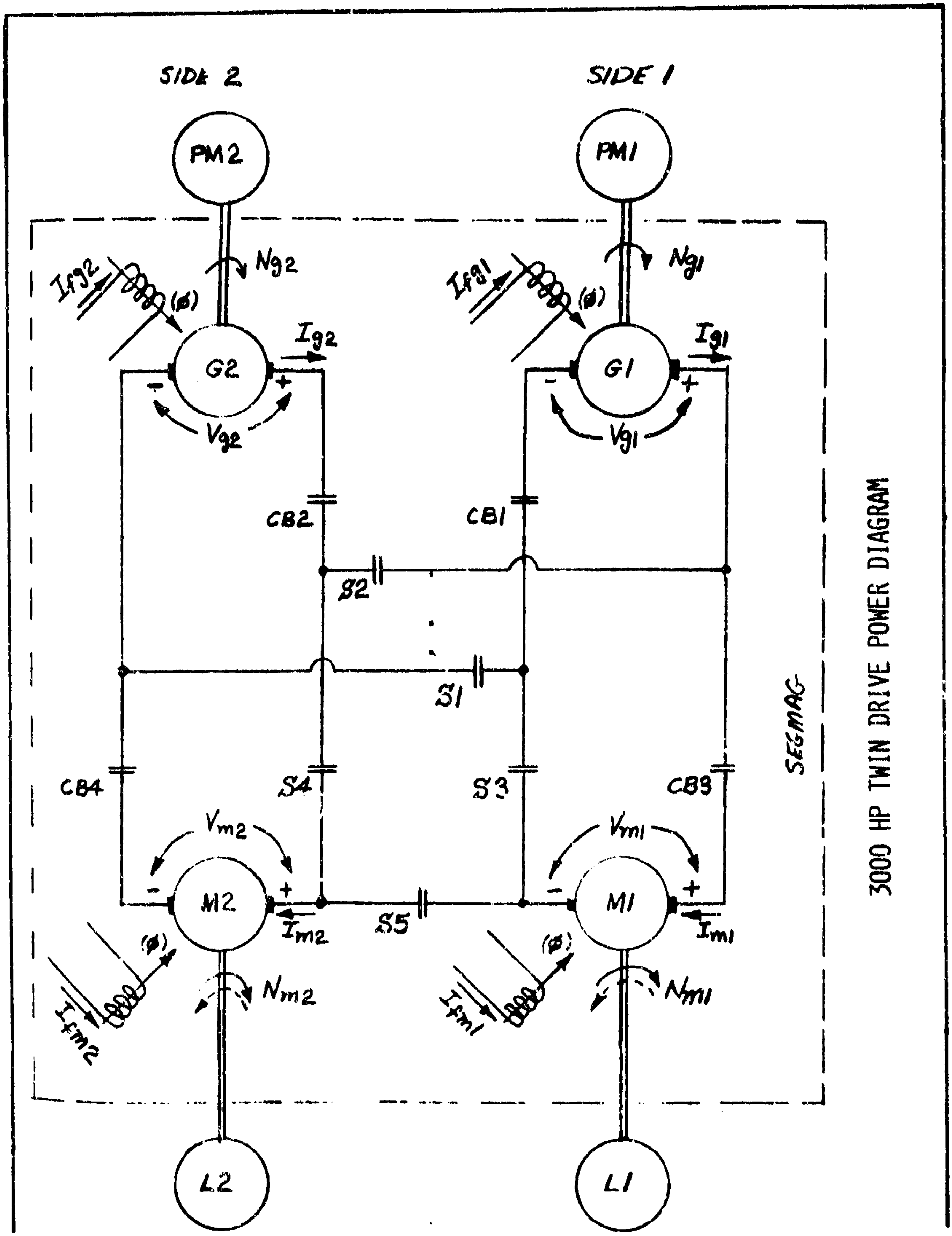


Figure 4.1. 3000 HP Test System Block Diagram

e. Interconnecting transmission lines.

f. Circuit breakers and circuit configuration contactors.

g. Thyristor controlled dynamic braking resistor.

h. Auxiliary support systems.

    1. Lubricating oil system
    2. Deionized cooling water system
    3. Brush atmosphere control system

i. Data acquisition and recording system.

Not shown on the diagram are the data acquisition sensors which are required by the control system to operate and protect the test system.

The following is a brief description of the function and content of each subsystem and is presented here to acquaint the reader with the overall system concept. More detailed descriptions of each subsystem are presented in Section 4.2.1.

Each SEGMAG generator and motor is nominally rated at 3000 HP. The generator rated speed is 3600 RPM while the motor rated speed is 1200 RPM. Both are water cooled, solid brush machines designed under the SEGMAG II concept.

The two generators and two motors will be operated as separately excited shunt dc machines in a variable armature voltage control mode. The motor output torque will be controlled by holding the motor fields constant and regulating the generator fields to control the armature loop voltage and current. The armature system will be operated ungrounded at a maximum loop voltage of 500 VDC.

The master control system will be a digital solid state control which provides automatic control and protection of the complete propulsion system. The SEGMAG control system consists of two major parts, a supervisory control and a dynamic control.

The supervisory control performs the following functions:

1. Controls normal system start-ups.
2. Controls normal system shutdown.
3. Performs a restart after minor malfunctions.
4. Performs rapid shutdown of the prime movers under certain emergency conditions.
5. Performs rapid deenergization of the SEGMAG fields and opens the armature circuit under fault conditions.
6. Determines when a transition from one configuration to another is required and performs the transition by opening or closing circuit breakers and contactors and reconfigures the dynamic control inputs accordingly.
7. Provides the proper inputs to the dynamic control system.
8. Provides a speed reference signal to the test stand prime move.

The dynamic control regulates the torque produced by the system in response to a "torque required" command which is under manual control of the system operator. When the "torque required" command is changed to a position which will require removing energy from the propulsion system, the dynamic control also provides signals to the configuration switchgear and the dynamic braking resistor/thyristor assembly to allow the system to operate in the regenerative region without overspeeding the prime mover. The need to remove energy from a propulsion system arises when the "torque required" command is placed in an astern position while the ship is still moving ahead. The forward movement of the ship through the water continues to drive the propeller in an ahead direction, thus requiring that energy be removed from the system in order to stop the propeller.

The transmission lines will be either enclosed bus or cable assemblies as necessary to suit the test installation. Since the transmission lines serve only to carry current from one point to another, they have a predictable and minimal effect on the test stand objectives. Thus, these items will not be discussed in great detail in this report.

The 3000 HP test system motor and generator field exciters will be phase controlled SCR thyristor converters which will convert the 460 VAC 3 phase service power into the DC needed for the SEGMAG machine fields. Both the motor and generator field exciters will be dual converters which are capable of operation in all four quadrants. Both the motor and generator field exciters will provide 200% reverse field forcing capability to collapse the machine fields for circuit protection.

The configuration control switchgear consists of 5 contactors and 4 circuit breakers. These will function as switches at the command of the system control to configure the armature circuits to operate in different system operating modes. These devices will be used to simulate the function of the zero load break switches in the 40,000 SHP system. The circuit breakers will have fault current interrupting capacity and the contactor will have load current interrupting ratings.

It will be noted that the test system switches will have circuit interrupting capabilities whereas those in the full scale tactical equipment will not. It was deemed prudent, however, to provide this circuit interrupting capability until the concept of controlling the system to zero current during switching operations has been demonstrated by test. Similarly, circuit breakers have been provided for circuit protection until the rapid field collapse protection concept has been proven by test.

The decision to place total dependence upon field collapsing as the primary mode of system protection, will be reviewed during the progress of the test program.

The 3000 HP test system auxiliary support systems consist of the lube oil supply system, the deionized cooling water supply system and the CO_2 cover gas atmospheric control system.

The lube oil supply system will be a conventional recirculating pressurized lube oil system with two positive displacement AC motor driven pumps. The major components of this system consists of a reservoir with a 3 minute retention time, a water-to-oil heat exchanger, a duplex strainer and a pressure regulating valve. The system will supply sufficient conditioned 2190 TEP oil for both SEGMAG II motors and both generators. This system will provide alarm and permissive operation signals for oil pressure and temperature to the master system control.

The 3000 HP test system deionized cooling water supply will consist of a recirculating water system which uses an AC motor driven centrifugal pump to circulate water from the reservoir through the filter and heat exchanger to the motors and generators. The water quality will be maintained in the range of 1 to 2 megohm-cm by circulating approximately 5% of the water flow through a deionizing resin bed back to the reservoir. The water-to-water heat exchanger will be sized to provide sufficient heat rejection into the cooling water heat sink available at the test site. One system serves both motors and generators.

The 3000 HP test system brush cover gas atmospheric control consists of a pressurized CO_2 storage cylinder, a pressure regulator and an H_2O bubbler for humidifying the gas flow. The system will supply cover gas to both SEGMAG II generators and both SEGMAG II motors.

The data acquisition and recording subsystem, which is part of the 3000 HP test system, will consist of a programmable data logger with a magnetic tape data storage adjunct. This data logger will scan those system operating measurements normally observed by the engine room personnel and will generate an alarm should any be outside of prescribed limits. All data will be recorded on magnetic tape. In addition, the data logger will record on printed tape those items normally recorded by the operators. A detailed discussion of this equipment is presented in Section 4.3.9.

4.1.1 **Test Objectives**

As stated in the introduction, the purpose of the 3000 HP test demonstration system is to verify the design features of the SEGMAG II machinery concept and control philosophy in actual system operation prior to the final development of tactical shipboard systems. This affords the opportunity to incorporate any desirable modifications, found during operation of the test system into the tactical design and thereby reduces the risks attendant with applying the SEGMAG II design concept to operational equipment.

In order to obtain maximum benefit from a test program, we should first establish what we intend to accomplish by executing the test plans.

The test demonstration system motors and generators have been designed to the same basic design limits that have been used in the conceptual design study of the 20,000 and 40,000 SHP propulsion systems. One exception should be noted; the brush current is lower than that planned for the full size plant. Therefore in regard to the rotating machinery, the objective of the test program is to provide information to substantiate the propriety of these design limits and to afford the opportunity to investigate alternatives which cannot be satisfactorily resolved at the design stage. In recognition that many of the machine characteristics will be investigated during back-to-back contractor tests, the system test effort will concentrate on verifying the contractor characterization of the machines under system operating conditions and to investigate machine characteristics under conditions which are not available during contractor tests. These later conditions involve parallel operation of generators, steady state system response and stability in addition to large transient performance.

Similarly the control system for the 3000 HP demonstration system is based on the same control philosophy which was used in the 40,000 SHP conceptual design studies. Therefore, the objective of the 3000 HP test system operation with regard to the control system, will be to verify the attributes of the control philosophy as applied to the SEGMAG machines and thus provide assurance of satisfactory operation of future derivative control systems. Again, because of the interdependence of the SEGMAG II motors and generators with the control system, the 3000 HP demonstration test plan must include both steady state and dynamic tests in order to allow investigation of the control system and machinery interaction under all conditions of operation.

Having established these test objectives we can now proceed to develop a test plan to best achieve these needs.

4.1.2 Test Program

All aspects of the operation of the control system and the test machines will be subject to investigation during test. However, several specific areas of operation which can best be examined by system operation have been identified. These operating areas will be given special consideration and are as follows:

a. Investigation of system operation and stability in the three principle operating modes at loads from no-load to full rated load. This includes operation of two generators in parallel, operation of one generator with one motor and operation of two motors in series.

b. Investigation of the ability of the system to automatically maintain the system conditions within the bounds required for zero current switching required for transitioning as is projected for use on the 40,000 SHP system.

c. Investigation of the motor and generator current collectors during the dynamic braking transients involving large transient currents and rapid speed changes.

d. Investigation of the generator and motor performance during the crash astern maneuver, during which the generator must supply high current at low voltage while the motor develops high torque at zero speed.

e. Comparison of specific operating performance differences arising from any differences in design of the leading test set to that of the second test set pair.

As pointed out in Section 4.1.1, except for brush current densities, the 3000 HP SEGMAG II machines have been designed to the same design parameter limits that have been used in the conceptual design study of the 20,000 SHP and 40,000 SHP tactical systems. Therefore an appropriate test program with the objective of establishing the suitability of these limits would be to operate the system under the same conditions as projected for the full scale system. Since the full scale system performance is expressed in per unit, then operation of the test system at the same per unit loads should result in exercising the test system at the same percentage values of the absolute parameters. Similarly, during dynamic testing, if the test machinery is operated at the same per unit load values and in the same absolute time profile as the full scale system, then the same specific Joule heating effects will occur in the material volumes.

It is recognized that this foregoing reasoning might be questioned on the basis that the ratio of surface area per unit volume varies inversely as the first power of the linear dimensions, thus influencing temperature results. However, this fact should not seriously invalidate the test results since as a first approximation, during transients, all heat can be assumed stored thus negating the question of the surface to volume ratio. For steady state results, suitable allowances can be made during the interpretation of the data to compensate for the size effects.

Another question that also arises at this time is whether we can achieve the same absolute time profile during transients as is forecast for the full size system. The answer to this question lies in the examination of the "H" constant of each system. The "H" inertial constant of a rotating system is defined as the ratio of the kinetic energy stored in the system at rated speed to the rated energy of the drive, thus:

$$H = \frac{\text{stored kinetic energy (kw-sec)}}{\text{rated power (kw)}}$$

The significance of this factor is that two different sized systems but with identical "H" constants will accelerate at the same per unit rate when subject to the same per unit torque. Thus, if we provide the test system with the same "H" constant as the projected system and subject it to the same per unit torques, we can expect the test system to respond to the same absolute time profile as is calculated for the full scale system.

As pointed out in Section 4.1, the prime movers and load absorbing devices are not supplied as part of the test system. Therefore, prior to the identification of these devices we cannot determine how closely the test system can be made to match the conceptual study system. In Section 4.2.1.4 the desired prime mover and load characteristics are discussed in detail.

It should also be recognized at this time that it may not be possible to obtain the exact desired prime mover and/or load devices needed to match the full size system. The deviations that these devices may have from the desired characteristics and the effect that these deviations will have upon the test results must be left for investigation at a later date.

4.2 System Description

4.2.1 Physical Description

4.2.1.1 System Layout

The anticipated layout of all the equipment planned to be installed at the test facility is shown in Figure 4.2. The description of each of these components (numbered to correspond with the layout) is as follows:

ITEM 1 - SEGMAG GENERATOR

The 3000 hp, 3600 rpm, 4 pole, water-cooled SEGMAG generator is rated at 505 volts, dc and 4660 amperes. Full load field excitation is ±100 volts dc, 175 amps. The generator preliminary outline is shown on Dwg. No. 1435-E-29 indicating the principal interfaces.

ITEM 2 - SEGMAG SERIES CONNECTED GENERATOR

The 3000 hp, 3600 rpm, 8 pole water-cooled, SEGMAG, series connected generator is rated at 505 volts dc, 4660 amperes. Full load excitation is ±100 volts dc, 175 amps. The generator preliminary outline is shown on Dwg. No. 639F505 indicating the principal interfaces.

ITEM 3 - SEGMAG MOTOR

The 3000 hp, 1200 rpm, 6 pole, water-cooled SEGMAG motor is rated at 500 volts dc, 4660 amperes. Full load excitation is ±115 volts dc, 175 amps. The preliminary motor outline is shown on Dwg. No. 639F503 indicating the principal interfaces.

ITEM 4 - SEGMAG MOTOR

The 3000 hp, 1200 rpm, 6 pole, water-cooled SEGMAG motor is rated at 500 volts dc, 4660 amperes. Full load excitation is ±115 volts, dc, 175 amperes. Some of the machine brushes will be capable of being lifted, to demonstrate this feature. The motor outline will be similar to Item 3, however, the location of the interfaces has not as yet been determined, although the number, type, and size of the physical interfaces will be similar to those of Item 3.

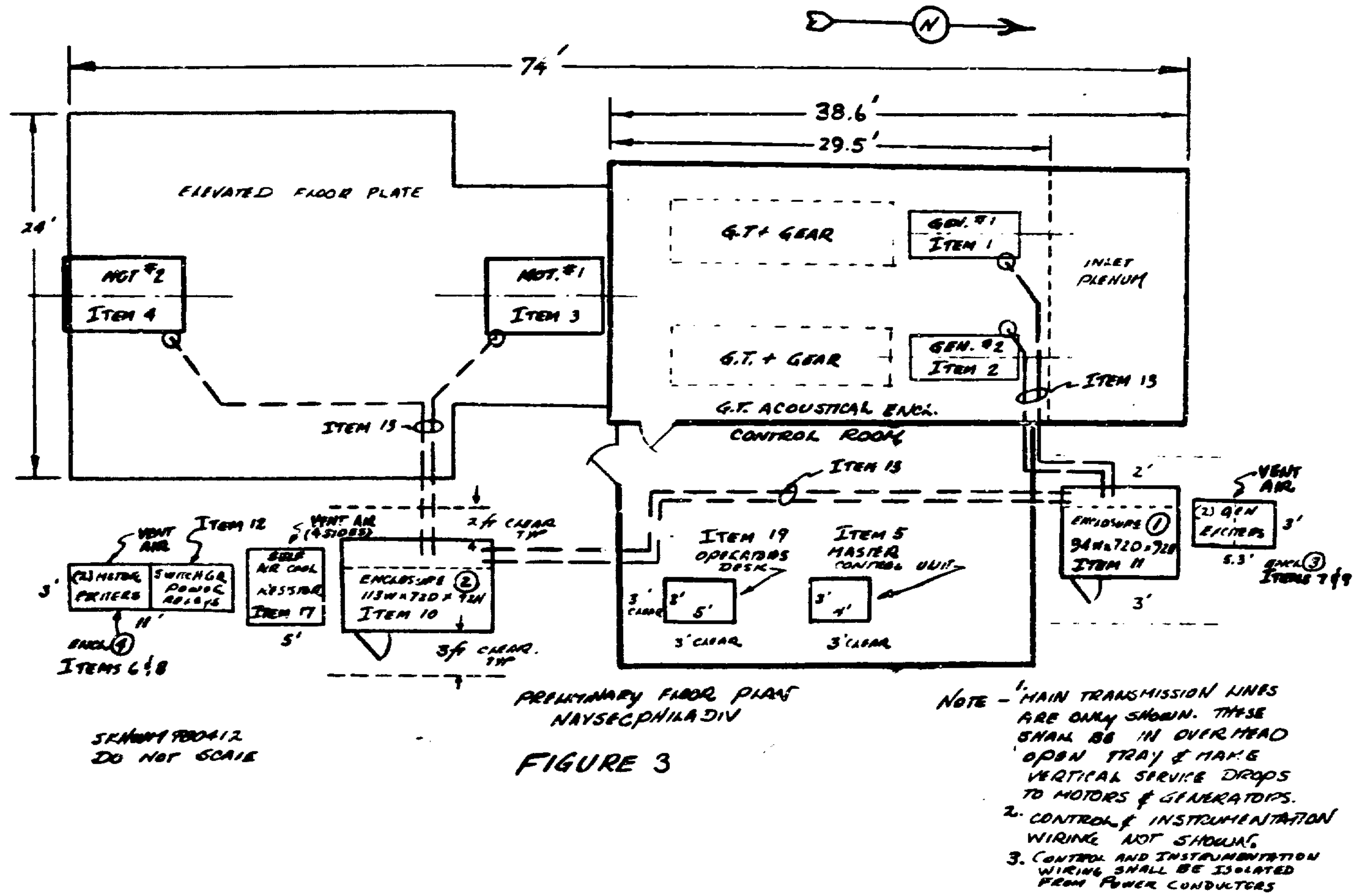


Figure 4.2. Preliminary Floor Plan of Test Facility

ITEM 5 - SEGMAG MASTER CONTROL UNIT

The SEGMAG master control unit consists of a solid state digital control system which will be located within a floor mounted instrumentation cabinet. The estimated physical size of the instrument cabinet and the proposed location and service clearances is shown on Figure 4.2. The power required to operate the control unit is approximately 20 kw at 460 v, 3 Phase, AC.

ITEM 6. - NO. 1 MOTOR EXCITER

The motor exciter is a self-ventilated phase controlled SCR converter unit which operates from * 460 vac 3 Ø power. The exciter output will be controlled by the SEGMAG master control unit. The power requirement is approximately 100 kw. The floor space requirement and proposed location of the exciter is shown on Figure 4.2. The exciter will be provided with a primary disconnect and Class 1 protection.

ITEM 7 - NO. 1 GENERATOR EXCITER

The generator exciter is a self-ventilated phase controlled SCR converter unit which operates from 480 vac 3 Ø power. The exciter output will be controlled by the SEGMAG master control unit. The power requirement is approximately 100 kw. The floor space requirement and proposed location of the exciter is shown on Figure 4.2. The exciter will be provided with a primary disconnect and Class 1 protection.

ITEM 8 - NO. 2 MOTOR EXCITER

The generator exciter is a self-ventilated phase controlled SCR converter which operates from 480 vac 3 Ø power. The exciter output will be controlled by the SEGMAG master control unit. The power requirement is approximately 100 kw. The floor space requirements and proposed location of the exciter is shown on Figure 4.2. The exciter will be provided with a primary disconnect and Class 1 protection.

ITEM 9 - NO. 2 GENERATOR EXCITER

The generator exciter is a self-ventilated phase controlled SCR converter unit which operates from 480 vac 3 ∅ power. The exciter output will be controlled by the SEGMAC master control unit. The power requirement is approximately 100 kw. The floor space requirements and porposed location of the exciter is shown on Figure 4.2. The exciter will be provided with a primary disconnect and Class 1 protection.

ITEM 10 - MOTOR CIRCUIT BREAKERS AND CONTACTORS

The switch gear consists of a cabinet which houses the circuit breakers and contactors to the two motors. The armature power schematic diagram showing the arrangement of the circuit breakers and contactors (switches) is shown on Figure 4.3. The power requirement is approximately 40 kw, at 460 v, 3 phase, AC. The physical size and proposed location of the switch gear enclosures are shown on Figure 4.3.

ITEM 11 - GENERATOR CIRCUIT BREAKERS AND CONTACTORS

The switch gear consists of a cabinet which houses the circuit breakers and contactors to the two generators. The armature power schematic diagram showing the arrangement of the circuit breakers and contactors (switches) is shown on Figure 4.3. The physical size and proposed location of the switch gear enclosures are shown on Figure 4.3.

ITEM 12 - SWITCHGEAR POWER RELAY CUBICLE

The switch gear power relay cubicle provides all of the interlocking and sequencing circuitry required to accept control signals and output actuating signals for all the breakers, contactors, and exciters. The proposed location for it is shown on Figure 4.3.

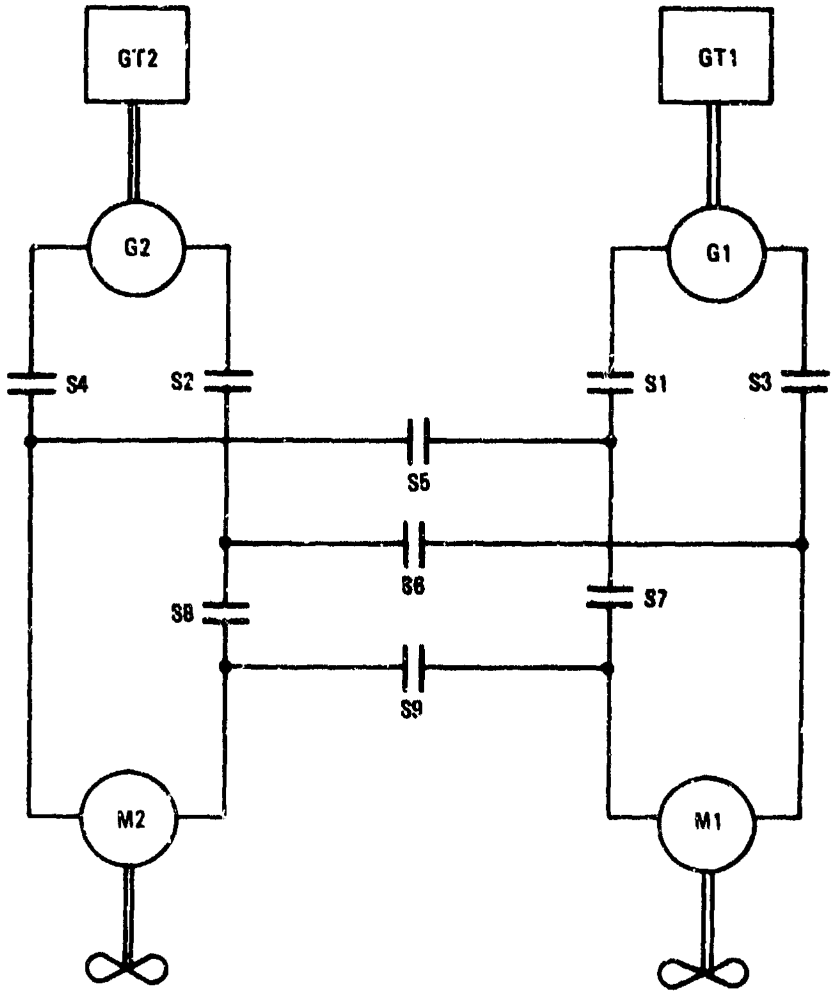


Figure 4.3. Power System Schematic

ITEM 13 - TRANSMISSION LINES

The transmission lines are tentatively planned to be power cables in open or ladder type cable trays. The cables shall have opposite polarities interweaved in order to reduce the external magnetic fields. The proposed cable consists of 6 single conductor power cables of 750 MCM, type KHH and the proposed cable runs are indicated on Figure 4.3.

ITEM 14 - LUBE OIL SYSTEM

The lube oil system consists of a conventional pressurized oil supply system with 2 ac drip proof motor drive pumps. One pump will supply the total system lubrication requirements while the second pump will be on standby. The motors will require a non-interruptable power supply to insure against loss of oil pressure due to power outages. The power requirement is approximately 5 kw at 460 v, 3 phase. The physical data for the system is shown on Table 4.1.

ITEM 15 - DEIONIZED CIRCULATING WATER SYSTEM

The deionized circulating water system consists of a storage tank, an ac drip proof motor driven circulating water pump, a heat exchanger and miscellaneous water conditioning equipment. The power requirements are approximately 15 kw at 460 v, 3 phase, AC. The physical requirements are given on Table 4.2.

TABLE 4.1

3000 HP SEGMAG TEST STAND
LUBE OIL SYSTEM FACILITY REQUIREMENTS

Number of Systems Supplied Per Stand	1
Floor Space Required	5' x 8'
Cooling Water Required	35 gpm
Cooling Water Temperature	85°F max.
Pressure Drop of Cooling Water Thru Heat Exchanger	10 psi
Heat Rejected to Cooling Water	167×10^3 Btu/Hr
Electrical Power Required: 460 vac, 3 Ø, 60 Hz, 5 amps, 0.8 p.f., non-interruptable	
Level of Top of Oil in Sump Above Floor	3 ft.

Lube oil system shall be located so as to provide a slope of 1 in/foot in drain lines from motors and generators back to top of oil in sump.

The facility shall supply stop valves for pipes supplying cooling water to the heat exchanger.

TABLE 4-19

3000 HP SEGMAG TEST STAND
DEIONIZED CIRCULATING WATER SYSTEM
FACILITY REQUIREMENTS

Number of Systems Supplied Per Stand	1
Floor Space Required	7' x 11'
Cooling Water Required	600 gpm
Cooling Water Temperature	80°F
Pressure Drop of Cooling Water Thru Heat Exchanger	10 psi
Heat Rejected to Cooling Water	1.5×10^6 Btu/hr

Electrical Power Required:

460 vac, 3 Ø, 60 Hz, 20 amps, 0.8 p.f.
120 V, 1 Ø, 60 Hz, 16 amps

ITEM 16 - COVER GAS SYSTEM

The cover gas system is not shown nor detailed. Tentatively, it will consist of an assembly of pressurized gas cylinders with pressure regulating and flow controls in addition to a water filled gas bubbler. It will not occupy significant space and thus is not shown.

