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HYBRID ELECTRIC VEHICLE SIMULINK TOOLBOX

USER'S GUIDE
TECHNICAL NOTES
PATHS VALIDATION

INTERIM REPORT
TFLRF No. 333

By

Ashok Nedungadi
U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
San Antonio, Texas

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13. ABSTRACT (Maximum 200 words)

A general purpose toolbox was developed for modeling and simulation of electric and hybrid electric vehicles (HEV). This simulation and modeling toolbox, referred to as PATHS (Performance Assessment Toolbox for Hybrid Systems) was developed using Matlab® and Simulink®. PATHS is a forward-looking model organized into a suite of libraries, each containing modular computer models of typical HEV components. The objective of the developed toolbox is to provide the user the ability to model, simulate and analyze the performance of a custom-built or pre-existing HEV. PATHS is a physics-based modeling and simulation toolbox. The equations used to model the different components were derived from classical text books, using sound engineering methods. PATHS was also validated against a 22-foot series hybrid shuttle bus operated on a chassis dynamometer.

This report is divided into the following sections: User's Guide, Technical Notes, and PATHS Validation.

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EXECUTIVE SUMMARY

The HEV toolbox was initially conceived as a "standard" set of modules for use in evaluating the performance of concept HEV architecture. This effort resulted in the development of a general-purpose HEV modeling and simulation toolbox, named PATHS (Performance Assessment Toolbox for Hybrid Systems). PATHS is based on principles of physics models, developed in Matlab® and Simulink®, is modularized into several libraries and uses the forward-looking approach. It can be used to obtain detailed performance characteristics of the modeled HEV or its sub-components, as well as perform parametric trade-off studies. Particularly useful is the ability to size components and evaluate their effects on vehicle performance in computer simulation prior to prototyping or fabricating hardware. The following are possible applications of the toolbox: evaluation of new drivetrain options / architectures; test and debug hybrid vehicle control strategies; sub-componentssizing and specifications; evaluation of hardware modifications on HEV performance; impact of software modifications on HEV performance and other sub-components; build a computer model of a HEV before hardware prototyping.

The following is the current list of libraries within PATHS: engine library, electric machine library, energy storage library, vehicle library, controllers library, couplings library, and a miscellaneous library. The multiple components within a library have the same input-output structure so that they can be interchanged in an HEV model. The user can also add to the library as long as the input-output structure of the particular library is maintained. PATHS is fully customizable as long as the user adheres to the input-output structure of each library and is aware of the existing naming convention of the variables.

Validation of PATHS was performed by first developing a computer model of a 22-foot series hybrid shuttle bus, followed by comparing its output to data collected from the same bus on a chassis dynamometer. The hybrid shuttle bus was placed on a heavy-duty chassis dynamometer and driven by a human operator, while data was collected from the drive motors, Auxiliary Power Unit (APU), batteries, and vehicle speed sensors. This data was compared with model predictions, executing the same driving profile as that of the hybrid bus. Both steady state and transient comparisons were made between the bus and the model. Fuel consumption predicted by the APU model was within 1% over 6 EPA cycles of measured data. The battery state of charge predicted by the lead-acid battery model was within 5% over 6 EPA cycles of measured data. The motor model predictions (transient / steady state) are within 10% of measured data for low speeds and lower throttle positions. Larger deviations between the measured and model predicted data at larger speeds and higher throttle positions. The dynamic vehicle model validated to within 2% of measured data.

This report is divided into the following sections: User's Guide, Technical Notes, and PATHS Validation.

FOREWARD/ACKNOWLEDGMENTS

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HYBRID ELECTRIC VEHICLE

SIMULINK TOOLBOX

(Commercial Vehicle Version)

USER'S GUIDE

Version 1.1

1.0 OVERVIEW OF DARPA HEV SIMULATION TOOLBOX

1.1 Background

The DARPA HEV Simulation Toolbox was initially conceived as a "standard" set of modules for use in evaluating the performance of concept Hybrid Electric Vehicle (HEV) architectures in simulated driving conditions. Two versions of the toolbox are in existence: one for commercial applications, and one for military applications. Both toolboxes contain the same modules. However, the simulation toolbox for military applications contains an additional library of military specific modules. The HEV simulation toolbox was collectively developed by the following organizations:

Southwest Research Institute (SwRI)	Dr. A. Nedungadi	(210) 522-3965
Univ. of TX Inst. for Adv. Technology (IAT)	Dr. Scott Fish	(512) 471-9060
Georgia Institute of Technology (GT)	Dr. Thomas Habetler	(404) 894-8929
Univ. of Hawaii (UH)	Dr. Vassilis Syrmos	(808) 956-3432
Univ. of TX Center of Electro-Mechanics (CEM)	Mr. John Kajs	(512) 471-4496

1.2 Introduction

This user's guide provides a concise description of the commercial version of the DARPA HEV simulation toolbox. Use of this toolbox is restricted to licensees of the software. An application for a license to the commercial version of the simulation toolbox is available by contacting SwRI (Dr. A. Nedungadi (210) 522-3965). All applications for a license agreement to use the military version of the simulation toolbox must be addressed to IAT (Dr. Scott Fish (512) 471-9060).

The simulation toolbox is organized into a suite of libraries, each containing modular computer models of typical HEV components. All the models were developed using MATLAB© and its graphical click-and-pick modeling tool, Simulink©. The objective of the developed toolbox is to provide the user the essential building blocks to simulate and analyze the performance of a custom built or pre-existing electric hybrid vehicle.

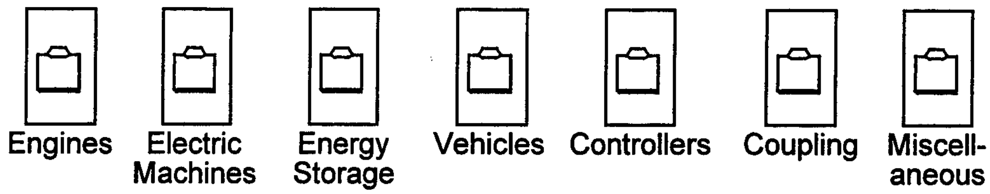


Figure 1. **Hybrid Electric Vehicle Simulink Toolbox (Commercial)**

The following list describes all the libraries and models available within the toolbox:

ENGINE LIBRARY

- ☐ Table lookup diesel engine without emissions
- ☐ Table lookup gas turbine engine without emissions
- ☐ Spark ignition dynamic engine with emissions

ELECTRIC MACHINE LIBRARY

- ☐ AC induction steady-state motor
- ☐ AC induction dynamic motor
- ☐ Permanent magnet steady-state generator
- ☐ Permanent magnet dynamic generator
- ☐ Table lookup steady-state generator

ENERGY STORAGE LIBRARY

- ☐ Lead acid battery
- ☐ flywheel battery
- ☐ Capacitor

VEHICLE LIBRARY

- ☐ Tracked vehicle
- ☐ Wheeled vehicle (version 1 and 2)
- ☐ Wheel (version 1 and 2)
- ☐ Driver

CONTROLLERS LIBRARY

- ☐ Energy management (2)
    - Energy storage system controller
    - APU controller
- ☐ System controller

COUPLINGS LIBRARY

- ☐ Gear box
- ☐ Engine-generator coupling
- ☐ Motor-wheel coupling (version 1 and 2)

MISCELLANEOUS LIBRARY

- ☐ DC-DC converter
- ☐ AC-AC converter
- ☐ AC-DC converter
- ☐ DC-AC converter
- ☐ Capacitor
- ☐ Roller bearing
- ☐ Magnetic bearing
- ☐ Windage model
- ☐ Driving profile

A rigid naming convention was used for all the variables used within the developed models. The first three alphabetic characters represent the abbreviation of the model name. The fourth single alphabetic character represents the possible device type, if one exists. The fifth single numeric character between 0 and 9 represents the number of instances of this item. The sixth character is a required underscore, followed by the variable name. Table 1 summarizes all the model names, the respective three character abbreviations that describe the particular model name, and all possible device types for each model.

Table 1. Summary Of Model Names, Abbreviations And Device Types

MODEL	ABBREVIATION	POSSIBLE DEVICE TYPES
Engine	eng	s (spark ignition) d (diesel) t (turbine) s (stirling)
Motor	mot	I (induction - steady-state) k (induction - dynamic)
Generator	gen	p (permanent magnet - steady-state) q (permanent magnet - dynamic)
Energy Storage System	ess	b (lead acid battery) f (flywheel) c (capacitor)
Axle	axl	none
Coupling	cpl	none
Wheel	whl	none
Vehicle	veh	none
Transmission	trm	m (manual) a (automatic)
Controller	ctl	none

For example, the variable motI1_VAr represents the first instance of the variable name VAr of the induction motor model. The variable genp2_J represents the second instance of the variable name J of the permanent magnet generator model. MATLAB© is case sensitive, therefore motI1_VAr is not the same as moti1_VAr.

The following format is used to describe each model. A table summarizes the required inputs and outputs of the model, followed by a list of constants that are used within the model. Any auxiliary calculations that are not part of the output are listed in the section of auxiliary calculations. This is followed by the first three lines of the mask (consult your Simulink manual) of the model. This is provided to enable the user to recreate the mask if it is accidentally deleted.

A list of assumptions is listed for each model, enabling the user to determine if the complexity of the model would suffice for the given application. Finally, typical values of the constants used within each of the models are presented to give the user an indication of the appropriate order of magnitude of the constants used during simulation of the different models.

This user's guide is accompanied by a technical notes document that contains all the differential equations/equations used within each of the models. These equations are provided to enable the user to assess the applicability of the particular model to the application in question. If certain modifications or extensions are required, the user will have to retrieve the particular model from the Simulink© environment and make the required changes.

It is assumed that the user is an experienced Simulink user since many of the developed models use similar advanced features. It is also assumed that the user has working knowledge of system modeling and interfacing modules with multiple inputs and outputs. The user interacts with the developed toolbox by simply dragging the required item from the appropriate toolbox library and connecting it with other modules while adhering to the input and output connections described in this manual.

The developed models have all been tested through numerous computer simulations. The equations used to model the different components were derived from classical text books, using sound engineering methods. Validation of the most essential components has been completed (see accompanying validation report). It is possible to tweak the parameters used within each model to make its performance compare to the physical system. This calibration task is left to the user if he/she needs to calibrate a particular model to a known physical system. The numerous simulations performed during the verification phase indicate that the simulation of a complex system, such as an electric hybrid vehicle, can be significantly affected by either parameter mismatch within a model or intercomponent mismatch. Typically, this is diagnosed by the simulation taking very small time steps or simulation instabilities.

2.0 ENGINE LIBRARY

The engine library contains three types of engines: (1) table lookup steady-state diesel engine without emissions, (2) table lookup steady-state gas turbine engine without emissions, and (3) a dynamic model of a spark ignition engine with emission calculations. In an HEV application, the engine model is typically connected to a generator using a mechanical coupling from the coupling library (see Section 6). The first two engine models incorporate a lag response time with steady-state performance tables. Their use maintains the shape of the torque vs. speed and throttle setting function while scaling for the desired shaft speed and torque at design conditions. The third engine model is a more detailed dynamic model of a spark-ignition engine.

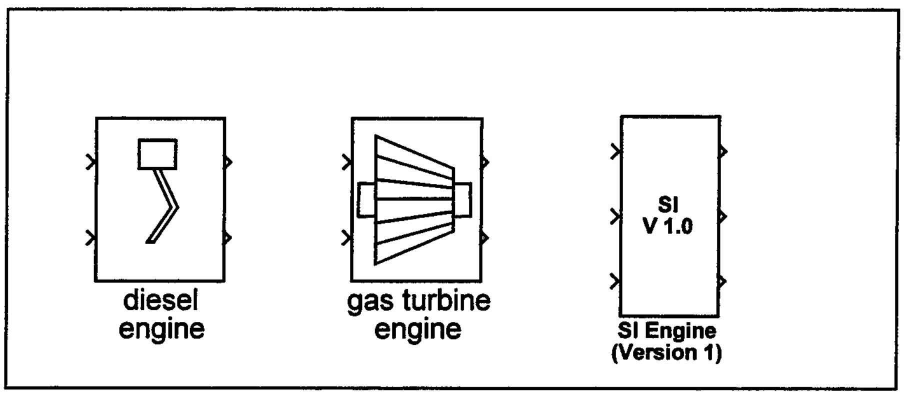
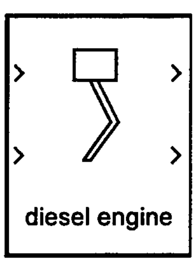


Figure 2. Engine Model Library

2.1 Diesel Engine



INPUTS	OUTPUTS
Non-Dimensional Throttle Control (0-1)	Vector of Engine Torque (N-m) and Inertia Constant (kg*m^2)
Engine Shaft Speed (RPM)	Fuel Mass (kg)

Purpose: The purpose of the diesel engine model is to accurately represent the engine torque and fuel consumption characteristics to its input throttle setting and shaft speed. The model is quasi-steady with a user-defined first order lag in response to the throttle. Other than the engine lag, the performance is determined by table lookup with steady-state performance data. The fuel consumption data is in lb/(hp hr) and is assumed not to vary with engine power rating. The torque table is scaled with the engine power and speed to remain consistent.

Parameters: Note: These values are loaded from disk through the mask or inputted by the user.

engd1_pwr	engine design power (hp)
engd1_spd	engine design speed (rpm)
engd1_J	inertia constant (kg*m^2)
fuel_mass_i	initial fuel mass (kg)
sample_N	max number of samples
sample_T	simulation time between samples

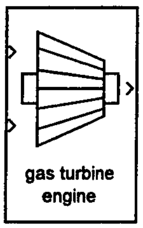
Auxiliary Calculations: None

Diesel Engine Mask

(1) ENGD
(2) Diesel Engine Block Definitions\n(Click on "Help" to list Inport and Outport Parameters.)|[pwr(hp),spd(rpm),J(kgm2)]|Initial Fuel Mass (kg)|[sample_N,sample_T]
(3) load('engd');pwr=@1(1)*746;spd=@1(2)*pi/30;J=@1(3);fuel_i=@2; sample_N=@3(1);sample_T=@3(2);
(4) *Drawing Command.*
(5) Diesel Engine Block Port Parameters.\n\nInport 1: Nondimensional command signal (throttle setting) from diesel engine controller block.\nInport 2: Speed from the generator coupler block.\n\nOutport 1: Vector of [ENGT_T, ENGT_J] output to the generator coupler block.

Model Equations: The diesel model here is composed of three parts. The first part applies a $1/\tau s$ transfer function to the throttle, modeling the response time lag in the actual machine to inputs from the throttle. The second two parts determine the output torque and specific fuel consumption from steady-state lookup tables that are scaled from a known diesel engine performance set. It is assumed that the steady-state performance tables are adequate when combined with the engine lag to describe the actual performance of a dynamic model. No calculations are included for emissions in this model.

2.2 Gas Turbine Engine



INPUTS	OUTPUTS
Non-Dimensional Throttle Control (0-1)	Vector of Engine Torque (N-m) and Inertia Constant (kg*m^2)
Engine Shaft Speed (RPM)	Fuel Mass (kg)

Purpose: The purpose of the gas turbine model is to accurately represent the engine torque and fuel consumption characteristics to its input throttle setting and shaft speed. The model is quasi-steady with a user-defined first order lag in response to the throttle. Other than the engine lag, the performance is determined by table lookup with steady-state performance data. The fuel consumption data is in lb/(hp hr) and is assumed not to vary with engine power rating. The torque table is scaled with the engine power and speed to remain consistent. The output fuel mass represents remaining mass of fuel in tanks connected to this engine. This data can be used to account for weight loss in time by vehicle dynamics models.

Parameters: Note: These values are loaded from disk through the mask or inputted by the user.

engt1_pwr	engine design power (hp)
engt1_spd	engine design speed (rpm)
engt1_J	inertia constant (kg*m^2)
fuel_mass_i	initial fuel mass (kg)
sample_N	max number of samples
sample_T	simulation time between samples

Auxiliary Calculations: None

Gas Turbine Engine Mask

(1) ENGT

(2) Gas Turbine Engine Block Definitions\n(Click on "Help" to list Inport and Outport Parameters.)|[pwr(hp),spd(rpm),J(kgm2)]|Initial Fuel Mass(kg)|[sample_N,sample_T]

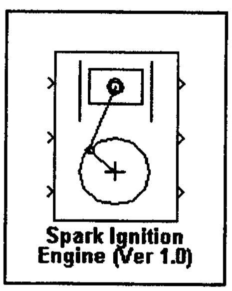
(3) load('engtdata');pwr=@1(1)*746;spd=@1(2)*pi/30;J=@1(3);fuel_i=@2; sample_N=@3(1);sample_T=@3(2);

(4) *Drawing Commands*

(5) Gas Turbine Engine Block Port Parameters.\n\nInport 1: Throttle Command (0->1).\nInport 2: Shaft Speed (RPM).\n\nOutport 1: Vector of [Shaft Torque (N*m),Inertia Constant (kg*m^2)].

Model Equations: The gas turbine model here is composed of three parts. The first part applies a $1/\tau s$ transfer function to the throttle, modeling the response time lag in the actual machine to inputs from the throttle. The second two parts determine the output torque and specific fuel consumption from steady-state lookup tables that are scaled from a known diesel engine performance set. It is assumed that the steady-state performance tables are adequate, when combined with the engine lag, to describe the actual performance of a dynamic model. No calculations are included for emissions in this model.

2.3 Spark Ignition Engine



INPUTS	OUTPUTS
Throttle Fraction [0-1]	Output Torque [Nm]
Desired Engine Speed [rpm]	Engine Inertia [kgm^2]
Engine ON/OFF Switch [0/1]	Total Fuel Consumed [kg]

% General constants:

eng_universal_gas_const: Universal gas constant [J/kmol/K]
eng_std_pres: Standard pressure [Pa]
eng_std_temp: Standard temperature [K]
eng_mol_wt_air: Molecular weight of the air [kg/kmol]
eng_gas_const_air: Specific gas constant for air [J/kg/K]
eng_std_air_density: Density of standard air [kg/m^3]
eng_mol_wt_exhaust: Molecular weight of exhaust gases [kg/kmol]
eng_gas_const_exhaust: Specific gas constant for exhaust gases [J/kg/K]

% Primary engine scaling parameters

eng_displacement:	Engine displacement [m^3]
eng_rated_speed:	Maximum engine rated speed [rad/s]

% Secondary engine scaling parameters

eng_compression_ratio:	Engine compression ratio [ ]
eng_rated_bmep:	Brake mean effective pressure at rated conditions [Pa]
eng_rated_torque:	Rated engine torque [N-m]
eng_rated_power:	Rated engine power [watts]
eng_rated_vol_eff:	Volumetric efficiency at rated conditions [fraction]
eng_rated_air_vol_flow:	Air volume flow rate at rated conditions [m^3/s]
eng_rated_air_mass_flow:	Air mass flow rate at rated conditions [kg/s]

% SI Engine 2 (Main model)

eng_ambient_pressure :	Ambient pressure [Pa]
eng_ambient_temperature:	Ambient temperature [K]
eng_ambient_air_density:	Density of ambient air [kg/m^3]
eng_inertia:	Engine rotary inertia [kg-m^2]
eng_off_torque_factor:	Factor for engine torque when engine is off [N-m / rad/s]

% Air fuel system (1)

eng_manifold_volume_ratio:	Ratio of intake manifold to engine displacement [ ]
eng_manifold_volume:	Volume of intake manifold [m^3]

% Air system (1.1)

eng_throttle_bypass_ratio:	Ratio of bypass flow area around throttle to total throttle area [fraction]
eng_rated_intake_vacuum:	Intake manifold vacuum at rated conditions [Pa]
eng_rated_pres_ratio_infl:	Pressure ratio influence factor (in flow equation) at rated conditions [fraction]
eng_max_air_flow:	Maximum air flow through throttle (choked) [kg/s]
eng_speed_density_weight:	Fractional weight for speed density air flow compared to mass flow sensor [fraction]

% Fuel system (1.2)

eng_af_ratio_speed:	Vector of engine speed for air fuel ratio [rad/s]
eng_af_ratio_Pi:	Vector of intake manifold pressure for air fuel ratio table [Pa];
eng_af_ratio_table:	Air fuel ratio table [number]

% Mixing and dynamics (1.3)

eng_liquid_fuel_fraction :	Fraction of fuel that stays in liquid form [fraction]
eng_fuel_evaporation_time_const:	Time constant for evaporation of liquid fuel in intake manifold wall [sec]

% Reciprocator air flow (2.1)

eng_vol_eff_speed:	Vector of engine speed for volumetric efficiency table [rad/s]
eng_vol_eff_Pi:	Vector of intake manifold pressure for volumetric efficiency table [Pa]
eng_vol_eff_table:	Volumetric efficiency table [number]

% Torque production (2.2)

eng_nominal_isfc:	(Nominal) indicated specific fuel consumption [kg/J]
eng_fmep_factor_0:	Correlation factor 0 for friction mean effective pressure [ ]
eng_fmep_factor_1:	Correlation factor 1 for friction mean effective pressure [ ]
eng_fmep_factor_2:	Correlation factor 2 for friction mean effective pressure [ ]

% Engine exhaust (2.3)

eng_stoich_af_ratio:	Stoichiometric air fuel ratio [ ]
eng_exh_temp_af_coef :	Correlation factor for effect of air fuel ratio on exhaust temp.[ ]
eng_exh_temp_speed:	Vector of engine speed for exhaust temperature table [rad/s]
eng_exh_temp_Pi:	Vector of intake manifold pressure for exhaust temp. table [Pa]
eng_exh_temp_table:	Exhaust temperature table [K]
eng_emissions_speed:	Vector of engine speed for engine emission tables [rad/s]
eng_emissions_Pi:	Vector of intake manifold pressure for engine out emission tables [Pa]
eng_emissions_HC_table:	Engine out hydrocarbon emissions table [kg/kg fuel]
eng_emissions_CO_table:	Engine out carbon monoxide emissions table [kg/kg/fuel]
eng_emissions_NOx_table:	Engine out oxides of nitrogen emissions table [kg/kg fuel]
eng_emissions_PM_table:	Engine out particulate matter emissions table [kg/kg fuel]

% Muffler and aftertreatment (3)

eng_rated_exhaust_pressure:	Exhaust pressure at rated conditions [Pa]
eng_exh_pres_scaling:	Scaling factor for matching exhaust pressure [ ]
eng_rated_exhaust_temperature:	Exhaust temperature at rated conditions [K]
eng_rated_exhaust_density:	Density of exhaust at rated conditions [kg/m^3]
eng_muffler_pressure_factor:	Correlation factor for engine muffler pressure [ ]
eng_catalyst_eff_NOx:	Catalyst conversion efficiency for oxides of nitrogen [ ]
eng_catalyst_eff_HC:	Catalyst conversion efficiency for hydrocarbons [ ]
eng_catalyst_eff_CO:	Catalyst conversion efficiency for carbon monoxide [ ]
eng_catalyst_eff_PM:	Catalyst conversion efficiency for particulate matter [ ]

The following variables (last value) are saved in work space for post run analysis:

eng_s_speed:	Engine speed [rad/sec]
eng_s_throttle:	Throttle [fraction]
eng_torque:	Engine torque [Nm]
eng_total_emissions:	Vector of total engine emissions [g]
eng_s_volumetric_efficiency:	Volumetric efficiency [number]
eng_s_pumping_torque:	Pumping loop torque [Nm]
eng_s_gross_torque:	Gross torque [Nm]
eng_s_combustion_torque:	Combustion torque [Nm]
eng_therm_eff_gross:	Gross thermal efficiency [fraction]
eng_s_friction_torque:	Friction torque [Nm]
eng_s_exhaust_temp:	Exhaust temperature [K]
eng_s_exhaust_gage_pressure:	Exhaust gage pressure [Pa]
eng_s_exhaust_pressure:	Exhaust absolute pressure [Pa]
eng_engine_emissions:	Vector of engine out emissions,HC,CO,NOx,PM [g/hr]
eng_vehicle_emissions:	Vector of vehicle out emissions,HC,CO,NOx,PM [g/hr]

Mask: None

Table 2 presents typical values used for the constants in the engine model

Table 2. Typical Constant Values in Engine Model

Constant	Value
eng_universal_gas_const:	8314.3 [J/kmol/K]
eng_std_pres:	101.3 [Pa]
eng_std_temp:	298.17 [K]
eng_mol_wt_air:	28.96 [kg/kmol]
eng_gas_const_air:	287.096 [J/kg/K]
eng_std_air_density:	1.1834 [kg/m^3]
eng_mol_wt_exhaust:	28.96 [kg/kmol]
eng_gas_const_exhaust:	287.096 [J/kg/K]
eng_displacement:	0.0018 [m^3]
eng_rated_speed:	628.3185 [rad/s]
eng_compression_ratio:	8
eng_rated_bmep:	1E6 [Pa]
eng_rated_torque:	1.131E4 [Nm]
eng_rated_power:	7.106E6 [watts]
eng_rated_vol_eff:	80 [%]
eng_rated_air_vol_flow:	0.072 [m^3/s]
eng_rated_air_mass_flow:	0.0852 [kg/s]
eng_ambient_pressure :	101300 [Pa]
eng_ambient_temperature:	298.17 [K]
eng_ambient_air_density:	1.1834 [kg/m^3]
eng_inertia:	0.1454 [kg-m^2]
eng_off_torque_factor:	-0.1 [N-m / rad/s]
eng_manifold_volume_ratio:	0.0018
eng_manifold_volume:	0.0018 [m^3]

