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A COMPARATIVE STUDY OF VARIOUS ELECTRIC PROPULSION SYSTEMS AND THEIR IMPACT ON A NOMINAL SHIP DESIGN

COURSES XIII-A AND VI

JUNE 1987

(1)

# A COMPARATIVE STUDY OF VARIOUS ELECTRIC PROPULSION SYSTEMS AND THEIR IMPACT ON A NOMINAL SHIP DESIGN

by

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B.S.M.E., United States Naval Academy, 1979

Submitted to the Departments of
Ocean Engineering and Electrical Engineering
in Partial Fulfillment of the
Requirements of the Degrees of

NAVAL ENGINEER

and

MASTER OF SCIENCE
in
ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1987 N00228-85-G-3262





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## ABSTRACT

Synchronous, permanent magnet, and induction machines are modeled using computer programs. The computer programs incorporate an optimization algorithm which converges on lowest weight, volume, and inefficiency. Machine designs for high and low rpms are performed, with a varying number of pole-pairs. The machine designs are analyzed to find the optimum combination of generator and motor for inclusion in a naval ship propulsion system.

Three ships are used for the system study, a baseline mechanical transmission ship, a ship retaining the same subdivision as the baseline but with the electric machinery, and an electric transmission ship with subdivision and machinery box arrangement chosen to benefit from the inherent arrangeability of electric transmissions.

Two generator/motor combinations are used in the final ship analysis. Both employ a 3600 rpm, six-pole synchronous generator, which turns at the shaft speed of the prime mover. One combination uses a 180 rpm, direct-drive, 16-pole synchronous motor, and the other uses an 1800 rpm, geared, 8-pole synchronous motor. Power converters are used in both combinations to control motor speed.

The geared combination in the rearranged ship demonstrated the best endurance speed efficiency, reducing the endurance fuel load by 18%, while maintaining the maximum and sustained speed of the baseline ship. The savings in ship volume translated to an additional twenty Tomahawk missile cells in the rearranged ship. When the fuel load was held at the tonnage of the baseline ship, endurance range increased as much as 25%.

Permanent magnet machines were not competitive in this study due to their high weight and volume, even though their individual machine efficiency was the highest of all types. Induction machines were not used as propulsion generators because of the inherent difficulties in control. The induction machine motor candidates were not competitive because of off-design-point inefficiency.

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## ACKNOWLEDGMENTS

Many people contributed to the completion of this thesis. My thesis advisor, Professor Kirtley, gave me great encouragement and constant help. My thesis reader, Capt. Clark Graham, posed tough questions that helped me focus on the correct issues. The atmosphere of M.I.T. was conducive to learning, and the presence of the brilliant staff and student body was extremely stimulating. The U.S. Navy provided the opportunity and funding for my studies. To all of the above, thank you.

Most of all, I thank my wife for being so loving and understanding, especially during the difficult process of authorship. To you, the reader, I recommend God, who makes everything possible and good.

Jim Davis

Table of Contents


1. Chapter One: Introduction............................9
   1.1. Review of electric drive........................10
   1.2. Optimization....................................20
   1.3. The objective function..........................21

2. Chapter Two. General Considerations.................24
   2.1. Optimization method.............................25
   2.2. Constraints.....................................26
   2.3. Geometric considerations........................29
   2.4. Efficiency and losses...........................29

3. Chapter Three. Synchronous machines.................32
   3.1. Assumptions.....................................32
   3.2. Machine description.............................33
      3.2.1. Efficiency.................................33
      3.2.2. Weight and volume..........................34
   3.3. Machine characteristics.........................41
   3.4. Verification....................................49

4. Chapter Four. Permanent Magnet Machines.............50
   4.1. Magnet material.................................50
      4.1.1. Magnet cost factor.........................51
   4.2. Assumptions.....................................51
   4.3. Machine description.............................52
      4.3.1. Efficiency.................................53
      4.3.2. Weight and volume..........................53
   4.4. Machine characteristics.........................60
   4.5. Verification....................................68

5. Chapter Five. Induction machines....................69
   5.1. Assumptions.....................................69
   5.2. Machine description.............................70
      5.2.1. Efficiency.................................70

5.2.2. Weight and volume........................77
5.3. Machine characteristics........................77
5.4. Verification..................................77

6. Chapter Six. Nominal ship design....................83
6.1. Technology sensitivity analysis.................83
6.2. ASSET ........................................83
6.2.1. Margins....................................85
6.3. Philosophy of effort...........................86
6.4. Baseline ship..................................89
6.5. Backfit ship...................................92
6.6. Rearranged ship................................93
6.7. Weight and volume algorithms...................93

7. Chapter Seven. Machine design and system synthesis..96
7.1. Machine matrix.................................96
7.2. Knee curves....................................98

8. Chapter Eight. Analysis...........................114
8.1. Direct effects.................................114
8.2. Indirect effects...............................117
8.3. Closure........................................126
8.3.1. Conclusions................................126
8.3.2. Recommendations............................127

References...........................................204

Appendices

A. Definitions of machine variables and constants......129
B. Synchronous Machines and General Relations..........140
C. Permanent magnet machine............................157
D. Induction machines..................................173
E. Weight and volume algorithms........................195
F. Advanced Surface Ship Evaluation Tool output........199

List of Figures


1. High rpm synchronous machine efficiency..............35
2. 180 rpm synchronous machine efficiency...............36
3. High rpm synchronous machine volume..................37
4. 180 rpm synchronous machine volume...................38
5. High rpm synchronous machine weight..................39
6. 180 rpm synchronous machine weight...................40
7. End view of a permanent magnet machine...............52
8. High rpm permanent magnet machine efficiency.........54
9. 180 rpm permanent magnet efficiency..................55
10. High rpm permanent magnet machine volume.............56
11. 180 rpm permanent magnet machine volume..............57
12. High rpm permanent magnet machine weight.............58
13. 180 rpm permanent magnet machine weight..............59
14. High rpm induction machine efficiency................71
15. 180 rpm induction machine efficiency.................72
16. High rpm induction machine volume....................73
17. 180 rpm induction machine volume.....................74
18. High rpm induction machine weight....................75
19. 180 rpm induction machine weight.....................76
20. Baseline ship subdivision and machinery arrangement..91
21. Layout of machinery spaces on rearranged ship........95
22. Curve of volume-efficiency for 3600 rpm generators..101
23. Curve of volume-weight for 3600 rpm generators......102
24. Curve of weight-efficiency for 3600 rpm generators..103
25. Curve of volume-efficiency for 180 rpm motors.......104
26. Curve of volume-weight for 180 rpm motors...........105
27. Curve of weight-efficiency for 180 rpm motors.......106
28. Curve of volume-efficiency for geared motors........107
29. Curve of volume-weight for geared motors............108
30. Curve of weight-efficiency for geared motors........109
31. Volume-efficiency curve for initial PM and PG comb..110
32. Volume-weight curve for initial PM and PG combinat..111
33. Weight-efficiency curve for initial PM and PG comb..112
34. Final combination transmission efficiencies.........113

35. Synchronous machine equivalent circuit..............140
36. Phase belt conductor area..........................141
37. Slot space factors.................................141
38. Stator turn........................................142
39. Synchronous machine vector diagram.................143
40. Typical magnetic circuit...........................157
41. Magnet operating point diagram.....................158
42. Permanent magnet machine diagram...................159
43. Permanent magnet hysteresis diagram................160
44. Magnet material on a developed rotor...............160
45. Induction machine equivalent circuit...............173
46. Stator slot diagram................................175
47. Typical rotor bar configuration....................176
48. Induction machine Thevenin equivalent circuit.......179
49. Hull isometric view of all ships...................200
50. Body plan of all ships ............................201
51. Plan view of subdivision in mechanical baseline sh..202
52. Plan view of subdivision in rearranged electrical ..203

List of Tables

1. Typical principle dimensions for various ship types..12
2. Optimizing characteristics for ship and transmissio..22
3. Optimization constraints during machine design.......26
4. Characteristics of 1800 rpm synchronous machines.....42
5. Characteristics of 2400 rpm synchronous machines.....43
6. Characteristics of 3000 rpm synchronous machines.....44
7. Characteristics of 3600 rpm synchronous machines.....45
8. Characteristics of 7200 rpm synchronous machines.....46
9. Characteristics of 180 rpm synchronous machines......47
10. Characteristics of more 180 rpm synchro..48
11. Characteristics of 1800 rpm magnet machines..........61
12. Characteristics of 2400 rpm magnet machines..........62
13. Characteristics of 3000 rpm magnet machines..........63
14. Characteristics of 3600 rpm magnet machines..........64

15. Characteristics of 7200 rpm magnet machines..........65
16. Characteristics of 180 rpm magnet machines...........66
17. Characteristics of more 180 rpm magnet machines......67
18. Characteristics of 1800 rpm induction machines.......78
19. Characteristics of 2400 rpm induction machines.......79
20. Characteristics of 3000 rpm induction machines.......80
21. Characteristics of 3600 rpm induction machines.......81
22. Characteristics of 180 rpm induction machines........82
23. Recommended technology assessment design margins.....86
24. Ship design items held constant during analysis......87
25. Ship design items allowed to float during analysis...88
26. Payload for baseline and variant ships...............90
27. Final combination knee curve scores.................100
28. Transmission efficiencies...........................115
29. Propulsion generator efficiencies...................115
30. Propulsion motor efficiencies.......................115
31. Direct volume and weight effects....................117
32. General ship characteristics........................119
33. Powering............................................120
34. Ship weights........................................122
35. Naval architectural analysis indices................123
36. Total differences...................................125
37. Listing of various functions used in computer prog..134
38. Listing of synchronous machine design program.......147
39. Listing of synchronous efficiency program...........154
40. Listing of permanent magnet machine design program..162
41. Listing of permanent magnet efficiency program......170
42. Listing of induction machine design program.........181
43. Listing of induction efficiency program.............191
44. Listing of off-line weight and volume program.......197

# Chapter One: Introduction

The use of electric drive as a propulsion method for naval ships brings to the ship design process improved arrangeability and efficiency, though electric machines may increase the weight of the plant. Water-cooled electric machines are being studied today for ship transmissions[1]; these are smaller and lighter, for the same power output, than air-cooled machines. They promise reduced overall weight for the ship through more economic prime mover loading, as less fuel will be needed on board. A review of the literature has found no work comparing various types of conventional motors and the effect of each type on the overall ship system when used as a propulsion method. St. John [1] showed the effects of a superconducting generator/motor transmission on the design of a DD963 destroyer hull. Many simulations of electric motors and their transients have been done. There have been several papers written on naval ship integrated electric propulsion systems[2]. Also, much effort has been expended in the area of electric motor design and optimization. Herein, various kinds of conventional electric machines are modeled. Those machines were used in ship designs to find the sensitivity of the designs to their use.

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1. Greene, Mole, Welch, and Seng, "Analysis of a High-Power Water-Cooled Electric Propulsion System," SNAME Trans., Vol 86, 1978, pp 140-162.

2. Ames, "Marine AC Generation Systems," LSE Journal, Vol 12(1), pp 13-29.

## 1.1. Review of electric drive

Navy ships operate in almost every salt water location in the world, including the Black Sea and the Indian Ocean. Regular deployments are made to the Mediterranean Sea, North and South Atlantic Ocean, and all areas of the Pacific. Ships transit the Suez and Panama Canals, the Saint Lawrence Seaway, and operate in the Arctic and Antarctic Oceans. These operations are made under greatly varying environmental conditions, ranging from the sub-freezing temperatures of the high latitudes to the hot, dusty conditions of the Middle East. All this variety requires ships (and men) capable of sustained and efficient operation under any known condition. To that end, naval ships are tremendously complicated systems.

It is impractical to equip naval ships for every contingency, but ship designers try to include as much as possible when deciding what systems, equipment, and spares to put aboard a ship. Once a ship is designed, or as part of the design process, political acceptance of the product and its purchase is required. Since ships cost tax dollars, there are usually limitations on the size and complexity of the design. Still, the designers try to work within the given constraints and produce an acceptable and survivable (in both the battle and political senses) design. Usually this results in a ship that has very small margins in available weight and volume.[3]

Weight (displacement) is a semi-direct measure of ship cost. Volume is required to place desired systems aboard a ship. Therefore, any design change that results in less required weight or volume with no decrease in ship

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3. To have small margins is to be limited in the quantity of additional system weight and volume that can be added to the ship over its lifetime. If a ship is limited in this fashion, the flexibility one has in backfitting new systems as the ship ages is significantly decreased.

effectiveness, is usually a welcome one.

There are several different kinds of ship propulsion systems now in use. They include steam, nuclear, diesel, and gas turbine, and there are two principle drive systems: mechanical and electric drive. Below is a crude comparison of the various propulsion systems, for the purpose of placing the thesis in perspective.

Steam plants burning coal or oil have been in use for over a hundred years. They require large amounts of prime ship volume, in the center part of the ship.[4] Steam is produced in boilers and used to power turbines that rotate the shafts and propellers through reduction gears. Steam plants are very reliable mechanically, but are not terribly economic. The large size of the system components demands that the boilers and turbine machinery be placed in the center of the ship. This necessitates long runs of shafting from the center to the stern of a ship. Shafts typically are 18"-24" hollow steel cylinders of two to four inch thickness; they are heavy and their required placement and length makes valuable volume unavailable for other use. All propulsion plants except for electric drive have this arrangement and shafting disadvantage. Steam plants are used in all sizes of ships, from the 3000-ton displacement frigates to the 50,000-ton battleships to the 80,000-ton aircraft carriers. See Table 1 for a list of ship types and principle dimensions.

Nuclear plants are steam plants with a different heat source. They also produce steam to power turbines and suffer the same volume disadvantages as conventional steam plants. They are also very heavy and very costly. Manning requirements are more stringent, since personnel levels are

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4. The center part of the ship is the most useful ship region to place and arrange systems. Ship designers try to keep free as much center ship volume as possible. This allows much greater flexibility in arranging systems that have large objects, such as boilers and turbines.

Table 1. Typical principle dimensions for various ship types

| Ship types | Total shaft horsepower | Length | Tonnage |
|---|---|---|---|
| Patrol Hydrofoil | 18,000 shp | 145 ft. | 240 |
| Frigate | 37,417 | 441 | 3880 |
| Destroyer | 78,555 | 510 | 6395 |
| Cruiser (non-nuclear) | 82,462 | 556 | 8872 |
| Cruiser (nuclear) | 77,460 | 590 | 3487 |
| Carrier (non-nuclear) | 280,000 | 1050 | 80,000 |
| Carrier (nuclear) | 270,000 | 1100 | 73,000 |
| Battleship | 212,000 | 887 | 58,000 |
| Submarine (nuclear, attack) | 15,000 | 292 | 4640 |
| Submarine (nuclear, strategic missiles) | 15,000 | 410 | 7880 |

Source: Jane's Fighting Ships 1985-86, Jane's Publishing Company, Ltd., London, edited by John Moore.

These numbers represent the geometric mean of several classes of ships within a type and should not be taken to be those of a particular ship. Their value lies in the appreciation of the differences between various ship types.

An apt weight comparison would be that a typical forty foot sailboat might displace fifteen tons.

The U. S. Navy has other ship types besides those listed above. They include amphibious warfare ships, submarine and destroyer tenders, and fleet oilers, and supply ships.

rigidly controlled and the operators of the propulsion plant must be nuclear trained. Nuclear plants are used on cruisers, submarines, and aircraft carriers.

Diesel propulsion plants have high weight to volume ratios, making their use costly in weight dollars, but cheaper in volume dollars.[5] They are very noisy, ruling out their use in antisubmarine warfare ships. Although very reliable mechanically, they require much tinkering and tuning. Their specific fuel consumption[6] is among the lowest of all the plants. Medium speed diesel engines are not commonly manufactured in the 25,000 hp range, which means diesel plants cannot be used in ships requiring high shaft horsepower. They are typically used in smaller ships as cruise engines and in amphibious warfare ships as main propulsion. (Amphibious warfare ships typically have lower top speeds than frigates or destroyers.)

Gas turbine propulsion plants seem to have many good points. They are reliable, quiet, relatively low weight, and come in power ranges that are useful in ships ranging from 300 ton hydrofoils to 8000 ton destroyers. They require large amounts of volume for intake and exhaust ducting, but this is not a great disadvantage. Their fuel economy is not as good as other plants, but this is not intrinsic to the gas turbine engine. It is a fault of the operating method; gas turbine plants have mostly been built with mechanical transmissions. Usually one or two engines are coupled to each shaft. If the ship is proceeding at high speed, the gas turbines are operating at their full

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5. When designing a ship, total ship cost is monitored by the use of marginal cost factors. Every additional cubic foot or ton of weight added has a marginal cost associated with it. When a ship's total cost is constrained, design changes that add cost are discouraged or must be offset by the reduction of other systems' weight or volume.

6. Specific fuel consumption is the ratio of pounds of fuel burned per horsepower-hour. SFC=lbf/hp-hr.

load design point and are relatively fuel economic. Good fuel economy is not usually realized, however. In the main, the ship proceeds at a cruise speed, using one gas turbine for each shaft, and the gas turbines operate at about half power. Specific fuel consumption rises rapidly as gas turbine power level drops, which makes for inefficient operation.

Usually, the above propulsion plants have mechanical transmissions. This means the main engines, whether they are diesels, gas turbines or steam turbines, are mechanically connected to the shafts and propellers. There is usually a reduction gear between the engine and shafting. These gears are large, very heavy, and expensive. To provide an idea of size, the largest, or "bull" gear in a typical locked-train double-reduction gear is about seven feet in diameter. The reduction gear must be placed in-line with the shafting, thereby using more of that prime ship volume. Some mechanical transmissions have cross-connections between shafts, but this is not common.

Electrical transmissions are characterized by prime movers of any type providing power to generators. The output electricity is conditioned and sent to propulsion motors via a distribution network. Cross-connection is done with switches and breakers. There can be a mechanical reduction gear if it is desired to operate the propulsion motors at higher than propeller rotational speeds. Direct-drive motors may also provide the desired propeller rpm, e.g., by controlling the field current in a DC motor. The propulsion motors can be very near the propeller, i.e. aft, eliminating the long runs of shafting associated with a mechanical transmission.

Naval ship propellers are of two types, controllable or fixed pitch. The pitch of a propeller is the distance the ship moves forward in the water for one turn of the propeller. A fixed pitch propeller has this characteristic distance the same at all times. A controllable pitch propeller can vary this distance by changing the angle of attack (the angle at which the blade slices through the water) of the propeller blades, including reversing the blade so that the ship moves astern. Controllable pitch propellers are practically required for propulsion plants that have non-reversing main engines, such as diesel and gas turbine plants.[7] Steam plants can reverse their propellers and shafts by use of an astern turbine, albeit much more slowly than a ship with a controllable pitch propeller system. Fixed pitch propellers have a slight advantage in efficiency (1-3%) over the controllable ones. This is mostly due to the large propeller hub required for varying the blade angle of a controllable pitch propeller. Quick reversal of shaft direction or propeller pitch means quick ship braking and/or ship reversal. This ship quickness is mandatory for antisubmarine operations and safe navigation. For example, the ability to stop "on a dime" may be important in a crowded sea lane, where a small wooden sailboat has the right of way over a powered naval vessel.

Electric drive seems to combine the best of all the propulsion plants. It has all the advantages of a conventional prime mover plus the advantage of electrical cross connection and better arrangements. In the cruise scenario above, the electric drive ship could have both shafts operating from one gas turbine engine. That engine would be coupled to an electric generator which would produce enough power to run the motors that turn each shaft. The drive motors would be placed at the stern of the ship, near the propellers, on the same level. The long runs of shafting would be replaced by electric cable, which is smaller, weighs less, and can be placed in non-prime real estate.

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7. Ships with non-reversing prime movers can also have a reversible reduction gear with a fixed pitch propeller instead of a controllable reversible pitch propeller. This is new technology for the United States and only the latest naval ship design, the DDG51, has a reversible reduction gear.

Cable is also in many cases cheaper than shafting, especially to repair. Since one gas turbine would provide power to both shafts, it would operate at a higher power level and would be therefore more fuel economic. A typical propulsion plant might consist of three gas turbines with three generators. Most ships have an even number of prime movers because mechanical shaft cross connection between shafts is not often used and each shaft in a mechanical transmission ship requires the same number of prime movers to balance loading at high power levels. The extra prime mover requires a lot of weight and volume. An advantage of electric drive is that it becomes possible and perhaps desirable to use an odd number of prime movers. Each of the two shafts would have one propulsion motor. The heavy reduction gears could be replaced by the motors, which would have an infinitely variable reduction ratio. The controllable pitch propeller system so far required by this gas turbine ship would be replaced by the cheaper, slightly smaller, and far less complicated fixed pitch propeller, adding a small efficiency gain. The hydraulic system used to vary blade angle would be eliminated. Ship braking and reversal would be accomplished by electrically controlling the motor rotation direction, combined with energy dissipation through the use of resistor banks.

A disadvantage of this arrangement would be the high weight of the propulsion motors. They would be special designs and have a high capital cost. Hopefully, the high weight of the motors would be offset by the reduction in shafting and fuel weight and the possible elimination of the reduction gears. The high cost would be made palatable by the savings in fuel over the life of the ship. A Life Cycle Cost comparison of various propulsion plants, including electric drive, is available in reference two.

The change to electric drive would likely be accompanied by an overall decrease in propulsion plant weight and volume. The ship could be smaller and lighter, and would require less onboard fuel for the same endurance range (the distance the ship can travel without refueling). Since less volume would be required for the fuel, the ship could be smaller and lighter. Since the ship would then be smaller and lighter, less horsepower would be required to achieve the same top speed. Since less horsepower would be required, the ship could be smaller and lighter. This is an example of the design spiral that would result in a smaller, lighter, cheaper, more risk-free ship. An example of this type of ship improvement is given in reference one. There is a limit on ship improvement, usually due to the non-propulsion systems or payload. One cannot make an ocean crossing missile ship the size of a small yacht.

So why are not all Navy ships electric drive? They are not largely because the technology has not existed in a usable, fully developed, and manageable form. Because of the high cost of naval ships (a small one may cost $350 million) and the lack of experience with current electric drive technology, the Defense Department is reluctant to build large electric drive ships. There _have_ been electric drive ships, including five battleships with 21 MW shaft output and two aircraft carriers with 135 MW shaft output. Over 160 escort vessels were built during the Second World War with turboelectric or diesel-electric drives ranging from about 4.5 to 9 MW.[8] A new class of ocean surveillance ship, the T-AGOS 19, is being built with diesel-electric propulsion, but it is only a 3500 shaft horsepower (shp) ship.

Electric drive was replaced by conventional mechanical transmission plants after World War Two because of the competition afforded by improved gear cutting methods. Double-reduction locked-train gear transmissions became the standard. Since the electric drive ships all had non-

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8. Doyle, T. J. and Harrison, J. H., "Navy Superconductive Machinery Program," Trans. SNAME, 1978, p. 20-1.

superconducting, air-cooled motors and generators, they had higher weight and increased space requirements and suffered in comparison with the mechanical transmission ships.[9] The importance of the improvement in power electronics must be mentioned. World War Two ships did not have the advantages afforded by those electronics.

Integrated electric drive propulsion must also be mentioned. This propulsion plant is the same as any of those discussed above, except that ship service electrical power is derived from the main propulsion plant, usually by taking power off the reduction gears or main propulsion generator. Power conditioning equipment, such as a cycloconverter, is needed to "clean up" the power and change it to fixed frequency for use in other equipment. Variable speed constant frequency equipment and concepts embody the integrated electric drive concept. The U. S. Navy has investigated this in some detail.[10]

Some requirements of electric drive may be viewed as disadvantages. The power from the electric generators has to be conditioned to provide frequency control of the propulsion motors. The power conditioners add weight and volume to the overall system, as well as reducing the efficiency of the transmission. Braking resistors, used to dynamically and quickly slow the propulsion motors, add more weight and volume to the system. There also may be a high-frequency radiated noise signature associated with alternating current systems that may be deleterious to the mission of the ship.

The research done to date has not explored specific motor types in detail. How can it be decided whether to put a synchronous, inductive, permanent magnet or other motor in

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9. Ibid.

10. Robey, Stevens, and Page, "Application of Variable Speed Constant Frequency Generators to Propulsion-Derived Ship Service," Naval Engineers Journal, May 1985.

the electric drive system? What makes the ship system "best"? The effect of each motor type on the ship system has not been analyzed. The electric transmissions used in the current version of the Advanced Surface Ship Evaluation Tool (ASSET), a ship design computer program written for the United States Navy by Boeing Computer Systems, Inc., are generic combinations of AC and DC motors and generators, using rough estimates of weight, volume, and efficiency. Ship designs more involved than the feasibility level need detail on just those items.

Motor design is a well known subject and there are many texts on the subject. The use of motors and pertinent technologies in a ship as a propulsion method is discussed in Greene, Powell, and Gripp [3]. The advantages of electric drive include flexibility of arrangement, controllability, variable reduction ratio, reliability, and provision of ship service power from the main bus. Jolliff and Greene [4] go on to propose a specific water-cooled Advanced Integrated Electric Propulsion Plant (AIEPP) for a frigate/destroyer-sized ship. They discuss the essential characteristics of such a plant, establish the feasibility of the drive system and identify the method to technically demonstrate the system. Acker, Greene, and Jolliff [5] present several modeling techniques and scaling relationships that allow estimation of volumes and weights of propulsion motors and generators, solid state power conditioners, electrical switchgear, and associated electrical propulsion systems components as functions of propeller shaft power. A case study of AIEPP is given in the paper by Kastner, Davidson, and Hills [6].

Simulation of electric motors and associated systems is a popular topic. Many persons have done work in this area, from the micro-consideration of high frequency inductance changes to the more macro-consideration of hunting transients, etc. Smith, Stronach, and Tsao [7] model a complete electromechanical marine drive system while Smith, Stronach, Tsao, and Goodman [8] concern themselves more with a marine power system, including pump drives. Nonlinearities and operational transients are addressed.

## 1.2. Optimization

Optimization is the process of making a system, subsystem, or idea the best it can be. "Best" is defined by an "objective function," a measure of what is optimum. For example, an optimal manufacturing process may produce the maximum number of units at the lowest cost. The objective function would combine units-produced with cost in an equation that could be analyzed to find the proper production level. The output of the objective function is a single scalar measure of "goodness." It may be difficult to represent complicated processes with only one number.

Optimization can be performed on a global or subordinate basis. The optimum motor might be the one that has the highest efficiency, even if that efficiency was achieved by designing a very large and heavy motor. The sub-system (the motor) has efficiency as its objective function. The ship in which the motor is to be placed may be optimum when its overall weight and volume are the lowest (ignoring cost, for example). A large, heavy motor, then, may not be optimum for the ship, even if it is very efficient. A good case study of motor optimization is the EPRI report authored by Fuchs, et al. [9]

"Optimization" can be an ill-defined term but there are fairly well defined methods of achieving it. Linear programming, Markov modeling, and Monte Carlo schemes are examples of these methods. The accessibility of high-speed digital computers has made multiple random excursions in a multi-variable space a much easier way of finding the "optimum" solution, provided an objective function and constraints can be devised to describe the problem. This method of random excursions (Monte Carlo scheme) and examples of it are among the methods described in references ten, eleven, and twelve.

Monte Carlo schemes take their name from the action of the roulette wheel in the gambling casinos of Monte Carlo. Around and around the wheel goes, stopping on random numbers. If the computing power is available, this is an acceptable method of exploring a large variable space. It can be much quicker than looking at every possible permutation of all variables.

The steepest-descent scheme is so named because optimization moves down the sharpest gradient of the objective function. From a valid design point, random steps are taken in every variable and the design point is moved "downhill" toward the objective function over the steepest slope. This is different from the "drunkard's walk," where the random steps are only evaluated on whether or not the objective function's output has improved, not if it is improving at the fastest possible rate.

Optimization is almost always subject to constraints. In the previous manufacturing process, warehouse space may be limited, so only a certain number of units may be stored. This could act to limit production. For motor design, constraints include maximum rotor tip speed, maximum current density, minimum power output, etc. All constraints should be combined with the objective function to yield a "constrained optimization."

### 1.3. The objective function

Optimization is not possible without an objective function. It may be very difficult to devise a good objective function for a complicated system such as a ship. It may be even harder to find one for a sub-system of that complicated system. There are very many characteristics that could be optimizing variables, and assembling them into one objective function with all the constraints is not easy.

Even with a properly defined objective function, it may be difficult to choose among designs that result from the constrained optimization. For example, a low-volume and low-weight motor may have poor efficiency. A very efficient motor may also be large and heavy. If all three elements are important, which is the best motor? Deciding between competing designs has been the subject of various papers, one of which is by Schweppe and Merrill [13]. In that paper, the authors suggest the use of "knee curves," saying that the essential characteristics of a multiple attribute tradeoff can be plotted on a series of x-y graphs. Uncompetitive designs are easily discerned and discarded. The decision process can be limited to only those designs that are competitive.

Table 2. Optimizing characteristics for ship and transmission

Weight
Volume
Efficiency
Cost
Reliability
Maintainability
Commonality
Manning

The above table lists many of the possible optimizing characteristics for the ship and its propulsion sub-system. Manning estimates are typically based on historical data and do not indicate that the baseline and variant ships will require a significantly different number of personnel. Commonality measures the use of the same equipment in other ships. Since there are no other electric drive ships at the power levels used in this thesis, commonality is not an issue. It is very difficult to discern maintainability and reliability differences between designs that are as close as the machine designs of this thesis, so these two characteristics were not made part of the objective function. Cost is a measure that should be part of this sort of optimization. The cost of the ship system, quantified in the ship displacement, was used in the final recommendations for the transmission sub-system. In the case of permanent magnet machines, the relative costs of magnet material and magnet steel were included in the objective function.

Weight, volume, and efficiency were made an explicit part of the objective function for the computer design of the machines. An Effective Weight was calculated for every machine design. The design with the lowest effective weight was the "best" within its class. The generic objective function is

Effective Weight = weight + ke*(1-efficiency) + kv*volume

where ke and kv are weighting factors for efficiency and volume, respectively. The weighting factors were obtained from changes in ship displacement for marginal changes in efficiency and volume of the transmission. They were modified to reflect the actual designs resulting from the process.

# Chapter Two. General Considerations

Only steady-state behavior of electric machines was modeled. The modeling of dynamic behavior is very difficult and was not viewed as being within the design problems posed by this thesis. The changes in machine design necessary to solve dynamic instabilities, etc., are much smaller than the approximate nature of the algorithms used here.

All derivation work was performed without specifying the number of winding turns or the number of rotor or stator slots. The only exception to this was the case of induction machines, where an arbitrary number of rotor slots was selected. This selection was necessary for the calculation of the equivalent circuit components. The number of rotor slots chosen, 71, was a number designed not to induce pole harmonics. Since no turn numbers were specified, units include volts-per-turn, ampere-turns, and impedance-per-turns-squared. Power is measured in watts.

All machines used as their synchronous frequency the maximum allowed by the particular combination of pole pairs and shaft rpm. Developmental work showed that the optimization algorithm converged to the highest frequencies, so the algorithm now starts at the highest possible frequencies.

Up to six pole pairs were used in the higher rpm machines and up to 25 pole pairs in the 180 rpm machines. Diminishing improvements in volume, weight, and efficiency show up at half these limits.

The random number generator was taken from Kelley and Pohl [14], with one change. After every run of each program, the random number generator seed is stored. This means the sequence of pseudo random numbers is not repeated until the full range possible has been used. For the machines, it gives differences at every run and means the multidimensional variable space is more fully explored.

## 2.1. Optimization method

The chosen optimization method is a combination of the Monte Carlo and steepest-descent schemes. A design point is established by randomly selecting machine geometric parameters, subject to constraints. Ten random steps are taken around the design point, in all variable directions. The effective weight of each random step is evaluated and compared with that of the design point. The best of the eleven is designated the new design point. More random steps are taken, and the process continues until no more improvement is seen in effective weight. At that point, the size of the random steps is halved, and the process repeats itself, with the step size continually halved (up to ten times). The best effective weight is the index to the best design. The number of original design points used in any particular run of a program is under user control. If ten original design points are desired, the algorithm will look at over a thousand designs.

The purpose of having original design points is to start the optimization process in different sectors of the multidimensional variable space. In this fashion, the optimization process zeroes in on several local "best" points.

The variables that are randomly selected include stator current density, rotor radius, air gap dimension, stator slot space factor, and rotor slot space factor. The back iron dimension (the iron behind the stator teeth) is sized to handle a saturation level of flux. The stator slot depth is originally sized as a random fraction of the back iron dimension, and the rotor slot depth is originally a random fraction of the rotor radius.

Only steady-state behavior was modeled in this algorithm. Dynamic modeling may or may not show different optimum configurations for machine types.

2.2. Constraints

The constraints placed on the optimization process are listed in the following table. The most difficult constraint to satisfy while still achieving a valid design was the rotor current density constraint in induction machines. Only a few valid designs were achieved in induction machines using the above algorithm, leaving some question about the application of the algorithm in the case of induction machines. Only those induction machine designs in which there was reasonable confidence were included in the thesis analysis.

Table 3. Optimization constraints during machine design

| | |
|---|---|
| Minimum air gap flux density | 1.05 tesla rms |
| Maximum (saturation) flux density | 1.5 tesla rms |
| Maximum rotor radius | 2.0 meters |
| Maximum rotor tip speed | 200.0 meters/sec |
| Stator and rotor space factor | 0.35 |
| Maximum rotor slot depth | 33% of rotor radius |
| Maximum synchronous reactance: | |
| synchronous machines | 2.0 per unit |
| permanent magnet machines | 3.0 per unit |
| Power factor | 0.8 |

The magnet steel chosen was 26 gauge M19. Its magnetic properties were found in USX technical data [15]. It has been observed that saturation flux levels in electric machines occur first where the area perpendicular to the flux path is the smallest. If the back iron dimension is made appropriately large, this saturation will first occur in the teeth, as is desirable. Accordingly, the back iron dimension was set to

$$dcore = \frac{Br\ r}{Bsat\ p}$$

where Br is the radial air gap flux density, r is the rotor radius, Bsat is the saturation flux density, and p is the number of pole pairs in the machine. This equation is derived from Gauss' Law.

If electric machines are to be installed in a ship, th 78 ey obviously will need to fit into the space designated for them. An electric machine with a two meter rotor radius is at least thirteen feet in envelope diameter. This is a very large machine to install in a machinery space where volume is already at a premium. The rotor radius limit descends from the physical ability to fit an electric machine in a ship.

The tip speed limitation represents the physical limit on material strength with regard to the rotor conductors. Rotor conductors may break free from the rotor at higher tangential velocities than this limit. The magnitude of the limit was taken from a tip-speed-limited, 3600 rpm, two-pole turbogenerator, and was verified against standard Navy design practices. Several as-built electric machines were analyzed and this number seemed to fit their characteristics well. The tip speed limit arises when choosing a rotor radius (given a particular frequency and number of poles), and is less stringent a constraint than maximum rotor radius.

Thermal considerations are often extremely important in machine design. The heat build-up in electric machines has led to many cooling schemes over the years, including natural convection, forced air cooling, and hydrogen cooling. One of the latest methods is liquid cooling of the stator and rotor conductors through cooling passages through the copper itself. This has been made possible by better de-ionizing methods for cooling fluid and better rotating seals for the rotor. Naturally, the cooling passages and insulation limit the amount of copper area in a slot cross section. The copper area in a typical conductor bar was measured and found to be about thirty-five percent of the bar cross section. This number was used for the stator and rotor slot space factors

Other thermal considerations must be made for permanent magnet materials, which suffer a degradation in flux as temperatures rise. Flux loss rises slowly with increasing temperature until about 100° C. Above 100° C, flux loss is more rapid. An assumption in the design of these machines is that there will be sufficient cooling in the operating space to limit ambient temperature to about 80° C. This, combined with the machine liquid cooling, should keep flux loss to a minimum. Transmission lines were assumed to function satisfactorily at the same temperature.

Insulation also has a thermal rating. No insulation class was specified in this thesis but a typical insulation used in electric generators by the Navy is Class F. For this class, a permissible rise of 100° C over an ambient temperature of 50° C is standard, but lesser insulation classes must run cooler. If a machine must be designed with a lesser insulation class, the consequent lower temperatures may result in a quieter machine and longer machine and insulation life. It probably will be larger than a machine with a greater class of insulation. The temperatures quoted above are at hot spots, not in the bulk of the machine.[11]

Along with the reduction in copper area for liquid cooling, a maximum current density was imposed. The copper losses, in the form of heat, have to be removed by the cooling fluid. There is a tradeoff between the size of the cooling passages, the allowable current density, and the rating of the machine. Twelve million amperes per square meter equates to forty amperes in a twelve gauge copper wire.

Rotor slots were constrained to no more than one third of the rotor radius. Some reasonable shaft diameter is required to transmit the mechanical torque. Stator slots were allowed to grow as needed to meet the stator current

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11. Private communication, D.F. Schmucker, Naval Sea Systems Command, Code 56Z31, 11 December 1986.

density limit.

Synchroronous reactance limits were taken from as-built machines. A power factor of 0.8 was used for all machines, though one researcher has indicated a power factor of 1.0 might be best for permanent magnot machines.[12]

## 2.3. Geometric considerations

End turns were modeled as described in Appendix B. While not exactly as machines are constructed, this model gives reasonable results. A length allowance equal to one rotor diameter on either end of the active length of the machine was made to allow for containment of the end turns.

Fractional slot pitches were not considered. A stator winding pitch of 0.8 was assumed, resulting in the elimination of the fifth harmonic from the steady-state output waveforms.

Once weight and volume were calculated, an extra ten percent was added to allow for the frame and foundation of the machine. The calculated weight included an additional three percent of the rotor weight to allow for bearings. It is the final envelope weight and volume that were used in the decision process.

## 2.4. Efficiency and losses

The general equation for efficiency is

$$\text{efficiency} = \frac{\text{minpwr}}{\text{minpwr} + \text{ph} + \text{pe} + \text{i2r} + \text{i2rr}}$$

where minpwr is the minimum mechanical power expected of the machine, ph is the hysteresis loss, pe is the eddy current

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12. Robey, H.N., "Permanent Magnet Machine Technology Assessment," DTNSRDC Report TM-27-80-87, September 1980.

loss, i2r is the stator copper loss, and i2rr is the rotor copper loss. This formulation is for a motor, but the efficiency calculated will not be significantly different if the machine is a generator.

Hysteresis and eddy current losses arise from currents circulating within the magnet steel that forms the rotor and stator. They are two different mechanisms and depend on the metallurgy of the steel.

Eddy currents are a result of the time-varying magnetic fields within the machine, and they oppose the change in flux density within the machine. Eddy current losses increase as the square of the electrical frequency of the machine and also as the square of the peak flux density. One method of lessening eddy current losses is to use thin laminations to build up the rotor and stator. If the varnish used on the laminations is sufficiently insulating, the eddy currents are limited to azimuthal circulation. Axial circulation is practically zero because of the small lamination thickness.

Hysteresis losses are inherent to magnetic materials, and are proportional to the total volume of the material, the area of the hysteresis loop, and the machine electrical frequency.

USX has developed equations to calculate eddy current and hysteresis losses. They are

$$ph = \frac{0.01445\ \beta\ f\ Br\ Hc}{D} \quad \text{and} \quad pe = \frac{0.4818\ \eta\ Bm^2\ t^2\ f^2}{rho\ D}$$

In these equations, $\beta$ is the hysteresis loss factor (the ratio of the actual hysteresis losses to the area of a square hysteresis loop passing through Br and Hc), f is the frequency in Hertz, Br is the residual induction in kilogauss, Hc is the coercive force in oersteds, D is the density in grams per cubic centimeters, rho is the electrical resistivity of M19 in microhm-cm, $\eta$ is the anomalous loss factor. The losses are in watts per pound of material. The numerical factors at the beginning of both equations were altered to reflect the use of SI units. The factors $\beta$, $\eta$, Br, Hc, rho, and D change with the type of magnetic material used. The thickness of the laminations, t, is 0.014 inches for 26 gauge steel. These equations do not reflect some variations caused by differences in silicon content and differences in processing treatments leading to variations in grain size and crystallographic texture.

## Chapter Three. Synchronous machines

Synchronous machines operate because of an interaction between stator and rotor flux waves. The rotor flux wave is developed by a field winding. The stator flux wave is developed by an armature winding. These two waves try to align themselves, which is how the machine action is produced. In the case of a motor, the armature wave is "rotating" around the periphery of the stator bore because of the 120° separation between the three phases. A rotating action ensues. In the case of a generator, the rotation is provided by a prime mover, such as a gas turbine, and voltage is induced in the stator phases.

Synchronous machines operate at a steady-state shaft speed specified by the number of poles and the electrical, or synchronous, frequency. This synchronous speed is maintained despite changes in load. This feature makes synchronous machines attractive for applications where speed control is important. Shaft rpm = (120·frequency)/(poles).

A derivation of the equations of synchronous machines and the computer modeling program are presented in Appendix B.

### 3.1. Assumptions

The rotors of synchronous machines may exhibit saliency, or may be smooth cylindrical rotors. The differences in properties and parameters among salient and round-rotor machines amount to only a few percent[13]. The approximate nature of the modeling means the saliency effects will not be important. Therefore, no special provision for salient rotors were made.

The ships used in this thesis have displacements of

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13. Fitzgerald, Kingsley, and Umans, Electric Machinery, McGraw-Hill, New York, 1983.

about 5000 LT ( 1 LT = 2240 lbs). Their fuel load is determined by the required range and transmission efficiency at endurance speed. It was first estimated that a one-percent increase in transmission efficiency would reduce total ship displacement by about 89 LT. The efficiency factor (ke = 90,000 kg/percent) corresponds to this 89 LT change in ship full load displacement. (89 LT x 2240 lbs/LT x 2.205 kg/lb) When this produced machines with efficiencies about 95%, it was doubled to 180,000. Obviously, this factor may be adjusted to any level. The volume efficiency factor (kv = 1286.1 kg/m$^3$) corresponds to the density of a LM-2500 gas turbine module. These factors were used throughout the thesis.

## 3.2. Machine description

Machines with shaft speeds of 1800, 2400, 3000, 3600, and 7200 rpm, with the number of pole pairs varying from one to six, were modeled. Also, 180 rpm machines using from one to twenty-five pole pairs were modeled. This provided a good coverage of the variable space.

### 3.2.1. Efficiency

Synchronous machine efficiency at full load was about 98.5% for the higher rpm machines, while the 180 rpm machines hovered around 93% to 94% efficiency. The number of pole-pairs seemed to have little effect in the high rpm machines, but there was an "arch" in the efficiency curve of the 180 rpm machines, peaking at 97% with 36 poles. Though not fully understood, the 24- and 26-pole 180 rpm machines had very low efficiencies. Generally speaking, machine efficiency was higher when rpm was higher. This was an expected result. Off-design-point efficiency was good for the higher rpm machines, but bad for the 180 rpm machines. (See the discussion in Chapter Seven.)

3.2.2. Weight and volume

Weight and volume increased almost linearly with the number of pole-pairs in the 180 rpm machine. This is almost certainly a function of tip-speed limitations, as the maximum tip speed in a machine is a function of the number of poles in the machine. When the rotor radius is limited, the machine must grow in length to develop enough torque. The weight and volume of these machines were much higher than for the higher rpm machines.

The higher rpm machines saw significant decreases in weight and volume when the number of pole-pairs increased from one to two. There also was an observable increase in weight and volume as the number of pole-pairs further increased. As rpm increased, the machines became smaller and lighter.