ITEM 17 - DYNAMIC BRAKING RESISTOR AND THYRISTOR ASSEMBLY

The dynamic braking resistor and thyristor assembly is tentatively planned to be a self-convection, air ventilated resistor assembly installed in a cabinet with the thyristors mounted on air-cooled heat sinks. Tentative floor space requirements are shown in Figure 4.2.

ITEM 18 - DATA LOGGER

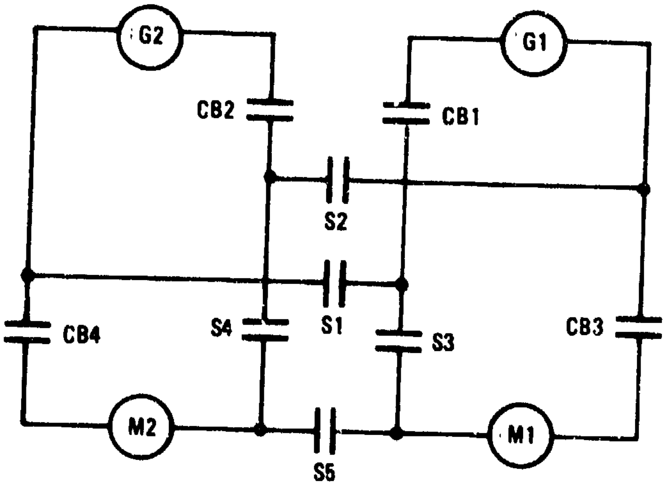
The data logger will be located on either the operator control desk or on the master control unit in the control room. This unit should be located adjacent to the system operator. The power and space requirements will be minimal and have been included in with the master control unit on Figure 4.2.

ITEM 19 - OPERATOR'S CONSOLE

The operator's console will be a steel fabricated desk with hinged sloping front and back hinged pinnacle. Standard operating devices will be mounted on the top and indicating meters will be mounted on the pinnacle face. Steel surfaces will be painted.

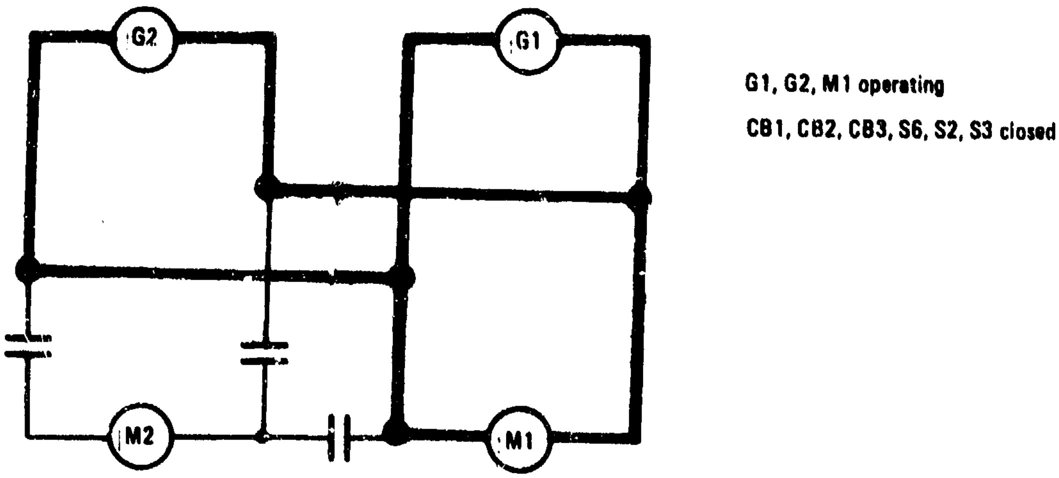
4.2.1.2 System Diagrams

Figure 4.4 shows a simplified diagram of the armature loop circuits provided for the 3000 HP test system. By closing selected switches, the system can be configured into any of a variety of ways. The three principal powered operating modes are full power, half and quarter

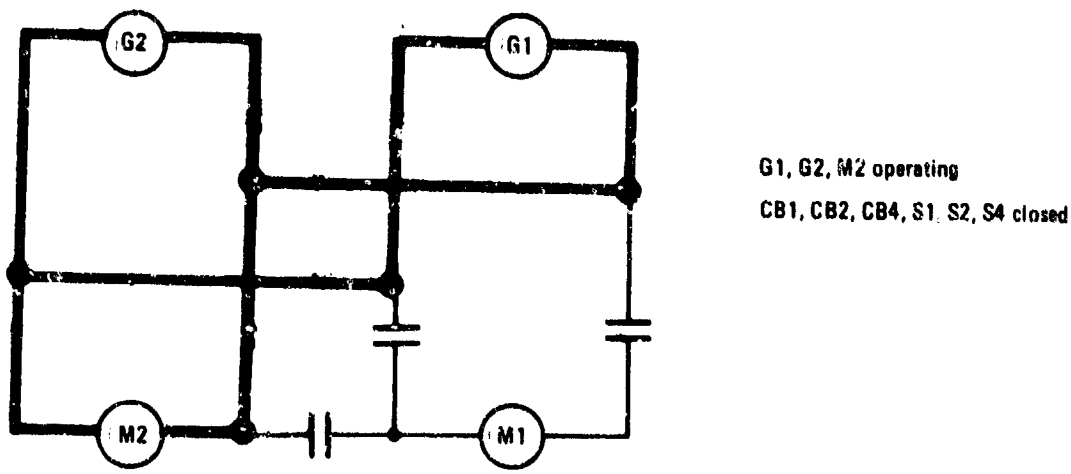


ALL switches (S1 thru S5) and circuit breakers (CB1 thru CB4) open

Figure 4.4. Zero Power Mode



a) F1



b) F2

Figure 4.5. Full Power Mode

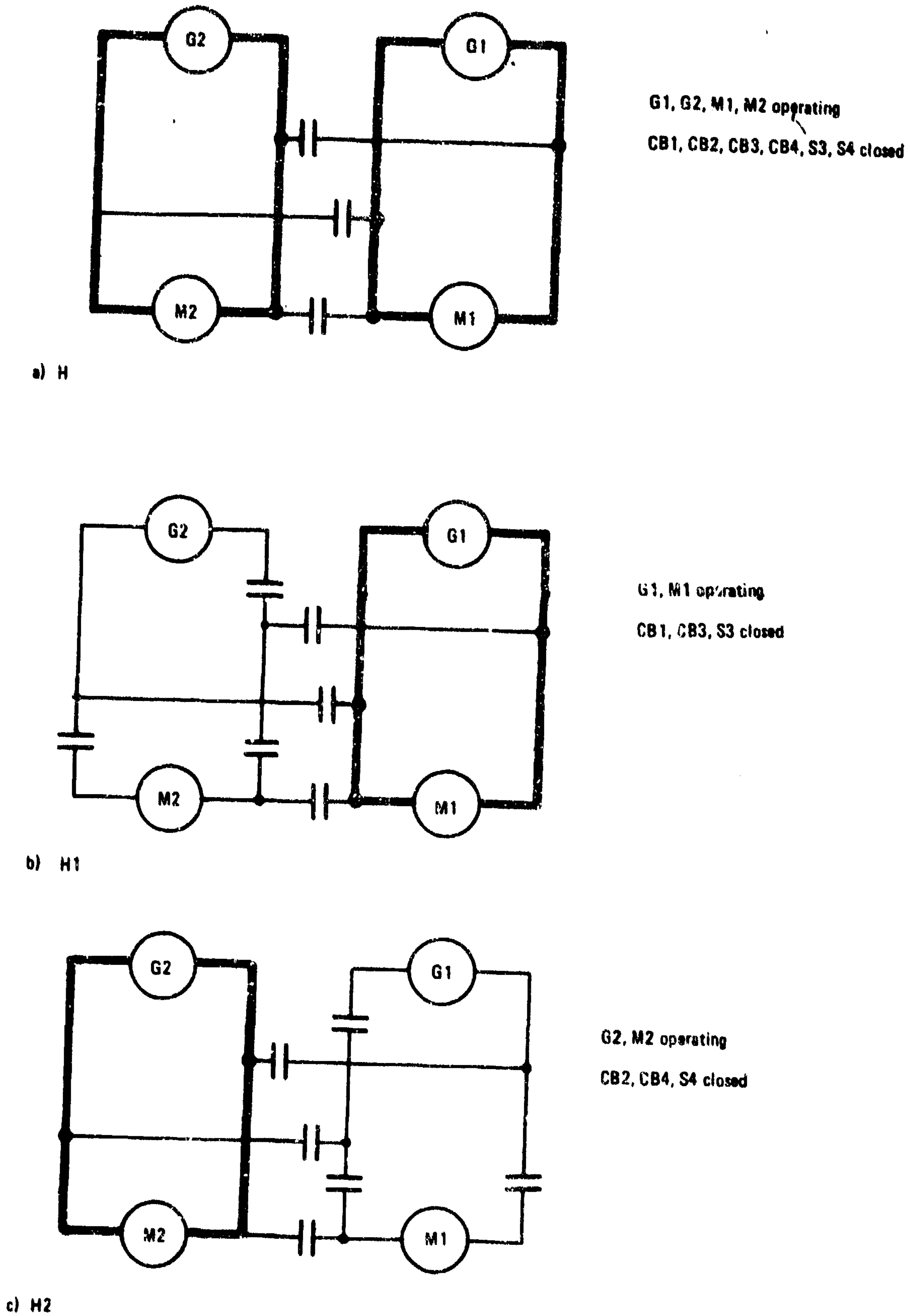
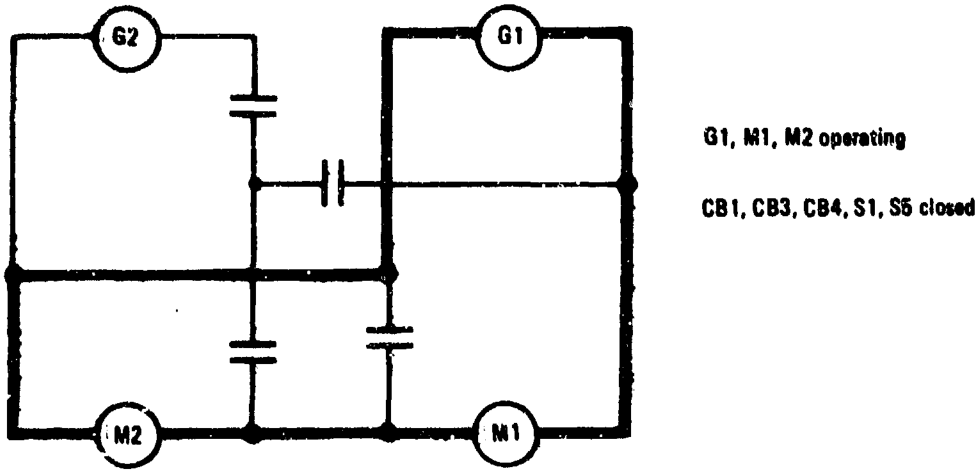
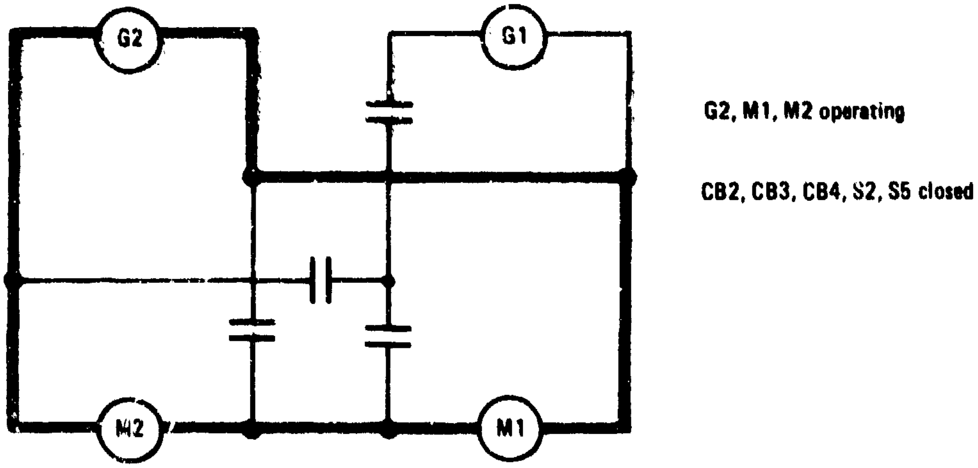


Figure 4.6. Half Power Mode



a) Q1



b) Q2

Figure 4.7. Quarter Power Mode

power modes. These three principal powered modes are shown respectively in Figures 4.5, 4.6, and 4.7. For discussion, Figure 4.4 will be termed the zero power mode since all switches are open and no power can be transmitted between the prime movers and the load. It should be noted that there are many other configurations possible. However, since most of these are variations of one of the principal modes, they are not shown at this time.

The full power Figure 4.5 will be used to investigate system operation wherein two generators operate in parallel to supply power to one motor. This configuration is the same as studied for the 40,000 SHP design with the exception that in the 40,000 SHP study, each generator was rated at one-half of the motor rating and thus, all machines operate at their rated load values in the full size system. Conversely, in the 3000 HP test system, the generators and motors are both rated at the same power, therefore, in the test system, the generators are each operating at one-half load when the motor is loaded to full load. This is not considered as a serious detriment in achieving the test objectives since the major objective in the full power mode is to investigate system operation of two generators in parallel without major emphasis on the machine loading conditions. It is also recognized that the generator will be operated at full power in the half load configuration.

The half power mode Figure 4.6 allows investigation of rated load operation of both the generator and motor while system operation of one motor with one generator is examined. The quarter power mode Figure 4.7 will allow investigation of system operation with two motors in series.

The half power mode Figure 4.6 also allows operating either shaft of machinery independently. Therefore if it becomes desirable to compare alternative features of one load set to those on the other, it may be done in this mode.

Not shown are alternate configurations for the full power, half power, and quarter power modes. Thus, in the full power mode, it is possible to operate the port side motor M2 rather than the starboard side motor M1. Similarly, in the half power mode, the system could be configured to operate motor M1 from generator G2 or to operate motor M2 from generator G1. These two connections cannot be done simultaneously, however. An alternate configuration is also available for the quarter power mode wherein generator G2 is used to power both motors. These alternate connections may be used if it is desired to investigate differences in the machine design features.

The half power mode Figure 4.6 will be used to conduct the crash astern maneuver on the side 2 shaft. If desired, the braking resistor could be connected to the opposite side and the maneuver conducted on the side 1 shaft.

4.2.1.3 Service Requirements

Tables 4.3 through 4.5 show the facility requirements that must be provided at the test site.

TABLE 4.3

ENVIRONMENTAL REQUIREMENTS

A.	Ambient air temperature	40°F to 86°F
B.	Ambient air quality	Non hazardous
C.	Humidity	10 to 90% R.H. non condensing
D.	Location	In door, dry
E.	Shock	Non-shock
F.	Background airborne noise	(Later)
G.	Background airborne EMI	(Later)

TABLE 4.4

ELECTRICAL REQUIREMENTS

		Per Machine	Total
A.	Field Exciters (4)	460 ±5% VAC, 3ϕ 60 Hz, 125 amps 0.8 P.F., 2% max volt unbalance	460 VAC, 3ϕ 60 Hz, 500 A 0.8 P.F.
B.	Switchgear (1 set)	- - -	460 VAC, 3ϕ 60 Hz, 25 amps
C.	Lube oil subsystems (1 per test stand)	- - -	460 VAC, 3ϕ 60 Hz, 5 amps, 0.8 P.F., must be non- interruptable
D.	Cooling water subsystem (1 per test stand)	- - -	460 VAC, 3ϕ, 60 Hz, 15 amps, 08 P.F. + 115 VAC, 1ϕ 60 Hz, 20 amps
E.	Data logger (1 per test stand)	- - -	115 VAC, 1ϕ 60 Hz, 30 amps

TABLE 4.5

MECHANICAL REQUIREMENTS

A.	Load absorber	(See Section 4.2.1.4)
B.	Prime mover	(See Section 4.2.1.4)
C.	Lube oil cooling water heat sink	85°C max temp 15 psig at cooler inlet flange Atmospheric drain pressure 30 GPM 120 x 10^3 Btu/Hr heat rejection
D.	Deionized water cooling water heat sink requirements	85°C max temp 20 psig at cooler inlet flange Atmospheric drain pressure 600 GPM 1.8 x 10^6 Btu/Hr heat rejection

4.2.1.4 Prime Mover and Load Assumptions

The gas turbine horsepower output vs speed is assumed to provide the 3000 hp at 3560 RPM as shown on Figure 4.8. The no-load speed is assumed to be 1800 RPM. The load device (water brake) is assumed to be capable of loading the motor with the steady state torque of 13,130 ft lbs at 1200 RPM as shown on Figure 4.9. For the transient crash back test, the load is assumed to provide the linear regenerative torque of zero ft-lbs at 800 RPM to 14,000 ft-lbs as shown in the fourth quadrant on Figure 4.9. This regenerative torque is contemplated to be supplied from the Number 2 generator-motor loop in a pre-programmed manner into the Number 1 motor generator loop.

4.2.2 System Operation

4.2.2.1 Control Concept

The control concept for this drive system is developed fully in a separate report entitled "SEGMAG 3 KHP/SHAFT System Control" enclosed in the Appendix of this report.

4.2.2.2 Operating Characteristics

4.2.2.2.1 Steady State System Operating Characteristics

The test program presented in Section 4.1 stated that one of the significant areas for investigation is the operation of the 3000 HP test stand under steady state conditions in each of the three principle configuration modes. Functionally the three modes are described as follows: two generators in parallel powering one motor, one generator powering one motor and one generator powering two motors connected in series. These three powered operating modes are named, full power, half power and quarter power respectively because the functional arrangement of machines in each mode duplicates those arrangements proposed for use in the 40,000 SHP system. These names, however, do not accurately describe the power levels of the machine operation on the test stand. When operating the test stand in the full power mode,

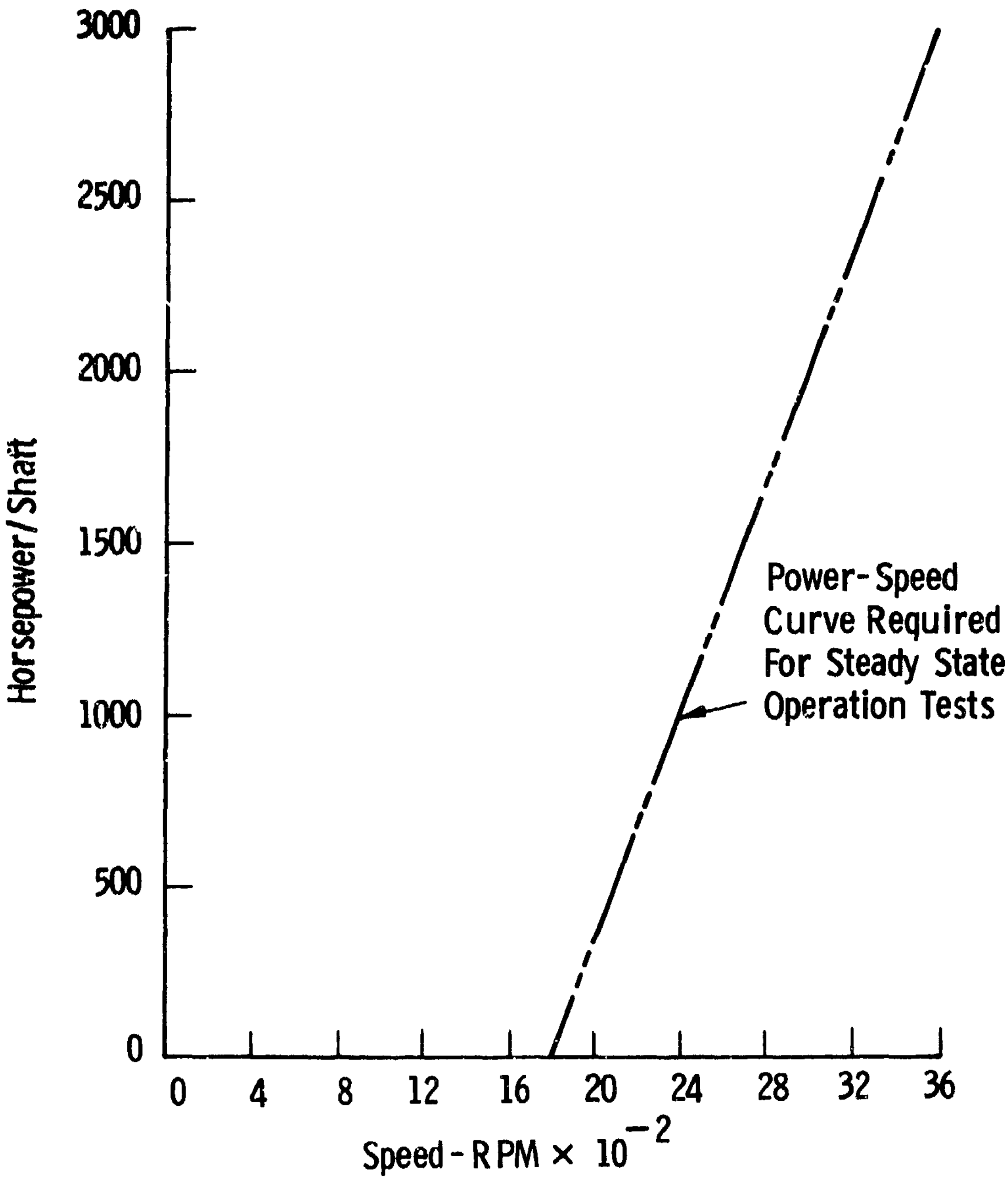


Figure 4.8. Prime Mover Power Vs. Speed

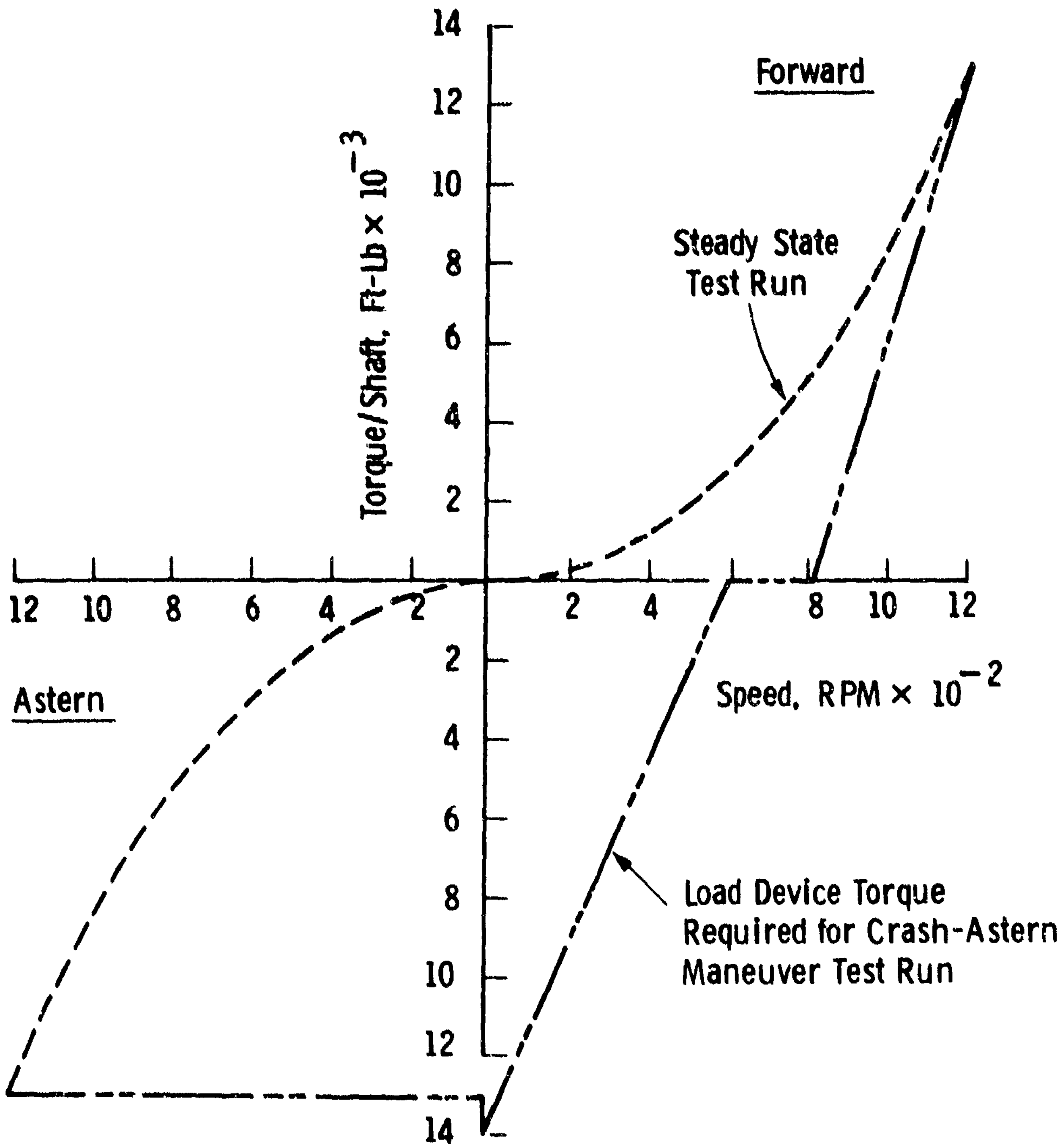


Figure 4.9. 3000 HP Test Stand, Torque Vs speed

only the motor will be operating at full load. The test generators will be operating at half load. In the half power mode, all test machines can operate at full power. In the quarter power mode, only the generator is operated at full power while the two motors are each operating at one half power.

4.2.2.2.2 Dynamic Characteristics

The tests of the system under steady state operating conditions would be conducted in accordance with the following general approach. (This assumes that prior to this time the electrical and mechanical capabilities of each of the test stand elements as separate devices have been verified.)

The test stand machines would be operated in each configuration and at selected load conditions for a sufficient length of time to achieve thermal stability for each selected condition. During this time and following stabilization, the system stability would be disturbed by making small sudden changes in the load in order to perturbate the system and to allow data to be taken on system response and stability.

4.3 Major Subsystems

4.3.1 2354 KW Generator

Design rationale and preliminary design details for the 2354 KW generator were described in Reference 3.1. The principal characteristics of the machine are displayed in Table 4.6, and the losses at rated load are shown in Table 4.7. The updated design drawings from which manufacturing drawings have been prepared are included as Appendix No. 8.

4.3.2 2240 KW Motor

As with the generator, the preliminary design of the 2240 KW (3000 hp) motor was fully described in Reference 3.1. The principal characteristics of the motor are displayed in Table 4.8, and the losses at rated load are shown in Table 4.9. The updated design drawings from which manufacturing drawings have been prepared are included in Appendix No. 9.