% Air system (1.1)

eng_throttle_bypass_ratio:	0.005
eng_rated_intake_vacuum:	3000 [Pa]
eng_rated_pres_ratio_infl:	0.234
eng_max_air_flow:	0.3642 [kg/s]
eng_speed_density_weight:	1
eng_af_ratio_speed:	[0.1667, 1]
eng_af_ratio_Pi:	[0, 88000, 102000];
eng_af_ratio_table:	[14.6, 14.6 ,13]
	[14.6, 14.6, 12.5]
eng_liquid_fuel_fraction :	0.5
eng_fuel_evaporation_time_const:	0.25 [sec]
eng_vol_eff_speed:	[0.1667 0.3333 0.5000 0.6667 0.8333 1.0000]
eng_vol_eff_Pi:	[20000 100000] [Pa]
eng_vol_eff_table:	[0.5000 0.7000
	0.5000 0.7500
	0.5000 0.8000
	0.5000 0.8900
	0.5000 0.8700
	0.5000 0.7700]
eng_nominal_isfc:	6.67E-8 [kg/J]
eng_fmep_factor_0:	0.75
eng_fmep_factor_1:	0.15
eng_fmep_factor_2:	0.05
eng_stoich_af_ratio:	14.6
eng_exh_temp_af_coef :	0
eng_exh_temp_speed:	[0.1667 1.0000] [rad/s]
eng_exh_temp_Pi:	[20000 100000] [Pa]
eng_exh_temp_table:	[673 823]
	[773 1173] [deg K]
eng_emissions_speed:	[673 823 773 1173] [rad/s]
eng_emissions_Pi:	[40000 50000 60000 70000 80000] [Pa]
eng_emissions_HC_table:	[0.0162 0.0146 0.0135 0.0124 0.0113]
	[0.0151 0.0139 0.0134 0.0121 0.0111]
	[0.0140 0.0136 0.0130 0.0120 0.0110]
	[0.0130 0.0133 0.0128 0.0118 0.0107]
	[0.0124 0.0131 0.0125 0.0112 0.0100]
	[kg/kg fuel]
eng_emissions_CO_table:	[0.0802 0.0831 0.0851 0.0837 0.0855]
	[0.0840 0.0860 0.0890 0.0887 0.0898]
	[0.0861 0.0894 0.0935 0.0941 0.0933]
	[0.0892 0.0921 0.0969 0.0987 0.0987]
	[0.0909 0.0959 0.0995 0.1013 0.1016]
	[kg/kg fuel]

eng_emissions_NOx_table:	[0.0279 0.0465 0.0584 0.0560 0.0517]
	[0.0384 0.0553 0.0633 0.0583 0.0539]
	[0.0482 0.0635 0.0673 0.0598 0.0558]
	[0.0569 0.0698 0.0695 0.0608 0.0571]
	[0.0632 0.0755 0.0715 0.0631 0.0593]
	[kg/kg fuel]

eng_emissions_PM_table:	[0 0 0 0 0]
	[0 0 0 0 0]
	[0 0 0 0 0]
	[0 0 0 0 0]
	[0 0 0 0 0]
	[kg/kg fuel]

eng_rated_exhaust_pressure:	40000 [Pa]
eng_exh_pres_scaling:	0.5
eng_rated_exhaust_temperature:	1173 [K]
eng_rated_exhaust_density:	0.4196 [kg/m^3]
eng_muffler_pressure_factor:	4.85E5
eng_catalyst_eff_NOx:	0.5
eng_catalyst_eff_HC:	0.5
eng_catalyst_eff_CO:	0.5
eng_catalyst_eff_PM:	0.5

Assumptions:

The following assumptions have been used for the quasi steady-state model:

- May be used with any type of engine:

  Spark ignited (SI) liquid fuel (gasoline)

  Spark ignited (SI) gaseous fuel (natural gas)

  Compression ignited (CI), typically called diesel engines

  Gas turbine

  Any other

- Uses steady-state maps for torque curves, fuel consumption and emissions.
- Any torque in the range of minimum to maximum is assumed to be available instantly.
- No transients of ANY KIND are included.
- Fastest model execution. Adequate in many vehicle models, including series hybrid applications where the engine is operating at steady or nearly steady conditions.

The following assumptions have been used in the Spark Ignited (SI) engine transient model:

- Liquid fueled (e.g. gasoline). Should not be used for gas fueled (e.g. natural gas) engines.
- Naturally aspirated (no turbocharging or supercharging). Most SI engines are naturally aspirated.
- Mean value torque model. Estimates average torque over engine cycle.
- Does not compute torque variation within a cycle.
- Assumes continuous flows. Does not consider manifold pressure waves or tuning. Tuning may be included through effect on volumetric efficiency.
- Three internal mode states associated with intake manifold emptying/filling manifold wall wetting by fuel catalyst bed temperature.
- Model does not consider any time delays associated with:
  - fueling decisions
  - fuel transport lag
  - torque production
- Engine is assumed to be fully warmed up at all times. Cold-start emissions are not calculated.
- Model does not simulate cranking or associated emissions.

3.0 ELECTRIC MACHINE LIBRARY

The electric machine library contains models of an AC induction motor as well as a permanent magnet generator. The AC induction motor model is connected to the wheel of an HEV either directly or via a motor wheel coupling. The generator is connected to an engine via an engine-generator coupling.

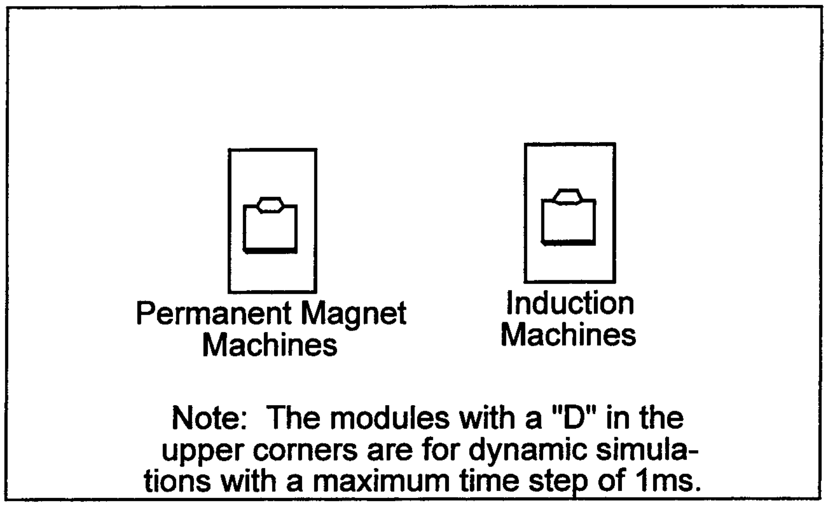


Figure 3. Machine Model Library

3.1 Steady-State Permanent Magnet Generator System Module with Fixed Efficiency Rectifier

INPUTS	OUTPUTS
DC Bus Voltage [V]	Rectifier Current [A]
DC Command Current [A]	[Output Torque [N·m], Machine Inertia [kg·m^2]]
Engine Speed [rpm]	

Constants as defined by the mask:

VAr:	Rated Power of Generator [W]
Vr:	Rated Line-Neutral Voltage of Generator [V]
nr:	Rated Speed of Generator [rad/s]
poles:	Number of Generator Poles [ ]
Ib:	Rated Line Current of Generator [A]
Zb:	Base Impedance of Generator for Per Unit [Ω]
wb:	Base Speed of Generator for Per Unit [rad/s]

Rspu:	Per Unit Stator Resistance [ ]
Rmpu:	Per Unit Iron Loss Resistance [ ]
Lqspu:	Per Unit Stator q-axis Inductance [ ]
Ldspu:	Per Unit Stator d-axis Inductance [ ]
Llspu:	Per Unit Stator Leakage Inductance [ ]
Lmdpu:	Per Unit Stator d-axis Magnetizing Inductance [ ]
Idfpu:	Per Unit PM "Field" Current [ ]
recteff:	Rectifier Efficiency [ ]
Inertia_out:	Machine Inertia [kg·m²]
sample_N:	Number of Samples to Save to the MATLAB® Workspace
sample_T:	Length of Time Between Each Sample

Auxiliary Calculations: None

Mask:

1. SS PM Generator System
2. SS PM Generator/Rectifier System|Gen Rtgs[P(hp),V(V),n(rpm)]:|Rtgs[poles,NLV(V),Core L(hp)]:|[Rs (ohms),Lqs,Lds,Lls (H)]:|Rectifier Efficiency:|Machine Inertia(kg*m*m):| [sample_N, sample_T]:
3. mvr=gencinit(@1,@2,@3); VAr = mvr(1,1);Vr = mvr(1,2); nr = @1(1,3); poles = @2(1,1); Rmpu = mvr(1,3); Ib = mvr(1,4); Zb = mvr(1,5); wb = mvr(1,6); Rspu = mvr(1,7); Lqspu=mvr(1,8); Ldspu = mvr(1,9); Llspu = mvr(1,10); Lmdpu = mvr(1,11); Idfpu=mvr(1,12); recteff = @4; Inertia_out = @5; sample_N = @6(1,1); sample_T=@6(1,2);

This module simulates a permanent-magnet generator connected to a dc bus through a three-phase rectifier. The module mask contains the example values for a 50 hp, 230 V generator, which is user changeable. The generator is connected to the dc bus through a three-phase, fully controlled PWM voltage source (boost-type) rectifier as shown in Figure 4. Please refer to the following assumptions for other important simulation details.

Assumptions:

- This module will only be used in simulations with a minimum time step of 100 ms or larger.

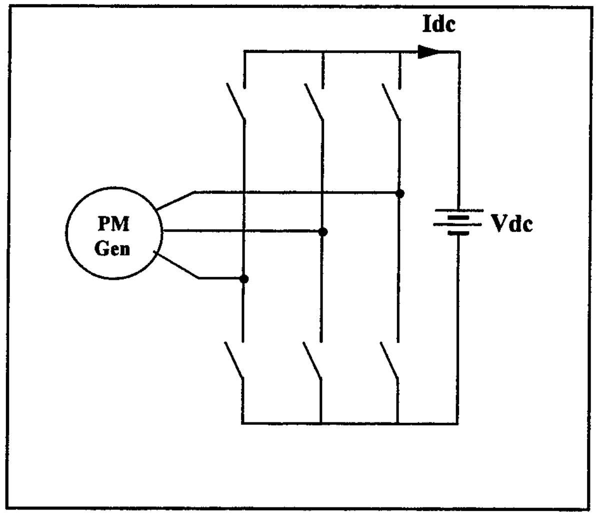


Figure 4. - Generator System Configuration. Ideal Switches Can Be IGBTS, BJTS or GTOS With Anti-Parallel Diodes

- The generator sign convention is that positive current is leaving the terminals of the machine. This current produces positive torque for positive speeds. For the module itself, a positive actual dc rectifier current (output #1) indicates the generating mode.
- Model does not include rectifier harmonic effects.
- The rectifier is assumed to have a fixed, user definable efficiency. The losses in the generator are modeled as stator copper and core loss (R_s and R_m, respectively in Figure 6).
- Within the module, a set of power values is computed at each time step in order to facilitate energy balance equations. The power values are as follows: the dc bus power, the mechanical power of the generator, the electrical power at the terminals of the machine, the rectifier loss power, and the total motor losses (core & copper losses). These values are *not* saved to the workspace automatically.
- The generator is controlled at all times with conventional "brushless dc" (also known as "field-oriented" or "vector") control. That is, the current in the generator is controlled to be in phase with the internal generator voltage (back emf).
- No provision is made for field weakening of the PM machine. If sufficient bus voltage is unavailable to maintain the control (this typically occurs when the speed is above the rated speed with rated bus voltage), then the generator is turned off (output power to the bus is zero) due to an "overspeed condition" for the given bus voltage.

- The generator current is limited to 1.5 times the value, which results in rated torque at rated speed. This also limits the direct axis flux in the machine.

- The user is cautioned that the machine parameters and rated values are not necessarily independent of one another. It is certainly possible to input values in the mask, which results in an uncontrollable machine or in control over a very small operating range.

Figure 5 shows the inputs and outputs of the steady-state generator model. Figure 6 depicts the steady-state synchronous d-q reference frame model used in the simulation. The electrical terminal voltage is calculated directly from this equivalent circuit using the command values of current and speed. The electrical and mechanical equations used in the simulation, and given by the equivalent circuit, are,

$$
\begin{aligned}
i_{qs}^e &= i_{qm}^e + \frac{1}{R_m}(\omega_r L_{ds} i_{dm}^e - \omega_r L_{md} I_{df}) \\
i_{ds}^e &= i_{dm}^e - \frac{\omega_r L_{qs} i_{qm}^e}{R_m} \\
v_{qs}^e &= -R_s i_{qs}^e + \omega_r L_{md} I_{df} - \omega_r L_{ds} i_{dm}^e \\
v_{ds}^e &= -R_s i_{ds}^e + \omega_r L_{qs} i_{qm}^e \\
\tau &= L_{md} I_{df} i_{qm}^e
\end{aligned}
$$

where the superscript *e* denotes the synchronous reference frame, and I_{df} is the fictitious current that corresponds to the strength of the permanent magnet. This current is internally calculated from the no load speed and voltage. The iron loss resistor, R_m, is calculated from the rated core losses value provided by the user.

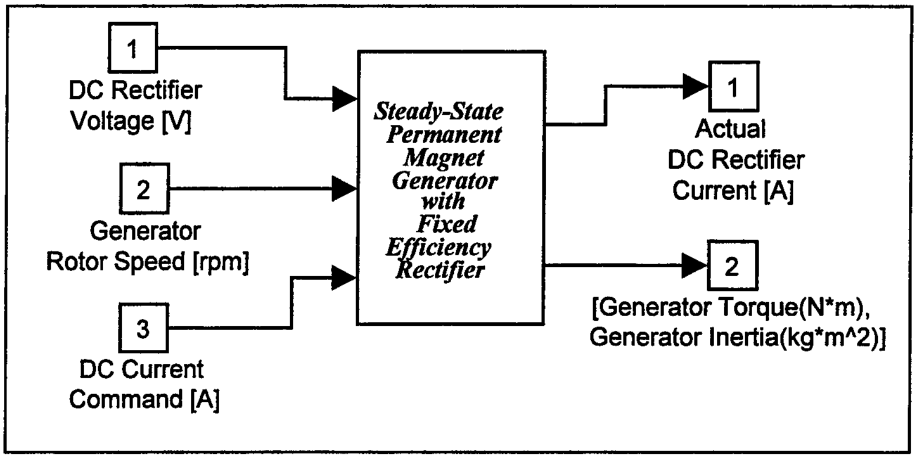


Figure 5 - Inputs and Outputs of PM Generator System

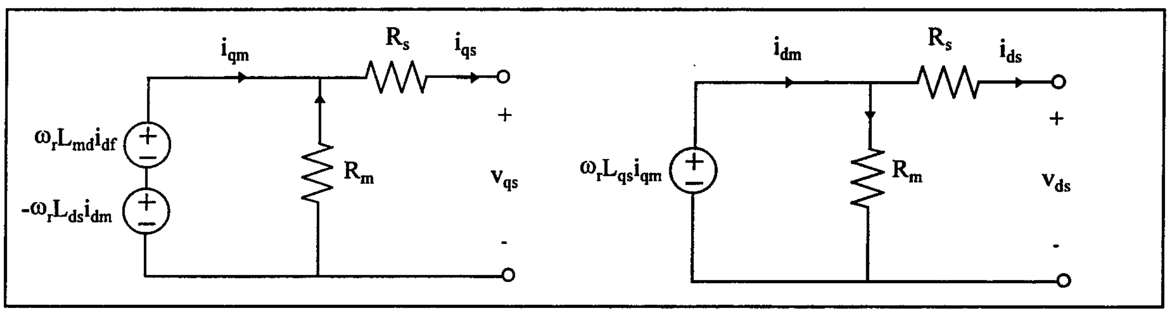


Figure 6 - Steady-State dq-Equivalent Circuits

The generator is controlled using conventional synchronous reference frame field orientation (i.e., "brushless dc" control) such that $i_{dm} = 0$.

When the mask is activated, the window in Figure 7 is displayed. The first input line asks the user to list the rated power, rated line, voltage, and rated speed of the generator. The next input line requests the values for the number of poles, the no-load voltage at rated speed, and the core losses at rated speed. The machine parameters of the per-phase stator resistance, per-phase q- and d-axis stator self inductances, and the per-phase leakage inductance are defined in the third line of the mask. The fixed efficiency of the rectifier is specified in line 4, and the system inertia is defined in the fifth input vector. Finally, the user can specify the number of samples and the time step between each sample for use in "To Workspace" blocks within the module. The default values listed in Table 3 describe a 50 horsepower permanent-magnet synchronous generator with a fixed efficiency rectifier.

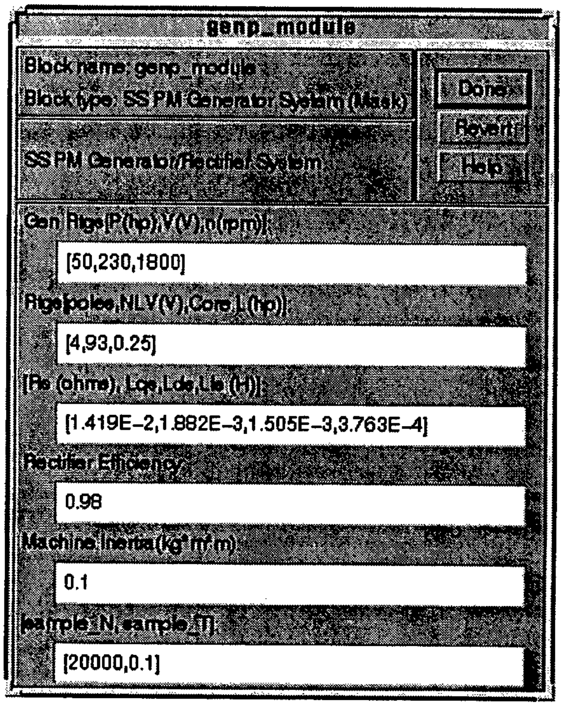


Figure 7 – Window Displayed When Mask Is Activated For The Permanent Magnet Generator Module With Fixed Rectifier Efficiency

Table 3. Machine Definitions and Values	
Machine Definitions	**Values**
Rated Power	50 hp
Rated Voltage	230 V
Rated Speed	1800 rpm
Number of Poles	4
No-Load Voltage @ Rated Speed	93 V
Core Losses @ Rated Voltage & Speed	0.25 hp
Per-Phase Stator Resistance, R_s	1.419E-2 Ω
Per-Phase Stator q-axis Inductance, L_q	1.882E-3 H
Per-Phase Stator d-axis Inductance, L_d	1.505E-3 H
Per-Phase Stator Leakage Inductance, L_{ls}	3.763E-4 H
Rectifier Efficiency	0.98
Machine Inertia	0.1 kg·m^2
Number of Samples Saved to Workspace	20000
Time Between each Saved Sample	0.1

3.2 Steady-State Permanent Magnet Generator System Module with Calculated Rectifier Losses

INPUTS	OUTPUTS
DC Bus Voltage [V]	Rectifier Current [A]
DC Command Current [A]	Output Torque [N·m]
Engine Speed [rpm]	Machine Inertia [kg·m^2]

Constants as defined by the mask:

VAr:	Rated Power of Generator [W]
Vr:	Rated Line-Neutral Voltage of Generator [V]
nr:	Rated Speed of Generator [rad/s]
poles:	Number of Generator Poles [ ]
Ib:	Rated Line Current of Generator [A]
Zb:	Base Impedance of Generator for Per Unit [Ω]
wb:	Base Speed of Generator for Per Unit [rad/s]
Rspu:	Per Unit Stator Resistance [ ]
Rmpu:	Per Unit Iron Loss Resistance [ ]
Lqspu:	Per Unit Stator q-axis Inductance [ ]
Ldspu:	Per Unit Stator d-axis Inductance [ ]
Llspu:	Per Unit Stator Leakage Inductance [ ]
Lmdpu:	Per Unit Stator d-axis Magnetizing Inductance [ ]
Idfpu:	Per Unit PM "Field" Current [ ]
fc:	PWM Switching Frequency of the Rectifier [Hz]
EQD:	Total Switching Energy Loss per Amp of the IGBT-Diode Combination [J/A]
Vnom:	Voltage at which EQD is specified [V]
rQ:	On State IGBT Resistance [Ω]
rD:	On State Diode Resistance [Ω]
VQ:	Forward Voltage Drop of the IGBT [V]
VD:	Forward Voltage Drop of the Diode [V]
PWM:	Determines if Sinusoidal(1) or Space Vector (0) PWM is used.[ ]
Inertia_out:	Machine Inertia [kg.m^2]
sample_N:	Number of Samples to Save to the MATLAB Workspace [ ]
sample_T:	Length of Time Between Each Sample [ ]

Auxiliary Calculations: None

Mask:

1. SS PM Generator System
2. SS PM Generator / Rectifier System|Gen Ratings[P(hp),V(V),n(rpm),J(kgm^2)]| Rtgs[poles,NLV(V),Core L(hp)]|[Rs(ohms),Lqs(H),Lds(H),Lls(H)]| Rect

[rQ,rD(ohms),VQ,VD(V)]|[PWM,f(Hz),EQD(J/A),Vnom(V)]| [sample_N, sample_T]:

3. mvr=gencinit(@1,@2,@3);VAr=mvr(1,1);Vr=mvr(1,2);nr=@1(1,3);poles=@2(1,1); Rmpu=mvr(1,3);Ib=mvr(1,4);Zb=mvr(1,5);wb=mvr(1,6);Rspu=mvr(1,7); Lqspu=mvr(1,8);Ldspu=mvr(1,9);Llspu=mvr(1,10);Lmdpu=mvr(1,11); Idfpu=mvr(1,12);rQ=@4(1,1);rD=@4(1,2);VQ=@4(1,3);VD=@4(1,4);PWM=@5(1,1); fc=@5(1,2);Inertia_out=@1(1,4);EQD=@5(1,3);Vnom=@5(1,4);sample_N=@6(1,1); sample_T=@6(1,2);

This module simulates a permanent-magnet generator connected to a dc bus through a three-phase rectifier. The module mask contains example values for a 50 hp, 230V generator, which are user changeable. The generator is connected to the dc bus through a three-phase fully controlled PWM voltage source (boost-type) rectifier as shown in Figure 8. The rectifier uses either the sinusoidal PWM method [1] or the space vector PWM method [2].

Assumptions:

- This module will only be used in simulations with a minimum time step of 100 ms or larger.
- The generator sign convention is such that positive current leaves the terminals of the machine. This current produces positive torque for positive speeds. A positive dc rectifier current (output #1) indicates the generating mode.

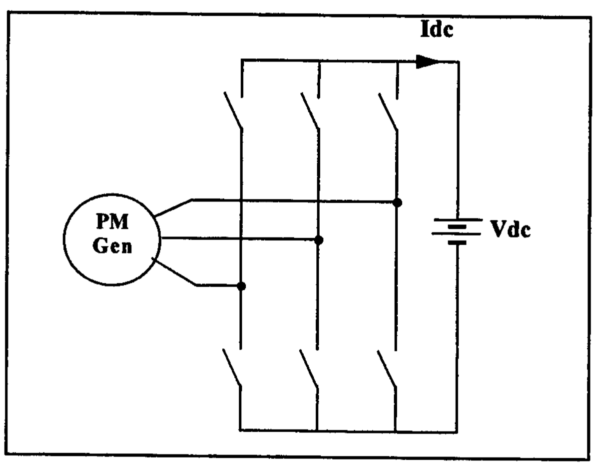


Figure 8 - Generator System Configuration:
Ideal Switches Can Be IGBTs, BJTs or GTOs With Antiparallel Diodes

- Within the module, a set of power values is computed at each time step in order to facilitate energy balance equations. The power values are as follows: the dc bus power, the mechanical power of the generator, the electrical power at the terminals of the machine, the rectifier loss power, and the total motor losses (core & copper losses). These values are *not* saved to the workspace automatically.
- Loss calculations for the Alt-Rev space vector PWM method [2] are based on the third harmonic PWM method since both control methods result in similar steady-state operation.
- Phase currents and phase voltages of the generator are assumed to be purely sinusoidal for rectifier loss calculations. This assumption is justifiable if the PWM frequency is reasonably high.
- The machine model does not include rectifier harmonic effects.
- The losses in the generator are modeled as stator copper loss (R_s in Figure 10) and core loss (R_m in Figure 10).
- The generator is controlled at all times with conventional "brushless dc" (also known as "field-oriented" or "vector") control. That is, the current in the generator is controlled to be in phase with the internal generator voltage (back emf).
- No provision is made for field weakening of the PM machine. If sufficient bus voltage is unavailable to maintain the control (this typically occurs when the speed is above the rated speed with rated bus voltage), the generator is turned off (output power to the bus is zero) due to an "overspeed condition" for the given bus voltage.
- The generator current is limited to 1.5 times the value, which results in rated torque at rated speed. This also limits the direct axis flux in the machine.
- The user is cautioned that the machine parameters and rated values are not necessarily independent of one another. It is certainly possible to input values in the mask, which result in an uncontrollable machine, or in control over a very small operating range.