Figure 1. High rpm synchronous machine efficiency

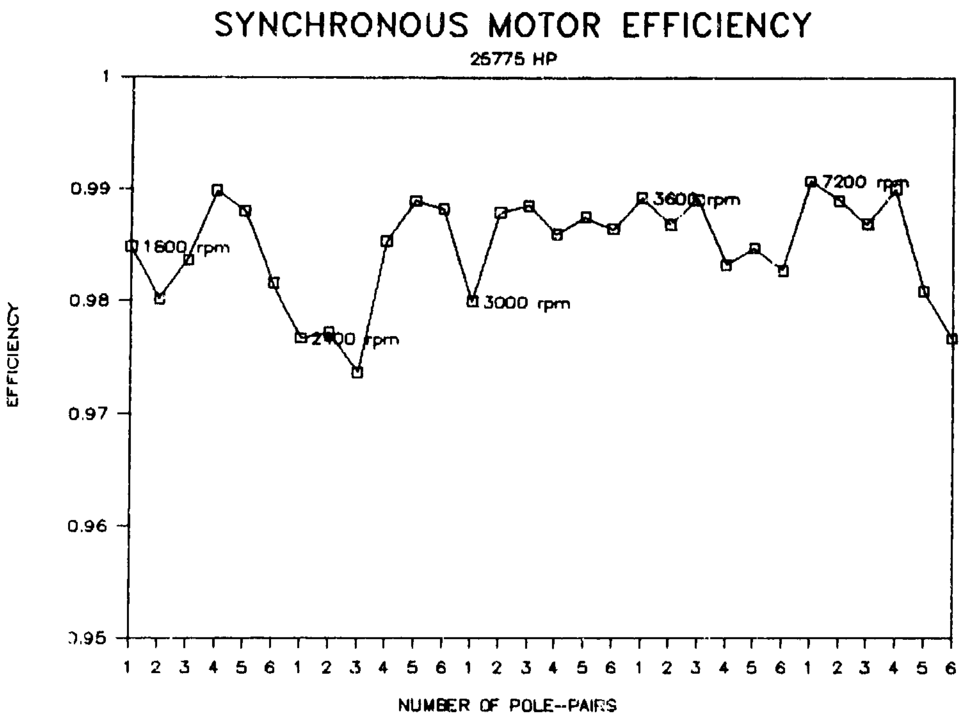


Figure 2. 180 rpm synchronous machine efficiency

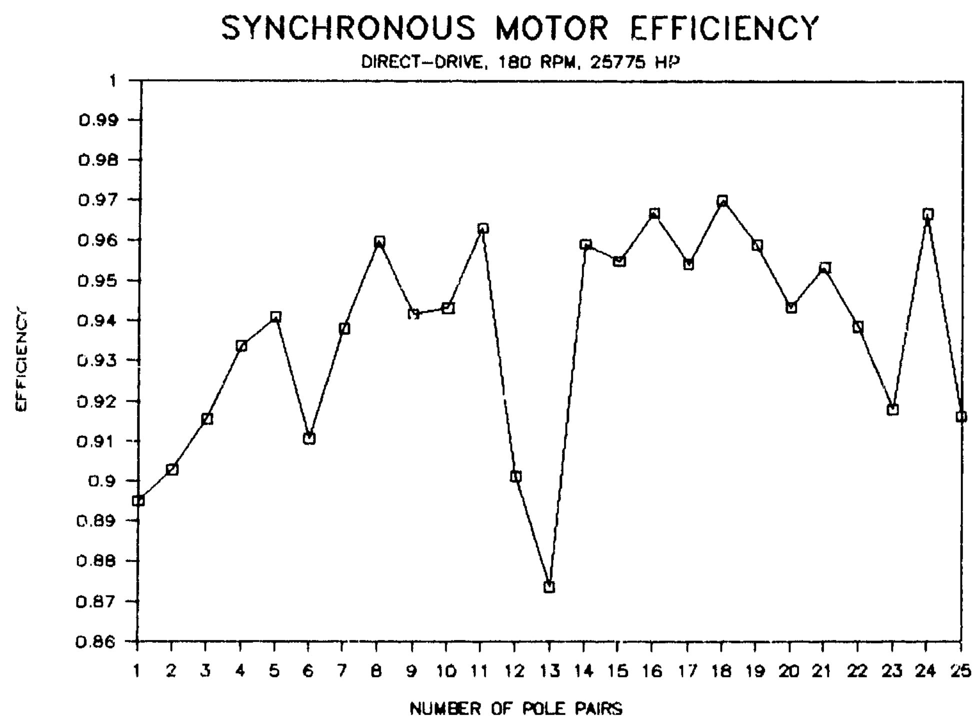


Figure 3. High rpm synchronous machine volume

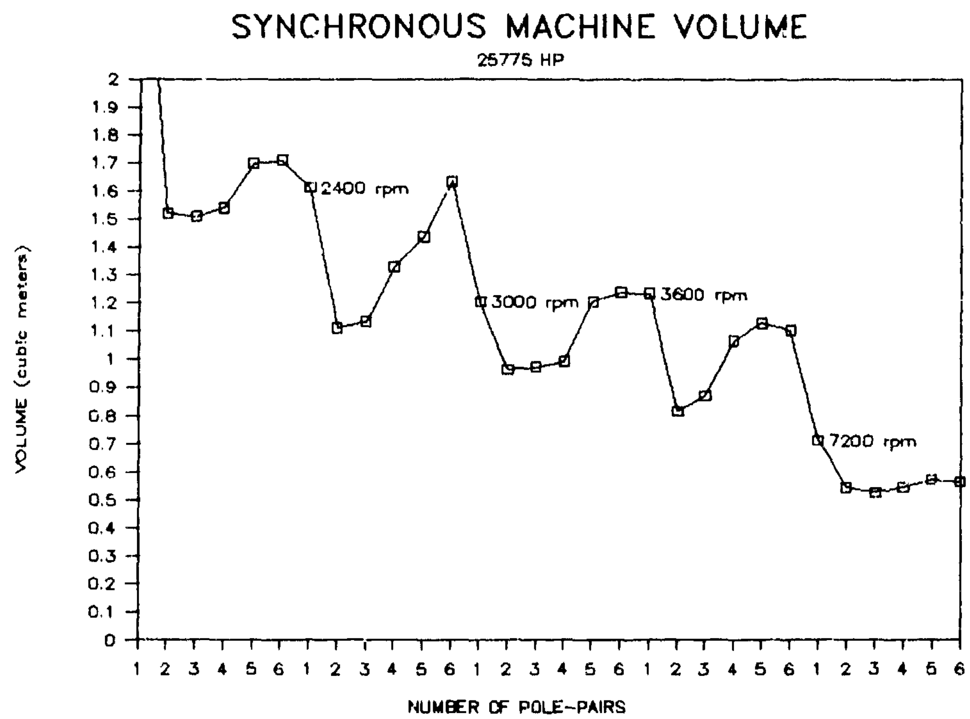


Figure 4. 180 rpm synchronous machine volume

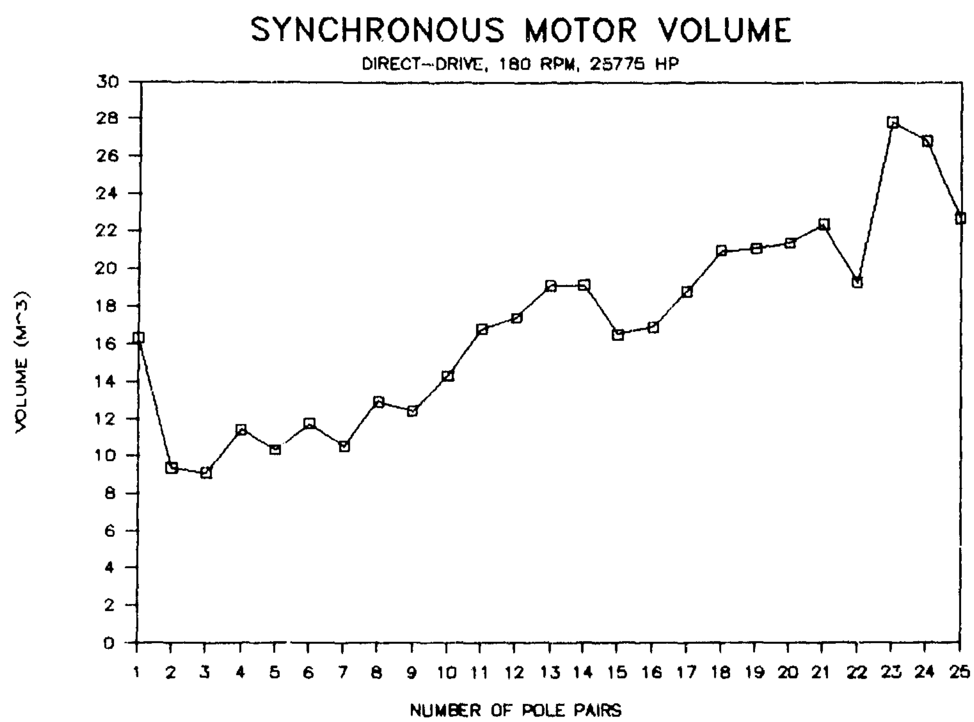


Figure 5. High rpm synchronous machine weight

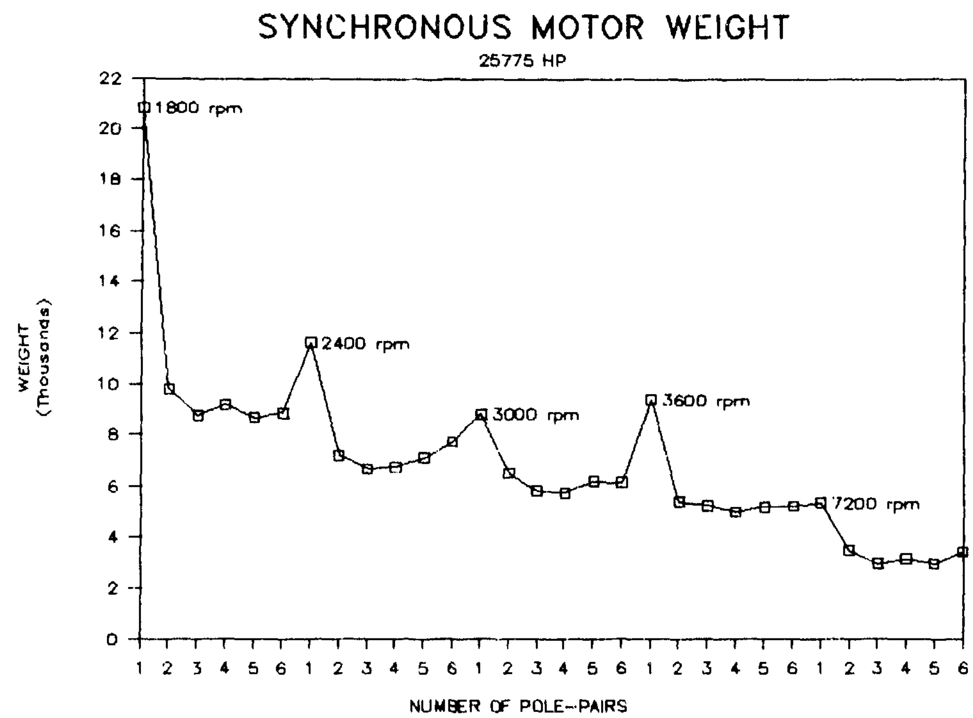
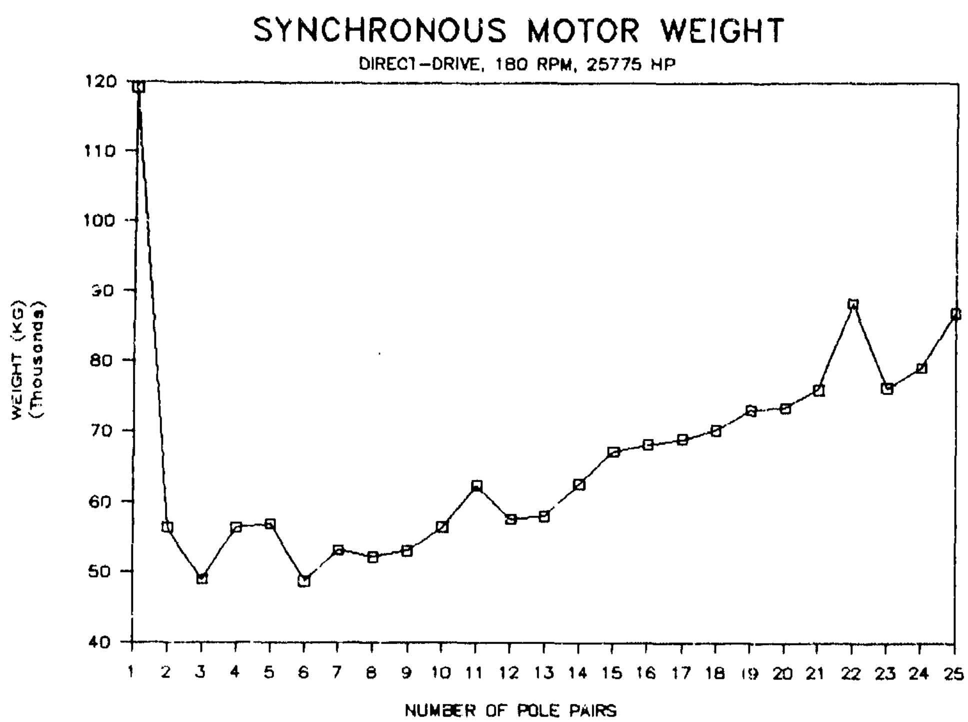


Figure 6. 180 rpm synchronous machine weight



3.3. Machine characteristics

The following tables give machine characteristics for many of the higher rpm and the 180 rpm synchronous machines designed for this thesis.

The stator slot factor tended to increase to the limit of 0.75, while the rotor slot factor moved around the value 0.58 quite a bit. This demonstrates a partial limit on the depth of the stator slots (to the same dimension as the back iron depth). The overall diameter was limited and more stator slot area was needed to develop the required power. Similarly, the stator current density converged to its cooling limit.

The longest higher rpm machine was 5.42 meters, while the largest overall diameter was 0.85 meters. Machines of this size will cause no difficulties when placed in the machinery spaces of most ships. The 180 rpm machines are larger, typically less than 6 meters long (discounting one 16 meter machine) and 1.8 meters in diameter. They are also good candidates for ship systems.

## Table 4. Characteristics of 1800 rpm synchronous machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 |
| stator current density | 8.00E+06 | 1.20E+07 | 1.20E+07 | 1.20E+07 | 1.20E+07 | 1.20E+07 |
| synchronous frequency | 30 | 60 | 90 | 120 | 150 | 180 |
| rotor radius | 0.1720 | 0.2077 | 0.2603 | 0.2905 | 0.3267 | 0.3189 |
| gap dimension | 0.0158 | 0.0440 | 0.0250 | 0.0124 | 0.0090 | 0.0092 |
| back iron depth | 0.1204 | 0.0727 | 0.0607 | 0.0508 | 0.0457 | 0.0372 |
| stator slot depth | 0.0772 | 0.0722 | 0.0607 | 0.0508 | 0.0457 | 0.0372 |
| rotor slot depth | 0.0401 | 0.1859 | 0.0747 | 0.1333 | 0.0907 | 0.0289 |
| stator slot factor | 0.653 | 0.750 | 0.750 | 0.749 | 0.750 | 0.748 |
| rotor slot factor | 0.650 | 0.447 | 0.687 | 0.659 | 0.449 | 0.528 |
| envelope volume | 2.781 | 1.522 | 1.509 | 1.541 | 1.697 | 1.709 |
| envelope weight | 20835.40 | 9827.96 | 8766.09 | 9186.03 | 8661.17 | 8853.21 |
| hysteresis loss | 16926.49 | 10677.39 | 17111.27 | 19469.83 | 31370.98 | 43892.02 |
| eddy current loss | 3033.2 | 3826.7 | 9198.8 | 13955.6 | 28107.7 | 47191.5 |
| stator copper loss | 275834.4 | 374646.5 | 293335.5 | 164289.8 | 173116.1 | 269901.7 |
| full load efficiency | 0.985 | 0.980 | 0.984 | 0.990 | 0.988 | 0.982 |
| active length | 4.670 | 1.794 | 1.498 | 1.513 | 1.348 | 1.741 |
| full load current density | 1.19E+07 | 1.06E+07 | 1.17E+07 | 4.58E+06 | 8.34E+06 | 1.89E+07 |
| no load current density | 4.40E+06 | 6.39E+06 | 7.00E+06 | 2.43E+06 | 4.24E+06 | 1.19E+07 |
| xs/turns-squared, p.u. | 1.99 | 0.86 | 0.87 | 1.11 | 1.20 | 0.78 |
| internal volts/turn, p.u. | 2.71 | 1.66 | 1.67 | 1.89 | 1.97 | 1.60 |
| overall length | 5.42 | 2.80 | 2.64 | 2.72 | 2.69 | 3.05 |
| overall diameter | 0.77 | 0.79 | 0.81 | 0.81 | 0.85 | 0.80 |

Table 5. Characteristics of 2400 rpm synchronous machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 190000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 2400 | 2400 | 2400 | 2400 | 2400 | 2400 |
| stator current density | 1.15E+07 | 1.20E+07 | 1.19E+07 | 1.20E+07 | 1.20E+07 | 1.07E+07 |
| synchronous frequency | 40 | 80 | 120 | 160 | 200 | 240 |
| rotor radius | 0.1563 | 0.1986 | 0.2388 | 0.2890 | 0.3141 | 0.3397 |
| gap dimension | 0.0273 | 0.0164 | 0.0089 | 0.0135 | 0.0109 | 0.0066 |
| back iron depth | 0.1094 | 0.0695 | 0.0557 | 0.0506 | 0.0440 | 0.0396 |
| stator slot depth | 0.0929 | 0.0695 | 0.0557 | 0.0505 | 0.0434 | 0.0396 |
| rotor slot depth | 0.0416 | 0.0215 | 0.0088 | 0.0563 | 0.1047 | 0.1040 |
| stator slot factor | 0.621 | 0.750 | 0.750 | 0.748 | 0.750 | 0.750 |
| rotor slot factor | 0.676 | 0.749 | 0.750 | 0.432 | 0.453 | 0.327 |
| envelope volume | 1.611 | 1.112 | 1.133 | 1.329 | 1.436 | 1.633 |
| envelope weight | 11619.57 | 7204.42 | 6677.15 | 6733.44 | 7106.43 | 7727.01 |
| hysteresis loss | 11981.17 | 14511.75 | 21941.41 | 27615.01 | 32769.75 | 47103.39 |
| eddy current loss | 2862.6 | 6934.5 | 15727.2 | 26391.9 | 39147.9 | 67525.7 |
| stator copper loss | 944605.4 | 427167.9 | 482231.4 | 232958.2 | 143185.6 | 114790.8 |
| full load efficiency | 0.977 | 0.977 | 0.974 | 0.985 | 0.989 | 0.988 |
| active length | 2.397 | 1.709 | 1.552 | 1.152 | 1.144 | 1.223 |
| full load current density | 2.11E+07 | 3.11E+07 | 5.39E+07 | 1.73E+07 | 7.83E+06 | 7.99E+06 |
| no load current density | 7.75E+06 | 1.28E+07 | 2.11E+07 | 9.64E+06 | 4.55E+06 | 4.32E+06 |
| xs/turns-squared, p.u. | 2.00 | 1.69 | 1.83 | 1.01 | 0.92 | 1.07 |
| internal volts/turn, p.u. | 2.72 | 2.43 | 2.56 | 1.80 | 1.72 | 1.85 |
| overall length | 3.13 | 2.57 | 2.54 | 2.36 | 2.44 | 2.61 |
| overall diameter | 0.77 | 0.71 | 0.72 | 0.81 | 0.82 | 0.85 |

Table 6. Characteristics of 3000 rpm synchronous machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 |
| stator current density | 1.20E+07 | 1.20E+07 | 1.20E+07 | 1.20E+07 | 1.10E+07 | 1.18E+07 |
| synchronous frequency | 50 | 100 | 150 | 200 | 250 | 300 |
| rotor radius | 0.1494 | 0.1890 | 0.2304 | 0.2432 | 0.2872 | 0.2974 |
| gap dimension | 0.0390 | 0.0172 | 0.0101 | 0.0052 | 0.0068 | 0.0088 |
| back iron depth | 0.1046 | 0.0662 | 0.0538 | 0.0426 | 0.0402 | 0.0347 |
| stator slot depth | 0.0862 | 0.0628 | 0.0537 | 0.0422 | 0.0402 | 0.0347 |
| rotor slot depth | 0.0904 | 0.0879 | 0.0372 | 0.0151 | 0.0784 | 0.0427 |
| stator slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 |
| rotor slot factor | 0.598 | 0.494 | 0.724 | 0.730 | 0.255 | 0.750 |
| envelope volume | 1.205 | 0.963 | 0.972 | 0.991 | 1.203 | 1.236 |
| envelope weight | 8815.49 | 6498.77 | 5801.99 | 5725.40 | 6176.39 | 6143.64 |
| hysteresis loss | 9574.79 | 14072.41 | 21089.10 | 31331.61 | 41076.93 | 46178.46 |
| eddy current loss | 2859.6 | 8405.7 | 18895.4 | 37429.9 | 61340.0 | 82749.7 |
| stator copper loss | 380285.7 | 212641.9 | 183124.5 | 204027.7 | 140446.5 | 134484.2 |
| full load efficiency | 0.980 | 0.988 | 0.989 | 0.986 | 0.988 | 0.986 |
| active length | 1.670 | 1.657 | 1.363 | 1.590 | 1.306 | 1.310 |
| full load current density | 1.53E+07 | 1.13E+07 | 1.38E+07 | 2.42E+07 | 1.40E+07 | 1.06E+07 |
| no load current density | 6.03E+06 | 5.23E+06 | 6.09E+06 | 9.63E+06 | 7.44E+06 | 6.96E+06 |
| xs/turns-squared, p.u. | 1.80 | 1.41 | 1.53 | 1.78 | 1.11 | 0.69 |
| internal volts/turn, p.u. | 2.53 | 2.16 | 2.27 | 2.51 | 1.89 | 1.52 |
| overall length | 2.42 | 2.48 | 2.32 | 2.58 | 2.48 | 2.53 |
| overall diameter | 0.76 | 0.67 | 0.70 | 0.67 | 0.75 | 0.75 |

Table 7. Characteristics of 3600 rpm synchronous machines

| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 3600 | 3600 | 3600 | 3600 | 3600 | 3600 |
| stator current density | 1.16E+07 | 1.20E+07 | 1.20E+07 | 1.19E+07 | 1.20E+07 | 1.20E+07 |
| synchronous frequency | 60 | 120 | 180 | 240 | 300 | 360 |
| rotor radius | 0.1413 | 0.1824 | 0.2191 | 0.2736 | 0.2846 | 0.2877 |
| gap dimension | 0.0139 | 0.0120 | 0.0123 | 0.0178 | 0.0209 | 0.0124 |
| back iron depth | 0.0989 | 0.0638 | 0.0511 | 0.0479 | 0.0398 | 0.0336 |
| stator slot depth | 0.0492 | 0.0638 | 0.0486 | 0.0479 | 0.0398 | 0.0336 |
| rotor slot depth | 0.0496 | 0.0541 | 0.0572 | 0.0298 | 0.0595 | 0.0385 |
| stator slot factor | 0.748 | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 |
| rotor slot factor | 0.733 | 0.409 | 0.528 | 0.679 | 0.691 | 0.654 |
| envelope volume | 1.233 | 0.814 | 0.870 | 1.065 | 1.127 | 1.102 |
| envelope weight | 9385.14 | 5377.73 | 5216.22 | 4979.26 | 5177.33 | 5190.73 |
| hysteresis loss | 14030.95 | 15587.02 | 22251.57 | 31042.24 | 36284.98 | 48590.52 |
| eddy current loss | 5028.6 | 11172.5 | 23924.3 | 44501.0 | 65021.1 | 104486.5 |
| stator copper loss | 190131.9 | 228605.1 | 165930.4 | 251863.9 | 196473.3 | 184008.6 |
| full load efficiency | 0.989 | 0.987 | 0.989 | 0.983 | 0.985 | 0.983 |
| active length | 3.258 | 1.493 | 1.372 | 0.890 | 0.975 | 1.166 |
| full load current density | 9.15E+06 | 1.94E+07 | 1.31E+07 | 2.47E+07 | 1.45E+07 | 1.73E+07 |
| no load current density | 3.38E+06 | 7.41E+06 | 6.99E+06 | 1.61E+07 | 1.12E+07 | 1.28E+07 |
| xs/turns-squared, p.u. | 1.99 | 1.89 | 1.10 | 0.71 | 0.43 | 0.48 |
| internal volts/turn, p.u. | 2.71 | 2.62 | 1.88 | 1.54 | 1.30 | 1.35 |
| overall length | 3.88 | 2.27 | 2.30 | 2.06 | 2.20 | 2.37 |
| overall diameter | 0.61 | 0.64 | 0.66 | 0.77 | 0.77 | 0.73 |

Table 8. Characteristics of 7200 rpm synchronous machines

| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 7200 | 7200 | 7200 | 7200 | 7200 | 7200 |
| stator current density | 1.20E+07 | 1.20E+07 | 1.16E+07 | 1.20E+07 | 1.20E+07 | 1.20E+07 |
| synchronous frequency | 120 | 240 | 360 | 480 | 600 | 720 |
| rotor radius | 0.1159 | 0.1710 | 0.1958 | 0.2044 | 0.2219 | 0.1932 |
| gap dimension | 0.0096 | 0.0093 | 0.0053 | 0.0093 | 0.0046 | 0.0055 |
| back iron depth | 0.0812 | 0.0599 | 0.0457 | 0.0358 | 0.0311 | 0.0225 |
| stator slot depth | 0.0405 | 0.0452 | 0.0457 | 0.0358 | 0.0311 | 0.0225 |
| rotor slot depth | 0.0329 | 0.0189 | 0.0105 | 0.0714 | 0.0138 | 0.0292 |
| stator slot factor | 0.750 | 0.750 | 0.749 | 0.750 | 0.750 | 0.750 |
| rotor slot factor | 0.511 | 0.617 | 0.661 | 0.633 | 0.468 | 0.570 |
| envelope volume | 0.711 | 0.544 | 0.525 | 0.544 | 0.572 | 0.564 |
| envelope weight | 5341.21 | 3476.08 | 2971.92 | 3136.32 | 2950.31 | 3427.07 |
| hysteresis loss | 17305.86 | 22097.70 | 28944.03 | 30808.73 | 50465.33 | 64447.34 |
| eddy current loss | 12404.5 | 31678.5 | 62239.7 | 83332.6 | 180863.2 | 277168.2 |
| stator copper loss | 149625.0 | 159505.1 | 162532.1 | 74543.2 | 143253.5 | 117812.4 |
| full load efficiency | 0.991 | 0.989 | 0.987 | 0.990 | 0.981 | 0.977 |
| active length | 2.863 | 1.212 | 0.972 | 1.081 | 1.082 | 1.952 |
| full load current density | 1.65E+07 | 2.71E+07 | 3.92E+07 | 7.81E+06 | 3.70E+07 | 1.72E+07 |
| no load current density | 6.14E+06 | 1.16E+07 | 1.46E+07 | 5.00E+06 | 1.99E+07 | 1.28E+07 |
| xs/turns-squared, p.u. | 1.97 | 1.59 | 1.97 | 0.74 | 1.08 | 0.48 |
| internal volts/turn, p.u. | 2.69 | 2.33 | 2.69 | 1.56 | 1.86 | 1.34 |
| overall length | 3.36 | 1.93 | 1.78 | 1.94 | 1.99 | 2.75 |
| overall diameter | 0.49 | 0.57 | 0.58 | 0.57 | 0.58 | 0.49 |

Table 9. Characteristics of 180 rpm synchronous machines

| | | | | | |
|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 180 | 180 | 180 | 180 | 180 |
| stator current density | 1.18E+07 | 1.12E+07 | 1.20E+07 | 9.25E+06 | 1.20E+07 |
| synchronous frequency | 3 | 6 | 9 | 12 | 15 |
| rotor radius | 0.2641 | 0.3738 | 0.4588 | 0.5869 | 0.5507 |
| gap dimension | 0.0331 | 0.0978 | 0.0723 | 0.0317 | 0.0198 |
| back iron depth | 0.1849 | 0.1308 | 0.1071 | 0.1027 | 0.0771 |
| stator slot depth | 0.0592 | 0.1308 | 0.1071 | 0.1027 | 0.0580 |
| rotor slot depth | 0.0500 | 0.1867 | 0.1934 | 0.0565 | 0.1079 |
| stator slot factor | 0.741 | 0.750 | 0.750 | 0.742 | 0.750 |
| rotor slot factor | 0.558 | 0.571 | 0.422 | 0.535 | 0.287 |
| envelope volume | 16.305 | 9.329 | 9.048 | 11.378 | 10.306 |
| envelope weight | 119110.5 | 56300.0 | 48896.8 | 56398.0 | 56899.5 |
| hysteresis loss | 10465.3 | 6915.1 | 9833.5 | 18267.4 | 23999.1 |
| eddy current loss | 187.5 | 247.8 | 528.6 | 1309.4 | 2150.3 |
| stator copper loss | 2.25E+06 | 2.06E+06 | 1.76E+06 | 1.34E+06 | 1.18E+06 |
| full load efficiency | 0.895 | 0.903 | 0.916 | 0.934 | 0.941 |
| active length | 14.913 | 3.135 | 2.590 | 2.376 | 3.708 |
| full load current density | 1.53E+07 | 1.25E+07 | 1.33E+07 | 1.91E+07 | 1.42E+07 |
| no load current density | 5.61E+06 | 6.14E+06 | 7.25E+06 | 8.93E+06 | 7.27E+06 |
| xs/turns-squared, p.u. | 2.00 | 1.28 | 1.04 | 1.38 | 1.19 |
| internal volts/turn, p.u. | 2.72 | 2.04 | 1.83 | 2.14 | 1.96 |
| overall length | 16.10 | 5.02 | 4.71 | 4.85 | 5.99 |
| overall diameter | 1.08 | 1.47 | 1.49 | 1.65 | 1.41 |

Table 10. Characteristics of more 180 rpm synchronous machines

| | | | | | |
|---|---|---|---|---|---|
| number of pole pairs | 6 | 7 | 8 | 9 | 10 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 180 | 180 | 180 | 180 | 180 |
| stator current density | 1.20E+07 | 1.20E+07 | 1.20E+07 | 1.20E+07 | 1.20E+07 |
| synchronous frequency | 18 | 21 | 24 | 27 | 30 |
| rotor radius | 0.6176 | 0.5729 | 0.7152 | 0.6943 | 0.7296 |
| gap dimension | 0.0647 | 0.0335 | 0.0229 | 0.0138 | 0.0396 |
| back iron depth | 0.0720 | 0.0573 | 0.0626 | 0.0540 | 0.0511 |
| stator slot depth | 0.0720 | 0.0569 | 0.0626 | 0.0540 | 0.0509 |
| rotor slot depth | 0.1652 | 0.0855 | 0.2046 | 0.0740 | 0.1420 |
| stator slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 |
| rotor slot factor | 0.368 | 0.750 | 0.374 | 0.283 | 0.615 |
| envelope volume | 11.693 | 10.486 | 12.870 | 12.385 | 14.273 |
| envelope weight | 48739.8 | 53234.1 | 52286.9 | 53189.2 | 56440.5 |
| hysteresis loss | 22385.0 | 27947.6 | 31793.9 | 42718.3 | 42086.1 |
| eddy current loss | 2406.8 | 3505.7 | 4557.9 | 6889.4 | 7541.6 |
| stator copper loss | 1.86E+06 | 1.24E+06 | 7.69E+05 | 1.14E+06 | 1.11E+06 |
| full load efficiency | 0.911 | 0.938 | 0.960 | 0.942 | 0.943 |
| active length | 2.225 | 3.418 | 2.045 | 2.549 | 2.365 |
| full load current density | 1.74E+07 | 1.11E+07 | 7.09E+06 | 1.98E+07 | 9.69E+06 |
| no load current density | 1.29E+07 | 7.98E+06 | 4.18E+06 | 1.07E+07 | 7.76E+06 |
| xs/turns-squared, p.u. | 0.48 | 0.53 | 0.89 | 1.08 | 0.36 |
| internal volts/turn, p.u. | 1.35 | 1.39 | 1.69 | 1.86 | 1.25 |
| overall length | 4.95 | 5.84 | 5.00 | 5.38 | 5.44 |
| overall diameter | 1.65 | 1.44 | 1.73 | 1.63 | 1.74 |

3.4. Verification

Data on a large turbogenerator, Big Sandy Unit Two, was available in reference sixteen; it was used to verify the synchronous machine design program. Big Sandy is rated at 907,000 kVA, power factor 0.9, at a rated voltage of 26 kV. When the machine parameters were input to the synchronous design program, it produced a machine very close to Big Sandy. It was judged that the design program would yield good results.

## Chapter Four. Permanent Magnet Machines

Permanent magnet machines are very similar to synchronous machines. The main difference lies in the method used to produce the field flux wave. Instead of a field current causing the wave, permanent magnets provide the flux. No exciter is used with these machines and there are no brushes.

### 4.1. Magnet material

Many different elements may be used to manufacture permanent magnets. Past designs used ceramics, aluminum-nickel-cobalt-iron-titanium (AlNiCo), and samarium-cobalt (SmCo). However, ceramic magnets do not produce sufficient residual flux (see Appendix C for an explanation of terms), and any magnet based on cobalt is high in cost and may be in limited supply. Recently, magnets of neodymium-iron-boron (NdFeB), have entered the marketplace. None of the constituents of the NdFeB magnets are strategic materials; it is expected that availability and cost will improve.

NdFeB magnets have a high Maximum Energy Product (MEP) that may be used advantageously by the machine designer. Data from Sumitomo Special Metals [17] indicates their NEOMAX line have MEPs as high as 37 MGOe, which is higher than the 30 MGOe of the SmCo magnets marketed as REC-30 by TDK Corporation [18]. High MEP is not the only criteria for magnet selection; flux stability, cost-to-performance ratio, ease of machine assembly, and other characteristics may enter the decision process. This study needed the best performance of its machines, so NdFeB was selected on the basis of its high MEP. Thermal stability was assumed to be satisfactory if the thermal considerations in Chapter Two were met.

Cost has been mentioned above. Magnet material is significantly more expensive than magnet steel and copper.

Magnets in the quantity used by a large production run of 25,000 hp machines might cost as much as $120 per pound,[14] compared with the 58¢ per pound of M19 steel.[15] Obviously, permanent magnet machines will be more expensive, but the cost of magnet materials may be made part of the optimization process. The degree of magnet overhang, discussed in Appendix C, also affects cost.

#### 4.1.1. Magnet cost factor

A change to the objective function was made to incorporate the cost of magnet material relative to magnet steel. The ratio of the above costs was taken and the result called the magnet cost factor, km. The objective function was modified to

Effective weight = (weight + km(magnet weight)) + ke(1 - effcy) + kv(volume + km(magnet volume))

An initial value for km of 170 was used, and several machines designed. Then a value of km = 25 was tried. The machines with km = 170 indeed had less magnet material in them, but at a cost. The change to km = 25 resulted in a larger machine (23.5%) with a lower stator current density, 20% more magnet material, and about a 1.5% increase in machine efficiency. That 1.5% translates to a lot of fuel aboard a ship, so it was decided to use km = 25. The extra magnet material will add about $22,000 per machine.

### 4.2. Assumptions

The largest obstacle to assembling high-power permanent magnet machines is their inherent residual magnetism. If

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14. Estimate by Mr. Yokokura, President of Sumitomo Special Metals of America.

15. Book price for 26 gauge M19 steel from Mr. Dagg of USX.

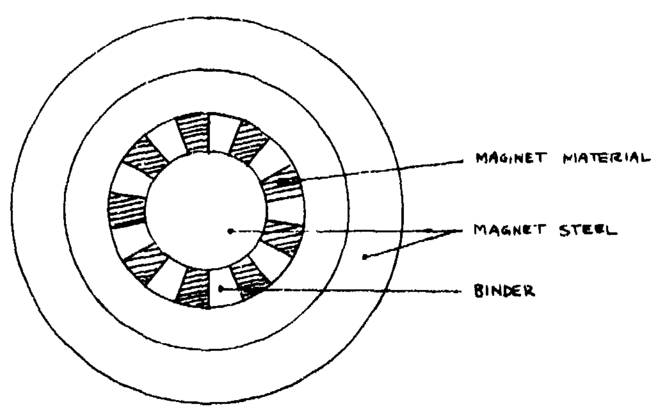
the magnets possess all of their properties at assembly, it will be extremely difficult to place the rotor (which contains the magnets) inside the stator. The rotor would be strongly attracted to the iron of the stator. Of course, the magnets may be magnetized after machine assembly, but it may be difficult to achieve MEP without elevated temperatures inside the machine. The assumption is made here that the magnets will be magnetized prior to assembly. The detailed design of the machine will have to include consideration of the jigs and fixtures necessary for assembly.

The only other assumption worthy of mention is that the load line may be modeled as described in Appendix C.

4.3. Machine description

The same rpm and pole-pair combinations were used as in the synchronous machines. The magnets on the rotor are arranged in a cylindrical-wedge configuration, as shown in the figure below.

Figure 7. End view of a permanent magnet machine




The rotor slot factor (lr) used in the other types of machines is called here the magnet slot factor and refers to the width of magnet per pole pitch. It may vary between 25% and 75% of the pole pitch, the same as for rotor slots in other machines.

The rotor slot depth, ds, does not exist in this machine. In this case, the rotor radius, r, is added to lm, the magnet radial dimension, to find the actual width of the rotating core. (In the synchronous and induction machines, dr was included in the rotor radius.)

### 4.3.1. Efficiency

For the higher rpm machines, efficiency within a particular rpm group decreased with an increasing number of poles. The most efficient machines, at about 99%, had four poles. This is higher than the synchronous or induction machines, largely because there are no rotor copper losses. The twelve-pole efficiencies were about 98%, which is not too large a spread.

The 180 rpm machines had a fairly flat efficiency curve (excepting one anomaly) up to about a 28-pole machine, where efficiency started to vary widely. There, the conflict between the number of pole-pairs and maximum rotor radius started to become significant. The flat efficiency was about 96.5%, which is less efficient than the higher rpm machines.

### 4.3.2. Weight and volume

The higher rpm machines had a general tendency toward lower weight and volume as rpm increased. Within an rpm group, the four- and six-pole machines had the lowest weight and volume. The smallest machines were larger than the synchronous machines.

Figure 8. High rpm permanent magnet machine efficiency

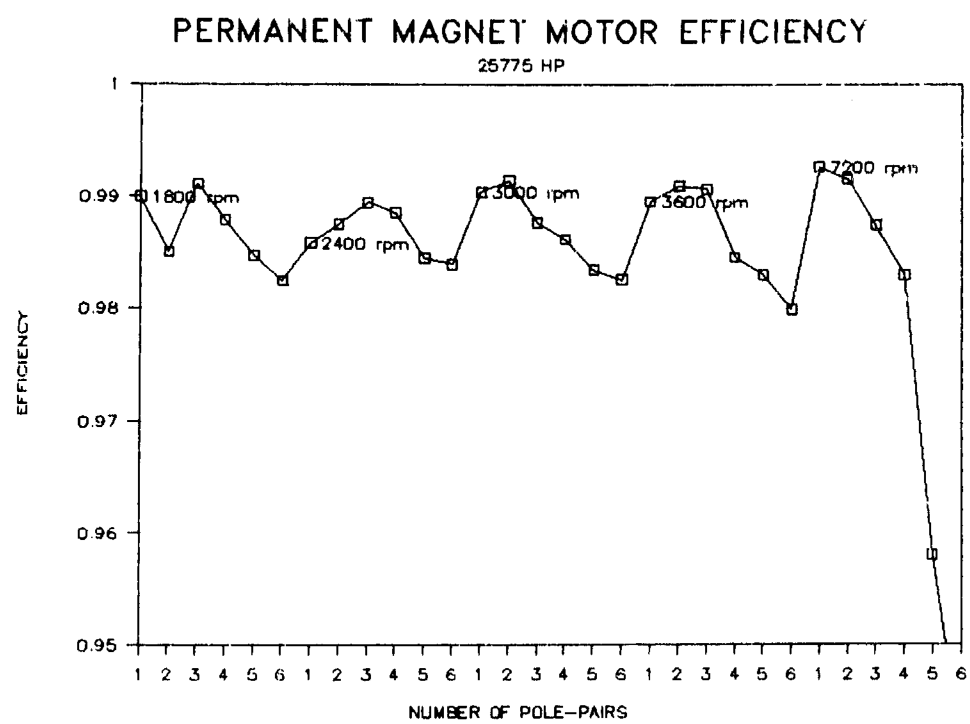


Figure 9. 180 rpm permanent magnet efficiency

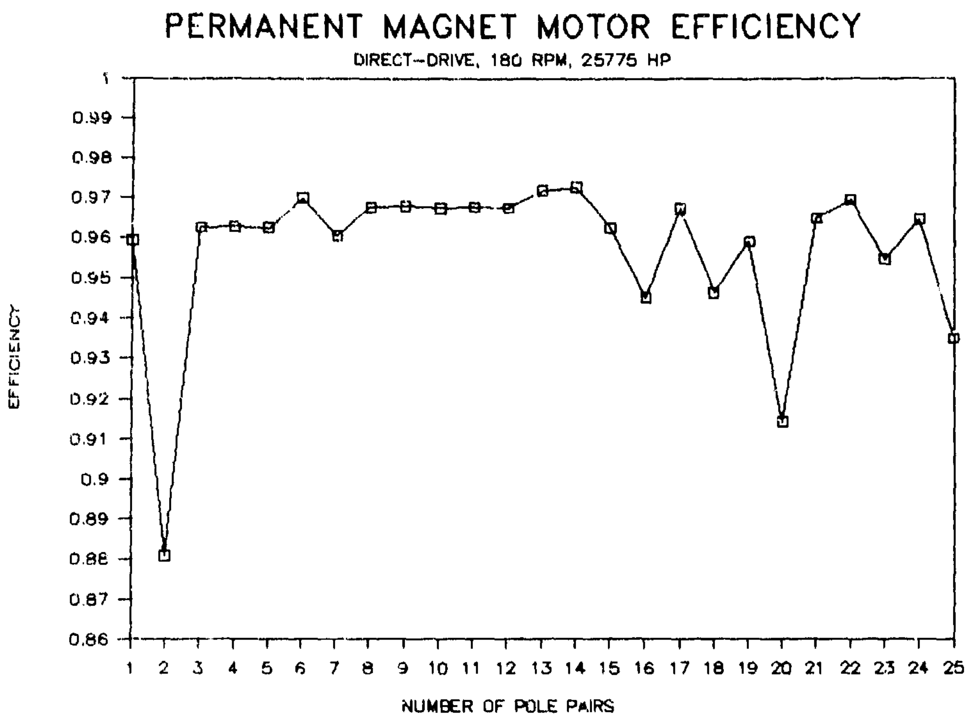


Figure 10. High rpm permanent magnet machine volume

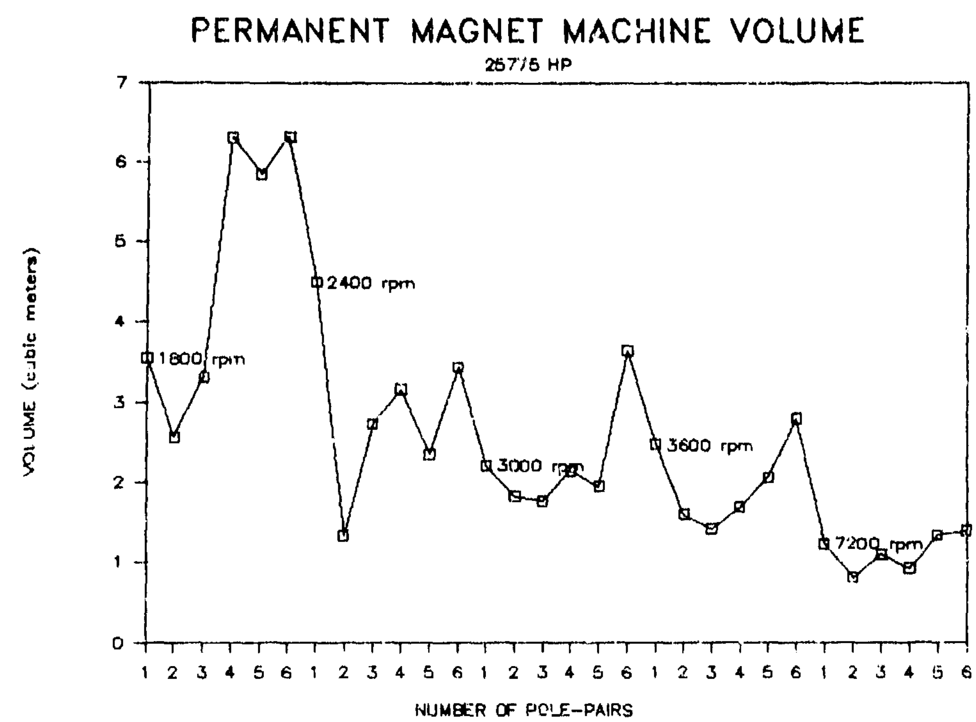


**Figure 11. 180 rpm permanent magnet machine volume**

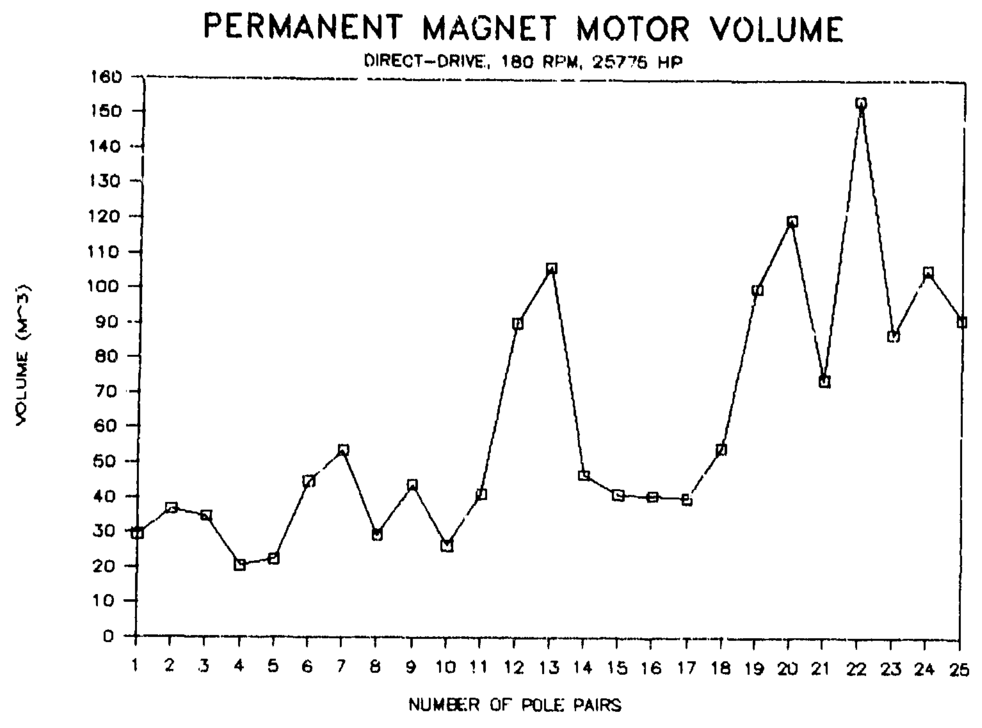


Figure 12. High rpm permanent magnet machine weight

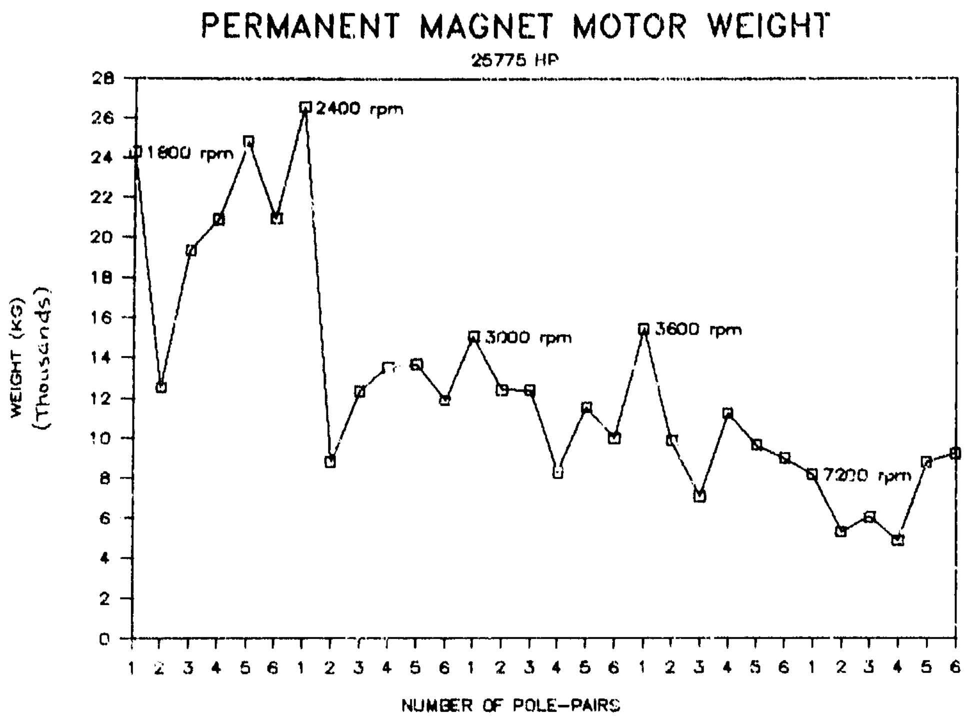
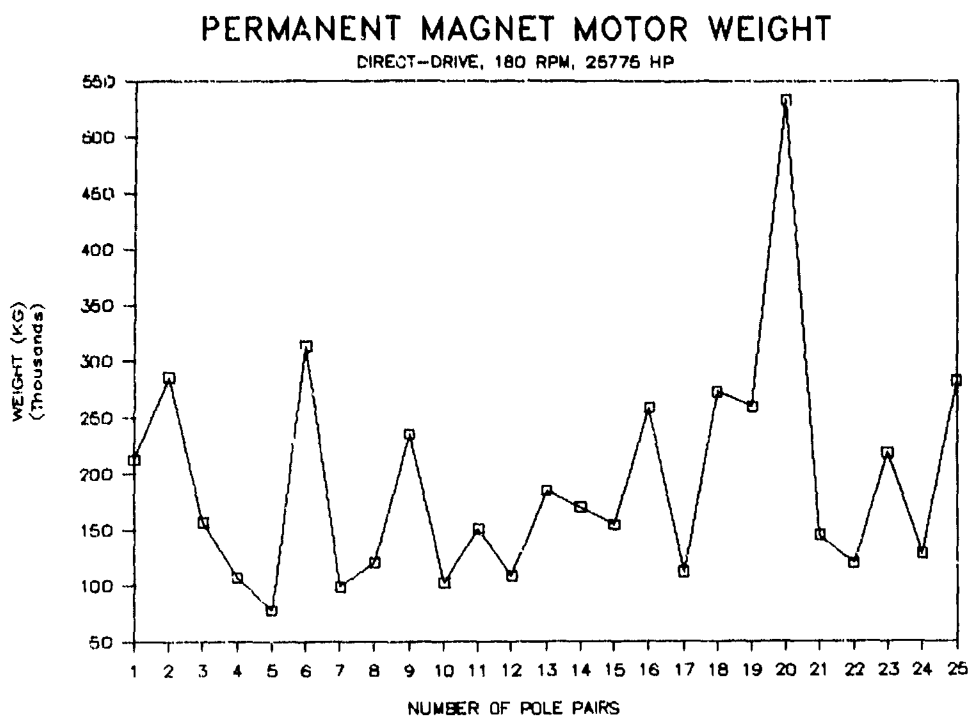


Figure 13. 180 rpm permanent magnet machine weight



The weight and volume of the 180 rpm machines increased with the number of pole-pairs. Again, the tip speed limitation is linked to this increase, as with the synchronous machines. There was a wide variation around the general increase, and these machines are large relative to all others. They are not competitive as ship propulsion motors because of their size.