4.3.3 Transmission Lines

The transmission lines will be tailored to suit the test stand installation. They will consist of multiple assemblies of single conductor commercial power cable or else enclosed, feeder bus duct. The overall system allocation of losses has allocated 18.64 KW loss for the transmission line and switchgear (difference between the generator output and the motor input). If the transmission line is sized for 1000 amps/in^2 and operates at a temperature of 90°C and dissipates half of the allocated loss, 9.32 KW, then it can be up to 96.3 feet long. (Based on 2 conductors with $\rho = 10.376\ \Omega$ Cir Mil/Foot at 20°C). If the

TABLE 4.6

PRELIMINARY GENERATOR DESIGN PARAMETERS

Rated Power	2354 kW
Rated Speed	3600 RPM
Rated Voltage	505 volts
Rated Current	4660 amps
Number of Poles	4
Number of Turns/Pole	1
Pole Face/Pitch Ratio	0.4
Rotor Bar Current Density	$465A/cm^2$ ($3000\ A/in^2$) RMS in Copper
Field Current Density	$465A/cm^2$ ($3000\ A/in^2$) RMS in Copper
Gap Flux Density	1.3T
Dimensions	
Rotor OD	0.53 m (21.65 in.)
Rotor Bar Thickness	0.899 cm (0.354 in.)
Rotor Iron ID	0.388 m (15.26 in.)
Stator ID	0.559 m (22.01 in.)
Field Coil Thickness	4.3 cm (1.70 in.)
Stator OD	0.793 m (31.21 in.)
Active Length	0.98 m (38.59 in.)
Current Collector Length	0.15 m (6.04 in.)
Bearing-Bearing Length	1.60 m (63 in.)
Electrical Weight	3344 Kg (7373 lb)
Efficiency at Full Load	97.1%

TABLE 4.7

GENERATOR LOSSES - RATED LOAD

(Losses in Kilowatts)

I^2R	- Rotor Bars	5.15
	- Stator Bars	1.91
	- Brush Holders	0.11
	- Stator End Rings	3.33
	- Sliding Connections	0.07
	- Field Winding	16.61
Brushes	- Friction	11.33
	- Contact	4.54
	- Ohmic	0.13
	- Shunt Contact	0.75
Eddy Currents	- Main Flux	3.96
	- Tooth Ripple	1.56
	- In Risers	0.80
	- In End Plates	2.44
	- Commutator Bars	1.78
	- In Cooling Tubes	0.31
	- Circulating Currents Between Bars	0.39
	- Core Loss	9.48
Seals		0.10
Bearings		15.4
Windage		2.55
	TOTAL	82.70
	Efficiency at 2354 HP	96.61%

TABLE 4.8

PRELIMINARY MOTOR DESIGN PARAMETERS

Rated Power	2237 KW (3000 HP)
Rated Speed	1200 RPM
Rated Voltage	500 Volts
Number of Poles	6
Number of Turns/Pole	2
Pole Face/Pitch Ratio	2/3
Rotor Bar Current Density	775A/cm^2 (5000 A/in^2) RMS in Copper
Field Current Density	465A/cm^2 (3000 A/in^2) in Copper
Gap Flux Density	1.3T
Dimensions	
Rotor OD	0.70 m (27.56 in.)
Rotor Bar Thickness	0.68 cm (0.27 in.)
Rotor Iron ID	0.77 m (18.8 in.)
Stator ID	0.71 m (27.8 in.)
Field Coil Thickness	7.1 cm (2.8 in.)
Stator OD	1.06 m (41.6 in.)
Active Length	0.76 m (29.86 in.)
Current Collection Length	13.9 cm/end (5.5 in/end)
Brg.-Brg. Length	1.35 m (53 in.)
Weight	4808 Kg (10,600 lb)
Efficiency at Full Load	95.9%

TABLE 4.9

MOTOR LOSSES AT RATED LOAD

(Losses in Kilowatts)

Rating: 3000 HP, 1200 RPM (6 poles)

I^2R Loss	- Rotor Bars	21.00	
	- Stator Bars	3.33	
	- Brush Holders	0.42	
	- Stator End Rings	8.19	
	- Bolted Connections	0.22	
	- Field Winding	18.00	
			51.16
Brushes	- Friction	18.78	
	- Slip Ring Contact	7.83	
	- Ohmic	0.37	
	- Shunt Contact	2.24	
	- Radial Field	0.03	
"Eddy Currents"	- Main Flux		29.25
"Eddy Currents"	- Main Flux	1.32	
	- Tooth Ripple	2.02	
	- Risers	1.01	
	- Commutator Bars	1.35	
	- End Plates	2.39	
	- Cooling Tubes	0.16	
	- Circulating Current	0.36	
	- Core Loss	4.42	
			13.03
Mechanical	- Seals	0.01	
	- Bearings	3.90	
	- Windage	0.43	
			4.34
		TOTAL	97.78
		EFFICIENCY	95.81%

distance between generator and motor is less than 96.3 feet, the losses will be reduced or else the allowed current density can be increased.

4.3.4 Switchgear

The switchgear will consist of 4 circuit breakers and 5 contactors. The circuit breakers will be open frame, dead front mounted. The breakers will be rated for 5000 AMPS continuous duty at 500 volt DC. The breakers will be provided with a 250 VDC closing solenoid and will be equipped for instantaneous series and shunt trips. The breakers will be of the DC current limiting type and are classified as semi-high speed under Nema Standard SG 3.14-1975.

The circuit breakers will be mechanically held closed by a spring loaded latch. The contactors will have a continuous duty rating of 6000 AMPS and a load break capability. The contactors will be operated on 250 VDC control circuit and will be magnetically held closed. The contactors will be electrically interlocked with the circuit breakers to prevent opening of the contactors under fault conditions.

The circuit breakers and their control relays along with the contactors will be assembled into a guarded enclosure and will occupy a floor space of approximately 10 feet by 6 feet. The top of the enclosure will stand 92 inches, however, an additional 18 inch clearance must be provided above the enclosure to allow for arc clearance.

The transmission line entrance into the circuit configuration switchgear will be determined to best suit the selected test site and the transmission line design.

4.3.5 Exciter

4.3.5.1 Technical Summary

The exciters for the SEGMAG machines used in the 3000 HP system test bed will be solid state power supplies designed for industrial applications. Since the motor and generator fields required the same power levels, a single exciter design will be used for each of the four SEGMAG machines. A simplified block diagram of the exciters is shown in Figure 4.10. Three phase power is fed to a converter through an isolation transformer. The output of the dual converter is a dc voltage that is applied to the machine field. The dual converter will develop either polarity of voltage or current as shown in Figure 3.16. A set of thrysitor gate drives are generated for each of the two converters that comprise a dual converter. The gate director circuit controls which set of gate drives are to be activated and synchronizes the drives with respect to the three-phase input voltages. The gate director circuit also delays the generation of gating firing voltages in response to the regulator output signal. The regulator circuit provides both current and voltage limitations on the output of the converters. Control of the converter output below these limits is determined by external control loops applied to the regulator.

The exciters will be capable of providing two times rated voltage for field forcing. In the 40,000 HP system, an exciter capable of 50 times rated voltage was considered as a means of limiting armature current faults that are above the current interruption ratings of available dc breakers. This method of armature current limiting would require additional development effort in the design of the exciter and insulation requirements of the field windings or the development of an adequate dc current interrupter. The armature current interruption requirements of the 3000 HP machines are within the ratings of available breakers. These machines would not require a high field forcing voltage technique to prevent damaging armature currents.

4.3.5.2 Physical Description

The field exciters for the 3000 HP test bed system will be an M5B thyristor power supply manufactured by the Industry Systems Division of the Westinghouse Electric Corporation in Buffalo, New York. The entire power supply is contained in a single, self-ventilated, NEMA I enclosure. The three phase power transformer and the primary

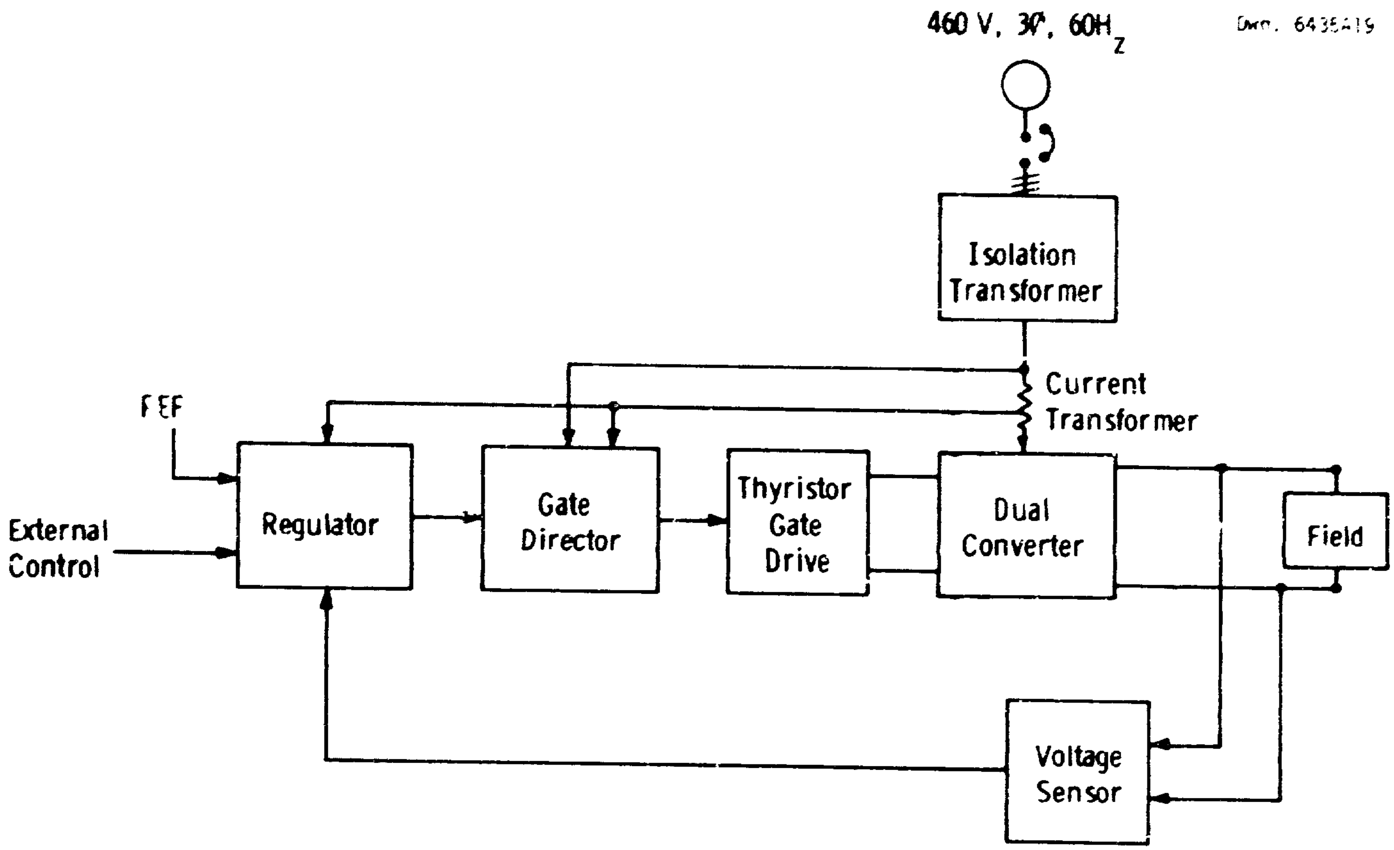


Figure 4.10. Simplified Block Diagram of a 3000 HP Test Bed Exciter

breaker are housed in the bottom compartment of the cabinet. A thyristor converter panel and an auxiliary panel, containing a control transformer, are mounted in the rear of the upper portion of the cabinet. The control circuits are placed on plug-in cards and are mounted on a swinging bay located on the rear of the front door. The output voltage and current meters, control pushbuttons, and indicator lights are located on the outside of the front door. Each exciter unit will be approximately 32 inches wide, 32 inches deep, 92 inches high and weigh approximately 1500 pounds.

4.3.6 Controls

4.3.6.1 General

This section outlines the implementation of the system control philosophy describ ed in The Appendix No. 7 of this report. The control philosophy includes two types of control functions described as a supervisory and a dynamic control system. The supervisory control basically monitors various digital signals developed within the system, to provide the desired operational modes. The dynamic control regulates the propulsion system to a selected system torque. In the 40,000 hp propulsion system study, a microcomputer system is proposed as a method of performing all of the supervisory control functions. A microcomputer reduces the number of components in a control system, thus improving the reliability of the control unit. It also permits additional self-checking function without increasing overall system complexity. Although it is possible to change the control by modifying the computer software, it does require additional equipment at the test site to implement and test the results of a program change. It is also possible that some operational modes will be found that require a higher processing speed than available in the selected microprocessor system. This would require an extensive modification of the microprocessor control that would be difficult to achieve at the test site. To minimize the time and effort required to implement control circuit modifications at the test site, the supervisory control for the 3000 hp test bed will be constructed with standard types of digital logic circuits.

4.3.6.2 Control Console

In Figure 4.11 is shown a block diagram of the 3000 hp test bed control system. Operator inputs are made available at the Control Console and are depicted in Figure 4.12. Those inputs include the motor torque references, system operating modes, machine permissive signals and motor-generator configuration selection and set switches. Visual readouts will be located at the control console to inform the operator of the selected and actual operating modes. Selected system parameters such as machine voltages and currents, and auxiliary functions that include switch and breaker positions, loss of oil pressure, etc., will also be displayed.

4.3.6.3 Master Control

The Master Control block contains all of the upper level and lower level supervisory control, dynamic control and the dynamic brake thyristor control as described in the system control philosophy for the Twin-Drive Demonstration System. The upper level supervisory control monitors the breaker and contactor switch positions, machine auxiliary functions and machine speed and current limits. If the value of these functions are correct, an orderly start-up of the system is allowed upon command from the control console. When the start-up sequence has been completed, the dynamic control is permitted to control the operation of the propulsion system.

4.3.6.4 Upper Level Supervisory Control

A block diagram of the upper level supervisory control section of the master control is shown in Figure 4.13.

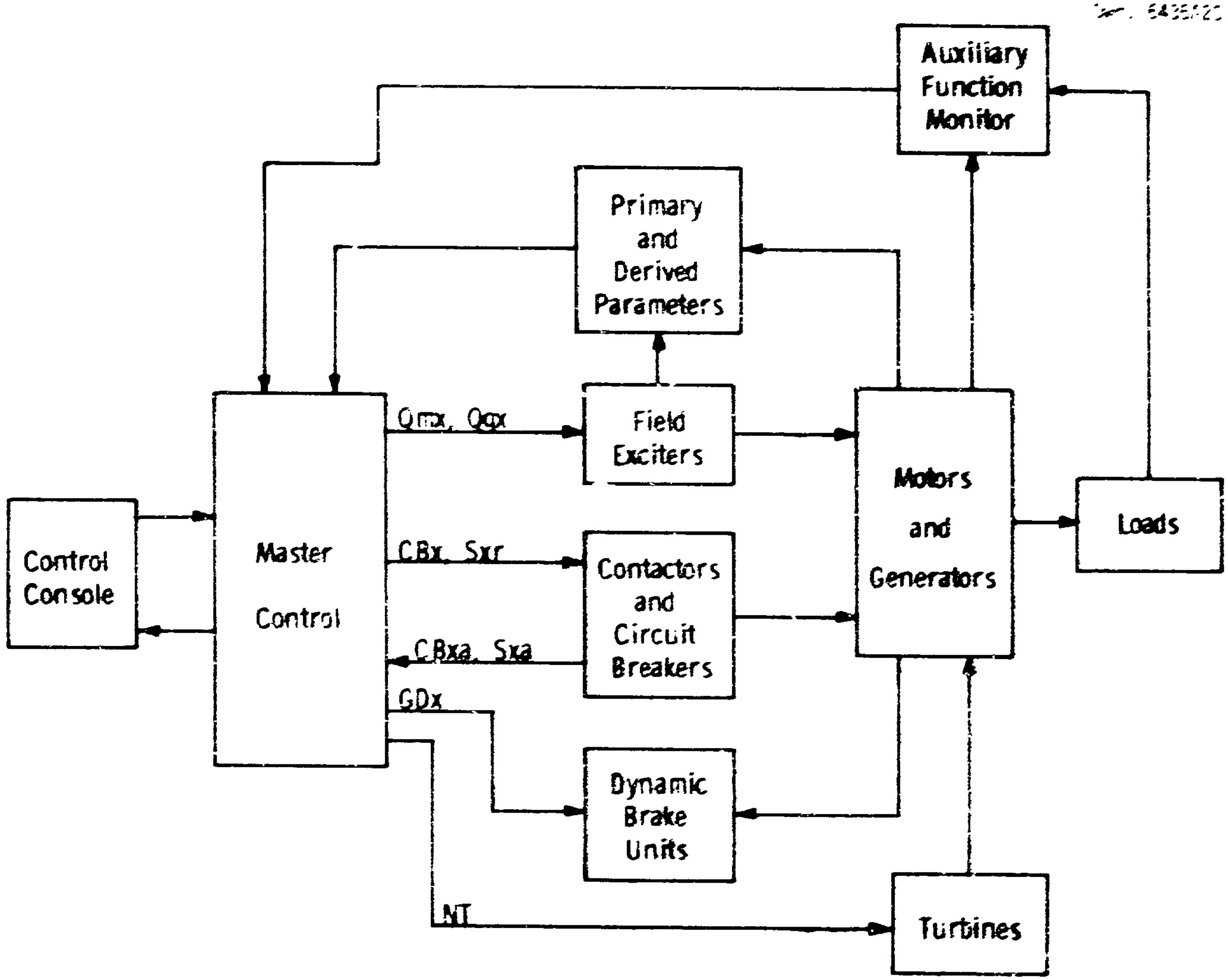


Figure 4.11. Block Diagram of the 3000 HP Test Bed Control System

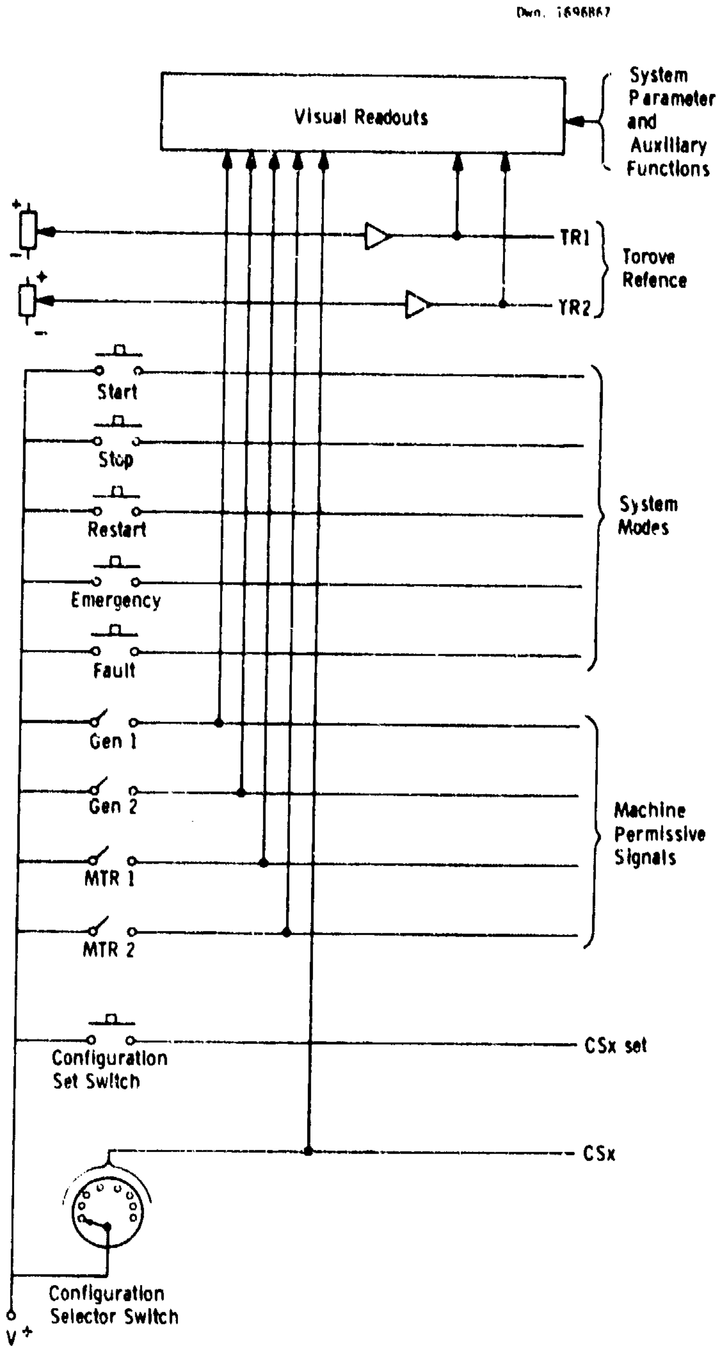


Figure 4.12. Test Bed Control Console Functions

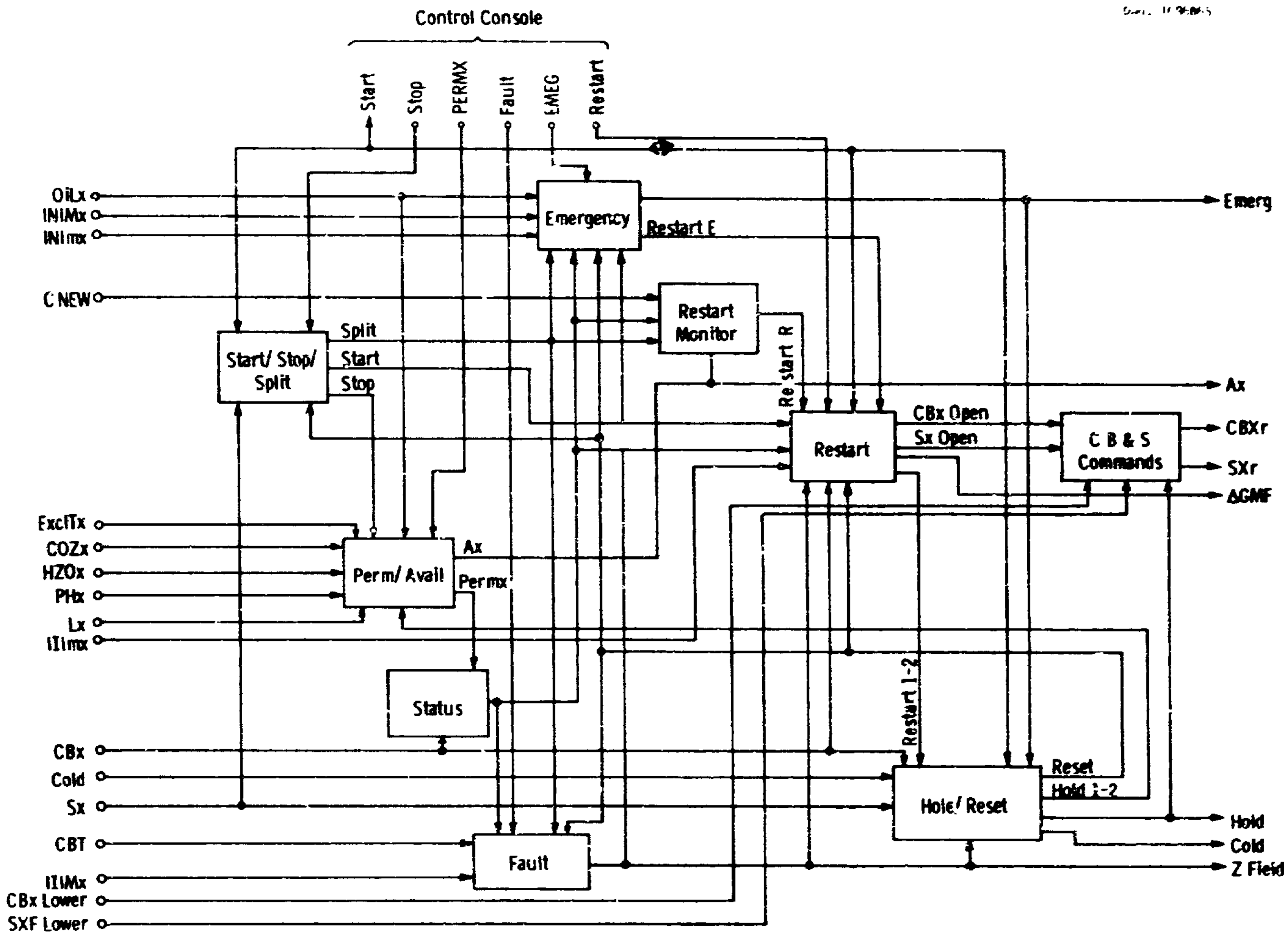


Figure 4.13. Upper Level Supervisory Control Section of Master Control

All input or output functions labeled with a subscript "X" indicate multiple signals. As the lower level supervisory and dynamic controls operate the propulsion system, the upper level supervisory control continuously monitors the various functions shown. If any of the input functions are outside of prescribed limits, the upper level control will regain system control and cause a propulsion system shutdown. There are several types of system shutdowns available. A stop command initiated at the control console, provides a complete and orderly shutdown of the system, concluding with all circuit breakers and switches opened and all machine field currents reduced to zero. An emergency shutdown immediately signals a shutdown of the prime mover followed by a controlled shutdown of the system. A fault condition will immediately command the circuit breaker to open, shut down the prime movers and rapidly de-energize the machine fields. These shutdowns may also be initiated at the control console. A restart command provides a partial shutdown of the system when a minor malfunction is detected. The machine permissive signals, activated at the control console, permit the operator to make a machine not available. The upper level supervisory portion of the master control is thus the dominant control during a system startup or shutdown interval. All control functions are readily performed by standard digital logic elements.

4.3.6.5 Lower Level Supervisory Control

The master control unit also contains a lower level supervisory control section that is shown as a block diagram in Figure 4.14. The lower level circuit directs the operation of circuit breakers, switches and exciter inputs in a proper sequence to permit a successful configuration change. A motor-generator configuration (C_{SX}) selected by the operator is compared to the availability of the machines involved.

If the machines are available, the required configuration information (C_{refX}) is sent to the configuration control. If all of the machines required to implement the change are not available, the configuration selector/reference circuit will automatically select the

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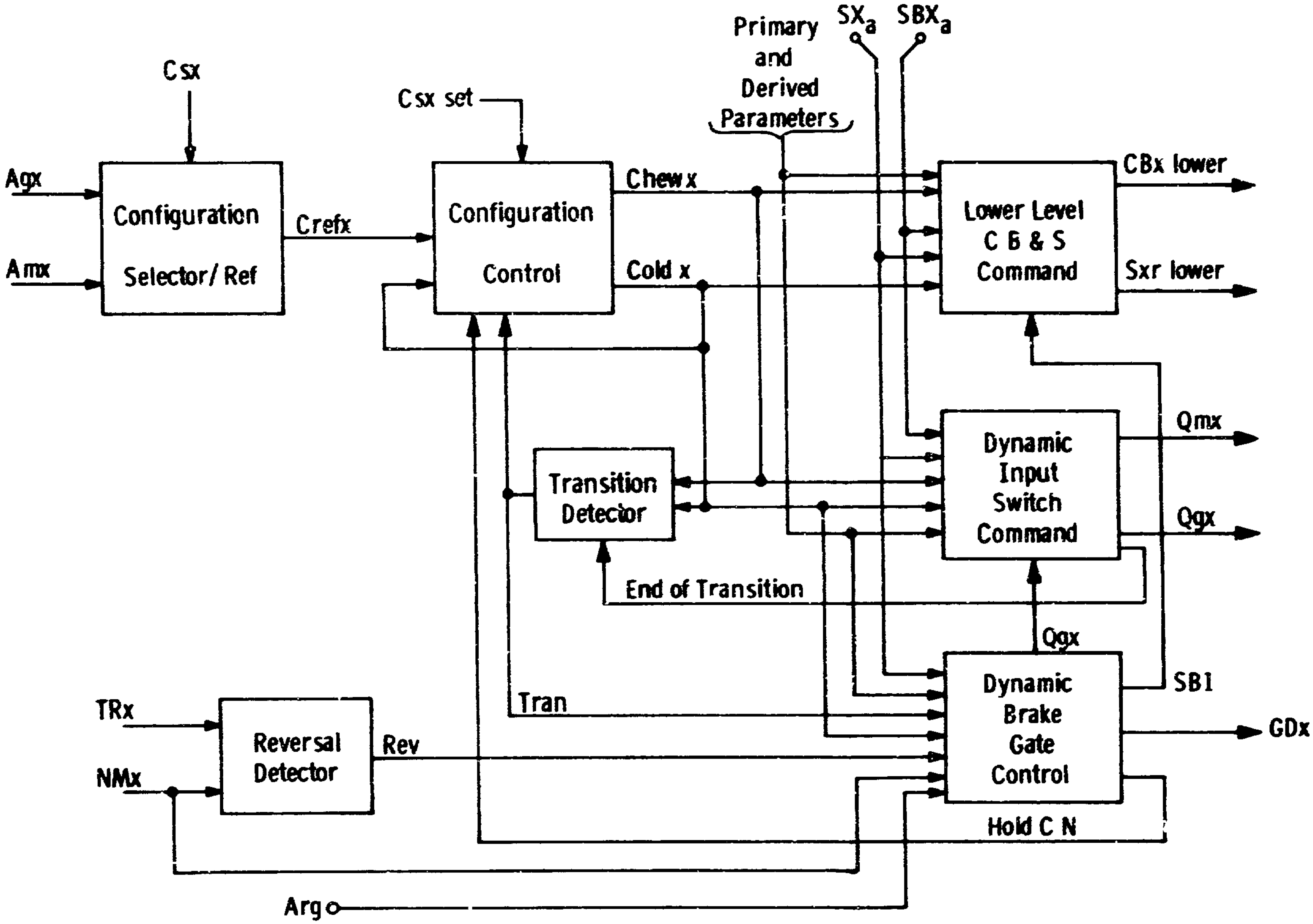

Figure 4.14. Lower Level Supervisory Control Section of Master Control

next largest power configuration that is available. In any event, before the new configuration is carried out, the operator must confirm the new selection by pressing the configuration set switch C_{SX} set. The desired configuration C_{refX} is compared to the present configuration stored in a $C_{old\ x}$ memory and a new configuration is determined and stored in a $C_{new\ x}$ memory. The new configuration may not be the same as C_{refX} since the control is programmed to permit a defined sequence of configuration changes. The allowable transitions between configuration is shown in the diagram of Figure 4.15. Note that a configuration change from quarter power Q2 to full power F2 must first pass through a zero power configuration and a half-power configuration H2. If a propeller reversal is detected, the $C_{new\ x}$ memory is inhibited and retains the same information as $C_{old\ x}$ memory until the reversal is completed. When $C_{new\ x}$ differs from $C_{old\ x}$ a transition is started and further changes in $C_{new\ x}$ or a reversal is inhibited until the transition is complete. For each configuration change, a specific operating sequence of circuit breakers, switches and exciter inputs are programmed. Those are described in the "Transition" section of the "3000 HP per shaft drive system controls" report located in the Appendix No. 7. At the conclusion of the transition, the data in $C_{old\ x}$ memory is changed to the $C_{new\ x}$ data and the inhibit signal to $C_{new\ x}$ and reversal is removed. If C_{refX} is not equal to $C_{old\ x}$, $C_{new\ x}$ will be given data to advance to the next system configuration and another transition sequence is started. This process continues until the system configuration is the same as the reference configuration C_{refX}. Each step in the sequence of breaker, switch and exciter input commands must be acknowledged by feedback signals from the breaker and switch auxiliary contacts or system parameters before the next step is taken. The lower level supervisory control will automatically change the system configuration to a lower power level if a machine in operation becomes unavailable. The final configuration will be lower than the power level selected by the operator and be dependent on the availability of machines.