Figure 10 shows the inputs and outputs of the steady-state permanent magnet generator model with calculated rectifier losses. Figure 11 depicts the steady-state synchronous d-q reference frame machine model used in the simulation. The electrical terminal voltage is calculated directly from this equivalent circuit using the command values of current and speed. The electrical and mechanical equations used in the simulation, and given by the equivalent circuit, are,

$$i_{qs}^e = i_{qm}^e + \frac{1}{R_m}(\omega_r L_{ds} i_{dm}^e - \omega_r L_{md} I_{df})$$

$$i_{ds}^e = i_{dm}^e - \frac{\omega_r L_{qs} i_{qm}^e}{R_m}$$

$$v_{qs}^e = -R_s i_{qs}^e + \omega_r L_{md} I_{df} - \omega_r L_{ds} i_{dm}^e$$

$$v_{ds}^e = -R_s i_{ds}^e + \omega_r L_{qs} i_{qm}^e$$

$$\tau = L_{md} I_{df} i_{qm}^e$$

where the superscript e denotes the synchronous reference frame and I_{df} is the fictitious current which corresponds to the strength of the permanent magnet. This current is internally calculated from the no load speed and voltage. The iron loss resistor, R_m, is calculated from the rated core losses value provided by the user.

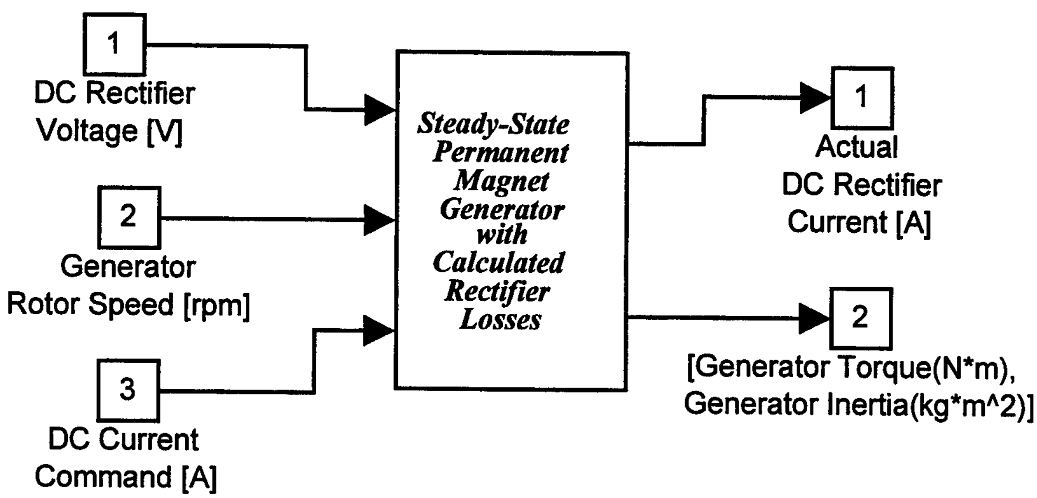


Figure 9. Steady-State Permanent Magnet Generator with Calculated Rectifier Losses

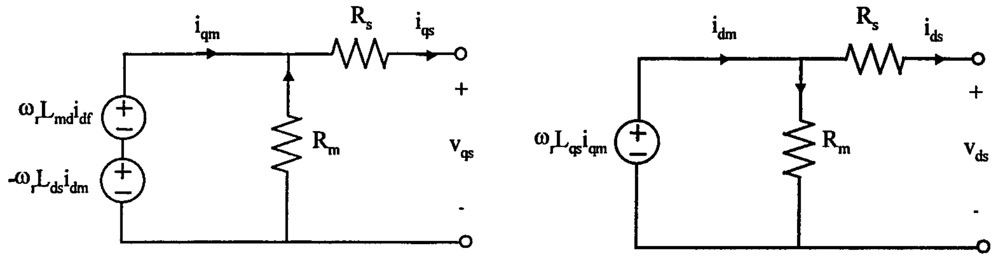


Figure 10 - Inputs and Outputs of PM Generator System with Calculated Rectifier Losses.

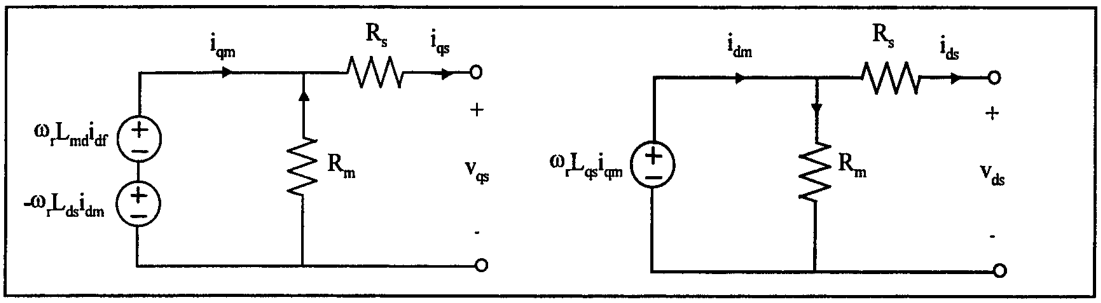


Figure 11 - Steady-State dq-Equivalent Circuits

The generator is controlled using conventional synchronous reference frame field orientation (i.e., "brushless dc" control) such that $i_{dm} = 0$.

The following are the machine variables used for the device loss calculations within the rectifier:

$$I_p = \sqrt{2}\, Ib\, \sqrt{2\left(Iqspu^2 + Idspu^2\right)}$$
$$V_p = \sqrt{2}\, Vr\, \sqrt{2\left(Vqspu^2 + Vdspu^2\right)}$$
$$\phi = \tan^{-1}\left(\frac{Vdspu}{Vqspu}\right) - \tan^{-1}\left(\frac{Idspu}{Iqspu}\right)$$
$$M = \frac{2V_p}{Vdc}$$

where

V_p	Peak machine output phase voltage
I_p	Peak output current of the machine
M	Modulation index

ϕ	Phase lag of the machine line current
Vdc	Voltage of the DC bus.
$Iqspu$	RMS q-axis machine output current
$Idspu$	RMS d-axis machine output current
$Vqspu$	RMS q-axis machine output phase voltage
$Vdspu$	RMS d-axis machine output phase voltage

Table 4 shows the equations governing the rectifier device currents.

Table 4. Equations Governing Rectifier Device Currents

Device Currents	Sinusoidal PWM	Space Vector PWM
$\overline{I_Q}$	$I_P\left(\frac{1}{2\pi}+\frac{M\cos\phi}{8}\right)$	$I_P\left(\frac{1}{2\pi}+\frac{\sqrt{3}M\cos\phi}{12}\right)$
$\overline{I_D}$	$I_P\left(\frac{1}{2\pi}-\frac{M\cos\phi}{8}\right)$	$I_P\left(\frac{1}{2\pi}-\frac{\sqrt{3}M\cos\phi}{12}\right)$
$\lvert I_Q\rvert_{RMS}$	$I_P\sqrt{\frac{1}{8}+\frac{M\cos\phi}{3\pi}}$	$I_P\sqrt{\frac{1}{8}+M\frac{30\cos\phi-\cos3\phi}{45\sqrt{3}\pi}}$
$\lvert I_D\rvert_{RMS}$	$I_P\sqrt{\frac{1}{8}-\frac{M\cos\phi}{3\pi}}$	$I_P\sqrt{\frac{1}{8}-M\frac{30\cos\phi-\cos3\phi}{45\sqrt{3}\pi}}$

where	$\overline{I_Q}$	Average current through the IGBT
	$\overline{I_D}$	Average current through the diode
	$\lvert I_Q\rvert_{RMS}$	RMS current through the IGBT
	$\lvert I_D\rvert_{RMS}$	RMS current through the diode

The rectifier losses are then calculated using the following equations:

Conduction losses:

$$P_{Q(cond)} = \overline{I_Q} \cdot VQ + |I_Q|^2_{RMS} \cdot rQ$$

$$P_{D(cond)} = \overline{I_D} \cdot VD + |I_D|^2_{RMS} \cdot rD$$

where	$P_{Q(cond)}$	Conduction power loss in the IGBT
	$P_{D(cond)}$	Conduction power loss in the diode

Switching losses:

$$P_{Q(sw)} = \frac{f \cdot E_Q \cdot I_p}{\pi} \left(\frac{Vdc}{Vnom} \right)$$

$$P_{D(sw)} = \frac{f \cdot E_D \cdot I_p}{\pi} \left(\frac{Vdc}{Vnom} \right)$$

$$P_{TOT(sw)} = P_{Q(sw)} + P_{D(sw)} = \frac{f \cdot EQD \cdot I_p}{\pi} \left(\frac{Vdc}{Vnom} \right)$$

where	$P_{Q(sw)}$	Switching power loss in the IGBT
	$P_{D(sw)}$	Switching power loss in the diode
	$P_{TOT(sw)}$	Total switching power loss
	Vdc	Voltage of the DC bus.
	E_Q	Switching energy loss per Amp of the IGBT
	E_D	Switching energy loss per Amp of the diode
	EQD	$E_Q + E_D$

The total rectifier loss power(P_{loss}) is six times the sum of the conduction and switching losses of the IGBT and the diode.

$$P_{loss} = 6\left(P_{Q(sw)} + P_{D(sw)} + P_{Q(cond)} + P_{D(cond)}\right)$$

IGBT Selection Guide:

Table 5 shows the IGBT modules that contain the antiparallel diodes.

Table 5. IGBT Modules that Contain the Antiparallel Diodes										
IGBT Module #	Frequency Range (kHz)	V_{CES} (V)	I_C @ T_J=25°C (A)	P_{DMAX} (W)	VQ_{MAX} @ T_J=25°C (V)	VD_{MAX} @ T_J=25°C (V)	EQD (@V_{nom}) @ T_J=125°C (mJ/A)	rQ @ T_J=125°C (mΩ)	rD @ T_J=125°C (mΩ)
IRGDDN300M06	3-10	600	400	1563	2.0	2.0	0.2 @ V_{nom}=300V	–	–
IRGDDN400M06	3-10	600	600	1984	2.0	2.0	0.2 @ V_{nom}=300V	–	–
IRGDDN600M06	3-10	600	800	2604	2.7	2.0	0.2 @ V_{nom}=300V	–	–
IRGDDN200M12	3-10	1200	420	1800	2.7	3.4	0.6 @ V_{nom}=600V	2.00	5.50
IRGDDN300M12	3-10	1200	560	2400	2.7	3.4	0.6 @ V_{nom}=600V	2.50	4.00
IRGDDN400M12	3-10	1200	400	2770	2.7	3.4	0.6 @ V_{nom}=600V	–	–
IRGDDN300K06	10-30	600	340	1563	2.7	2.0	0.15@ V_{nom}=300V	–	–
IRGDDN400K06	10-30	600	520	1984	2.7	2.0	0.15@ V_{nom}=300V	–	–
IRGDDN600K06	10-30	600	680	2604	2.7	2.0	0.15@ V_{nom}=300V	–	–

where V_{CES} Maximum Continuous Collector to Emitter Voltage

I_C Maximum Continuous Collector Current

P_{DMAX} Maximum Power dissipation

VQ_{MAX} Maximum Collector to Emitter ON Voltage

VD_{MAX} Maximum Forward Voltage Drop of the Diode

EQD Total Switching Energy Loss per Amp of the IGBT-Diode Combination

V_{nom} Collector Voltage at which EQD is specified

rQ On State IGBT Resistance

rD On State Diode Resistance

T_J Device Junction Temperature

The value of on-state resistance of the IGBT and diode is found by calculating the inverse of the slope of the device current versus device voltage curve (during conduction).

When the mask is activated, the window in Figure 11 is displayed. The first input line asks the user to list the rated power, rated line voltage, and rated speed of the generator as well as the system inertia. The next input line requests the values for the number of poles, the no load voltage at rated speed, and the core losses at rated speed. The machine parameters of per-phase stator resistance, per-phase q- and d-axis stator self inductances, and the per-phase leakage inductance are defined in the third line of the mask. The rectifier is described by the next two input vectors of the mask. In the first vector, the on-state resistance of the switching devices(rQ) and the diodes(rD) and their respective forward voltage drops are defined. The second input vector for the rectifier specifies the PWM method (1 for Sinusoidal/0 for Space Vector), the switching frequency, the total switching energy loss per amp of the switching device/diode combination, and the collector voltage at which this switching loss occurs.

Finally, the user can specify the number of samples and the time step between each sample for use in "To Workspace" blocks within the module. The default values, which describe a 50 horsepower permanent-magnet synchronous generator with a three-phase IGBT boost rectifier, are listed in Table 6 on the following page.

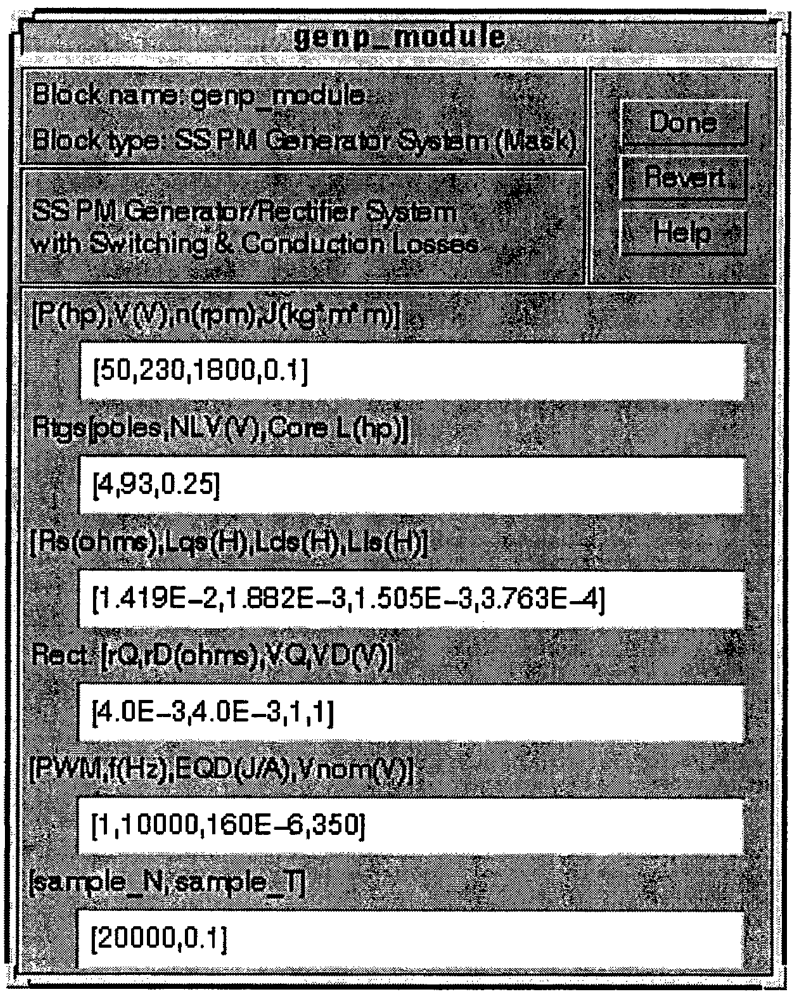


Figure 12. <u>**Window Displayed When Mask Is Activated For The Permanent Magnet Generator Module With Calculated Rectifier Losses**</u>

Table 6. Default Values	
Machine and Rectifier Definitions	**Values**
Rated Power, P	50 hp
Rated Voltage, V	230 V
Rated Speed, n	1800 rpm
Number of Poles, poles	4
No-Load Voltage @ Rated Speed, NLV	93 V
Core Losses @ Rated Voltage & Speed, Core L	0.25 hp
Per-Phase Stator Resistance, R_s	1.419E-2 Ω
Per-Phase Stator q-axis Inductance, L_{qs}	1.882E-3 H
Per-Phase Stator d-axis Inductance, L_{ds}	1.505E-3 H
Per-Phase Stator Leakage Inductance, L_{ls}	3.763E-4 H
Machine Inertia, J	0.1 $kg{\cdot}m^2$
PWM Switching Frequency of the Rectifier, f_c	10000 Hz
Total Switching Energy Loss per Amp of the IGBT-Diode Combination, EQD	160 □J/A
Voltage at which EQD is specified, Vnom	350 V
On State IGBT Resistance, rQ	4.0E-3 □
On State Diode Resistance, rD	4.0E-3 □
Forward Voltage Drop of the IGBT, VQ	1 V
Forward Voltage Drop of the Diode, VD	1 V
Type of PWM used [Sinusoidal(1) or Space Vector(0)]	1
Number of Samples to Save to the MATLAB Workspace, sample_N	20000
Length of Time Between Each Sample, sample_T	0.1

References:

[1] Ken Berringer, Jeff Marvin and Philippe Perruchoud, "Semiconductor Power Losses in AC Inverters," *Conference Record-IAS Annual Meeting* (IEEE Industry Applications Society), pp. 882-886, 1995.

[2] Philippe J.P. Perruchoud and Peter J. Pinewski, "Power Losses for Space Vector Modulation Techniques," *IEEE Workshop on Power Electronics in Transportation*, pp. 167-173, Oct. 1996.

3.3 Steady-State Induction Generator System with Fixed Efficiency Rectifier

INPUTS	OUTPUTS
DC Bus Voltage [V]	Rectifier Current [A]
DC Command Current [A]	[Output Torque [N·m], Machine Inertia [$kg{\cdot}m^2$]]
Engine Speed [rpm]	

Constants as defined by the mask:

VAr:	Rated Power of Motor [W]
Vr:	Rated Line-Neutral Voltage of Motor [V]
wb:	Base Speed of Motor for Per Unit [rad/s]
wmr:	Rated Speed of Motor [rad/s]
poles:	Number of Motor Poles [ ]
corel:	Core Losses of Motor @ Rated Voltage & Speed [W]
SLL:	Stray Load Losses of Motor @ Rated Voltage & Speed [W]
Ib:	Base Line Current of Motor [A]
Zb:	Base Impedance of Motor for Per Unit [Ω]
Rspu:	Per Unit Stator Resistance [ ]
Rrpu:	Per Unit Rotor Resistance [ ]
Lspu:	Per Unit Stator Inductance [ ]
Lrpu:	Per Unit Rotor Inductance [ ]
Lmpu:	Per Unit Magnetizing Inductance [ ]
fluxr:	Per Unit Rotor Flux @ Rated Conditions [ ]
recteff:	Inverter Efficiency [ ]
Inertia_out:	Machine Inertia [kg·m^2]
sample_N:	Number of Samples to Save to the MATLAB® Workspace
sample_T:	Length of Time Between Each Sample

Auxiliary Calculations: None

Mask:

1. SS Induc. Generator Sys.
2. SS Induction Generator/Rectifier System|Gen Rtgs[P(hp),V(V),f(Hz)]:|Rtgs[n(rpm),CL(hp), SLL(hp)]:|[Rs,Rr (ohms), Lls,Llr,Lm (H)]:|Rectifier Efficiency:|Machine Inertia(kg*m*m):|[sample_N, sample_T]:
3. mvr=genIinit(@1,@2,@3);VAr=mvr(1,1);Vr=mvr(1,2);wb=mvr(1,3);wmr=mvr(1,4); poles=mvr(1,5);corel=mvr(1,6);SLL=mvr(1,15);Ib=mvr(1,7);Zb=mvr(1,8);Rspu=mvr(1,9); Rrpu=mvr(1,10);Lmpu=mvr(1,11);Lspu=mvr(1,12);Lrpu=mvr(1,13);fluxr=mvr(1,14); recteff=@4; Inertia_out=@5;sample_N=@6(1,1);sample_T=@6(1,2);')

This module simulates a three-phase squirrel cage induction generator and a three phase boost-type or voltage-sourced (IGBT) rectifier supply. The module mask contains the example values for a 50 hp, 230 V generator, which are user changeable. The core losses and stray load losses are included in the model and can be set in the module mask as well. Please refer to the assumptions below for other important simulation details.

Assumptions:

- This module will only be used in simulations with a minimum time step of 100 ms or larger.
- The generator is controlled at all times with conventional "field-oriented" or "vector" control. That is, the slip frequency and current in generator are regulated to provide dynamic control of the generator torque.
- The flux in the generator is limited to its rated value (≈ rated V/f).
- The torque is limited to the peak or pullout torque for rated flux. The current is therefore limited to the current at peak torque.
- When the bus voltage is not sufficient to provide rated flux, field weakening is enabled which maintains maximum bus voltage on the generator. In this mode, the flux is inversely proportional to the generator speed, and the peak torque is inversely proportional to the square of the generator speed.
- At low speeds, the rotor copper losses significantly affect the performance of the induction generator. When in the *motoring* mode, the actual DC current can overshoot the requested value substantially. To protect the HEV system and eliminate large overshoot in the *motoring mode*, the q-axis stator current is limited to 1.5 pu in addition to the previously discussed limits.
- The copper losses are modeled by R_s and R_r' in
- **Figure** 13. The core losses are calculated to be proportional to the generator flux. The stray load losses are proportional to the generator torque.
- The generator sign convention is that positive current is leaving the terminals of the machine. This current produces positive torque for positive speeds. For the module itself, a positive actual dc rectifier current (output #1) indicates the generating mode.
- Within the module, a set of power values is computed at each time step in order to facilitate energy balance equations. The power values are as follows: the dc bus power, the mechanical power of the generator, the electrical power at the terminals of the machine, the rectifier loss power, and the total motor losses (core, stray load, and copper losses). These values are *not* saved to the workspace automatically.

- The model does not include rectifier harmonic effects.
- The rectifier is assumed to have a fixed, user-definable efficiency.

Figure 13 shows the inputs and outputs of the steady-state induction generator model. Figure 14 depicts the per-phase equivalent circuit model of the induction machine, and defines the generator parameters. Figure 15 shows the induction generator model after the transformation to the synchronous d-q reference frame. The electrical terminal voltages and currents are calculated directly from this equivalent circuit and the mechanical equations using the command values of torque and speed. The synchronous reference frame electrical and mechanical equations used in the simulation are,

$$
\begin{aligned}
v_{qs}^e &= -R_s i_{qs}^e + \omega \lambda_{ds}^e \\
v_{ds}^e &= -R_s i_{ds}^e - \omega \lambda_{qs}^e \\
0 &= R_r i_{qr}^e + (\omega - \omega_r)\lambda_{dr}^e \\
0 &= R_r i_{dr}^e - (\omega - \omega_r)\lambda_{qr}^e \\
\lambda_{qs}^e &= -(L_m + L_{ls}) i_{qs}^e + L_m i_{qr}^e \\
\lambda_{ds}^e &= -(L_m + L_{ls}) i_{ds}^e + L_m i_{dr}^e \\
\lambda_{qr}^e &= (L_m + L_{lr}) i_{qr}^e - L_m i_{qs}^e \\
\lambda_{dr}^e &= (L_m + L_{lr}) i_{dr}^e - L_m i_{ds}^e \\
\tau &= L_m (i_{ds}^e i_{qr}^e - i_{qs}^e i_{dr}^e)
\end{aligned}
$$

where the *e* superscript denotes the synchronous reference frame.