4.4. Machine characteristics

The following tables give the machine characteristics of the permanent magnet machines designed for this study. The stator slot factor, ls, tended to the maximum of 0.75 for the higher rpm and 180 rpm machines. This occurred as the optimization algorithm tried to minimize envelope volume and weight. The rotor slot factor, lr, was a constant 0.378 for all machines. The rotor slot factor was calculated to produce load-line (MEP) operating flux, as derived in Appendix B. With a different magnet material selection (and a consequent change in operating point flux), a different lr would have resulted.

The magnet overhang tended toward the maximum limit, in an attempt to achieve the highest flux levels. Permanent magnet machines cannot rival the flux level produced by the field winding of a synchronous machine, but the optimization algorithm did its best.

The per-unit synchronous reactance-per-turns-squared was limited to 3.0 in these machines. This reactance tended toward the limit, but was lower with an increasing number of pole-pairs in the 180 rpm machines. It was very difficult to achieve valid designs with $x_{smax}$ = 2.0, as in the synchronous machines. If an $x_{smax}$ greater than 2.0 is unacceptable, these machines will be less competitive.

The amount of magnet material varied from 50 kg to a few hundred kg in the higher rpm machines to 700-4000 kg in the 180 rpm machines. The cost of 700 kg of NdFeB is about

Table 11. Characteristics of 1800 rpm magnet machines

| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 |
| stator current density | 7.49E+06 | 1.20E+07 | 7.32E+06 | 9.14E+06 | 8.00E+06 | 1.04E+07 |
| synchronous frequency | 30 | 60 | 90 | 120 | 150 | 180 |
| rotor radius | 0.2887 | 0.3396 | 0.3643 | 0.5964 | 0.5544 | 0.6068 |
| gap dimension | 0.0326 | 0.0382 | 0.0067 | 0.0188 | 0.0067 | 0.0123 |
| back iron depth | 0.1332 | 0.0870 | 0.0530 | 0.0742 | 0.0502 | 0.0482 |
| stator slot depth | 0.0687 | 0.0742 | 0.0456 | 0.0353 | 0.0263 | 0.0277 |
| magnet radial dimension | 0.0342 | 0.0401 | 0.0070 | 0.0198 | 0.0071 | 0.0130 |
| stator slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 | 0.644 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 |
| envelope volume | 3.548 | 2.558 | 3.309 | 6.304 | 5.847 | 6.319 |
| envelope weight | 24280.7 | 12528.8 | 19366.5 | 20910.3 | 24826.4 | 20948.1 |
| hysteresis loss | 20581.5 | 20298.5 | 52315.8 | 80505.5 | 121495.4 | 124368.0 |
| eddy current loss | 3688.1 | 7274.8 | 28124.3 | 57704.9 | 108857.1 | 133717.2 |
| stator copper loss | 171150.0 | 265272.5 | 93554.8 | 98867.0 | 69323.3 | 85961.4 |
| full load efficiency | 0.990 | 0.985 | 0.991 | 0.988 | 0.985 | 0.982 |
| active length | 2.328 | 0.876 | 2.833 | 0.933 | 1.888 | 1.257 |
| magnet weight | 405.184 | 262.376 | 157.355 | 273.763 | 178.613 | 246.460 |
| magnet volume | 0.055 | 0.035 | 0.021 | 0.037 | 0.024 | 0.033 |
| xs/turns-squared, p.u. | 2.994 | 2.339 | 2.996 | 1.165 | 1.611 | 0.920 |
| magnet overhang | 0.001 | 0.298 | 0.315 | 0.326 | 0.331 | 0.329 |
| air gap flux density | 0.619 | 0.687 | 0.642 | 0.722 | 0.671 | 0.700 |
| overall length | 3.750 | 2.548 | 4.345 | 3.473 | 4.160 | 3.786 |
| overall diameter | 1.047 | 1.078 | 0.939 | 1.450 | 1.275 | 1.390 |

Table 12. Characteristics of 2400 rpm magnet machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 100000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 2400 | 2400 | 2400 | 2400 | 2400 | 2400 |
| stator current density | 12000000 | 12000000 | 12000000 | 10202750 | 11959030 | 11997423 |
| synchronous frequency | 40 | 80 | 120 | 160 | 200 | 240 |
| rotor radius | 0.3594 | 0.0005 | 0.4018 | 0.4408 | 0.3361 | 0.4760 |
| gap dimension | 0.0371 | 0.1883 | 0.0136 | 0.0088 | 0.0032 | 0.0165 |
| back iron depth | 0.1640 | 0.0420 | 0.0625 | 0.0504 | 0.0290 | 0.0379 |
| stator slot depth | 0.0657 | 0.0249 | 0.0341 | 0.0325 | 0.0234 | 0.0300 |
| magnet radial dimension | 0.0390 | 0.1970 | 0.0143 | 0.0092 | 0.0033 | 0.0173 |
| stator slot factor | 0.340 | 0.750 | 0.750 | 0.750 | 0.749 | 0.678 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 |
| envelope volume | 4.497 | 1.342 | 2.727 | 3.157 | 2.349 | 3.438 |
| envelope weight | 26548.1 | 8797.0 | 12335.3 | 13510.2 | 13660.4 | 11877.1 |
| hysteresis loss | 34028.8 | 18160.1 | 46136.0 | 68103.9 | 86724.5 | 91478.9 |
| eddy current loss | 8130.4 | 8677.9 | 33069.4 | 65087.5 | 103604.3 | 131141.0 |
| stator copper loss | 234324.1 | 217110.2 | 127316.4 | 90617.2 | 112825.8 | 91721.4 |
| full load efficiency | 0.986 | 0.987 | 0.989 | 0.988 | 0.984 | 0.984 |
| active length | 1.536 | 4.392 | 1.291 | 1.387 | 3.061 | 1.129 |
| magnet weight | 384.207 | 10.204 | 167.444 | 128.106 | 73.723 | 217.676 |
| magnet volume | 0.052 | 0.001 | 0.023 | 0.017 | 0.010 | 0.029 |
| xs/turns-squared, p.u. | 2.417 | 0.282 | 1.973 | 1.965 | 2.879 | 0.751 |
| magnet overhang | 0.018 | 0.330 | 0.331 | 0.315 | 0.338 | 0.324 |
| air gap flux density | 0.617 | 0.635 | 0.676 | 0.672 | 0.640 | 0.692 |
| overall length | 3.278 | 5.938 | 3.010 | 3.222 | 4.431 | 3.168 |
| overall diameter | 1.260 | 0.511 | 1.024 | 1.065 | 0.783 | 1.121 |

Table 13. Characteristics of 3000 rpm magnet machines

| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 |
| stator current density | 10639824 | 9557320. | 12000000 | 11999567 | 12000000 | 11400662 |
| synchronous frequency | 50 | 100 | 150 | 200 | 250 | 300 |
| rotor radius | 0.2480 | 0.2394 | 0.2239 | 0.0003 | 0.3116 | 0.4837 |
| gap dimension | 0.0227 | 0.0075 | 0.0035 | 0.1603 | 0.0027 | 0.0375 |
| back iron depth | 0.1121 | 0.0510 | 0.0317 | 0.0175 | 0.0267 | 0.0428 |
| stator slot depth | 0.0405 | 0.0369 | 0.0235 | 0.0074 | 0.0224 | 0.0312 |
| magnet radial dimension | 0.0238 | 0.0079 | 0.0037 | 0.1683 | 0.0028 | 0.0394 |
| stator slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.747 | 0.681 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 |
| envelope volume | 2.213 | 1.834 | 1.771 | 2.143 | 1.950 | 3.643 |
| envelope weight | 15051.7 | 12394.7 | 12381.0 | 8254.8 | 11507.2 | 9968.3 |
| hysteresis loss | 22692.8 | 36848.2 | 57339.4 | 45284.3 | 91118.4 | 95620.6 |
| eddy current loss | 6777.4 | 22010.1 | 51374.8 | 54098.3 | 136066.7 | 171347.8 |
| stator copper loss | 157512.6 | 108787.2 | 132086.7 | 170766.7 | 97680.0 | 74849.0 |
| full load efficiency | 0.990 | 0.991 | 0.988 | 0.986 | 0.983 | 0.983 |
| active length | 2.395 | 3.719 | 5.490 | 16.723 | 3.005 | 0.732 |
| magnet weight | 250.152 | 123.693 | 91.981 | 15.685 | 55.765 | 338.030 |
| magnet volume | 0.034 | 0.017 | 0.012 | 0.002 | 0.008 | 0.046 |
| xs/turns-squared, p.u. | 2.934 | 2.993 | 2.997 | 0.043 | 2.991 | 0.351 |
| magnet overhang | 0.007 | 0.009 | 0.326 | 0.325 | 0.311 | 0.336 |
| air gap flux density | 0.618 | 0.619 | 0.627 | 0.623 | 0.637 | 0.736 |
| overall length | 3.574 | 4.738 | 6.415 | 18.039 | 4.274 | 2.975 |
| overall diameter | 0.847 | 0.669 | 0.565 | 0.371 | 0.727 | 1.191 |

Table 14. Characteristics of 3600 rpm magnet machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 160000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 3600 | 3600 | 3600 | 3600 | 3600 | 3600 |
| stator current density | 12000000 | 12000000 | 11966619 | 11677983 | 11998747 | 11975558 |
| synchronous frequency | 60 | 120 | 180 | 240 | 300 | 360 |
| rotor radius | 0.3044 | 0.2596 | 0.3006 | 0.2526 | 0.3700 | 0.4536 |
| gap dimension | 0.0228 | 0.0088 | 0.0121 | 0.0025 | 0.0063 | 0.0173 |
| back iron depth | 0.1454 | 0.0574 | 0.0462 | 0.0268 | 0.0332 | 0.0371 |
| stator slot depth | 0.0332 | 0.0442 | 0.0411 | 0.0208 | 0.0223 | 0.0240 |
| magnet radial dimension | 0.0240 | 0.0092 | 0.0127 | 0.0026 | 0.0067 | 0.0182 |
| stator slot factor | 0.750 | 0.553 | 0.750 | 0.735 | 0.750 | 0.749 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 |
| envelope volume | 2.475 | 1.602 | 1.427 | 1.694 | 2.063 | 2.801 |
| envelope weight | 15468.5 | 9853.6 | 7072.7 | 11238.1 | 9644.1 | 8977.4 |
| hysteresis loss | 29048.1 | 36290.0 | 37383.1 | 84962.0 | 92749.9 | 104238.5 |
| eddy current loss | 10410.6 | 26012.0 | 40193.3 | 121798.6 | 166203.6 | 224148.8 |
| stator copper loss | 163951.5 | 114166.3 | 104037.5 | 95474.6 | 73859.8 | 66008.1 |
| full load efficiency | 0.990 | 0.991 | 0.991 | 0.985 | 0.983 | 0.980 |
| active length | 1.394 | 2.276 | 1.279 | 4.322 | 1.669 | 0.907 |
| magnet weight | 221.175 | 113.409 | 104.478 | 58.252 | 91.121 | 175.220 |
| magnet volume | 0.030 | 0.015 | 0.014 | 0.008 | 0.012 | 0.024 |
| xs/turns-squared, p.u. | 2.960 | 2.977 | 2.067 | 2.981 | 1.490 | 0.593 |
| magnet overhang | 0.336 | 0.324 | 0.327 | 0.333 | 0.340 | 0.339 |
| air gap flux density | 0.664 | 0.641 | 0.663 | 0.630 | 0.661 | 0.708 |
| overall length | 2.799 | 3.386 | 2.581 | 5.352 | 3.202 | 2.863 |
| overall diameter | 1.012 | 0.740 | 0.800 | 0.605 | 0.864 | 1.064 |

Table 15. Characteristics of 7200 rpm magnet machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 7200 | 7200 | 7200 | 7200 | 7200 | 7200 |
| stator current density | 12000000 | 12000000 | 8393050. | 12000000 | 12000000 | 12000000 |
| synchronous frequency | 120 | 240 | 360 | 480 | 600 | 720 |
| rotor radius | 0.2266 | 0.1938 | 0.2622 | 0.2627 | 0.2467 | 0.2418 |
| gap dimension | 0.0146 | 0.0059 | 0.0095 | 0.0041 | 0.0020 | 0.0022 |
| back iron depth | 0.1045 | 0.0423 | 0.0392 | 0.0289 | 0.0209 | 0.0171 |
| stator slot depth | 0.0285 | 0.0284 | 0.0315 | 0.0244 | 0.0114 | 0.0104 |
| magnet radial dimension | 0.0153 | 0.0062 | 0.0099 | 0.0043 | 0.0021 | 0.0023 |
| stator slot factor | 0.749 | 0.750 | 0.750 | 0.750 | 0.748 | 0.750 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 |
| envelope volume | 1.247 | 0.811 | 1.113 | 0.931 | 1.356 | 1.398 |
| envelope weight | 8186.9 | 5319.9 | 6052.8 | 4898.9 | 8797.5 | 9221.7 |
| hysteresis loss | 30513.8 | 38176.1 | 65438.7 | 72593.1 | 172996.0 | 218032.2 |
| eddy current loss | 21871.7 | 54727.9 | 140716.0 | 208133.7 | 620002.2 | 937689.5 |
| stator copper loss | 90777.3 | 71500.7 | 38515.8 | 52482.8 | 49628.2 | 49815.1 |
| full load efficiency | 0.993 | 0.992 | 0.987 | 0.983 | 0.958 | 0.941 |
| active length | 1.552 | 2.384 | 1.621 | 1.542 | 3.965 | 4.508 |
| magnet weight | 110.276 | 57.403 | 87.115 | 36.486 | 42.995 | 50.295 |
| magnet volume | 0.015 | 0.008 | 0.012 | 0.005 | 0.006 | 0.007 |
| xs/turns-squared, p.u. | 2.946 | 2.884 | 1.258 | 2.246 | 1.608 | 1.142 |
| magnet overhang | 0.322 | 0.331 | 0.307 | 0.328 | 0.338 | 0.319 |
| air gap flux density | 0.648 | 0.635 | 0.647 | 0.650 | 0.631 | 0.629 |
| overall length | 2.578 | 3.207 | 2.747 | 2.627 | 4.968 | 5.493 |
| overall diameter | 0.748 | 0.541 | 0.685 | 0.640 | 0.562 | 0.543 |

Table 16. Characteristics of 180 rpm magnet machines

| | | | | | |
|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 180 | 180 | 180 | 180 | 180 |
| stator current density | 7.80E+06 | 1.18E+07 | 1.20E+07 | 1.09E+07 | 1.20E+07 |
| synchronous frequency | 3 | 6 | 9 | 12 | 15 |
| rotor radius | 0.4399 | 0.1787 | 0.9745 | 0.7389 | 0.8993 |
| gap dimension | 0.0413 | 0.0036 | 0.0201 | 0.0166 | 0.0214 |
| back iron depth | 0.1994 | 0.0377 | 0.1491 | 0.0779 | 0.0865 |
| stator slot depth | 0.0932 | 0.0282 | 0.0327 | 0.0476 | 0.0630 |
| magnet radial dimension | 0.0433 | 0.0038 | 0.0212 | 0.0174 | 0.0225 |
| stator slot factor | 0.463 | 0.531 | 0.750 | 0.750 | 0.740 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.378 |
| envelope volume | 29.375 | 36.694 | 34.709 | 20.521 | 22.314 |
| envelope weight | 211948.9 | 284972.1 | 156312.7 | 107071.7 | 77934.3 |
| hysteresis loss | 20311.6 | 53970.7 | 47089.7 | 41032.7 | 36926.0 |
| eddy current loss | 364.0 | 1934.3 | 2531.5 | 2941.1 | 3308.5 |
| stator copper loss | 7.90E+05 | 2.54E+06 | 6.97E+05 | 7.01E+05 | 7.11E+05 |
| full load efficiency | 0.960 | 0.881 | 0.963 | 0.963 | 0.962 |
| active length | 12.100 | 171.774 | 3.195 | 4.560 | 1.866 |
| magnet weight | 4072.4 | 2079.6 | 1941.0 | 1048.8 | 1087.7 |
| magnet volume | 0.550 | 0.281 | 0.262 | 0.142 | 0.147 |
| xs/turns-squared, p.u. | 2.996 | 2.990 | 2.981 | 2.983 | 2.870 |
| magnet overhang | 0.003 | 0.034 | 0.332 | 0.010 | 0.339 |
| air gap flux density | 0.619 | 0.619 | 0.674 | 0.618 | 0.704 |
| overall length | 14.198 | 172.518 | 7.258 | 7.651 | 5.639 |
| overall diameter | 1.548 | 0.496 | 2.353 | 1.762 | 2.140 |

Table 17. Characteristics of more 180 rpm magnet machines

| | | | | | |
|---|---|---|---|---|---|
| number of pole pairs | 6 | 7 | 8 | 9 | 10 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| magnet factor | 25 | 25 | 25 | 25 | 25 |
| shaft rpm | 180 | 180 | 180 | 180 | 180 |
| stator current density | 6.03E+06 | 1.20E+07 | 1.20E+07 | 9.42E+06 | 1.20E+07 |
| synchronous frequency | 18 | 21 | 24 | 27 | 30 |
| rotor radius | 0.6047 | 1.2439 | 0.9696 | 0.9792 | 0.9526 |
| gap dimension | 0.0139 | 0.1161 | 0.0089 | 0.0031 | 0.0079 |
| back iron depth | 0.0426 | 0.1117 | 0.0546 | 0.0469 | 0.0430 |
| stator slot depth | 0.0337 | 0.0627 | 0.0312 | 0.0255 | 0.0360 |
| magnet radial dimension | 0.0146 | 0.1219 | 0.0093 | 0.0033 | 0.0083 |
| stator slot factor | 0.536 | 0.750 | 0.748 | 0.575 | 0.748 |
| rotor slot factor | 0.378 | 0.378 | 0.378 | 0.378 | 0.376 |
| envelope volume | 44.578 | 53.524 | 29.253 | 43.668 | 26.292 |
| envelope weight | 313139.6 | 98601.8 | 120336.5 | 234296.3 | 102286.2 |
| hysteresis loss | 186214.5 | 67518.3 | 96060.7 | 214344.0 | 101073.4 |
| eddy current loss | 20021.3 | 8469.3 | 13770.9 | 34568.5 | 18111.9 |
| stator copper loss | 3.91E+05 | 7.15E+05 | 5.34E+05 | 3.91E+05 | 5.31E+05 |
| full load efficiency | 0.970 | 0.960 | 0.968 | 0.968 | 0.967 |
| active length | 24.182 | 0.651 | 3.523 | 7.417 | 3.167 |
| magnet weight | 3800.1 | 3431.9 | 932.5 | 704.3 | 714.1 |
| magnet volume | 0.514 | 0.464 | 0.126 | 0.095 | 0.097 |
| xs/turns-squared, p.u. | 0.546 | 0.525 | 2.350 | 2.990 | 2.391 |
| magnet overhang | 0.010 | 0.329 | 0.336 | 0.340 | 0.325 |
| air gap flux density | 0.619 | 0.859 | 0.669 | 0.644 | 0.671 |
| overall length | 26.715 | 6.579 | 7.474 | 11.360 | 7.042 |
| overall diameter | 1.390 | 3.049 | 2.128 | 2.109 | 2.079 |

$150,000, rendering the 180 rpm machines less economic to build. A machine such as these may cost between four and eight million dollars. Only those machines with magnet costs that are reasonable with respect to the other material costs should be candidates for design.

In all the permanent magnet machines, stator current density went to the maximum. The overall length and overall diameter of the more reasonable machines would allow them to fit in machinery spaces aboard a ship.

## 4.5. Verification

No high-power permanent magnet machines were discovered during the search to find a benchmark. Because of the high material cost and the competition afforded by synchronous and induction machines, it seems none have been built. Several paper studies were found [13, 19, 20, 21, and 22], and the parameters resulting from this computer modeling seem to agree with them. The machine size is what was expected, given the lower air gap flux density. The efficiency was higher than the synchronous and induction machines. All-in-all, this modeling gave good machines.

# Chapter Five. Induction machines

The stator of an induction machine is the same as those of synchronous and permanent magnet machines. The rotor is significantly different. There is no independent mechanism to produce a rotor flux wave. The rotor winding is shorted, whether it is wound or cast, so that as the stator flux wave passes over the rotor, currents are induced in the winding. These currents produce only a small reaction flux, but it still tends to align with the stator flux wave. When at operating speeds, the rotor speed is a bit slower than the stator flux wave speed, and the difference in speeds is called slip. Typically, slip is a few percent of the stator frequency. The rotor currents are at slip frequency. If the rotor and stator speeds were the same, slip would be zero, there would be no tendency to align and torque would be zero. Then, the rotor would lag behind the stator until current was induced in the rotor winding by the passing stator flux wave and torque was again produced.

If solid bars are used as the rotor winding, they are shorted at the ends of the rotor by end rings, to form what is called a "squirrel cage" rotor. If actual turns are used, the winding may be shorted through external resistances to affect the starting and torque-slip characteristics of the machine. Fitzgerald et al [23] and Alger [24] discuss induction machine characteristics in some detail.

## 5.1. Assumptions

A squirrel cage rotor was assumed for these machines. Copper was designated as the material for the rotor bars. However, these machines will be fed from a frequency changer, so only one layer of bars was used and the effects of magnetic diffusion ignored in the analysis (see Appendix D for a derivation of the components of an induction machine equivalent circuit). The number of rotor bars was arbitrarily set at 71. This quantity should not cause undesirable harmonics, as it will not be an integral multiple of the number of poles or stator slots in any machine. The number and width of the rotor bars were inextricably entwined and could not be separated in the analysis.

### 5.2. Machine description

An attempt was made to design the same rpm and pole-pair machines as was performed for the synchronous and permanent magnet models, but problems in limiting rotor current density allowed only a few of the machines to be designed. For example, no 7200 rpm machines were designed and 180 rpm machines could only be designed with up to twelve poles. All of the induction machines are listed in the tables starting on page . Only medium confidence should be placed in the induction machine designs, as there were some convergence difficulties in slip. (Slip is not listed in the tables for that reason.)

#### 5.2.1. Efficiency

The higher rpm machines showed a slight increase in efficiency as rpm increased. There was much movement around the average value of 97.5%. The movement decreased as rpm increased. With only six machines, it is hard to detect a trend in 180 rpm machine efficiency. Apparently, efficiency did increase with the number of pole-pairs, with all efficiencies below 90%. Developmental studies for this thesis showed that off-design-point efficiencies for the 180 rpm machines were sometimes below 70% for the endurance speed condition.

**Figure 14. High rpm induction machine efficiency**

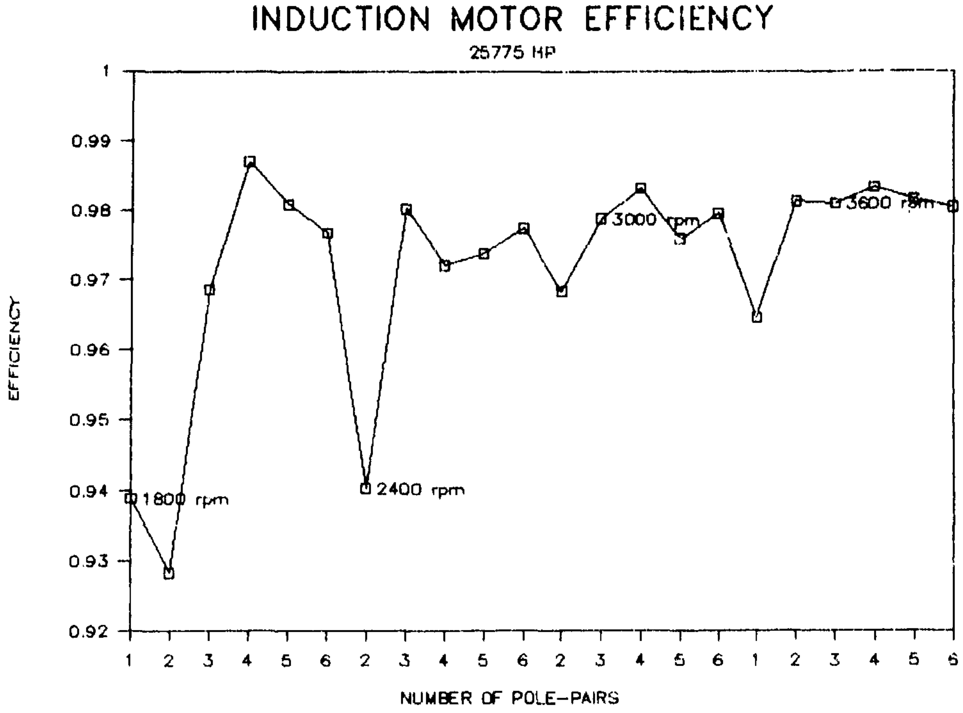


Figure 15. 180 rpm induction machine efficiency

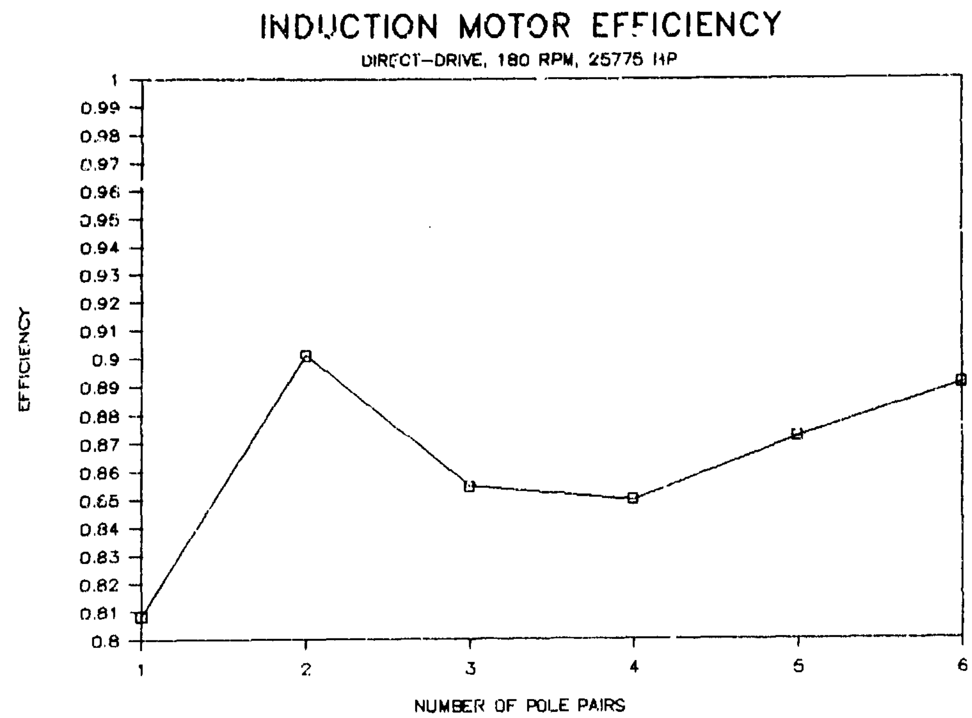


Figure 16. High rpm induction machine volume

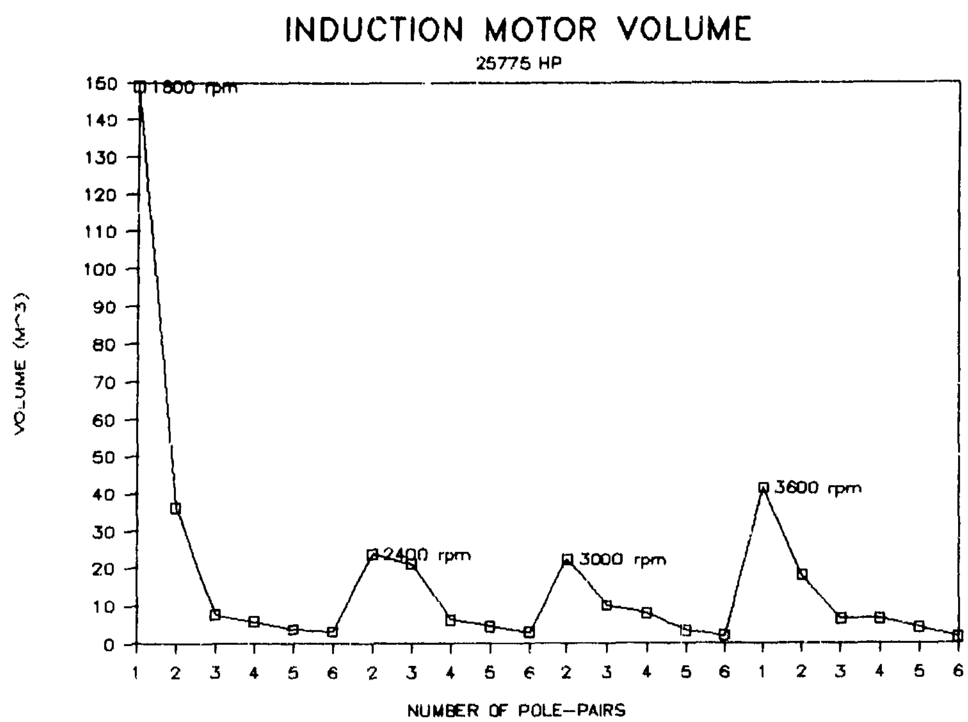


Figure 17. 180 rpm induction machine volume

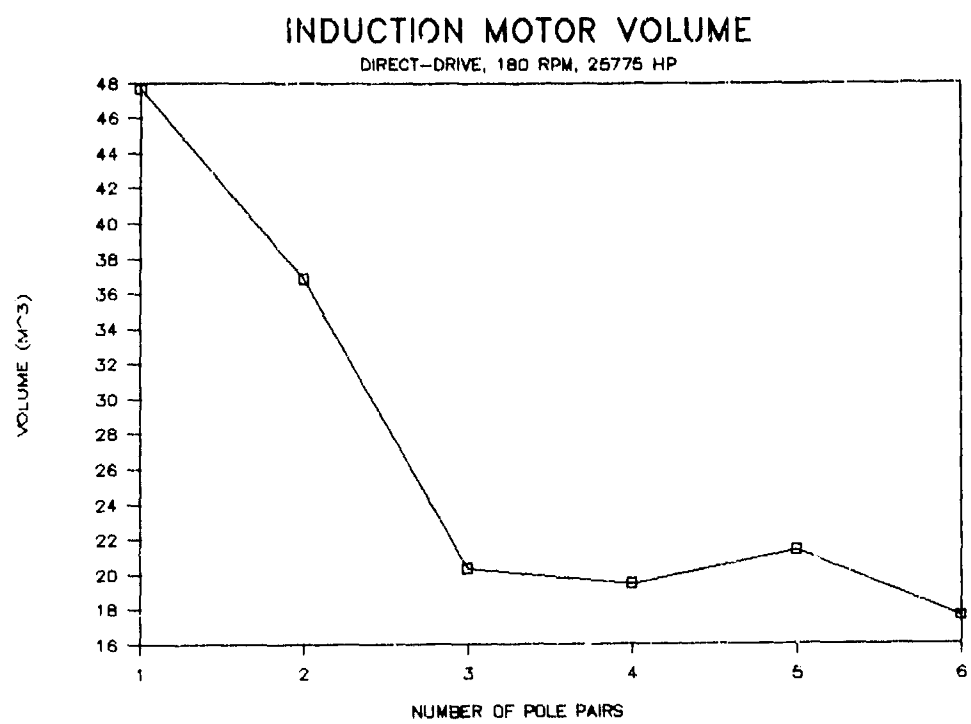


Figure 18. High rpm induction machine weight

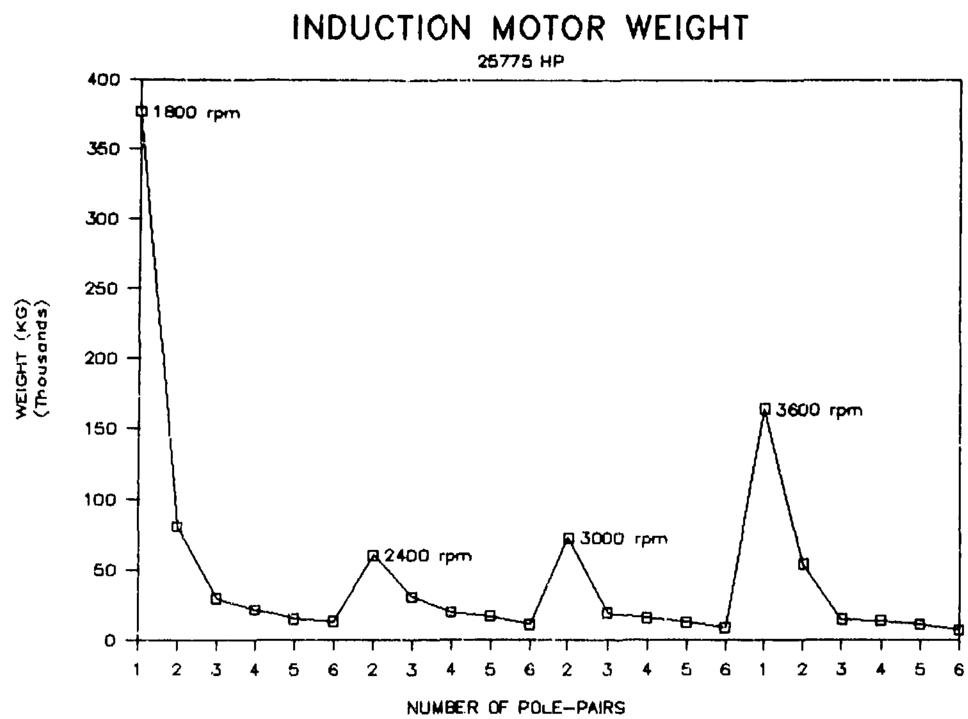
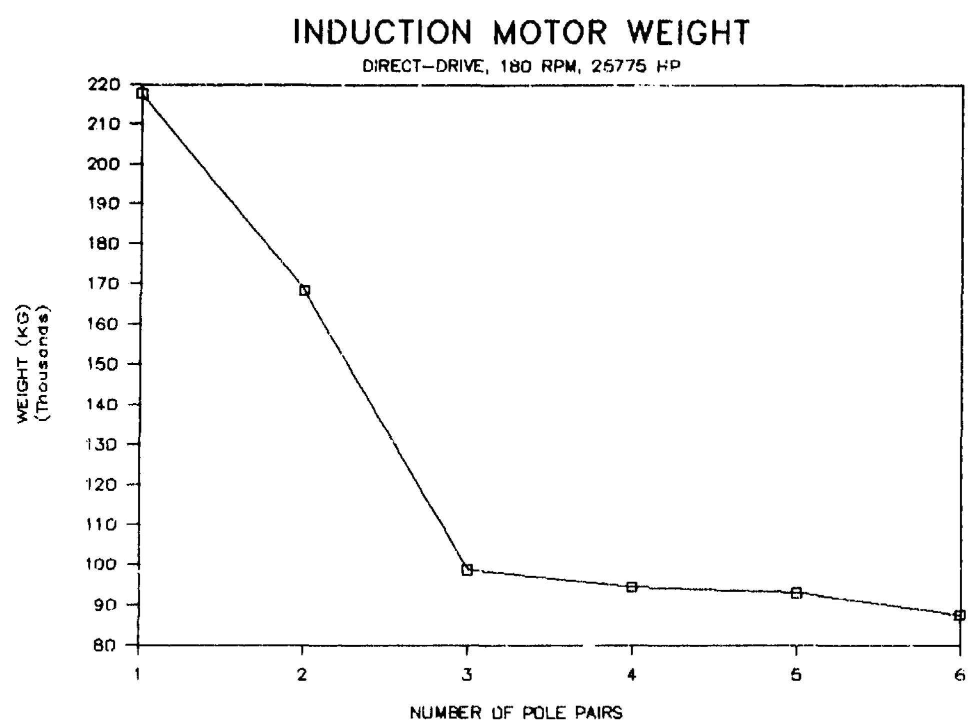


Figure 19. 180 rpm induction machine weight



#### 5.2.2. Weight and volume

The best of the high rpm machines rivaled the synchronous machines in weight and volume. The worst were very bad. Weight and volume decreased with an increase in the number of poles, but not necessarily with the increases in rpm. For the 180 rpm machines, both weight and volume decreased dramatically as the number of poles went from two to six, with much lower decreases after that. The 180 rpm machines were uncompetitive in the synthesis process.

### 5.3. Machine characteristics

The previously mentioned rotor current density difficulty showed in the rotor slot factor, which was at the limit of 0.75 for almost every motor. The stator slot factor gradually grew with the increase in poles, arriving at 0.75. The length and diameter of both the 180 and higher rpm machines is such that they would fit in machinery spaces.

### 5.4. Verification

Induction machines were expected to be close to synchronous machines in volume, weight, and efficiency. They were, and this comparison served as the verification for the induction machine model. Because the confidence level in the designed machines is only medium, more work would be needed to verify that these machines would have the advertised properties if built.