CONFIGURATION TABLE

		GENERATORS OPERATING			
		None	1	2	1 & 2
MOTORS OPERATING	None	Z	–	–	–
	1	–	H1	–	F1
	2	–	–	H2	F2
	1&2	–	Q1	Q2	H

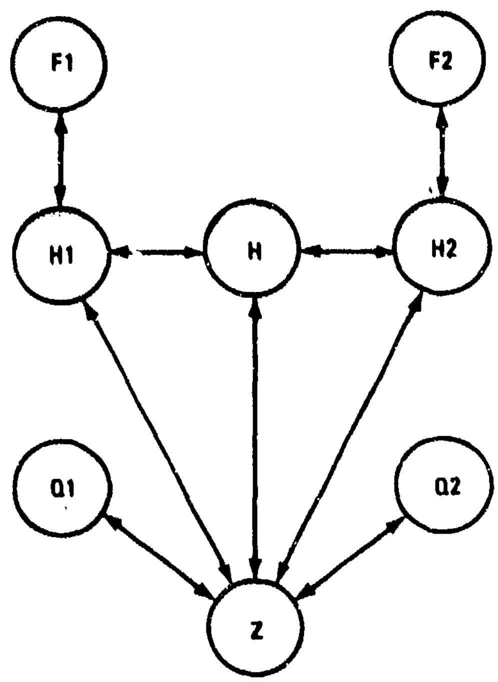

Figure 4.15. Allowable Transitions Between Motor-Generator Configurations

4.3.6.6 Dynamic Control

The basic propulsion system consists of a turbine-generator unit supplying electrical power to a motor-propeller load. The turbine-generator is operated at a constant speed. The primary means of controlling the speed-torque output of the motor is by controlling the generator field flux or current. For normal operating modes, the motor field current is held at a fixed value and motor torque is controlled by regulating the generator field current. In this instance, the generator field current is controlled by a closed loop regulator that responds to an error signal developed between the torque reference and the electromagnetic torque of the motor. In other instances, the generator field current must respond to other system parameters, i.e., generator current when a zero armature current is required or generator voltage when zero generator voltage is desired. To obtain the required system performance during normal and transitory operating modes, the generator field exciter control responds to eleven different signals. These signals represent primary or derived system parameters and are shown in Figure 4.16 for generator 1. These parameters are placed in the field regulator circuit by solid state switches activated by the Exciter Input Switch Command Signals Q_{gx}. Only one of the regulator input switches is closed at any given time.

Similar types of system parameters are grouped to minimize the number of compensation circuits (CF_x) required. A typical compensation circuit is shown in Figure 4.17. The transfer function of each compensation circuit would be established to ensure a stable closed loop control for each type of system parameter input. The compensation circuit outputs are applied to a field exciter control input circuit shown in Figure 4.18. This circuit consists of a rate limit circuit and an integrator that controls the delay firing angle of the converter field exciter. The generator 2 exciter is controlled with an identical circuit.

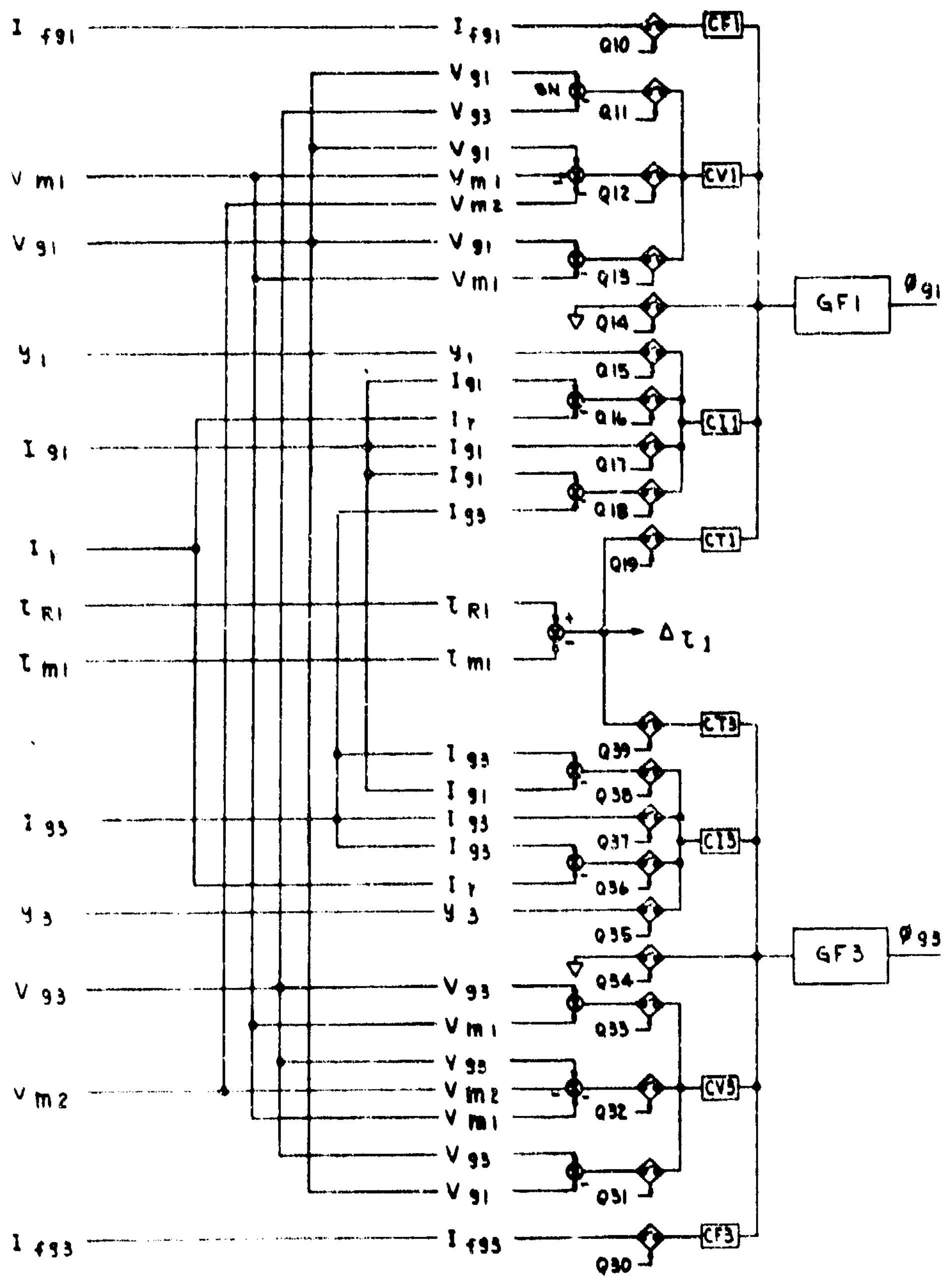

Figure 4.16. Functional Diagram of a Generator Field Exciter Dynamic Control

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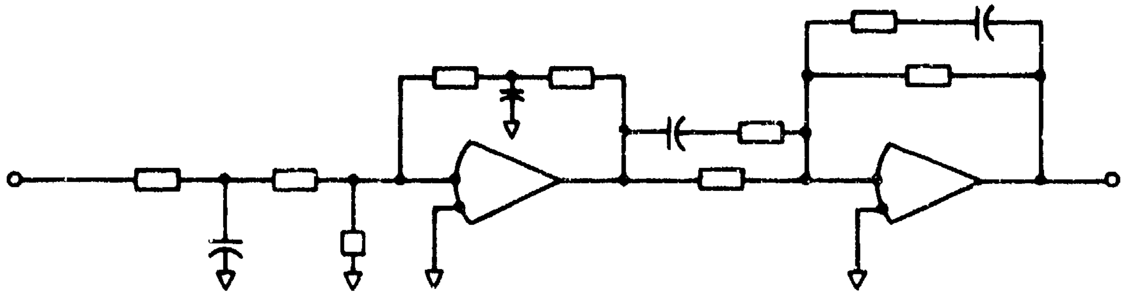

Figure 4.17. Typical Content of a Compensating Block Shown on Figure 4.16.

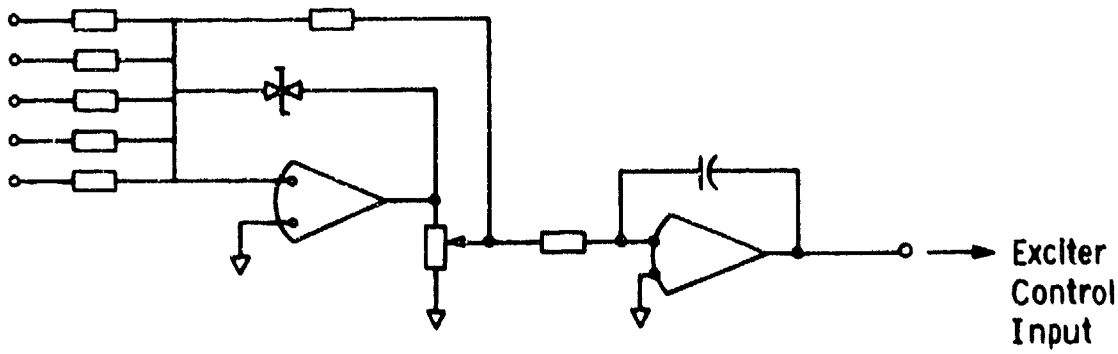

Figure 4.18. Typical Content of a Field Exciter Control Input Functional Block Shown in Figure 4.16

In a similar manner, the lower level supervisory section of the master control applies the desired control parameter to the motor exciter regulator. In Figure 4.19 is shown a diagram of the exciter dynamic control for motor 1. An identical circuit would control the motor 2 exciter. Any one of seven solid-state switches may be closed to obtain the proper motor control loop for normal or transitory operating modes. The derived parameter α'_{m1} permits the motors to develop unequal torques that may be commanded during a quarter power configuration. The dynamic control for the motor exciters also employs compensation circuits and exciter input control circuits as described for the generator dynamic control.

4.3.6.7 Dynamic Brake Control

In the 3000 hp Test Bed System, a simulation of the dynamic braking technique of a 40,000 hp propulsion system will be undertaken. A description of the dynamic brake power circuit is given in Section 3.8. A similar thyristor-resistor braking unit will be developed for the 3000 hp system. A functional block diagram of a dynamic brake unit is shown in Figure 4.20. Thyristor gate drive circuits are activated by gate drive signals (GDX) developed in the Dynamic Gage Control Circuit. This circuit also controls the operation of the brake contactor (SB1) and generator field exciter inputs (Q_{gx}). These control signals are developed sequentially when a reversal command (Rev) is recognized. Basicially, the dynamic braking mode consists of two intervals of sequenced events normally separated by a waiting period. The first interval recognizes a braking command and prepares the propulsion system for a braking interval. Before the braking interval may be started, the ship's speed or propeller watermill rpm must be below a given value. This is to protect the machines from excessive armature currents and torques that will be required to stop the propeller rotation. The maximum value of motor speed (N_m) permitted for braking is also dependent on the configuration of the machines ($C_{old\ x}$). When the motor speed has fallen to the proper level, the braking interval is

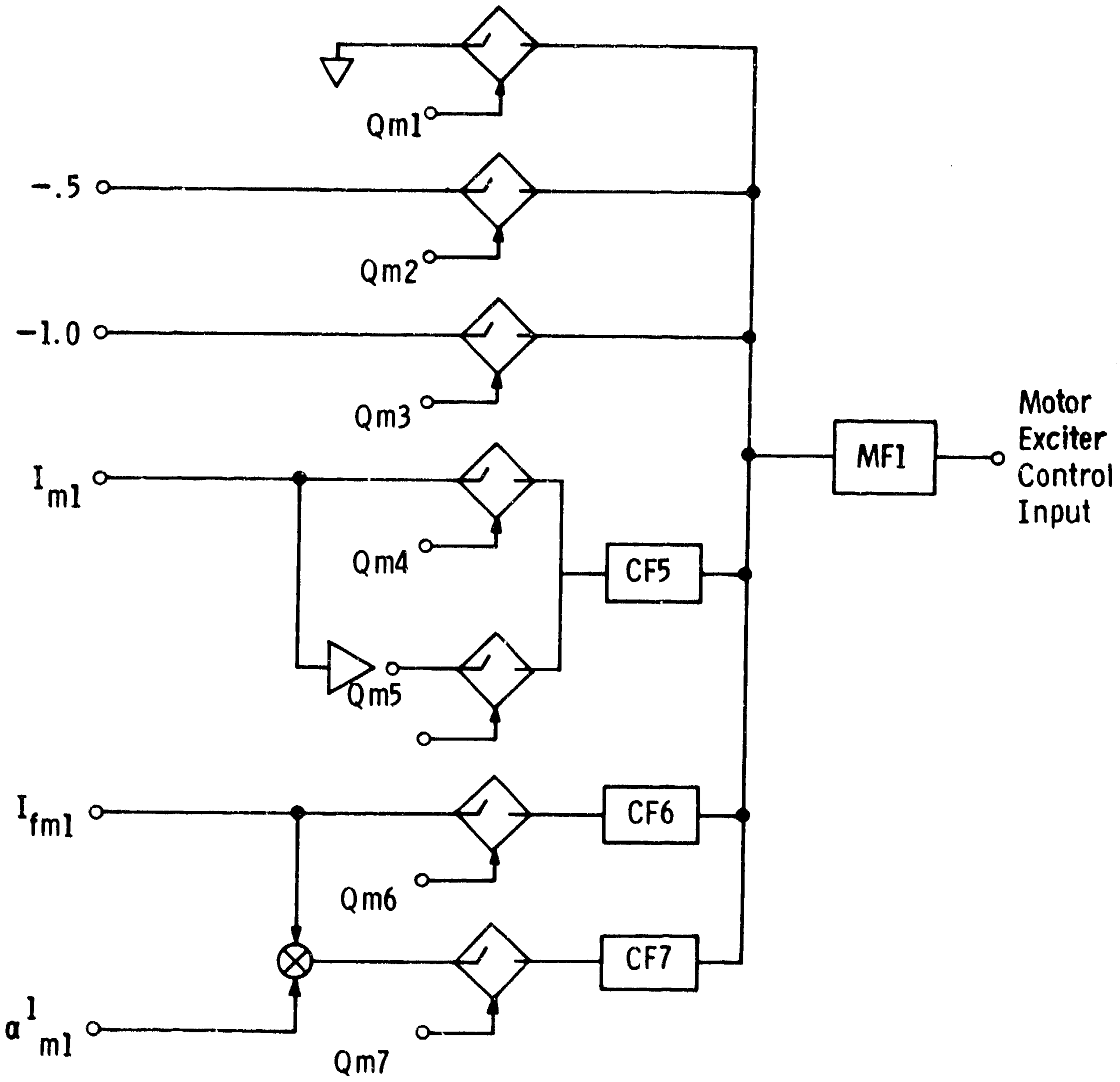

Figure 4.19. Functional Diagram of a Motor Field Exciter Dynamic Control

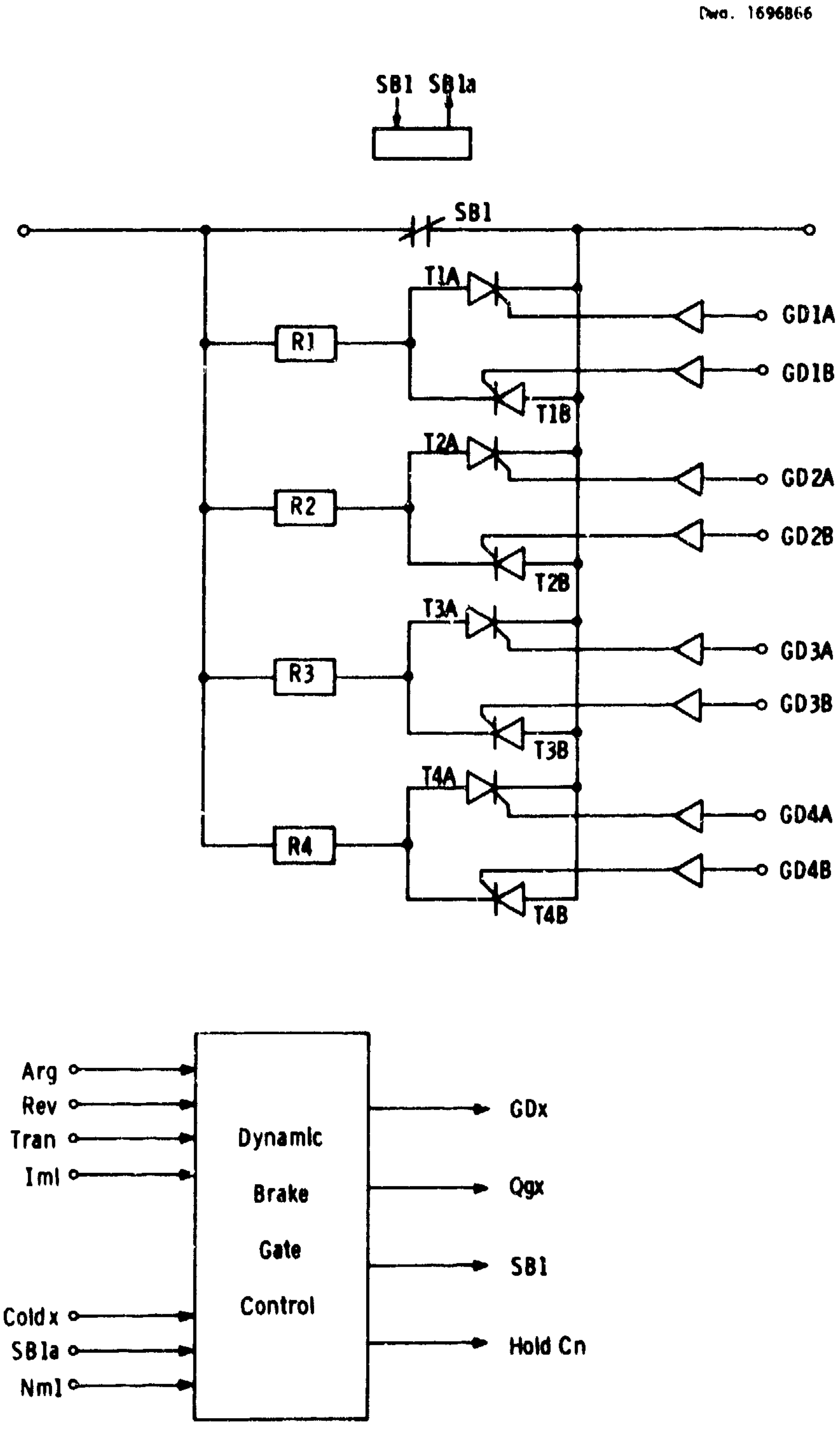

Figure 4.20. Functional Block Diagram of a Dynamic Brake Control

started. The motor armature current (I_m) is observed as the thyristors are sequentially gaged on to maintain a given level of current. Each time the motor current falls below a given level, the next thyristor is gated on until finally the braking contactor is closed. At this time, the anti-regeneration signal (Arg) is checked to ensure safe return to normal operation.

When the operator initiates the described braking mode, it must be completed before normal operation is resumed. The waiting period required for the motor speed to fall to a preselected value in a shipboard application may be approximately ten seconds. It would be desirable if the operator had the option to abort the braking mode during this period. The simplified logic diagram shown in Figure 4.21 would provide this option and is described as follows:

To initiate a braking mode the inputs to the AND element A1 must indicate a reversal command (Rev) and the absence of a configuration transition (T_{ran}). A reversal command is generated when the polarities of torque reference (T_R) and motor rotation (N_m) differ. The logic expression for this condition is:

$$(T_T>0)\cdot(N_m>0) + (T_R>0)\cdot(N_m>0)$$

A transition is indicated whenever $C_{new\ x}\ C_{old\ x}$. If the reversal command is recognized the output of a flip-flop (FF1) is set to a logic "1". This signal (Hold CN) inhibits any change in the $C_{new\ x}$ memory and activates the sequence "A" routine that follows.

1. Generator exciter input to Ig.
2. Ig = 0, open SB1.
3. SB1 open, generator exciter input to Eg.
4. Eg = 0, sequence "A" complete.

The completion of sequence "A" sets FF2 and a waiting interval begins. During this period the operator has the option of continuing the reversal mode or returning to a normal operation by the position of the torque

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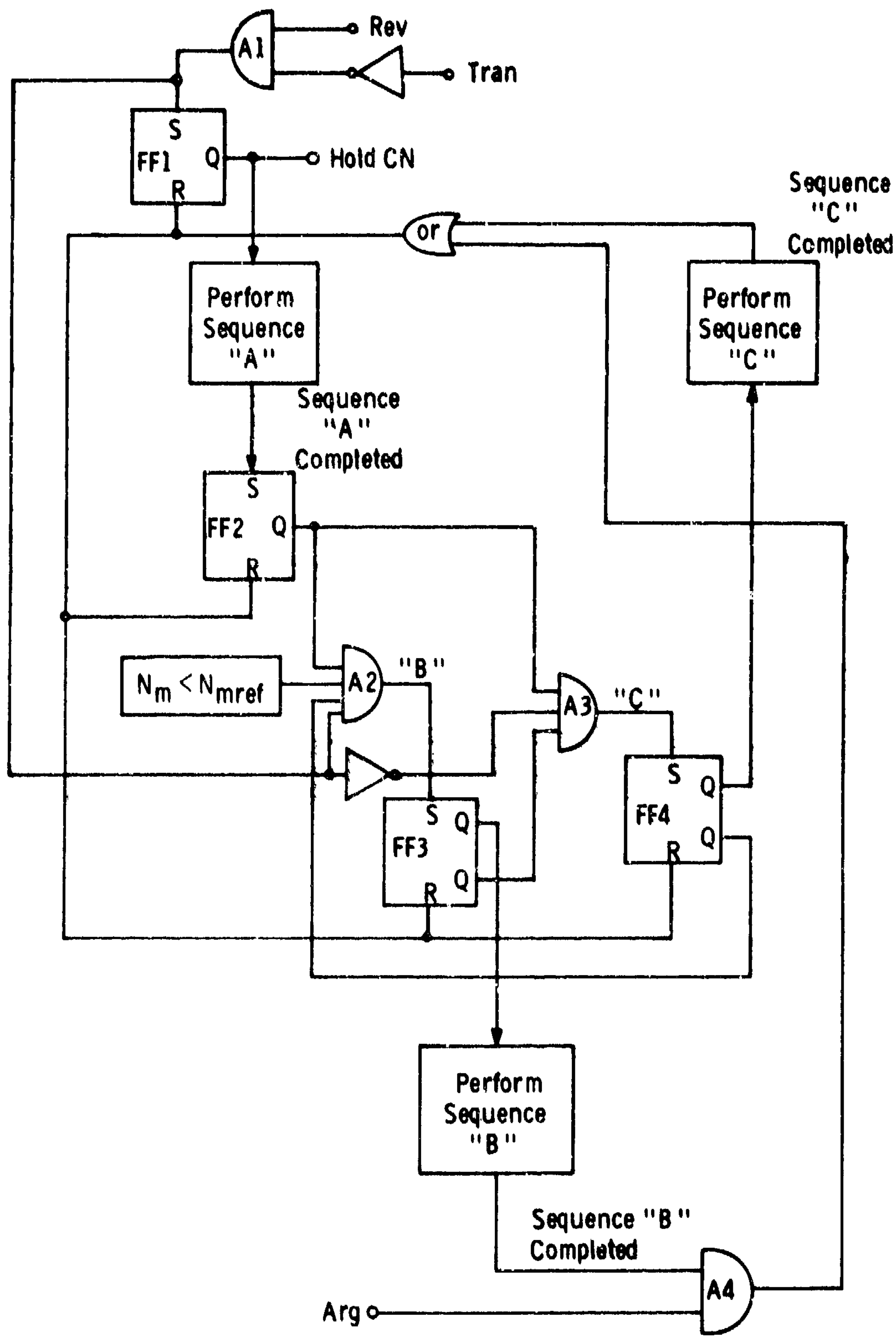


Figure 4.21. Dynamic Brake Control Logic Diagram

control lever. If the reversal command is retained and the motor speed (N_m) becomes less than a reference speed ($N_{m\ ref}$)., and AND element (A2) switches to a logic "1", setting FF3 and inhibiting FF4. The circuit is now committed to a continuance of the braking mode as sequence "B" is initiated and proceeds as follows:

1. Gate on T1.
2. Delay 0.02 sec, $I_m < I_{ref}$, Gate on T2.
3. Delay 0.02 sec, $I_m < I_{ref}$, Gate on T3.
4. Delay 0.02 sec, $I_m < I_{ref}$, Gate on T4.
5. Delay 0.02 sec, $I_m < I_{ref}$, Close SB1.
6. SB1 closed, sequence "B" complete.

After sequence "B" is completed, the anti-regeneration logic output (Arg) is checked to determine if the generator field may be returned to torque control without the regeneration of power. Arg is a logical "1" when the motor speed (N_{m1}) is approximately zero and the relationship between torque reference (T_{R1}) and the motor torque (T_{m1}) meet the following logic expression:

$$(N_{m1} \approx 0)\cdot[(T_{R1} > T_{m1})\cdot(T_{R1} > 0) + (T_{R1} < T_{m1})\cdot(T_{R1} < 0)]$$

The dynamic brake control circuit is then reset and the generator field is controlled by the torque reference.

When sequence "A" is completed the operator may return the system to torque control and abort the braking sequence "B". This would require the operator to remove the reverse command before the motor speed becomes less than the motor reference speed. If this action is taken FF4 is set and FF3 is inhibited. The control now performs sequence "C" as follows:

1. Generator exciter input to $(V_{g1}-V_{m1})$.
2. $(V_{g1}-V_{m1}) = 0$, close SB1.
3. SB1 closed, generator exciter input to $(T_{R1}-T_{m1})$.
4. Input $(T_{R1}-T_{m1})$, sequence "C" completed.