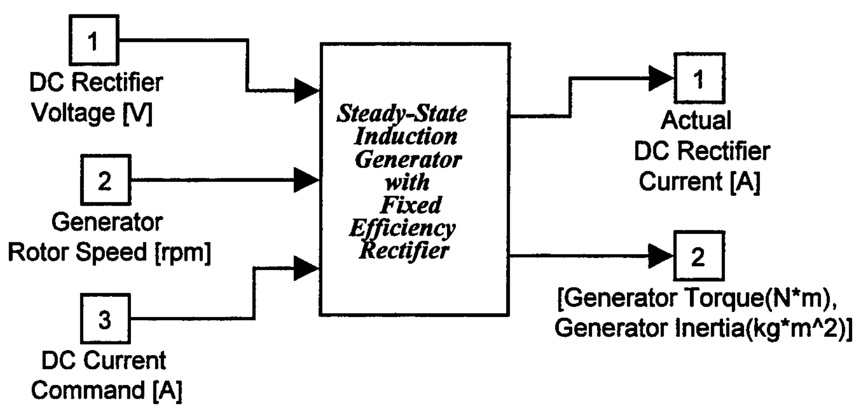


Figure 13. Inputs And Outputs Of The Steady-State Induction Generator Model With A Fixed Efficiency Rectifier

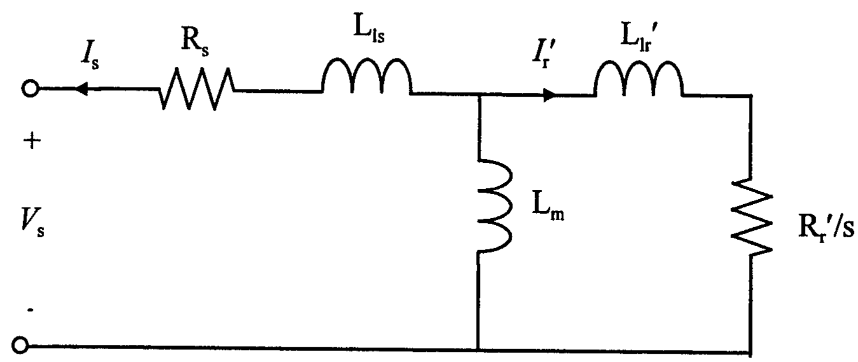


Figure 14. **<u>Induction Machine Per Phase Equivalent Circuit</u>**

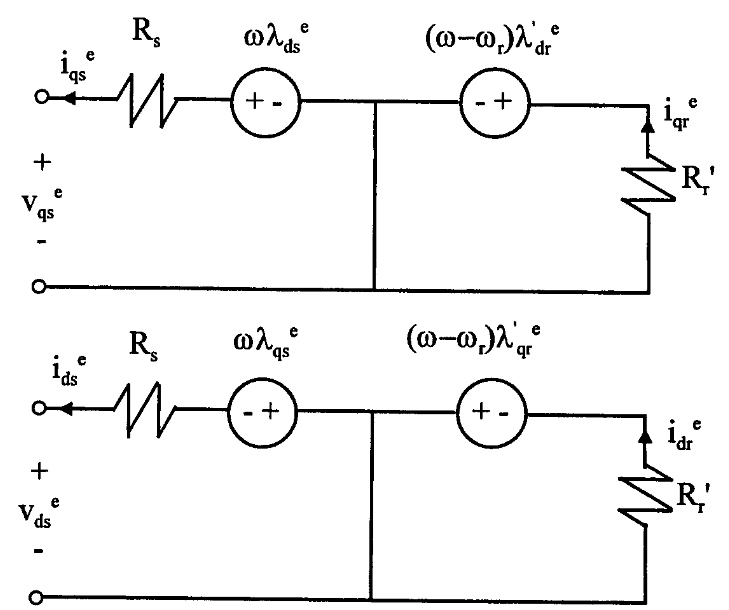


Figure 15. **<u>Steady-State dq Equivalent Circuit Of An Induction Generator</u>**

The generator is controlled using conventional rotor flux field orientation ("brushless dc" control) such that in the synchronous reference frame, $\lambda_{qr}^e = 0$.

When the mask is activated, the window in Figure 15 is displayed. The first input line asks the user to list the rated power, rated line voltage and rated frequency of the induction generator. The next input line requests the values for the rated speed, and the rated core and stray load losses that occur under rated operating conditions. The per-phase machine parameters of stator and rotor resistance, stator and rotor leakage inductance, and the magnetizing inductance are defined in the third line of the mask. The fixed efficiency of the rectifier is specified in line 4, and the system inertia is defined in the fifth input vector. Finally, the user can specify the number of samples and the time step between each sample for use in "To Workspace" blocks within the module. The default values listed in Table 7 below describe a 50 horsepower induction generator with a fixed efficiency rectifier.

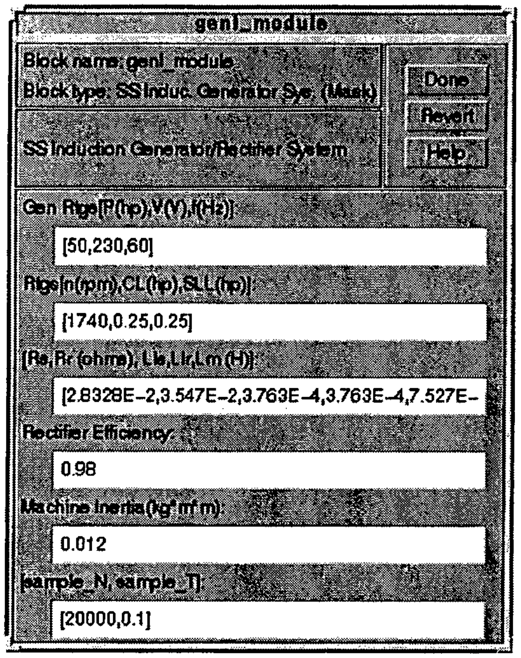


Figure 16. **<u>Window Displayed When Mask Is Activated For The Induction Generator Module With Fixed Rectifier Efficiency</u>**

Table 7. Default Values

Machine Definitions	Values
Rated Power	50 hp
Rated Voltage	230 V
Rated Frequency	60 Hz
Rated Speed	1740 rpm
Core Losses @ Rated Voltage & Speed	0.25 hp
Stray Load Losses @ Rated Voltage & Speed	0.25 hp
Per-Phase Stator Resistance, R_s	2.8328E-2 Ω
Per-Phase Rotor Resistance, R_r	3.547E-2 Ω
Per-Phase Stator Leakage Inductance, L_{ls}	3.763E-4 H
Per-Phase Rotor Leakage Inductance, L_{lr}	3.763E-4 H
Per-Phase Magnetizing Inductance, L_m	7.527E-3 H
Rectifier Efficiency	0.98
Motor Inertia	0.012 [$kg \cdot m^2$]
Number of Samples Saved to Workspace	20000
Time Between each Saved Sample	0.1

3.4 Steady-State Induction Machine - Traction Motor System with Fixed Efficiency Inverter

INPUTS	OUTPUTS
DC Bus Voltage [V]	Inverter Current [A]
Rotor Speed [rpm]	[Output Torque [N·m], Machine Inertia [kg·m^2]
Per Unit Input Torque Command[ ]	

Constants as defined by the mask:

VAr:	Rated Power of Motor [W]
Vr:	Rated Line-Neutral Voltage of Motor [V]
wb:	Base Speed of Motor for Per Unit [rad/s]
wmr:	Rated Speed of Motor [rad/s]
poles:	Number of Motor Poles [ ]
corel:	Core Losses of Motor @ Rated Voltage & Speed [W]
SLL:	Stray Load Losses of Motor @ Rated Voltage & Speed [W]
Ib:	Base Line Current of Motor [A]
Zb:	Base Impedance of Motor for Per Unit [Ω]
Rspu:	Per Unit Stator Resistance [ ]
Rrpu:	Per Unit Rotor Resistance [ ]
Lspu:	Per Unit Stator Inductance [ ]
Lrpu:	Per Unit Rotor Inductance [ ]
Lmpu:	Per Unit Magnetizing Inductance [ ]
fluxr:	Per Unit Rotor Flux @ Rated Conditions [ ]
inveff:	Inverter Efficiency [ ]
Inertia_out:	Machine Inertia [kg·m^2]
sample_N:	Number of Samples to Save to the MATLAB® Workspace
sample_T:	Length of Time Between Each Sample

Auxiliary Calculations: None

Mask:

1. SS Induction Motor Sys
2. SS Induction Motor/Inverter System|Rated [P(hp),V(V),f(Hz)]:|Rated [n(rpm),CL(hp),SLL(hp)]:|[Rs,Rr (ohms), Lls,Llr,Lm (H)]:|Inverter Efficiency:|Machine Inertia(kg*m*m):|[sample_N,sample_T]:
3. mvr=motlinit(@1,@2,@3); VAr=mvr(1,1); Vr=mvr(1,2); wb=mvr(1,3); wmr=mvr(1,4); poles=mvr(1,5); corel=mvr(1,6); SLL=mvr(1,15); Ib=mvr(1,7); Zb=mvr(1,8); Rspu=mvr(1,9); Rrpu=mvr(1,10); Lspu=mvr(1,12); Lrpu=mvr(1,13); Lmpu=mvr(1,11); fluxr=mvr(1,14); inveff=@4; Inertia_out=@5; sample_N=@6(1,1); sample_T=@6(1,2);

This module simulates a three-phase, squirrel-cage induction motor and a three-phase, boost-type or voltage-sourced (IGBT) inverter supply. The module mask contains the example values for a 50 hp, 230 V motor, which are user changeable. The core losses and stray load losses are included in the model and can be set in the module mask as well. Please refer to the assumptions below for other important simulation details.

Assumptions:

- This module will only be used in simulations with a minimum time step of 100 ms or larger.
- The motor is controlled at all times with conventional "field-oriented" or "vector" control. That is, the slip frequency and current in motor are regulated to provide dynamic control of the motor torque.
- The flux in the motor is limited to its rated value (≈ rated V/f).
- The torque is limited to the peak or pullout torque for rated flux. The current is therefore limited to the current at peak torque.
- When the bus voltage is not sufficient to provide rated flux, field weakening is enabled, which maintains maximum bus voltage on the motor. In this mode, the flux is inversely proportional to the motor speed, and the peak torque is inversely proportional to the square of the motor speed.
- The copper losses are modeled by R_s and R_r' in Figure 17. The core losses are calculated to be proportional to the motor flux. The stray load losses are proportional to the motor torque.
- The sign convention for the motor module is that positive current enters the terminals of the machine. Positive current produces positive torque, i.e., positive dc inverter current (output #1) indicates the module is motoring.
- Within the module, a set of power values is computed at each time step in order to facilitate energy balance equations. The power values are as follows: the dc bus power, the mechanical power of the motor, the electrical power at the terminals of the machine, the inverter loss power, and the total motor losses (core, stray load, and copper losses). These values are *not* saved to the workspace automatically.

- The model does not include inverter harmonic effects.
- The inverter is assumed to have a fixed, user-definable efficiency.

Figure 17 shows the inputs and outputs of the steady-state induction motor model. Figure 18 depicts the per-phase equivalent circuit model of the induction machine and defines the motor parameters. Figure 19 shows the induction motor model after the transformation to the synchronous d-q reference frame. The electrical terminal voltages and currents are calculated directly from this equivalent circuit and the mechanical equations using the command values of torque and speed. The synchronous reference frame electrical and mechanical equations used in the simulation are,

$$v_{qs}^e = R_s i_{qs}^e + \omega \lambda_{ds}^e$$
$$v_{ds}^e = R_s i_{ds}^e - \omega \lambda_{qs}^e$$
$$0 = R_r i_{qr}^e + (\omega - \omega_r)\lambda_{dr}^e$$
$$0 = R_r i_{dr}^e - (\omega - \omega_r)\lambda_{qr}^e$$
$$\lambda_{qs}^e = (L_m + L_{ls}) i_{qs}^e + L_m i_{qr}^e$$
$$\lambda_{ds}^e = (L_m + L_{ls}) i_{ds}^e + L_m i_{dr}^e$$
$$\lambda_{qr}^e = (L_m + L_{lr}) i_{qr}^e + L_m i_{qs}^e$$
$$\lambda_{dr}^e = (L_m + L_{lr}) i_{dr}^e + L_m i_{ds}^e$$
$$\tau = L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e)$$

where the *e* superscript denotes the synchronous reference frame.

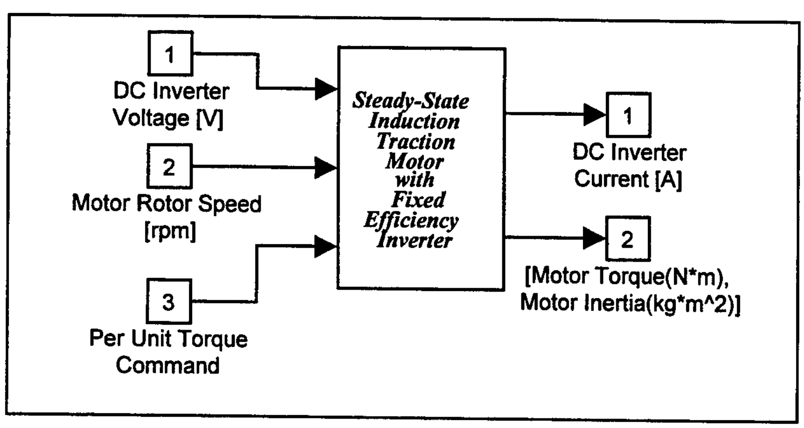


Figure 17. Inputs And Outputs Of Induction Motor System With Fixed Efficiency Inverter

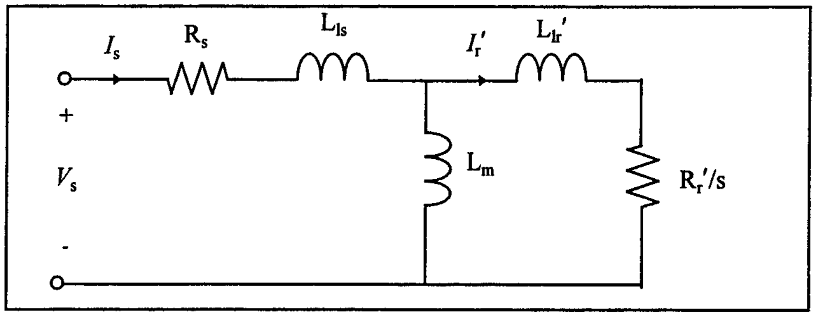


Figure 18. <u>Induction Machine Per Phase Equivalent Circuit</u>

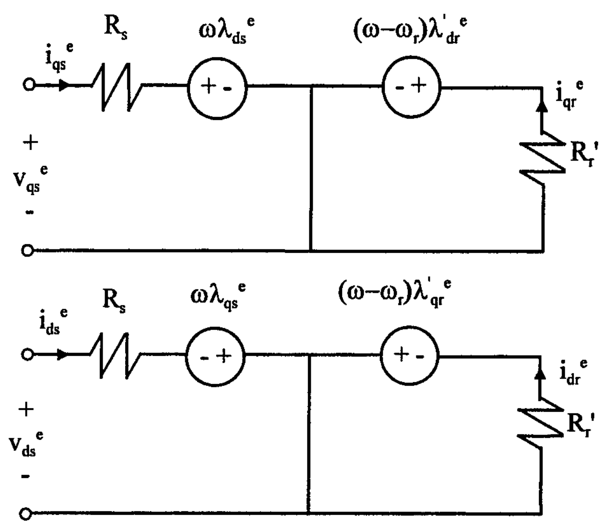


Figure 19. <u>Steady-State dq Equivalent Circuit Of An Induction Motor</u>

The motor is controlled using conventional rotor flux field orientation ("brushless dc" control) such that in the synchronous reference frame, $\lambda_{qr}^e = 0$.

When the mask is activated, the window in Figure 19 is displayed. The first input line asks the user to list the rated power, rated line voltage and rated frequency of the induction motor. The next input line requests the values for the rated speed, and the rated core and stray load losses that occur under rated operating conditions. The per-phase machine parameters of stator and rotor resistance, stator and rotor leakage inductance, and the magnetizing inductance are defined in the third line of the mask. The fixed efficiency of the inverter is specified in line 4 and the system inertia is defined in the fifth input vector. Finally, the user can specify the number of samples and the time step between each sample for use in "To Workspace" blocks within the module. The default values, which describe a 50 horsepower induction machine/traction motor with a fixed efficiency inverter, are listed in Table 8 on the following page.

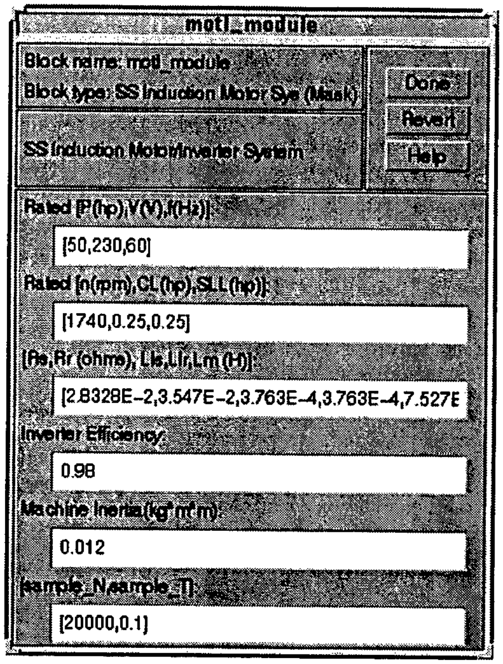


Figure 20. Window Displayed When Mask Is Activated For The Induction Machine – Traction Motor Module With Fixed Rectifier Efficiency

Table 8. Default Values	
Machine Definitions	**Values**
Rated Power	50 hp
Rated Voltage	230 V
Rated Frequency	60 Hz
Rated Speed	1740 rpm
Core Losses @ Rated Voltage & Speed	0.25 hp
Stray Load Losses @ Rated Voltage & Speed	0.25 hp
Per-Phase Stator Resistance, R_s	2.8328E-2 Ω
Per-Phase Rotor Resistance, R_r	3.547E-2 Ω
Per-Phase Stator Leakage Inductance, L_{ls}	3.763E-4 H
Per-Phase Rotor Leakage Inductance, L_{lr}	3.763E-4 H
Per-Phase Magnetizing Inductance, L_m	7.527E-3 H
Inverter Efficiency	0.98
Motor Inertia	0.012 [kg·m^2]
Number of Samples Saved to Workspace	20000
Time Between each Saved Sample	0.1

3.5 Steady-State Induction Machine - Traction Motor System with Calculated Inverter Losses

INPUTS	OUTPUTS
DC Bus Voltage [V]	Inverter Current [A]
Rotor Speed [rpm]	[Output Torque [N·m], Machine Inertia [kg·m^2]]
Per Unit Input Torque Command[ ]	

Constants as defined by the mask:

VAr:	Rated Power of Motor [W]
Vr:	Rated Line-Neutral Voltage of Motor [V]
wb:	Base Speed of Motor for Per Unit [rad/s]
wmr:	Rated Speed of Motor [rad/s]
poles:	Number of Motor Poles [ ]
corel:	Core Losses of Motor @ Rated Voltage & Speed [W]
SLL:	Stray Load Losses of Motor @ Rated Voltage & Speed [W]
Ib:	Base Line Current of Motor [A]
Zb:	Base Impedance of Motor for Per Unit [Ω]
Rspu:	Per Unit Stator Resistance [ ]
Rrpu:	Per Unit Rotor Resistance [ ]
Lspu:	Per Unit Stator Inductance [ ]
Lrpu:	Per Unit Rotor Inductance [ ]
Lmpu:	Per Unit Magnetizing Inductance [ ]
fluxr:	Per Unit Rotor Flux @ Rated Conditions [ ]
Inertia_out:	Machine Inertia [kg·m^2]
fc:	PWM Switching Frequency of the Inverter [Hz]
EQD:	Total Switching Energy Loss per Amp of the IGBT-Diode Combination
[J/A]	
Vnom:	Voltage at which EQD is specified [V]
rQ:	On State IGBT Resistance [Ω]
rD:	On State Diode Resistance [Ω]
VQ:	Forward Voltage Drop of the IGBT [V]
VD:	Forward Voltage Drop of the Diode [V]
PWM:	Determines if Sinusoidal(1) or Space Vector (0) PWM is used.[ ]
sample_N:	Number of Samples to Save to the MATLAB® Workspace
sample_T:	Length of Time Between Each Sample

Auxiliary Calculations: None

Mask:

1. SS Induction Motor Sys
2. SS Induction Motor/Inverter System|Rated [P(hp), V(V), f(Hz), Machine Inertia(kg*m*m)]:|Rated [n(rpm), CL(hp), SLL(hp)]:|[Rs,Rr (ohms), Lls, Llr, Lm (H)]:|Inverter [rQ, rD (ohms), VQ, VD(V)]:|Inverter [PWM, fc(Hz), EQD(J/A), Vnom (V)]:|[sample_N,sample_T]:
3. mdefn=motlinit(@1,@2,@3); VAr=mdefn(1,1); Vr=mdefn(1,2); wb=mdefn(1,3); wmr=mdefn(1,4); poles=mdefn(1,5); corel=mdefn(1,6); SLL=mdefn(1,15); Ib=mdefn(1,7); Zb=mdefn(1,8); Rspu=mdefn(1,9); Rrpu=mdefn(1,10); Lspu=mdefn(1,12); Lrpu=mdefn(1,13); Lmpu=mdefn(1,11); fluxr=mdefn(1,14); rQ=@4(1,1); rD=@4(1,2); VQ=@4(1,3);VD=@4(1,4); PWM=@5(1,1); fc=@5(1,2); EQD=@5(1,3); Vnom=@5(1,4); Inertia_out=@1(1,4); sample_N=@6(1,1); sample_T=@6(1,2);

This module simulates a three-phase, squirrel-cage induction motor and a three-phase, boost-type or voltage-sourced (IGBT) inverter supply. The three phase inverter employs either the sinusoidal PWM method [1] or the space vector PWM method [2]. The module mask contains the example values for a 50 hp, 230 V motor, which are user changeable. The core losses and stray load losses are included in the model and can be set in the module mask as well. Please refer to the assumptions below for other important simulation details.

Assumptions:

- This module will only be used in simulations with a minimum time step of 100 ms or larger.
- The motor is controlled at all times with conventional "field-oriented" or "vector" control. That is, the slip frequency and current in motor are regulated to provide dynamic control of the motor torque.
- The flux in the motor is limited to its rated value (≈ rated V/f).
- The torque is limited to the peak or pullout torque for rated flux. Therefore, the current is therefore limited to the current at peak torque.
- When the bus voltage is not sufficient to provide rated flux, field weakening is enabled which maintains maximum bus voltage on the motor. In this mode, the flux is inversely proportional to the motor speed, and the peak torque is inversely proportional to the square of the motor speed.

- The copper losses are modeled by R_s and R_r' in Figure 21. The core losses are calculated to be proportional to the motor flux. The stray load losses are proportional to the motor torque.
- The sign convention for the motor module is that positive current enters the terminals of the machine. Positive current produces positive torque, i.e., positive dc inverter current (output #1) indicates the module is motoring.
- Within the module, a set of power values is computed at each time step to facilitate energy balance equations. The power values are as follows: the dc bus power, the mechanical power of the motor, the electrical power at the terminals of the machine, the inverter loss power, and the total motor losses (core, stray load, and copper losses). These values are *not* saved to the workspace automatically.
- Loss calculations for the Alt-Rev space vector PWM method [2] are based on the third harmonic PWM method since both control methods result in similar steady-state operation.
- Phase currents and phase voltages of the machine are assumed to be purely sinusoidal for inverter loss calculations. This assumption is justifiable if the PWM frequency is reasonably high.
- The model does not include inverter harmonic effects.

Figure 21 shows the inputs and outputs of the steady-state induction motor model. Figure 22 depicts the per-phase equivalent circuit model of the induction machine and defines the motor parameters. Figure 23 shows the induction motor model after the transformation to the synchronous d-q reference frame. The electrical terminal voltages and currents are calculated directly from this equivalent circuit and the mechanical equations using the command values of torque and speed. The synchronous reference frame electrical and mechanical equations used in the simulation are,

$$v_{qs}^e = R_s i_{qs}^e + \omega \lambda_{ds}^e$$
$$v_{ds}^e = R_s i_{ds}^e - \omega \lambda_{qs}^e$$
$$0 = R_r i_{qr}^e + (\omega - \omega_r)\lambda_{dr}^e$$
$$0 = R_r i_{dr}^e - (\omega - \omega_r)\lambda_{qr}^e$$
$$\lambda_{qs}^e = (L_m + L_{ls}) i_{qs}^e + L_m i_{qr}^e$$
$$\lambda_{ds}^e = (L_m + L_{ls}) i_{ds}^e + L_m i_{dr}^e$$
$$\lambda_{qr}^e = (L_m + L_{lr}) i_{qr}^e + L_m i_{qs}^e$$
$$\lambda_{dr}^e = (L_m + L_{lr}) i_{dr}^e + L_m i_{ds}^e$$
$$\tau = L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e)$$

where the e superscript denotes the synchronous reference frame.