Table 18. Characteristics of 1800 rpm induction machines

| | | | | | | |
|---|---|---|---|---|---|---|
| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 |
| primary amp-turns | 6.10E+05 | 7.74E+05 | 2.44E+05 | 1.91E+05 | 1.86E+05 | 1.79E+05 |
| synchronous frequency | 30 | 60 | 90 | 120 | 150 | 180 |
| rotor radius | 0.9236 | 1.0197 | 0.4638 | 0.4352 | 0.4060 | 0.3945 |
| gap dimension | 0.0262 | 0.0039 | 0.0036 | 0.0029 | 0.0049 | 0.0051 |
| back iron depth | 0.1894 | 0.0173 | 0.1073 | 0.0093 | 0.0405 | 0.0460 |
| stator slot depth | 2.1467 | 0.5423 | 0.3375 | 0.3490 | 0.1902 | 0.1388 |
| rotor slot depth | 0.2051 | 0.3399 | 0.1546 | 0.1451 | 0.1353 | 0.1176 |
| stator slot factor | 0.285 | 0.641 | 0.355 | 0.640 | 0.699 | 0.749 |
| rotor slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 | 0.748 |
| envelope volume | 148.863 | 36.240 | 7.558 | 5.880 | 3.760 | 3.164 |
| envelope weight | 376603.7 | 80669.2 | 29447.0 | 21499.7 | 15333.1 | 13395.9 |
| hysteresis loss | 180951.2 | 19122.1 | 68838.7 | 39013.4 | 47456.7 | 48214.8 |
| eddy current loss | 32425.7 | 6853.2 | 37006.8 | 27964.1 | 38040.3 | 51839.3 |
| stator copper loss | 1.03E+06 | 1.45E+06 | 498668.3 | 165391.9 | 264414.2 | 320360.8 |
| full load efficiency | 0.939 | 0.928 | 0.969 | 0.987 | 0.981 | 0.977 |
| active length | 0.191 | 0.090 | 0.759 | 0.930 | 1.000 | 1.081 |
| rotor copper loss | 8427.7 | 8543.0 | 19627.2 | 22347.5 | 30471.4 | 37148.9 |
| maximum torque | 185470 | 185470 | 185470 | 185470 | 185470 | 185470 |
| terminal volts/turn | 234.31 | 45.07 | 266.45 | 233.56 | 193.76 | 189.53 |
| air gap volts/turn | 63.29 | 32.92 | 126.58 | 145.45 | 145.98 | 153.34 |
| R1/turns-squared | 9.23E-07 | 8.09E-07 | 2.80E-06 | 1.50E-06 | 2.54E-06 | 3.32E-06 |
| X1/turns-squared | 3.70E-04 | 3.89E-05 | 9.60E-04 | 9.53E-04 | 6.82E-04 | 6.17E-04 |
| Xm/turns-squared | 2.51E-03 | 4.41E-03 | 1.23E-02 | 1.28E-02 | 6.23E-03 | 5.15E-03 |
| X2/turns-squared | 2.03E-05 | 3.66E-05 | 3.76E-04 | 6.52E-04 | 7.79E-04 | 9.08E-04 |
| R2/turns-squared | 4.50E-08 | 9.97E-09 | 3.89E-07 | 5.37E-07 | 6.62E-07 | 8.49E-07 |
| overall length | 3.990 | 4.184 | 2.629 | 2.682 | 2.644 | 2.680 |
| overall diameter | 6.572 | 3.166 | 1.824 | 1.593 | 1.283 | 1.169 |

Table 19. Characteristics of 2400 rpm induction machines

| | | | | | |
|---|---|---|---|---|---|
| number of pole pairs | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 2400 | 2400 | 2400 | 2400 | 2400 |
| primary amp-turns | 5.94E+05 | 3.78E+05 | 2.45E+05 | 1.78E+05 | 1.93E+05 |
| synchronous frequency | 80 | 120 | 160 | 200 | 240 |
| rotor radius | 0.7541 | 0.7958 | 0.4803 | 0.4126 | 0.3841 |
| gap dimension | 0.0069 | 0.0020 | 0.0094 | 0.0087 | 0.0081 |
| back iron depth | 0.0952 | 0.0013 | 0.0834 | 0.0575 | 0.0448 |
| stator slot depth | 0.6169 | 0.5475 | 0.2755 | 0.2341 | 0.1561 |
| rotor slot depth | 0.2514 | 0.1979 | 0.1601 | 0.1375 | 0.1197 |
| stator slot factor | 0.454 | 0.477 | 0.417 | 0.413 | 0.750 |
| rotor slot factor | 0.750 | 0.750 | 0.639 | 0.568 | 0.750 |
| envelope volume | 23.889 | 21.180 | 6.201 | 4.554 | 2.942 |
| envelope weight | 60526.1 | 30880.0 | 19931.3 | 17243.1 | 11459.0 |
| hysteresis loss | 78227.5 | 26111.4 | 80426.4 | 86278.8 | 54014.3 |
| eddy current loss | 37381.4 | 18716.2 | 76864.2 | 103071.8 | 77433.0 |
| stator copper loss | 1.10E+06 | 334484.0 | 376335.4 | 306069.2 | 282567.9 |
| full load efficiency | 0.940 | 0.980 | 0.972 | 0.974 | 0.978 |
| active length | 0.142 | 0.189 | 0.533 | 0.909 | 0.852 |
| rotor copper loss | 8819.4 | 7426.0 | 17135.5 | 21589.8 | 27954.3 |
| maximum torque | 139102.5 | 139102.5 | 139102.5 | 139102.5 | 139102.5 |
| terminal volts/turn | 103.23 | 113.69 | 229.60 | 346.92 | 212.59 |
| air gap volts/turn | 51.27 | 72.14 | 122.69 | 179.75 | 156.78 |
| R1/turns-squared | 1.04E-06 | 7.82E-07 | 2.08E-06 | 3.23E-06 | 2.52E-06 |
| X1/turns-squared | 1.50E-04 | 2.32E-04 | 7.89E-04 | 1.67E-03 | 7.40E-04 |
| Xm/turns-squared | 3.88E-03 | 1.25E-02 | 3.37E-03 | 4.31E-03 | 3.35E-03 |
| X2/turns-squared | 6.22E-05 | 1.56E-04 | 4.63E-04 | 1.07E-03 | 9.36E-04 |
| R2/turns-squared | 2.84E-08 | 4.44E-08 | 2.97E-07 | 7.69E-07 | 6.73E-07 |
| overall length | 3.186 | 3.380 | 2.492 | 2.594 | 2.420 |
| overall diameter | 2.946 | 2.693 | 1.697 | 1.426 | 1.186 |

Table 20. Characteristics of 3000 rpm induction machines

| | | | | | |
|---|---|---|---|---|---|
| number of pole pairs | 2 | 3 | 4 | 5 | 6 |
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 3000 | 3000 | 3000 | 3000 | 3000 |
| primary amp-turns | 3.10E+05 | 3.62E+05 | 2.80E+05 | 1.76E+05 | 1.37E+05 |
| synchronous frequency | 100 | 150 | 200 | 250 | 300 |
| rotor radius | 0.5198 | 0.6366 | 0.5580 | 0.3660 | 0.3325 |
| gap dimension | 0.0138 | 0.0036 | 0.0070 | 0.0070 | 0.0039 |
| back iron depth | 0.1789 | 0.0134 | 0.0178 | 0.0503 | 0.0388 |
| stator slot depth | 0.8926 | 0.3785 | 0.3668 | 0.2274 | 0.1288 |
| rotor slot depth | 0.1733 | 0.2122 | 0.1860 | 0.1220 | 0.1093 |
| stator slot factor | 0.340 | 0.607 | 0.545 | 0.476 | 0.721 |
| rotor slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 |
| envelope volume | 22.412 | 10.122 | 8.000 | 3.379 | 2.065 |
| envelope weight | 72906.0 | 19541.1 | 15961.5 | 13000.9 | 9016.0 |
| hysteresis loss | 185978.6 | 25156.1 | 44235.6 | 74610.2 | 52848.0 |
| eddy current loss | 111088.5 | 22539.3 | 52845.5 | 111415.1 | 94701.2 |
| stator copper loss | 322718.0 | 359218.8 | 221369.1 | 269959.2 | 226785.8 |
| full load efficiency | 0.968 | 0.979 | 0.983 | 0.976 | 0.980 |
| active length | 0.383 | 0.189 | 0.307 | 0.818 | 1.006 |
| rotor copper loss | 8574.1 | 9089.1 | 9006.9 | 18292.9 | 25568.1 |
| maximum torque | 111282 | 111282 | 111282 | 111282 | 111282 |
| terminal volts/turn | 421.67 | 101.44 | 174.86 | 361.45 | 251.07 |
| air gap volts/turn | 119.20 | 72.02 | 102.80 | 179.30 | 200.52 |
| R1/turns-squared | 1.12E-06 | 9.14E-07 | 9.39E-07 | 2.91E-06 | 4.01E-06 |
| X1/turns-squared | 1.31E-03 | 1.96E-04 | 5.04E-04 | 1.78E-03 | 1.09E-03 |
| Xm/turns-squared | 4.47E-03 | 6.93E-03 | 3.82E-03 | 5.33E-03 | 9.00E-03 |
| X2/turns-squared | 1.82E-04 | 1.72E-04 | 3.25E-04 | 9.97E-04 | 1.54E-03 |
| R2/turns-squared | 1.60E-07 | 5.15E-08 | 1.08E-07 | 6.66E-07 | 1.01E-06 |
| overall length | 2.517 | 2.750 | 2.567 | 2.310 | 2.352 |
| overall diameter | 3.210 | 2.064 | 1.899 | 1.301 | 1.008 |

Table 21. Characteristics of 3600 rpm induction machines

| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 3600 | 3600 | 3600 | 3600 | 3600 | 3600 |
| primary amp-turns | 2.72E+05 | 1.70E+05 | 2.99E+05 | 2.95E+05 | 2.05E+05 | 1.23E+05 |
| synchronous frequency | 60 | 120 | 180 | 240 | 300 | 360 |
| rotor radius | 0.4964 | 0.4350 | 0.5150 | 0.5305 | 0.4338 | 0.3144 |
| gap dimension | 0.0061 | 0.0027 | 0.0033 | 0.0088 | 0.0079 | 0.0030 |
| back iron depth | 0.3428 | 0.0133 | 0.0238 | 0.0238 | 0.0258 | 0.0367 |
| stator slot depth | 1.3891 | 1.0052 | 0.3606 | 0.3236 | 0.2792 | 0.1181 |
| rotor slot depth | 0.1654 | 0.1308 | 0.1717 | 0.1768 | 0.1446 | 0.1045 |
| stator slot factor | 0.290 | 0.338 | 0.585 | 0.688 | 0.553 | 0.750 |
| rotor slot factor | 0.750 | 0.750 | 0.750 | 0.750 | 0.750 | 0.749 |
| envelope volume | 41.461 | 17.960 | 6.532 | 6.536 | 4.331 | 1.722 |
| envelope weight | 164461.5 | 54127.3 | 14922.3 | 14074.1 | 11549.4 | 7593.8 |
| hysteresis loss | 261300.3 | 145818.0 | 34381.6 | 42814.0 | 62801.7 | 52473.1 |
| eddy current loss | 93647.7 | 104519.7 | 36966.2 | 61376.6 | 112537.8 | 112835.4 |
| stator copper loss | 341655.1 | 107764.3 | 288857.8 | 210564.6 | 173450.1 | 192320.6 |
| full load efficiency | 0.965 | 0.981 | 0.981 | 0.983 | 0.982 | 0.981 |
| active length | 0.393 | 0.700 | 0.247 | 0.249 | 0.480 | 0.964 |
| rotor copper loss | 7562.3 | 7220.5 | 10787.1 | 9954.8 | 11162.4 | 23436.6 |
| maximum torque | 92735 | 92735 | 92735 | 92735 | 92735 | 92735 |
| terminal volts/turn | 475.12 | 702.61 | 143.82 | 142.32 | 275.51 | 261.98 |
| air gap volts/turn | 140.25 | 218.89 | 91.39 | 94.86 | 149.83 | 218.01 |
| R1/turns-squared | 1.54E-06 | 1.25E-06 | 1.07E-06 | 8.08E-07 | 1.37E-06 | 4.25E-06 |
| X1/turns-squared | 1.67E-03 | 3.93E-03 | 3.70E-04 | 3.59E-04 | 1.13E-03 | 1.18E-03 |
| Xm/turns-squared | 2.39E-02 | 4.19E-02 | 9.66E-03 | 2.80E-03 | 3.94E-03 | 1.26E-02 |
| X2/turns-squared | 1.20E-04 | 4.65E-04 | 2.54E-04 | 3.05E-04 | 7.24E-04 | 1.84E-03 |
| R2/turns-squared | 1.98E-07 | 4.57E-07 | 1.03E-07 | 9.68E-08 | 2.79E-07 | 1.07E-06 |
| overall length | 2.403 | 2.451 | 2.320 | 2.406 | 2.247 | 2.234 |
| overall diameter | 4.469 | 2.913 | 1.805 | 1.773 | 1.494 | 0.944 |

Table 22. Characteristics of 180 rpm induction machines

| number of pole pairs | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| power, hp | 25775 | 25775 | 25775 | 25775 | 25775 | 25775 |
| efficiency factor | 180000 | 180000 | 180000 | 180000 | 180000 | 180000 |
| volume factor | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 | 1286.1 |
| shaft rpm | 180 | 180 | 180 | 180 | 180 | 180 |
| primary amps-turns | 1054077 | 564571.5 | 569333.6 | 510008.9 | 512534.4 | 324264.5 |
| synchronous frequency | 3 | 6 | 9 | 12 | 15 | 18 |
| rotor radius | 0.9956 | 0.7236 | 0.6896 | 0.6616 | 0.7411 | 0.6962 |
| gap dimension | 0.0025 | 0.0060 | 0.0195 | 0.0334 | 0.0235 | 0.0054 |
| back iron depth | 0.0227 | 0.0240 | 0.1568 | 0.1158 | 0.1038 | 0.0812 |
| stator slot depth | 0.6714 | 0.7116 | 0.2536 | 0.2231 | 0.2200 | 0.1466 |
| rotor slot depth | 0.3319 | 0.2412 | 0.2299 | 0.2039 | 0.1845 | 0.1501 |
| stator slot factor | 0.590 | 0.563 | 0.734 | 0.750 | 0.694 | 0.718 |
| rotor slot factor | 0.750 | 0.750 | 0.750 | 0.683 | 0.696 | 0.701 |
| envelope volume | 47.668 | 36.837 | 20.316 | 19.450 | 21.357 | 17.600 |
| envelope weight | 217524.1 | 168344.2 | 98690.0 | 94554.9 | 93084.7 | 87558.9 |
| hysteresis loss | 4551.5 | 16194.6 | 19356.0 | 24294.6 | 31609.4 | 36548.6 |
| eddy current loss | 81.6 | 580.4 | 1040.6 | 1741.4 | 2832.1 | 3929.6 |
| stator copper loss | 4.41E+06 | 1.96E+06 | 3.05E+06 | 3.15E+06 | 2.59E+06 | 2.09E+06 |
| full load efficiency | 0.808 | 0.901 | 0.854 | 0.850 | 0.872 | 0.891 |
| active length | 0.825 | 2.047 | 1.854 | 2.486 | 2.159 | 3.090 |
| rotor copper loss | 1.08E+05 | 1.29E+05 | 2.08E+05 | 2.23E+05 | 1.94E+05 | 2.14E+05 |
| maximum torque | 1854700 | 1854700 | 1854700 | 1854700 | 1854700 | 1854700 |
| terminal volts/turn | 61.849 | 104.401 | 58.731 | 76.530 | 76.097 | 87.418 |
| air gap volts/turn | 29.510 | 53.243 | 45.967 | 59.124 | 57.510 | 77.345 |
| R1/turns-squared | 1.33E-06 | 2.05E-06 | 3.14E-06 | 4.04E-06 | 3.28E-06 | 6.61E-06 |
| X1/turns-squared | 5.08E-05 | 1.58E-04 | 6.01E-05 | 9.01E-05 | 9.33E-05 | 1.12E-04 |
| Xm/turns-squared | 1.21E-02 | 4.61E-03 | 8.17E-04 | 4.60E-04 | 5.08E-04 | 2.49E-03 |
| X2/turns-squared | 1.89E-05 | 6.91E-05 | 7.91E-05 | 1.37E-04 | 1.27E-04 | 2.40E-04 |
| R2/turns-squared | 1.16E-07 | 4.44E-07 | 4.33E-07 | 7.40E-07 | 6.20E-07 | 1.15E-06 |
| overall length | 4.817 | 4.965 | 4.691 | 5.266 | 5.217 | 5.897 |
| overall diameter | 3.384 | 2.930 | 2.239 | 2.068 | 2.177 | 1.859 |

## Chapter Six. Nominal ship design

### 6.1. Technology sensitivity analysis

Technology sensitivity analyses, such as this thesis, must be able to quantitatively compare similar technologies. The pertinent differences must be made apparent through appropriate analysis. Inherent in the analysis must be the consideration of the global system complexity. Naval ships are extremely complex and the effects of various technologies can be lost in the complexity. One methodology for technology characterization in naval ships has been proposed by Goddard [25]. This method has been followed to show the benefits of electric drive.

### 6.2. ASSET

The Advanced Surface Ship Evaluation Tool (ASSET) was developed over several years to be the U. S. Navy's premier ship design computer program. It has its roots in HANDE, a hydrofoil design program developed in the 1970's. The ship design spiral is traversed in an iterative fashion until convergence on a number of parameters is achieved. Boeing Computer Services is the contractor for ASSET, under the supervision of the David Taylor Naval Ship Research and Development Center, at Carderock, Maryland.[16] It is divided into large modules by ship type. These modules include Monohulls, Hydrofoils, and SWATH ships.

The geometry of a particular ship is input to ASSET. The following were used as characteristic ship traits: full load displacement, certain Ship Work Breakdown Structure (SWBS) weight groups,[17] endurance fuel load at 20 knots,

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16. Greenwood, R.W., and Fuller, A.L., "Development of a Common Tool for Ship Design and Technology Evaluation," Proc. SNAME New England Section Marine Computers 1986.

17. See Appendix E for more information on SWBS.

draft, maximum and sustained speed for 51,550 installed horsepower, and transverse GM. From the changes in these parameters during the various computer runs, the effects of transmission choices were noted.

The inputs to ASSET describe the ship that is being designed. The outputs cover the range of calculations possible in structures, volume, space, machinery, propeller characteristics, resistance, powering, and weight. There are ASSET performance modules on cost, stability, hydrostatics, seakeeping, manning and space but the usual synthesis output is of more use during a technology sensitivity analysis.

The descriptions of several ships are contained in an ASSET data base. For a particular ship, a Current Model is maintained that holds all of the parameters to describe that particular ship. In ASSET Version 2.0, over 380 parameters are used for each ship description. User control over most of these parameters is possible, or control may be given to the executive program which will then "design" a ship subject to whatever constraints the user desires.

Some intricacies of ship design are not handled well by ASSET. For example, the program is not able to handle equipment re-arrangements easily, and almost all equipment-level volumes are approximated from studies of past ships.[18] For this reason, some equipment-level weights and volumes need to be calculated off-line and input to the program through its weight adjustment facility, especially if accuracy in these areas is important to the study being performed.

The baseline ship used in these studies has a full load displacement of 5485 LT, carries 272 crew members, is 425 feet long, and has a primary mission of anti-submarine war-

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18. The Enhanced Machinery Module [27], in the process of being made available, will improve the situation dramatically. Some of the relationships from that module were used in calculating electric propulsion weights.

fare (ASW). It is armed for that purpose and has equipment in keeping with its size The baseline ship is described in more detail below.

### 6.2.1. Margins

A naval ship design has margins in weight, vertical center of gravity (KG), space, ship service electrical generation, propulsion power, accommodations, and structural strength which allow for equipment, mission, and system growth over its projected thirty year life. Without these margins, the ship would be difficult to modify, because whatever might be added in these areas would have to be paid for by a removal. For example, if a 50 ton radar system were added, the original 40 ton radar system and 10 tons of fuel might be removed to leave the ship at its original weight. With margins, the 10 tons of fuel might not be removed.

Margins are typically split into Acquisition and Service Life allowances. Acquisition margins recognize the fact that ship specifications change over the design cycle and during construction. For example, the fourth ship built may have a different weapons system than the first, with a different electrical requirement. If the electrical generation plant had to be changed during construction to accommodate the new weapons system, the total cost might be prohibitive. If an Acquisition margin is built into the original design, this may not occur. A Service Life margin makes allowance for configuration changes over the life of the ship.

The ASSET program uses margins when synthesizing a ship. The margins are under operator control. The margins suggested by Goddard and used in this analysis are listed in the table.[19]

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19. Goddard, C.H., "A Methodology for Technology Characterization and Evaluation for Naval Ships," S.M. NAME AND O.E. thesis, MIT, 1985, p. 31.

Table 23. Recommended technology assessment design margins for a monohull surface combatant

| | Acquisition | Service Life |
|---|---|---|
| Weight[a] | 12.5% of SWBS 1-7 | 10% |
| KG | 12.5% of KG 1-7 | 1.0 ft. |
| Space | 0 (no excess volume) | 0 |
| Electrical[b] | 20% | 20% |
| Propulsion power[c] | 10% total EHP prior to prelim body plan<br>8% prior to self-propelled model tests | |
| Accommodations | Accom = 1.1 x ship manning at delivery | |
| Strength | 2.24 KSI of marginal stress at delivery<br>(Max primary stress for hull material) | |

Notes:

a. The service life weight margin applies only to naval architectural limits of the ship (reserve buoyancy, stability, structures), not to the final design weight.

b. In sizing the electric plant, the calculated maximum electric load plus these design margins shall be met with one generator out of service. The remaining generators shall not be loaded in excess of 90%. Note that the service life margin is not applied to SWBS group 200 which would be expected to remain stable over the life of the ship.

c. Performance requirements (sustained speed, endurance range) are met at delivery full load displacement.

## 6.3. Philosophy of effort

The nature of this technology characterization required that certain limits be imposed on the total effort. (If the Naval Sea Systems Command were to do this study, many people would simultaneously be employed to investigate every detail.) Some items were fixed, some were allowed to float with the design.

The hardest item to handle is volume. There are very few ways of adjusting volume as easily as weight is adjusted. One way is through the use of Marginal Volume Factors, which equate a weight penalty with every increase in volume. (See Howell [26].)

The differences among transmission systems appear primarily in the machinery spaces and fuel tanks of a ship.

ASSET can handle the tankage changes without aid. However, it does no equipment arrangement or space analysis inside the machinery spaces, leaving that for arrangement experts to do off-line. It was decided to keep the machinery space volume the same in all ships of this study, no matter how that volume was divided into spaces. Changes in equipment volume will be noted in the analysis and left for the advantage of others in machinery space rearrangement.

Moderate to high technical risk has been accepted in specifying equipment cooling. Current densities at the limits of cooling technology are used, assuming that liquid cooling of both the stator and rotor can be performed. Lower current densities would be required if such cooling were not possible, resulting in slightly larger, heavier, less efficient machines. This last statement was proven during the course of the thesis research, as the first (chronologically) current densities used were two-thirds larger than those listed herein.

Other risk areas include the use of advanced vacuum switchgear and the assumed efficiencies of reduction gears and power converters. These are low risk items; the technology is well understood and commercially available.

Table 24. Ship design items held constant during analysis

| | |
|---|---|
| Endurance speed | 20 knots |
| Endurance range[a] | 5500 nautical miles |
| Machinery box volume | 109,670 $ft^3$ |
| Installed horsepower | 51,550 hp |
| Payload weight, volume, and electrical requirements | |
| Length | 425 ft. |
| Beam | 55 ft. |
| Ship electrical load | 2030 kW (24 hr. avg) |
| Ship molded lines | |
| Manning | |
| Deckhouse and superstructure geometry | |

Table 25. Ship design items allowed to float during analysis

| |
|---|
| Maximum and sustained speeds |
| Endurance fuel load |
| Ship full load displacement |
| Ship draft |
| Ship resistance and powering |
| Ship arrangement outside machinery spaces |

Note:

a. Endurance range was allowed to float as a comparison between two electrical transmission ships and the mechanical transmission baseline ship. It was held constant for the rearranged ship.

Most of the ship synthesis has been left to ASSET though parameters from Goddard were used where possible. ASSET designs a reasonable, generic ship with good seakeeping characteristics. As shown above, some ship characteristics were frozen to ensure transmission comparisons were not performed with different ships. Leaving the ship synthesis to ASSET allowed concentration on the specifics of the propulsion plant.

6.4. Baseline ship

The baseline ship has a mechanical transmission, i.e., two power trains consisting of a gas turbine, clutch and coupling, reduction gear, shafting, and propeller. There are two machinery rooms, each containing one gas turbine. The gas turbine used as the model is the General Electric LM-2500, rated at 25,775 brake horsepower. This is a very common marine gas turbine. It and its predecessors are powering the latest classes of naval combatant, such as the DD963, FFG7, and DDG51.

The locked-train double-reduction gears are reversible, allowing the use of fixed-pitch propellers. There is no mechanical cross-connect allowed between the shafts. Except for the power level, this is the gear system being employed on the DDG51 class. Gears of this sort are about one percent inefficient[20] per reduction stage. Since these are double-reduction gears, an efficiency of 98% was used.

An endurance speed of 20 knots has been specified. This is in keeping with standard fleet practices. An endurance range of 5500 nautical miles permits ocean crossings without refueling. The lack of a cross-connect capability between the two shafts means at least two gas turbines will

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20. Inefficiency = 1 - efficiency. Information on stage inefficiency is from a conversation with Mr. Samuel Shank, the author of the ASSET Enhanced Machinery Module [27].

be on-line during endurance cruising. This is inherently inefficient; some operators alleviate the inefficiency by declutching one shaft and free-wheeling that propeller, reaching desired speeds by loading up the operating gas turbine.

A measure of initial static stability is the ratio GM/Beam. GM is the vertical distance between the center of gravity and the metacenter of the ship. Typical values for this ratio are 8-10%. A lower value (6.5%) has been accepted for purposes of comparison with the variants. A large ship redesign effort would have been necessary to bring GM/B into a better range.

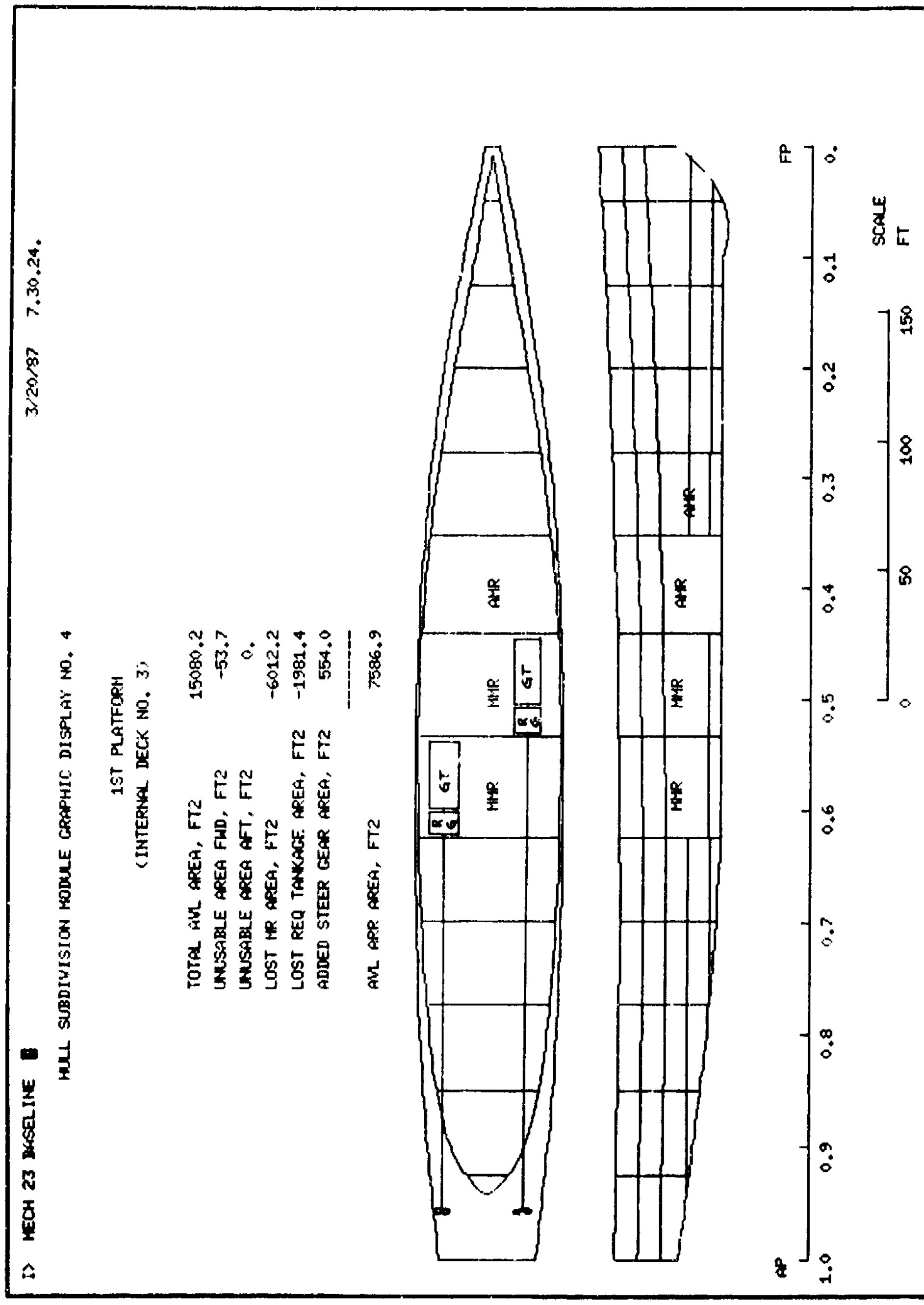
The electrical generation plant consists of three gas turbines, each driving a 2000 kW generator. The data used for the gas turbines was taken from the Detroit Allison 501K turbine-generator set used aboard the DD963 ships.

Both the deckhouse and main hull are constructed of High Tensile Strength (yield stress = 50,000 psi) steel. Active stabilizing fins and a sonar dome are included in the design. The payload is listed in Table 26. A coarse layout of the machinery spaces is shown in Figure 20.

Table 26. Payload for baseline and variant ships

FFG7 Command and control suite
Satellite, UHF, and HF communications
SLQ32V3 electronic countermeasures
NIXIE acoustic countermeasure
SPS-49 two-dimensional air search and tracking radar
SPS-55 surface search and tracking radar
SQR-19 towed array surveillance system
MK92 missile and gun fire control system
Harpoon fire control system
LAMPS III helicopters and support system
JP-5 aviation fuel
MK32 over-the-side torpedo system
MK13 guided missile launching system
MK75 76mm gun
Close-In-Weapon-System
Small arms
Appropriate ammunition and reloads

**Figure 20. Baseline ship subdivision and machinery arrangement**



6.5. Backfit ship

If the mechanical transmission of the baseline ship were replaced with an electrical transmission without changing the subdivision of the ship, it would be as if an older ship had been updated. or "backfitted," with new technology. This is the idea behind the first variant ship.

Propulsion motors and generators were added into the propulsion plant, in the original spaces. Shafting still runs from the machinery spaces to the propellers. A reduction gear is still necessary for higher rpm propulsion motors, but electrical cross-connect may improve the endurance fuel efficiency.

Some rearrangement within the machinery space is necessitated by the backfit. The machinery spaces in the baseline ship are not long enough to contain the stack-up length of gas turbine, generator, motor, and reduction gear, without "folding" the power train. This may be accomplished by changing the design of the reduction gear or by placing the gas turbine and generator (which require a mechanical connection) side-by-side (or transversely) with the motor and reduction gear (another mechanical connection), using transmission line to electrically connect them. Since there are a variety of ways to rearrange the machinery box, and since the chosen method has no effect on the analysis, the rearrangement was not specified.

The propulsion generators and motors may operate at different rotational speeds, and therefore different electrical frequencies, so power converters must be used between them. Power converters change the frequency of the power being transferred between the generators and motors, through the use of cycloconverters or thyristors. They add another inefficiency to the transmission. A reasonable estimate of the efficiency of an 18 MW power converter is 97%.[21]

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21. Professor John Kassakian, MIT, private communication.

## 6.6. Rearranged ship

The second variant ship takes advantage of the benefits of machinery space rearrangement. The same machinery space total volume is preserved but split into five spaces. The propulsion motors are placed very near the propellers, resulting in much shorter shafting runs and an increased GM/B ratio. The decrease in shaft length means a decrease in shaft weight and more space available outside the machinery box. The shafts previously ran through shaft alleys that may be returned to other uses. This rearrangement is almost certainly not the optimum one and can be improved in the sense of space efficiency. It is an arrangement, however, that can demonstrate the benefits to be expected of a ship designed for electric drive. Power converters again connect the generators and motors. Transmission line forms the connections, at a much lower weight than shafting.

Many other choices in large components are possible for this rearranged ship. For example, three propulsion generators and gas turbines driving two or four propulsion motors might have been chosen. The number of prime movers was retained from the mechanical baseline ship, however, to make the comparison of transmissions realistic. Too many changes might have obscured the fundamental differences in efficiency, weight and volume.

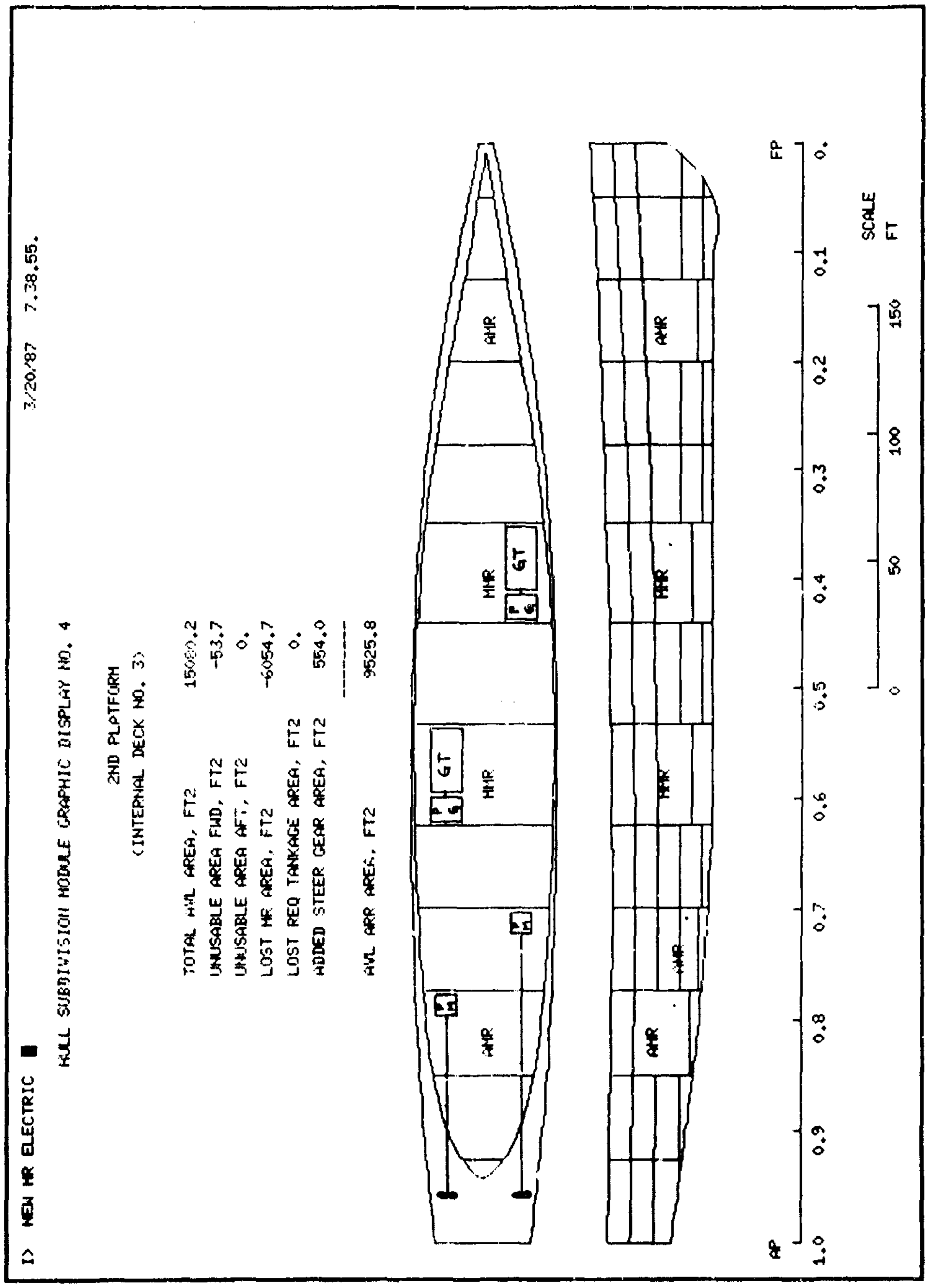
Both geared and direct-drive propulsion motors were used in this variant. When geared motors are used, the reduction gears are also placed near the propellers. A coarse layout of the rearranged ship is shown in Figure 21.

## 6.7. Weight and volume algorithms

Few components in this thesis are exact commercial models. The weight, volume, and other characteristics are taken from those for which data was available. The equations for shafting and reduction gears were taken from the

ASSET theory manuals [28], while the switchgear and braking resistor equations came from the ASSET Enhanced Machinery Module [27], which is not yet generally available. These equations represent much study by ship and equipment designers, incorporating equipment which is commercially available. Where possible, the ASSET equations were verified against other studies and actual equipment [29, 30, 31]. For example, the machinery in the FFG7 was used as a model and verification for reduction gears and shafting. Appendix E gives more explanation, as well as presenting a computer program used to generate weight and volume figures.

Figure 21. Layout of machinery spaces on rearranged ship



## Chapter Seven. Machine design and system synthesis

### 7.1. Machine matrix

During this study, synchronous, permanent magnet, and induction machines were designed at shaft speeds of 180, 1800, 2400, 3000, 3600, and 7200 rpm. The number of pole-pairs for the 180 rpm machines ran from one to twenty-five. For the higher rpm machines, from one to six pole-pairs were used. If every machine could be a generator or a motor, a 165x165 machine matrix results. From these 27,225 possible combinations, two were chosen and input to the two variant ships for synthesis in ASSET.

These particular rpms were chosen partially because of the choice of the gas turbine. The LM-2500 operates at a full-load speed of 3600 rpm, making multiples and "nice" fractions of that speed desirable. A 3600 rpm, two-pole machine has a synchronous frequency of 60 hertz, the standard in the United States. A four-pole machine at 1800 rpm is also a 60 hertz machine. If "nice" frequencies result from rpm choices, results may not be obscured. The low rpm machine is tied to propeller rpm. For the baseline ship, maximum speed propeller rpm is 170 rpm. A ten rpm allowance for "battle override" gives a requirement for 180 rpm.

The reduction in the number of machine combinations is a bit more difficult to explain. First, it was observed that reduction gears add greatly to the weight and volume of the transmission and detract from its efficiency. Second, induction generators are notoriously difficult to control. It was then decided that generators would not be induction machines and any generators used would operate at the same shaft speed as the gas turbine, eliminating a possible reduction gear. The matrix then measured 12x165 and had 1980 combinations.

From this point on, the decision theory espoused in Schweppe and Merrill [13] was used, specifically using "knee sets" to eliminate uncompetitive designs. The consideration, or Figure-of-Merit, was always minimum weight, volume, and inefficiency. These external characteristics are those "seen" by a ship design (since propulsion current and voltage were specified in terms of turns -- fertile ground for another tradeoff study). Initially, individual motors of all of the higher rpms were considered together to select the best geared propulsion motors. Since the weight and volume of a reduction gear varies with shaft rpm, the weight and volume of the reduction gear was included with that of the machine to select the best machine-gear system. Direct-drive machines were also selected. The 3600 rpm synchronous and permanent magnet machines were also considered separately as propulsion generators.

Once the initial selection of machines was made, the matrix measured 5x11, or 55 combinations. All of the combinations were plotted in knee curves that showed the volume, weight, and inefficiency of each transmission. The volume and weight of shafting, braking resistors, cooling systems, power converters, and the inefficiency of the power converters were common to all combinations and were not included at this level. The inefficiency of any reduction gears was included where appropriate. Three of the generators were synchronous machines and two were permanent magnet machines. Of the motors, two were 1800 rpm synchronous machines, two were 1800 rpm permanent magnet machines, three were 1800 rpm induction machines, and two were 180 rpm synchronous machines. The 1800 rpm motors clearly dominated the higher rpm machines, largely because of the differences in reduction gear weight and volume.

Since there was no single dominating combination, ten of the 55 combinations were selected. These ten were among the best at least twice on the knee curves. These ten combinations were composed of only synchronous machines.

Programs to calculate off-design-point efficiency were written. Each motor and generator was evaluated at the power level and rpm appropriate for the sustained and endurance speed conditions of the ship, using the delivered horsepower (DHP) and propeller rpm taken from the ASSET synthesis run on the baseline mechanical ship. Some of the combinations had very low endurance efficiencies. There was a sharp division evident between the geared (lower weight, much higher volume) and the direct-drive systems.

The ten combinations, with their maximum, sustained, and endurance speed transmission inefficiencies, were again made the subject of knee curves. A simple scoring scheme was devised to rank the combinations according to their grouping on these last knee curves. If a combination was in the best group on a particular knee curve, it was given two points for that curve. If it was in the second best group, it received one point. If it was in neither the best or second best group, it received no points. When the scores were totaled, two combinations stood out. One was a geared drive system and one a direct-drive system. These two combinations were used in both of the variant ships and are the subject of the next chapter.

7.2. Knee curves

Figures 22 through 24 show the knee curves for the propulsion generators. The first letter of the generator ID indicates whether it is a synchronous machine or a permanent magnet machine. All of the generators are 3600 rpm machines. The generators selected were SB (four poles), SC (six poles), SD (eight poles), PB (four poles), and PC (six poles). Generator SA was not selected because of its poor showing on the volume-weight curve, even though it was competitive on the volume-efficiency curve.

The 180 rpm, direct-drive propulsion motor curves are in Figures 25 through 27. They were not combined with geared motors because one of the points being investigated was whether or not geared motors were "better" than direct-drive motors. The clumping of the machines necessitated other graphs on different scales to distinguish between the machines. Machines 1-25 are synchronous, 26-50 are permanent magnet, and 51-56 are induction machines. The number within a group indicates the number of poles in the machine, e.g., machine 32 has (32-25)x2=14 poles. Valid designs with over twelve poles were not achieved for the induction machines. Machines 3, 8, 11, and 16 were selected for further work. These are all synchronous motors.

The higher rpm motors were combined with their reduction gears to form system knee curves. In all of these knee curves, machines 1-6 are 1800 rpm, 7-12 are 2400 rpm, 13-18 are 3000 rpm, 19-24 are 3600 rpm, and 25-30 are 7200 rpm. Figure 28 is the volume-efficiency curve for synchronous machines, showing the distinct grouping of the machine-gear systems due to the high volume of the reduction gears. Note the high values of the permanent magnet machines in the volume-weight curve Figure 29. The clumping of induction motors around the low inefficiencies is shown in the weight-efficiency curve of Figure 30. From these curves, the motors on page 97 were selected.

The initial motor and generator combinations were made and plotted on more knee curves (Figures 31 to 33). On those curves, the high-volume or high-weight nature of the combinations can be seen. Since the multiple-attribute decision theory embodied in knee curves does not say how to select between high-volume or high-weight, the best of each were selected. Combinations 1, 2, 8, 9, 12, 13, 19, 20, 30, and 31 were chosen. The off-design-point efficiencies were calculated and all of the information was plotted. Figure 34 is a bar-graph of the maximum, sustained, and endurance speed transmission efficiencies of the various combinations, including the reduction gears, if any, and power converters. The final combination knee curves are summarized in the scoring scheme of Table 27, which was explained on page 98 . Combinations 12 and 20 were chosen to use in the ships of the study.

This is a good method to choose among the possible machines. During the course of this thesis, the above path was followed through several complete iterations and a few partial ones. As stated in Schweppe and Merrill, knee curves serve very well to eliminate uncompetitive options, allowing concentration on the better ones.