When sequence "C" is completed, the dynamic brake control circuit is reset and the system is controlled by the torque reference.

4.3.6.8 Turbine Speed Control

The motor control may also control the speed of the turbine-generator to achieve optimum speed for the best specific fuel consumption of the turbine at a given power level. The manner of obtaining optimum turbine speed is given in the section entitled "SEGMAG Twin-drive demonstration System". This control will be a slow responding regulator that may be overridden to rapidly cut off fuel to the turbine when load on the turbine is suddenly reduced.

4.3.6.9 Primary and Derived Parameters

The Motor Control unit controls the operation of the propulsion system in accordance to the information supplied by the Control Console to implement the required control and to protect the system from operating in a possible destructive mode. Various information on the system performance must be made available. These include primary parameters such as machine voltages and currents. Others include derived parameters such as the electromagnetic motor torque that is developed from the product of motor armature current and motor field current. These parameters will be developed for the 3000 hp system in a manner similar to those described for the 40,000 hp system in Section 3.6.2.6. In addition, the master control is informed of any inadequate performance of the auxiliary systems. These include the lube oil system, the CO_2 system and the H_2O system. Information on the performance of the prime mover and loads together with any auxiliary system will also be required.

4.3.7 Auxiliary Subsystems

4.3.7.1 Lube Oil System

The lube oil supply subsystem is a conventional pressurized recirculating lube oil system. It will have a non-pressurized reservoir with a 3 minute retention time, two AC motor driven submerged suction positive displacement pumps, a heat exchanger and a duplex lube oil strainer. The pressure at the supply header will be regulated by a regulating valve which will bypass a portion of the pump output back to the reservoir.

Figure 4.22 is a schematic diagram of the lube oil system. Table 4.10 is a listing of the lube oil system operating parameters and facility requirements.

The L.O. subsystem is mounted on a steel sub-base suitable for handling by either crane or fork lift. The system is designed to connect to the cooling water available at the test site. Stop valves will be supplied for the lube oil fluid piping. The system will be supplied with magnetic motor starters and will require a 460 VAC, 3Ø, 60 Hz non-interruptable power supply. The system will be provided with two stage output pressure switch and a two stage reservoir level switch. In addition, a temperature switch will be provided on the lube oil header. The temperature of the lube oil will be manually controlled by throttling the cooling water supply to the heat exchanger.

The output pressure level of the lube oil system will be monitored by a two level pressure switch which will be connected to the motor controller to automatically start the standby pump should the lube oil supply pressure drop below a preset minimum. This action also sends an alarm signal to the master control console. If the output pressure drops below the second pressure setting, the master control console will declare an emergency and shut down the test stand equipment.

Similarly, the temperature of the lube oil supply header is monitored by a temperature switch. This switch provides an alarm on high lube oil temperature allowing orderly corrective action by the system operator.

The lube oil drain lines will operate at atmospheric pressure and will drain by gravity back to the lube oil sump.

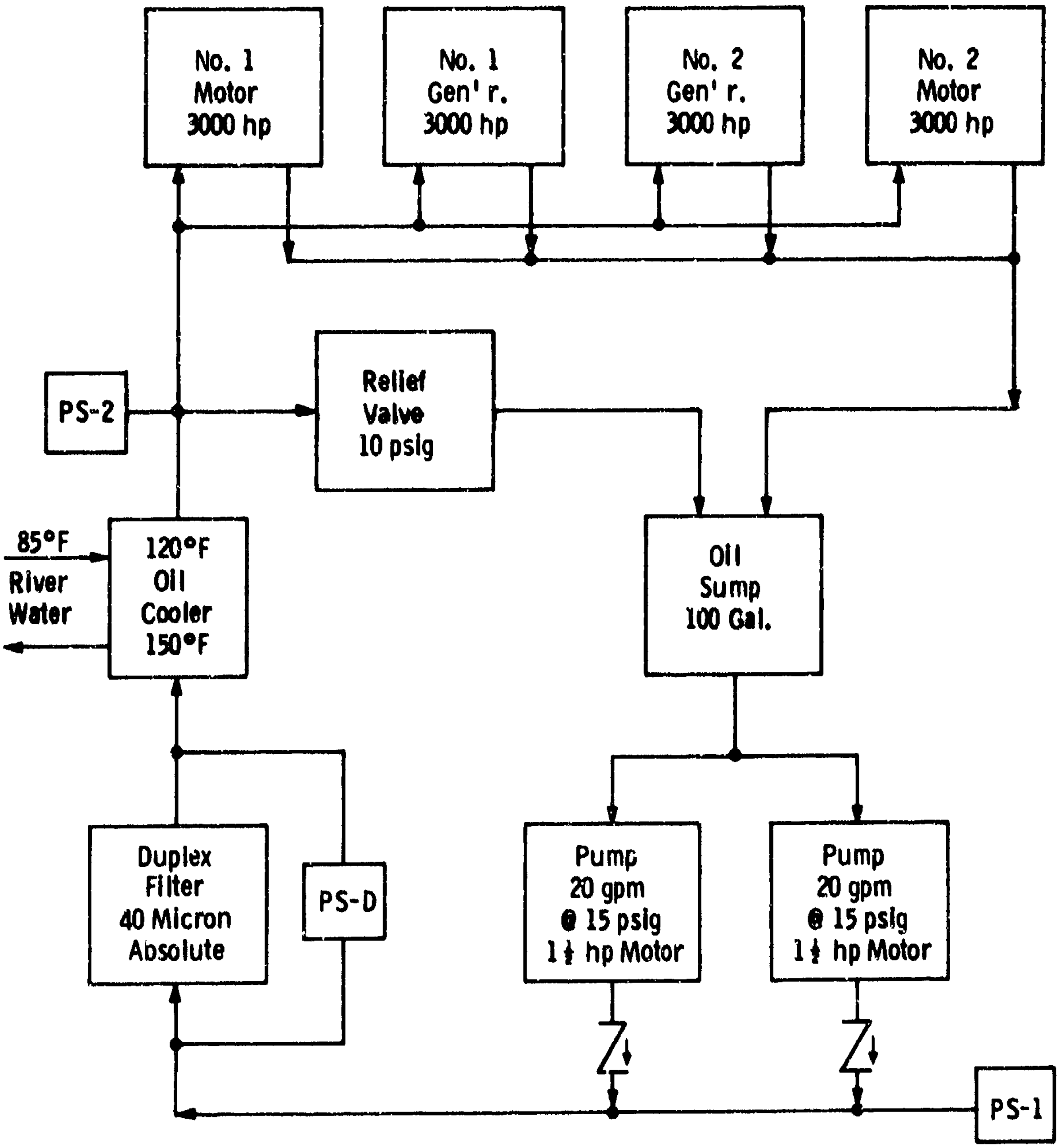


Figure 4.22 Lubrication System Schematic Diagram

TABLE 4.10

LUBE OIL SYSTEM PARAMETERS

Oil Specification	2190 TEP
Sump Capacity	378.5ℓ (100 gallons)
Motor Driven Pump Capacity (2 supplied)	1.26ℓ/sec (20 GPM) per pump
AC Motor Size	1-1/2 HP
AC Power Required	3Ø/60 Hz/460 VAC (non-interruptable)
Maximum L.O. Temperature to Test Stand	48.9°C
Filtration	50 micron (nominal)
Lube Oil Pressure Available at Outlet Flange of Strainer	137.9 KPa (20 psig)
Heat Rejection to Heat Sink	49.14 KW (167,700 Btu/hr)
Cooling Water Required by Heat Sink	2.08ℓ/sec (33 GPM)
Maximum Temperature of Cooling Water Heat Sink	30°C
Pressure Drop of Cooling Water Through Cooler	43.45 KPa (6.3 psig)
Floor Space Required	1.5 x 2.5 meters

4.3.7.2 Cooling Water System

The cooling water system consists of a storage reservoir, two main circulating water pumps, a secondary water conditioning pump, a filter, water conditioning columns and a heat exchanger.

Figure 4.23 is a flow diagram of the cooling water system showing the arrangement of the system elements. Two submerged suction centrifugal pumps are provided in the main circulating water loop to allow flexibility in adjusting the supply flow to meet system demands in various operating configurations. When all four machines are in operation, both main pumps will be required. When three or less machines are in operation, only one pump will be required while the other main pump will be in standby. This provides differing degrees of protection against complete loss of flow in all modes.

The system is also provided with a secondary loop to allow circulation of a small flow of water through the conditioning beds independently from the main flow and, thus, maintain the required water quality. This will also allow conditioning the water with the main circulating loop secured.

The secondary water conditioning loop will be automatically controlled by a resistivity sensor located in the storage tank which starts the secondary loop pump. When the water quality in storage rises above 2 megohm-cm, the conditioning pump will be stopped.

The pressure in the main loop will be unregulated and will be determined by the number of pumps in operation and the system demand. The temperature of the main circulating water can be manually controlled by regulating the heat sink cooling water flow to the heat exchanger.

Alarm switches will be provided on the output header for low pressure and high temperature alarms. In addition, a resistivity cell will be located in the filter outlet flow which will alarm when the water quality drops below 1 megohm-cm. The secondary loop will also be provided with a high conductivity alarm to provide a warning that the water conditioning columns are becoming depleted.

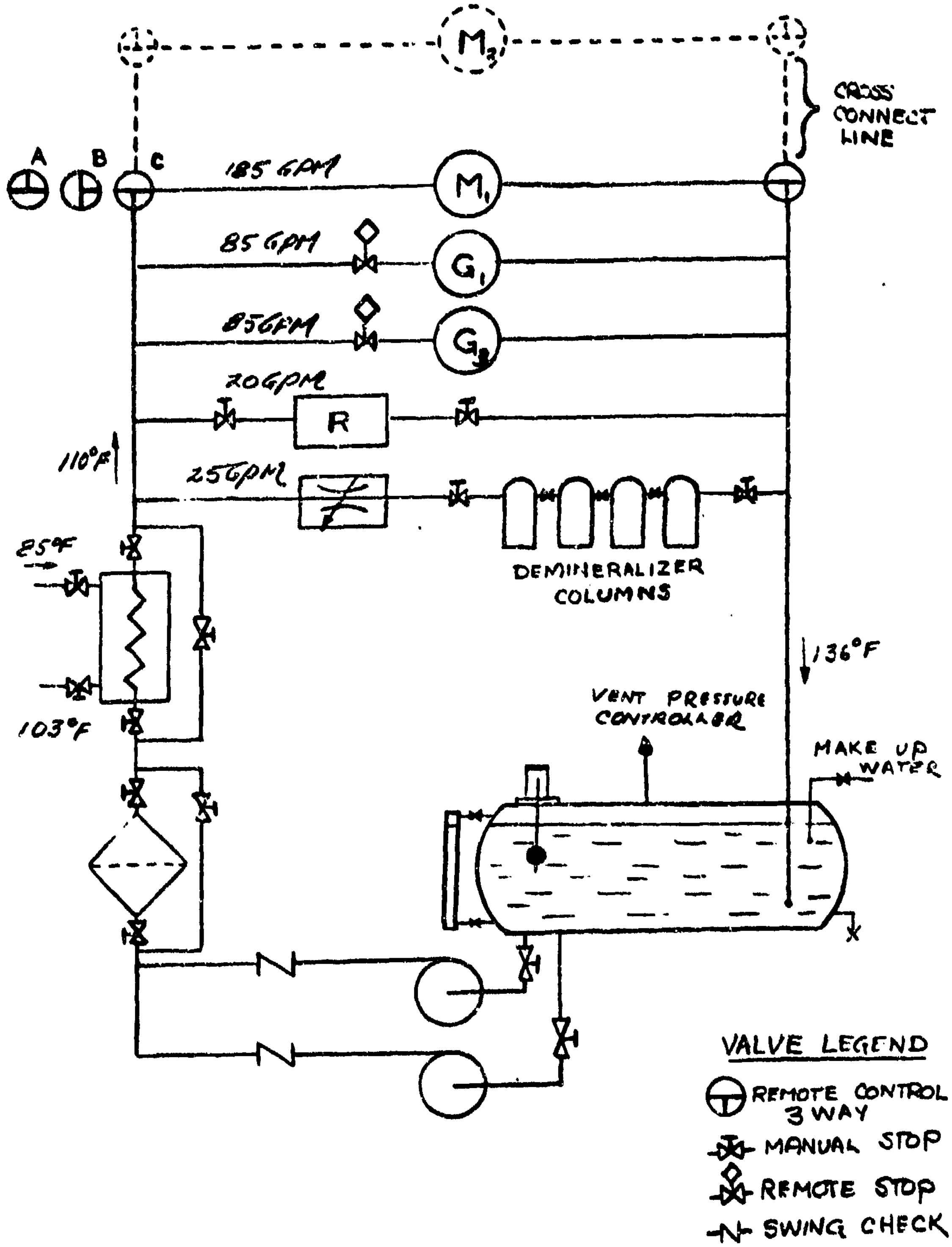


Figure 4.23. Cooling Water System Flow Diagram

A storage tank level alarm is provided to warn of low level in the storage tank and to allow manual replenishment of the water in storage.

The heat exchanger is sized to cool the deionized water to 32.2°C (90°F) when all four machines are in service at full load and when supplied with heat sink cooling water at 26.7°C (80°F). When the heat sink water temperature is below 26.7°C (80°F) or when less than four machines are operating at full load, the deionized cooling water will be cooled to a lower temperature. Manual regulation of the heat sink water flow rate will be required for light loads of minimum temperature heat sink water.

The system will be mounted on a steel bedplate suitable for overhead crane handling.

The system operating parameters are shown in Table 4.11.

4.3.8 Dynamic Braking Resistor

The preliminary design for a four stage dynamic braking resistor is presented. Although the resistance values are no longer current, the intent here is to show the basic design approach.

The resistor elements consist of stainless steel plates which are slotted in such a manner that the current follows a serpentine path. Twenty plates are connected so as to provide four steps of resistance. A housing which has the form of an open box supports the plates (including shock loading) and also serves as a tank for cooling water.

The salient features of the braking resistor are summarized in Table 4.12. In service, the housing is flooded, immersing the plates in deionized water. The water system used for the machines maintains a continuous 75.7 litre/min (20 gpm) flow through the resistor, thus, carrying away the heat generated during a reversal.

TABLE 4.11

SEGMAG COOLING WATER SYSTEM PARAMETERS

Storage Tank Capacity	2271 1 (600 gallons)
Main Cooling Pump Capacity	6.31 l/sec (100 gpm)
Maximum Temperature of Cooling Water (at maximum heat load and maximum temp of heat sink)	32.2°C
Cooling Water Header Pressure (design point)	103.4 KPa (15 psig)
Main Pump Motor Rating (2 supplied)	5 hp 460 VAC, 3Ø, 60 Hz 7.6 Amp 0.8 p.f.
Secondary Cooling Loop Pump Capacity	0.63 l/sec (10 gpm)
Secondary Cooling Loop Motor Rating	1/2 hp 460 VAC, 3Ø, 60 Hz 1 Amp 0.8 p.f.
Floor Space Requirement	2.5 x 3.5 meters
Maximum Temperature of Cooling Water Heat Sink	27°C
Maximum Heat Rejection to Cooling Water Heat Sink	452 KW (1.54×10^6 Btu/hr)
Filtration	25 Micron Nominal

TABLE 4.12

DYNAMIC BRAKING RESISTOR FEATURES

Weight, Dry	359 kg (792 lb)
Weight, Wet	399 kg (879 lb)
Size:	
Width	0.44 m (17.3 in)
Length	0.63 m (24.7 in)
Height	0.66 m (25.8 in)
Material	Type 316 stainless steel
Resistance/Energy Absorbed	
R4	0.0571Ω/7.63 MJ
R3	0.0949Ω/2.28 MJ
R2	0.0597Ω/1.14 MJ
R1	0.0353Ω/0.91 MJ

Type 316 stainless steel is used exclusively except for the electrical insulating material that separates the plates from each other and from the housing. Regarding shock, the braking resistor is designed for static G loads of 30, 45 and 75 in the longitudinal, side, and vertical directions respectively. Under these loads, the maximum stress is no greater than the yield strength of the material which is taken to be 207 MPa (30 kpsi).

During a reversal, the resistors are introduced into the circuit in the order R4, R3, R2 and R1. The values shown for the energy absorbed are for the full power crash back maneuver. Neglecting heat transfer to the water, the plate temperature rise varies between 113°C (for R4) and 123°C (for R1). Considering the plates and water (without flow) as a combined heat sink, the temperature rise would be 44°C.

Figure 4.24 shows a side view of the dynamic braking resistor. The housing is externally ribbed for added strength. In the cut away section, the resistor plates can be seen. The plates are stacked longitudinally, separated by insulating spacers at the top and bottom. Some of these are slightly saw toothed to allow for thermal expansion and preload. A top support restrains the plates in the vertical direction and provides mechanical support around the open top of the housing.

The face of a typical resistor plate is shown in the end view cross-section, Figure 4.25. After installation of the plates and insulating spacers, the wedge is forced into place providing a side preload. The cover on top of the housing prevents water spillage and collects any boil off when energy is dissipated in the dynamic resistor.

Two plate configurations are used. Ten are 9.5 mm (0.375 in.) thick with thirteen slots while the other ten are 15.9 mm (0.625 in.) thick with 9 slots). These are referred to as thin and thick plates respectively. All twenty plates are 0.305 m (12 in.) wide by 0.358 m (14.1 in.) high.

The electrical connections between plates and the leads are shown in Figure 4.26. All connections are at the top of the plates. The resistance stage R4 uses all ten of the thick plates. The other three stages use combinations of the thin plates.

4.3.9 Instrumentation

After construction, the machines will be subjected to certain measurements, among which may be the following:

1. armature resistance
2. armature inductance
3. field resistance
4. field inductance
5. saturation curves
6. speed torque curves

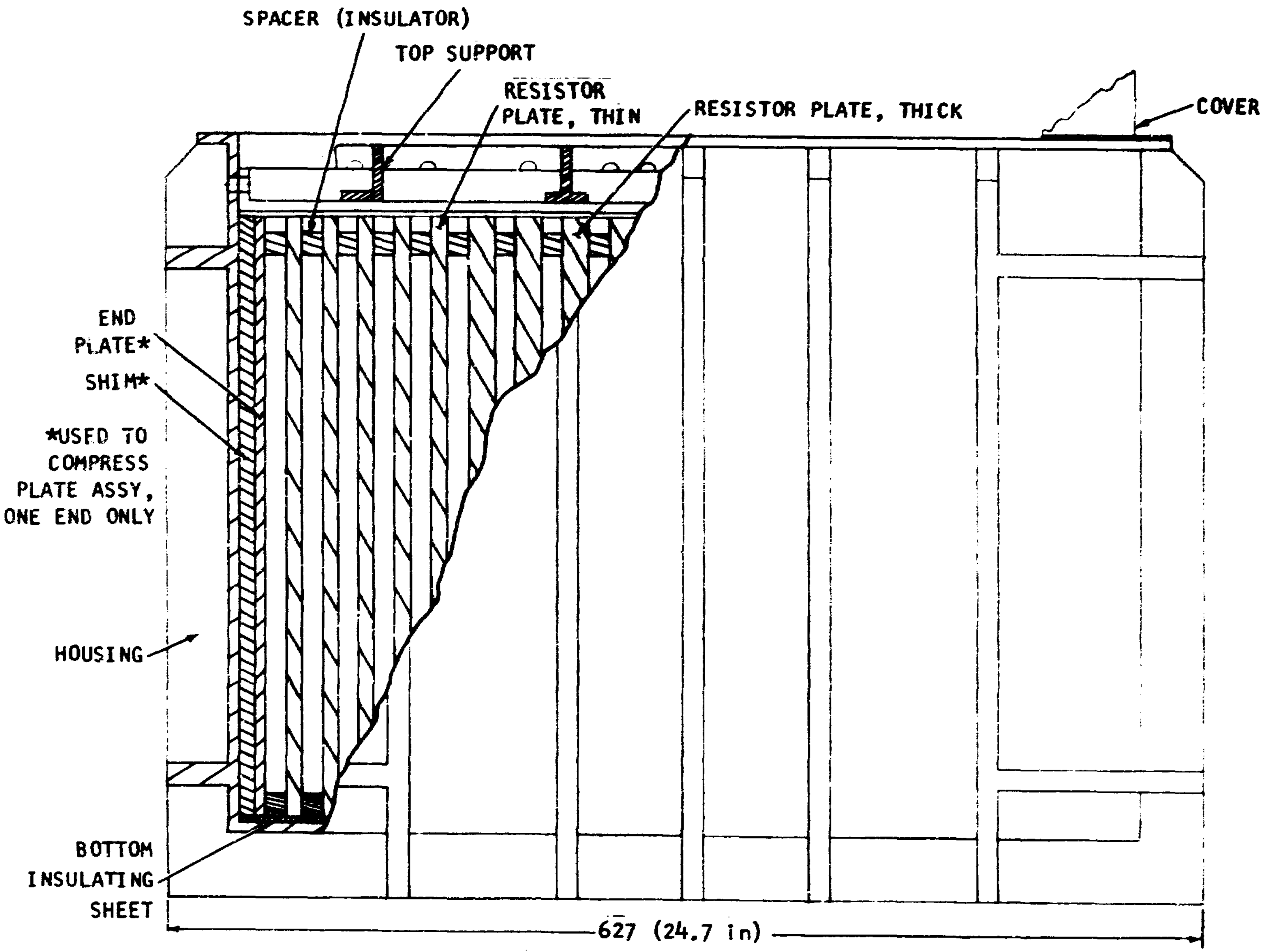


Figure 4.24. Dynamic Braking Resistor - Side View

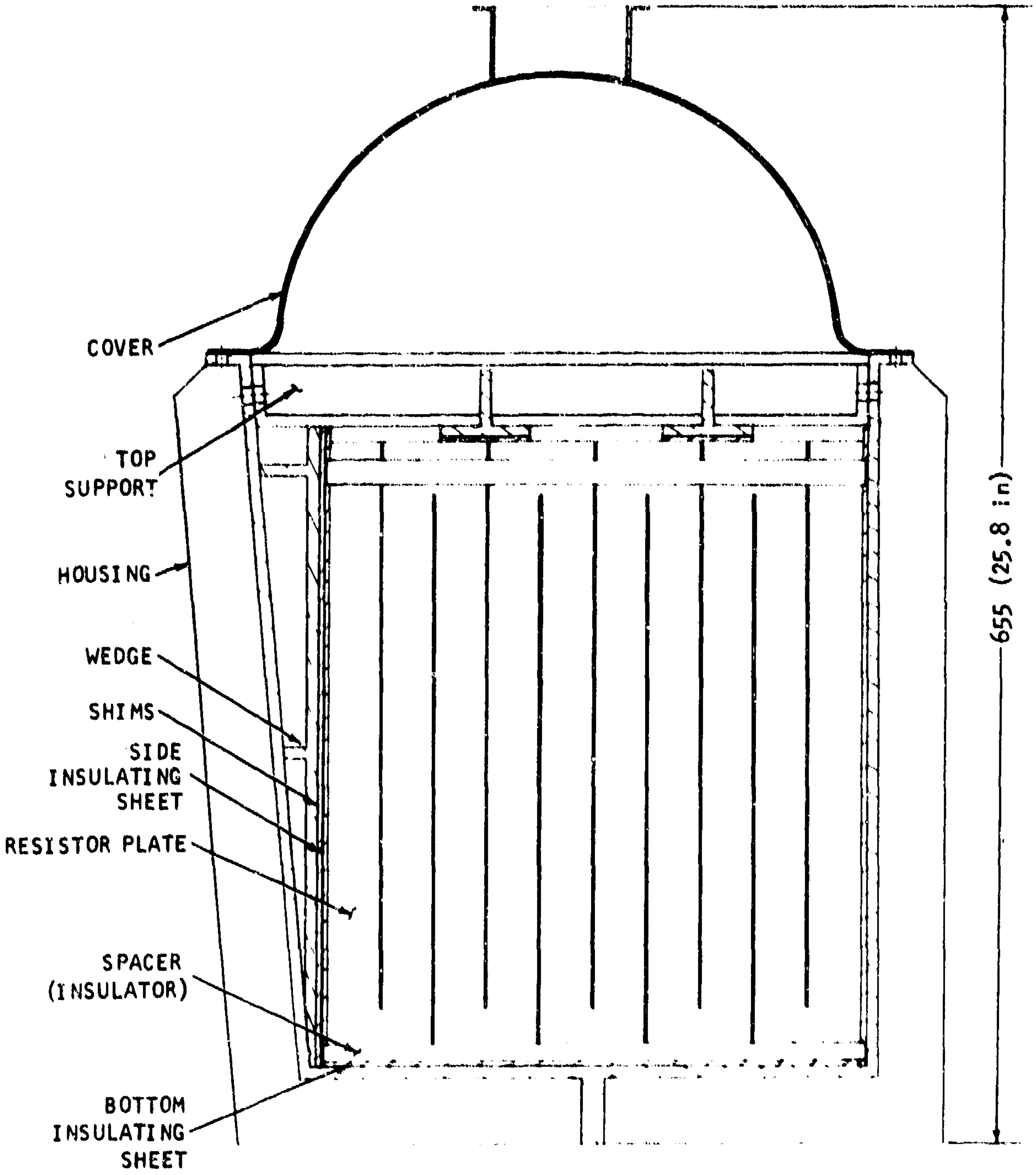


Figure 4.25. Dynamic Braking Resistor - End View Section

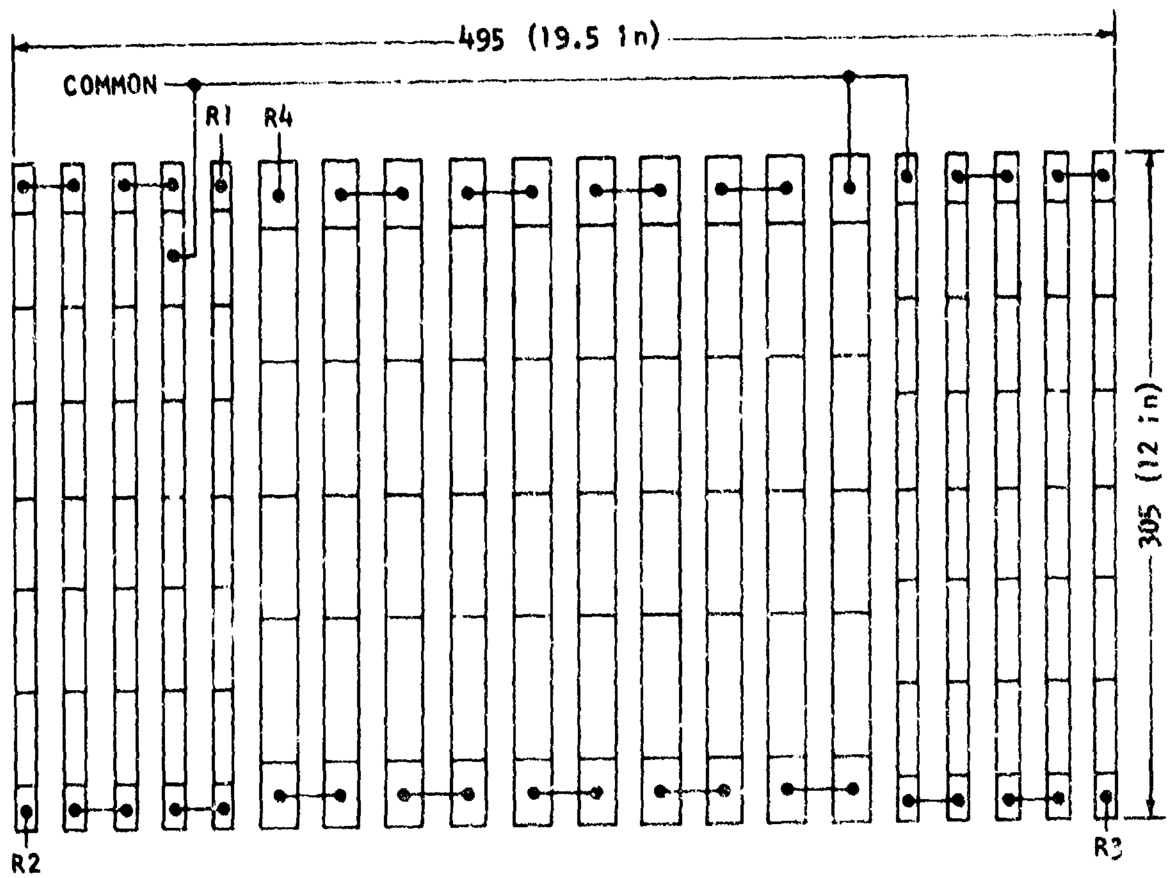


Figure 4.26. Resistor Plates and Connections - Top View

The machines will then be subjected to a series of special manufacturer's tests at the Westinghouse R&D Center to confirm the design objectives. These manufacturer's tests are intended to verify the machine's performance, confirm the design objectives and provide fundamental data of these innovative designs. These objectives require special instrumentation to be installed in the machine during and after assembly to measure certain design parameters. Some of the parameters of interest for the generator are listed on Table 4.13 and for the motor on Table 4.14. These tables also list the expected range of the variables, the location and type of instrumentation and the action required for anomalous variations.