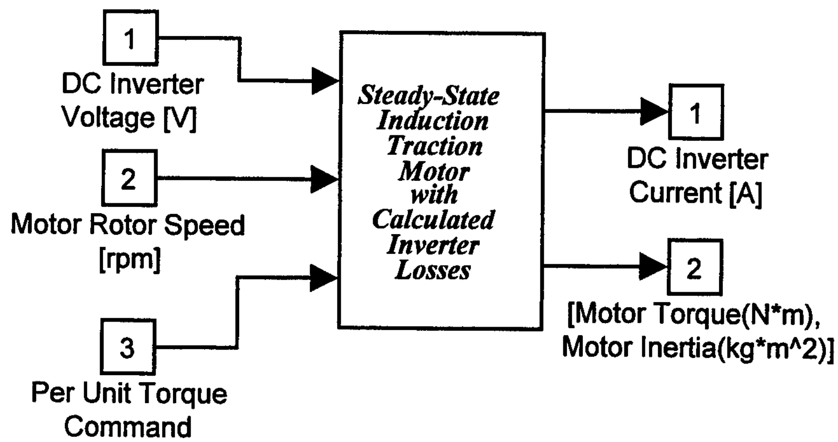


Figure 21. Inputs And Outputs Of Induction Traction Motor System With Calculated Inverter Losses

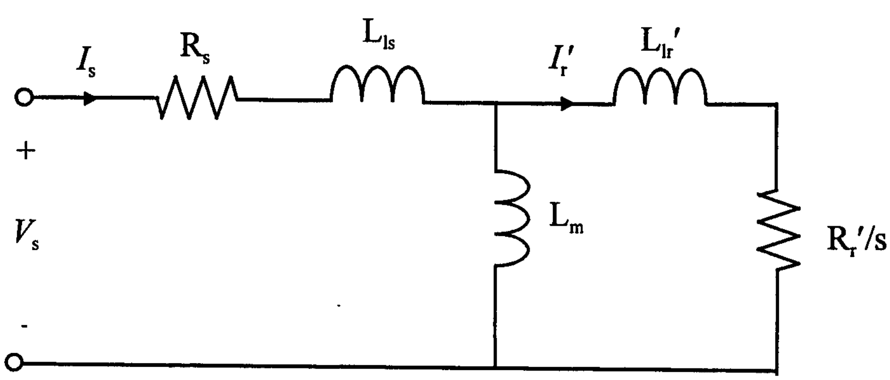


Figure 22. Induction Machine Per Phase Equivalent Circuit

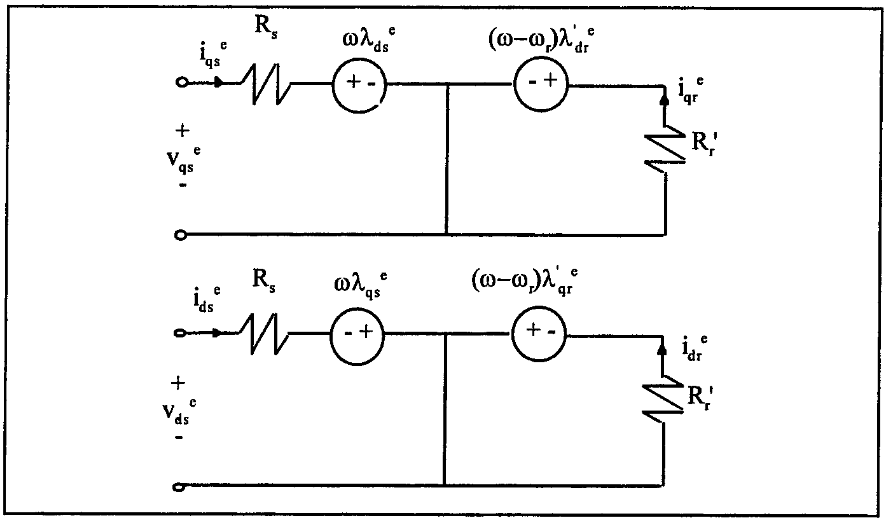


Figure 23. Steady-State dq Equivalent Circuit Of An Induction Motor

The motor is controlled using conventional rotor flux field orientation ("brushless dc" control) such that in the synchronous reference frame, $\lambda_{qr}^{e} = 0$.

The following are the machine variables used for device loss calculations within the inverter:

$$I_P = \sqrt{2}\, Ib \sqrt{2\left(Iqspu^2 + Idspu^2\right)}$$
$$V_p = \sqrt{2}\, V \sqrt{2\left(Vqspu^2 + Vdspu^2\right)}$$
$$\phi = \tan^{-1}\left(\frac{Vdspu}{Vqspu}\right) - \tan^{-1}\left(\frac{Idspu}{Iqspu}\right)$$
$$M = \frac{2V_P}{Vdc}$$

where

V_P	Peak machine output phase voltage
I_P	Peak output current of the machine
M	Modulation index
ϕ	Phase lag of the machine line current
Vdc	Voltage of the DC bus.
Iqspu	RMS q-axis machine output current
Idspu	RMS d-axis machine output current
Vqspu	RMS q-axis machine output phase voltage
Vdspu	RMS d-axis machine output phase voltage

Table 9 shows the equations governing the inverter device currents.

Table 9. Equation Governing the Inverter Device Currents		
Device Currents	**Sinusoidal PWM**	**Space Vector PWM**
$\overline{I_Q}$	$I_p\left(\frac{1}{2\pi}+\frac{M\cos\phi}{8}\right)$	$I_p\left(\frac{1}{2\pi}+\frac{\sqrt{3}M\cos\phi}{12}\right)$
$\overline{I_D}$	$I_p\left(\frac{1}{2\pi}-\frac{M\cos\phi}{8}\right)$	$I_p\left(\frac{1}{2\pi}-\frac{\sqrt{3}M\cos\phi}{12}\right)$
$\lvert I_Q\rvert_{RMS}$	$I_p\sqrt{\frac{1}{8}+\frac{M\cos\phi}{3\pi}}$	$I_p\sqrt{\frac{1}{8}+M\frac{30\cos\phi-\cos3\phi}{45\sqrt{3}\pi}}$
$\lvert I_D\rvert_{RMS}$	$I_p\sqrt{\frac{1}{8}-\frac{M\cos\phi}{3\pi}}$	$I_p\sqrt{\frac{1}{8}-M\frac{30\cos\phi-\cos3\phi}{45\sqrt{3}\pi}}$

where $\overline{I_Q}$ Average current through the IGBT

$\overline{I_D}$ Average current through the diode

$\lvert I_Q\rvert_{RMS}$ RMS current through the IGBT

$\lvert I_D\rvert_{RMS}$ RMS current through the diode

The inverter losses are then calculated using the following equations:

Conduction losses:

$$P_{Q(cond)}=\overline{I_Q}\cdot VQ+\lvert I_Q\rvert_{RMS}^2\cdot rQ$$
$$P_{D(cond)}=\overline{I_D}\cdot VD+\lvert I_D\rvert_{RMS}^2\cdot rD$$

where $P_{Q(cond)}$ Conduction power loss in the IGBT

$P_{D(cond)}$ Conduction power loss in the diode

Switching losses:

$$P_{Q(sw)} = \frac{f \cdot E_Q \cdot I_p}{\pi}\left(\frac{Vdc}{Vnom}\right)$$

$$P_{D(sw)} = \frac{f \cdot E_D \cdot I_p}{\pi}\left(\frac{Vdc}{Vnom}\right)$$

$$P_{TOT(sw)} = P_{Q(sw)} + P_{D(sw)} = \frac{f \cdot EQD \cdot I_p}{\pi}\left(\frac{Vdc}{Vnom}\right)$$

where

$P_{Q(sw)}$	Switching power loss in the IGBT
$P_{D(sw)}$	Switching power loss in the diode
$P_{TOT(sw)}$	Total switching power loss
Vdc	Voltage of the DC bus
E_Q	Switching energy loss per Amp of the IGBT
E_D	Switching energy loss per Amp of the diode
EQD	$E_Q + E_D$

The total inverter loss power (P_{loss}) is six times the sum of the conduction and switching losses of the IGBT and the diode.

$$P_{loss} = 6\left(P_{Q(sw)} + P_{D(sw)} + P_{Q(cond)} + P_{D(cond)}\right)$$

IGBT Selection Guide:

Table 10 shows the IGBT modules that contain antiparallel diodes.

Table 10. IGBT Modules that Contain Antiparallel Diodes

IGBT Module #	Frequency Range (kHz)	VCES (V)	IC @ TJ=25°C (A)	PDMAX (W)	VQMAX @ TJ =25°C (V)	VDMAX @ TJ=25°C (V)	EQD (@Vnom) @ TJ=125°C (mJ/A)	rQ (mΩ) @TJ =125°C	rD (mΩ) @TJ=125°C
IRGDDN300M06	3-10	600	400	1563	2.0	2.0	0.2 @ V_{nom}=300V	–	–
IRGDDN400M06	3-10	600	600	1984	2.0	2.0	0.2 @ V_{nom}=300V	–	–
IRGDDN600M06	3-10	600	800	2604	2.7	2.0	0.2 @ V_{nom}=300V	–	–
IRGDDN200M12	3-10	1200	420	1800	2.7	3.4	0.6 @ V_{nom}=600V	2.00	5.50
IRGDDN300M12	3-10	1200	560	2400	2.7	3.4	0.6 @ V_{nom}=600V	2.50	4.00
IRGDDN400M12	3-10	1200	400	2770	2.7	3.4	0.6 @ V_{nom}=600V	–	–
IRGDDN300K06	10-30	600	340	1563	2.7	2.0	0.15 @ V_{nom}=300V	–	–
IRGDDN400K06	10-30	600	520	1984	2.7	2.0	0.15 @ V_{nom}=300V	–	–
IRGDDN600K06	10-30	600	680	2604	2.7	2.0	0.15 @ V_{nom}=300V	–	–

where	V_{CES}	Maximum Continuous Collector to Emitter Voltage
	I_C	Maximum Continuous Collector Current
	P_{DMAX}	Maximum Power dissipation
	VQ_{MAX}	Maximum Collector to Emitter ON Voltage
	VD_{MAX}	Maximum Forward Voltage Drop of the Diode
	EQD	Total Switching Energy Loss per Amp of the IGBT-Diode Combination
	V_{nom}	Collector Voltage at which EQD is specified
	rQ	On State IGBT Resistance
	rD	On State Diode Resistance
	T_J	Device Junction Temperature

The value of on-state resistance of the IGBT and diode is found by calculating the inverse of the slope of the device current versus device voltage curve(during conduction).

When the mask is activated, the window in Figure 24 is displayed. The first input line asks the user to list the rated power, rated line voltage, and rated frequency of the induction motor as well as the system inertia. The next input requests the values for the rated speed, and the rated core and stray load losses that occur under rated operating conditions. The per-phase machine parameters of stator and rotor resistance, stator and rotor leakage inductance, and the magnetizing inductance are defined in the third line of the mask. The inverter is described by the next two input vectors of the mask. In the first vector, the on-state resistance of the switching devices (rQ) and the diodes (rD) and their respective forward voltage drops are defined. The second input vector for the inverter specifies the PWM method (1 for Sinusoidal/0 for Space Vector), the switching frequency, the total switching energy loss per amp of the switching device/diode combination, and the collector voltage at which this switching loss occurs. Finally, the user can specify the number of samples and the time step between each sample for use in "To Workspace" blocks within the module. The default values listed in Table 11 on the following page describe a 50 horsepower induction machine/traction motor with a three-phase IGBT boost inverter.

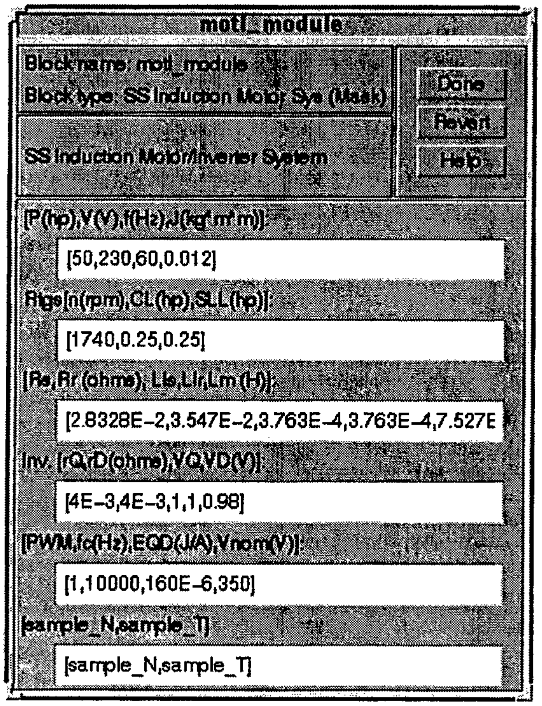


Figure 24. Window Displayed When Mask Is Activated For The Induction Machine – Traction Motor Module With Calculated Inverter Losses

Table 11. Default Values

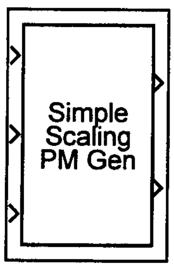
Machine and Inverter Definitions	Values
Rated Power	50 hp
Rated Power	50 hp
Rated Voltage	230 V
Rated Frequency	60 Hz
Rated Speed	1740 rpm
Stray Load Losses @ Rated Voltage & Speed	0.25 hp
Core Losses @ Rated Voltage & Speed, Core L	0.25 hp
Per-Phase Stator Resistance, R_s	2.8328E-2 Ω
Per-Phase Rotor Resistance, R_r	3.547E-2 Ω
Per-Phase Stator Leakage Inductance, L_{ls}	3.763E-4 H
Per-Phase Rotor Leakage Inductance, L_{lr}	3.763E-4 H
Per-Phase Magnetizing Inductance, L_m	7.527E-3 H
Motor Inertia	0.012 [kg·m^2]
PWM Switching Frequency of the Inverter, fc	10000 Hz
Total Switching Energy Loss per Amp of the IGBT-Diode Combination, EQD	160 □J/A
Voltage at which EQD is specified, Vnom	350 V
On State IGBT Resistance, rQ	4.0E-3 □
On State Diode Resistance, rD	4.0E-3 □
Forward Voltage Drop of the IGBT, VQ	1 V
Forward Voltage Drop of the Diode, VD	1 V
Type of PWM used [Sinusoidal(1) or Space Vector(0)]	1
Number of Samples to Save to the MATLAB Workspace, sample_N	20000
Length of Time Between Each Sample, sample_T	0.1

References:

[1] Ken Berringer, Jeff Marvin and Philippe Perruchoud, "Semiconductor Power Losses in AC Inverters," *Conference Record-IAS Annual Meeting* (IEEE Industry Applications Society), pp. 882-886, 1995.

[2] Philippe J.P. Perruchoud and Peter J. Pinewski, "Power Losses for Space Vector Modulation Techniques," *IEEE Workshop on Power Electronics in Transportation*, pp. 167-173, Oct. 1996.

3.6 Table lookup steady-state generator (No electrical parameters)



INPUT	OUTPUT
Desired AC Current (Amps)	Shaft Torque (N-m)
Shaft Speed (rpm)	DC Current (Amps)
DC Bus Voltage (V)	Actual AC Current (Amps)

Purpose: ****

Parameters:

llimw_mot	vector of shaft speed (rad/s) for lookup of limit current (motor mode)
llimw_gen	vector of shaft speed (rad/s) for lookup of limit current (motor mode)
llim_mot	vector of limit currents in motor mode
llim_gen	vector of limit currents in generator mode
mtrp1_Voc	line to line voltage (V) for machine at design speed but open circuit
mtrp1_Vd	line to line voltage (V) for machine at design conditions
mtrp1_Np	number of poles
mtrp1_n	shaft speed (rad/s) for machine at design conditions
mtrp1_I	line to line current (A) for machine at design conditions
mtrp1_J	motor inertia constant (kg*m^2)
mtrp1_eff	motor efficiency (0-1)
mtrp1_conv_eff	converter efficiency (0-1)

Auxiliary Calculations:

Ke = Voc/ ω_d ω_d is design speed in rad/s

$$K_t = \frac{I * V_d * \sqrt{3}}{\omega_d} \eta_m$$

$$Ls = \sqrt{\frac{V_d^{\,2} - V_{oc}^{\,2}}{(I * \omega_d * Np/2)^2}}$$

genp1_module1 Mask

(1) genp_simp
(2) Simple Scaling PM Generator Definitions (Click on "Help" to list Inport and Outport parameters.)|Limit Current Lookup Vectors|Ke & Kt|[Motor Efficiency,Converter Efficiency]|[Npoles,Ls]|Inertia Constant (kg*m^2)
(3) Ilimw_mot=@1(1,:);Ilimw_gen=@1(2,:);Ilim_mot=@1(3,:);Ilim_gen=@1(4,:); Ke=@2(1);Kt=@2(2);eff_motor=@3(1);c1=sqrt(3)/@3(2);c2=sqrt(3)*@3(2); npLs=@4(1)*@4(2)/2;J=@5;
(4) Simple\nScaling\nPM Gen
(5) Simple Scaling PM Generator Block Port Parameters\n\nInport 1: DC Bus Voltage (V).\nInport 2: Shaft Speed (RPM).\nInport 3: AC Current Command (A).\n\n Outport 1: DC Current (A).\nOutport 2: Vector of [Shaft Torque (N*m), Inertia Constant (kg*m^2)].

Modeling Equations

$V_{ac} = K_e * \omega_d$ where η_m is the machine efficiency

$T = I_{ac} * K_t * \eta_m$ for motor mode (Iac >0)

$I_{ac} * K_t / \eta_m$ for generator mode (Iac<0)

$$I_{dc} = \frac{V_{ac} * I_{ac} * \sqrt{3}}{V_{dc}} \left(\frac{1}{\eta_c}\right)$$ for motor mode (Iac >0)

$$= \frac{V_{ac} * I_{ac} * \sqrt{3}}{V_{dc}} \eta_c$$ for generator mode (Iac<0)

and η_c is the converter efficiency

4.0 ENERGY STORAGE LIBRARY

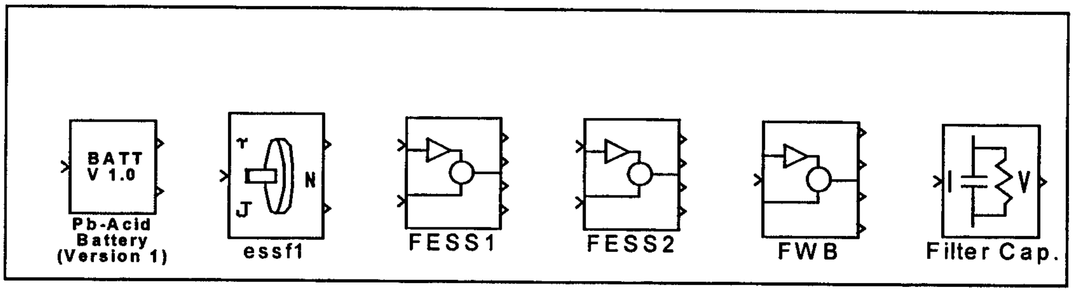
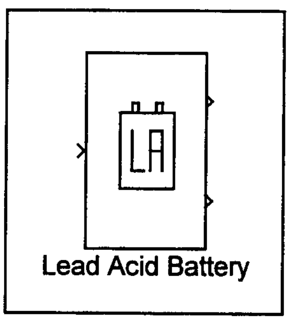


Figure 25. **Battery Model Library**

The energy-storage library contains modules that can be used to store or deliver energy to an HEV. The energy-storage device is typically located between a power management controller and the traction motor.

4.1 Lead Acid Battery



INPUTS	OUTPUTS
System Current Sum [A]	DC Bus Voltage [V]
	State-Of-Charge [ ]

Constants as defined by the mask:

tot_num:	Total Number of Series Cells in System [ ]
Eoc:	Open-Circuit Voltage of a Single Cell [V]
cell_r:	Internal Resistance of a Cell [Ω]
cell_K:	Polarization Resistance of a Cell[Ω]
term_Rb:	Terminal Resistance of the Battery System [Ω]
Ct:	Terminal Capacitance of the Battery System [F]
C5:	Discharge Capacity @ 5 hour rate and 30°C [A-hr]
chrg_eff:	Charge Efficiency of the Battery [ ]
dischrg_eff:	Discharge Efficiency of the Battery [ ]
amb_T:	Ambient Temperature in °C (-20°C to 60°C)
init_ECP:	Initial Polarization Voltage [V]
init_SOC:	Initial State-of-Charge of Battery System (0-1)
init_Q:	Initial Energy within the Battery

Auxiliary Calculations: None

Mask:

1. Lead-Acid Battery - ESS
2. Lead-Acid Battery-Series Cell Configuration| [Num of Cells, Eoc(V) of cell]: |Cell Defns[r,Kpr (ohms)]: |Term Defns[Rb(ohms),Ct(F)]: |Chrg Defns[Cap(A-hrs)]: |[chg eff,dischg eff,temp(C)]: |[Init K V(V),Init SOC(0-1)]:
3. tot_num=@1(1,1); Eoc=@1(1,2); cell_r=@2(1,1); term_Rb=@3(1,1); cell_K=@2(1,2); Ct=@3(1,2); C5=@4(1,1); amb_T=@5(1,3); chrg_eff=@5(1,1); dischrg_eff=@5(1,2); init_ECP=@6(1,1); init_SOC=@6(1,2); init_Q=C5*3600*(1-@6(1,2));

Assumptions:

- The battery model is valid for the temperature range -20°C to 60°C.
- The internal resistance of the battery is considered constant throughout the battery operation. Typically, this varies with battery state of charge and temperature.
- When modeling a collection of batteries, each battery is assumed to have the same open circuit voltage and state of charge. In actuality, this is not true, since each battery can be at a different state of charge and therefore have a different open circuit voltage.
- Positive current entering the battery charges, negative current discharges
- The electrode polarization is not big.
- Electromotive potential E is the function of SOC and temperature.
- Polarization resistance depends on both the SOC and the direction of the current.
- Capacity is the function of temperature and current.
- Acid electrolyte mole concentration (if flooded battery) is 5M when the battery is fully charged.

The inputs and outputs of the lead-acid battery, energy-storage system are shown in Figure 26.

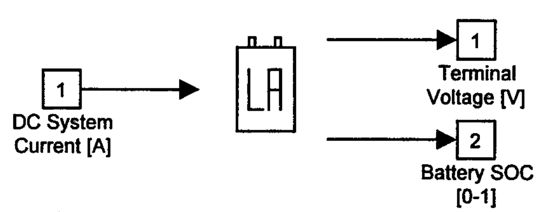


Figure 26. <u>Inputs And Outputs Of Lead-Acid Battery Energy-Storage System</u>

The mask contains default values for 300V – 25 12V cell, lead-acid battery system. These values are listed in Table 12. An example of the mask window for this module is displayed in Figure 27. The first input line asks for the number of cells within the energy storage system and the open circuit voltage of a single cell. The next input vector defines the internal cell resistance and the polarization resistance of a cell. The terminal resistance and capacitance of the energy-storage system are listed in next input vector. The total capacity of the energy-storage system is defined in the fourth vector. The fifth input vector contains the values for the ambient temperature of the system as well as the system's charge and discharge efficiencies. The initial state of the energy-storage system is defined by the initial polarization voltage and the initial state of charge.

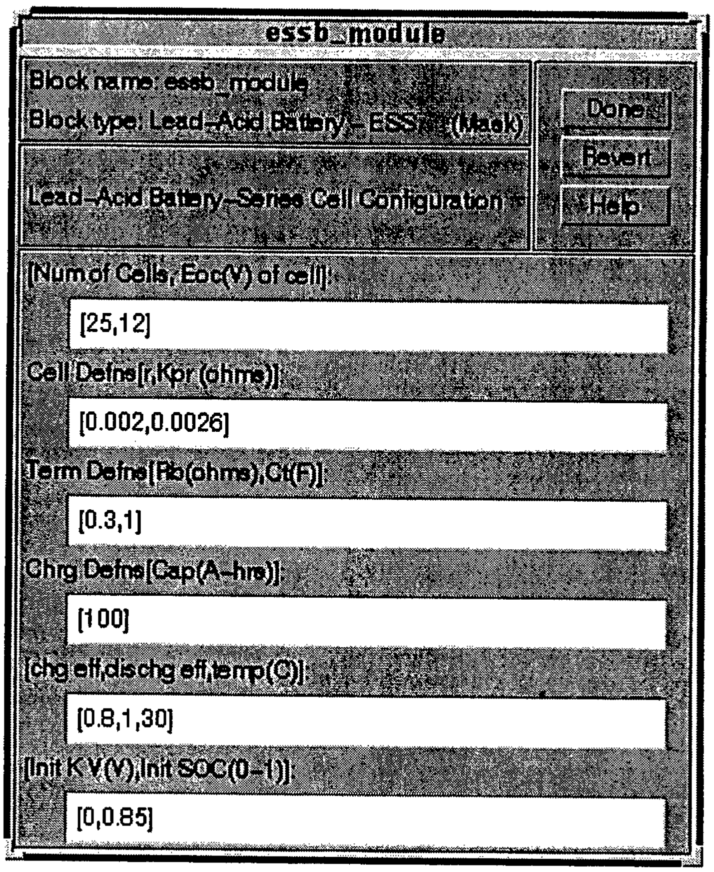
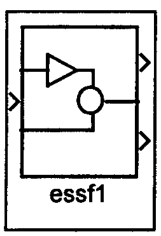


Figure 27. **<u>Window Displayed When Mask Is Activated For The Lead Acid Battery – Energy Storage System</u>**

Table 12. Default Values	
System Definitions	**Values**
Total Number of Batteries	25 cells
Single Battery Open-Circuit Voltage	12 V
Internal Resistance(r) of a Battery	2.0E-3 Ω
Polarization Resistance(K) of a Battery	2.6E-3 Ω
Terminal Resistance(Rb) of the Battery Pack	0.3 Ω
Terminal Capacitance of the Battery Pack	1.0 F
Discharge Capacity @ 5 hour rate and 30°C for a Battery	100 [A-hr]
Charge Efficiency of the Battery System	0.8
Discharge Efficiency of the Battery System	1
Ambient Temperature in °C	30°C
Initial Polarization Voltage(η)	0
Initial State-of-Charge of the Battery System(0-1)	0.85

4.2 Flywheel Battery



INPUTS	OUTPUTS
Input Current (A)	DC Bus Voltage (V)
	Flywheel State of Charge (0-1)

Purpose:

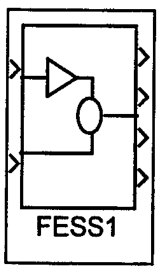
This block models a flywheel battery and an associated internal controller. The model incorporates a simple flywheel model with a steady-state PM motor/generator model and inverter/rectifier. The inputs and outputs are the same as the chemical battery making this device appear as a controllable DC voltage source. In order to make voltage an output, this model includes a capacitor and resistor in parallel across the terminal. The choice of capacitance to maintain stability in the bus voltage is dependent on the peak loads, and time step being used in the simulation. Note that this capacitance does not relate directly to a capacitor rating required on the bus. Though some form of capacitance will be required, its exact value will require a higher fidelity simulation running at much smaller time steps than the 1/10 sec typically used for this model. The controller included in this model is a sample of a simple technique for maintaining a specified voltage on the bus. Other control methods may also be desired and may be implemented by the user by unmasking the block.