Table 27. Final combination knee curve scores

| Combo ID | Firsts | Seconds | Total |
|---|---|---|---|
| 1 | 3 | 1 | 7 |
| 2 | 3 | 0 | 6 |
| 8 | 1 | 0 | 2 |
| 9 | 0 | 1 | 1 |
| 12 | 6 | 1 | 13 |
| 13 | 4 | 0 | 8 |
| 19 | 1 | 1 | 3 |
| 20 | 3 | 4 | 10 |
| 31 | 0 | 2 | 2 |

Conclusion: test combinations 12 and 20

Figure 22. Curve of volume-efficiency for 3600 rpm generators

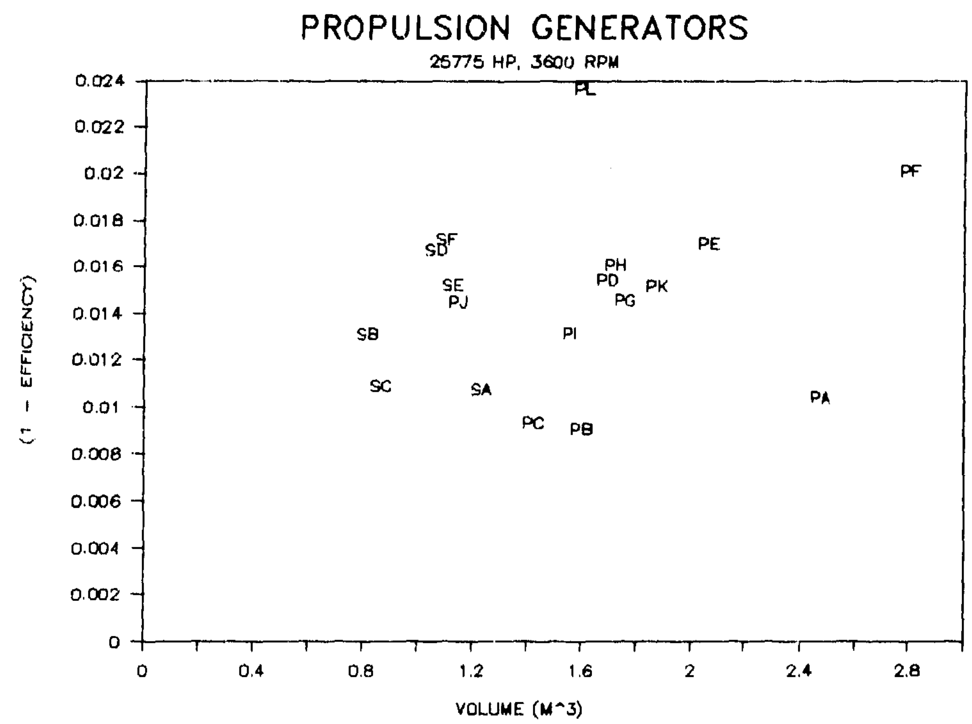


Figure 23. Curve of volume-weight for 3600 rpm generators

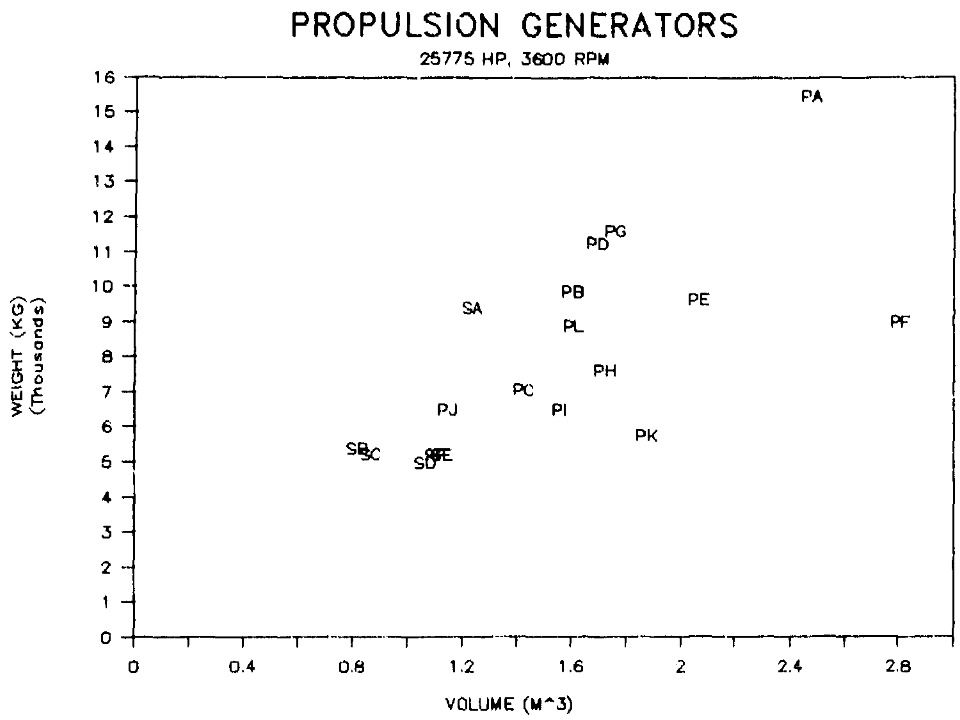


**Figure 24. Curve of weight-efficiency for 3600 rpm generators**

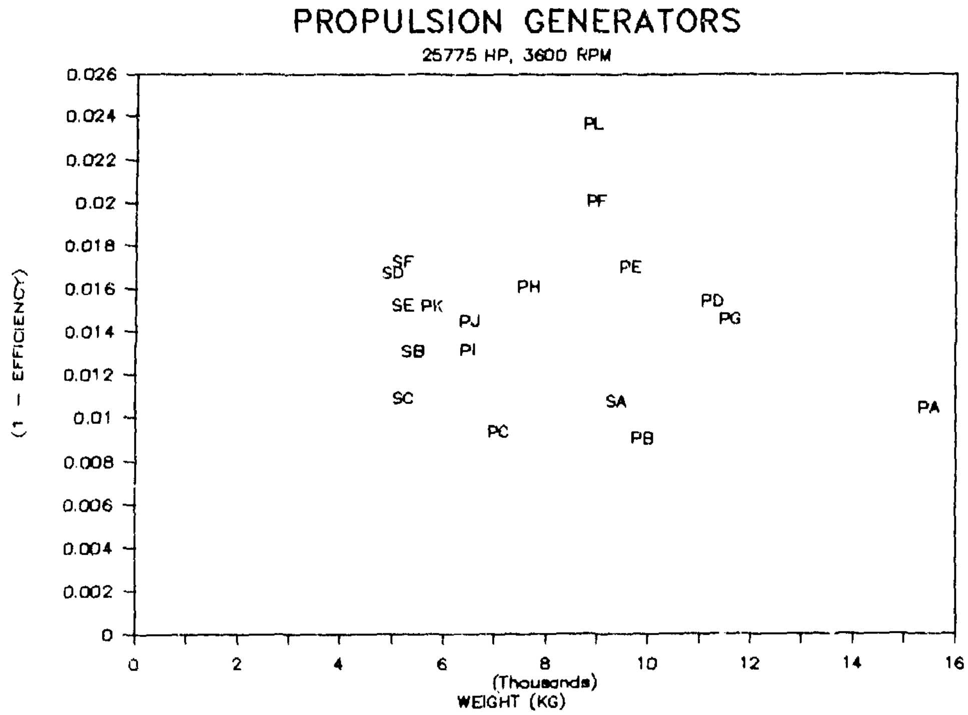


Figure 25. Curve of volume-efficiency for 180 rpm motors

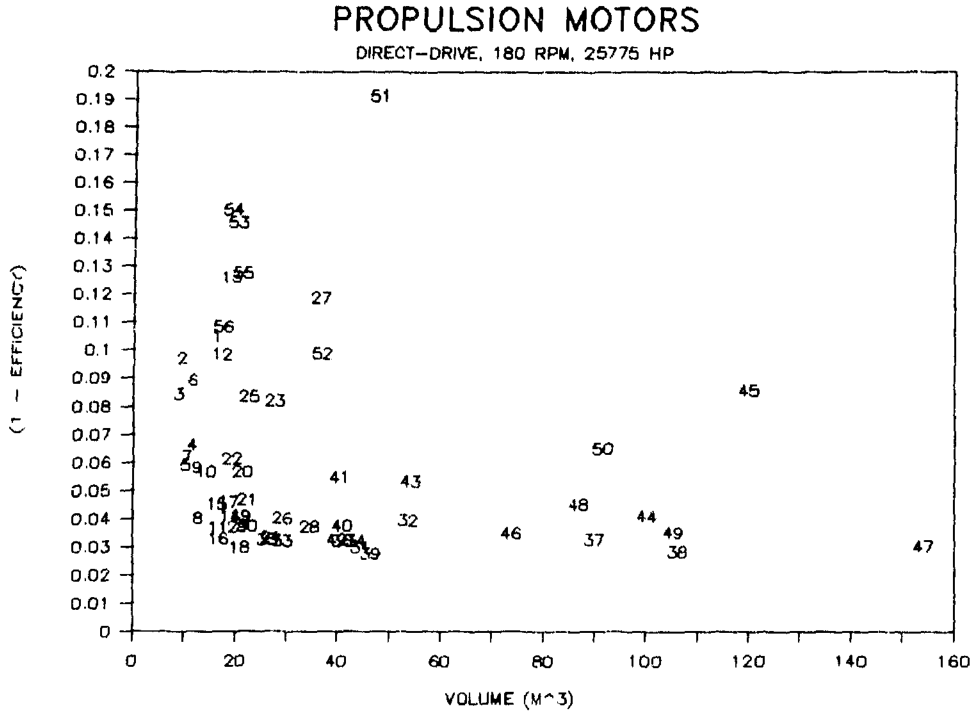


Figure 26. Curve of volume-weight for 180 rpm motors

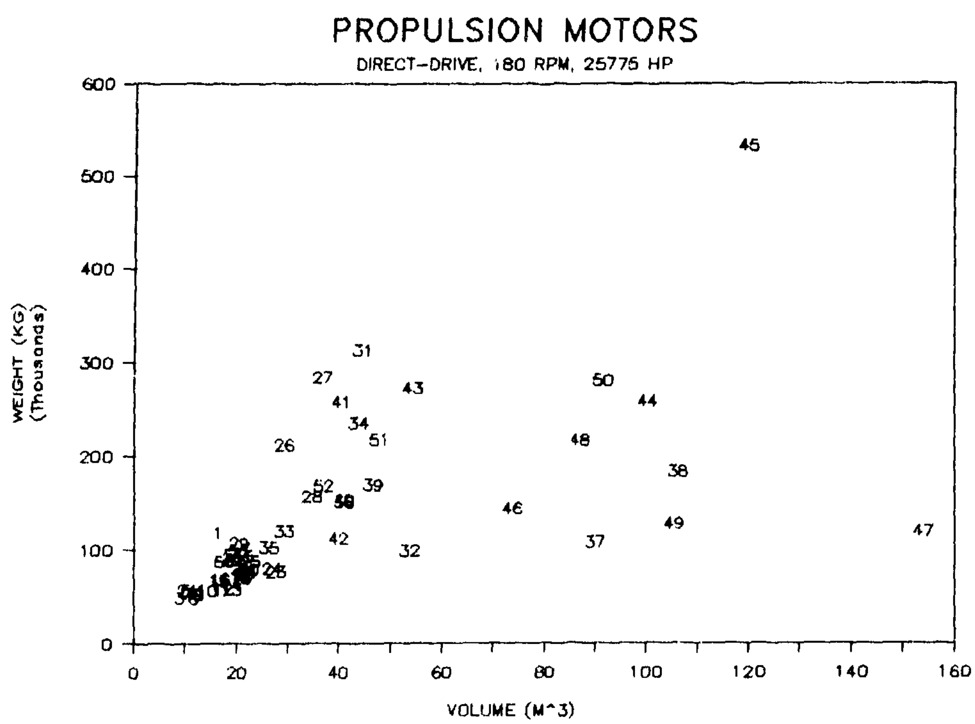


Figure 27. Curve of weight-efficiency for 180 rpm motors

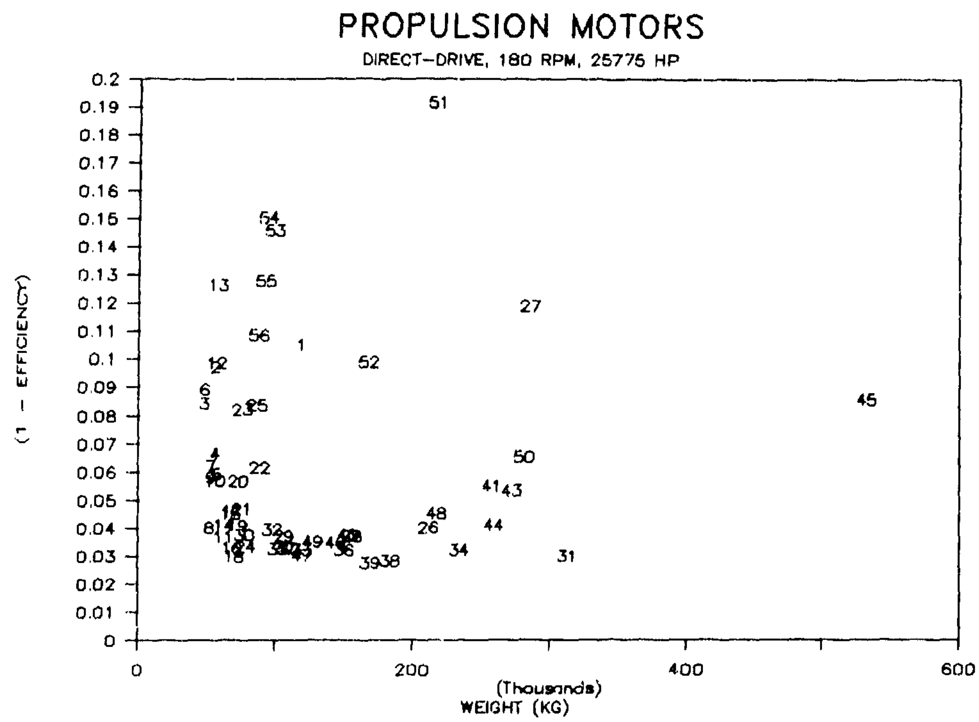


Figure 28. Curve of volume-efficiency for geared motors

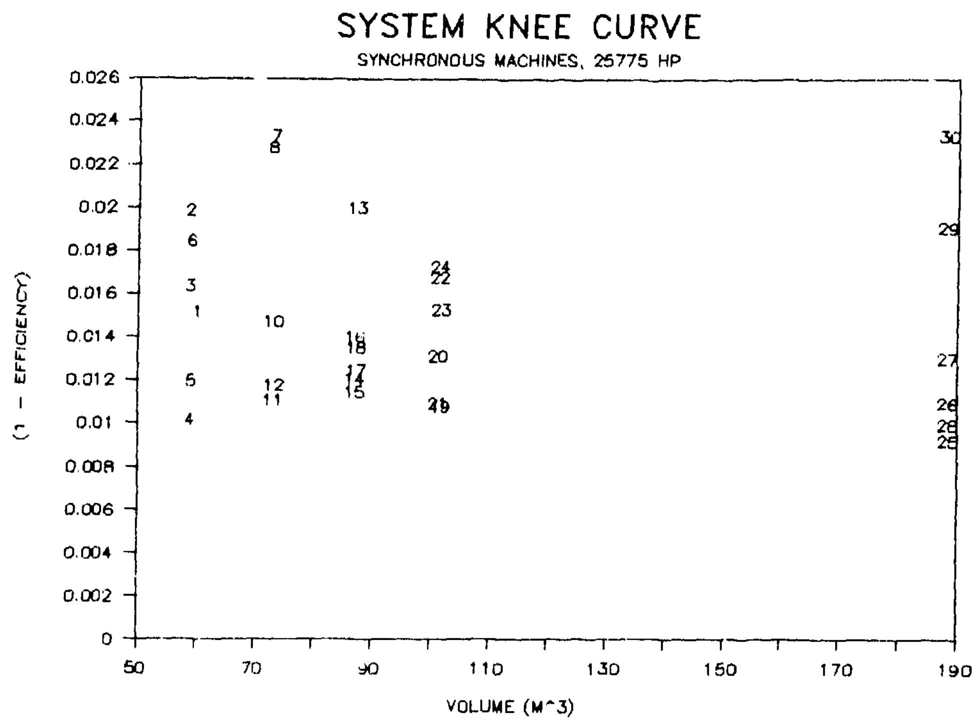


Figure 29. Curve of volume-weight for geared motors

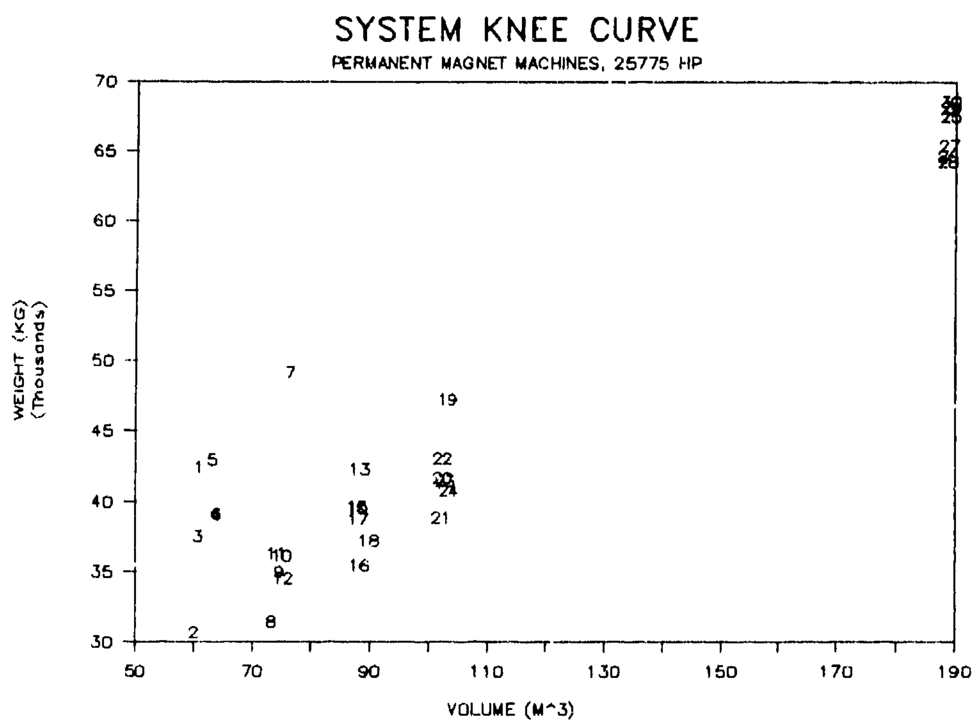


Figure 30. Curve of weight-efficiency for geared motors

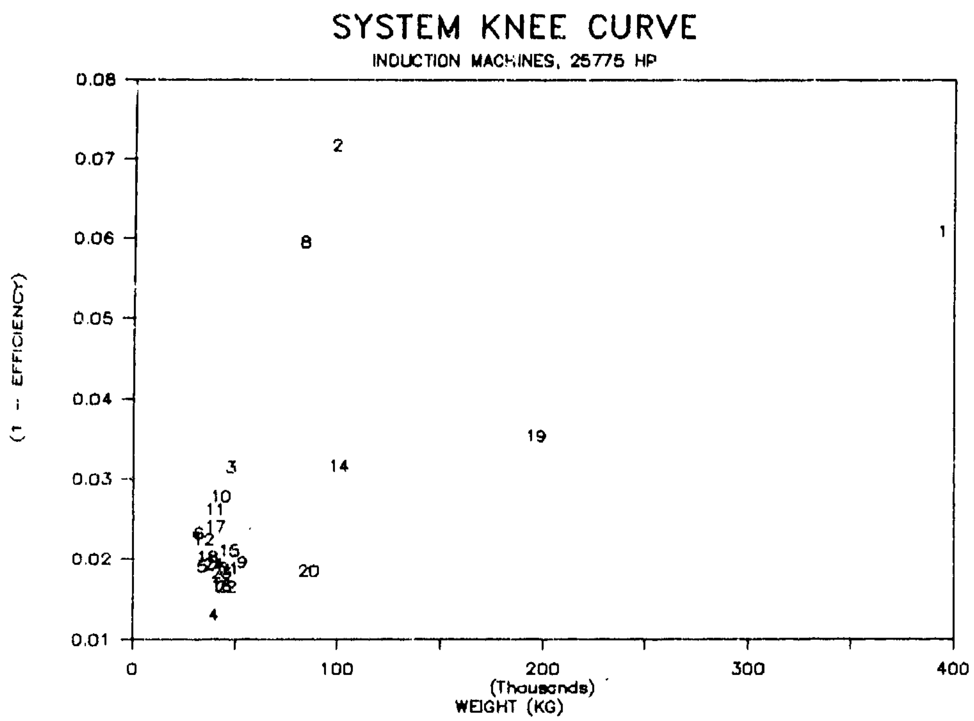


Figure 31. Volume-efficiency curve for initial PM and PG combinations

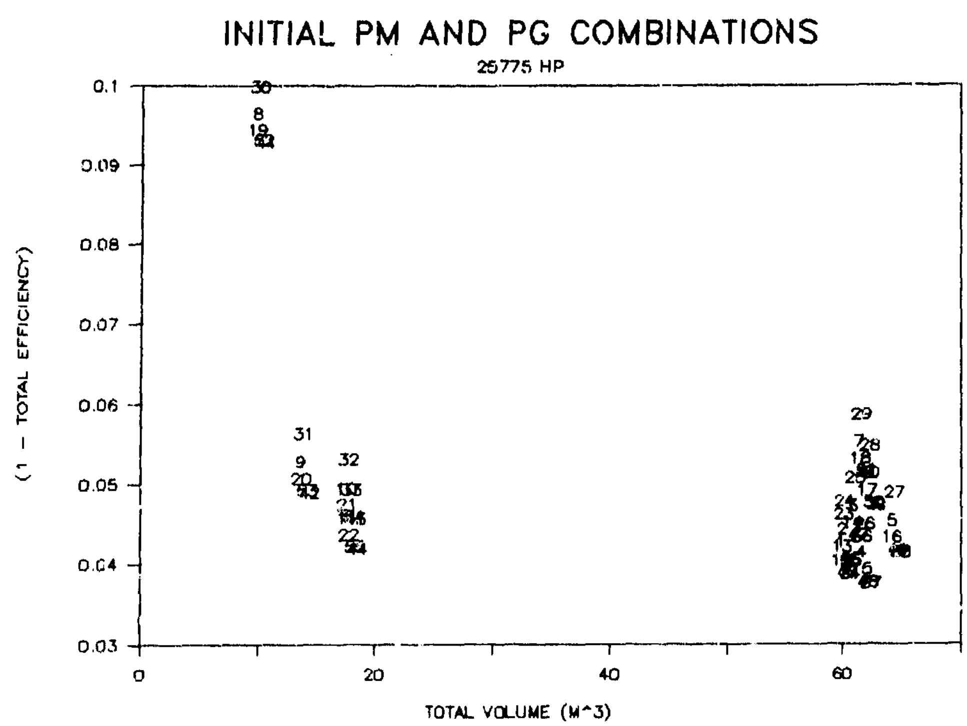


Figure 32. Volume-weight curve for initial PM and PG combinations

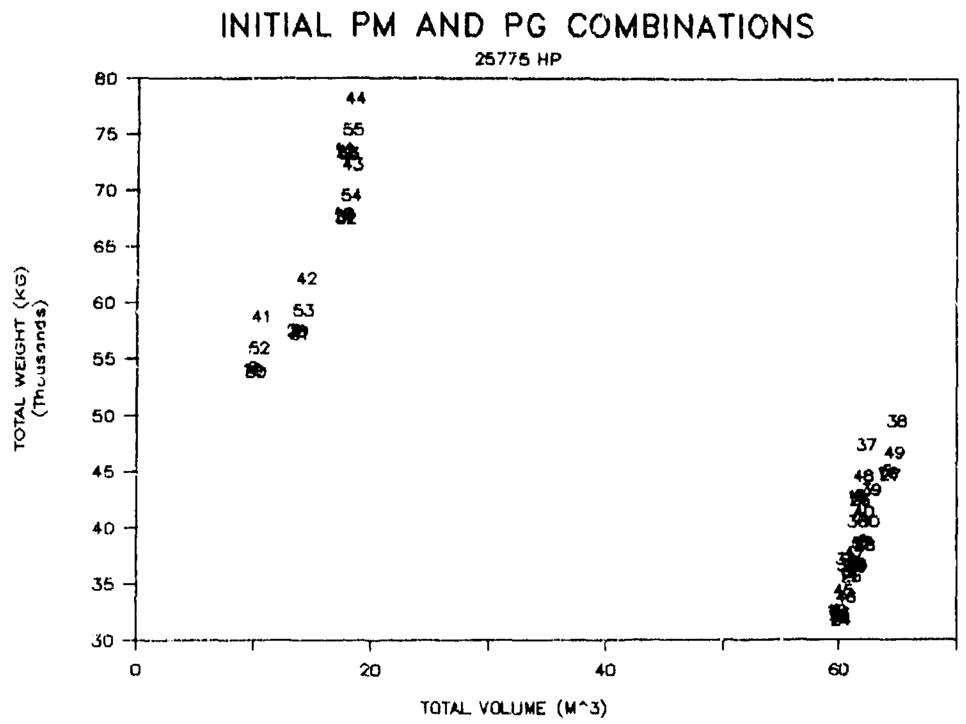


Figure 33. Weight-efficiency curve for initial PM and PG combinations

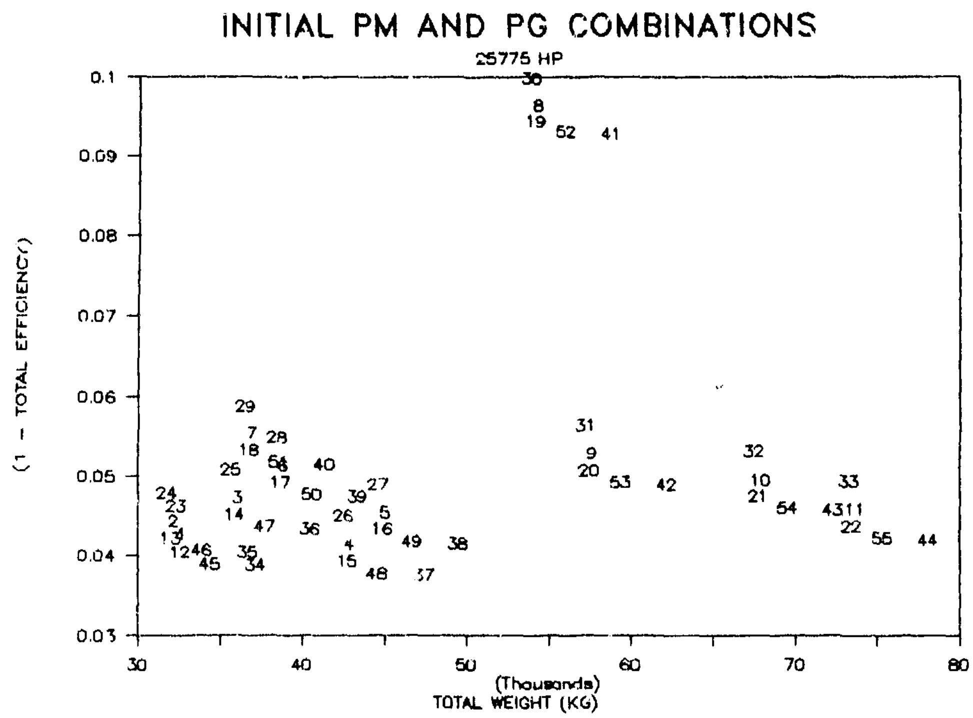
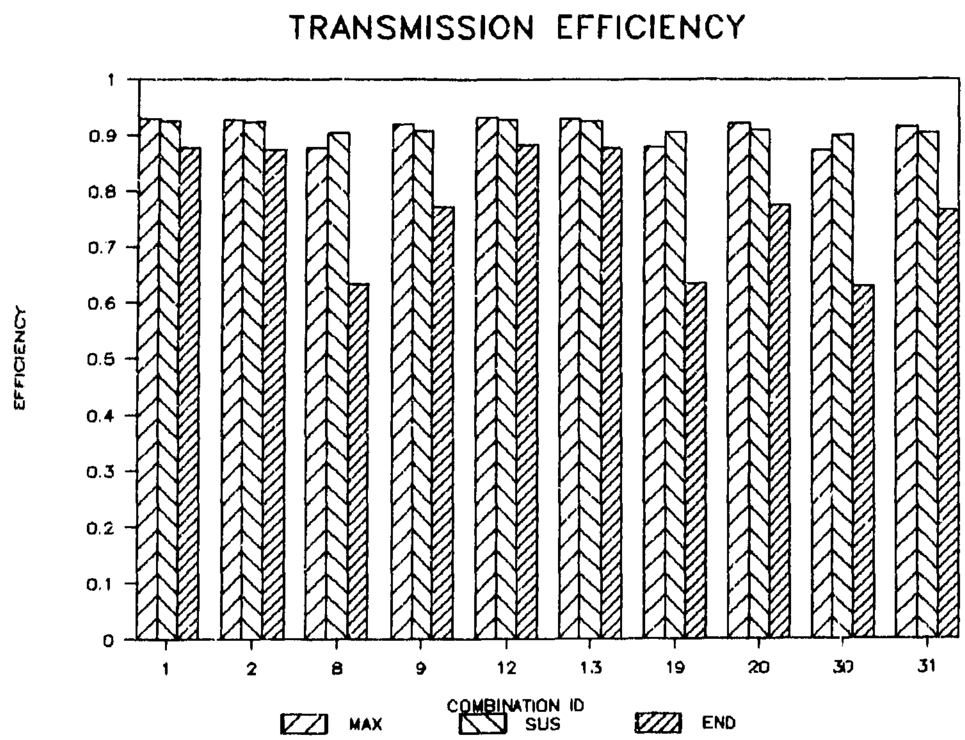


Figure 34. Final combination transmission efficiencies



# Chapter Eight. Analysis

This chapter presents an analysis of the ships with electric transmissions. Standard naval architectural methods have been used to observe and comment on the variant ships, comparing them to the mechanical baseline ship. Conclusions and recommendations follow the analysis.

The names used to describe the various ships imply their internal arrangement, equipment, and ASSET Design Mode Indicator (DMI). The two DMIs used were ENDURANCE, when endurance range was held constant at 5500 NM, and FUEL WT, when the usable fuel weight was held constant at 996.6 LT.[22] The ship names are as follows:

MECH 23 BASELINE: Baseline, mechanical transmission
ELEC 23 BASELINE 12: Backfit ship, geared motors
ELEC 23 BASELINE 20: Backfit ship, direct-drive motors
NEW MR ELEC 12: Rearranged ship, geared motors
NEW MR ELEC 20: Rearranged ship, direct-drive motors
CONSTANT FUEL ELEC 23 BASE 12: Backfit ship, geared motors
CONSTANT FUEL ELEC 23 BASE 20: Backfit ship, direct-drive motors

## 8.1. Direct effects

The direct effects of an electric transmission are the changes in weight and volume of the propulsion system, as well as the transmission efficiency. Included are the weight and volume of the propulsion motors and generators, transmission lines, cooling systems, switchgear, power converter, exciter, braking resistor, any reduction gears and their associated gear oil, and shafting. These items are listed in Table 31. A positive difference from the baseline ship means a heavier and/or larger ship.

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21. Professor John Kassakian, MIT, private communication.

22. Not all fuel in a ship is usable. There are nooks and corners of fuel tanks that are inaccessible to the fuel sys-

Note that the only variant that has a lower direct weight effect than the baseline is NEW MR ELEC 12. The accumulation of weight increases in the others makes them heavier, while NEW MR ELEC 12 has lower motor and shafting weight than the rest. Geared drive is always lighter than direct-drive, largely due to the high weight of the direct-drive propulsion motors. With respect to volume, direct-drive is always smaller than geared drive, because of the reduction gears. All electric transmissions are larger than the mechanical baseline, but the smallest variants, within motor type groups, are the rearranged ships.

Table 28 contains the maximum, sustained, and endurance speed transmission efficiencies of the two generator-motor combinations. Note that the off-design-point efficiency of the direct-drive combination is significantly lower than the geared combination, even though it does not have the added inefficiency of reduction gears. This is in large part due to the poor efficiency of the slowly rotating direct-drive motor at the endurance speed.

Table 28. Transmission efficiencies

| Combo | Maximum | Sustained | Endurance | |
|---|---|---|---|---|
| 12 | 0.9307 | 0.9266 | 0.8817 | geared combination |
| 20 | 0.9209 | 0.9093 | 0.7754 | direct-drive combination |

Endurance efficiency with one generator driving two motors.

Table 29. Propulsion generator efficiencies

| PG ID | Maximum | Sustained | Endurance | |
|---|---|---|---|---|
| SC | 0.9891 | 0.9870 | 0.9737 | geared combination |
| SC | 0.9891 | 0.9872 | 0.9768 | direct-drive combination |

Table 30. Propulsion motor efficiencies

| PM ID | Maximum | Sustained | Endurance | |
|---|---|---|---|---|
| S4 | 0.9898 | 0.9876 | 0.9526 | geared combination |
| SL8 | 0.9598 | 0.9496 | 0.8184 | direct-drive combination |

The above tables show the efficiencies of the motor and generator used in two particular combinations. The efficiency of the motor, reduction gears, and power converter have a direct effect on the efficiency of the generator, as they change the loading point of the generator. Generally, motors and generators are more efficient when they are loaded more closely to their design point. (The same is true of gas turbines.) The inefficiencies of the power converters and reduction gears, if any, are included in the transmission efficiencies.

Table 31. Direct volume and weight effects

| | MECH 23 BASELINE | ELEC 23 BASELINE 12 | ELEC 23 BASELINE 20 | NEW MR ELEC 12 | NEW MR ELEC 20 | CONSTANT FUEL ELEC 23 BASE 12 | CONSTANT FUEL ELEC 23 BASE 20 |
|---|---|---|---|---|---|---|---|
| **Electric Propulsion weights: in LT** | | | | | | | |
| PMs | 0 | 18.08 | 102.94 | 18.08 | 102.94 | 18.00 | 102.94 |
| PGs | 0 | 10.27 | 10.27 | 10.27 | 10.27 | 10.27 | 10.27 |
| Trans lines | 0 | 0.18 | 0.18 | 0.77 | 0.77 | 0.18 | 0.18 |
| Cooling sys | 0 | 5.98 | 5.98 | 5.98 | 5.98 | 5.98 | 5.98 |
| Switchgear | 0 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 |
| Power converter | 0 | 7.16 | 7.16 | 7.16 | 7.16 | 7.16 | 7.16 |
| Exciters | 0 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 |
| Braking resistor | 0 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| Reduction gears | 78.90 | 41.19 | 0.00 | 41.19 | 0.00 | 41.19 | 0.00 |
| Shafting | 69.00 | 66.84 | 66.84 | 41.72 | 41.72 | 66.84 | 66.84 |
| W298 (op fluid) | 14.7 | 14.7 | 0 | 14.7 | 0 | 14.7 | 0 |
| Direct effect | 162.60 | 179.46 | 208.43 | 154.93 | 183.90 | 179.46 | 208.43 |
| Diff fm Baseline | 0 | 16.86 | 45.83 | -7.67 | 21.30 | 16.86 | 45.83 |
| **Electric Propulsion volumes: in cubic feet** | | | | | | | |
| PMs | 0 | 108.86 | 909.13 | 108.86 | 909.13 | 108.86 | 909.13 |
| PGs | 0 | 61.49 | 61.49 | 61.49 | 61.49 | 61.49 | 61.49 |
| Trans lines | 0 | 20.9 | 20.9 | 6.39 | 6.39 | 0.33 | 0.33 |
| Cooling sys | 0 | 200 | 200 | 200 | 200 | 200 | 200 |
| Switchgear | 0 | 70.2 | 70.2 | 70.2 | 70.2 | 70.2 | 70.2 |
| Power converter | 0 | 1089.73 | 1089.73 | 1089.73 | 1089.73 | 1089.73 | 1089.73 |
| Exciters | 0 | 245.02 | 245.02 | 245.02 | 245.02 | 245.02 | 245.02 |
| Braking resistor | 0 | 1422.88 | 1422.88 | 1422.88 | 1422.88 | 1422.88 | 1422.88 |
| Reduction gears | 2731.04 | 1425.75 | 0.00 | 1425.75 | 0.00 | 1425.75 | 0.00 |
| Shafting | 517.71 | 501.5 | 501.5 | 306.06 | 306.06 | 501.5 | 501.5 |
| Direct effect | 3248.75 | 5146.33 | 4520.85 | 4936.38 | 4310.90 | 5125.76 | 4500.28 |
| Diff fm Baseline | 0.00 | 1897.58 | 1272.10 | 1687.63 | 1062.15 | 1877.01 | 1251.53 |

## 8.2. Indirect effects

Indirect effects are again composed of weights and volumes, but these are the ripple effects of the propulsion system through the ship. For example, if a transmission is more efficient at endurance speed, it should be expected that less onboard fuel would be needed to achieve the same endurance range as a less efficient transmission. This is indeed the case. Another important indirect effect is the change in full load displacement, which is tied to the powering characteristic of the ship.[23] The following tables list the characteristics and indirect effects of the various ship configurations.

Every electric transmission had lower maximum and sustained speeds than the baseline ship (by about 0.43 knots), but also lower EHP requirements at those speeds. The lower EHPs are a reflection of lower drafts (less resistance). The lower speeds show that the transmission efficiencies of the variant ships are lower than the mechanical baseline ship. There are more components in the electrical power trains, hence the lower efficiencies. The speed difference of 0.43 knots may be regarded by some as significant; it is about the speed reduction to be expected by a fouled bottom.

The endurance range of all ships except those with constant fuel load is 5500 NM. The fuel load in the others varies greatly, showing the benefit of electrical cross-connection. In the two constant fuel ships, there was an increase in the endurance range of 1350 and 1400 NM, respectively, for the geared and direct-drive transmissions. This is an indication of fuel cost savings from the electric transmission. If a ship refuels every three steaming days (receiving a third of its tank capacity), steams 100 days each year, and fuel is priced at about $18 per barrel, this represents about a $600,000 savings per ship per year.

The initial static transverse stability of the variants was degraded by the change in propulsion equipment. As previously stated, the 6.5% GM/Beam ratio of the mechanical baseline ship is not as large as desired for an actual ship, but provided a benchmark to measure relative changes.

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tem. Typically, 95% of the onboard fuel is usable.

23. For the same molded lines, ships with higher displacements will have greater wetted surface areas and higher

Table 32. General ship characteristics

| | MECH 23 BASELINE | ELEC 23 BASELINE 12 | ELEC 23 BASELINE 20 | NEW MR ELEC 12 | NEW MR ELEC 20 | CONSTANT FUEL ELEC 23 BASE 12 | CONSTANT FUEL ELEC 23 BASE 20 |
|---|---|---|---|---|---|---|---|
| LBP | 425 | 425 | 425 | 425 | 425 | 425 | 425 |
| Ship disp FL | 5485 | 5297.5 | 5417.1 | 5234.7 | 5353.4 | 5484.1 | 5530.2 |
| Diff fm Baseline | 0 | -187.5 | -67.9 | -250.3 | -131.6 | -0.9 | 45.2 |
| Nav beam | 55 | 55.04 | 55.02 | 55.04 | 55.03 | 55 | 55 |
| Nav draft | 16.44 | 16.07 | 16.31 | 15.95 | 16.18 | 16.44 | 16.53 |
| Depth sta 10 | 38 | 38 | 38 | 38 | 38 | 38 | 38 |
| Accommodations | 272 | 272 | 272 | 272 | 272 | 272 | 272 |
| GMt/B | 0.065 | 0.059 | 0.058 | 0.061 | 0.064 | 0.063 | 0.061 |
| GMl | 950.01 | 973.41 | 959.1 | 979.76 | 967.39 | 950.07 | 943.41 |
| Full load KG | 23.23 | 23.87 | 23.75 | 23.84 | 23.53 | 23.34 | 23.44 |
| LCB/LBP | 0.516 | 0.514 | 0.515 | 0.513 | 0.514 | 0.516 | 0.516 |
| LCF/LBP | 0.565 | 0.565 | 0.565 | 0.564 | 0.565 | 0.565 | 0.565 |
| Wetted surface | 23347.7 | 23010 | 23230.5 | 22886.3 | 23115.7 | 23346.6 | 23425.8 |
| Cp | 0.6 | 0.596 | 0.598 | 0.594 | 0.597 | 0.6 | 0.601 |
| Waterplane area | 17641 | 17575.9 | 17624.8 | 17539.8 | 17602 | 17640.9 | 17653.2 |
| Hull volume | 618504 | 618504 | 618504 | 618504 | 618504 | 618504 | 618504 |
| Dkhs volume | 121528 | 121528 | 121528 | 121528 | 121528 | 121528 | 121528 |
| Total volume | 740032 | 740032 | 740032 | 740032 | 740032 | 740032 | 740032 |
| Endur fuel vol | 44365 | 36592 | 39647 | 36367 | 39396 | 44364 | 44364 |
| Machy box vol | 109671 | 109671 | 109671 | 109624 | 109624 | 109671 | 109671 |

Table 33. Powering

| | MECH 23 BASELINE | ELEC 23 BASELINE 12 | ELEC 23 BASELINE 20 | NEW MR ELEC 12 | NEW MR ELEC 20 | CONSTANT FUEL ELEC 23 BASE 12 | CONSTANT FUEL ELEC 23 BASE 20 |
|---|---|---|---|---|---|---|---|
| Powering: | | | | | | | |
| Vmax | 29.13 | 29.02 | 28.83 | 29.09 | 28.9 | 28.82 | 28.7 |
| EHP @ Vmax | 34821 | 33131 | 32741 | 33154 | 32763 | 33066 | 32700 |
| Vsus | 27.94 | 27.82 | 27.6 | 27.88 | 27.66 | 27.63 | 27.48 |
| EHP @ Vsus | 28163 | 26684 | 26165 | 26700 | 26181 | 26636 | 26136 |
| Endurance | 5500 | 5500 | 5500 | 5500 | 5500 | 6550 | 6086 |
| EHP @ Vend | 6851 | 6632 | 6772 | 6557 | 6698 | 6851 | 6905 |
| HPi | 51550 | 51550 | 51550 | 51550 | 51550 | 51550 | 51550 |
| kWi | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 |
| Avg 24 hr load | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 |

In the constant fuel ships, the high weight of the propulsion motors and propulsion motors and propulsion generators, combined with a smaller amount of vertically-lower fuel reduced GM/B by over one-half percent, a not inconsiderable amount. For the rearranged variants, GM/B decreased less than the two previous ships. They also have less low fuel, but the propulsion generators are lower than in the backfit ships and the propulsion motors are very much lower. Only a very small decrease in GM/B was seen in the constant fuel ships because the constant fuel load compensated for the increased high weight of the electric transmission. The longitudinal metacentric height, GMl, increased for all variants, though it seems it should have decreased with the decrease in waterplane area and draft. The machinery space volume was the same for all ships.

There were no big surprises in the area of weight. The structural weight (W100) encloses the same volume in every ship, so it was about constant. The propulsion plant weight (W200) varied with the type of transmission. Weight groups W300, W400, W500, W600, and W700 were virtually identical in every ship, and the variable loads were dominated by the change in fuel weight. The Design and Builders Margin is a function of the light ship weight (summation of W100 through W700), so the margin weight moved with the light ship weight. The miles-per-gallon figure of NM/LT of fuel shows the endurance efficiency of electrical cross-connection.

Only a few comments need be made regarding Table 35. The structural weight fraction shows the changes in full load displacement, remembering that the W100 weights were all about the same. The same may be said for the weight fraction of the W300 through W700 groups and payload weight. Higher propulsion plant weights in the variant ships drove up the W200 fraction, except for NEW12. The fuel weight fraction shows the same behavior as the miles-per-gallon figure.

Table 34. Ship weights

| | MECH 23 BASELINE | ELEC 23 BASELINE 12 | ELEC 23 BASELINE 20 | NEW MR ELEC 12 | NEW MR ELEC 20 | CONSTANT FUEL ELEC 23 BASE 12 | CONSTANT FUEL ELEC 23 BASE 20 |
|---|---|---|---|---|---|---|---|
| Weight: | | | | | | | |
| DFM onboard | 1049.1 | 865.3 | 937.5 | 860 | 931.6 | 1049.1 | 1049.1 |
| Usable fuel wt | 996.6 | 822 | 890.6 | 817 | 885 | 996.6 | 996.6 |
| Diff fm Baseline | 0 | -183.8 | -111.6 | -189.1 | -117.5 | 0 | 0 |
| NM per LT fuel | 5.52 | 6.69 | 6.18 | 6.73 | 6.21 | 6.57 | 6.11 |
| Payload weight | 571.2 | 571.2 | 571.2 | 571.2 | 571.2 | 571.2 | 571.2 |
| W100 | 1684.8 | 1686 | 1692 | 1660.6 | 1666.6 | 1686.2 | 1692.1 |
| W200 | 343.6 | 351.8 | 387.1 | 326.1 | 361.3 | 351.9 | 387.1 |
| W300 | 236.5 | 236.5 | 236.5 | 236.5 | 236.5 | 236.5 | 236.5 |
| W400 | 302.2 | 302.2 | 302.2 | 302.2 | 302.2 | 302.2 | 302.2 |
| W500 | 615.4 | 613.5 | 614.3 | 613.5 | 614.2 | 615.4 | 615.4 |
| W600 | 426.6 | 426.6 | 426.6 | 426.6 | 426.6 | 426.6 | 426.6 |
| W700 | 95.9 | 95.9 | 95.9 | 95.9 | 95.9 | 95.9 | 95.9 |
| Loads | 1317.1 | 1120.9 | 1193.2 | 1115.6 | 1187.2 | 1305.1 | 1304.9 |
| D&B margin | 463.1 | 464.1 | 469.3 | 457.7 | 462.9 | 464.3 | 469.5 |
| Disp FL | 5485.2 | 5297.5 | 5417.1 | 5234.7 | 5353.4 | 5484.1 | 5530.2 |

Table 35. Naval architectural analysis indices

| | MECH 23 BASELINE | ELEC 23 BASELINE 12 | ELEC 23 BASELINE 20 | NEW MR ELEC 12 | NEW MR ELEC 20 | CONSTANT FUEL ELEC 23 BASE 12 | CONSTANT FUEL ELEC 23 BASE 20 |
|---|---|---|---|---|---|---|---|
| L/D | 11.18 | 11.18 | 11.10 | 11.18 | 11.18 | 11.18 | 11.18 |
| L/B | 7.73 | 7.72 | 7.72 | 7.72 | 7.72 | 7.73 | 7.73 |
| B/T | 3.345 | 3.425 | 3.373 | 3.451 | 3.401 | 3.345 | 3.327 |
| GM1/LBP | 2.235 | 2.290 | 2.257 | 2.305 | 2.276 | 2.235 | 2.220 |
| W100/Dfl | 0.307 | 0.318 | 0.312 | 0.317 | 0.311 | 0.307 | 0.306 |
| W200/Dfl | 0.063 | 0.066 | 0.071 | 0.062 | 0.067 | 0.064 | 0.070 |
| W300/Dfl | 0.043 | 0.045 | 0.044 | 0.045 | 0.044 | 0.043 | 0.043 |
| W400/Dfl | 0.055 | 0.057 | 0.056 | 0.058 | 0.056 | 0.055 | 0.055 |
| W500/Dfl | 0.112 | 0.116 | 0.113 | 0.117 | 0.115 | 0.112 | 0.111 |
| W600/Dfl | 0.078 | 0.081 | 0.079 | 0.081 | 0.080 | 0.078 | 0.077 |
| W700/Dfl | 0.017 | 0.018 | 0.018 | 0.018 | 0.018 | 0.017 | 0.017 |
| Wfuel/Dfl | 0.182 | 0.155 | 0.164 | 0.156 | 0.165 | 0.182 | 0.180 |
| Wpayload/Dfl | 0.104 | 0.108 | 0.105 | 0.109 | 0.107 | 0.104 | 0.103 |
| Wld/Dfl | 0.240 | 0.212 | 0.220 | 0.213 | 0.222 | 0.238 | 0.236 |
| Vmb/Vtot | 0.148 | 0.148 | 0.148 | 0.148 | 0.148 | 0.148 | 0.148 |
| HPi/Dfl | 9.398 | 9.731 | 9.516 | 9.848 | 9.629 | 9.400 | 9.322 |
| HPi*Vmax/Dfl | 273.76 | 282.39 | 274.35 | 286.47 | 278.29 | 270.91 | 267.53 |
| kWi/Dfl | 1.094 | 1.133 | 1.108 | 1.146 | 1.121 | 1.094 | 1.085 |
| Nt/Dfl | 0.050 | 0.051 | 0.050 | 0.052 | 0.051 | 0.050 | 0.049 |
| Vtot/Dfl | 134.914 | 139.695 | 136.610 | 141.370 | 138.236 | 134.941 | 133.816 |
| W100/Vtot | 5.100 | 5.103 | 5.122 | 5.026 | 5.045 | 5.104 | 5.122 |
| W200/HPi | 14.930 | 15.287 | 16.821 | 14.170 | 15.700 | 15.291 | 16.821 |
| Vmb/HPi | 2.127 | 2.127 | 2.127 | 2.127 | 2.127 | 2.127 | 2.127 |
| W300/kWi | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 |
| Vmb/(HPi+kWi) | 1.906 | 1.906 | 1.906 | 1.905 | 1.905 | 1.906 | 1.906 |
| W500/Vtot | 1.863 | 1.857 | 1.859 | 1.857 | 1.859 | 1.863 | 1.363 |
| W600/Vtot | 1.291 | 1.291 | 1.291 | 1.291 | 1.291 | 1.291 | 1.291 |
| Dfl/Vtot | 16.603 | 16.035 | 16.397 | 15.845 | 16.204 | 16.600 | 16.739 |

For this technology characterization, everything devolves to total values. What is the total effect on the ship, once the individual pieces are put together? Table 36 gives the bottom line. The electric propulsion plants are larger and heavier than their mechanical drive cousin; however, the extra weight and volume are more than compensated by the savings in fuel weight and volume. If a ship is designed from the beginning to be an "optimized" electric drive ship, over 6300 cubic feet of volume and 250 LT may be saved. The savings might be used for other systems, to reduce the overall size and cost of the ship (maybe allowing a larger buy, since 30 ships times 250 LT is a 7500 LT ship), or to extend the naval architectural limits of the ship design.

If a ship is backfitted with this technology, it is unlikely that tank volume can be recovered. However, the dual benefits of increased time-on-station and better fuel economy are realized. In this case, the choice between geared or direct-drive systems can be made by selecting the system with the most leverage, i.e., if the ship is volume-limited, use the lower volume direct-drive system (since the shafts are already in place).

To put the volume and weight savings in perspective, note that 6300 cubic feet and 250 LT translates to twenty Tomahawk missile cells. The ship would be volume limited, with about 200 LT of weight savings still unused. This is a significant addition to the firepower of any ship, and the unused weight allows for ship growth.