In addition to the special instrumentation required for these manufacturer's tests, the machines will also be instrumented for measuring the type of data normally acquired aboard ship for electrical propulsion systems. The parameters of interest for the generator are listed on Table 4.15 and for the motor on Table 4.16. These last two tables list the variables that will be measured and recorded during the system tests that will be conducted at NAVSEC, Philadelphia Division. Parameters on Tables 4.13 and 4.14 will not be measured during the system tests at NAVSEC unless it is found necessary to do so. For the most part, this can be accommodated quite readily since most of the sensors will still be available.

TABLE 4.13

3000 HP GENERATOR - MANUFACTURER'S TEST INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Stator Bar Currents	7	0-1300 A	Current Shunts	On stator bars of one pole	Oscilloscope indication, record
Rotor Bar Currents	28	0-350 A	Coil, Integrator	On rotor bars of one pole	Oscilloscope indication
Field Waveform	1	0-1.5 Tesla	Coil, Integrator	Internal, on rotor surface	Oscilloscope indication
Collector Flux Density	4	-.1 to +.1 Tesla	Coil, Integrator	Collector	Oscilloscope indication, record
Shaft Voltage	1	0-500 Volts	Brush, Voltmeter	Shaft	Indicate, record
Rotor Dynamics	5	0-1.1 mm	Bently-Nevada Probes	Internal on two planes	Record, in place balance, monitor performance runs
Stator Dynamics	4	0-0.25 mm	IRD Accelerator	Two on bearing housing, two on machine frame	Record, monitor
Rotor, Axial Thrust	1	0-0.25 mm	Dial Indicator	External on shaft	Record, monitor
Brush-Contact Drop	4	0-.1 volt	Voltmeter	Drive end leading brush, drive end trailing brush, water end leading brush, water end, trailing brush	Record
Switch Ring Rotor Bar Temperature	1	0-100°C (32-212°F)	Thermocouple	In bar under brush track	Record

TABLE 4.13 (CONT'D)

3000 HP GENERATOR - MANUFACTURER'S TEST INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Brush Temperature	4	0-100°C (32-212°F)	Thermocouple	In brushes used to measure contact drop	Record
Brush Holder Temperature	2	0-100°C (32-212°F)	Thermocouple	In holder used to measure contact drop	Record
Brush-to-Holder Voltage	2	0-0.1 Volt	Voltmeter	On holder used to measure contact drop	Record
Air Gap Flux Density	1	-1.6 to +1.6 Tesla	Search Coil	Surface of Rotor	Oscilloscope indication

TABLE 4.14

3000 HP MOTOR - MANUFACTURER'S TEST INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Stator Bar Currents	7	0-1300 A	Current Shunts	On stator bars of one pole	Oscilloscope indication, record
Rotor Bar Currents	16	0-600 A	Coil, Integrator	On rotor bars of one pole	Oscilloscope indication
Field Waveform	1	0-1.5 Tesla	Coil, Integrator	Internal, on rotor surface	Oscilloscope indication
Collector Flux Density	4	-.1 to +.1 Tesla	Coil, Integrator	Collector	Oscilloscope indication, record
Shaft Voltage	1	0-500 Volts	Brush, Voltmeter	Shaft	Indicate, record
Rotor Dynamics	5	0-1.1 mm	Bently Nevada Probes	Internal on two planes	Record, in place balance, monitor performance runs
Stator Dynamics	4	0-0.25 mm	IRD Accelerometer	Two on bearing housing, two on machine frame	Record, monitor
Rotor, Axial Thrust	1	0-0.25 mm	Dial Indicator	External on shaft	Record, monitor
Brush-Contact Drop	4	0-.1 volt	Voltmeter	Drive end leading brush, drive end trailing brush, water end loading brush, water end, trailing brush	Record
Switch Ring Rotor Bar Temperature	1	0-100°C (32-212°F)	Thermocouple	In bar under brush track	Record

TABLE 4.14 (CONT'D)

3000 HP MOTOR - MANUFACTURER'S TEST INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Brush Temperature	4	0-100°C (32-212°F)	Thermocouple	In brushes used to measure contact drop	Record
Brush Holder Temperature	2	0-100°C (32-212°F)	Thermocouple	In holder used to measure contact drop	Record
Brush-to-Holder Voltage	2	0-0.1 Volt	Voltmeter	On holder used to measure contact drop	Record
Air Gap Flux Density	1	-1.6 to +1.6 Tesla	Search Coil	Surface of Rotor	Oscilloscope indication

TABLE 4.15

3000 HP GENERATOR INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Rotor Cooling Water Flow	1	1-2 ℓ/sec (15-32 gpm)	Flow Meter	External to machine on inlet header	Recorded, warning given at flows less than 1 ℓ/sec
Field Coil Cooling Water Flow	4	63-126 mℓ/sec (1-2 gpm)	Diff. Press. Sensor and Orifice	Internal to machine at each coil inlet	Recorded, automatic machine shut down at less than 30 mℓ/sec
Current Collect Cooling Water Flow	16	19-57 mℓ/sec (.3-.9 gpm)	Diff. Press.	Internal to machine in inlet to each collector	Recorded, automatic shut-down at less than 6 mℓ/sec
Stator Cooling Water Flow	1	1-2 ℓ/sec (15-32 gpm)	Flow Meter	External to machine on inlet header	Recorded, warning given at flows less than 1 ℓ/sec
Rotor Cooling Water Inlet Temperature	1	15-55°C (59-149°F)	Iron-Const. Thermocouple	External to machine on inlet header.	Recorded
Rotor Cooling Water Outlet Temperature	1	15-65°C (59-149°F)	Iron-Const. Thermocouple	External to machine on outlet header	Recorded, warning at 52°C (125°F), automatic shut-down at 65°C (149°F)
Cooling Water Manifold Inlet Temperature	2	15-65°C (59-149°F)	Iron-Const. Thermocouple	Internal to machine on inlet line	Recorded
Field Coil Water Outlet Temperature	4	15-65°C (59-149°F)	Iron-Const. Thermocouple	Internal to machine on discharge line	Recorded, automatic shut-down at 65°C (149°F)
Current Collector Water Outlet Temperature	16	15-64°C (59-149°F)	Iron-Const. Thermocouple	Internal to machine at each holder outlet	Recorded, automatic shut-down at 65°C

TABLE 4.15 (CONT'D)

3000 HP GENERATOR INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Bearing Oil Flow	2	250-750 mℓ/sec (4-12 gpm)	Flowmeter	External to machine at each bearing oil inlet	Recorded
Bearing Temperature	2	32-82°C (90-180°F)	Iron-Const. Thermocouple	In bearing housing	Recorded, automatic shut-down at 82°C (180°F)
Shaft Speed	1	0-4300 rpm	Tachometer	External to machine by connector shaft	Control parameter, record, warning at 3780 rpm, automatic shutdown at 4300 rpm
Shaft Torque	1	-6000 to +6000 Nm/rad (-4425 to +4425 lb/ft)	Strain Gauge on Rotor	External to machine on input shaft	Record, control parameter
Armature Voltage	1	-600 to +600 volts	Voltmeter	Generator bus in breaker cubicle	Record, control parameter
Armature Current	1	-9000 to +9000 amps	Current Shunt	Generator bus in breaker cubicle	Control parameter, record, interrupt at 9000 amps
Field Voltage	1	-250 to +250 Volts	Voltmeter	Field power supply output	Control parameter, record
Field Current	1	-350 to +350 Amps	Current Shunt	Field power supply output	Control parameter, record
Field Coil Temperature	12	22-150°C (71.6-300°F)	Iron-Const. Thermocouple	Imbedded in field coil	Record, alarm at 150°C
Cooling Water Inlet Manifold Pressure	1	0-100 kPA (0-15 psi)	Pressure Guage	Cooling water inlet manifold	Record

TABLE 4.15 (CONT'D)

3000 HP GENERATOR INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Cooling Water Outlet Manifold Pressure	1	0-50 kPA (0-7 psi)	Pressure Gauge	Cooling Water Outlet Manifold	Record
Rotor Bar Hot Spot Temperatures	4	20-122°C (68-250°F)	Thermocouples	Internal to rotor winding	Record, alarm at 122°C
Collector Bar Temperature	1	20-122°C (68-250°F)	Thermocouple	Internal to machine rotor at a collector bar	Record, alarm at 122°C
Stator Bar Hot Spot Temperature	4	20-122°C (68-250°F)	Thermocouple	Internal to Stator Winding	Record, alarm at 122°C

TABLE 4.16

3000 HP MOTOR INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Rotor Cooling Water Flow	1	1-2 ℓ/sec (16-32 gpm)	Flow Meter	External to machine on inlet header	Recorded, warning given at flows less than 1 ℓ/sec
Field Coil Cooling Water Flow	6	63-126 mℓ/sec (1-2 gpm)	Diff. Press. Sensor and Orifice	Internal to machine at each coil inlet	Recorded, automatic machine shut down at less than 30 mℓ/sec
Current Collect Cooling Water Flow	24	19-57 mℓ/sec (.3-.9 gpm)	Diff. Press.	Internal to machine in inlet to each collector	Recorded, automatic shut-down at less than 6 mℓ/sec
Stator Cooling Water Flow	1	1-2 ℓ/sec (16-32 gpm)	Flow Meter	External to machine on inlet header	Recorded, warning given at flows less than 1 ℓ/sec
Rotor Cooling Water Inlet Temperature	1	15-55°C (59-149°F)	Iron-Const. Thermocouple	External to machine on inlet header.	Recorded
Rotor Cooling Water Outlet Temperature	1	15-65°C (59-149°F)	Iron-Const. Thermocouple	External to machine on outlet header	Recorded, warning at 52°C (125°F), automatic shut-down at 65°C (149°F)
Cooling Water Manifold Inlet Temperature	2	15-65°C (59-149°F)	Iron-Const. Thermocouple	Internal to machine on inlet line	Recorded
Field Coil Water Outlet Temperature	6	15-65°C (59-149°F)	Iron-Const. Thermocouple	Internal to machine on discharge line	Recorded, automatic shut-down at 65°C (149°F)
Current Collector Water Outlet Temperature	24	15-64°C (59-149°F)	Iron-Const. Thermocouple	Internal to machine at each holder outlet	Recorded, automatic shut-down at 65°C

TABLE 4.16 (CONT'D)

3000 HP MOTOR INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Bearing Oil Flow	2	250-750 mℓ/sec (4-12 gpm)	Flowmeter	External to machine at each bearing oil inlet	Recorded
Bearing Temperature	2	32-82°C (90-180°F)	Iron-Const. Thermocouple	In bearing housing	Recorded, automatic shut-down at 82°C (180°F)
Shaft Speed	1	0-1350 rpm	Tachometer	External to machine or motor shaft	Control parameter, record, warning at 1250 rpm, automatic shutdown at 1350 rpm
Shaft Torque	1	-17627 to +17627 Nm/rad (-13,000 to +13000 lb/ft)	Strain Gauge on Rotor	External to machine on input shaft	Record, control parameter
Armature Voltage	1	-600 to +600 volts	Voltmeter	Motor bus in breaker cubicle	Record, control parameter
Armature Current	1	-9000 to +9000 amps	Current Shunt	Motor bus in breaker cubicle	Control parameter, record, interrupt at 9000 amps
Field Voltage	1	-250 to +250 Volts	Voltmeter	Field power supply output	Control parameter, record
Field Current	1	-350 to +350 Amps	Current Shunt	Field power supply output	Control parameter, record
Field Coil Temperature	12	22-150°C (71.6-300°F)	Iron-Const. Thermocouple	Imbedded in field coil	Record, alarm at 150°C
Cooling Water Inlet Manifold Pressure	1	0-100 kPA (0-15 psi)	Pressure Guage	Cooling water inlet manifold	Record

TABLE 4.16 (CONT'D)

3000 HP MOTOR INSTRUMENTATION

Parameter	No. of Sensors	Expected Range	Sensing Device	Location	Action
Cooling Water Outlet Manifold Pressure	1	0-50 kPA (0-7 psi)	Pressure Gauge	Cooling Water Outlet Manifold	Record
Rotor Bar Hot Spot Temperatures	6	20-122°C (68-250°F)	Thermocouples	Internal to rotor winding	Record, alarm at 122°C
Collector Bar Temperature	1	20-122°C (68-250°F)	Thermocouple	Internal to machine rotor at a collector bar	Record, alarm at 122°C
Stator Bar Hot Spot Temperature	4	20-122°C (68-250°F)	Thermocouple	Internal to Stator Winding	Record, alarm at 122°C

VOLUME B - HYDROFOIL CRAFT

SECTION 1

INTRODUCTION - (See Volume A)

1.2 Exceptions

A requirement specified in the work directive for the hydrofoil craft was that the maximum motor diameter should not exceed 42" in order to fit within the pad. After a rather thorough analysis it was determined that the motor stator diameter should be at least 54" in order to permit the motor to operate below its first critical frequency. In addition, the end frame diameter must be about 58", although with some redesign this might be reduced to the 54" stator diameter if the internal connections between brush holders were accomplished in a different manner. A reconsideration of the maximum pod diameter should be undertaken to determine if the pod diameter in the motor area could be modified to accommodate this motor.

1.3 Development Risks - Same as Volume A

SECTION 2

DESCRIPTION

2.1 Physical Description

The propulsion system for the hydrofoil craft consists of a single 15,000 KW generator driving a 20,000 hp, 1200 RPM motor per shaft. The generator would be similar to the generators proposed for the destroyer type ship. The mode of control would be similar to that for the destroyer with the exception that the equipment always operates in the split plant arrangement and also that reversing capability is not required. Dynamic braking could still be utilized for rapid stopping if necessary. One of the major differences in the two systems is that the generators are mounted high on the first deck and the motors located in the pods directly connected by short shafts to the supercavitating propellers. Power is thus transmitted electrically down the struts which simplifies the machinery arrangement. Rotary swivel joints in the electrical power transmission lines permit the foils to be raised for hull born operation.

2.1.1 System Layouts, Hydrofoil Ship

The hydrofoil ship type specified for the arrangement study is a 750 ton 50 knot ship with the canard configuration of foils. Foil-borne propulsion is by supercavitating propellers located at the two pods which also support the aft foils. For hull borne propulsion a separate system will be provided, this not being a part of this study.

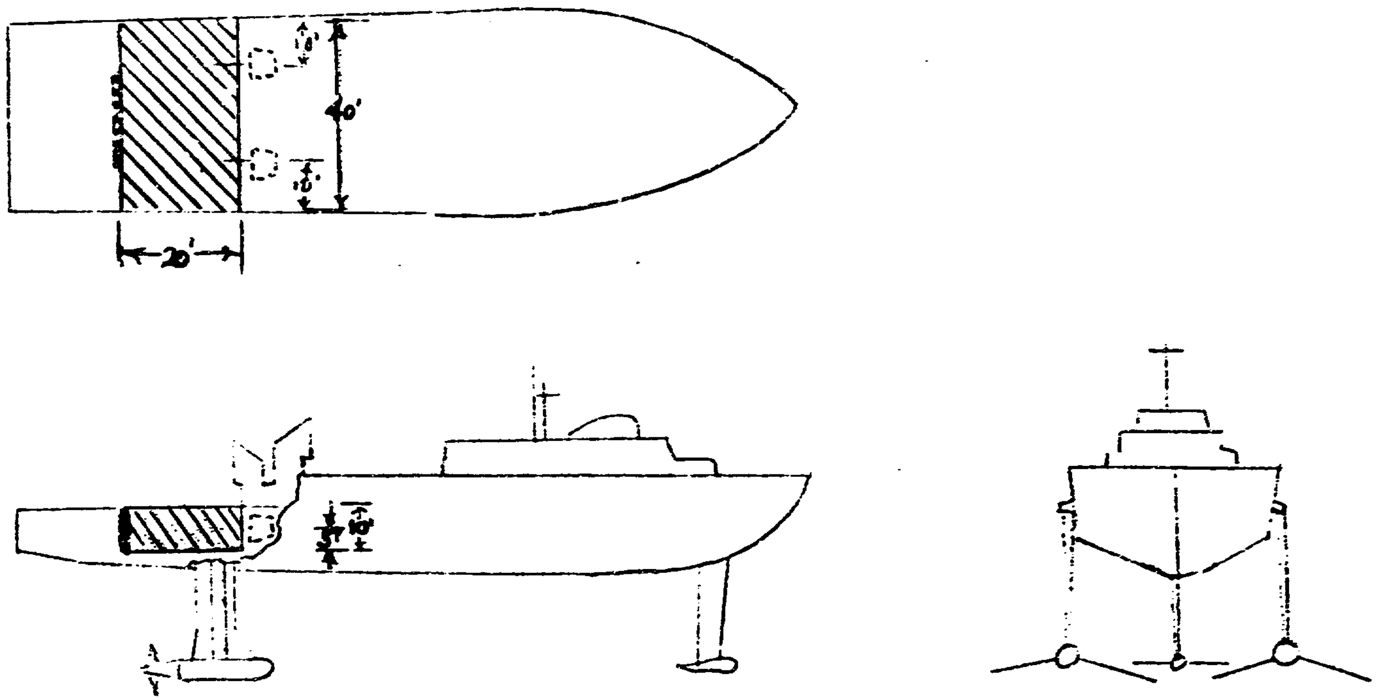
The foilborne propulsion power is furnished by two LM-2500 gas turbines, each driving a generator at 3600 rpm. The two propellers operate at 1200 rpm max. and are powered by a direct drive motor, one for each pod, delivering 20,000 SHP to the propeller. The propeller, its shafting and the thrust bearing are not included in this study. The motor is not expected to absorb any externally imposed thrust or lateral loads at the coupling.

Each strut is 36' long and is hinged to rotate 200° into the elevated, retracted, position. An electrical current path joint across the hinge is required and this is a part of the study.

The SEGMAG motor has been designed to as small a diameter as feasible consistent with the speed rating of 1200 rpm plus the objective of providing a rotor stiff in bending with a high critical speed. Even so, the outside diameter of the frame is 54" and the diameter over the end bracket flanges is 58", and this size requires a larger diameter pod than has been allotted by Figure B2.1, which gives the allotted dimensions for the electrical machinery and controls.

The space allowed for the generators and controls is 20' long x 40' wide x 10' high, with ships service connections being available at the after bulkhead of the space. Looking first at a plan view of the generator space and the gas turbine room, Figure B2.2, the gas turbines are shown enclosed in the sound barrier shock mounted housing provided on DD963. On the hydrofoil ship these enclosures and mounts may not be required - the question should be addressed in a separate study, the study to include the dynamics of the interface shafting between power turbine and generator. Also the space taken by the gas turbines and the intake ducts on the DD963 is increased by the auxiliary air demand, so that again more detail examination is warranted in this area.

As envisioned in the Work Statement requirements of Figure B2.1, and reflected in the plan view Figure B2.2, the turbine output shaft drives through the forward bulkhead of the generator room, possibly requiring a bulkhead shaft seal - a difficult design matter at 3600 rpm. In any event, in the arrangement shown, the generator coupling flange is located in the turbine room, so that the bulkhead seal housing must be split and have an outside diameter larger than the generator coupling OD in order to allow rotor removal.



NOTES:

1. Crosshatched areas are available drive system space. Machinery arrangements within the generator space dimensions must permit personnel access.
2. Symbol (▬▬▬) indicates location of ship services described in enclosure (5).

Figure B-2.1. Hydrofoil Ship Space Allotted for Machinery

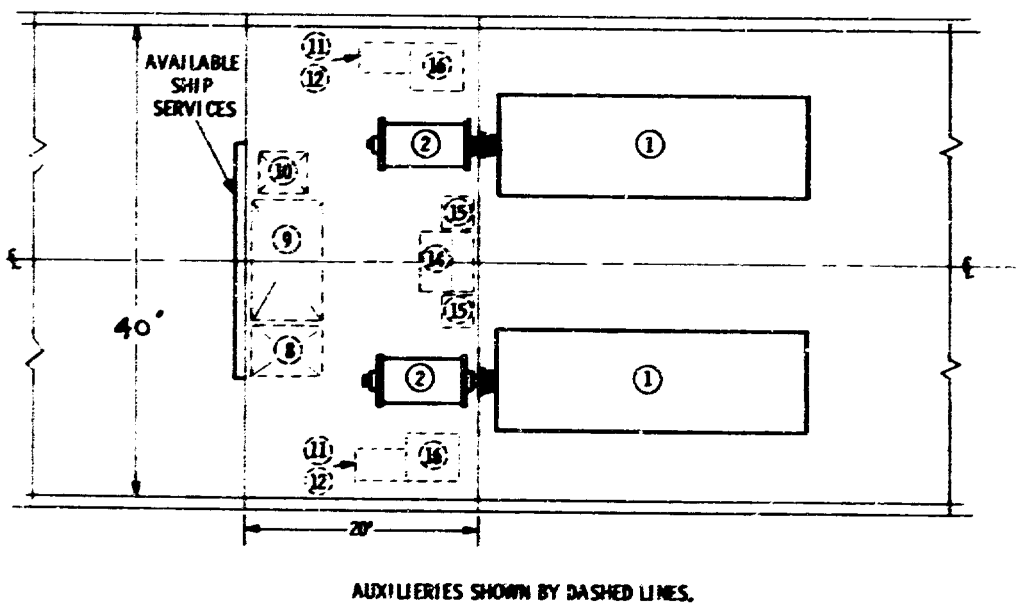


Figure B2.2. Hydrofoil Ship Arrangement, Plan View

Shown in outline and in dashed lines are the mechanical auxiliaries, the electrical switchgear and the controls necessary to operate the electric propulsion system. The numbered labels correspond to the items of Table B2.1 listing the main components, auxiliaries and controls. Not shown in the arrangement sketches of Figures B2.2 and B2.3 are the electrical bus work, cables and piping associated with the propulsion system. Figure B2.3 is the hydrofoil ship in elevation, shown from the air intakes aft to the transom. Shown also in outline are the main struts and pods, positioned in the operating mode. Not shown are the hull borne propellers, shafting and engines. The general outline in elevation is similar to that developed by Boeing for a proposed DEH and depicted in the paper referenced below.*

TABLE B2.1

LEGEND FOR FIGURES B2.2, B2.3 and B2.4

Item	
1	Propulsion gas turbine
2	Propulsion generator
3	Propulsion motor
4	Thrust bearing
5	Lubricating oil system
6	Cooling water system for motor and generators
7	Brush atmosphere system
8	Generator exciters and control
9	Motor exciter and control
10	Control console with logic boards and supervisory control
11	Interface relay cabinet
12	Switchgear

*DEH, A High Endurance Escort Hydrofoil for the Fleet, Aroner and Hubbard, AIAA Paper No. 74-311, February 1974.

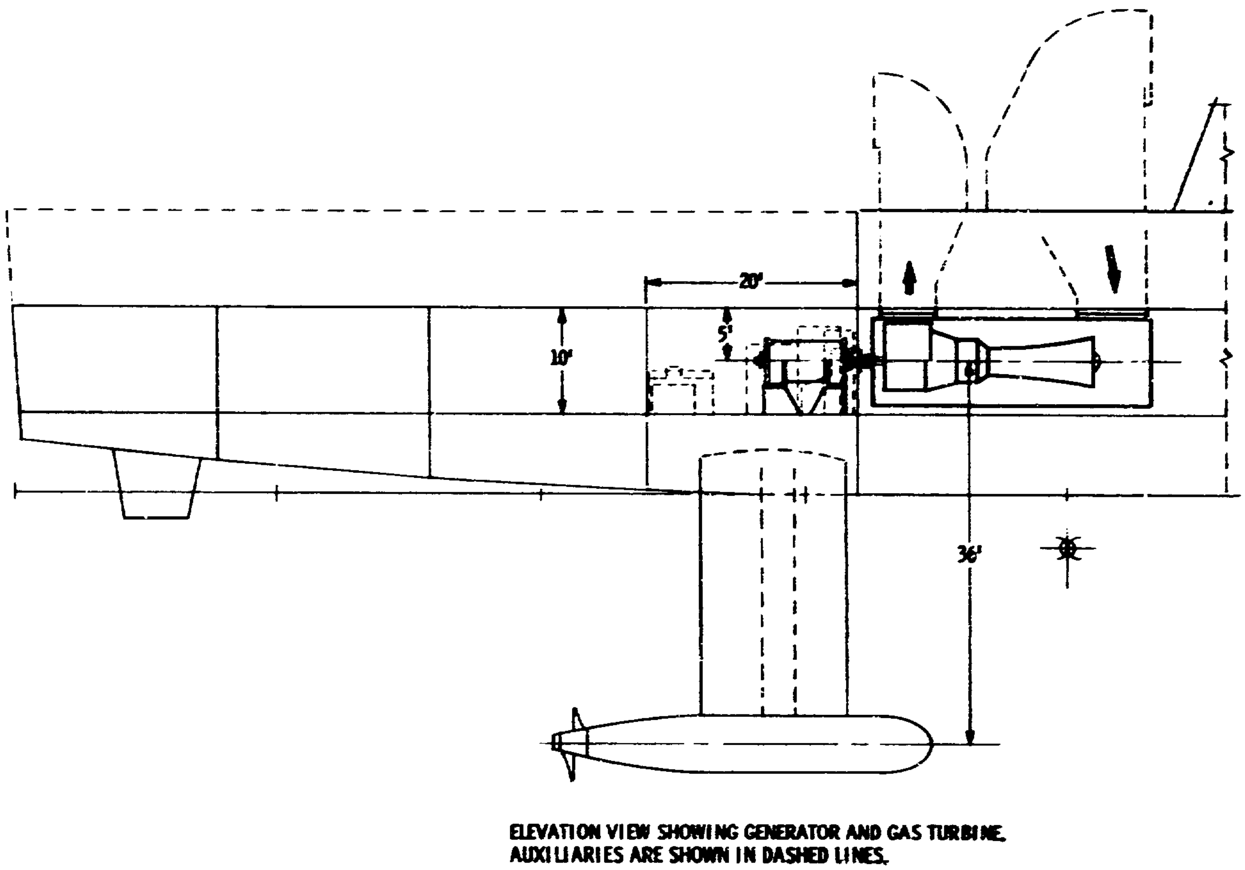


Figure B2.3. Hydrofoil Ship Arrangement, Elevation

Again the space utilized for the generators and controls is the 20' long x 10' high allotment of Figure B2.1. It is evident from Figure B2.2 and B2.3 that the space allotted is entirely adequate for the generators and auxiliaries. It should be noted that the dynamic braking resistors and controls required for the destroyer system are not needed for the hydrofoil, and are not shown.