Parameters:

Auxiliary Calculations: None

Flywheel Battery Mask: *no mask)*

4.2.1 Flywheel Battery (Roller Bearings)



INPUTS	OUTPUTS
Voltage (V)	Output Current (A)
Current Command (A)	Speed (RPM)
	Discharge Efficiency (0-1)
	Charge Efficiency (0-1)

Purpose:

There are two major components and one auxiliary component of this system:

1. Motor/Generator and Converter
2. Flywheel
3. Efficiency Calculation

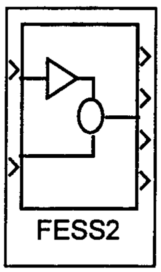
This subsystem uses a permanent magnet generator. The 'current command' is the current command provided to the generator controller. The 'output current' is the actual current output to the DC Bus. Inputs for the 'Flywheel Subsystem' are DC Voltage, generator torque, generator inertia, and bearing loads. The 'Flywheel Subsystem' has outputs of auxiliary current draw, stored mechanical power, and rotor speed.

Parameters:

Auxiliary Calculations: None

Flywheel Energy Storage Subsystem 1 Mask: *(no mask)*

4.2.2 Flywheel Battery (Magnetic Bearings)



INPUTS	OUTPUTS
Voltage (V)	Output Current (A)
Current Command (A)	Speed (RPM)
	Discharge Efficiency (0-1)
	Charge Efficiency (0-1)

Purpose:

There are two major components and one auxiliary component of this system:

1. Motor/Generator and Converter
2. Flywheel
3. Efficiency Calculation

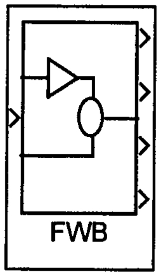
This subsystem uses a permanent magnet generator. The 'current command' is the current command provided to the generator controller. The 'output current' is the actual current output to the DC Bus. Inputs for the 'Flywheel Subsystem' are DC Voltage, generator torque, generator inertia, and bearing loads. The 'Flywheel Subsystem' has outputs of auxiliary current draw, stored mechanical power, and rotor speed.

Parameters:

Auxiliary Calculations: None

Flywheel Energy Storage Subsystem II Mask: *(no mask)*

4.2.3 Flywheel Battery (Simple Model)



INPUTS	OUTPUTS
Input Current (A)	Voltage (V)
	SOC (0-1)
	Discharge Efficiency (0-1)
	Charge Efficiency (0-1)

Purpose:

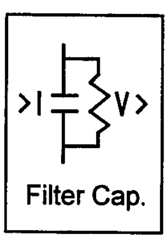
This block models a flywheel battery with a simple feed-forward control and low gain feedback. The feed-forward signal exactly balances the input current. There is a low gain feedback to keep the bus voltage near its reference to adjust for losses.

Parameters:

Auxiliary Calculations: None

Flywheel Battery System Mask: *(no mask)*

4.3 Capacitor



INPUTS	OUTPUTS
Current [amps]	Voltage [volts]

Constants:

cap_capacitance: Capacitance [F]
cap_resistance: Self-discharge resistance [Ω]
cap_initial_voltage: Initial Charge Voltage [V]

Auxiliary Calculations: None

Mask:

(1) Capacitor Module

(2) Capacitor Module|Capacitance [F]|Self-Discharge Resistance [ohms]|Initial Voltage [V]

(3) Capacitance=@1;Resistance=@2;Initial_Voltage=@3;

Assumptions:

- For most capacitors the primary loss mechanism is the series resistance of the capacitor. This has been ignored in this model to avoid algebraic loops which could arise. There are other secondary effects such as hysteresis which could be modeled, but in general these effects are neglected.

The following presents typical values of the constants used in the capacitor model

Constant	Value
cap_capacitance:	20E-3 [F]
cap_resistance:	2E6 [Ω]
cap_initial_voltage:	230 [V]

5.0 VEHICLE LIBRARY

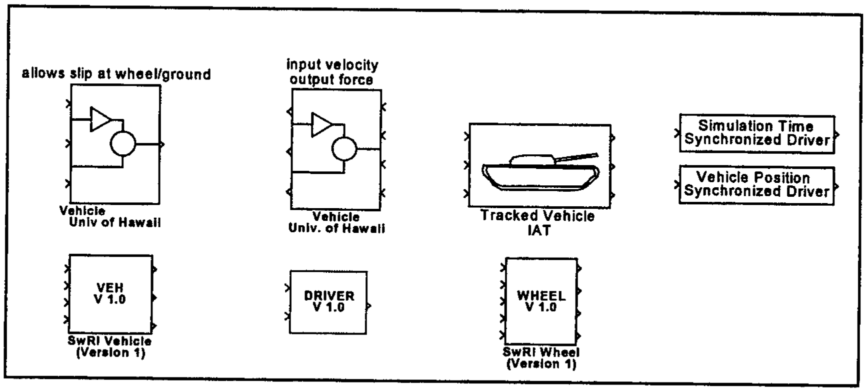
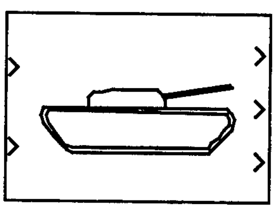


Figure 28. Vehicle Model Library

This library contains models of both tracked and wheeled vehicles. There are two versions for the wheeled vehicle and wheel modules. The first version contains a differentiator block, and the second version avoids this differentaitor block through reformulation of the dynamic equations. Both versions have been tested to produce the same results, although version 2 executes faster than version 1.

5.1 Tracked Vehicle



INPUTS	OUTPUTS
Fuel Mass(kg)	Sprocket (Axle) Speed (rpm)
Vector of [Shaft Torque(N-m), Eff Motor + Coupling Inertia (kg*m^2)	Vehicle Position (m)
Terrain Gradient (rad)	Vehicle Velocity (rpm)

Purpose:

The purpose of this block is to simulate the dynamics of a tracked vehicle by summing forces from various inputs, including aerodynamic drag, rolling resistance, and drag due to slope. This sum is divided by the inertia of the vehicle to determine its acceleration, which is then integrated once for velocity and twice for position. Note that this model does not include active suspension loads.

Parameters:

track_r	radius (m) of track drive sprocket
track_b	track damping constant (N/(rad/s)) for friction torque
track_J	effective inertia of track (in vehicle reference frame, Kg* m^2)
veh_mass	Gross vehicle mass less fuel (kg)
veh_Cd	coefficient of aerodynamic drag of the vehicle
veh_A	Frontal area of vehicle (m^2)
veh_pos_i	Initial position of vehicle (m)
veh_spd_i	Initial velocity of vehicle (m/s)
veh_RR_m:	Rolling resistance of vehicle (velocity independent) [N/kg]
veh_RR_v:	Rolling resistance vs. velocity [N/(m/s)]
sample_N	max number of samples
sample_T	simulation time between samples

Auxiliary Calculations: None

Vehicle Mask

(1) Tracked-Vehicle Dynamics

(2) Tracked Vehicle Dynamics Block Definitions\n(Click on "Help" to list Inport and Outport parameters.)|[Sprocket Radius (m), Damping Constant (N*s), Inertia (kg*m^2)]|Vehicle Mass (kg)|{RR_m (N/kg),RR_v (N*s/m),Cd,Affront]|[Initial Position (m),Initial Speed (m/s)]|[sample_N,sample_T]

(3) r=@1(1);b=@1(2);J=@1(3);mass=@2;RR_m=@3(1);RR_v=@3(2);Cd=@3(3); A=@3(4);pos_i=@4(1);spd_i=@4(2);sample_N=@5(1);sample_T=@5(2);

(4) *Drawing Commands*

(5) Tracked-Vehicle Dynamics Block Port Parameters\n\nInport 1: Fuel Mass (kg).\nInport 2: Vector of [Shaft Torque (N*m), Effective Motor+Coupling Inertia (kg*m^2)].\nInport 3: Terrain Gradient (radians).\n\nOutport 1: Sprocket (Axle) Speed (RPM).\nOutport 2: Vehicle Position (m)\nOutport 3: Vehicle Velocity (m/s)

Model Equations:

This model is appropriate for modeling heavy vehicles and in particular, vehicles with tracks, where there is data on the static rolling resistance. It assumes that there are five forces acting on the vehicle:

The aerodynamic force: Faero = Cd*Area*vel^2

The static rolling resistance: Frrm = Rm*vehicle mass

The dynamic rolling resistance: Frrv = Rv*vel

The gravity force (dependent on grade in direction of travel):

Fgrad = vehicle mass * g * sin(grad)

The effective thrust force of the drive train: an input (see note below)

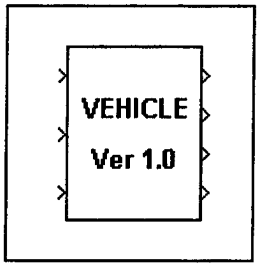
These forces are summed and divided by the effective mass of the vehicle to determine its acceleration. This acceleration can then be integrated to determine the velocity of the vehicle.

The effective mass of the vehicle is determined by the following equation, which accounts for fuel usage and rotational inertia of the drive train.

$$m_{effective} = m_{dry} + m_{fuel} + m_{effdrivetrain}$$

Note that the effective thrust available from the drive train has had all velocity-dependent torques deducted in previous blocks, but has not had any deduction for inertial effects. These inertial effects are collected in this block and accounted for in meffdrivetrain.

5.2 Wheeled Vehicle (Version 1)



Inputs	Outputs
Vehicle Velocity [m/s]	Total Load on Vehicle [N]
Road Grade [radian]	Maximum Traction Force [N]
Fuel Mass [kg]	Total Vehicle Mass [kg]
Vehicle Acceleration [m/s^2]	

Constants:

veh_air_density:	Density of the air that the vehicle is exposed to [kg/m^3]
veh_aero_drag_coef:	Drag coefficient of vehicle [ ]
veh_front_area:	Frontal area of vehicle [m^2]
veh_normal_wind:	Wind velocity normal to vehicle motion [m/s]
veh_parallel_wind:	Head wind velocity [m/s]
veh_coef_yaw_sens:	Coefficient of yaw sensitivity of the vehicle during motion [ ]
veh_drag_coef:	Aerodynamic drag coefficient [ ]
veh_fs:	Vehicle speed dependent rolling coefficient [ ]
veh_f0:	Vehicle speed independent rolling coefficient [ ]
Timesteps_max:	Maximum number of the array size of variables saved to workspace during simulation

Auxiliary Calculations:

yout_veh:	An array consisting of two vectors: actual vehicle velocity [km/hr] and distance traveled [km]
veh_RR_tract_loss:	Rolling resistance energy loss during acceleration [kWh]
veh_RR_regen_loss:	Rolling resistance energy loss during deceleration [kWh]
veh_aero_regen_loss:	Aerodynamic resistance energy loss during acceleration [kWh]
veh_aero_tract_loss:	Aerodynamic resistance energy loss during deceleration [kwh]
veh_inertial_tract_energy:	Total energy required to accelerate vehicle [kwh]
veh_inertial_regen_energy:	Total recovery energy available during deceleration [kwh]

Mask:

(1) Vehicle Module

(2) Vehicle Module (SwRI)|[Air Density [kg/m^3],Vehicle Aero Drag Coeff [ ]]|Vehicle frontal Area [m^2]|[Normal Wind Speed [m/s], Parallel Wind Speed [m/s]]|[Speed
Effect Friction Coef [],road friction coefficient [],Vehicle coef of yaw sensitivity [ ] |Vehicle Mass [kg]|Maximum Time Steps [ ]

(3) veh_air_density=@1[1];veh_aero_drag_coef=@1[2];veh_front_area=@2; veh_normal_wind=@3[1];veh_parallel_wind=@3[2];veh_fs=@4[1];veh_f0=@ 4[2];veh_coef_yaw_sens=@4[3];veh_mass=@5;timesteps_max=@6;

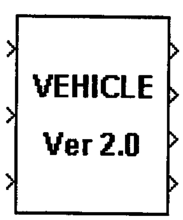
Assumptions:

- The total load acting on the vehicle is the sum of all the driving resistance forces. These consist of the aerodynamic drag, tire rolling resistance, and road grade dependent loads. In the calculation of aerodynamic forces, the effect of head wind and normal wind components have been included. In the computation of the tractive resistance, the effect of the vehicle speed on the traction coefficient has been considered.
- The total vehicle mass includes the weight of the fuel, which decreases as the heat engine produces power.

The following presents typical values used for the constants in the vehicle model

Constant	Value
veh_air_density:	1.23 [kg/m^3]
veh_aero_drag_coef:	0.4 [ ]
veh_front_area:	3.0 [m^2]
veh_normal_wind:	0.0 [m/s^2]
veh_parallel_wind:	0.0 [m/s^2]
veh_coef_yaw_sens:	0.002 [ ]
veh_drag_coef:	0.4 [ ]
veh_fs:	0.005 [ ]
veh_f0:	0.01 [ ]
Timesteps_max:	10000 [ ]

5.3 Wheeled Vehicle (Version 2)



INPUTS	OUTPUTS
Driving force into vehicle [N]	Velocity of vehicle [m/s]
Mass of fuel consumed [kg]	
Brake fraction [ ]	
Wheel mass [kg]	
Road grade [rad]	

Constants:

same as Wheeled Vehicle (Version 1) (see Section 5.2)

Auxiliary calculations:

veh1_accel_hist:	Vehicle acceleration history
veh1_speed_hist	Vehicle speed history
veh1_position_hist	Vehicle position history

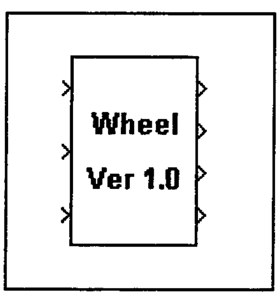
Mask:

(1) Vehicle Module
(2) Vehicle Module|Air Density (kg/m^3), Aero Drag Coeff ( )|Vehicle Frontal Area (m^2)|Normal Wind Speed (m/s),Parallel Wind Speed (m/s)|Spd-dep Rolling Coef,V-indep Roll Coeff,Yaw Sens Coeff|Vehicle Chassis Mass (kg), Road/Tire Friction Coefficient [ ]|Record Variable Quantity and Time (#,sec)
(3)veh_air_density=@1(1);veh_aero_drag_coef=@1(2);veh_front_area=@2;veh_normal_wind =@3(1);veh_parallel_wind=@3(2);veh_fs=@4(1);veh_f0=@4(2);veh_coef_yaw_sens=@4(3); veh_mass=@5(1);roadtire_frict_coef=@5(2);sample_N=@6(1);sample_T=@6(2);

Assumptions: Same as Wheeled Vehicle (Version 1) (see Section 5.2)

For typical values for the constants, please refer to Section 5.2.

5.4 Wheel (Version 1)



Inputs	Outputs
Driving force into vehicle [N]	Velocity of vehicle [m/s]
Mass of fuel consumed [kg]	
Brake fraction []	
Wheel mass [kg]	
Road grade [rad]	

Constants:

whl1_tr:	Wheel Tire Radius [m]
whl1_mass:	Wheel mass [kg]
motor_N_max:	Maximum motor speed [rpm]
timesteps_max:	Maximum number of the array size of variables saved to workspace during simulation

Auxiliary Calculations:

service_brk_energy:	Energy loss during application of the mechanical brake [kWh]
whl_tract_energy:	Energy delivered to the wheels during acceleration [kWh]
whl_regen_energy:	Energy recovered by the vehicle during deceleration of wheel [kWh]

Mask:

(1) Wheel Module

(2) Wheel Module (SwRI)|Wheel Tire Radius [m]|Wheel Tire Mass [kg]|Max Motor Speed [rpm]|Max Timesteps [ ]

(3) whl_tr=@1;whl_mass=@2;motor_N_max=@3;timesteps_max=@4;

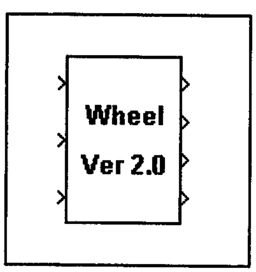
Assumptions:

The vehicle velocity and acceleration are based on the assumption that the entire mass of the vehicle is concentrated at the wheel center.

The following presents typical values used for the constants in the wheel model.

Constant	Value
whl1_tr:	0.3 [m]
whl1_mass:	25 [kg]
motor_N_max:	7000 [rpm]
timesteps_max:	10000

5.5 Wheel (Version 2)



INPUTS	OUTPUTS
Input Torque [Nm]	Driving Force [N]
Coupler Inertia [kg m^2]	Rotational Speed of Wheel [rad/sec]
Vehicle Velocity [m/s]	Equivalent mass [kg]

Constants:

whl1_tr:	Wheel Tire Radius [m]
whl1_mass:	Wheel mass [kg]

Auxiliary Calculations: None

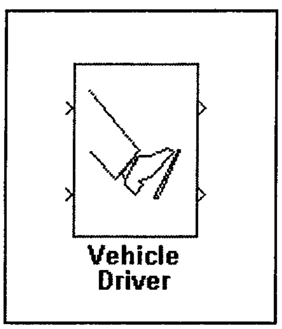
Mask:

1. WHEEL MODULE
2. WHEEL MODULE (SwRI)\n\n T1,V,J1 (in) <=> F,N2,m (out)|Wheel System's Tire Radius [m]| Total Wheel Mass (Wheel,Tire, and Brake Sys) [kg]
3. wheel_radius = @1; wheel_mass = @2;

Assumptions:

The vehicle velocity and acceleration are based on the assumption that the entire mass of the vehicle is concentrated at the wheel center.

5.6 Driver



INPUTS	OUTPUTS
Desired Speed [m/s]	Driver Power Demand [ ]
Actual Speed [m/s]	

Constants:

dvr_proport_gain: Proportional gain of PID controller within driver model [ ]
dvr_integral_gain: Integral gain of PID controller within driver model [ ]
dvr_deriv_gain: Derivative gain of PID controller within driver model [ ]

Auxiliary Calculations:

yout_dvr: vector containing:

1. PID controller output (driver power demand) [ ]
2. Desired speed [m/s]
3. Actual speed [m/s]

Mask: None

Assumptions:

The driver is modeled as a PID controller with fixed gains. The controller output is dependent on its gains and the error between the desired and actual vehicle speed.

The following shows typical values for the constants of the driver model.

Constants	Value
dvr_proport_gain:	0.2 [ ]
dvr_integral_gain:	0.001 [ ]
dvr_deriv_gain:	0 [ ]

6.0 CONTROLLER LIBRARY

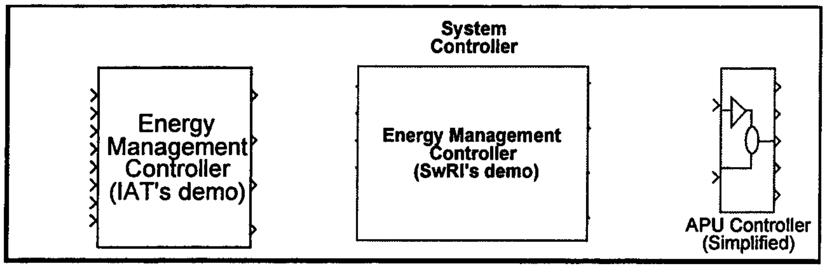
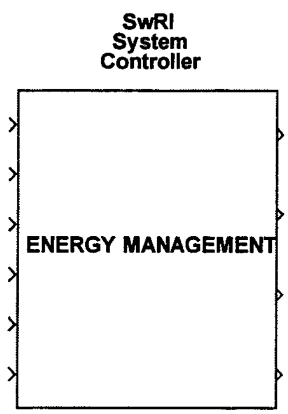


Figure 29. Controller Library

The controller library contains examples of energy-management controllers, which are dependent on the HEV application at hand. Therefore, these controllers are provided as examples of possible energy-management controllers, which the user can use as a basis to develop custom power management controllers. This library also includes controllers for the energy storage device and the APU.

6.1 Energy Management Controller (I)



INPUTS	OUTPUTS
Generator Output Current [Amps]	Battery Current Command [Amps]
Drive Motor Current Draw [Amps]	Engine Throttle Command [0-1]
System Voltage [Volts]	Generator Current Command [Amps]
ESS Current Requirement [Amps]	Engine ON/OFF [1/0]
*ESS State of Charge [ ]	
Engine Speed [rpm]	
*ESS: Energy Storage System	

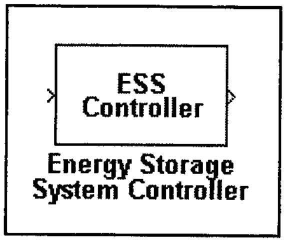
Constants: None

Auxiliary Calculations: None

Mask: None

Assumptions: Specific to application

6.1.1 Energy Storage System



INPUTS	OUTPUTS
*ESS State of Charge	ON/OFF signal to **APU [1/0]
*ESS: Energy Storage System **APU: Alternate Power Unit	

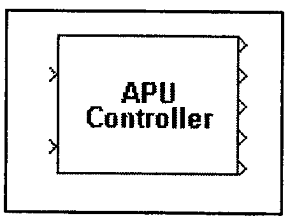
Constants: None

Auxiliary Calculations: None

Mask: None

Assumptions: Specific to application

6.1.2 APU Controller



INPUTS	OUTPUTS
ESS State of Charge [ ]	Engine Throttle Command [0-1]
Engine Speed [rpm]	Generator Current Command [Amps]
	Engine ON/OFF [1/0]

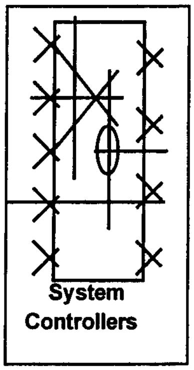
Constants: None

Auxiliary Calculations: None

Mask: None

Assumptions: Specific to application

6.2 System Controller



INPUTS	OUTPUTS
Generator Output Current (A)	Engine Throttle Command
Drive Motor Output Current (A)	Generator Current Command
System Voltage (V)	Battery Power Command
ESS Percent Power Command	Engine On/Off
Engine Speed (RPM)	

Parameters:

Auxiliary Calculations: None

System Controllers Mask: None

7.0 COUPLING LIBRARY

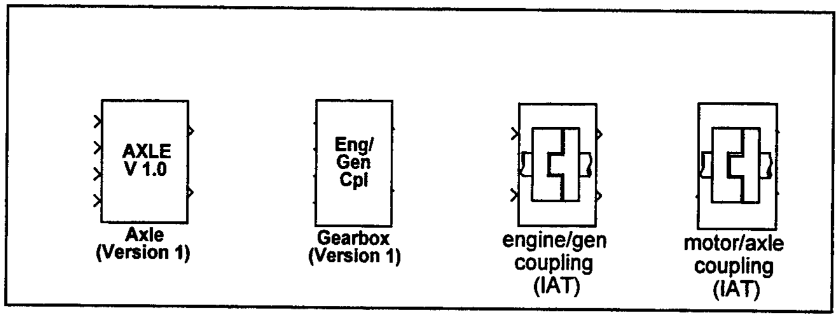
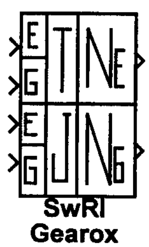


Figure 30. Coupling Model Library

The coupling library contains mechanical couplers representing shaft-to-shaft connections between blocks. These couplings allow for a gear ratio and an efficiency of power transfer. Couplers are typically located between the engine and the generator, as well as between the traction motor and the wheel.