Table 36. Total differences

| | MECH 23 BASELINE | ELEC 23 BASELINE 12 | ELEC 23 BASELINE 20 | NEW MR ELEC 12 | NEW MR ELEC 20 | CONSTANT FUEL ELEC 23 BASE 12 | CONSTANT FUEL ELEC 23 BASE 20 |
|---|---|---|---|---|---|---|---|
| Total volumes: | | | | | | | |
| Fuel volume | 44365 | 36592 | 39647 | 36367 | 39396 | 44364 | 44364 |
| Fuel diff | 0 | -7773 | -4718 | -7998 | -4969 | -1 | -1 |
| Prpln volume | 3248.75 | 5146.33 | 4520.85 | 4936.38 | 4310.90 | 5125.76 | 4500.28 |
| Prpln diff | 0.00 | 1897.58 | 1272.10 | 1687.63 | 1062.15 | 1877.01 | 1251.53 |
| Total | 47613.75 | 41738.33 | 44167.85 | 41303.38 | 43706.90 | 49489.76 | 48864.28 |
| Total diff | 0.00 | -5875.42 | -3445.90 | -6310.37 | -3906.85 | 1876.01 | 1250.53 |
| | | | | | | | |
| Total weights: | | | | | | | |
| Dfl difference | 0.00 | -187.50 | -67.90 | -250.30 | -131.60 | -0.90 | 45.20 |
| prpln diff | 0.00 | 16.86 | 45.83 | -7.67 | 21.30 | 16.86 | 45.83 |
| fuel diff | 0.00 | -183.80 | -111.60 | -189.10 | -117.50 | 0.00 | 0.00 |
| other | 0.00 | -20.56 | -2.13 | -53.53 | -35.40 | -17.76 | -0.63 |

### 8.3. Closure

#### 8.3.1. Conclusions

This thesis has demonstrated the usefulness of electric drive transmissions in reducing ship weight and volume. Electric drive transmissions are better than mechanical drive transmissions on a ship basis. They provide, besides the weight and volume advantages, substantial arrangement flexibility and the opportunity to use new technologies in the ship design arena. The technical risk associated with these different technologies is minimal, as there is much industrial experience with electric machines, advanced switchgear, and the like. If the weight and volume reductions are reinvested in the ship design through more optimum arrangements and subdivision, a substantially more efficient ship may be realized. Such a ship could successfully compete with the best of current ships.

Small, light, high-power motors can be designed to a fair degree of detail with a computer optimization scheme if a meaningful objective function can be devised. For a ship system, the objective function should contain measures for volume, weight, efficiency, and relative cost (if a particular material is significantly more expensive than other used). A steepest-descent scheme can be combined with a Monte Carlo scheme to quickly converge on the objective function.

The use of electric drive, and its consequent electrical cross-connect, can reduce the endurance fuel load by as much as 17.5%. When used in combination with an improved machinery arrangement and subdivision, that percentage can rise to 18%. If the fuel load stays constant, the endurance range may increase as much as 25%.

On both an equipment weight basis and a ship weight basis, systems composed of a direct-drive propulsion generator (with the same shaft rpm as the prime mover) and a geared propulsion motor are better than those systems using no gears. Regarding volume, a non-geared system has lower equipment volume but higher ship volume due to the lower endurance fuel efficiency.

Geared propulsion motors have better off-design-point efficiencies than those in direct-drive systems, primarily due to their higher rpm. A reduction in output power (in a motor) of 75% means only a few percent reduction in efficiency for a geared motor, while the same power reduction means a 20% or more efficiency reduction for a direct-drive motor.

Permanent magnet machines do not appear attractive for ship propulsion systems. They are both heavier and larger than candidate systems using synchronous, and, to a smaller extent, induction machines. Their low air gap flux density is the main detractor. Current permanent magnet materials cannot develop the energy product to compete with other alternatives, even though the NdFeB magnets are now in the marketplace. Induction machines may be useful as propulsion motors, but in this thesis they did not appear so. Therefore, ship propulsion generators and motors should only be synchronous machines.

### 8.3.2. Recommendations

The same modeling approach used in this thesis should be taken with variable reluctance machines (VRM). Although no VRMs have been built at ship propulsion power levels, it is not inconceivable that they could serve in such a capacity.

The induction machine model used here needs refinement, especially in the area of limiting maximum rotor current density. All of the machines need an analysis of their transient and dynamic characteristics.

The recent advent of liquid hydrogen temperature superconducting materials may signal an era where conventional machines are overshadowed by the smaller, higher-flux machines possible with superconducting technology. However, if these new materials fail to provide the required current density, design of satisfactory machines may not be possible.

Integrated electric ship service propulsion plants may be beneficial additions to electric drive technology. Their influence on the systems suggested here may be an area of interest for future ship designs.

Appendix A. Definitions of machine variables and constants.

| | |
|---|---|
| bd | magnet operating point flux density, Tesla. Used in permanent magnet machines. |
| BETA | hysteresis loss factor of M19 magnetic steel. The figure 2.5 was used. |
| br | air gap flux density, Tesla. Used only in permanent magnet machine model. |
| BR | air gap flux density, 1.05 rms Tesla. |
| BR1 | residual induction, 7.89 kilogauss, of M19 magnetic steel,at BSAT and T1. |
| BREM | remanence flux of NdFeB, 1.21 Tesla. |
| BRNGS | weight percentage of rotor shaft bearings, 1.03, or three percent of rotor weight. |
| BSAT | max flux density anywhere, 1.5 rms Tesla. |
| CP | stator coil pitch. The figure 0.8 was used. |
| CRHO | copper electrical resistivity, 1.724E-8 ohm-meters. |
| cw | copper weight, kg. |
| D | density, 7.65e3 kg/m3, of M19 magnetic steel. |
| dcore | back iron depth, meters. |
| DCU | copper density, 8968.0 kg/meter$^3$. |
| DMAG | density of NdFeB, 7.4e3 kg/meter$^3$. |
| doa | overall machine diameter, meters. |
| dr | depth of rotor slots, meters. |
| ds | depth of stator slots, meters. |
| eaf | p.u. internal voltage, used in syn only. |
| effcy | efficiency, defined as $$effcy = \frac{output\ power}{output\ power + ph + pe + i2r + i2rr}$$ |
| ew | effective weight of machine, a combination of weight, volume, and efficiency. Used as the objective criteria for the optimization scheme. |
| freq | machine synchronous frequency, Hz. |
| g | air gap dimension, meters. |

| | |
|---|---|
| gams | stator geometric factor, non-dimensional. Used to find convergence on active length. |
| gamr | rotor geometric factor, non-dimensional. Used to find convergence on active length. |
| GMIN | minimum machine air gap, 0.002 meters. |
| HC1 | coercive force, 0.48 oersteds, of M19 magnetic steel, at BSAT and T1. |
| i1 | induction machine primary current, amps. |
| i2 | induction machine load current, amps. |
| i2r | copper loss, watts, on stator. |
| i2rr | copper loss, watts, on rotor. |
| jr | full load rotor current density, amps/$m^2$. |
| jrnl | no load rotor current density, used in syn only. |
| js | full load stator current density, amps/$m^2$. |
| JSMAX | maximum stator current density, 12e6 amps/$meter^2$ |
| ke | efficiency weighting factor. |
| KM | magnet material cost weighting factor, defined as |

$$KM = \frac{\$ \text{ per pound of magnet material}}{\$ \text{ per pound of magnetic iron}}$$

| | |
|---|---|
| ks[] | harmonic winding factors. |
| kv | volume weighting factor. |
| l | machine active length. |
| le | rotor winding space factor, used in induction machine. |
| ler | combined length of rotor end windings. |
| lm | radial dimension of permanent magnet. |
| loa | overall machine length, meters. |
| lr | ratio of rotor slot width to slot pitch. In permanent magnet machines, defined as ratio of magnet width to rotor "slot" pitch. |
| lrat | length ratio, used in permanent magnet program to calculate the effect of magnet overhang. |
| ls | ratio of stator slot width to slot pitch. |

| | |
|---|---|
| MAX_TIP_SPEED | maximum allowable rotor tangential velocity, 200 meters per second. |
| minpwr | minimum required power of the machine, horsepower. |
| MU | MU of air, $4\pi e{-7}$ Henries/meter. |
| MUR | NdFeB relative reversible permeability. The figure 1.05 was used. |
| nr | number of rotor bars in induction machine. |
| NU | anomalous loss factor of M19 magnetic steel. The figure of 2 was used. |
| overhang | percentage of magnet overhang. |
| p | number of machine pole-pairs. |
| PC | permanence coefficient of NdFeB. The figure 1.1 was used. |
| pe | eddy current loss, watts. |
| PF | power factor of all machines. The figure 0.8 was used. |
| PI | 3.141592654. |
| ph | hysteresis loss, watts. |
| PSI | Trated/Tpullout for induction motor. The figure 0.55 was used. |
| r | rotor radius, meters. |
| r1pl | per length primary resistance, ohms/meter. |
| r2pl | per length secondary resistance, ohms/meter. |
| rcv | rotor copper volume, meters$^3$. |
| re1pl | per length Thevénin equivalent resistance. |
| RHO | electrical resistivity, 52 micro-ohm-cm, of M19 magnetic steel. |
| riv | rotor iron volume, meters$^3$. |
| RMAX | maximum rotor radius, 2.0 meters. |
| rpm | machine shaft revolutions per minute, referred to as rotor speed. |
| RSF | rotor slot space factor. The figure 0.35 was used. |
| scv | stator copper volume, meters$^3$, |
| siv | stator iron volume, meters$^3$. |
| slip | guessed slip of the induction machine. |

| | |
|---|---|
| slip1 | larger derived slip. |
| slip2 | smaller derived slip. |
| smax | maximum machine slip. |
| SSF | stator slot space factor. The figure 0.35 was used. |
| T1 | thickness, 0.014 inch, of M19 magnetic steel. |
| tmaxpl | per length maximum torque. |
| v1apl | per length Thevénin equivalent voltage. |
| va | \|P+jQ\|, VA rating, volt-amps. |
| vagpl | per length air gap voltage. |
| vol | machine envelope volume, meters$^3$, with a margin. |
| VOLALL | volume allowance for frame and foundation. A ten percent allowance was used. |
| volmag | volume of permanent magnet material, meters$^3$. |
| vtpl | per length terminal voltage. |
| w | electrical frequency, radians per second. |
| wr | width of rotor slots. |
| wm | mechanical angular velocity of rotor, radians per second. |
| wt | weight of copper and iron in a machine, plus a margin. |
| WTALL | weight margin for frame and foundation. A ten percent margin was used. |
| wt_iron | iron weight, kg. |
| wtmag | weight of permanent magnet material, kg. |
| x1pl | per length primary impedance. |
| x2pl | per length secondary impedance. |
| xbeltpl | per length belt impedance. |
| xe1pl | per length Thevévin equivalent impedance. |
| xmpl | per length air gap magnetizing impedance. |
| xrdpl | per length rotor differential leakage impedance. |
| xrspl | per length rotor slot leakage impedance. |
| xs | p.u. synchronous impedance. |
| xsepl | per length stator end turn impedance. |
| xslot | slot impedance. |
| xsdpl | per length stator differential leakage impedance. |

xsspl per length stator slot leakage impedance.

xzzpl per length zig-zag impedance.

Table 37. Listing of various functions used in computer programs

```
/*** a pseudo random number generator ***/
#define   MULTIPLIER   25173
#define   MODULUS      32768
#define   INCREMENT    13849
#define   MODFLT      32768.0
double random()
{
        extern long int seed;
        seed=(MULTIPLIER*seed+INCREMENT) % MODULUS;
        return(seed/MODFLT);
}



double swf(n)             /* stator winding factor */
        int n;            /* harmonic order */
        {
        double kp, kb;
        extern double cos(), sin();
        kp=cos(0.3142*n);        /* pitch factor, assumes 0.8 coil pitch */
        kb=(sin(0.5236*n))/(0.5236*n);          /* breadth factor, from
                        Kirtley's "Basic Formulas ... " and assumes an
                        electrical winding angle of 60° */
        return(kp*kb);
        }


double abs(q)
        double q;
{
if (q < 0.0)
        q= (-1.0)*q;
return(q);
}


double sinh(u)
        double u;
{
double exp(), ans;

ans = 0.5*(exp(u) - exp(-u));
return(ans);
}


double cosh(u)
        double u;
```

```
{
double exp(), ans;

ans = 0.5*(exp(u) + exp(-u));
return(ans);
}

double rwf(n)            /* rotor winding factor, same comments as swf() */
        int n;
        {
        double kp, kb;
        extern double sin();
        kp=1;
        kb=(sin(0.5236*n))/(0.5236*n);
        return(kp*kb);
        }


#define tol 1.0e-6
#define pi 3.141592654

double besi (p,x)               /* bessel I(order, arg) */
double x;
int p;
        {
        double bi;
        int bia();
        double exp(),sqrt(),bis();
        if (p<0) abort (" besi: negative index");
        if (x<0) abort (" besi: negative argument");
        if (x>60) bi=exp(x)/sqrt(2*pi*x);
        if((x<12)||bia(p,x,&bi)) bi=bis(p,x);
        return (bi);
        }

double bis(p,x)
double x;
int p;
        {
        double fabs();
        double xx;
        int i,fk,k;
        double bi=0;
        double t=1;
        xx=x/2.;
        for (i=1;i<p+1;i++) t=t*xx/i;
        if (t<1.0e-36) bi=0;
        else
                {
                bi=t;
                xx=xx*xx;
                for (k=1;(k<1001)&&((fabs(t)-fabs(bi*tol))>0);k++)
                        {
                        fk=k*(p+k);
```

```
                        t=t*xx/fk;
                        bi=bi+t;
                        }
                }
        return (bi);
        }

int bia(p,x,pbi)
double x,*pbi;
int p;
        {
        int ist,fn,k,fk;
        double xx,bi,t;
        double fabs(),sqrt(),exp();
        fn=4*p*p;
        t=1.0;
        bi=1.0;
        xx=0.125/x;
        for (k=1;(k<30)&&((fabs(t)-fabs(bi*tol))>0);k++)
                {
                fk=(2*k-1)*(2*k-1);
                t=t*xx*(fk-fn)/k;
                bi=bi+t;
                }
        if (k==31) ist=1;
        else
                {
                ist=0;
                bi=bi*exp(x)/sqrt(2.0*pi*x);
                }
        *pbi=bi;
        return (ist);
        }

double besk(p,x)        /* modified bessel function Kp(x) */
double x;
int p;
        {
        double bk;
        double exp(),sqrt(),k0(),k1();
        if (p<0) abort (" besk: negative index ");
        if (x<0) abort (" besk: negative arguement ");
        if (x>60) bk=exp(-x)/sqrt(2.0*x/pi);
        else if (p==0) bk=k0(x);
        else if (p==1) bk=k1(x);
        else    {
                double g0,g1,gj;
                int j;
                g0=k0(x);
                g1=k1(x);
                for (j=2;j<p+1;j++)
                        {
                        gj=2*(j-1)*g1/x+g0;
                        g0=g1;
```

```
                        gl=gj;
                        }
                bk=gj;
                }
        return (bk);
        }

double k0(x)
double x;
        {
        double bk;
        double log(),sqrt(),exp();
        if (x<1)
                {
                double a,b,z,c,g0,x2j,f,hj,rj;
                int j;
                b=0.5*x;
                a=.57721566+log(b);
                c=b*b;
                g0=-a;
                x2j=1;
                f=1;
                hj=0;
                for (j=1;j<7;j++)
                        {
                        rj=1.0/j;
                        x2j=x2j*c;
                        f=f*rj*rj;
                        hj=hj+rj;
                        g0=g0+x2j*f*(hj-a);
                        }
                bk=g0;
                }
        else
                {
                double t[12],a,b,c,pa;
                int l;
                a=exp(-x);
                b=1.0/x;
                c=sqrt(b);
                t[0]=b;
                for (l=1;l<12;l++) t[l]=t[l-1]*b;

                pa  = 1.2533141-.1566642*t[0];
                pa += .08811128*t[1]-.09139095*t[2];
                pa += .1344596*t[3]-.2299850*t[4];
                pa += .3792411*t[5]-.5247277*t[6];
                pa += .5575368*t[7]-.4262633*t[8];
                pa += .2184518*t[9]-.06680977*t[10]+.009189383*t[11];

                bk=a*c*pa;
                }
        return (bk);
        }
```

```
double k1(x)
double x;
        {
        double bk;
        double log(),exp(),sqrt();
        if (x<1)
                {
                double a,b,c,g1,x2j,f,hj,rj;
                int j;
                b=x/2;
                a=.57721566+log(b);
                c=b*b;
                x2j=b;
                f=1;
                hj=1;
                g1=1.0/x+x2j*(.5+a-hj);
                for (j=2;j<9;j++)
                        {
                        x2j=x2j*c;
                        rj=1.0/j;
                        f=f*rj*rj;
                        hj=hj+rj;
                        g1=g1+x2j*f*(.5+(a-hj)*j);
                        }
                bk=g1;
                }
        else
                {
                double a,b,c,t[12],pa;
                int l;
                a=exp(-x);
                b=1.0/x;
                c=sqrt(b);
                t[0]=b;
                for (l=1;l<12;l++) t[l]=t[l-1]*b;

                pa  = 1.2533141+.4699927*t[0]-.1468583*t[1];
                pa += .1280427*t[2]-.1736432*t[3]+.2847618*t[4];
                pa += -.4594342*t[5]+.5283381*t[6]-.6632295*t[7];
                pa += .5050239*t[8]-.2581304*t[9];
                pa += .07880001*t[10] -.01082418*t[11];

                bk=a*c*pa;
                }
        return (bk);
        }

double besip (p,arg)             /* deriv of bes I(order, arg) */
int p;
double arg;
{
double x,y,z;
x = besi (p-1,arg);
```

```
y = p * besi (p,arg)/arg;
z = x - y;
return (z);
}

double beskp(p,arg)             /* deriv of bes K(order, arg) */
int p;
double arg;
{
double x,y,z;
x = -besk (p-1,arg);
y = - p * besk (p,arg)/arg;
z = x + y;
return (z);
            }
```

Appendix B. Synchronous Machines and General Relations

An equivalent circuit for a synchronous machine is

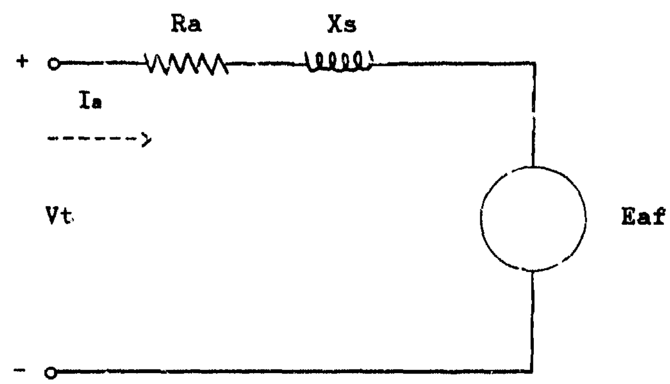



Figure 35. Synchronous machine equivalent circuit

where Ra is the stator resistance and Xs is the synchronous reactance. The internal voltage of the machine, Eaf, is developed between the stator and rotor across the air gap. The current direction is shown as if the machine is a motor.

$$V_{ta} = R_a I_a + jX_s I_a + E_{af}$$

Eaf represents a mutual coupling between the stator and rotor, and

$$E_{af} = \frac{\omega M I_f}{\sqrt{2}} \quad \text{where} \quad M = \frac{4 \mu_o k_1 k_f l r N_s N_f}{\pi g p^2}$$

$I_f$ is field current, Nf is the number of series field turns and $k_f$ is the fundamental rotor winding factor. Since it is never desired to specify the number of turns on either the stator or the rotor, a scheme has been devised so that derivations are conducted in volts-per-turn, ampere-turns, and ohms-per-turn-squared, which results in power in watts.

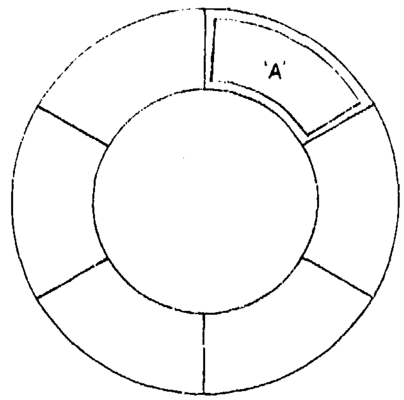



Figure 36. Phase belt conductor area

For the stator, the transverse area can be divided into phase belts. The area labelled 'A' is the area occupied by phase 'a', in one direction. Then, $N_s I_a = A_a J_a$, where $J_a$ is the current density in phase 'a' conductors. The area has some effective conductor area, subject to the need for conductor cooling passages and insulation area. Therefore, for stator and rotor currents, analysis yields

$$I_a = \frac{A_a J_a}{N_s} \qquad \text{and} \qquad I_f = \frac{A_f J_f}{N_f}$$

It is also desired never to specify the number of slots on either the stator and rotor. Accordingly, slot space factors are defined as

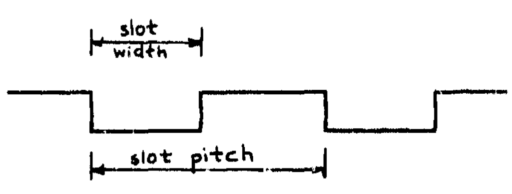



Figure 37. Slot space factors

$$l_s = \frac{\text{stator slot width}}{\text{stator slot pitch}} \qquad l_r = \frac{\text{rotor slot width}}{\text{rotor slot pitch}}$$

For a typical turbogenerator conductor bar, the copper area is about thirty-five percent of the conductor envelope area. Variables titled SSF (stator slot space factor) and RSF (rotor slot space factor) embody this thirty-five percent. The conductor area of a single stator phase in one direction

$$A_s = \frac{(r+g)\ 2\pi\ ls\ ds\ SSF}{6}$$

and, for the rotor,

$$A_r = \frac{r\ 2\pi\ lr\ dr\ RSF}{2}$$

There is only one phase on the rotor.

The armature resistance is

$$Ra = \frac{rho\ l_t\ Ns}{A_s / Ns}$$

where rho is the electrical resistivity of copper and $l_t$ is the turn length. If a stator turn can be modeled as

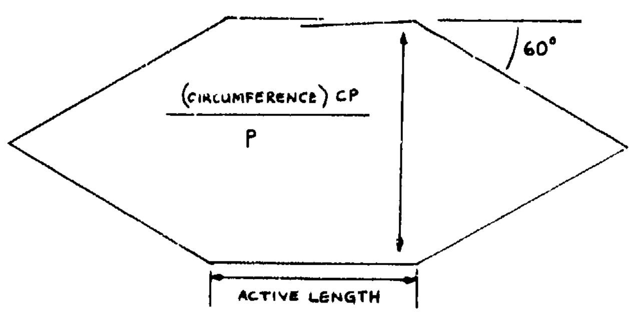



Figure 38. Stator turn

and the circumfrence is $2\pi(r+g)$, then

$$l_t = 2l + 2\left\{ \frac{2\pi\ (r+g)\ CP\ \sqrt{(4/3)}}{p} \right\}$$

where $\sqrt{(4/3)}$ is $(1/\sin(60°))$ and CP is the coil pitch. Then

$$\frac{Ra}{Ns^2} = \frac{2\ rho\ \{\ l + (2\pi(r+g)CP/p)\sqrt{(4/3)}\ \}}{\pi\ (r+g)\ ls\ ds\ SSF}$$

The stator and rotor copper losses are

$$R_a I_a^2 = \text{rho}\ l_t\ A_a\ J_a^2 \qquad R_f I_f^2 = \text{rho}\ l_{tf}\ A_f\ J_f^2$$

The rotor is full pitched.

The vector diagram for the synchronous machine equivalent circuit is (assuming Ra ==> 0)

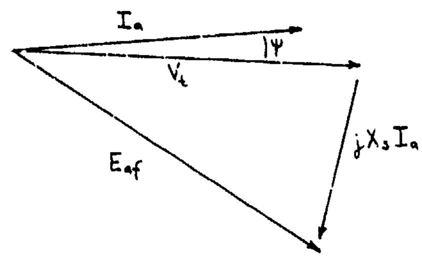



Figure 39. Synchronous machine vector diagram

By use of the law of cosines,

$$Eaf^2 = Vt^2 + (XsI_a)^2 - 2VtXsI_a \cos(\tau + 90°)$$

where $\tau$ is the power factor angle. If this equation is put into per unit form, with eaf = Eaf/Vt and xs = $XsI_a$/Vt, then

$$eaf^2 = 1 + xs^2 + 2\ xs\ \sin(\tau)$$

xs can be calculated, allowing the calculation of eaf. There is simple linear relationship between eaf, the no-load rotor current density (jrnl), and the full-load rotor current density (jr). It is jr = (eaf)(jrnl), because Eaf is directly proportional to $I_f$ and $I_f$ is directly proportional to $J_f$. Ampere's Law states

$$\oint H_r \cdot \bar{d}l = \int J \cdot \bar{n}\ dA$$

If one chooses an integration path around half of the rotor,

$$\mu_o\ H\ 2g = \mu_o\ \frac{4}{\pi}\ \frac{Nf\ I_f\ k_f}{p}$$

If the no-load condition is chosen, and it is recognized that Br is essentially constant with increases in Vt (because when Vt increases, so must Eaf), then

$$Br = \frac{2 \mu_o \ r \ lr \ dr \ RSF \ k_f \ jrnl}{g \ p}$$

and $$jrnl = \frac{Br \ g \ p}{2 \mu_o \ r \ lr \ dr \ RSF \ k_f}$$

The synchronous reactance is a measure of flux linkage within the machine. It is Xs = w Ls = w (Lal + 1.5 Laa), where Laa is the armature single phase inductance and Lal is the slot leakage inductance. The factor of 1.5 is derived from the 120° separation between the three phases of these machines, as

$$XsI_a = w \ (I_a Lal + I_a Laa + I_b Lab + I_c Lac)$$

Due to the symmetry of the machine,

$$Lab = Lba = Lac = Lca = Lbc = Lcb = -0.5 \ Laa$$

Then, $XsI_a = w \ I_a \ (Lal + 1.5 \ Laa)$.

Self-inductance is

$$Laa = \frac{4 \mu_o \ k_s^2 \ Ns^2 \ l \ r}{\pi \ g \ p^2}$$

from Ampere's Law and L = (flux/current). If a single conductor per slot is postulated and the effects of slot teeth are ignored, then the leakage inductance is

$$Lal = \frac{slots}{(pole)(phase)} (Pself + Pmutual) \ Ns^2$$

where P is reluctance. For this conductor configuration,

$$Pself = \frac{\mu_o\ l}{3}\ ds\ ws \quad \text{and} \quad Pmutual = \frac{\mu_o\ l}{2}\ ds\ ws,$$

with ws equal to slot width. Since ws is not known, we use the stator slot space factor, ls, multiplied by the number of slots to yield

$$(slots)\ ws = ls\ \pi\ (r+g) \qquad \text{Therefore,}$$

$$Lal = \frac{5\ Ns^2\ \mu_o\ l\ ds\ ls\ \pi\ (r+g)}{36\ p}$$

The real power developed by the machine is

$Pwr = 3\ Vt\ I_a\ pf$, where pf is the power factor. Through the use of Lenz' Law and Ampere's Law, terminal voltage may be expressed as

$$Vt = \frac{2\ r\ l\ w\ Br\ k_w}{p}$$

Using our previous relation for $I_a$, the expression for Pwr is

$$Pwr = \frac{2\pi\ r\ l\ w\ Br\ k_w\ J_a\ SSF\ (r+g)\ ls\ ds\ pf}{p}$$

Finally, winding factors need to be derived. The winding breadth factor, $k_b$, is

$$k_{bn} = \frac{\sin(m\ n\ \Gamma/2)}{m\ \sin(n\ \Gamma/2)}$$

where $\Gamma$ is the electrical angle between adjacent slots, n is the harmonic order, and m is the number of slots per pole per phase. The winding pitch factor, $k_p$, is

$k_{pn} = \sin(n\,\alpha/2)$   where $\alpha$ is the electrical angle

between sides of the coils (pitch angle). For a three phase winding, $\alpha = 2\pi\,p$. If a 0.8 coil pitch is assumed (which will rid the machine of certain harmonics during balanced operation) then $\alpha = 180°(1 - 0.8) = 36°$ and $k_{pn} = \sin(0.3142\ n)$. Assumptions are needed to calculate $k_{bn}$ without specifying the number of stator slots or turns. If the winding angle is specified as did Kirtley [32], then

$$k_{bn} = \frac{\sin(n\,\theta_w/2)}{(n\,\theta_w/2)}$$

A reasonable electrical winding angle is 60°, since most of the stator periphery will contain turns. The breadth factor devolves to $k_{bn} = \sin(0.5236\ n)/(0.5236\ n)$, for which the fundamental harmonic factor equals 0.955. The winding factor is the product of the breadth and pitch factors. For the rotor, a pitch factor of one is assumed.

Table 38. Listing of synchronous machine design program

```
#include "stdio.h"
#include "def.h"

/* program name:  syn.c for synchronous, round rotor machines */

long int seed;                    /* start point for random number generator */
double b[26][26], h[11][26], ks[8], kr[8];
        /* b is "best" array, h is "hold" array, ks/kr are winding factors */
main()
{
double design_point(), rnd_walk(), swf(), rwf(), ke, kv, minpwr,
        stepsize, random(), abs(), freq, rpm;
int p, iteration, i, j, best, print_out(), loops;
FILE *fopen(), *fp;

printf("\nReading input data from SYN.DAT . . .");

fp=fopen("syn.dat","r");  /* input seed for random numbers */
fscanf(fp,"%d",&seed);
fscanf(fp, "%d", &p);              /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);        /* input machine power, derived fm ASSET */
minpwr*=746.0;                     /* convert to watts */
fscanf(fp, "%lf", &ke);            /* CERs for Effective Weight */
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);           /* machine max shaft rpm  */
fclose(fp);

printf("\nHow many loops do you want? ");
scanf("%d", &loops);

printf("\n\nDoing program calculations . . .\n");

for (i=1; i < 8; i+=2)                    /* harmonic winding factors   */
        {
        ks[i]=swf(i);
        kr[i]=rwf(i);
        }

freq=rpm*p/60.0;                   /* max electrical frequency */

/*  MAIN BODY OF THE PROGRAM */

for (i=1; i <= loops; ++i)
        {
        stepsize=0.1;
        iteration=0;
        design_point(minpwr, p, ke, kv, freq);
                                        /* put stuff in the hold array */
        while (iteration <= 10)
                {
```

```
                rnd_walk(minpwr, p, stepsize, ke, kv, freq);
                                        /* stagger around */
                best=0;                 /* index to best EW of the lot */
                for (j=1; j<=10; ++j)
                        if (h[j][18] < h[best][18])
                                best=j;         /* find the best machine */
                if (abs((h[0][18] - h[best][18])/h[0][18]) < 0.005)
                                        /* small improvement in EW */
                        {
                        stepsize/=2.0;
                        ++iteration;
                        }
                else                    /* transfers best to 0 position */
                        {
                        for (j=1; j <= 25; ++j)
                                h[0][j] = h[best][j];
                        }
                }
        for (j=1; j <= 25; ++j)
                b[i][j]=h[best][j];             /* keep the best machine */
        }

best=1;
for (i=1; i <= locps; ++i)
        if (b[i][18] < b[best][18])
                best=i;         /* find and keep the best of the best */
minpwr/=746.0;                          /* turn back into hp */

print_out(best, p, minpwr, ke, kv, rpm);   /* output to disk file */

fp=fopen("syn.dat","w");                /* output seed */
fprintf(fp,"%d", seed);
fprintf(fp,"\n%d", p);
fprintf(fp,"\n%lf", minpwr);
fprintf(fp,"\n%lf", ke);
fprintf(fp,"\n%lf", kv);
fprintf(fp,"\n%lf", rpm);
fclose(fp);
}
/*  END OF MAIN PROGRAM; ALL THAT FOLLOW ARE FUNCTIONS */

double design_point(minpwr, p, ke, kv, freq)
                                /* determines a random design point */
double minpwr, ke, kv, freq;
int p;
{
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
        va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal,
        cw, siv, scv, riv, rcv, loa, doa, wt_iron, find_siv();
extern double sqrt(), random();
int c=0, d=0;

while (d != 1) {
while (c != 1)
```

```
        {
        r=random()*RMAX;
        if ((2*PI*r*freq/p) < MAX_TIP_SPEED)  /* check rotor tip speed */
                break;
        }

w=2*PI*freq;
lr=random()*0.5 + 0.25;             /* rotor slot factor */
dr=random()*r/5.0;                  /* slot no deeper than 20% of rotor radius */
dcore=(BR*r)/(BSAT*p);              /* back iron depth */
ds=random()*0.9*dcore;              /* slot depth < 90% of body depth */
while (c != 1)                      /* gap dimension */
        {
        g=random()*(0.1*r - GMIN) + GMIN;
                if (g > 0)
                        break;
        }
ls=random()*0.5 + 0.25;             /* stator slot factor */
js=random()*JSMAX;                  /* full load stator current density */

jrnl=(BR*g*p)/(8*MU*RSF*r*dr*lr*kr[1]); /* noload rotor current density */

xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) + xsal))
                        /(12*r*BR*ks[1]);
                                        /* p.u. synch impedance */
if (xs > 2.0)
        continue;                       /* don't want xs too big */
else
        ++d;

eaf=sqrt(1 + xs*xs + 2*xs*0.6); /* 0.6 is sin(τ), pwr factor angle,
        eaf is p.u. internal voltage at full load */

jr=eaf*jrnl;                            /* jr full load, linear with eaf */

l=(minpwr*p)/(2*BR*w*ks[1]*r*SSF*ds*PI*(r+g)*ls*js*PF);  /* active length */

va=2*PI*r*l*w*BR*ks[1]*js*SSF*(r+g)*ds*ls/p;        /* va rating */

siv = find_siv(l, r, g, ds, dcore, ls);             /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                         /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(1 + 2.3094*PI*(r+g)*CP/p);
                                                    /* stator copper volume */
rcv = 2*PI*r*dr*lr*(1 + 2.3094*PI*r/p);             /* rotor copper volume */
cw = (rcv + scv)*DCU;                               /* total copper weight */
loa = l + 4*(r+g);                                  /* length-over-all */
doa = 2*(r+g+ds+dcore);                             /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);            /* machine envelope volume */

wt = WTALL*(cw + D*(BRNGS*riv + siv));              /* machine weight in kg */
```

```
wt_iron = D*(riv + siv);                    /* iron weight only */

ph = 31.86225*BETA*freq*B?1*HC1*wt_iron/D;
        /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*HU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */

i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                                        /* stator copper loss in watts */
                                                /* revised 1-12-87 */

i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                                /* rotor excitation losses, 1-12-87 */
i2r+=i2rr;                      /* total copper losses */


effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + ke*(1-effcy) + kv*vol;                  /* Effective weight */

h[0][1]=js;      h[0][2]=freq;    h[0][3]=w;       h[0][4]=r;       h[0][5]=g;
h[0][6]=dcore;   h[0][7]=ds;      h[0][8]=dr;      h[0][9]=ls;      h[0][10]=lr;
h[0][11]=vol;    h[0][12]=wt;     h[0][13]=ph;     h[0][14]=pe;     h[0][15]=i2r;
h[0][16]=va;     h[0][17]=effcy;  h[0][18]=ew;     h[0][19]=l;      h[0][20]=jr;
h[0][21]=jrnl;   h[0][22]=xs;     h[0][23]=eaf;    h[0][24]=loa;    h[0][25]=doa;
        /* this section just changed all the variables in the "hold" array */

return;
}}



double rnd_walk(minpwr, p, stepsize, ke, kv, freq)
                        /* walks about design_point 10 times */
        double stepsize, minpwr, ke, kv, freq;
        int p;
{
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
        va, ph, pe, i2r, vol, wt, effcy, ew, xsi, xs5, xs7, xsal,
        cm, siv, scv, riv, rcv, loa, doa, wt_iron, find_siv();
extern double sqrt(), random();
int i=1;


while (i <= 10)
        {
        /* read in the walk around the design point */

        js=h[0][1]*(1 + stepsize*(random() - 0.5));
        if (js > JSMAX)
                js = JSMAX;             /* reset to limit */
        w=2*PI*freq;
        r=h[0][4]*(1 + stepsize*(random() - 0.5));
```

```
	if ((w*r/p) > MAX_TIP_SPEED)
		continue;		/* go to next try if violated */
	g=h[0][5]*(1 + stepsize*(random() - 0.5));
		if (g < GMIN)
			g=GMIN;		/* reset to the limit */
	dcore=(BR*r)/(BSAT*p);		/* most efficient use of iron */
	ds=h[0][7]*(1 + stepsize*(random() - 0.5));
		if (ds > dcore)		/* can't have too-deep slots */
			ds=dcore;	/* reset to the limit */
	dr=h[0][8]*(1 + stepsize*(random() - 0.5));
	ls=h[0][9]*(1 + stepsize*(random() - 0.5));
		if (ls > 0.75)
			ls=0.75;	/* reset to the limit */
		if (ls < 0.25)
			ls=0.25;
	lr=h[0][10]*(1 + stapsize*(random() - 0.5));
		if (lr > 0.75)
			lr=0.75;	/* reset to the limit */
		if (lr < 0.25)
			lr=0.25;

	/* computation section of the walk */
jrnl=(BR*g*p)/(8*MU*RSF*r*dr*jr*kr[1]); /* noload rotor current density */

xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) + xsal))
			/(12*r*BR*ks[1]);
					/* p.u. synch impedance */
if (xs > 2.0)
	continue;				/* can't have xs too big */

eaf=sqrt(1 + xs*xs + 2*xs*0.6);   /* 0.6 is sin(r), pwr factor angle,
				eaf is p.u. internal voltage at full load */

jr=eaf*jrnl;				/* jr full load, linear with eaf */

l=(minpwr*p)/(2*BR*w*ks[1]*r*SSF*ds*PI*(r+g)*ls*js*PF);  /* active length */

va=2*PI*r*l*w*BR*ks[1]*js*SSF*(r+g)*ds*ls/p;	/* va rating */

siv = find_siv(l, r, g, ds, dcore, ls);    /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);			/* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(1 + 2.3094*PI*(r+g)*CP/p);
						/* stator copper volume */
rcv = 2*PI*r*dr*lr*(1 + 2.3094*PI*r/p);		/* rotor copper volume */
cw = (rcv + scv)*DCU;				/* total copper weight */
loa = l + 4*(r+g);				/* length-over-all */
doa = 2*(r+g+ds+dcore);				/* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);		/* machine envelope volume */

wt = WTALL*(cw + D*(BRWES*riv + siv));		/* machine weight in kg */
```

```
wt_iron = D*(riv + siv);                    /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
        /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */

i2r = 2.0*SSF*ds*CRHO*PI*ls (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                                        /* stator copper loss in watts */
                                                /* revised 1-12-87  */

i2rr = 2.0*RSF*dr*r*r*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                                /* rotor excitation losses, 1-12-87 */
i2r+=i2rr;                      /* total copper losses */

effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + ke*(1-effcy) + kv*vol;                  /* Effective weight */

h[i][1]=js;     h[i][2]=freq;   h[i][3]=w;      h[i][4]=r;      h[i][5]=g;
h[i][6]=dcore;  h[i][7]=ds;     h[i][8]=dr;     h[i][9]=ls;     h[i][10]=lr;
h[i][11]=vol;   h[i][12]=wt;    h[i][13]=ph;    h[i][14]=pe;    h[i][15]=i2r;
h[i][16]=va;    h[i][17]=effcy; h[i][18]=ew;    h[i][19]=l;     h[i][20]=jr;
h[i][21]=jrnl;  h[i][22]=xs;    h[i][23]=eaf;   h[i][24]=loa;   h[i][25]=doa;
        /* this section just changed all the variables in the "hold" array */

        ++i;                    /* go to the next h[i][] */
        }

return;
}



print_out(best, p, minpwr, ke, kv, rpm)
        int best, p;
        double minpwr, ke, kv, rpm;
{
char outfile[14];
FILE *fpo, *fopen();
int i;

printf("\nWhat is the name of the file where you want the output? ");
scanf("%s", outfile);

fpo=fopen(outfile, "w");


fprintf(fpo,"%d", p);
fprintf(fpo,"\n%lf", minpwr);
fprintf(fpo,"\n%lf", ke);
fprintf(fpo,"\n%lf", kv);
fprintf(fpo,"\n%lf", rpm);
```

```
for (i=1; i <= 25; ++i)
        fprintf(fpo,"\n%lf",b[best][i]);
fprintf(fpo, "\n");
fclose(fpo);
}



double find_siv(l, r, g, ds, dcore, ls)
        double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}
```

Table 39. Listing of synchronous efficiency program

```
#include "stdio.h"
#include "def.h"

/*  program name:  seff.c to find efficiency of synchronous machines */
/*  works with only a single machine */

main()
{
FILE *fopen(), *fp;
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
        va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal, ks[8],
        siv, riv, wt_iron, find_siv(), pmeff, pmjs, pmrpm, dhp, rpm, minpwr,
        ke, kv, freq;
extern double swf(), sqrt();
int e=0, f, p, i;
char infile[14];

for (i=1; i < 8; i+=2)                    /* harmonic winding factors   */
        {
        ks[i]=swf(i);
        }
xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);

printf("\nCalculates efficiency of a single motor.\n");
while (e != 1)
{
f = 0;
printf("What is the name of the input file? ");
scanf("%s", infile);
fp = fopen(infile, "r");
fscanf(fp, "%d", &p);             /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);
minpwr *= 746.0;          /* now in watts */
fscanf(fp, "%lf", &ke);
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);
fscanf(fp, "%lf", &js);
fscanf(fp, "%lf", &freq);
fscanf(fp, "%lf", &w);
fscanf(fp, "%lf", &r);
fscanf(fp, "%lf", &g);
fscanf(fp, "%lf", &dcore);
fscanf(fp, "%lf", &ds);
fscanf(fp, "%lf", &dr);
fscanf(fp, "%lf", &ls);
fscanf(fp, "%lf", &lr);
fscanf(fp, "%lf", &vol);
fscanf(fp, "%lf", &wt);
```

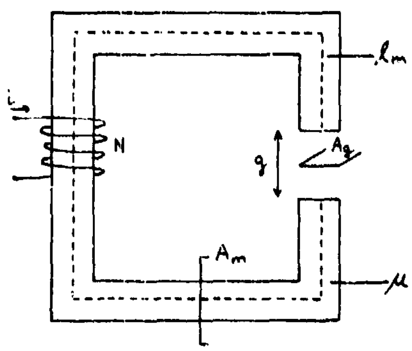
```
fscanf(fp, "%lf", &ph);
fscanf(fp, "%lf", &pe);
fscanf(fp, "%lf", &i2r);
fscanf(fp, "%lf", &va);
fscanf(fp, "%lf", &effcy);
fscanf(fp, "%lf", &ew);
fscanf(fp, "%lf", &l);
fscanf(fp, "%lf", &jr);
fscanf(fp, "%lf", &jrnl);
fclose(fp);

siv = find_siv(l, r, g, ds, dcore, ls);            /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                        /* rotor iron volume */
wt_iron = D*(riv + siv);                      /* iron weight only */

while (f != 1)
{
printf("\nWhat is the sustained speed machine horsepower? ");
scanf("%lf", &dhp);
dhp *= 746.0;
printf("What is the sustained speed machine rpm? ");
scanf("%lf", &parpm);
freq = parpm*p/60.0;                          /* max electrical frequency */
pmjs = js*dhp/minpwr;                         /* PM stator current */
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) + xsal))
                        /(12*r*BR*ks[1]);        /* p.u. synch impedance */
eaf=sqrt(1 + xs*xs + 2*xs*0.6); /* 0.6 is sin(τ), pwr factor angle,
        eaf is p.u. internal voltage at full load */
jr=eaf*jrnl;                                  /* jr full load, linear with eaf */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
        /* hysteresis loss in watts, uses iron weight of machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */
i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                                              /* stator copper loss in watts */
i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                                 /* rotor excitation losses, 1-12-87 */
pmeff = dhp/(dhp + ph + pe + i2r + i2rr);
printf("\n   Sustained speed efficiency is %lf", pmeff);

printf("\nWhat is the endurance speed machine horsepower? ");
scanf("%lf", &dhp);
dhp *= 746.0;
printf("What is the endurance speed machine rpm? ");
scanf("%lf", &parpm);
pmjs = js*dhp/minpwr;                         /* PM stator current */
freq = parpm*p/60.0;                          /* max electrical frequency */
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) + xsal))
                        /(12*r*BR*ks[1]);        /* p.u. synch impedance */
eaf=sqrt(1 + xs*xs + 2*xs*0.6); /* 0.6 is sin(τ), pwr factor angle,
        eaf is p.u. internal voltage at full load */
jr=eaf*jrnl;                                  /* jr full load, linear with eaf */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
```

```
i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
paeff = dhp/(dhp + ph + pe + i2r + i2rr);
printf("\n   Endurance efficiency is %lf", paeff);

printf("\nSame machine? ");
scanf("%d", &f);
if (f == 0)
        continue;
else if (f == 2)
        {
        e = 1;
        break;
        }
}               /* end of f-loop */
}               /* end of e-loop */
}               /* end of main program */

double find_siv(l, r, g, ds, dcore, ls)
        double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
            }
```

Appendix C. Permanent magnet machine

The equivalent circuit for a permanent magnet machine is almost identical to that of a synchronous machine. The only difference is the source of the internal voltage, which develops the field flux wave that interacts with the armature flux wave. The field flux wave is a result of permanent magnets built into the rotor to develop magnetic poles.

A typical magnetic circuit, combined with Ampere's Law, shows




$$H_m l_m + H_g g = Ni$$

Figure 40. Typical magnetic circuit

We use a constitutive law of $B = \mu H$ and assume that any steel has $\mu = \infty$. If flux leakage is about zero, $B_m A_m = B_g A_g$ since flux is solenoidal. Then,

$$l_m = \frac{Ni - H_g g}{H_m} \quad \text{and} \quad A_m = \frac{\mu_o H_g A_g}{B_m}$$

The magnet volume is

$$V_m = l_m A_m = \frac{(Ni - H_g g)\, \mu_o H_g A_g}{H_m B_m}$$

Minimum magnet volume occurs when the magnet's maximum energy product (MEP), $H_m B_m$, is a maximum. If current is zero and only magnitudes are used,

$$V_m = \frac{g \; B_g^2 \; A_g}{\mu_o \; H_m \; B_m}$$

The load line of the magnet is developed as

$$\frac{l_m}{A_m} = \frac{g \; B_m}{\mu_o \; H_m \; A_g} \qquad \text{and}$$

$$\frac{B_m}{H_m} = \mu_o \; \frac{l_m}{g} \; \frac{A_g}{A_m} = P_c$$

The permanance coefficient, Pc, is the slope of the load line. On a magnet diagram

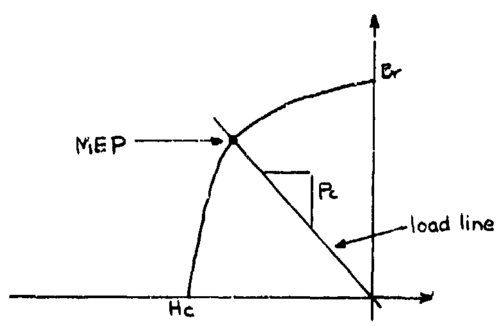



Figure 41. Magnet operating point diagram

A good algorithm for machine design is to adjust the geometric dimensions to operate at the MEP, on the load line. If operation at MEP is assumed, the needed slope is determined, the dimensions are randomly generated, $\mu_o H_g$ is calculated, and the design is maximized for $\mu_o H_g$ and minimized for magnet volume, then a search technique has been delineated.