The elevation view Figure B2.3 shows the machinery outline of the gas turbine within the noise isolation enclosure. The generator is provided with a foundation independent of the turbine. A study should be made of the arrangement of a common bedplate for the gas turbine and generator, with and without noise enclosure, and with and without shock mounts, with the gas turbine generator unit not separated by the bulkhead shown in Figures B2.2 and B2.3. The results of such a study may show a significant weight saving and better running speed dynamics for the power turbine - generator rotor systems.

The SEGMAG motor mounted in the main drive pod is shown in partial section in Figure B2.4. Although there is more than adequate allotted length for the motor and its auxiliaries, the 42" diameter allocation of Figure B2.1 is 16" less than the overall diameter of the motor. Allowing 6" of thickness for pod wall structure, the pod size for the 20,000 SHP 1200 rpm motor described in the motor and generator section of this report* is 58" inside diameter and 70" outside diameter (5'-10" diameter). It may be possible to reduce the motor OD by several inches by refinement of the end bracket flange design. However, reduction to 42" overall diameter does not seem to be within the realm of possibility at the present writing.

The motor is supported at each end of the stator iron by a 2" wide girth flange encircling the motor frame barrel. This girth flange extends through an elongated section to join the strut structure

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*Westinghouse Dwg. 1289J35, 20,000 HP Hydrofoil Motor

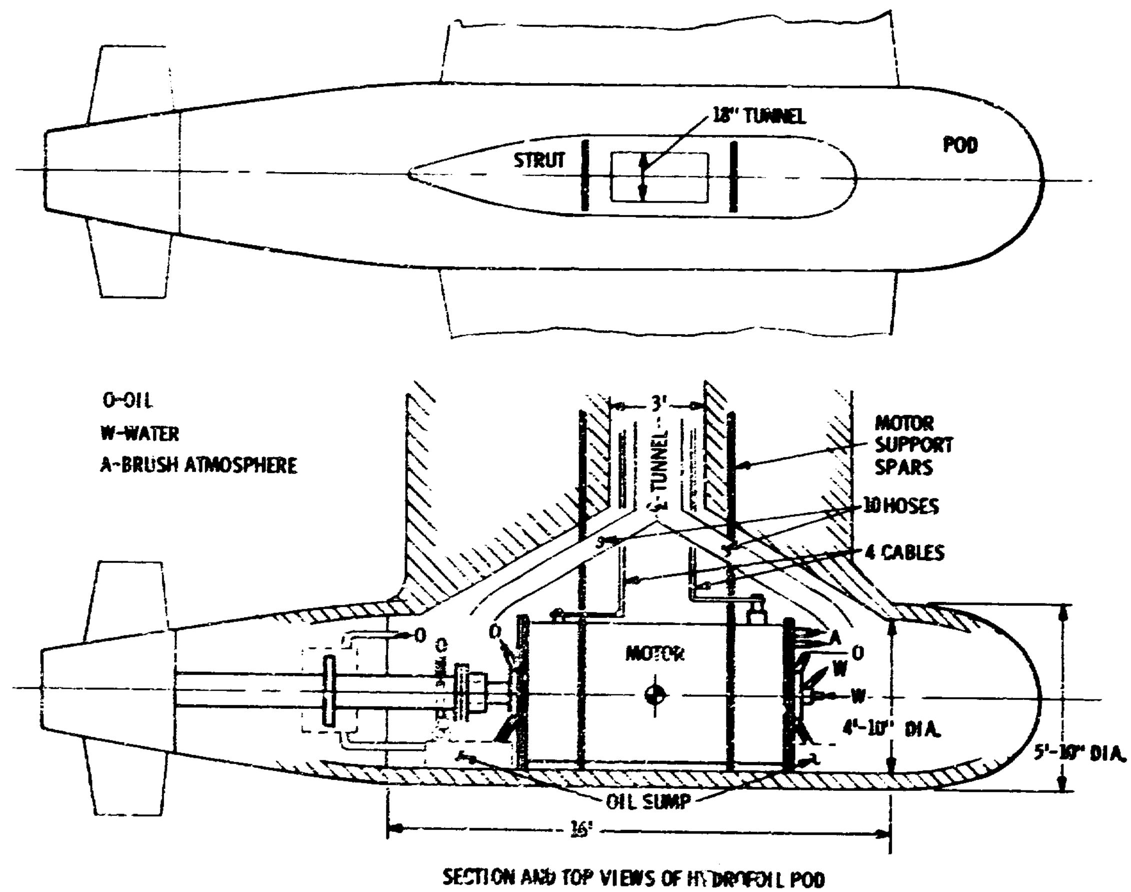

Figure B2.4. Hydrofoil Ship Arrangement, Pod Section in a configuration not yet designed but shown schematically in Figure B2.4. The motor C.G. is shown offset forward of the strut center to balance the weight of the propeller and shafting.

No flexible coupling is provided at the shaft-motor interface. Detail examination of the shaft misalignment requirements may show that a flexible coupling is needed.

Aside from waterfoil control power requirements and monitoring systems, the propulsion motor pod must be provided with these service connections:

DC power cables or buses, rated at 2000 volts, 7500 amperes
DC field excitation cables
Lubricating oil supply and return lines
Cooling water supply and return lines
Brush atmosphere supply and return ducts

The electric services would be by cables and the other services by hoses, all of which would lead down through the 36" x 18" tunnel space allotted within the strut by Figure B2.1. Special design work is required to be done at the hinged joint to accommodate the 200° rotation angle through which the hoses must move. The electrical cables are addressed later.

It is evident from the relatively congested space within the pod and the strut that great attention will have to be given the enveloping structure of pod and strut to allow assembly and disassembly of the machinery. It is also rather evident that all pod mounted components must have the attribute of long time operation without any attention or maintenance. In addition, it is understood that regardless of design, construction and maintenance efforts, eventually the pod will flood with seawater and probably with the full head of water pressure (about 15 psig). So that prudent design would insure watertight construction of all machinery and electrical components, or else other safeguards against seawater intrusion such as pressure buffered interiors.

No local electric circuit protection is provided, the circuit breakers, switches and fuses being located in the hull. The supply through hoses of the motor cooling water and the brush atmosphere presents no especial difficulty, since these systems operate full and the return lines will be pressurized.

The lubricating oil system presents more difficult problems. Normally, motor bearing housings have atmospheric pressure drain systems leading to a sump at ambient pressure. Usual designs of shaft seals require nearly atmospheric pressure and non-solid oil at the last space between bearing and seal. Therefore the drain systems and the sump will have to be given special design attention for this pod mounted motor.

Even more important the sump must be scavenged continuously by a positive displacement pump to return the oil to the hull-located main lube oil system. This pump should preferably be shaft driven and backed up by an electric pump for redundancy. The sump would probably operate nearly dry.

Fortunately the motor lube oil system need be operative only when the pod and strut are in the vertical downward position. Means must be provided to isolate and possibly drain the system prior to raising the struts and inverting the pod and motor.

An alternate design and arrangement of the motor bearings should be studied in depth to eliminate the above lube oil system problems. This alternate design would follow locomotive traction motor practices and employ cylindrical roller bearings in lieu of babbitted sleeve bearings and grease lubrication instead of oil lubrication. Speeds and loads are well within proven grease lubricated motor roller bearing practice. Regreasing intervals for rail transportation motors are long, ranging from one to several years, depending upon the severity of service, and thus would be consistent with naval ship availability schedules.

Use of grease lubricated roller bearings would eliminate the problems inherent with a hull-mounted lube oil system servicing the motor in the pod. The main thrust bearing for the propeller would still require a supply of lube oil. However, in the usual arrangement of housing the interior is pressurized slightly above ambient so that drainage and return of oil to the hull is not complicated by a sump.

2.2 System Block Diagrams

The main propulsion system power blade diagram is shown on Figure B2.5, which simply shows a turbine generator driving a propulsion motor for each shaft. The plant is always operated in the split mode. The physical characteristics of the system are tabulated on Table B2.2, which lists the major characteristics of the ship, and the mechanical and electrical characteristics of the generator and the motor.

2.3 System Operation

2.3.1 Normal Operation

This section which describes normal operation is divided into the following major parts: electrical diagrams, system performance, and representative mission.

2.3.1.1 Electrical Diagrams

The propulsion system power schematic is shown in Figure B2.6. Each SEGMAG dc generator (G1 and G2) is driven directly by a LM-2500 gas turbine (GT1 and GT2). The SEGMAG dc motors (M1 and M2) are located in the pods, each directly coupled to a propeller. The nominal rating for the generators and motors is 15 MW (20,000 hp) at rotational speeds of 3600 rev/min and 1200 rev/min respectively.

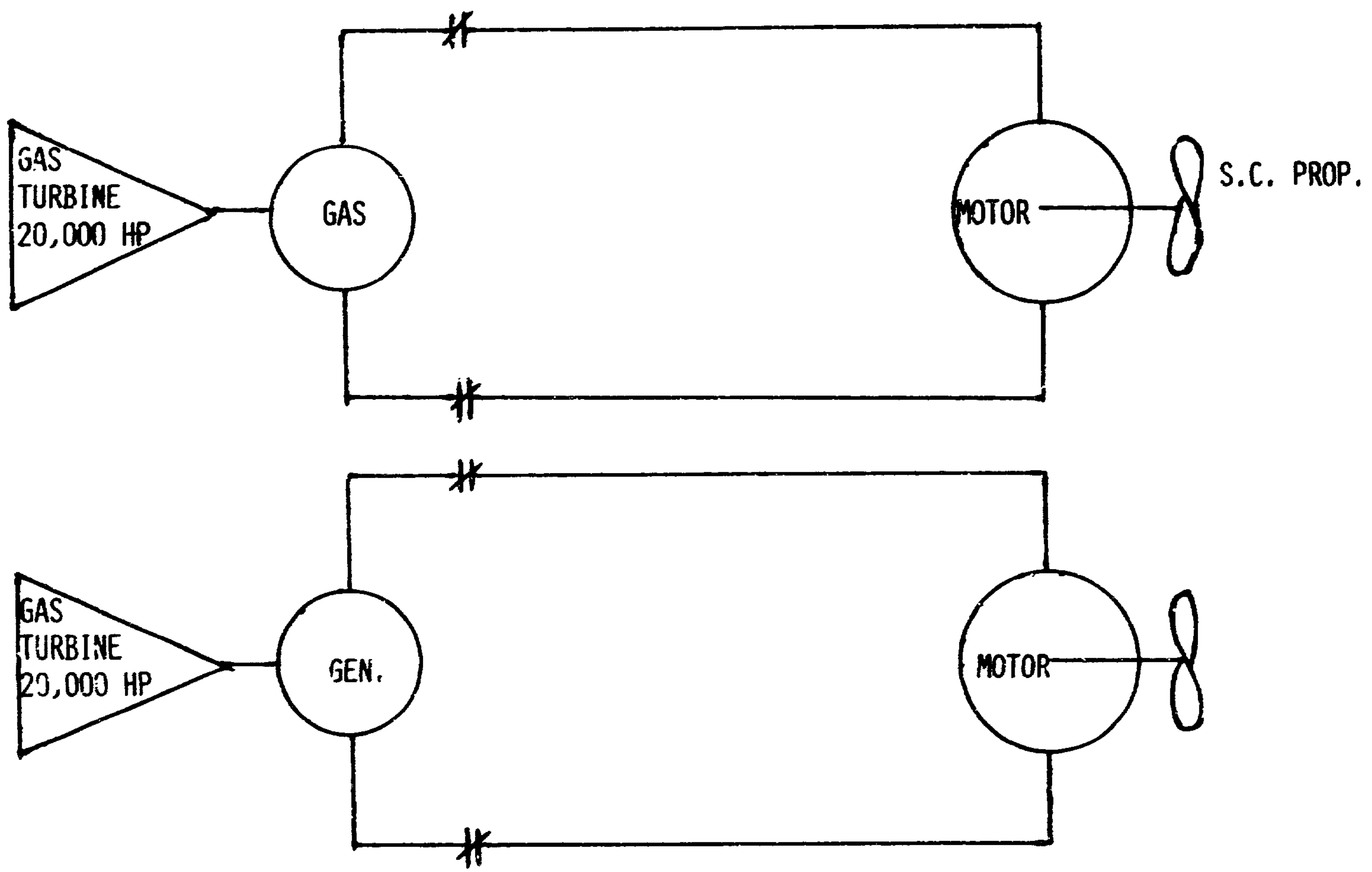

Figure B2.5. Hydrofoil Ship Power Diagram

TABLE B2.2

BASELINE PROPULSION SYSTEM FOR HYDROFIOL SHIP

Ship Data

Displacement	680 Metric Tons (750 Tons)
Ship's Speed	25.7 M/S (50 Knots = 84.4 FPS)
Prime Movers	Two - 14.9 MW (Two - 20,000 HP) LM 2500 Gas Turbines
Propeller Speed	123.6 r/s (1180 RPM) @ Max. Torque of 118.2 kNm (87,200 lb ft)

Generator Data

Nominal Rating	Electrical	Mechanical
	15. MW	1.15 m (45.2") Stator OD
	2,000 Volts	0.61 m (24.0") Rotor OD
	7,500 Amps	0.28 m (11.0") Rotor ID
	377 r/s	2.58 m (100") $Length_{BB}$
	4 Poles	10.8 Mg (23,645 Lbs) Tot. Wt.

Motor Data

Nominal Rating	Electrical	Mechanical
	15. MW	1.37 m (54") Stator OD
	2,000 Volts	0.98 m (38.5") Rotor OD
	7,500 Amps	0.58 m (23") Rotor ID
	126 r/s (1,200 RPM)	2.36 m (93") $Length_{BB}$
	6 Poles	15.4 Mg (34,000 Lbs) Tot. Wt.

TABLE B2.2 (Cont'd)

20 KHP HYDROFOIL MOTOR LOSSES - KILOWATTS

I^2R:	
Rotor	101.2
Stator	45.6
End Connections	22.1
Field	65.8
Brushes:	
Friction	83.9
Contact	20.9
Eddy Currents:	
Pole Rise	4.2
Tooth Ripple	4.2
Core	14.1
End Plate	30.0
Collector Bar	6.0
Mechanical:	
Windage	1.1
Bearing	6.9
TOTAL	406.0

Efficiency at 14,900 KW = 97.3%

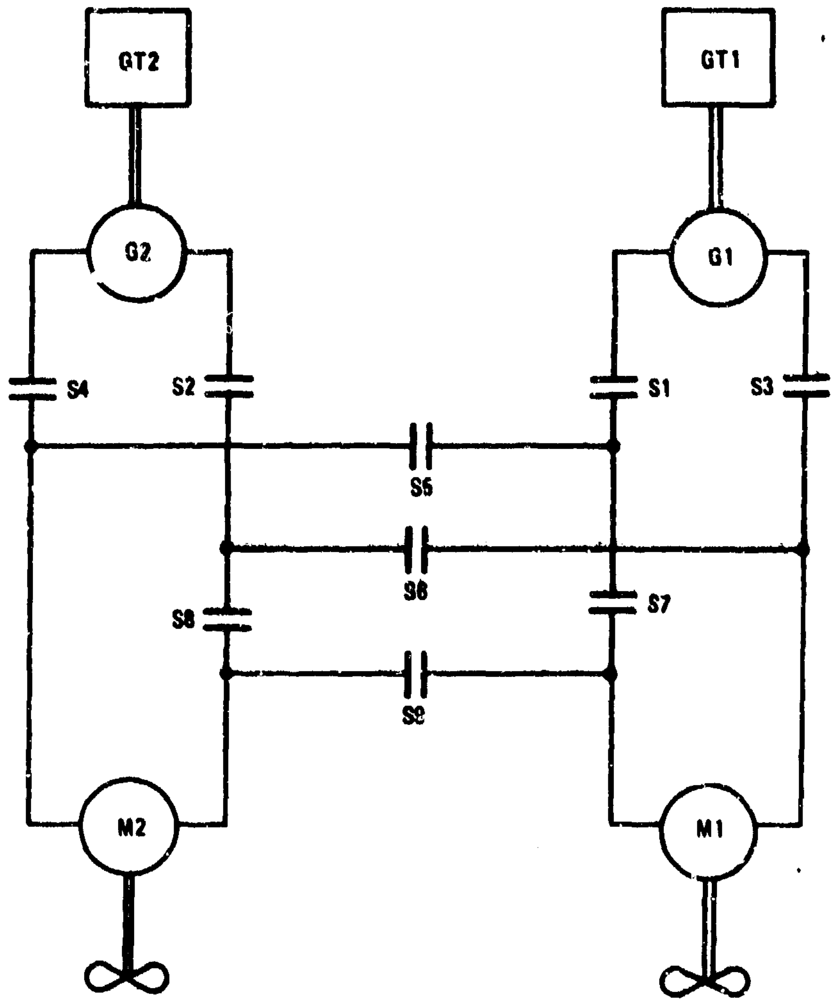

Figure B2.6. Hydrofoil Ship Propulsion System Power Schematic

The transmission lines between the SEGMAG machines are shown including the nine switches (S1 through S9) used to configure the system. In the full power configuration (see Figure B2.7) each generator is connected to one motor. Figure B2.8 shows a typical half power configuration whereby the two motors in series are powered by a single generator.

In the idle and zero power configurations, all of the switches are open and thus the propulsion system is de-energized.

The operator may select one of three configurations: idle, half power, and full power. The zero power configuration serves as an intermediary between these three.

When a configuration change is called for, the control system performs the task of making the transitions by controlling the machine fields and commanding the appropriate switches to open or close. First a transition to the zero power configuration is made, followed by a transition to the configuration selected by the operator.

2.3.1.2 System Performance

2.3.1.2.1 Steady State Operating Characteristics

First the manner in which the machine fields are adjusted by the control system is described. This is followed by a discussion of the operating characteristics including efficiencies and fuel costs.

In the full power configuration, the motor fields are held constant at their rated values of 274A. Each generator powers one motor and its field is adjusted to produce an armature current which will match the motor torque with the reference torque.

In the half power configuration, the motor fields are held constant over most of the motor torque range at 68 percent of their rated values (185A). One generator powers both motors in series and its field is adjusted to produce the required armature current up to a limiting value of 7650A. If this current is insufficient to develop

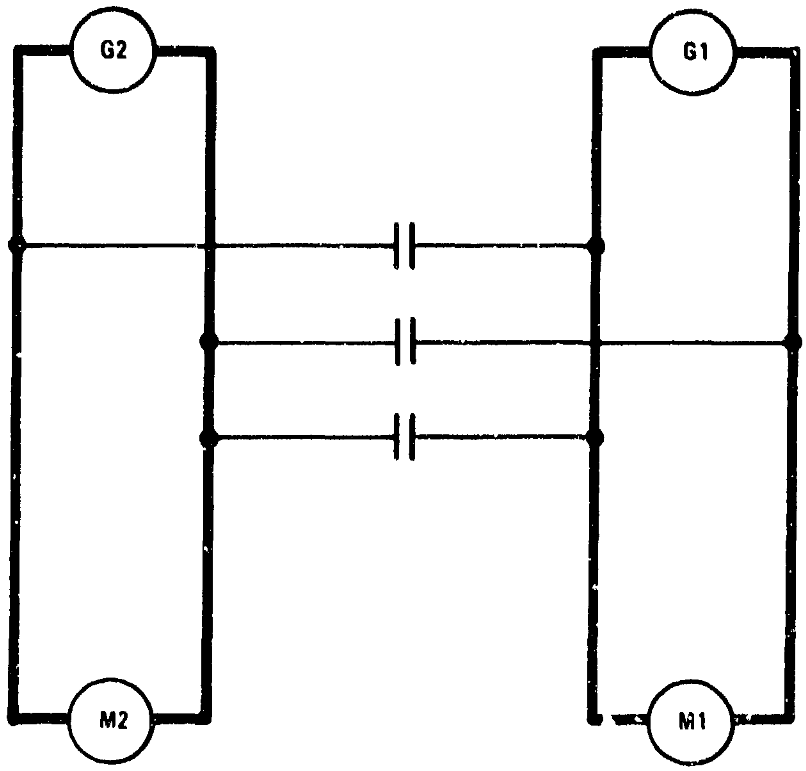

Figure B2.7. Full Power Configuration Electrical Diagram

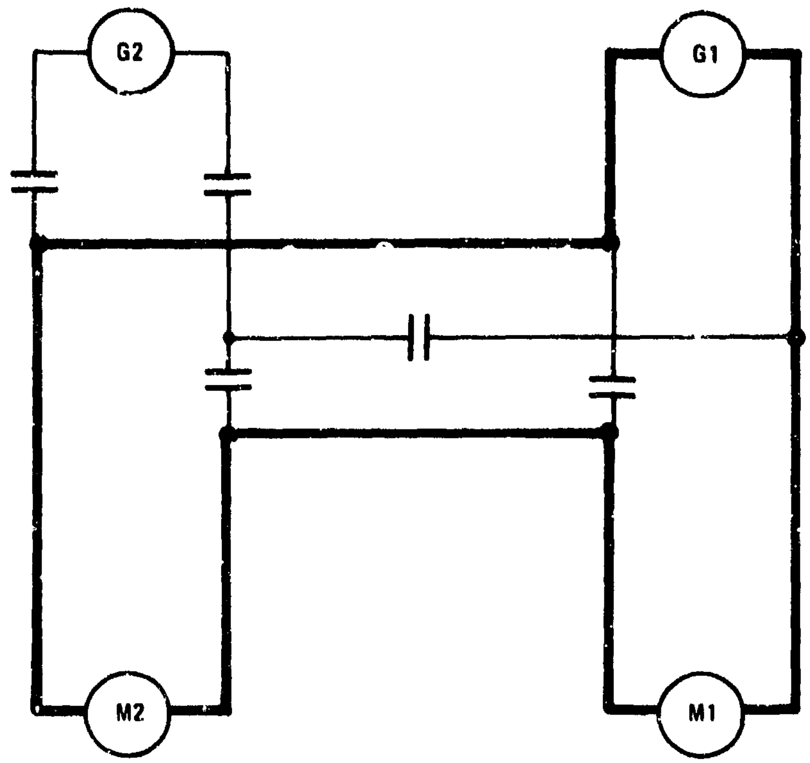

Figure B2.8. Half Power Configuration Electrical Diagram (Typical) the commanded motor torques, the motor fields are increased, but they become limited at a generator voltage of 2200V.

When unequal motor torques are called for, the motor fields must be set at different values due to the series connection. Differential torques up to a ratio of 2 to 1 may be achieved.

The operating characteristics for two steady state conditions are listed in Table B2.3. The first condition is a high speed cruise point. The propulsion system is in the full power configuration and the propeller speeds are both 1180 rev/min. The values shown are for a single machine.

The second column shows the characteristics for a medium speed cruise point. The propulsion system is in the half power configuration and the propellers are both turning at 880 rev/min. The current is 7650 A through the generator and motors. The generator voltage (2007 V) is approximately twice that of a single motor due to the series connection of the three machines.

At this particular operating point, the motor fields are at 185 A and the armature current is at its upper limit. If the motor torques were diminished, the motor fields would remain constant and the armature current would be reduced. If, on the other hand, the motor torques were made larger, the armature current would be held constant and the motor fields would be increased.

The power input, losses, and power output for two points are listed in Table B2.4. The values shown are on a total system basis. For instance, in the full power configuration the machine losses for a single generator would be one-half of the tabulated value.

Table B-2.5 lists the component and system efficiencies for two points. The efficiencies are defined in Section 2.3.1.2.3.

A fuel cost breakdown, summed for each component type is shown for two points in Table B2.6.

TABLE B2.3

PROPULSION SYSTEM OPERATING CHARACTERISTICS

Power Configuration Operating Point	Full Hi Speed Cruise, 1180 rev/min	Half Med Speed Cruise, 880 rev/min
Gas Turbine		
Specific Fuel		
Consumption, kg/kW-hr	0.246	0.245
(lb/hp-hr)	(0.404)	(0.403)
Generator Input		
Power, kW	15139	15549
(hp)	(20302)	(20852)
Speed, rev/min	3261	3300
Torque, kNm	44.33	44.99
(10^3 lb-ft)	(32.70)	(33.19)
Generator Output		
Power, kW	14947	15353
Voltage, V	1968	2007
Current, A	7593	7650
Generator Field		
Current, A	243	245
Motor Input	14936	7665
Power, kW	1967	1002
Voltage, V	7593	7650
Current, A		
Motor Output		
Power, kW	14609	7397
(hp)	(19591)	(9920)
Speed, rev/min	1180	880
Torque, kNm	118.23	80.27
(10^3 lb-ft)	(87.20)	(59.20)
Motor Field		
Current, A	274	185

Note: Values given are for a single machine

TABLE B2.4

PROPULSION SYSTEM POWER FLOW

Power Configuration Operating Point	Full Hi Speed Cruise, 1180 rev/min	Half Med Speed Cruise, 880 rev/min
Generator Input Power, kW (hp)	30278 (40603)	15549 (20852)
Generator Machine Losses, kW	384	196
Transmission Line Losses, kW	22	23
Motor Machine Losses, kW	654	536
Motor Output Power, kW (hp)	29218 (39182)	14794 (19839)

Note: Values given are summed for each component type

TABLE B2.5

COMPONENT AND SYSTEM EFFICIENCIES

Power Configuration Operating Point	Full Hi Speed Cruise, 1180 rev/min	Half Med Speed Cruise, 880 rev/min
Efficiency		
Generator	98.73%	98.74%
Transmission Line	99.93%	99.85%
Motor	97.81%	96.50%
System	96.50%	95.14%

TABLE B2.6

FUEL COST BREAKDOWN

Power Configuration Operating Point	Full Hi Speed Cruise, 1180 rev/min	Half Med Speed Cruise, 880 rev/min
Gas Turbine		
Fuel Consumption, kg/hr	7458	3808
(lb/hp-hr)	(16442)	(8395)
Auxiliary Electric		
Power Consumption		
Generator Excitation, kW	135	69
Motor Excitation, kW	135	62
Lube Oil Pumps, kW	7	7
Cooling Water Pumps, kW	37	37
Total, kW	314	175
Total Fuel Cost, kg/hr	142	79
(lb/hr)	(314)	(175)
Sea Water		
Flow Rate		
Lube Oil Systems, l/min	151	151
Cooling Water Systems, l/min	3028	3028
Total, l/min	3179	3179
(gpm)	(840)	(840)
Total Fuel Cost, kg/hr	11	11
(lb/hr)	(25)	(25)
System		
Total Fuel Cost, kg/hr	7612	3899
(lb/hr)	(16781)	(8595)

Note: Values given are summed for each component type

2.3.1.2.2 Transient Operating Characteristics

The maximum available motor torque and the steady-state propeller torque are shown in Figure B2.9. Comparison of these torque characteristics is important since the torque difference provides a measure of the ability of the propulsion system to accelerate the ship.

In the full power configuration, each motor field current is held constant at a value of 274 A. When maximum motor torque is called for, the armature current is maintained at its maximum value (7650 A) and therefore the motor torque is constant over the propeller speed range of 0 to 1200 rev/min.

The maximum motor torque line (119 kNm) intersects the propeller steady-state torque curve at a motor-propeller speed of approximately 1190 rev/min. At this operating point, the power required from each gas turbine is about 15400 kW (20600 hp).

In the half power configuration, the generator is controlled in such a manner that the armature current is maintained at a constant value of 7650 A. The motor field characteristics, and therefore the motor torque curve, fall into two regimes with the change over occurring at a motor speed of approximately 650 rev/min.

In the first regime, 0 to 650 rev/min, each motor field is held constant at its rated value (274 A) and the maximum available motor torque is the same as that for the full power configuration. At 650 rev/min, the voltage across each motor is nearly 1100 V.

In the second regime, i.e., motor speeds in excess of 650 rev/min, the motor fields are reduced such that the generator voltage is maintained at a constant value of 2200 V. The power required from the gas turbine is approximately 17000 kW (22800 hp), and since the power is (nearly) constant, the motor torque is proportional to the reciprocal of the motor speed.