7.1 Engine Generator Coupling



INPUTS	OUTPUTS
Engine Torque [Nm]	Engine Speed [rpm]
Generator Torque [Nm]	Generator Speed [rpm]
Engine Inertia [kgm^2]	
Generator Inertia [kgm^2]	

Constants:

cpl_speed_ratio: Ratio of input shaft speed to output shaft speed of the coupler
cpl_efficiency: Efficiency of coupler

Auxiliary Calculations: None

Mask: None

7.2 Motor Wheel Coupling (I)

Inputs	Outputs
Input Torque [Nm]	Output Torque [Nm]
Output Side Rotational Speed [rpm]	Input Side Rotational Speed [rpm]
Inertia of the driving component	Axle inertia at input [kg $\cdot$m^2]
	Axle inertia at output [kg $\cdot$m^2]

Constants:

axl1_gear_ratio:	Axle Gear Ratio (Output Gear Radius/Input Gear Radius) [ ]
axl1_J1:	Axle Inertia at input [kg$\cdot$m^2]
axl1_J2:	Axle Inertia at output [kg$\cdot$m^2]
axl1_efficiency:	Axle Efficiency from input to output [ ]

Auxiliary Calculations: None

Mask:

(1) Axle Module
(2) Axle Module (SwRI)|Axle Gear Ratio [ ]|Axle Input Side Inertia [kg$\cdot$m^2]|Axle Output Side Inertia [kg$\cdot$m^2]|Axle Efficiency [ ]
(3) axl_gear_ratio=@1;axl_J1=@2;axl_J2=@3;axl_efficiency=@4;

Assumptions:

- Internal efficiencies between the individual gears within the axle subsystem have not been considered. These are modeled by the variable axl_efficiency, which represents the overall inefficiency from the input to output shaft.
- The axle module dynamics (see Section 5.1, Technical Notes) is based on the analysis of two spur gears, one on the input side and the other on the output side. The dynamic model will need additional enhancements if more complex gear systems such as planetary gears are to be considered for the axle.
- Backlash effects within the gears have not been considered in the development of the axle model.

The following presents typical values used for the constants in the axle model

Constant	Value
axl1_gear_ratio:	2 [ ]
axl1_J1:	10 [kg·m^2]
axl1_J2:	10 [kg·m^2]
axl1_efficiency:	96.13 %
axl_mass:	100 kg

7.3 Motor Wheel Coupling (II)

INPUTS	OUTPUTS
Input Torque [Nm]	Output Torque [Nm]
Wheel Rotational Speed [rpm]	Input Side Rotational Speed [rpm]
Inertia of the driving component [kgm^2]	Output Equivalent Inertia [kg·m^2]
	Power Consumed [kg·m^2]

Constants:

axl1_gear_ratio:	Axle Gear Ratio (Output Gear Radius/Input Gear Radius) [ ]
axl1_J1:	Axle Inertia at input [kg·m^2]
axl1_J2:	Axle Inertia at output [kg·m^2]
axl1_efficiency:	Axle Efficiency from input to output [ ]

Auxiliary Calculations: None

Mask:

(1) Axle Module
(2) AXLE MODULE (SwRI)\n\nT1,N2,J1 <=> T2,N1,J2|Axle Gear Ratio [ ]|Axle Efficiency [ ]|Axle Input Gear Inertia [kg*m2]|Axle Output Gear Inertia [kg*m2]
(3) gear_ratio = @1;efficiency = @2;ingear_inertia = @3;outgear_inertia = @4

Assumptions: See Section 7.2.

8.0 MISCELLANEOUS LIBRARY

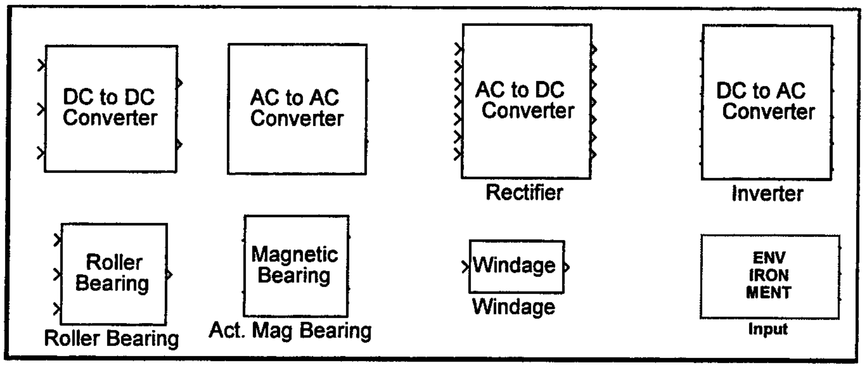
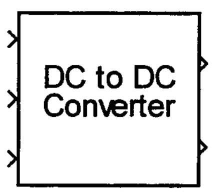


Figure 31. Miscellaneous Components Library

This library contains electrical couplings that convert electrical power between separate buses. These couplings include variations in voltage and account for power transfer inefficiencies. Other bearing models such as roller and magnetic bearings are also included in this library.

8.1 DC-DC Converter



INPUTS	OUTPUTS
High Voltage Power Command (W)	High Side Current (A)
High Voltage (V)	Low Side Current (A)
Low Voltage (V)	

Purpose:

The DC-DC Converter block models a solid state converter that inverts, transforms, and rectifies electricity between two DC buses. This model is a simple power transformer with efficiency that accounts for the direction of power flow. The frequency of the inverted power is assumed to be high to reduce ripple effects on the DC bus with small capacitors. The power required to be moved from the high voltage bus to the low voltage bus is input as a function of time, and the model determines the associated DC currents on each bus. Note the sign convention on the currents and power variables. The controller that supplies the power signal in watts must insure that the bus voltages are within desired ranges. Note that the currents are determined to conserve power, and may become large as voltages are decreased by this and other load paths.

Parameters:

dcdc1_eff	Efficiency of DC/DC Converter (0-1)

Auxiliary Calculations: None

DC-DC Mask

(1) DC to DC Converter

(2) DC to DC Converter Block Definitions\n(Click on "Help" to list Inport and Outport parameters.)|Efficiency (0-1)

(3) eff=@1;

(4) DC to DC\nConverter

(5) DC to DC Converter Block Port Parameters\n\nInport 1: High Voltage Power Command (W).\nInport 2: High Voltage (V).\nInport 3: Low Voltage (V).\n\n Outport 1: High Side Current (A).\nOutport 2: Low Side Current (A).

Model Equations:

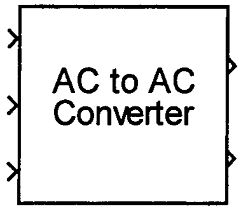
$I_{hi} = P_{hi}/V_{hi}$ — $I_{hi} > 0$ is current **into** the converter

$I_{lo} = I_{hi}*\eta$ — when $P > 0$ (power flows from hi to lo voltage)

$I_{hi}*(1/\eta)$ — when $P < 0$

- note that $I_{lo}>0$ represents current flow **out** of the converter

8.2 AC-AC Converter



INPUTS	OUTPUTS
High Voltage Power Command (W)	High Side Current (A_rms)
High Voltage (Vrms_ll)	Low Side Current (A_rms)
Low Voltage (Vrms_ll)	

Purpose:

The AC-AC Converter block models a solid state or conventional iron transformer for changing the voltage between two AC buses. This model is a simple power transformer with efficiency, which accounts for the direction of power flow. It follows the same convention used in the DC-DC converter. The power required to be moved from the high voltage bus to the low voltage bus is input as a function of time, and the model determines the associated DC currents on each bus. Note the sign convention on the currents and power variables. The controller, which supplies the power signal in watts, must insure that the bus voltages are within desired ranges. Note that the currents are determined to conserve power and may become large as voltages are decreased by both this and other load paths. The power transferred through this model assumes that both buses are at a Power Factor of 1. Later modifications could allow for more detailed treatment of not PF=1 conditions.

Parameters:

aca_eff Efficiency of AC/AC Converter (0-1)

Auxiliary Calculations: None

AC-AC Mask

(1) AC to AC Converter
(2) AC to AC Converter Block Definitions\n(Click on "Help" to list Inport and Outport parameters.)|Efficiency (0-1)

(3) eff=@1;
(4) AC to AC\nConverter
(5) AC to AC Converter Block Port Parameters\n\nInport 1: High Voltage Power Command (W)\nInport 2: High Voltage (Vrms_ll).\nInport 3: Low Voltage (Vrms_ll).\n\nOutport 1: High Side Current (A_rms).\nOutport 2: Low Side Current (A_rms).

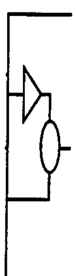
Model Equations:

$I_{hi} = P_{hi}/(sqrt(3)*V_{hi})$ $I_{hi} > 0$ is current **into** the converter

$I_{lo} = I_{hi}*\eta$ when $P > 0$ (power flows from hi to lo voltage)
$I_{hi}*(1/\eta)$ when $P < 0$

- note that $I_{lo}>0$ represents current flow **out** of the converter

8.3 AC-DC converter



ACDCRec

INPUTS	OUTPUTS
Input DC Bus Voltage [Volts]	Output DC Bus Voltage [Volts]
Magnetizing Per Unitized Current [ ]	Output Magnetizing Per Unitized Current [ ]
Per Unitized Stator Current along q axis [ ]	Output Per Unitized Stator Current along q axis [ ]
Per Unitized Stator Voltage along q axis [ ]	Output Per Unitized Stator Voltage along q axis [ ]
Per Unitized Stator Current along d axis [ ]	Output Per Unitized Stator Current along d axis [ ]
Per Unitized Stator Voltage along d axis [ ]	Output Per Unitized Stator Voltage along d axis [ ]

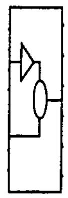
Auxiliary Calculations: None

Mask: None

Assumptions:

- The buck rectifier type is valid for simulations that require positive DC rectifier command.
- Rectifier harmonic effects are not modeled.
- The rectifier is assumed to have a fixed, user-definable efficiency.

8.4 DC-AC Converter



INPUTS	OUTPUTS
Input Bus DC Voltage [Volts]	Output Per Unitized Stator Voltage in the q axis [ ]
Per Unitized Synchronous magnetic field speed [ ]	Output Per Unitized Stator Current in the q axis [ ]
Per Unitized Stator Voltage in the q axis [ ]	Output Per Unitized Stator Voltage in the d axis [ ]
Per Unitized Stator Current in the q axis [ ]	Output Per Unitized Stator Current in the d axis
Per Unitized Stator Voltage in the d axis [ ]	Output Per Unitized Rotor Current in the q axis [ ]
Per Unitized Stator Current in the d axis [ ]	Output Per Unitized Rotor Current in the d axis [ ]
Per Unitized rotor Current in the q axis [ ]	
Per Unitized rotor Current in the d axis [ ]	

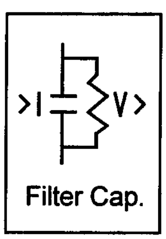
Auxiliary Calculations: None

Mask: None

Assumptions:

- The model is a fully controlled boost inverter.
- The model does not include inverter harmonic effects.

8.5 Capacitor



INPUTS	OUTPUTS
Current (A)	Voltage (V)

Purpose: To model a parallel capacitor and resistor.

Parameters:

CM_Cap	Capacitance (F)
CM_Res	Self-Discharge Resistance (Ohms)
CM_V	Initial Voltage (V)

Auxiliary Calculations: None

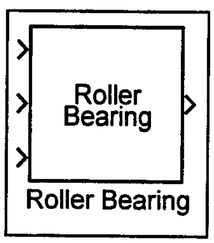
Capacitor Module Mask

(1) Capacitor Module
(2) Capacitor Module|Capacitance [F]|Self-Discharge Resistance [Ohms]|Initial Voltage [V]
(3) Capacitance=@1;Resistance=@2;Initial_Voltage=@3;
(4) *Drawing Commands*
(5) Input is Current in Amps\n Output is Voltage in Volts

Model Equations:

$$I - \frac{V}{R} = C\frac{dV}{dt}$$

8.6 Roller Bearing



INPUTS	OUTPUTS
Radial Force (N)	Torque (N-m)
Thrust Force (N)	
Bearing Speed (RPM)	

Purpose:

To models a roller bearing. Drag torque is calculated based on thrust load, radial load, and viscous drag. An example follows showing extraction of parameters from typical manufacturer's data.

Parameters:

RB_rad	Radial Load Coefficients [Tr (N-m), Fro (N), Er (Exponent)]
RB_thr	Thrust Load Coefficients [Tt (N-m), Fto (N), Et (Exponent)]
RB_vis	Viscous Drag Coefficients [Tv (N-m), No (RPM), Ev (Exponent)]

Auxiliary Calculations: None

Roller Bearing Mask

(1) Roller Bearing
(2) T = Tr*(Fr/Fro)^Er \n + Tt*(Ft/Fto)^Et\n + Tv*(N/No)^Ev|Radial Coefficients[Tr(N-m), Fro(Force), Er(Exponent)]|Thrust Coefficients[Tt(N-m), Fto(Force), Et(Exponent)]|Viscous Coefficients[Tv(N-m), No(RPM), Ev(Exponent)]
(3) RE=@1(3);RK=@1(1)/@1(2)^RE;AE=@2(3);AK=@2(1)/@2(2)^AE; VE=@3(3);VK=@3(1)/@3(2)^VE;
(4) Roller\nBearing
(5) This bearing model calculates the drag due to normal ball bearings. Normally radial and thrust exponents (Er & Et) are near 1.5, viscous exponent (Ev) is usually 2/3. Model uses the absolute value of the input forces and speed for calculations.\n\nInput 1is Radial Force (Fr)\nInput 2 is Thrust Force (Ft)\nInput 3 is Speed (N)\n\nOutput is Bearing Drag in N-m

Model Equations:

$$\tau = \tau_r\left(\frac{F_r}{F_{ro}}\right)^{E_r} + \tau_t\left(\frac{F_t}{F_{to}}\right)^{E_t} + \tau_v\left(\frac{N}{N_o}\right)^{E_v}$$

Example of Extraction of Inputs from Manufacturers Data

Table 13. Typical Manufacturer's Data

Radial Force (lbs)	Radial Torque (N-m)	Thrust Force (lbs)	Thrust Torque (N-m)	Rotor Speed (RPM)	Lube Torque (N-m)
40	0.0013		0.0042	1000	0.0962
50	0.0018		0.0058	2000	0.1528
70	0.0030		0.0092	4000	0.2425
100	0.0051		0.0153	6000	0.3178
130	0.0075		0.0222	8000	0.3850
180	0.0121		0.0352	12000	0.5045
240	0.0185		0.0527	16000	0.6111
350	0.0326		0.0895		
450	0.0472		0.1271		
600	0.0729		0.1897		
820	0.1172		0.2923		
1100	0.1832		0.4380		

Choose Nominal Force of 100 lbs, Maximum of 1100 lbs and Speed=16000 RPM

F_{ro}=100 lbs T_{ro}=.0051 N-m

$$E_r = \frac{\ln(T_{max}/T_{ro})}{\ln(F_{max}/F_{ro})} = \frac{\ln(.1832/.0051)}{\ln(1100/100)} = 1.49$$

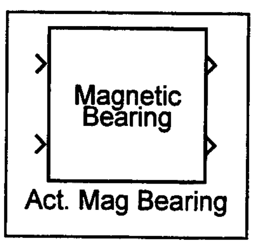
F_{to} =100 lbs T_{to}=.0153 N-m

$$E_t = \frac{\ln(T_{max}/T_{to})}{\ln(F_{max}/F_{to})} = \frac{\ln(.438/.0153)}{\ln(1100/100)} = 1.40$$

No=16000 Tv=.611

$$E_v = \frac{\ln(T_1/T_v)}{\ln(N_1/N_o)} = \frac{\ln(.2425/.611)}{\ln(4/16)} = .667$$

8.7 Magnetic Bearing



INPUTS	OUTPUTS
Force (N)	Electric Power (W)
Speed (RPM)	Drag Torque (N-m)

Purpose:

The magnetic bearing approximately models an active magnetic bearing. Bearings are assumed to have a defined relationship between air gap flux and force. This model linearly interpolates the electric losses and rotating losses for the given input force at the base speed. The rotating losses are assumed to be due to eddy current and hysteresis losses in the magnetic core of the rotor. The eddy current losses will be proportional to speed squared, while the hysteresis losses will be proportional to the speed. This allows scaling for speed variations of these rotating torques to account for speed effects.

Parameters:

MB_F	Vector of Input Forces (N)
MB_elc_loss	Vector of Electric Losses (W)
MB_rot_loss	Vector of Hysteresis Rotational Losses (W) at Base Speed
MB_cur_rot_loss	Vector of Eddy Current Rotational Losses (W) at Base Speed
MB_spd	Base Speed (RPM)

Auxiliary Calculations: None

Magnetic Bearing Mask

(1) Mag Bearing
(2) Active Magnetic Bearing Model|Input Force|Electric Losses (W)|Hysteresis Rotational Losses (W) at Base Speed|Eddy Current Rotational Losses (W) at Base Speed|Base Speed (RPM)
(3) Input=@1;Electric=@2;Hysteresis=@3/@5*30/pi;Eddy=@4/@5/@5*30/pi;
(4) Magnetic\nBearing
(5) All losses are calculated as curve fits as a function of input force. Electric power is assumed independent of speed. Hysteresis losses are assumed to increase linearly with speed. Eddy current losses are assumed to increase as the speed squared. Hysteresis and eddy current losses appear as mechanical drag torque.\n\nInput 1 is Force\nInput 2 is Speed in RPM\n\nOutput 1 is Electric Power Draw in Watts\nOutput 2 is Drag Torque in N-m

Model Equations:

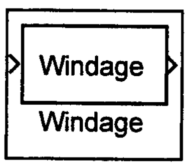
$P_{out} = \mathrm{Fit}\,(F, P_{elect}, F_{in})$
$H_F = \mathrm{Fit}\,(F, P_{hyst}, F_{in})$
$E_F = \mathrm{Fit}\,(F, P_{eddy}, F_{in})$

$$\tau\omega = H_F\left(\frac{N}{N_o}\right) + E_F\left(\frac{N}{N_o}\right)^2$$

where

P_{out} is the required electrical power
τ is the drag torque
F is the input force
N is the input rotational speed
F_{in} is the array specified in the mask under 'Input Force'
P_{elect} is the array specified in the mask under 'Electric Losses...'
P_{hyst} is the array specified in the mask under 'Hysteresis...'
P_{eddy} is the array specified in the mask under 'Eddy Current...'
Fit(V,Y,X) is a linear interpolation of the 'Y' vs. 'X' data at x value 'V'

8.8 Windage



INPUTS	OUTPUTS
Speed (RPM)	Drag Torque (N-m)

Purpose: To calculate windage as a function of speed for a constant vacuum pressure.

Parameters:

W_spd	Base Speed (RPM)
W_drag_spd	Drag at Base Speed (W)
W_De	Speed Exponent for Drag Power

Auxiliary Calculations: None

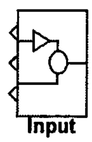
Windage Mask:

(1) Windage Module
(2) Windage Equation\nP=Po(N/No)^De|Base Speed (RPM) [No]|Drag at Base Speed (W) [Po]|Speed Exponent for Drag Power [De]
(3) Drag_Const=@2*30/pi/((@1^@3);Drag_Exp=@3-1;
(4) Windage
(5) Models rotor windage assuming a constant vacuum level. The exponent (De) will normally vary from De=2 at reasonable vacuum (<.001 torr) to De=3 at poor vacuum (>1 torr).\n\nInput is speed in RPM\nOutput is drag torque in N-m

Model Equations:

$$\tau\omega = P_o\left(\frac{N}{N_o}\right)^{De}$$

8.9 Driving Profile



INPUTS	OUTPUTS
	Driving cycle
	Road Gradient
	Head Wind data

The driving profile model provides the environmental/operating inputs to the simulation. These are: driving cycle in which vehicle velocity is described as a function of time, road gradient, and head-wind information as a function of time.

Auxiliary Calculations: None

Mask: None

Assumptions: Application dependent

9.0 LIST OF ALL VARIABLES

Table 14. Motor Wheel Coupling			
Variable	Description	Units	Type
axl1_J1	Inertia at input side of coupling	kgm^2	Scalar
axl1_J2	Inertia at output side of coupling	kgm^2	Scalar
axl1_efficiency	Coupling efficiency	-	Scalar
axl1_gear_ratio	Coupling gear ratio	-	Scalar
axl1_mass	Mass of coupling	kg	Scalar
axl1_name	Name of coupling	-	Scalar
axl1_weight	Weight of coupling	N	Scalar
shft_log_name	Name of coupling shift logic	-	Scalar

Table 15. Constants			
Variable	Description	Units	Type
c_bar_Pa	Conversion factor from bar to Pascal	-	Scalar
c_ft_m	Conversion factor from ft to m	-	Scalar
c_hp_kW	Conversion factor from hp to kW	-	Scalar
c_in3_m3	Conversion factor from in^3 to m^3	-	Scalar
c_inHg_Pa	Conversion factor from in Hg to Pascal	-	Scalar
c_in_m	Conversion factor from in to m	-	Scalar
c_kPa_Pa	Conversion factor from kPa to Pa	-	Scalar
c_lb_kg	Conversion factor from lb-mass to kg	-	Scalar
c_lbf_N	Conversion factor from lb-force to N	-	Scalar
c_lbft_Nm	Conversion factor from ft-lb to Nm	-	Scalar
c_lbft2_kgm2	Conversion factor from lb-mass ft^2 to kgm^2	-	Scalar
c_lbphphr_kgpkWhr	Conversion factor from lb per hp hr to kg per kWhr	-	Scalar
c_liter_m3	Conversion factor from liter to m^3	-	Scalar
c_psi_Pa	Conversion factor from psi to Pa	-	Scalar
c_rpm_radps	Conversion factor from rpm to rad per sec	-	Scalar

Table 16. Engine-Generator Coupling			
Variable	Description	Units	Type
cpl1_speed_ratio	Coupling ratio	-	Scalar

Table 17. Driving Profile			
Variable	Description	Units	Type
cycle	Table of time (first column in sec) versus desired speed (second column in m/s)		Vector (Nx2)
cycle_name	Name of driving cycle	-	Scalar
road_grade	Gradient of road	rad	Scalar

Table 18. Driver			
Variable	**Description**	**Units**	**Type**
dvr1_name	Name of driver	-	Scalar
dvr1_weight	Driver weight	N	Scalar
dvr_deriv_gain	Derivative gain of driver PID controller	-	Scalar
dvr_integral_gain	Integral gain of driver PID controller	-	Scalar
dvr_proport_gain	Proportional gain of driver PID controller	-	Scalar

Table 19. Spark Ignition Engine			
Variable	**Description**	**Units**	**Type**
eng1_cat_cnvtr_name	Engine catalic converter	-	scalar
eng1_cat_cnvtr_weight	Engine catalic converter weight	N	scalar
eng1_fuel_HV	Engine fuel heat value	J/kg	scalar
eng1_fuel_density	Engine fuel density	kg/l	scalar
eng1_fuel_weight	Engine fuel weight	N	scalar
eng1_name	Engine name	-	scalar
eng1_weight	Engine weight	N	scalar
eng_af_ratio_Pi	Vector of intake manifold pressure for air fuel ratio	Pa	vector (1x3)
eng_af_ratio_speed	Vector of engine speed for air fuel ratio	rad/sec	vector (1x2)
eng_af_ratio_table	Engine air fuel ratio table	-	Matrix (2x3)
eng_ambient_air_density	Engine ambient air density	kg/m^3	scalar
eng_ambient_pressure	Engine ambient pressure	Pa	scalar
eng_ambient_temperature	Engine ambient temperature	K	scalar
eng_catalyst_eff_CO	Catalyst conversion efficiency for carbon monoxide	-	scalar
eng_catalyst_eff_HC	Catalyst conversion efficiency for hydro carbons	-	scalar
eng_catalyst_eff_NO	Catalyst conversion efficiency for nitrogen oxides	-	scalar
eng_catalyst_eff_PM	Catalyst conversion efficiency for particulate matter	-	scalar
eng_compression_ratio	Engine compression ratio	-	scalar
eng_displacement	Engine displacement	m^3	scalar
eng_emissions_CO_table	Table of engine emissions for carbon monoxide	kg/kg fuel	Matrix (5x5)
eng_emissions_HC_table	Table of engine emissions for hydro carbons	kg/kg fuel	Matrix (5x5)
eng_emissions_NOx_table	Table of engine emissions for nitrogen oxides	kg/kg fuel	Matrix (5x5)
eng_emissions_PM_table	Table of engine emissions for particulate matter	kg/kg fuel	Matrix (5x5)
eng_emissions_Pi	Vector of intake manifold pressure	Pa	Vector (1x5)
eng_emissions_speed	Vector of engine speed for different emissions	rad/sec	Vector (1x5)
eng_exh_pres_scaling	Scaling factor for matching exhaust pressure		scalar
eng_exh_temp_Pi	Vector of intake manifold pressure for exhaust temperature	Pa	vector (1x2)
eng_exh_temp_af_coeff	Engine exhaust temperature to air	-	scalar