Magnets may "overhang" the active length at either end to account for manufacturing imprecision and to permit a smaller armature diameter. This overhang affects the developed flux.

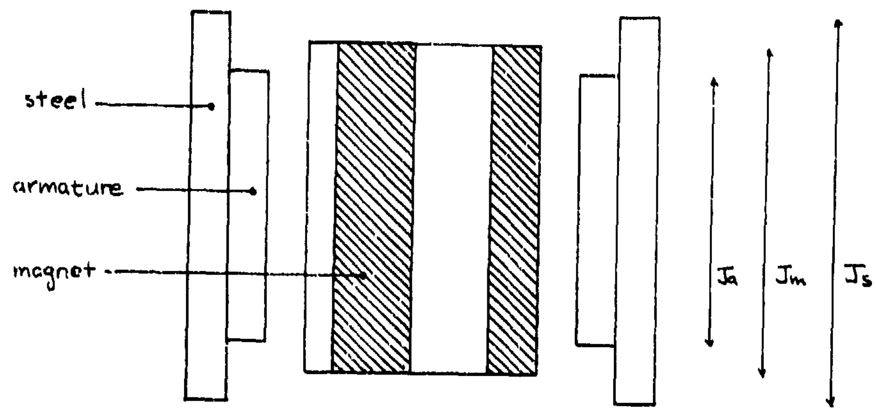



Figure 42. Permanent magnet machine diagram

The flux per pole, Ø, with overhang and a given Ja and Jm, is the same as would exist in a configuration in which Ja' = Jm' = Ja + ND and there were no overhang. N is a non-linear parameter promulgated in graph form by Ireland [33]. A good power fit for N is

$$N = 0.38558 \left(\frac{\delta Jm}{D}\right)^{0.70813}$$

where $\frac{\delta Jm}{D}$ = overhang and $0 \leq$ overhang $\leq 0.34$. Then,

$$Y = \frac{\frac{Ja}{D} + \frac{\delta Jm}{D}}{\frac{Ja}{D} + N} \qquad \text{and} \qquad \O_{with} = \O_{w/o}\, Y$$

This flux-with-overhang is applied to the problem as would be the usual flux. What is the usual flux? A permanent magnet hysteresis diagram shows the residual flux density to be defined at a single point.

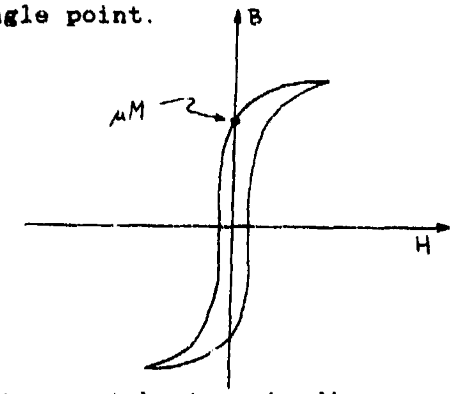



Figure 43. Permanent magnet hysteresis diagram

The magnet does not operate at that point, but rather on the load line. Also, there is not magnet material at every point along the circumference of the rotor. A Fourier series is a good way to find the flux-without-overhang. Using a developed rotor,

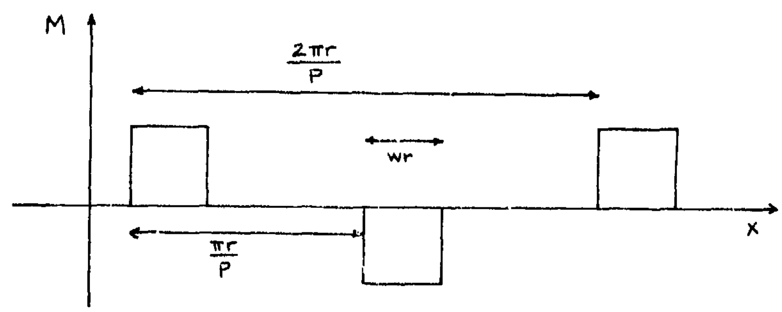



Figure 44. Magnet material on a developed rotor

$$\mu M = Bd$$

$$lr = \frac{wr}{\pi r/p} = \frac{p\ wr}{\pi\ r}$$

$$B(x) = \sum_{n=1}^{\infty} An \cos\left(\frac{n\ \pi\ x}{T}\right), \qquad T = \frac{2\pi r}{p}$$

$$A_n = \frac{2}{T} \int_0^T B(x) \cos\left(\frac{n\pi x}{T}\right) dx \quad \text{for } n = 1, 2, 3 \ldots$$

$$B(x) = \begin{cases} B_d & \text{for } 0 \le x \le (\pi r\ l_r/p) \\ 0 & \text{for } (\pi r\ l_r/p) \le x \le (\pi r/p) \\ B_d & \text{for } (\pi r/p) \le x \le (\pi r/p)(1+l_r) \\ 0 & \text{for } (\pi r/p)(1+l_r) \le x \le (2\pi r/p) \end{cases}$$

After integration and manipulation,

$$A_n = \frac{2B_d}{\pi} \left[ \sin\left(\frac{\pi\ l_r}{2}\right) - \cos\left(\frac{\pi\ l_r}{2}\right) + 1 \right]$$

The equation represents only the fundamental term of the Fourier series. The flux-without-overhang is

$$B_r = \frac{2B_d}{\pi} \left[ \sin\left(\frac{\pi\ l_r}{2}\right) - \cos\left(\frac{\pi\ l_r}{2}\right) + 1 \right] \cos\left(\frac{xp}{2r}\right)$$

As is usual in steady-state analysis, the magnitude is used.

The next quantity to find is Bd. If the magnet operates on the load line, the operating point flux is

$$B_d = \frac{B_{rem}}{1 + \mu_r / P_c} \qquad \text{where } \mu_r \text{ is the relative}$$

reversible permeability of the magnet and Brem and Pc are as previously defined. With this relative permeability, the magnet length is $l_m = g\ \mu_r$. The magnetic machine can now be specified. An end view with dimensions is given in Chapter Four.

Table 40. Listing of permanent magnet machine design program

```
#include "stdio.h"
#include "def.h"

/* program name: pmm.c for permanent magnet machines */

long int seed;                  /* start point for random number generator */
double b[101][27], h[1][27], ks[8];
        /* b is "best" array, h is "hold" array, ks are winding factors */
main()
{
double design_point(), rnd_walk(), swf(), ke, kv, km, minpwr,
        stepsize, random(), abs(), freq, rpm;
int p, iteration, i, j, best, print_out(), loops;
FILE *fopen(), *fp;

printf("\nReading input data from PMM.DAT . . .");

fp=fopen("pmm.dat","r");  /* input seed for random numbers */
fscanf(fp,"%d",&seed);
fscanf(fp, "%d", &p);          /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);     /* input machine power, derived fm ASSET */
minpwr*=746.0;                 /* convert to watts */
fscanf(fp, "%lf", &ke);         /* CERs for Effective Weight */
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &km);
fscanf(fp, "%lf", &rpm);        /* machine max shaft rpm  */
fclose(fp);

printf("\nHow many loops do you want? ");
scanf("%d", &loops);
printf("\n\nDoing program calculations . . .\n");

for (i=1; i < 8; i+=2)                  /* harmonic winding factors   */
        {
        ks[i]=swf(i);
        }

freq=rpm*p/60.0;                /* max electrical frequency */

/* MAIN BODY OF THE PROGRAM */

for (i=1; i <= loops; ++i)
        {
        printf("\ni=%d", i);
        stepsize=0.1;
        iteration=0;
        design_point(minpwr, p, ke, kv, km, freq);
                                        /* put stuff in the hold array */
        while (iteration <= 10)
                {
                rnd_walk(minpwr, p, stepsize, ke, kv, km, freq);
```

```
                                /* stagger around */
        best=0;                 /* index to best EW of the lot */
        for (j=1; j<=10; ++j)
                if (h[j][18] < h[best][18])
                        best=j;         /* find the best machine */
        if (abs((h[0][18] - h[best][18])/(h[0][18]+.001)) < 0.005)
                                /* small improvement in EW */
                                /* 0.001 takes care of div by zero */
                {
                stepsize/=2.0;
                ++iteration;
                }
        else                    /* transfers best to 0 position */
                {
                for (j=1; j <= 26; ++j)
                        h[0][j] = h[best][j];
                }
        }
    for (j=1; j <= 26; ++j)
        b[i][j]=h[best][j];             /* keep the best machine */
    }
best=1;
for (i=1; i <= loops; ++i)
    if (b[i][18] < b[best][18])
        best=i;         /* find and keep the best of the best */
minpwr/=746.0;                          /* turn back into hp */

print_out(best, p, minpwr, ke, kv, km, rpm);    /* output to disk file */

fp=fopen("pmm.dat","w");                /* output seed */
fprintf(fp,"%d", seed);
fprintf(fp,"\n%d", p);
fprintf(fp,"\n%lf", minpwr);
fprintf(fp,"\n%lf", ke);
fprintf(fp,"\n%lf", kv);
fprintf(fp,"\n%lf", km);
fprintf(fp,"\n%lf", rpm);
fclose(fp);
}
/*  END OF MAIN PROGRAM; ALL THAT FOLLOW ARE FUNCTIONS */

double design_point(minpwr, p, ke, kv, km, freq)
                        /* determines a random design point */
double minpwr, ke, kv, km, freq;
int p;
{
double r, js, ls, lr, dcore, ds, g, w, l, xs, va, ph, wtmag,
    pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal, lm, volmag,
    bd, find_lr(), cw, siv, scv, riv, loa, doa, find_siv(), wt_iron;
extern double sqrt(), random();
int c=0, d=0;

while (d != 1) {
while (c != 1)
```

```
        {
        r=random()*RMAX;
        if ((2*PI*r*freq/p) < MAX_TIP_SPEED)  /* check rotor tip speed */
              break;
        }

w=2*PI*freq;
bd=BREM/(1 + MUR/PC);              /* air gap flux, operating point, from magnet
                                           characteristics */
lr=find_lr(bd);                    /* find magnet slot factor */

while (c != 1)                     /* gap dimension */
        {
        g=random()*(0.1*r - GMIN) + GMIN;
              if (g > 0)
                     break;
        }
lm=g*MUR;                          /* radial length of magnet, see PM-8, 12/15/86 */

ls=random()*0.5 + 0.25;            /* stator slot factor */
js=random()*JSMAX;                 /* full load stator current density */
dcore=(bd*(r+lm))/(BSAT*p);        /* back iron depth */
ds=random()*0.9*dcore;             /* slot depth < 90% of body depth */

xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);
xs=(MU*js*SSF*(r+g+lm)*(r+g+lm)*o_.PI*ls
              * (12*(xs1 + xs5 + xs7)/(PI*g*p) + xsal))/(12*(r+lm)*bd*ks[1]);
                                          /* p.u. synch impedance */
if (xs > 3.0)
        continue;                         /* don't want xs too big */
else
        ++d;                       /* my escape hatch -- mission complete */

l=(minpwr*p)/(2*bd*w*ks[1]*(r+lm)*SSF*ds*PI*(r+g+lm)*ls*js*PF);
                                          /* active length */

va=2*PI*(r+lm)*l*w*bd*ks[1]*js*SSF*(r+g+lm)*ds*ls/p;       /* VA rating */

siv = find_siv(l, r, g, ds, dcore, ls, lm);        /* stator iron volume */
riv = l*PI*r*r;                                   /* rotor iron volume */
scv = 2*PI*(r+g+lm)*ds*ls*(l + 2.3094*PI*(r+g+lm)*CP/p);
                                                  /* stator copper volume */
cw = scv*DCU;                                     /* total copper weight */
loa = l + 4*(r+g+lm);                             /* length-over-all */
doa = 2*(r+g+lm+ds+dcore);                        /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);          /* machine envelope volume */

wt = WTALL*(cw + D*(BRNGS*riv + siv));            /* machine weight in kg */
wt_iron = D*(riv + siv);                  /* iron weight only */

ph = 31.86225*BETA*freq*BP1*HC1*wt_iron/D;
```

```
        /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */

volmag=2*PI*r*l*lm*lr;            /* magnet volume */
wtmag=volmag*DMAG;                /* magnet weight */

i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g+lm)*CP/p) *js*js*(r+g+lm)*ls;
                                        /* stator copper loss in watts */
                                                /* revised 1-12-87  */

effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + km*wtmag + ke*(1-effcy) + kv*(vol + km*volmag);
                                        /* Effective weight */

h[0][1]=js;     h[0][2]=freq;   h[0][3]=w;      h[0][4]=r;      h[0][5]=g;
h[0][6]=dcore;  h[0][7]=ds;     h[0][8]=lm;     h[0][9]=ls;     h[0][10]=lr;
h[0][11]=vol;   h[0][12]=wt;    h[0][13]=ph;    h[0][14]=pe;    h[0][15]=i2r;
h[0][16]=va;    h[0][17]=effcy; h[0][18]=ew;    h[0][19]=l;
h[0][20]=wtmag; h[0][21]=volmag;        h[0][22]=xs;
h[0][23]=0.0;   /* this one makes overhang=0 */ h[0][24]=bd;    h[0][25]=loa;
h[0][26]=doa;
        /* this section just changed all the variables in the "hold" array */

return;
}}



double rnd_walk(minpwr, p, stepsize, ke, kv, km, freq)
                        /* walks about design_point 10 times */
        double stepsize, minpwr, ke, kv, km, freq;
        int p;
{
double r, js, ls, lr, dcore, ds, g, w, l, xs, va, ph, pe, i2r,
        vol, wt, effcy, ew, xsl, xs5, xs7, xsal, lm, volmag, wtmag, bd,
        find_lr(), find_br(), hr, overhang, lrat, cw, siv, scv, riv, loa,
        doa, find_siv(), wt_iron;
extern double sqrt(), random();
int i=1, j, check=0, ccj;


while (i <= 10)
        {
        /* read in th  walk around the design point */

        js=h[0][1]*(1 + stepsize*(random() - 0.5));
        if (js > JSMAX)
                js = JSMAX;                     /* reset to limit */
        w=2*PI*freq;
        r=h[0][4]*(1 + stepsize*(random() - 0.5));
        if ((w*r/p) > MAX_TIP_SPEED)
```

```
		continue;			/* go to next try if violated */
	g=h[0][5]*(1 + stepsize*(random() - 0.5));
		if (g < GMIN)
			g=GMIN;		/* reset to the limit */

	overhang=random()*0.34;		/* magic number "0.34" from the book
				on permanent magnets by James Ireland.
				The effect of overhang is to concentrate air
				gap flux, or reduce leakage. */
	l=h[0][19];
	lm=g*MUR;			/* new lm, based on the new g */
	bd=BREM/(1 + MUR/PC);	/* magnet operating point flux density */
	lr=find_lr(bd);			/* find new lr */
	ls=h[0][9]*(1 + stepsize*(random() - 0.5));
		if (ls > 0.75)
			ls=0.75;		/* reset to the limit */
		if (ls < 0.25)
			ls=0.25;


	for (j=1; j <= 10; ++j)		/* magnet char convergence loop */
		{
		lrat=l/(2*(r+g+lm));
		br=bd*find_br(overhang, lrat);
				/* find effect of overhang on air gap flux */
		dcore=(br*(r+lm))/(BSAT*p);	/* most efficient use of iron */
		ds=h[0][7]*dcore/h[0][6]; /* keep them in the same ratio
					as upon exit fm design_pt */

		xs1=ks[1]*ks[1];
		xs5=(ks[5]*ks[5]/25);
		xs7=(ks[7]*ks[7]/49);
		xsal=(5*ls*PI*ds/18);
xs=(MU*js*SSF*(r+g+lm)*(r+g+lm)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p)
				+ xsal))/(12*(r+lm)*br*ks[1]);
					/* p.u. synch impedance */
		l=(minpwr*p)/(2*br*w*ks[1]*(r+lm)*SSF*ds*PI*(r+g+lm)*ls*js*PF);
					/* active length */
		}		/* end of magnet char convergence loop */

	if (xs > 3.0)
		{
		++check;
		if (check > 25)			/* can't close on decent xs */
			{
			for (ccj=i; ccj <= 10; ++ccj)
				h[ccj][18]=10000000.0;
				/* make this random walk undesirable */
			printf(" burp");
			break;			/* go to next design point */
			}
		continue;			/* can't have xs too big */
		}
```

```
va=2*PI*(r+lm)*l*w*br*ks[1]*js*SSF*(r+g+lm)*ds*ls/p;        /* VA rating */

siv = find_siv(l, r, g, ds, dcore, ls, lm);         /* stator iron volume */
riv = l*PI*r*r;                                     /* rotor iron volume */
scv = 2*PI*(r+g+lm)*ds*ls*(l + 2.3094*PI*(r+g+lm)*CP/p);
                                                    /* stator copper volume */
cw = scv*DCU;                                       /* total copper weight */
loa = l + 4*(r+g+lm);                               /* length-over-all */
doa = 2*(r+g+lm+ds+dcore);                          /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);            /* machine envelope volume */

wt = WTALL*(cw + D*(BRNGS*riv + siv));              /* machine weight in kg */
wt_iron = D*(riv + siv);                    /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
        /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */

volmag=2*PI*r*l*(1.0+(overhang*(2*(r+g+lm))))*lm*lr;        /* magnet volume */
wtmag=volmag*DMAG;                          /* magnet weight */

i2r = 2.0*SSF*ds*CRHO*PI* (l + 2.3094*PI*(r+g+lm)*CP/p) *js*js*(r+g+lm)*ls;
                                            /* stator copper loss in watts */
                                                    /* revised 1-12-87  */


effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + km*wtmag + ke*(1-effcy) + kv*(vol + km*volmag);
                                            /* Effective weight */


h[i][1]=js;      h[i][2]=freq;    h[i][3]=w;       h[i][4]=r;       h[i][5]=g;
h[i][6]=dcore;   h[i][7]=ds;      h[i][8]=lm;      h[i][9]=ls;      h[i][10]=lr;
h[i][11]=vol;    h[i][12]=wt;     h[i][13]=ph;     h[i][14]=pe;     h[i][15]=i2r;
h[i][16]=va;     h[i][17]=effcy;  h[i][18]=ew;     h[i][19]=l;
h[i][20]=wtmag;  h[i][21]=volmag;           h[i][22]=xs;
h[i][23]=overhang;                h[i][24]=br;     h[i][25]=loa;    h[i][26]=doa;
        /* this section just changed all the variables in the "hold" array */

        ++i;                    /* go to the next h[i][] */
        check=0;
        }

return;
}



print_out(best, p, minpwr, ke, kv, km, rpm)
        int best, p;
        double minpwr, ke, kv, km, rpm;
{
char outfile[14];
```

```
FILE *fpo, *fopen();
int i;

printf("\nWhat is the name of the file where you want the output? ");
scanf("%s", outfile);

fpo=fopen(outfile, "w");

fprintf(fpo,"%d", p);
fprintf(fpo,"\n%lf", minpwr);
fprintf(fpo,"\n%lf", ke);
fprintf(fpo,"\n%lf", kv);
fprintf(fpo,"\n%lf", km);
fprintf(fpo,"\n%lf", rpm);
for (i=1; i <= 26; ++i)
        fprintf(fpo, "\n%lf", b[best][i]);
fprintf(fpo, "\n");
fclose(fpo);
}



double find_lr(br)                          /* bracketing */
        double br;
{
extern double cos(), sin();
int c=0;
double lr=0.5, top=1.0, tbr=0.0, abs(), btm=0.0;

while (c!=1)
        {
        tbr=(2*BREM* (sin(0.5*PI*lr) - cos(0.6*PI*lr) + 1.0))/PI;
        if (abs((br-tbr)/br) <= 0.001)    /* check for convergence */
                break;
        if (br > tbr)
                {
                btm=lr;
                lr=btm + (top- btm)/2.0;
                }
        else                                /* br < tbr */
                {
                top=lr;
                lr=btm + (top-btm)/2.0;
                }
        if (abs((top-lr)/top) <= 0.0005)  /* no convergence */
                {
                printf("\n%lf", lr);
                abort("no solution for lr");
                }
        }
return(lr);
}
```

```
double find_br(overhang, lrat)
        double overhang, lrat;
{
extern double pow();
double expon=0.706133501, factor=0.385576838, enn, yyy;
                                  /* enn is Ireland's N, yyy is Ireland's Y */

enn = factor * pow(overhang, expon);
yyy = (lrat + overhang)/(lrat + enn);
return(yyy);
}

double find_siv(l, r, g, ds, dcore, ls, lm)
        double l, r, g, ds, dcore, ds, ls, lm;
{
double one, two, three, four;

one = (r+g+lm+ds+dcore)*(r+g+lm+ds+dcore) - (r+g+lm)*(r+g+lm);
two = 2*PI*(r+g+lm)*ds*ls;
three = (r+g+lm+ds+dcore)*(r+g+lm+ds+dcore) - (r+g+lm+ds)*(r+g+lm+ds);

four = l*(PI*one - two) + PI*4*(r+g+lm)*three;
return(four);
}
```

Table 41. Listing of permanent magnet efficiency program

```
#include "stdio.h"
#include "def.h"

/* program name: peff.c to find efficiency of permanent magnet machines */
/*       works with a single machine */

main()
{
FILE *fopen(), *fp;
double r, js, ls, lr, dcore, ds, dr, g, w, l, xs, lm, km, sgeff=1.0,
        va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal, ks[8],
        siv, riv, wt_iron, find_siv(), pmeff, pyeff, teff, pgjs, pmjs,
        perpm, geff=0.98, pceff=0.99, gr, dhp, rpm, minpwr, ke, kv, freq,
        wtmag, volmag, overhang, bd;
extern double swf(), sqrt();
int e=0, f, p, i;
char infile[14];
siv = find_siv(l, r, g, ds, dcore, ls, lm);        /* stator iron volume */
riv = l*PI*r*r;                                    /* rotor iron volume */
wt_iron = D*(riv + siv);                 /* iron weight only */

printf("\nCalculates efficiency for a single machine.\n");
while (e != 1)
{
f = 0;
printf("What is the name of the input file? ");
scanf("%s", infile);
fp = fopen(infile, "r");
fscanf(fp, "%d", &p);            /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);
minpwr *= 746.0;          /* now in watts */
fscanf(fp, "%lf", &ke);
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &km);
fscanf(fp, "%lf", &rpm);
fscanf(fp, "%lf", &js);
fscanf(fp, "%lf", &freq);
fscanf(fp, "%lf", &w);
fscanf(fp, "%lf", &r);
fscanf(fp, "%lf", &g);
fscanf(fp, "%lf", &dcore);
fscanf(fp, "%lf", &ds);
fscanf(fp, "%lf", &lm);
fscanf(fp, "%lf", &ls);
fscanf(fp, "%lf", &lr);
fscanf(fp, "%lf", &vol);
fscanf(fp, "%lf", &wt);
fscanf(fp, "%lf", &ph);
fscanf(fp, "%lf", &pe);
fscanf(fp, "%lf", &i2r);
fscanf(fp, "%lf", &va);
```

```
fscanf(fp, "%lf", &effcy);
fscanf(fp, "%lf", &ew);
fscanf(fp, "%lf", &l);
fscanf(fp, "%lf", &wtmag);
fscanf(fp, "%lf", &volmag);
fscanf(fp, "%lf", &xs);
fscanf(fp, "%lf", &overhang);
fscanf(fp, "%lf", &bd);
fclose(fp);

while (f != 1)
{
printf("\nWhat is the sustained speed machine horsepower? ");
scanf("%lf", &dhp);
dhp *= 746.0;
printf("What is the sustained speed machine rpm? ");
scanf("%lf", &pmrpm);
freq = pmrpm*p/60.0;                        /* max electrical frequency */
pmjs = js*dhp/minpwr;                       /* PM stator current */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
        /* hysteresis loss in watts, uses iron weight of machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */
i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g+lm)*CP/p) *js*js*(r+g+lm)*ls;
                                            /* stator copper loss in watts */
pmeff = dhp/(dhp + ph + pe + i2r);
printf("\n   Sustained efficiency is %lf", pmeff);

printf("\n\nWhat is the endurance speed machine horsepower? ");
scanf("%lf", &dhp);
dhp *= 746.0;
printf("What is the endurance speed machine rpm? ");
scanf("%lf", &pmrpm);
pmjs = js*dhp/minpwr;                       /* PM stator current */
freq = pmrpm*p/60.0;                        /* max electrical frequency */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g+lm)*CP/p) *js*js*(r+g+lm)*ls;
pmeff = dhp/(dhp + ph + pe + i2r);
printf("\n   Endurance efficiency is %lf", pmeff);

printf("\nSame machine? ");
scanf("%d", &f);
if (f == 0)
        continue;
else if (f == 2)
        {
        e = 1;
        break;
        }
}               /* end of f-loop */
}               /* end of e-loop */
}               /* end of main program */
```

```
double find_siv(l, r, g, ds, dcore, ls, lm)
        double l, r, g, ds, dcore, ls, lm;
{
double one, two, three, four;

one = (r+g+lm+ds+dcore)*(r+g+lm+ds+dcore) - (r+g+lm)*(r+g+lm);
two = 2*PI*(r+g+lm)*ds*ls;
three = (r+g+lm+ds+dcore)*(r+g+lm+ds+dcore) - (r+g+lm+ds)*(r+g+lm+ds);

four = l*(PI*one - two) + PI*4*(r+g+lm)*three;
return(four);
}
```

Appendix D. Induction machines

The equivalent circuit for an induction machine is shown in the figure.

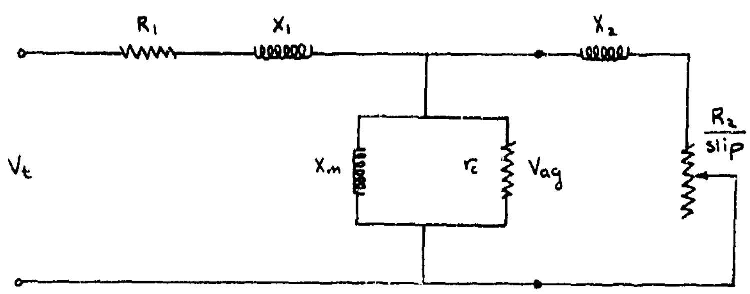



Figure 45. Induction machine equivalent circuit

The stator leakage reactance, X1, is the sum of the stator differential leakage reactance (Xsd), the stator slot leakage reactance (Xss), and the stator end turn leakage reactance (Xse). In turn, Xsd is the sum of the belt and zig-zag reactances.

The rotor leakage reactance, X2, is the sum of the rotor differential leakage reactance (Xrd), the rotor slot leakage reactance (Xrs), and the skew leakage (Xskew). Xm is the magnetizing reactance and Rc is the core resistance. R1 and R2 are the stator and rotor resistances, respectively.

A derivation of the properties of electric machines, using Ampere's Law and the constitutive relation earlier postulated, yields the result that

$$\text{flux} = \sum_{\substack{n=6k\pm1 \\ k=0}}^{\infty} I \ \frac{\mu_o}{g} \ \frac{6 \ N_s^2}{\pi \ n^2} \ \frac{l \ r}{p^2} \ k_s^2 \ \cos(wt)$$

From this important stator inductances are taken.

Belt leakage reactance (Xbelt) is the sum of the reactances due to phase-belt harmonics of an "infinite" slot winding. In most machines, the most important harmonics present are the fifth and seventh, as the third is canceled in balanced operation. Then the belt reactance is

$$X_{belt} = \frac{6 \mu_o w N_s^2 l r}{\pi g p^2} \left[ \left( \frac{k_{s5}}{5} \right)^2 + \left( \frac{k_{s7}}{7} \right)^2 \right]$$

This is the harmonic form of the fundamental mutual reactance of Appendix B. The winding factor is again the product of the pitch and breadth winding factors.

Zig-zag reactance is leakage due to all the air gap harmonics that would be produced if the winding had one slot per pole per phase. For a phase belt of one slot, with each slot carrying the same current and equally separated in time and space phase, the zig-zag reactance alone would be present. Belt leakage occurs because phase belts are actually several slots wide. Zig-zag reactance has harmonic orders higher than seven, with the same form as Xbelt. No even or triplen harmonics will be present.

The fundamental harmonic of the flux yields the magnetizing reactance, Xs, which can be viewed as that required to "energize" the air gap.

$$X_m = \frac{6 \mu_o w N_s l r k_s^2}{\pi g p^2}$$

Figure 46 shows a typical stator slot. The stator slot leakage reactance, summing the self and mutual reactances, is

$$X_{ss} = \frac{18 w \mu_o l N_s^2}{n_s^2} \left( \frac{d2}{w2} + \frac{d_s}{2 w_s} \right) \left( \frac{n_s}{6} + p N_p \right)$$

where ns is the number of stator slots and $N_p$ is the coil throw, in slots. $N_p$ = (CP ns)/(6 p), a result available by manipulation.

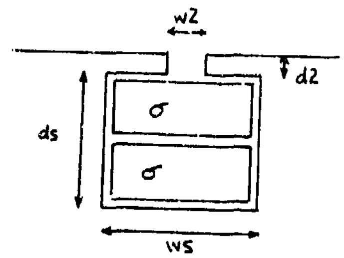



Figure 46. Stator slot diagram

Then,

$$X_{ss} = \frac{3\ w\ \mu_o\ l\ N_s^2}{ns} \left(\frac{d2}{w2} + \frac{ds}{2\ ws}\right)(1 + CP)$$

and

$$ns = \frac{(1 - ls)\ 2\pi\ (r+g)}{ws}$$

where we have traded the need for the knowledge of the number of stator slots for the need to know the width of an individual slot. A reasonable relationship between slot dimensions is d2 = ds and w2 = ws. Then,

$$X_{ss} = \frac{3\ \mu_o\ w\ l\ N_s^2\ ds\ (1 + CP)}{ls\ 2\pi\ (r+g)}$$

The stator end turn leakage reactance may be estimated by treating the two end regions as a single helically shaped winding. If the active region of the machine is ignored and the helix given air core properties, the inductance can be found from standard sources.

$$X_{se} = \frac{-16\ w\ \pi\ \mu_o\ r^2\ \sin^2(\theta_w/2)\ N_r^2}{\theta_w^2\ le\ p^2}\ I_p'\left(\frac{p\pi r}{le}\right) K_p'\left(\frac{p\pi r}{le}\right)$$

where le is the combined length of both end windings.

Presume the winding radius to be r. with helix pitch $\theta_w = \pi/3$ and

$$le = 2\pi r \tan(\pi/3)\, N_p/ns$$

$I_p'$ and $K_p'$ are the first derivatives with respect to their arguments of the hyperbolic Bessel functions $I_p$ and $K_p$. When the three phases are summed, a multiplier of 1.5 will be realized. Finally, using the previous results for $N_p$,

$$Xse = \frac{81\ w\ \mu_o\ N_s^2\ r}{p\pi^2\ CP\ \tan(\pi/3)}\quad I_p'\left(\frac{p\pi r}{le}\right) K_p'\left(\frac{p\pi r}{le}\right)$$

Stator resistance is R1 = (rho lt $N_s$)/($A_s$/$N_s$), as in Appendix B, leading to

$$R1 = \frac{6\ CRHO\ N_s^2\ (1 + \sqrt{(4/3)}\ 2\pi(r+g)\ CP/p)}{SSF\ ds\ \pi\ (r+g)\ ls}$$

When the actual calculation is performed, l is not known. A guess-and-iterate scheme is used. Iteration continues until convergence on l is achieved.

Rotor resistance uses a similar scheme, but the presence of rotor bars and end rings instead of turns changes it somewhat. A model of a rotor bar is below.

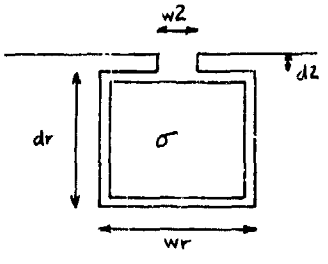



Figure 47. Typical rotor bar configuration

Induction motor transformer models provide a way to find rotor resistances and inductances. The flux density produced by the stator and rotor is

$$B = \frac{\mu_o}{g} (F_s + F_r)$$

The stator mmf is $F_s = -j \frac{3 N_s k_s w_s}{\pi p} I_1$, where $I_1$ is stator current and $w_s$ is slip frequency. Rotor mmf is

$$F_r = -j \frac{w_s r^2}{p^2} \frac{B_r}{Z_s}$$

where $Z_s$ is the rotor surface impedance. The air gap voltage, or voltage across Xm, is defined in terms of the flux density and rotor mmf as

$$Vag = -j \frac{w}{w_s} \frac{2 p l N_s k_s}{r} F_r$$

If rotor mmf is now identified with rotor current referred to the stator winding,

$F_r = -j \frac{3 N_s k_s}{\pi p} I_2$, where $I_2$ is rotor current. Then,

$$Vag = - \frac{Z_s w}{w_s} \frac{6 l N_s^2 k_s^2}{\pi r} I_2$$

Separating $Z_s$ into its real and reactive parts and using a rotor surface model to describe the relation between rotor electric field amplitude and rotor surface current yields

$$R2 = \frac{12 l N_s^2 k_s^2}{nr} r_{slot}$$

$$Xrs = \frac{12 l N_s^2 k_s^2}{nr} x_{slot}$$

$$Xrd = \frac{6 \mu_o w l N_s^2 r k_s^2}{\pi g} \Sigma \left\{ \left(\frac{1}{p+k*nr}\right)^2 + \left(\frac{1}{p-k*nr}\right)^2 \right\}$$

If magnetic diffusion is ignored, end ring resistance can be calculated by comparing losses in the rings and slot. The ratio of current densities is found by the ratio of the areas. This is then squared and multiplied by the ratio of volumes. When summed,

$$R2 = \frac{12\ l\ N_s^2\ k_s^2}{nr}\ r_{slot}\ [1 + \frac{nr\ r\ wr}{\pi\ l\ ler\ p^2}]$$

$r_{slot}$ = CRHO/(dr wr), nr is the number of rotor bars and ler is the end ring length, approximated as ler = $2\pi$ (r - wr/4 - ds/2). The rotor bar width, wr, is found by specifying nr and observing that (nr wr) = ($2\pi$ lr).

Rotor skew leakage arises when the rotor slots are skewed angularly along the axial length to prevent rotor cogging. Then, flux does not fully link the bars. When the effect is integrated over the rotor, it is seen that

$Xskew = Xm\ [1 - (2 \sin(skew/2)/skew)^2]$ with the amount of skew measured in radians. When typical values of skew are input, we see that (Xskew/Xm) ≈ 0.5%. This is a negligible effect and will be ignored.

From the previous rotor bar model, it is seen that

$x_{slot} = w\ \mu_o\ (d2/w2 + dr/2\pi r)$. Assume that d2 = wr/4 and w2 = wr/4. Then $x_{slot} = w\ \mu_o\ (1 + dr/2wr)$.

Fitzgerald et al [23] state that only small errors result if Rc is omitted. Therefore, the core branch may be omitted.

Once the components of the equivalent circuit have been calculated, the designer must turn to power and torque considerations. The internal mechanical power of the machine is

$$P = \frac{(1 - slip)}{slip}\ 3\ I_2^2\ R2$$

The air gap voltage has been previously defined. The terminal voltage, Vt, may be found from Vag by means of a voltage divider and a Thevenin equivalent circuit developed.

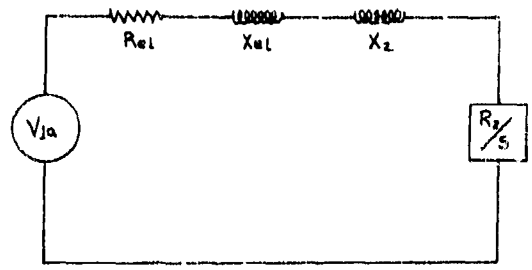



Figure 48. Induction machine Thevenin equivalent circuit

$$V1a = Vt \frac{j\,Xm}{R1 + j(X1 + Xm)}$$

Rel + jXel = (R1 + jX1) in parallel with jXm. Then operating point torque is

$$T = \frac{1}{w} \frac{3\,V1a^2\,(R2/slip)}{(Rel + R2/slip)^2 + (Xel + X2)^2}$$

Torque is a maximum when the power delivered to (R2/slip) is a maximum. By matching load and Thevenin impedances, the power is a maximum and a slip-at-maximum-torque is found

$$s_{max} = \frac{R2}{(Rel^2 + (Xel + X2)^2)^{0.5}}$$

and the corresponding torque is

$$T_{max} = \frac{1}{w} \frac{1.5\,V1a^2}{Rel + (Rel^2 + (Xel + X2)^2)^{0.5}}$$

Typical induction motors have the ratio between maximum and operating point torque as

$$\frac{T}{T_{max}} \approx 0.55$$

which is used to find the machine active length to use in the circuit component calculations. The equation for rated torque can be manipulated to yield a quadratic expression for operating point slip, or a Newton's method convergence can be used to find operating point slip. Convergence on slip and active length through Newton's method is used to generate the machines of this thesis.

Finally, rotor copper losses are (1 - slip)P; stator copper losses are found using $I_1$ and R1.