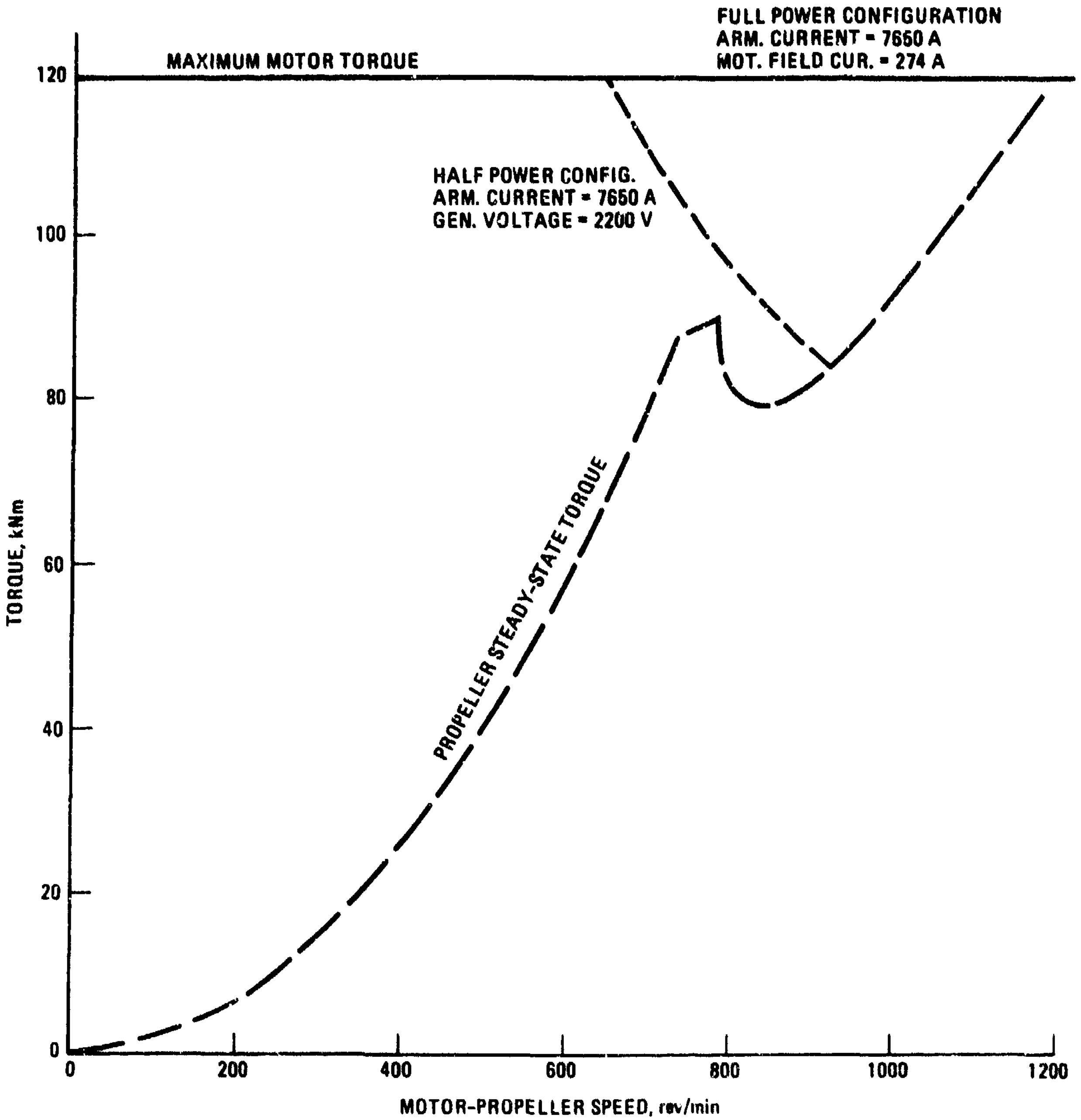

Figure B2.9. Maximum Available Motor Torque

An important feature of the SEGMAG propulsion system is the ability to provide sufficient torque for the hullborne to foilborne transition in the half power configuration, i.e., operating with one turbine. As shown in Figure B2.9, there is nearly a 10 percent torque margin at the worst point (propeller steady state torque at 90 kNm at 787 rev/min).

2.3.1.3 Representative Mission

The 241 hour mission profile is shown in Table B2.7. The values listed are taken from the DTNSRDC Work Directive, Enclosure (3) for a hydrofoil craft.

Pertinent steady state system operating characteristics for each step of the profile were integrated over the complete 241 hour mission. The makeup of the fuel consumed is listed in Table B2.8 and a summary of the mission performance is shown in Table B2.9.

The steady state system operating characteristics for Steps 4 through 10 of the mission profile are shown in Table B2.10. When the pods are up (Steps 1, 2, 3, 11, and 12), the propulsion system is shut down.

TABLE B2.7

HYDROFOIL MISSION PROFILE

Step	Time (Hours)	Operation	Turbine Status*			Motor & Generator Status**	Propulsion Motor***				
								Starboard		Port	
			Cold	Warm	Hot		Pods	Speed	Torque	Speed	Torque
1	-A	Dockside	2	0	0	Warm	Up	0	0	0	0
2	0	Dockside	2	0	0	Cold	Up	0	0	0	0
3	0-1	Harbor Man'g	2	0	0	Cold	Up	0	0	0	0
4	1-1.1	Harbor Man'g	0	2	0	Cold	Down	0	0	0	0
5	1.1-6	Takeoff-Hi Spd Crs	0	0	2	Cold	Down	1180	87200	1180	87200
6	6-12	Hi Speed Cruise	0	0	2	Cold	Down	1050	73000	1050	73000
7	12-220	Patrol	2	0	0	Cold	Down	0	0	0	0
8	220-220.1	Patrol	1	1	0	Cold	Down	0	0	0	0
9	220.1-230	Takeoff-Med Spd Crs	1	0	1	Cold	Down	880	59200	880	59200
10	230-240	Med Speed Cruise	1	0	1	Cold	Down	840	58500	880	59200
11	240-241	Harbor Man'g	2	0	0	Cold	Up	0	0	0	0
12	241+B	Dockside	2	0	0	Warm	Up	0	0	0	0

*See enclosure (5)

**Warm - 300°K, cold - suitable for stable superconductor operation

***Speed in RPM, torque in pound-feet
Two operating turbines may be used if takeoff with a single unit is impossible
A speed and torque of 880 RPM and 59,200 ft-lbs may be substituted if differential speed capability is impossible

TABLE B2.8

FUEL CONSUMED DURING MISSION

	Fuel Consumed kg	(lb)
Turbines	147307	(324756)
Auxiliary Electric		
Motor Excitation	2904	(6402)
Generator Excitation	3035	(6691)
Lube Oil Systems	1673	(3688)
Cooling Water Systems	1140	(2513)
Total	3970	(8752)
Sea Water		
Lube Oil Systems	130	(287)
Cooling Water Systems	335	(739)
Total	465	(1025)
System Total	151742	(334534)

TABLE B2.9

SUMMARY OF INTEGRATED MISSION PERFORMANCE

Mission Fuel Consumption, kg/hr	630
(lb/hr)	(1388)
Specific Fuel Consumption, kg/kW-hr	0.250
(lb/hp-hr)	(0.411)
Mission Efficiency	95.77%

TABLE B2.10

MISSION STEADY STATE SYSTEM PERFORMANCE

Mission Profile Step 4. Harbor Maneuvering
Turbine Power, Total 10 KW (13 hp)
Motor Power, Total 0 KW (0 hp)
System Efficiency (Motor Power/Turbine Power) ______
Total System Fuel Consumption 769 kg/hr (1695 lb/hr)

Ship Services

Auxiliary Electric		
Generator Excitation	1	kW
Motor Excitation	1	kW
Lube Oil Pumps	7	kW
Cooling Water Pumps	0	kW
Total	9	kW

Sea Water		
Lube Oil Systems	151	l/min
Cooling Water Systems	0	l/min
Total	151	l/min

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr	77.645	77.645
Fuel consumption, kg/hr	382	382
Generator		
Input Power, kW	5	5
Speed, rev/min	1800	1800
Output Power, kW	0	0
Output Voltage, V	0	0
Output Current, A	0	0
Field Current, A	0	0
Motor		
Input Power, kW		
Input Voltage, V		
Input Current, A		
Output Power, kW		
Speed, rev/min		
Field Current, A	0	0

TABLE B2.10 (Cont)

Mission Profile Step	5. Takeoff - High Speed Cruise	
Turbine Power, Total	30278 KW	(40603 hp)
Motor Power, Total	29219 KW	(39183 hp)
System Efficiency (Motor Power/Turbine Power)	96.50%	
Total System Fuel Consumption	7612 kg/hr	(16781 lb/hr)

Ship Services

Auxiliary Electric		
Generator Excitation	135	kW
Motor Excitation	135	kW
Lube Oil Pumps	7	kW
Cooling Water Pumps	37	kW
Total	314	kW

Sea Water		
Lube Oil Systems	151	l/min
Cooling Water Systems	3028	l/min
Total	3179	l/min

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr	0.246	0.246
Fuel Consumption, kg/hr	3729	3729
Generator		
Input Power, kW	15139	15139
Speed, rev/min	3261	3261
Output Power, kW	14947	14947
Output Voltage, V	1968	1968
Output Current, A	7593	7593
Field Current, A	243	243
Motor		
Input Power, kW	14936	14936
Input Voltage, V	1967	1967
Input Current, A	7593	7593
Output Power, kW	14609	14609
Speed, rev/min	1180	1180
Field Current, A	274	274

TABLE E2.10 (Cont)

Mission Profile Step	6. High Speed Cruise	
Turbine Power, Total	22555 KW	(30247 hp)
Motor Power, Total	21766 KW	(29188 hp)
System Efficiency (Motor Power/Turbine Power)	96.50%	
Total System Fuel Consumption	6105 kg/hr	(13459 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	137 kW	Lube Oil Systems	151 l/min
Motor Excitation	135 kW	Cooling Water Systems	3028 l/min
Lube Oil Pumps	7 kW	Total	3179 l/min
Cooling Water Pumps	37 kW		
Total	316		

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr	0.264	0.264
Fuel Consumption, kg/hr	2975	2975
Generator		
Input Power, kW	11277	11277
Speed, rev/min	2888	2888
Output Power, kW	11322	11322
Output Voltage, V	1751	1751
Output Current, A	6357	6357
Field Current, A	244	244
Motor		
Input Power, kW	11125	11125
Input Voltage, V	1750	1750
Input Current, A	6357	6357
Output Power, kW	10883	10883
Speed, rev/min	1050	1050
Field Current, A	274	275

TABLE B2.10 (Cont)

Mission Profile Step 7. Patrol
Turbine Power, Total 0 KW (0 hp)
Motor Power, Total 0 KW (0 hp)
System Efficiency (Motor Power/Turbine Power) ----
Total System Fuel Consumption 5 kg/hr (10 lb/hr)

Ship Services

Auxiliary Electric			Sea Water		
Generator Excitation	1	kW	Lube Oil Systems	151	l/min
Motor Excitation	1	kW	Cooling Water Systems	0	l/min
Lube Oil Pumps	7	kW	Total	151	l/min
Cooling Water Pumps	0	kW			
Total	9	kW			

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr		
Fuel Consumption, kg/hr	0	0
Generator		
Input Power, kW		
Speed, rev/min		
Output Power, kW		
Output Voltage, V		
Output Current, A		
Field Current, A	0	0
Motor		
Input Power, kW		
Input Voltage, V		
Input Current, A		
Output Power, kW		
Speed, rev/min		
Field Current, A	0	0

TABLE B2.10 (Cont)

Mission Profile Step	8. Patrol		
Turbine Power, Total	5 KW	(	7 hp)
Motor Power, Total	0 KW	(	0 hp)
System Efficiency (Motor Power/Turbine Power)	---		
Total System Fuel Consumption	387 kg/hr	(	852 lb/hr)

Ship Services

Auxiliary Electric			Sea Water		
Generator Excitation	1	kW	Lube Oil Systems	151	l/min
Motor Excitation	1	kW	Cooling Water Systems	0	l/min
Lube Oil Pumps	7	kW	Total	151	l/min
Cooling Water Pumps	0	kW			
Total	9	kW			

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr	77.645	
Fuel Consumption, kg/hr	382	0
Generator		
Input Power, kW	5	
Speed, rev/min	1800	
Output Power, kW	0	
Output Voltage, V	0	
Output Current, A	0	
Field Current, A	0	0
Motor		
Input Power, kW		
Input Voltage, V		
Input Current, A		
Output Power, kW		
Speed, rev/min		
Field Current, A	0	0

TABLE B2.10 (Cont)

Mission Profile Step 9. Takeoff - Medium Speed Cruise
Turbine Power, Total 15549 KW (20851 hp)
Motor Power, Total 14793 KW (19838 hp)
System Efficiency (Motor Power/Turbine Power) 95.14%
Total System Fuel Consumption 3899 kg/hr (8595 lb/hr)

Ship Services

Auxiliary Electric		Sea Water	
Generator Excitation	____ kW	Lube Oil Systems	151 l/min
Motor Excitation	____ kW	Cooling Water Systems	3028 l/min
Lube Oil Pumps	____ kW	Total	3179 l/min
Cooling Water Pumps	____ kW		
Total	____ kW		

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr	0.245	
Fuel Consumption, kg/hr	3808	0
Generator		
Input Power, kW	15549	
Speed, rev/min	3300	
Output Power, kW	15353	
Output Voltage, V	2007	
Output Current, A	7650	
Field Current, A	245	0
Motor		
Input Power, kW	7665	7665
Input Voltage, V	1002	1002
Input Current, A	7650	7650
Output Power, kW	7397	7397
Speed, rev/min	880	880
Field Current, A	185	185

TABLE B2.10 (Cont)

Mission Profile Step	10. Medium Speed Cruise	
Turbine Power, Total	15121 KW	(20278 hp)
Motor Power, Total	14374 KW	(19276 hp)
System Efficiency (Motor Power/Turbine Power)	95.1%	
Total System Fuel Consumption	3814 kg/hr	(8408 lb/hr)

Ship Services

Auxiliary Electric

Generator Excitation	66	kW
Motor Excitation	61	kW
Lube Oil Pumps	7	kW
Cooling Water Pumps	37	kW
Total	171	kW

Sea Water

Lube Oil Systems	151	l/min
Cooling Water Systems	3028	l/min
Total	3179	l/min

	Starboard	Port
Turbine		
Specific Fuel Consumption, kg/kW-hr	0.246	
Fuel Consumption, kg/hr	3725	0
Generator		
Input Power, kW	15121	
Speed, rev/min	3241	
Output Power, kW	14929	
Output Voltage, V	1951	
Output Current, A	7650	
Field Current, A	238	0
Motor		
Input Power, kW	7240	7665
Input Voltage, V	946	1002
Input Current, A	7650	7650
Output Power, kW	6977	7397
Speed, rev/min	840	880
Field Current, A	183	185

2.4 Environmental Considerations

2.4.1 to 2.4.5 - Same as Volume A

2.4.5 Critical Speed and Vibration of 20 k HP Hydrofoil Motor

The undamped-rigid lateral natural frequency of the 20 k HP hydrofoil motor rotor is 7346 rpm.

The oil lubricated bearings are of the partial-arc, hydrodynamic type. One 0.208 meter (8 in) dia. bearing is at each end of the rotor. Bearing to bearing length is 2.413 m (95 in). The oil film spring and damping properties calculated were 0.525 GN/m (3×10^6 lb_f/in) and 0.35 GN/m (2×10^6 lb_f/in), respectively.

The dynamic model includes only the torque tube for calculating the stiffness of the rotor. The weight of the punchings, rotor bars, and banding are included, however, in the frequency calculations.

The damped-flexible lateral natural frequency is 3442 rpm. The calculations use the above oil film properties and a pedestal stiffness of 2.627 GN/m (15×10^6 lb_f/in). The specification critical is defined:

N_C = 1200 x 1.10 x 1.25 = Operating Speed x Turbine Overspeed criteria x Safety Factor

N_C = 1200 x 1.10 x 1.25 = 1650 rpm

Since $N_C < 3442$ rpm; this machine will operate below its first lateral natural frequency.

The rotor will be rough balanced at several stages of the fabrication sequence. This should make the rotor final balance a small precision balance or just a check balance.

3.1 19.6 MW Generator

Two of the generators described in Section 3.1 of Volume A will be used in the hydrofoil application. Generator performance during the representative mission is described in Section 2.

3.2 15 MW Motor

The hydrofoil propulsion motor has a rating of 15 MW (20,000 HP) at a speed of 1200 rpm. In design concept, it is similar to the 30 MW (40,000 hp) machine for the destroyer application, with specific characteristics selected to produce a high efficiency machine suitable for pod mounting.

3.2.1 Exceptions

In order to achieve a motor design with an adequate critical speed margin, it was necessary to design the motor with a length-to-diameter ratio which was smaller than that dictated by pod design in the work directive. The given diameter of the pod was 1.07 m (42 in.); however, the motor design has a 1.36 m (53.5 in.) diameter.

3.2.2 Technical Summary

Table B3.1 summarizes the principal characteristics of the hydrofoil motor. These characteristics were determined by iteration to yield an efficient and lightweight machine which could operate well below the first critical speed (1600 rpm).

3.2.3 Physical Description

The preliminary design layout of the 15 MW hydrofoil motor is shown in Figure B3.1, Westinghouse drawing 1289J35. The losses calculated for the motor performing at full load are shown in Table B3.2. The design criteria for insulation thickness, mechanical stresses, operating temperatures, bar-to-bar voltage and coolant flow velocity were the same as those for the 30 MW destroyer motor.

TABLE B3.1

15 MW (20,000 hp) HYDROFOIL MOTOR CHARACTERISTICS

Machine speed	1200 rpm
Voltage	2000 V
Current	7688 A
Pole face to pole pitch ratio	0.5
Poles	6
Turns per pole	3
Mechanical gap	0.381 cm (0.15 in.)
Rotor OD	0.965 in. (28 in.)
Stator OD	1.36 in. (53.5 in.)
Active length	1.48 m (57.8 in.)
Rotor current density (RMS)	930 A/cm^2 (6000 A/in^2)
Rotor conductor height	1.332 cm (0.525 in.)
Conductor strand diameter	0.051 cm (0.020 in.)
Brush voltage drop	0.1V
Brush friction coefficient	0.15
Brush pressure	68 kPa (10 lb/in^2)
Total brush area (1500 A/in^2)	37.16 cm^2 (5.76 in^2)
Field ampere turns per pole	27,581
Field current density	465 A/cm^2 (3000 A/in^2)
Flux densities:	
Air gap	1.3T
Rotor iron	1.6T
Stator teeth	1.7T
Stator back iron	1.8T
Collector OD	0.965 m (38 in.)
Collector length	26.9 cm (10.75 in.)
Bearing diameter	0.259 m (10.21 in.)
Bearing ℄ - ℄ length	2.36 m (93 in.)

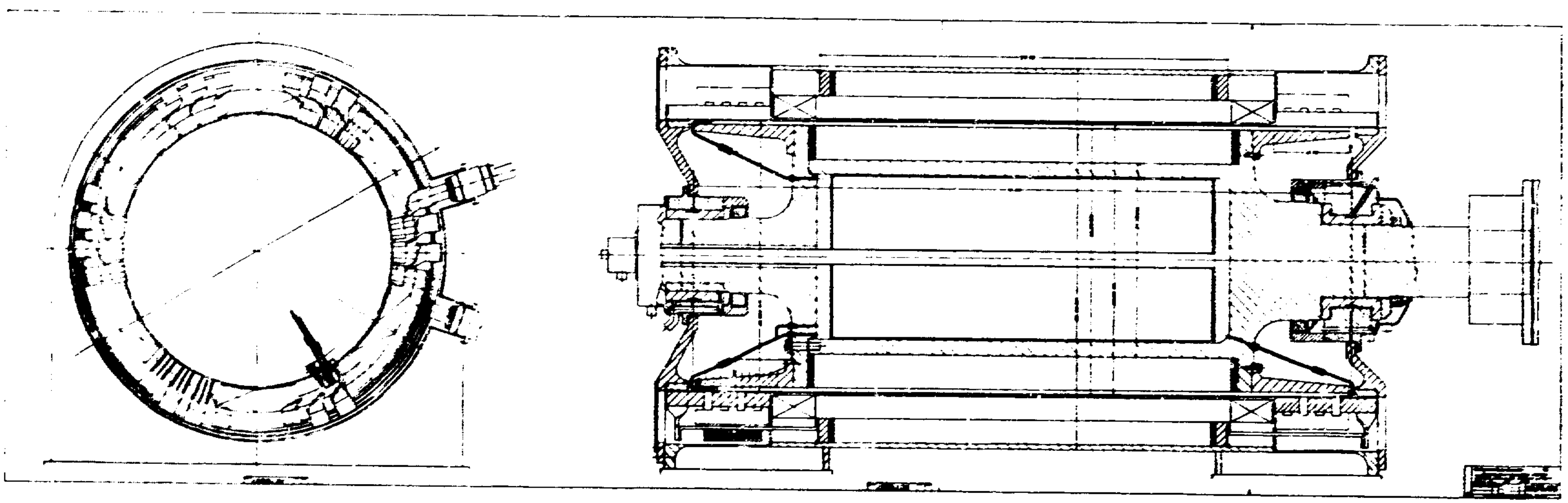

Figure B3.1. 15 MW (20,000 hp) Hydrofoil Motor Preliminary Design Layout

TABLE B3.2

20 KHP HYDROFOIL MOTOR LOSSES - KILOWATTS

I^2R - Rotor		101.2
- Stator		45.6
- End Connections		22.1
- Field		65.8
Brushes - Friction		83.9
- Contact		20.9
Eddy Currents - Pole Rise		4.2
- Tooth Ripple		4.2
- Core		14.1
- End Plate		30.0
- Collector Bar		6.0
Mechanical - Windage		1.1
- Bearing		6.9
	TOTAL	406.0
Efficiency at 20,000 HP (14,900 KW)		97.3%

The design has a smaller pole-face-to-pole-pitch ratio than the 30 MW, 168 rpm machine (0.5 vs 0.58) and the number of poles is less (6 vs 18), principally due to the substantial speed difference. The techniques of construction and the elements of design are similar, however, and all material properties are the same.

3.2.4 Operation During Representative Mission

The motor performance during the hydrofoil representative mission is displayed in Section 2.

3.2.5 Environmental Conditions

The flux plot of Figure B3.2 illustrates that the stray flux from the machine is negligible.

3.2.6 Reliability, Maintainability and Safety

The failure modes, requirements and techniques for maintenance and electrical safety requirements for the hydrofoil motor are similar to those for the 30 MW motor of Volume A, Section 3.2. Allowance must be made in the design of the pod to provide for routine maintenance and regular overhaul of the motor.

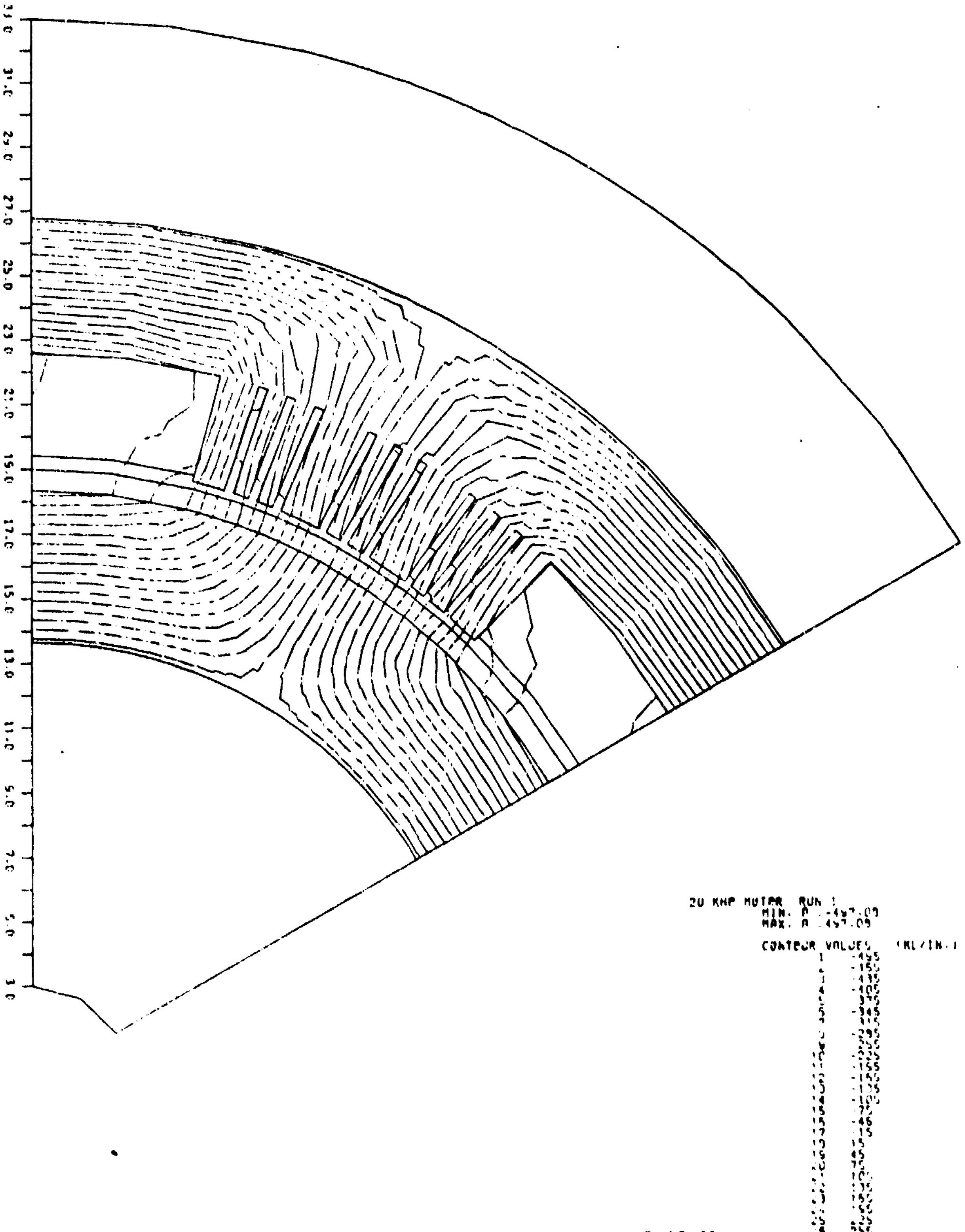

Figure B3.2. Flux Plot for 15 MW Hydrofoil Motor

TABLE B3.3

Major Design Features for the 20,000 HP Hydrofoil Motor

Rated Voltage		2000 volts
Rated Current		7688 Amps
Rated Speed		1200 RPM
Number of Poles		6
Number of Circuits per Pole		3
Pole Face to Pole Pitch Ratio		.5
Gap Flux Density		1.3
Nominal Iron Flux Density in Stator Back Iron		1.8
Nominal Iron Flux Density in Rotor		1.6
Current Densities	- Rotor Bars	6000 A/in^2 RMS
		10,800 A/in^2 Peak
	- Stator End Rings	3000 A/in^2
	- Stator Bars	6900 A/in^2
	- Field Winding	3000 A/in^2
Major Dimensions	- Rotor OD	38.00 inches
	- Rotor Iron ID	20.38 inches
	- Stator OD	53.50 inches
	- Stator ID	38.5
	- Mechanical Gap	.15 inches
	- Rotor Bar Thickness	.525 inches
	- Banding Thickness	.08 inches
	- Stator Active Length	57.80 inches
	- Rotor Lamination Length	60.80 inches
	- Bearing ¢ - ¢ Length	93.00 inches
	- Bearing Diameter	10.25 inches
	- Current Collector Diameter	38.00 inches

TABLE B3.4

Hydrofoil Motor Losses at Rated Conditions
(Losses in Kilowatts)

I^2R	- Rotor Bars	101.2
	- Stator Bars	46.6
	- End Connections	22.1
	- Field Windings	65.7
Brushes	- Friction	56.0
	- Contact & Ohmic	29.3
	- Shunt Contact	5.5
Eddy Currents	- Main Flux	4.2
	- Tooth ripple	4.2
	- End Plates	30.0
	- Collector Bars	6.0
	- Core Loss	14.1
Bearings		6.9
Windage		1.2
		393.0 KW
Efficiency at 20,000 HP		97.4%