Table 42. Listing of induction machine design program

```
#include "stdio.h"
#include "def.h"

/* program name:  ind.c for induction machines, 4/19/87 */

long int seed;                  /* start point for random number generator */
double b[26][33], h[11][33], xs[42];
        /* b is "best" array, h is "hold" array, xs are winding factors */
main()
{
double design_point(), rnd_walk(), swf(), ke, kv, minpwr,
        stepsize, random(), abs(), freq, rpm, ks[43];
int p, iteration, i, j, best, print_out(), loops, flag;
FILE *fopen(), *fp;

printf("\nReading input data from IND.DAT . . .");

fp=fopen("ind.dat","r");        /* input seed for random numbers */
fscanf(fp,"%d",&seed);
fscanf(fp, "%d", &p);           /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);     /* input machine power, derived fm ASSET */
minpwr*=746.0;                  /* convert to watts */
fscanf(fp, "%lf", &ke);         /* CERs for Effective Weight */
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);                /* machine max shaft rpm  */
fclose(fp);

printf("\nHow many loops do you want? ");
scanf("%d", &loops);
printf("\n\nDoing program calculations . . .\n");

for (i=1; i < 42; i+=2)                 /* harmonic winding factors   */
        {
        ks[i]=swf(i);
        xs[i] = (ks[i]*ks[i])/(i*i);
        }
freq=rpm*p/60.0;                        /* max electrical frequency */

/*  MAIN BODY OF THE PROGRAM */

for (i=1; i <= loops; ++i)
        {
        printf("\n%d", i);
        stepsize=0.1;
        iteration=0;
        flag = 0;
        design_point(minpwr, p, ke, kv, freq, &flag);
                                        /* put stuff in the hold array */
        if (flag == 1)
                {
                h[0][18] = 10000000.0;
```

```
                best = 0;
                }
        while ((iteration <= 10) && (flag != 1))
                {
                rnd_walk(minpwr, p, stepsize, ke, kv, freq);
                                        /* stagger around */
                best=0;                 /* index to best EW of the lot */
                for (j=1; j<=10; ++j)
                        {
                        if (h[j][18] < 1.0)
                                continue;
                        if (h[j][18] < h[best][18])
                                best=j;         /* find the best machine */
                        }
                if (abs((h[0][18] - h[best][18])/h[0][18]) < 0.005)
                                        /* small improvement in EW */
                        {
                        stepsize/=2.0;
                        ++iteration;
                        }
                else                    /* transfers best to 0 position */
                        {
                        for (j=1; j <= 32; ++j)
                                h[0][j] = h[best][j];
                        }
                }
        for (j=1; j<= 32; ++j)
                b[i][j]=h[best][j];             /* keep the best machine */
        }

best=1;
for (i=1; i <= loops; ++i)
        {
        if (b[i][18] < 1.0)
                continue;
        if (b[i][18] < b[best][18])
                best=i;         /* find and keep the best of the best */
        }
minpwr/=746.0;                          /* turn back into hp */

print_out(best, p, minpwr, ke, kv, rpm);        /* output to disk file */

fp=fopen("ind.dat","w");                /* output seed */
fprintf(fp,"%d", seed);
fprintf(fp,"\n%d", p);
fprintf(fp,"\n%lf", minpwr);
fprintf(fp,"\n%lf", ke);
fprintf(fp,"\n%lf", kv);
fprintf(fp,"\n%lf", rpm);
fclose(fp);
}
/*  END OF MAIN PROGRAM; ALL THAT FOLLOW ARE FUNCTIONS */

double design_point(minpwr, p, ke, kv, freq, fla)
```

```
                                /* determines a random design point */
double minpwr, ke, kv, freq;
int p, *fla;
{
double r, ls, lr, dcore, ds, dr, wr, g, w, wm, l, i2rr,
       r1, r2, xbelt, xzz, xss, xse, x1, xrd, xrs,
       xm, vag, vt, v1a, re1, xe1, tmax, radical, sb, i1a, i1b,
       x2, va, ph, pe, i2r, vol, wt, effcy, ew, le, tminpwr,
       sa, sc, cw, siv, scv, riv, rcv, loa, doa, r2smax, ttmax;
double ler, f1, f2, f3, slip, smax, jr, js,
       i1, i2, xslot, wt_iron;
extern double sqrt(), random(), cos(), sin(), cosh(), sinh(), vrat(),
       floor(), besip(), beskp(), tan(), find_siv(), swf();
int cslip=0, nr=71, ccr=1, ccg, ccs=1, k;
w=2*PI*freq;                    /* synchronous frequency in rad per sec */
wm=w/p;                         /* mech angular velocity in rad per sec */
l = 10.0;                       /* initial guess on length */
tmax = minpwr/(wm*PSI);         /* pull-out torque */

while (cslip != 1)
       {
       r=random()*RMAX;
       if ((2*PI*r*freq/p) < MAX_TIP_SPEED)  /* check rotor tip speed */
              break;
       }
lr=random()*0.5 + 0.25;         /* rotor slot factor */
dr=random()*r/3.0;              /* slot no deeper than 33% of rotor radius */
dcore=(BR*r)/(BSAT*p);          /* back iron depth */
ds=random()*0.9*dcore;          /* slot depth < 90% of body depth to start */
g=random()*(0.1*r - GMIN) + GMIN;
if (g < GMIN)
       g = GMIN;
ls=random()*0.5 + 0.25;         /* stator slot factor */
f1=0.;
f2=0.;
f3=0.;
for (k=1; k < 100; ++k)
       {
       f1 = (1./(p + k*nr)) * (1./(p + k*nr));
       f2 = (1./(p - k*nr)) * (1./(p - k*nr));
       f3 += f1 + f2;
       }
while (ccr <= 5)                /* start convergence loop on r */
{
if (ccs > 5)                    /* we've had trouble with jr */
       {
       r *= jr/JSMAX;
       if (r > (MAX_TIP_SPEED*p/w))
              r = MAX_TIP_SPEED*p/w;
       if (r > RMAX)
              r = RMAX;
       lr *= jr/JSMAX;
       if (lr > 0.75)
              lr = 0.75;
```

```
	}
wr = (8*PI*lr*(r - dr/2.))/(4*nr + PI*lr);	/* rotor slot width */
ler = 2*PI*(r - wr/4.0 - dr/2.0);	/* end ring length */

ccs = 1;
while (ccs <= 5)		/* start convergence loop on ds and dr */
{
ccg = 1;
while (ccg <= 10)		/* start convergence loop on length */
	{
	r1 = (6*CRHO*(1 + 2.3094*PI*(r+g)*CP/p))/(SSF*ds*PI*(r+g)*ls);
	r2 = (6*xs[1]*CRHO*l*(1 + (2*r*r*lr)/(ler*p*p)))/(PI*r*lr*dr);
	xbelt = (6*w*l*MU*r*(xs[5] + xs[7])/(PI*g*p*p));
	xzz = (6*w*l*MU*r*(xs[11] + xs[13] + xs[17] + xs[19] + xs[23] +
		xs[29] + xs[31] + xs[37] + xs[41]))/(PI*g*p*p);
	xss = (3*MU*w*l*ds*(1+CP))/(ls*2*PI*(r+g));
	le = (PI*r*CP*tan(PI/3))/(3*p);
	xse = (27*w*l*MU*r*r*(-beskp(p, p*PI*r/le)*besip(p, p*PI*r/le)))/
			(PI*le*p*p);
	x1 = xbelt + xzz + xss + xse;
	xrd = (6*MU*w*l*xs[1]*r*f3)/(PI*g);
	xrs = (6*xs[1]*w*l*MU*(wr+0.5*dr))/(lr*PI*(r - (dr/2.0) - (wr/8.0)));
	x2 = xrd + xrs;
	xm = (6*MU*w*l*r*xs[1])/(PI*g*p*p);
	vag = 2*r*BR*w*l*swf(1)/p;		/* air gap voltage */
	re1 = (xm*xm*r1)/(r1*r1 + (x1+xm)*(x1+xm));
				/* thev equiv resistance */
	xe1 = (xm*(r1*r1 + x1*x1 + x1*xm))/(r1*r1 + (x1+xm)*(x1+xm));
				/* thev equiv inductance */
	r2smax = sqrt(re1*re1 + (xe1+x2)*(xe1+x2));	/* r2 at smax */
	vt = vag/vrat(r2smax, x2, x1, xm, r1);
				/* terminal voltage at smax */
	v1a = (vt*xm)/sqrt((x1 + xm)*(x1 + xm) + (r1*r1));
				/* thevenin equivalent voltage */
	ttmax = (1.5*v1a*v1a)/(wm*(re1+sqrt(re1*re1+(xe1+x2)*(xe1+x2))));
		/* test maximum torque */
	if (abs((tmax-ttmax)/tmax) <= 0.005)
		break;			/* we have convergence */
	l *= tmax/ttmax;		/* reset l, reiterate */
	++ccg;
	if (ccg > 10)
		{
		*fla = 1;
		printf("\n flag set on length");
		return;
		}
	}				/* end convergence loop on length */

smax = r2/sqrt(re1*re1 + (xe1+x2)*(xe1+x2));
slip = smax/3.0;		/* starting point for slip converge */
cslip = 1;
while (cslip <= 20)
	{			/* start convergence loop on slip */
```

```
        tminpwr = (3*vla*vla*r2/slip)/((rel+r2/slip)*(rel+r2/slip) +
                (xel+x2)*(xel+x2));
        if (abs((minpwr-tminpwr)/minpwr) <= 0.005)
                break;                  /* we have convergence */
        slip *= tminpwr/minpwr;
        ++cslip;
        }                               /* end convergence loop on slip */

i2 = vag*sqrt((r2/slip)*(r2/slip) + x2*x2)/((r2/slip)*(r2/slip) + x2*x2);
jr = (3*i2)/(PI*l*r*dr*r*RSF);             /* rotor current density */
if (jr > JSMAX)
        {
        dr *= jr/JSMAX;
        if (dr > (r/3))
                dr = r/3;               /* reset to limit */
        }
i1a = (r2/slip)*(xm+x2) - x2*r2/slip;
i1b = x2*(xm+x2) + (r2/slip)*(r2/slip);
i1 = vag*sqrt(i1a*i1a + i1b*i1b)/(xm*(x2*x2 + (r2/slip)*(r2/slip)));
js = (3.0*i1)/(PI*(r+g)*ds*ls*SSF);
if (js > JSMAX)
        ds *= js/JSMAX;
if ((js <= JSMAX) && (jr <= JSMAX))
        break;
++ccs;
}                               /* end convergence loop on ds and dr */
if (ccs <= 5)
        break;
++ccr;
if (ccr > 5)
        {
        *fla = 1;
        printf("\n flag set on r");
        return;
        }
}                               /* end convergence loop on r */

                        /* calculations */

smax = r2/sqrt(rel*rel + (xel+x2)*(xel+x2));
siv = find_siv(l, r, g, ds, dcore, ls);         /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                     /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(l + 2.3094*PI*(r+g)*CP/p);
                                                /* stator copper volume */
rcv = wr*dr*(nr*l + 2*ler);                     /* rotor copper volume */
cw = (rcv + scv)*DCU;                           /* total copper weight */
loa = l + 4*(r+g);                              /* length-over-all */
doa = 2*(r+g+ds+dcore);                         /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);                /* machine envelope volume */
wt = WTALL*(cw + D*(BRNGS*riv + siv));          /* machine weight in kg */
wt_iron = D*(riv + siv);                        /* iron weight only */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;      /* hysteresis loss in watts, uses iron weight of
machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
```

```
       /* eddy current loss in watts, uses iron weight of machine */
i2r=3.0*il*il*rl;               /* stator copper loss in watts */
i2rr = slip*minpwr;             /* rotor copper loss in watts */
vt = sqrt((vag+il*rl)*(vag+il*rl) + (il*xl)*(il*xl));   /* rated voltage */
va = 3*vt*il;                   /* VA rating at terminals */
effcy=(minpwr)/(minpwr + ph + pe + i2r + i2rr); ew=wt + ke*(1-effcy) + kv*vol;          /* Ef-
fective weight */

h[0][1]=il;     h[0][2]=freq;   h[0][3]=w;      h[0][4]=r;      h[0][5]=g;
h[0][6]=dcore;  h[0][7]=ds;     h[0][8]=dr;     h[0][9]=ls;     h[0][10]=lr;
h[0][11]=vol;   h[0][12]=wt;    h[0][13]=ph;    h[0][14]=pe;    h[0][15]=i2r;
h[0][16]=va;    h[0][17]=effcy; h[0][18]=ew;    h[0][19]=l;     h[0][20]=i2rr;
h[0][21]=smax;  h[0][22]=tmax;  h[0][23]=vt;    h[0][24]=slip;  h[0][25]=vag;
h[0][26]=rl;    h[0][27]=xl;    h[0][28]=xm;    h[0][29]=x2;    h[0][30]=r2;
h[0][31]=loa;   h[0][32]=doa;
       /* this section just changed all the variables in the "hold" array */

return;
}



double rnd_walk(minpwr, p, stepsize, ke, kv, freq)
                        /* walks about design_point 10 times */
       double stepsize, minpwr, ke, kv, freq;
       int p;
{
double r, ls, lr, dcore, ds, dr, wr, g, w, wm, l, i2rr, ila, ilb,
       rl, r2, xbelt, xzz, xss, xse, xl, xrd, xrs, r2smax, ttmax,
       xm, vag, vt, vla, rel, xel, tmax, radical, sb, tminpwr,
       x2, va, ph, pe, i2r, vol, wt, effcy, ew, le, cw, siv, scv,
       sa, sc, riv, rcv, loa, doa, jr, js,
       ler, f1, f2, f3, slip, smax, il, i2, xslot, wt_iron;
extern double sqrt(), random(), cos(), sin(), cosh(), sinh(), vrat(),
       besip(), beskp(), tan(), find_siv(), swf();
int d, i=1, ccg, ccr, ccs, nr=71, k, cslip;
f1=0.;
f2=0.;
f3=0.;
for (k=1; k < 100; ++k)
       {
       f1 = (1./(p + k*nr)) * (1./(p + k*nr));
       f2 = (1./(p - k*nr)) * (1./(p - k*nr));
       f3 += f1 + f2;
       }
while (i <= 10)                 /* ten steps around the design point */
       {
       /* read in the walk around the design point */
       w=2*PI*freq;
       r=h[0][4]*(1 + stepsize*(random() - 0.5));
       if ((w*r/p) > MAX_TIP_SPEED)
              continue;               /* go to next i-loop if violated */
       g=h[0][5]*(1 + stepsize*(random() - 0.5));
              if (g < GMIN)
```

```
                    g=GMIN;             /* reset to the limit */
          dcore=(BR*r)/(BSAT*p);        /* most efficient use of iron */
          ds=h[0][7]*(1 + stepsize*(random() - 0.5));
          dr=h[0][8]*(1 + stepsize*(random() - 0.5));
          if (dr > r/3.0)
                dr = r/3.0;             /* reset to the limit */
          ls=h[0][9]*(1 + stepsize*(random() - 0.5));
                if (ls > 0.75)
                      ls=0.75;          /* reset to the limit */
                if (ls < 0.25)
                      ls=0.25;
          lr=h[0][10]*(1 + stepsize*(random() - 0.5));
                if (lr > 0.75)
                      lr=0.75;          /* reset to the limit */
                if (lr < 0.25)
                      lr=0.25;

  wm=w/p;                           /* mech angular velocity in rad per sec */
  l = h[0][19];                             /* length starting point */
  tmax = h[0][22];                          /* pull-out torque */

  ccs = 1;
  ccr = 1;                  /* first time thru, no adj in r */
  while (ccr <= 5)                  /* start convergence loop on r */
  {
  if (ccs > 5)
        {
         r *= jr/JSMAX;
         if (r > (MAX_TIP_SPEED*p/w))
                r = MAX_TIP_SPEED*p/w;
         if (r > RMAX)
                r = RMAX;
        lr *= jr/JSMAX;
         if (lr > 0.75)
                lr = 0.75;
        }
  wr = (8*PI*lr*(r - dr/2.))/(4*nr + PI*lr);      /* rotor slot width */
  ler = 2*PI*(r - wr/4.0 - dr/2.0);               /* end ring length */
  ccs = 1;
  while (ccs <= 5)              /* start convergence loop on ds and dr*/
         {
         ccg = 1;
         while (ccg <= 10)                 /* start convergence loop on length */
        {
        r1 = (6*CRHO*(1 + 2.3094*PI*(r+g)*CP/p))/(SSF*ds*PI*(r+g)*ls);
        r2 = (6*xs[1]*CRHO*l*(1 + (2*r*r*lr)/(ler*p*p)))/(PI*r*lr*dr);
        xbelt = (6*w*l*MU*r*(xs[5] + xs[7])/(PI*g*p*p));
        xzz = (6*w*l*MU*r*(xs[11] + xs[13] + xs[17] + xs[19] + xs[23] +
              xs[29] + xs[31] + xs[37] + xs[41]))/(PI*g*p*p);
        xss = (3*MU*w*l*ds*(1+CP))/(ls*2*PI*(r+g));
        le = (PI*r*CP*tan(PI/3))/(3*p);
        xse = (27*w*l*MU*r*r*(-beskp(p, p*PI*r/le)*besip(p, p*PI*r/le)))/
                    (PI*le*p*p);
        xl = xbelt + xzz + xss + xse;
```

```
        xrd = (6*MU*w*l*xs[1]*r*f3)/(PI*g);
        xrs = (6*xs[1]*w*l*MU*(wr+0.5*dr))/(lr*PI*(r - (dr/2.0) - (wr/8.0)));
        x2 = xrd + xrs;
        xm = (6*MU*w*l*r*xs[1])/(PI*g*p*p);

        vag = 2*r*BR*w*l*swf(1)/p;              /* air gap voltage */
        rel = (xm*xm*r1)/(r1*r1 + (x1+xm)*(x1+xm));
                                        /* thev equiv resistance */
        xel = (xm*(r1*r1 + x1*x1 + x1*xm))/(r1*r1 + (x1+xm)*(x1+xm));
                                        /* thev equiv inductance */
        r2smax = sqrt(rel*rel + (xel+x2)*(xel+x2));     /* r2 at smax */
        vt = vag/vrat(r2smax, x2, x1, xm, r1);
                                        /* terminal voltage at smax */
        v1a = (vt*xm)/sqrt((x1 + xm)*(x1 + xm) + (r1*r1));
                                        /* thevenin equivalent voltage */
        ttmax = (1.5*v1a*v1a)/(wm*(rel+sqrt(rel*rel+(xel+x2)*(xel+x2))));
                /* test maximum torque */
        if (abs((tmax-ttmax)/tmax) <= 0.005)
                {
                ccg = 1;
               break;                   /* we have convergence */
                }
        l *= tmax/ttmax;                /* reset l, reiterate */
        ++ccg;
        }                               /* end convergence loop on length */
        if (ccs > 5)
        break;
        smax = r2/sqrt(rel*rel + (xel+x2)*(xel+x2));
        slip = smax/3.0;
                                          /* starting point for slip converge */
        cslip = 1;
        while (cslip <= 20)
        {                                /* start convergence loop on slip */
        tminpwr = (3*v1a*v1a*r2/slip)/((rel+r2/slip)*(rel+r2/slip) +
                (xel+x2)*(xel+x2));
        if (abs((minpwr-tminpwr)/minpwr) <= 0.005)
                break;                   /* we have convergence */
        slip *= tminpwr/minpwr;
        ++cslip;                        /* no more than 20 tries */
        }                       /* end convergence loop on slip */

i2 = vag*sqrt((r2/slip)*(r2/slip) + x2*x2)/((r2/slip)*(r2/slip) + x2*x2);
jr = (3*i2)/(PI*lr*dr*r*RSF);                   /* rotor current density */
if (jr > JSMAX)
        {
        dr *= jr/JSMAX;
        if (dr > (r/3))
                dr = r/3;               /* reset to limit */
        }
i1a = (r2/slip)*(xm+x2) - x2*r2/slip;
i1b = x2*(xm+x2) + (r2/slip)*(r2/slip);
i1 = vag*sqrt(i1a*i1a + i1b*i1b)/(xm*(x2*x2 + (r2/slip)*(r2/slip)));
js = (3.0*i1)/(PI*(r+g)*ds*ls*SSF);
if (js > JSMAX)
```

```
        ds *= js/JSMAX;
if ((js <= JSMAX) && (jr <= JSMAX))
        break;
++ccs;
}                               /* end convergence loop on ds and dr */
if ((ccs <= 5) || (ccg > 10))
        break;
++ccr;
}                               /* end convergence loop on r */

if ((ccg > 10) || (ccs > 5) || (cslip > 20) || (ccr > 5))
        {                       /* no design convergence */
        for (d=i; d <=10; ++d)
                h[d][18] = 10000000.0;
        printf("burp ");
        break;
        }
                        /* calculations */
smax = r2/sqrt(rel*rel + (xel+x2)*(xel+x2));
siv = find_siv(l, r, g, ds, dcore, ls);         /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                     /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(1 + 2.3094*PI*(r+g)*CP/p);
                                                /* stator copper volume */
rcv = wr*dr*(nr*l + 2*ler);                     /* rotor copper volume */
cw = (rcv + scv)*DCU;                           /* total copper weight */
loa = l + 4*(r+g);                              /* length-over-all */
doa = 2*(r+g+ds+dcore);                         /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);                /* machine envelope volume */
wt = WTALL*(cw + D*(BRNGS*riv + siv));          /* machine weight in kg */
wt_iron = D*(riv + siv);                        /* iron weight only */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;      /* hysteresis loss in watts, uses iron weight of
machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */
i2r = 3.0*i1*i1*r1;             /* stator copper loss in watts */
i2rr = slip*minpwr;             /* rotor copper loss in watts */
vt = sqrt((vag+i1*r1)*(vag+i1*r1) + (i1*x1)*(i1*x1));   /* rated voltage */
va = 3*vt*i1;                   /* VA rating at the terminals */
effcy=(minpwr)/(minpwr + ph + pe + i2r + i2rr); ew=wt + ke*(1-effcy) + kv*vol;                /* Ef-
fective weight */

h[i][1]=i1;     h[i][2]=freq;   h[i][3]=w;      h[i][4]=r;      h[i][5]=g;
h[i][6]=dcore;  h[i][7]=ds;     h[i][8]=dr;     h[i][9]=ls;     h[i][10]=lr;
h[i][11]=vol;   h[i][12]=wt;    h[i][13]=ph;    h[i][14]=pe;    h[i][15]=i2r;
h[i][16]=va;    h[i][17]=effcy; h[i][18]=ew;    h[i][19]=l;     h[i][20]=i2rr;
h[i][21]=smax;  h[i][22]=tmax;  h[i][23]=vt;    h[i][24]=slip;  h[i][25]=vag;
h[i][26]=r1;    h[i][27]=x1;    h[i][28]=xm;    h[i][29]=x2;    h[i][30]=r2;
h[i][31]=loa;   h[i][32]=doa;
        /* this section just changed all the variables in the "hold" array */
        ++i;
        }

return;
}
```

```
print_out(best, p, minpwr, ke, kv, rpm)
        int best, p;
        double minpwr, ke, kv, rpm;
{
char outfile[14];
FILE *fpo, *fopen();
int i;

printf("\nWhat is the name of the file where you want the output? ");
scanf("%s", outfile);

fpo=fopen(outfile, "w");


fprintf(fpo,"%d", p);
fprintf(fpo,"\n%lf", minpwr);
fprintf(fpo,"\n%lf", ke);
fprintf(fpo,"\n%lf", kv);
fprintf(fpo,"\n%lf", rpm);
for (i=1; i <= 32; ++i)
        fprintf(fpo,"\n%e",b[best][i]);
fprintf(fpo, "\n");
fclose(fpo);
}


double find_siv(l, r, g, ds, dcore, ls)
        double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}

double vrat(r2smax, x2, x1, xm, r1)     /* ratio of vag/vt */
        double r2smax, x2, x1, xm, r1;
{
double a, b, c, d, vrat;
extern double sqrt();

a = r2smax*(xm+x1) + r1*(x2+xm);
b = r1*r2smax - xm*x2 - x1*(x2+xm);
c = a*r2smax - b*x2;
d = b*r2smax + a*x2;

vrat = (xm*sqrt(c*c + d*d))/(a*a + b*b);
return(vrat);}
```

Table 43. Listing of induction efficiency program

```
#include "stdio.h"
#include "def.h"

/*  program name:  ieff.c to find efficiency of induction machines */
/*       works with a single machine */
main()
{
FILE *fopen(), *fp;
double r, ls, lr, dcore, ds, dr, q, w, i, i2rr, va, ph, pe, i2r, vol,
        wt, effcy, ew, siv, riv, wt_iron, find_siv(), pmeff, pgeff, teff,
        pmrpm, geff=0.98, pceff=0.99, gr, dhp, rpm, minpwr, ke, kv, freq,
        sgeff=1.0, wr, wm, r1, r2, x1, xm, vag, vt, v1a, rei, xel, radical,
        x2, sa, sb, sc, slip, slip1, slip2, smax, i1, i2, tmax;
extern double sqrt();
int e=0, f, p, i;
char infile[14];
printf("\nCalculates efficiency for a single machine.\n");

while (e != 1)
{
f = 0;
printf("What is the name of the input file? ");
scanf("%s", infile);
fp = fopen(infile, "r");
fscanf(fp, "%d", &p);             /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);
minpwr *= 746.0;          /* now in watts */
fscanf(fp, "%lf", &ke);
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);
fscanf(fp, "%lf", &i1);
fscanf(fp, "%lf", &freq);
fscanf(fp, "%lf", &w);
fscanf(fp, "%lf", &r);
fscanf(fp, "%lf", &q);
fscanf(fp, "%lf", &dcore);
fscanf(fp, "%lf", &ds);
fscanf(fp, "%lf", &dr);
fscanf(fp, "%lf", &ls);
fscanf(fp, "%lf", &lr);
fscanf(fp, "%lf", &vol);
fscanf(fp, "%lf", &wt);
fscanf(fp, "%lf", &ph);
fscanf(fp, "%lf", &pe);
fscanf(fp, "%lf", &i2r);
fscanf(fp, "%lf", &va);
fscanf(fp, "%lf", &effcy);
fscanf(fp, "%lf", &ew);
fscanf(fp, "%lf", &l);
fscanf(fp, "%lf", &i2rr);
fscanf(fp, "%lf", &smax);
```

```
fscanf(fp, "%lf", &tmax);
fscanf(fp, "%lf", &vt);
fscanf(fp, "%lf", &slip);
fscanf(fp, "%lf", &vag);
fscanf(fp, "%lf", &r1);
fscanf(fp, "%lf", &x1);
fscanf(fp, "%lf", &xm);
fscanf(fp, "%lf", &x2);
fscanf(fp, "%lf", &r2);
fclose(fp);

while (f != 1)
{
printf("\nWhat is the sustained speed machine horsepower? ");
scanf("%lf", &dhp);
dhp *= 746.0;
printf("What is the sustained speed machine rpm? ");
scanf("%lf", &pmrpm);
freq = pmrpm*p/60.0;                          /* PM frequency */

v1a = (vt*xm)/sqrt((x1 + xm)*(x1 + xm) + (r1*r1));
                                              /* thevinin equivalent voltage */
re1 = (xm*xm*r1)/(r1*r1 + (x1+xm)*(x1+xm));
                                              /* thev equiv resistance */
xe1 = (xm*(r1*r1 + x1*x1 + x1*xm))/(r1*r1 + (x1+xm)*(x1+xm));
                                              /* thev equiv inductance */
sa = re1*re1 + (xe1+x2)*(xe1+x2); /* pieces of slip quadratic */
sb = 2*re1*r2 - (3*1*v1a*v1a*r2/dhp);
sc = r2*r2;
radical = sb*sb - 4*sa*sc;
if (radical < 0.0)
        abort("\nGot a negative radical in the slip eqn.");
slip1 = (-sb + sqrt(radical))/(2*sa);
slip2 = (-sb - sqrt(radical))/(2*sa);
if ((slip1 < 0.0) && (slip2 < 0.0))
        abort("\nTwo negative slips.");
                        /* now we will use the smallest positive slip */
else if ((slip1 < 0.0) && (slip2 > 0.0))
        slip = slip2;
else if ((slip1 > 0.0) && (slip2 < 0.0))
        slip = slip1;
else
        slip = (slip1 > slip2) ? slip2 : slip1;
                                                  /* tslip=min(slip1, slip2) */
if (slip > smax)
        abort("\n slip is more than smax.");
siv = find_siv(l, r, g, ds, dcore, ls);           /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                       /* rotor iron volume */
wt_iron = D*(riv + siv);                      /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
        /* hysteresis loss in watts, uses iron weight of machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
        /* eddy current loss in watts, uses iron weight of machine */
```

```
i2 = sqrt((slip*dhp)/(3*r2*(1-slip)));            /* load current */
i1 = i2 + vag/xm;                         /* i2 plus magnetizing current */

i2r=3.0*i1*i1*r1;                         /* stator copper loss in watts */
i2rr = slip*dhp;                /* rotor copper loss in watts */
pmeff = dhp/(dhp + ph + pe + i2r + i2rr);
printf("\n   Sustained efficiency is %lf", pmeff);

printf("\n\nWhat is the endurance speed machine horsepower? ");
scanf("%lf", &dhp);
dhp *= 746.0;
printf("What is the endurance speed machine rpm? ");
scanf("%lf", &pmrpm);
freq = pmrpm*p/60.0;                      /* PM frequency */
sb = 2*rel*r2 - (3*l*vla*vla*r2/dhp);
radical = sb*sb - 4*sa*sc;
if (radical < 0.0)
        abort("\nGot a negative radical in the slip eqn.");
slip1 = (-sb + sqrt(radical))/(2*sa);
slip2 = (-sb - sqrt(radical))/(2*sa);
if ((slip1 < 0.0) && (slip2 < 0.0))
        abort("\nTwo negative slips.");
else if ((slip1 < 0.0) && (slip2 > 0.0))
        slip = slip2;
else if ((slip1 > 0.0) && (slip2 < 0.0))
        slip = slip1;
else
        slip = (slip1 > slip2) ? slip2 : slip1;
if (slip > smax)
        abort("\n slip is more than smax.");
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
i2 = sqrt((slip*dhp)/(3*r2*(1-slip)));            /* load current */
i1 = i2 + vag/xm;                         /* i2 plus magnetizing current */
i2r=3.0*i1*i1*r1;                         /* stator copper loss in watts */
i2rr = slip*dhp;                /* rotor copper loss in watts */
pmeff = dhp/(dhp + ph + pe + i2r + i2rr);
printf("\n   Endurance efficiency is %lf", pmeff);

printf("\nSame machine? ");
scanf("%d", &f);
if (f == 0)
        continue;
else if (f == 2)
        {
        e = 1;
        break;
        }
}               /* end of f-loop */
}               /* end of e-loop */
}               /* end of main program */


double find_siv(l, r, g, ds, dcore, ls)
```

```
        double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}
```

## Appendix E. Weight and volume algorithms

The ability to correctly characterize a new naval ship technology depends in part on the ability to calculate the weight and volume associated with that technology. Algorithms for this purpose were taken from a variety of sources, including the Advanced Surface Ship Evaluation Tool (ASSET) theory manuals. The ASSET algorithms are the result of data analysis for naval ships that have been constructed, as well as studies for other ship designs.

The Ship Work Breakdown Structure (SWBS) categorizes all ship weights. The general categories are:

| | |
|---|---|
| W100 | Ship structures |
| W200 | Propulsion plant |
| W300 | Electric generation plant |
| W400 | Command and control equipment |
| W500 | Auxiliaries and distributed systems |
| W600 | Outfit and furnishings |
| W700 | Ship armament |
| WF00 | Ship Loads |

Within W200 are several sub-groups that pertain to electric propulsion. They are:

| | |
|---|---|
| W235 | Electric propulsion devices |
| W235.1 | Propulsion motors |
| W235.2 | Propulsion generators |
| W235.3 | Transmission lines and propulsion cables |
| W235.4 | Cooling systems |
| W235.5 | Switchgear |
| W241.1 | Locked-train-double-reduction reduction gears |
| W242 | Propulsion clutches and couplings |
| W243 | Shafting |
| W244 | Propulsion shaft bearings |
| W245 | Propeller weight |

ASSET allows SWBS groups to be adjusted in weight, which allows technology sensitivity analyses, such as this thesis, to be performed. Only a few of the W235 sub-groups need to be calculated outside of ASSET and adjusted within ASSET. These are W235.1, W235.2, W235.4, W235.5, W241.1, and W243. The W235.1 and W235.2 weights and volumes were calculated as part of the machine design. The rest of the needed W235 weights were calculated in "wt.c", a copy of which follows. These algorithms are the U. S. Navy standard, and were verified against actual ships and components.

Shafting and transmission line weights are dependent on motor and generator positions within a ship. Their weights and volumes were calculated from ASSET equations, using the layouts of the baseline and variant ships.

Where no volume equation was found in the ASSET documentation, or where the result of such an equation was unrealistic, a literature search generally found enough actual equipment to permit a relationship to be empirically determined. A linear scaling of such volumes provided adequate results.

Table 44. Listing of off-line weight and volume program

```c
#include "stdio.h"

#define         K       150.75          /* gear hardness factor */

        /* program name:  wt.c, to find the weights of SWBS groups */

main()
{
FILE *fp, *fopen();
double xg, xm, zg, zm, pa, ng, nm, grm, grg, np, dhp, gn, ds, q, ne,
        w235, w2353, w2354, w2355, w241=0.0, w243, w298=0.0, xprop,
        wpc, vpc, ppc, wexc, vexc, wbrk, vbrk, pm, v235,
        v2353=0.0, v2354=0.0, v2355, v241, v243;
extern double sqrt(), pow();

printf("\nThis program calculates SWBS 200 weights for screen output.");
printf("\n\nWhat is the LCG of the propulsion generator(s)? ");
scanf("%lf", &xg);
printf("What is the LCG of the propulsion motor(s)? ");
scanf("%lf", &xm);
printf("What is the VCG of the propulsion generator(s)? ");
scanf("%lf", &zg);
printf("What is the VCG of the propulsion motor(s)? ");
scanf("%lf", &zm);
printf("What is the number of propulsion generator(s)? ");
scanf("%lf", &ng);
printf("What is the number of propulsion motor(s)? ");
scanf("%lf", &nm);
printf("What is the number of gas turbines aboard? ");
scanf("%lf", &ne);
printf("What is the rated horsepower of each gas turbine? ");
scanf("%lf", &pa);
printf("What is the propeller rpm? ");
scanf("%lf", &np);
printf("How much horsepower is delivered to each propeller? ");
scanf("%lf", &dhp);
printf("What is the LCG of the propeller? ");
scanf("%lf", &xprop);
printf("What is the gear ratio at the propulsion motor? ");
scanf("%lf", &grm);
printf("What is the gear ratio at the propulsion generator? ");
scanf("%lf", &grg);

/* W235.3 Transmission lines */
w2353 = 0.000009*(xm-xg+zg-zm+27)*(pa*746/30000); /* LT, enhanced */
v2353 = 0.06545*(xm-xg+zg-zm+27);       /* cubic feet, enhanced */

/* W235.4 Cooling systems */
w2354 = 0.26*pa*ng/2240;                                /* LT */
v2354 = 100.0*ng;                       /* swag */
```

```
/* W235.5 Switch gear */
w2355 = 0.26*(ng + 2*nm); /* enhanced ASSET, LT */
v2355 = 45.0*w2355;              /* switchgear volume, ft^3, enhanced */

ppc = 0.000939523*pa/nm;    /* power converter rating, MW, enhanced ASSET */
wpc = nm*3.55*ppc/12;            /* weight pwr conv, LT, enhanced ASSET */
vpc = nm*540*ppc/12;             /* vol pwr conv, LT, enhanced ASSET */

pm = pa*746/1000000;             /* motor rating in MW */
wexc = (ne + nm)*pow((pm/30), 0.3);        /* weight of exciters, LT, enhanced */
vexc = 70*wexc;                  /* vol of exciters, ft^3 */
wbrk = 0.26*pm*nm;               /* weight of braking resistors, LT, enhanced */
vbrk = 37*pm*nm;          /* vol of resistors, ft^3, enhanced */


w235 = w2353 + w2354 + w2355 + wpc + wexc + wbrk;
v235 = v2353 + v2354 + v2355 + vpc + vexc + vbrk;

/* W241 locked-train double reduction gears */
if (grg != 1.0)           /* there are pg gears, btw gt and pg */
        w241 = (1.57*pa*pow((grg+1), 3.0)*ng)/(3600*grg*grg*grg*K);
if (grm != 1.0)           /* there are pm gears, btw pm and propeller */
        w241 += (1.57*dhp*pow((grm+1), 3.0)*nm)/(np*grm*grm*K);        /* LT */
v241 = w241*34.612;              /* cubic feet, ratioed fm FFG7 */

/* W243 Shafting */
ds = 2.152*pow((4.22347*dhp/np), 0.333);   /* shaft diam, sq inches */
w243 = 1.5708*ds*ds*2*(xprop - xm - 1.0)/2240;                   /* LT */
v243 = 0.01091*ds*ds*(xprop - xm - 6.0);                   /* ft^3 */

/* W298.1  LTDR operating fluids, additon to wt in ASSET */
if (grg != 1.0)
        w298 = 0.27*pa*ng/2240;
if (grm != 1.0)
        w298 += 0.27*pa*nm/2240;                           /* LT */

printf("\n\nW235.3 Transmission lines   %7.2lf LT  %7.2lf ft^3", w2353, v2353);
printf("\nW235.4 Cooling systems      %7.2lf LT  %7.2lf ft^3", w2354, v2354);
printf("\nW235.5 Switchgear           %7.2lf LT  %7.2lf ft^3", w2355, v2355);
printf("\n       Power converters     %7.2lf LT  %7.2lf ft^3", wpc, vpc);
printf("\n       Exciters             %7.2lf LT  %7.2lf ft^3", wexc, vexc);
printf("\n       Braking resistors    %7.2lf LT  %7.2lf ft^3", wbrk, vbrk);
printf("\n\nW235 Electric propulsion    %7.2lf LT  %7.2lf ft^3, less PGs and PMs", w235, v235);
printf("\nW241 Reduction gears        %7.2lf LT  %7.2lf ft^3", w241, v241);
printf("\nW243 Shafting               %7.2lf LT  %7.2lf ft^3", w243, v243);
printf("\nW298 Gear operating fluid   %7.2lf LT\n\n", w298);
}
```

## Appendix F. Advanced Surface Ship Evaluation Tool output

The output of ASSET is in text and graphic form. The total text output for any particular synthesis run is more than thirty pages. Following are several graphic outputs of ASSET, showing the mechanical and electrical transmission ships used in this thesis.

Figure 49. Hull isometric view of all ships

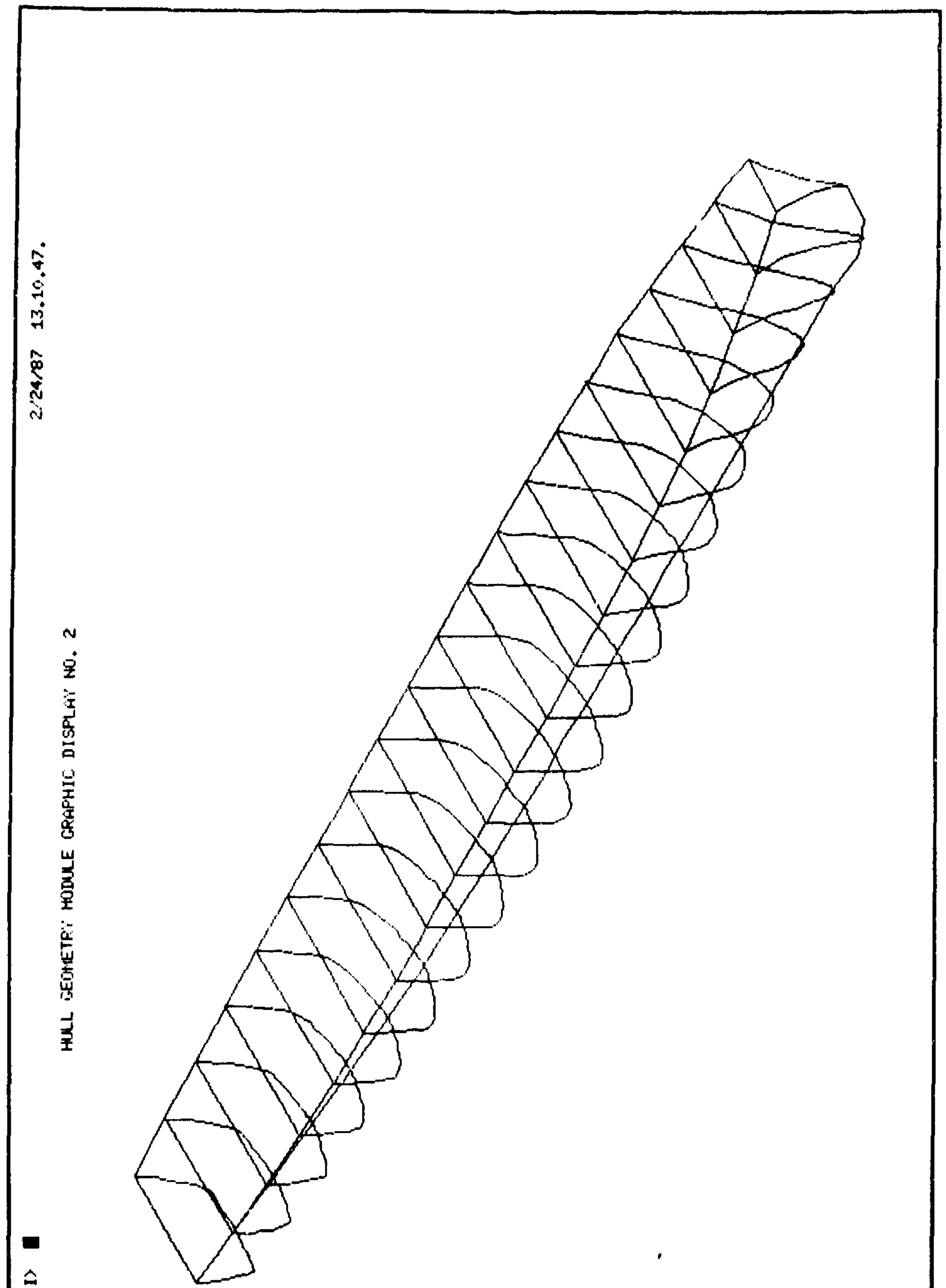


Figure 50. Body plan of all ships

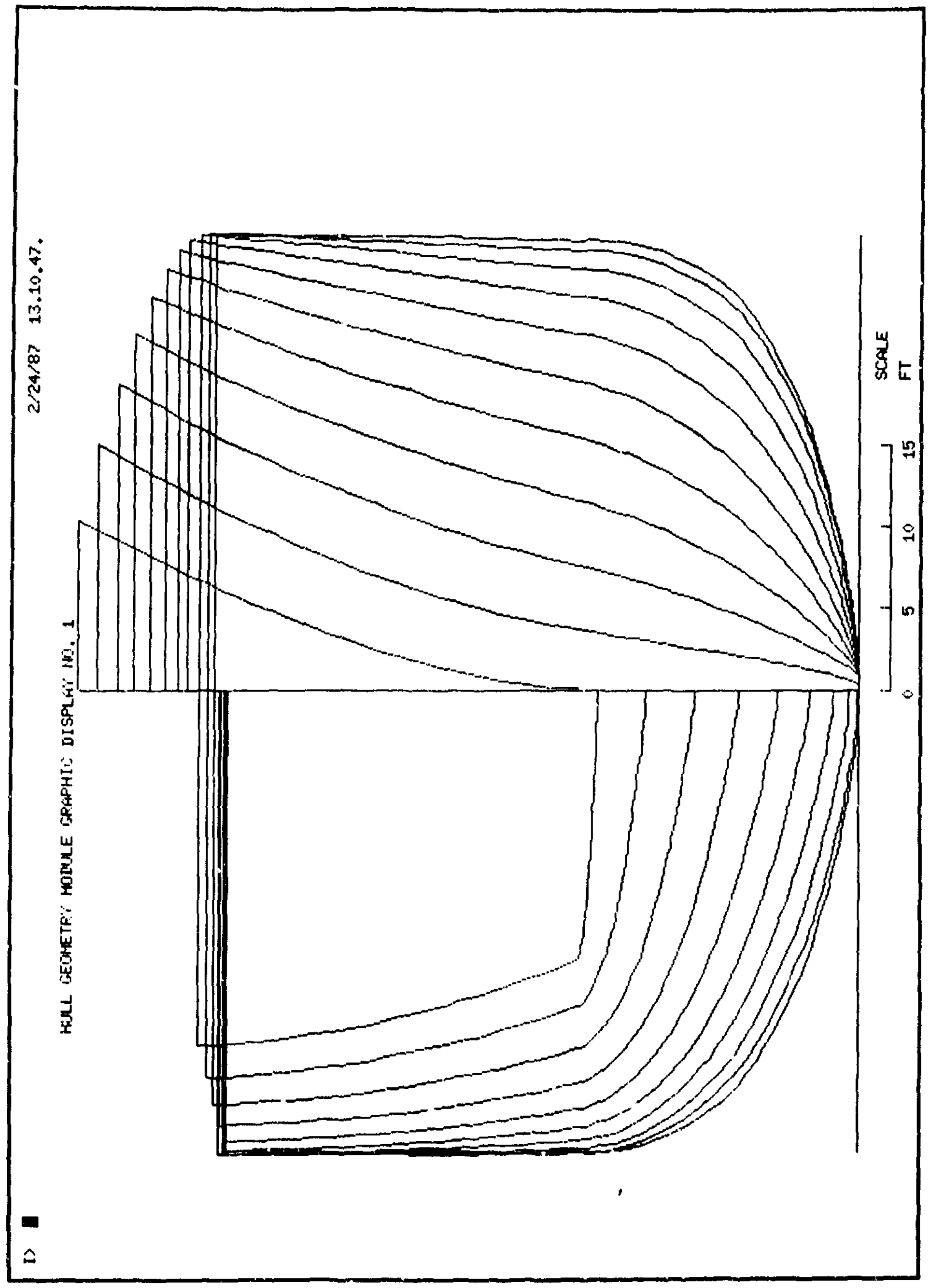


Figure 51. Plan view of subdivision in mechanical baseline

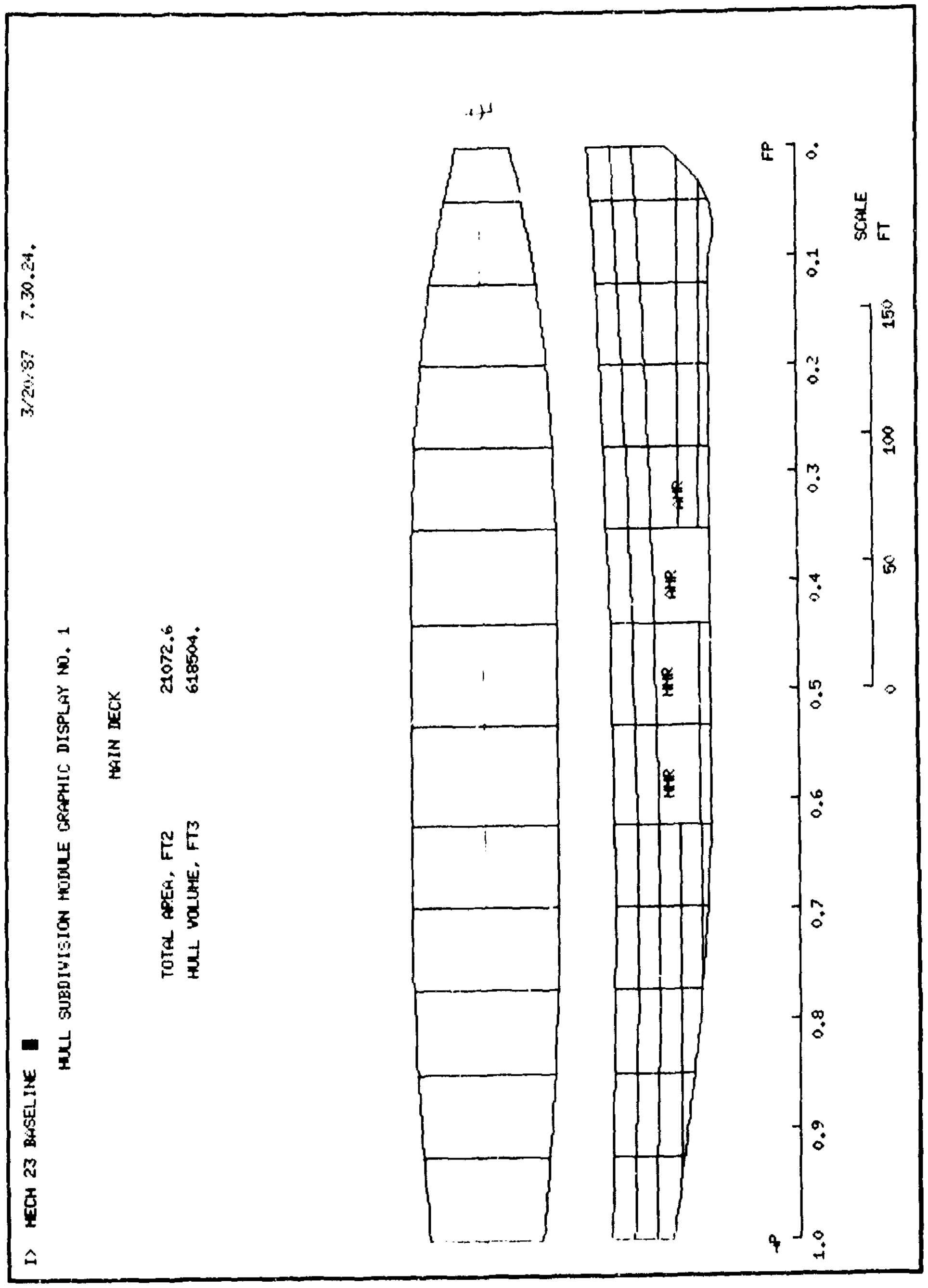
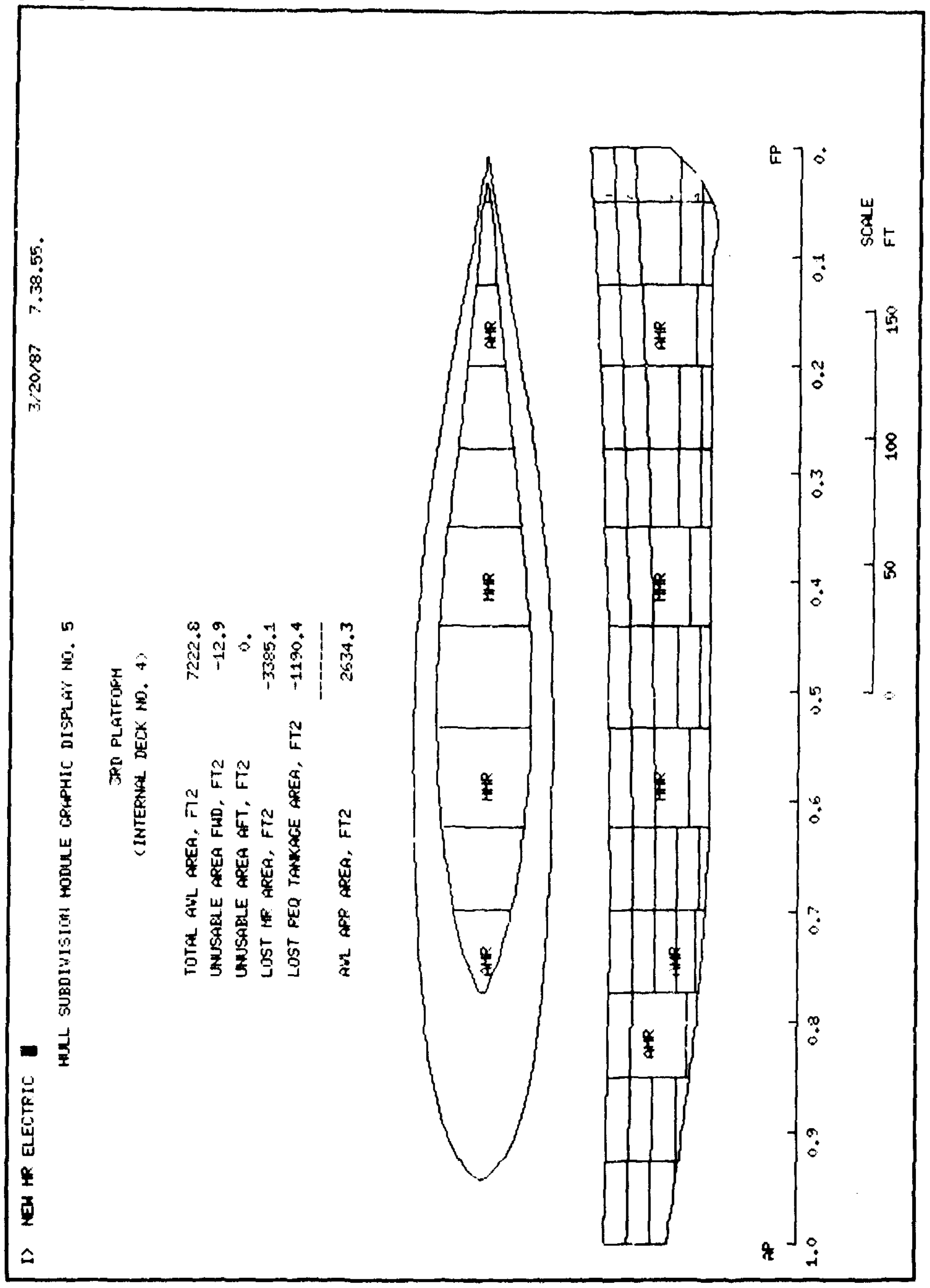


Figure 52. Plan view of subdivision in rearranged electrical ship



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