Table 19. Spark Ignition Engine			
Variable	Description	Units	Type
	fuel ratio coefficient		
eng_exh_temp_speed	Vector of engine speed for exhaust temperature	rad/sec	vector (1x2)
eng_exh_temp_table	Exhaust temperature table	K	Matrix (2x2)
eng_fmep_factor_0	Correlation factor 0 for friction mean effective pressure	-	scalar
eng_fmep_factor_1	Correlation factor 1 for friction mean effective pressure	-	scalar
eng_fmep_factor_2	Correlation factor 2 for friction mean effective pressure	-	scalar
eng_fuel_evaporation_time_constant	Time constant for fuel evaporation in intake manifold wall	sec	scalar
eng_gas_const_air	Specific gas constant for air	J/kg/K	scalar
eng_gas_const_exhaust	Specific gas constant for exhaust gases	J/kg/K	scalar
eng_inertia	Engine rotary inertia	kgm^2	scalar
eng_liquid_fuel_fraction	Fraction of fuel that stays in liquid form	-	scalar
eng_manifold_volume	Engine intake manifold volume	m^3	scalar
eng_max_air_flow	Engine max air flow	kg/s	scalar
eng_mol_wt_air	Molecular weight of air through throttle	kg/kmol	scalar
eng_mol_wt_exhaust	Molecular weight of exhaust gases	kg/kmol	scalar
eng_muffler_pressure_factor	Engine muffler pressure correlation factor	-	scalar
eng_nominal_isfc	Engine nominal indicated specific fuel consumption	kg/J	scalar
eng_off_torque_fact	Factor for torque when engine is off	Nm/rad/s	scalar
eng_rated_air_mass_flow	Rated air mass flow for engine	kg/s	scalar
eng_rated_air_vol_flow	Rated air volume flow for engine	m^3/s	scalar
eng_rated_bmep	Rated Brake Mean Effective Pressure	Pa	scalar
eng_rated_exhaust_density	Rated exhaust air density	kg/m^3	scalar
eng_rated_exhaust_pressure	Rated exhaust gas pressure		scalar
eng_rated_exhaust_temperature	Rated exhaust gas temperature		scalar
eng_rated_intake_vacuum	Intake manifold vacuum at rated conditions	Pa	scalar
eng_rated_power	Rated engine power	Watts	scalar
eng_rated_pres_ratio_infl	Pressure ratio influence factor (in flow equation) at rated conditions [fraction]	-	scalar
eng_rated_speed	Maximum engine speed	rad/s	scalar
eng_rated_torque	Rated engine torque		scalar
eng_rated_vol_eff	Rated engine volumetric efficiency	-	scalar
eng_speed_density_weight	Fractional weight for speed density air flow compared to mass flow sensor [fraction]	-	scalar
eng_std_air_density	Density of standard air	kg/m^3	scalar

Table 19. Spark Ignition Engine			
Variable	**Description**	**Units**	**Type**
eng_std_pres	Standard pressure	Pa	scalar
eng_std_temp	Standard temperature	K	scalar
eng_stoich_af_ratio	Correlation factor for effect of air fuel ratio on exhaust temperature	-	scalar
eng_throttle_bypass_ratio	Ratio of bypass flow area around throttle to total throttle area	-	
eng_universal_gas_const	Universal gas constant	J/kmol/K	scalar
eng_vol_eff_Pi	Table of intake manifold pressure vs. vol efficiency	Pa	Vector (1x2)
eng_vol_eff_speed	Table of engine speed for vol efficiency	rad/s	Vector (1x6)
eng_vol_eff_table	Table of engine volumetric efficiencies	-	Matrix (6x2)

Table 20. Lead Acid Battery			
Variable	**Description**	**Units**	**Type**
essb1_name	Battery name	-	scalar
essb1_weight	Battery weight	N	scalar
essb_C	Internal capacitance of a cell	F	scalar
essb_C5	Discharge capacity @ 5 hour rate at 30 Celsius for a cell	A-hr	scalar
essb_CT	Terminal capacitance	F	scalar
essb_E	Open circuit voltage of a cell	V	scalar
essb_I5	Discharge current @ 5 hour rate for a cell	A	scalar
essb_K	Polarization resistance of a cell	Ω	scalar
essb_Q0	Initial charge in battery cell	A-hr	scalar
essb_Rb	Terminal resistance for the battery	Ω	scalar
essb_chrg_eff	Battery charge efficiency	-	scalar
essb_dischrg_eff	Battery discharge efficiency	-	scalar
essb_init_ECP	Battery initial polarization voltage	V	scalar
essb_init_SOC	Battery initial state of charge	-	scalar
essb_r	Internal resistance of a cell	Ω	scalar
essb_tot_num	Total number of batteries	-	scalar

Table 21. Permanent Magnet Generator			
Variable	**Description**	**Units**	**Type**
genp1_ctrl_dgain	Derivative gain of PID controller for generator	-	scalar
genp1_ctrl_igain	Integral gain of PID controller for generator	-	scalar
genp1_ctrl_pgain	Proportional gain of PID controller for generator	-	scalar
genp1_ctrlr_name	Generator controller name	-	scalar
genp1_ctrlr_weight	Generator controller weight	N	scalar
genp1_name	Generator name	-	scalar
genp1_weight	Generator weight	N	scalar

Table 22. AC Induction Motor			
Variable	Description	Units	Type
motl1_ctrlr_name	Motor controller name	-	scalar
motl1_ctrlr_weight	Motor controller weight	N	scalar
motl1_name	Motor name	-	scalar
motl1_weight	Motor weight	N	scalar
motor_N_max	Maximum rated speed of motor	rpm	scalar

Table 23. Simulation Constants			
Variable	Description	Units	Type
sample_N	Number of samples to save to workspace	-	scalar
sample_T	Time step length between saved samples	-	scalar

Table 24. Vehicles			
Variable	Description	Units	Type
veh1_aero_drag_coef	Aerodynamic drag coefficient	-	scalar
veh1_air_density	Air density	kg/m^3	scalar
veh1_chassis_weight	Chassis Weight	N	scalar
veh1_coef_yaw_sens	Coefficient of sensitivity to yaw	-	scalar
veh1_f0	Vehicle speed independent rolling coefficient	-	scalar
veh1_front_area	Frontal area of vehicle	m^2	scalar
veh1_fs	Vehicle speed dependent rolling coefficient	-	scalar
veh1_mass	Vehicle mass	kg	scalar
veh1_name	Vehicle name	-	scalar
veh1_normal_wind	Wind velocity normal to vehicle motion	m/s	scalar
veh1_parallel_wind	Head wind velocity	m/s	scalar
veh1_passengers_weight	Passenger weight	N	scalar
veh1_roadtire_frict_coeff	Road tire coefficient of friction	-	scalar

Table 25. Miscellaneous			
Variable	Description	Units	Type
weight_total	Total vehicle weight	N	scalar

Table 26. Wheel			
Variable	Description	Units	Type
whl1_mass	Wheel mass	kg	scalar
whl1_radius	Wheel radius	m	scalar
whl1_tr	Wheel radius	m	scalar

N: Length of the time (sim_time) vector

HYBRID ELECTRIC VEHICLE SIMULINK TOOLBOX

(Commercial Vehicle Version)

Technical Notes

Version 1.1

1.0 INTRODUCTION

These technical notes provide the equations used within the individual modules of the DARPA Hybrid Electric Vehicle (HEV) simulation toolbox, hereinafter referred to as PATHS (**P**erformance **A**ssessment **T**oolbox for **H**ybrid **S**ystems). These technical notes accompany the User's Guide for the HEV simulation toolbox. Use of PATHS is restricted to government-funded projects, following explicit permission by DARPA/SwRI only. All inquiries to obtain permission to use PATHS must be directed to Dr. A. Nedungadi at Southwest Research Institute (210-522-3965).

PATHS is developed under the MATLAB/SIMULINK© environment, and is provided to users in source code form. An experienced MATLAB/SIMULINK© user can easily trace the inputs to the outputs and determine the transfer function between these two. The following notes provide the user with the basic principles of physics that have been employed to model the individual modules of PATHS. Modules that use table lookup methods are not described in this document, since these are not based on principles of physics. Cursory equations describing the internal operation within certain modules are provided in the User's Guide. In this case, the user is referred to the User's Guide for information on the underlying technical equations. All equations of controller modules of the controllers library (refer to User's Guide) have been omitted since these are based on classical PID control laws. As a result, this document contains technical equations for the following modules, which is a subset of the entire PATHS software (please refer to the User's Guide for a complete listing of all modules of PATHS):

ELECTRIC MACHINE LIBRARY

- ☐ AC induction steady state motor
- ☐ Permanent magnet steady state generator
- ☐ AC Induction dynamic motor
- ☐ Permanent magnet dynamic generator

ENERGY STORAGE LIBRARY

- ☐ Lead acid battery
- ☐ flywheel battery
- ☐ Capacitor

VEHICLE LIBRARY

- ☐ Wheeled vehicle (version 1 and 2)
- ☐ Wheel (version 1 and 2)

COUPLINGS LIBRARY

- ☐ Gear box
- ☐ Engine-generator coupling
- ☐ Motor-wheel coupling (version 1 and 2)

MISCELLANEOUS LIBRARY

- ☐ Roller bearing
- ☐ Magnetic bearing
- ☐ Windage model

2.0 ELECTRIC MACHINE LIBRARY

2.1 Steady State AC Induction Motor

Figure 32 shows the inputs and outputs of the steady-state induction motor model - motl1_module. Figure 33 depicts the per-phase equivalent circuit model of the induction machine and defines the motor parameters. Figure 34 shows the induction motor model after the transformation to the synchronous d-q reference frame. The electrical terminal voltages and currents are calculated directly from this equivalent circuit and the mechanical equations using the command values of torque and speed. The synchronous reference frame electrical and mechanical equations used in the simulation are,

$$v_{qs}^e = R_s i_{qs}^e + \omega \lambda_{ds}^e$$
$$v_{ds}^e = R_s i_{ds}^e - \omega \lambda_{qs}^e$$
$$0 = R_r i_{qr}^e + (\omega - \omega_r)\lambda_{dr}^e$$
$$0 = R_r i_{dr}^e - (\omega - \omega_r)\lambda_{qr}^e$$
$$\lambda_{qs}^e = (L_m + L_{ls}) i_{qs}^e + L_m i_{qr}^e$$
$$\lambda_{ds}^e = (L_m + L_{ls}) i_{ds}^e + L_m i_{dr}^e$$
$$\lambda_{qr}^e = (L_m + L_{lr}) i_{qr}^e + L_m i_{qs}^e$$
$$\lambda_{dr}^e = (L_m + L_{lr}) i_{dr}^e + L_m i_{ds}^e$$
$$\tau = L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e)$$

where the *e* superscript denotes the synchronous reference frame.

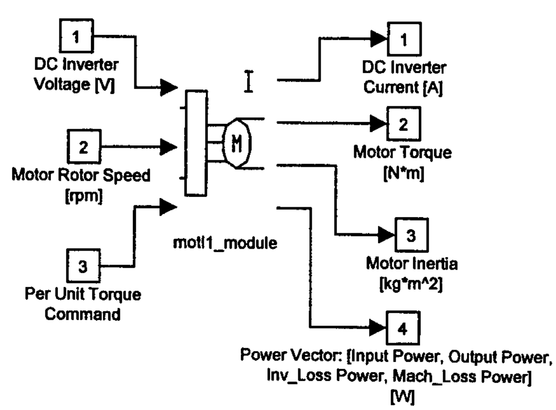


Figure 32. Inputs and Outputs of motl1_module

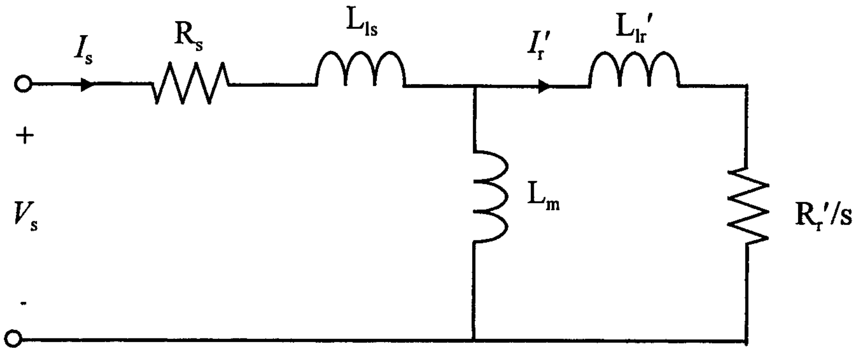


Figure 33. Induction Machine Per Phase Equivalent Circuit

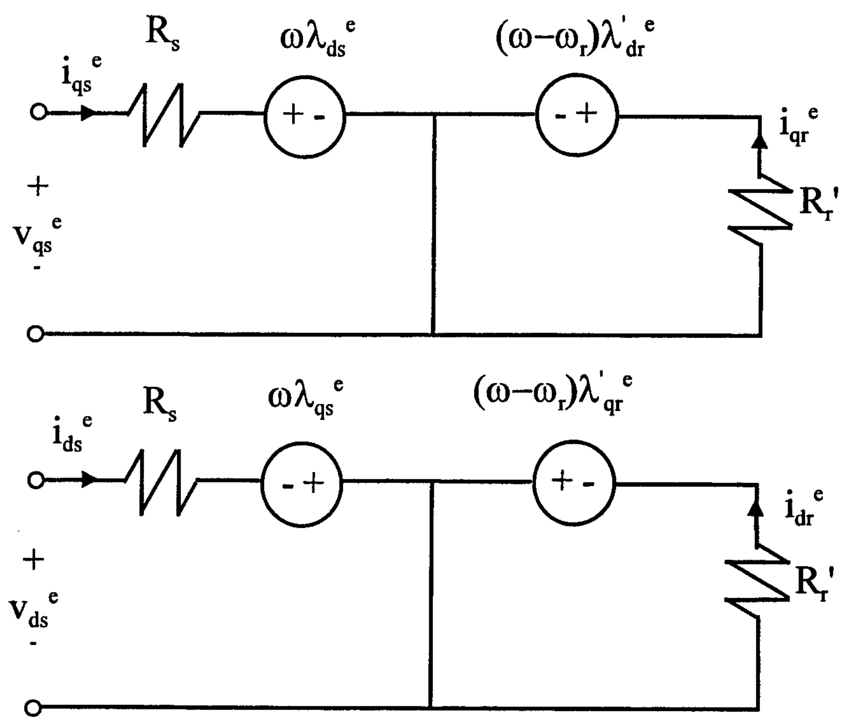


Figure 34. Steady-state dq equivalent circuit of an induction motor

The motor is controlled using conventional rotor flux field orientation (i.e., "brushless dc" control) such that in the synchronous reference frame, $\lambda_{qr}^e = 0$.

2.2 Steady State Permanent Magnet Generator

Figure 35 shows the inputs and outputs of the steady-state generator model - genp1_module. Figure 36 depicts the steady-state synchronous d-q reference frame model used in the simulation. The electrical terminal voltage is calculated directly from this equivalent circuit using the command values of current and speed. The electrical and mechanical equations used in the simulation, and given by the equivalent circuit, are,

$$i_{qs}^e = i_{qm}^e + \frac{1}{R_m}(\omega_r L_{ds} i_{dm}^e - \omega_r L_{md} I_{df})$$
$$i_{ds}^e = i_{dm}^e - \frac{\omega_r L_{qs} i_{qm}^e}{R_m}$$
$$v_{qs}^e = -R_s i_{qs}^e + \omega_r L_{md} I_{df} - \omega_r L_{ds} i_{dm}^e$$
$$v_{ds}^e = -R_s i_{ds}^e + \omega_r L_{qs} i_{qm}^e$$
$$\tau = L_{md} I_{df} i_{qm}^e$$

where the superscript *e* denotes the synchronous reference frame, and I_{df} is the fictitious current, which corresponds to the strength of the permanent magnet. This current is internally calculated from the no load speed and voltage. The iron loss resistor, R_m , is calculated from the rated core losses value provided by the user.

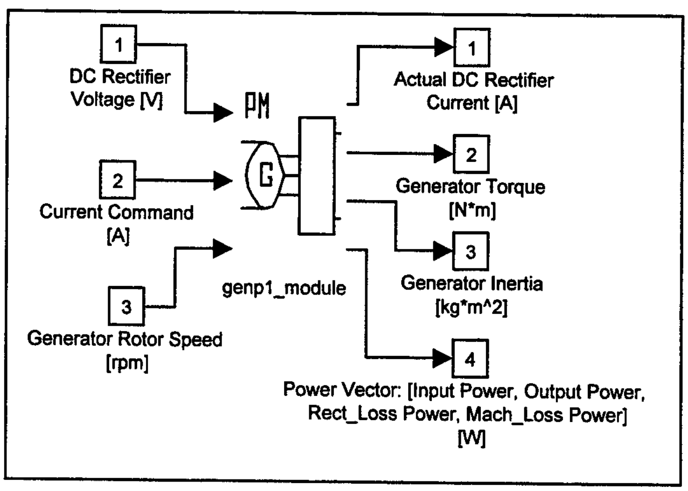


Figure 35. Inputs and Outputs of genp1_module

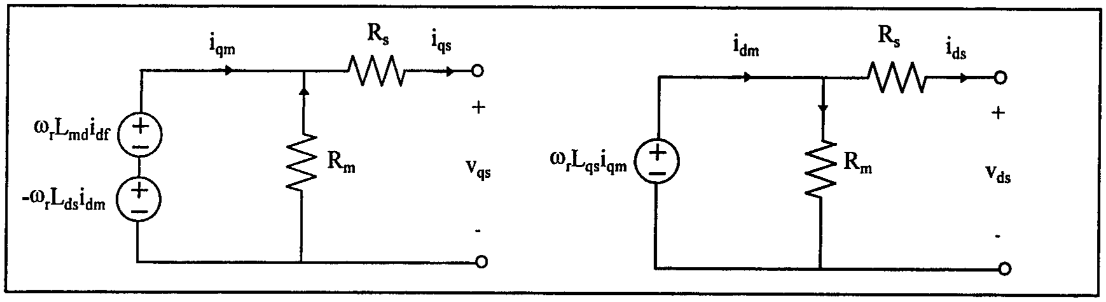


Figure 36. Steady-State dq-Equivalent Circuits

The generator is controlled using conventional synchronous reference frame field orientation (i.e., "brushless dc" control) such that $i_{dm} = 0$.

2.3 AC Induction Dynamic Motor

Figure 37 below shows the inputs and outputs for the induction motor/boost inverter system. The standard steady-state induction machine, per-phase equivalent circuit is shown in the previous section. Please refer to this section for information about what each resistance or inductance referenced in the mask relates to electrically.

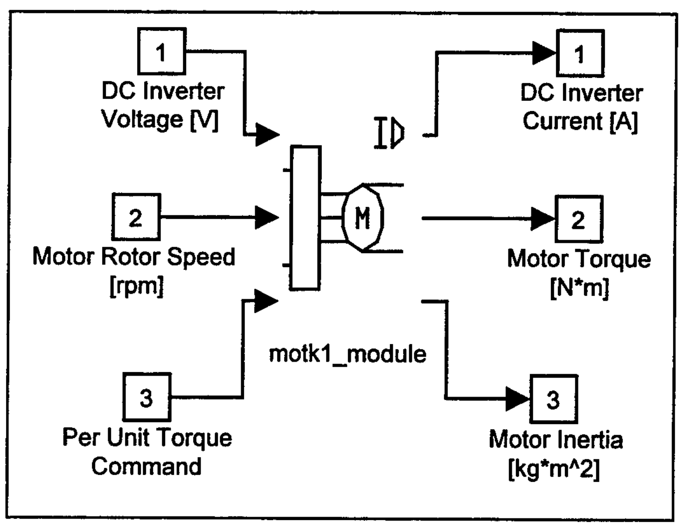


Figure 37. Inputs and Outputs of motk1_module

Figure 38 depicts the synchronous reference frame d-q dynamic model of the induction machine and defines the motor parameters. The electrical terminal voltages and currents are calculated directly from this equivalent circuit and the mechanical equations using the command values of torque and speed. The synchronous reference frame electrical and mechanical equations used in the simulation are,

$$
\begin{aligned}
v_{qs}^e &= R_s i_{qs}^e + \omega \lambda_{ds}^e + \dot{\lambda}_{qs}^e \\
v_{ds}^e &= R_s i_{ds}^e - \omega \lambda_{qs}^e + \dot{\lambda}_{ds}^e \\
0 &= R_r i_{qr}^e + (\omega - \omega_r)\lambda_{dr}^e + \dot{\lambda}_{qr}^e \\
0 &= R_r i_{dr}^e - (\omega - \omega_r)\lambda_{qr}^e + \dot{\lambda}_{dr}^e \\
\lambda_{qs}^e &= (L_m + L_{ls}) i_{qs}^e + L_m i_{qr}^e \\
\lambda_{ds}^e &= (L_m + L_{ls}) i_{ds}^e + L_m i_{dr}^e \\
\lambda_{qr}^e &= (L_m + L_{lr}) i_{qr}^e + L_m i_{qs}^e \\
\lambda_{dr}^e &= (L_m + L_{lr}) i_{dr}^e + L_m i_{ds}^e \\
\tau &= L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e)
\end{aligned}
$$

where the *e* superscript in the equations denotes the synchronous reference frame.

The motor is controlled using conventional rotor flux field orientation (i.e., "brushless dc" control) such that in the synchronous reference frame, $\lambda_{qr}^e = 0$. The stator currents, i_{qs}^e and i_{ds}^e, are controlled in the synchronous reference frame through a standard PI current regulator. The PI gains are user-definable.

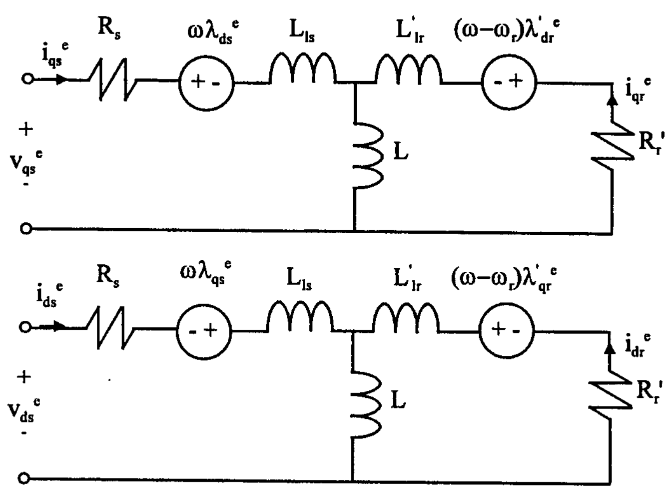


Figure 38. Dynamic dq equivalent circuit of an induction motor

2.4 Permanent Magnet Dynamic

Figure 39 shows the inputs and outputs of the dynamic generator model - genq1_module. Figure 40 depicts the dynamic synchronous d-q reference frame model used in the simulation. The electrical terminal voltage is calculated directly from this equivalent circuit using the command values of current and speed. The electrical and mechanical equations used in the simulation, and given by the equivalent circuit, are,

$$i_{qs}^e = i_{qm}^e + \frac{1}{R_m}(\omega_r L_{ds} i_{dm}^e - \omega_r L_{md} I_{df} + L_{qs} \dot{i}_{qm}^e)$$

$$i_{ds}^e = i_{dm}^e - \frac{1}{R_m}(\omega_r L_{qs} i_{qm}^e - L_{ds} \dot{i}_{dm}^e)$$

$$v_{qs}^e = -R_s i_{qs}^e + \omega_r L_{md} I_{df} - \omega_r L_{ds} i_{dm}^e - L_{qs} \dot{i}_{qm}^e$$

$$v_{ds}^e = -R_s i_{ds}^e + \omega_r L_{qs} i_{qm}^e - L_{ds} \dot{i}_{dm}^e$$

$$\tau = L_{md} I_{df} i_{qm}^e$$

where the superscript e denotes the synchronous reference frame, and I_{df} is the fictitious current, which corresponds to the strength of the permanent magnet. This current is internally calculated from the no load speed and voltage. The iron loss resistor, R_m, is calculated from the rated core losses value provided by the user.

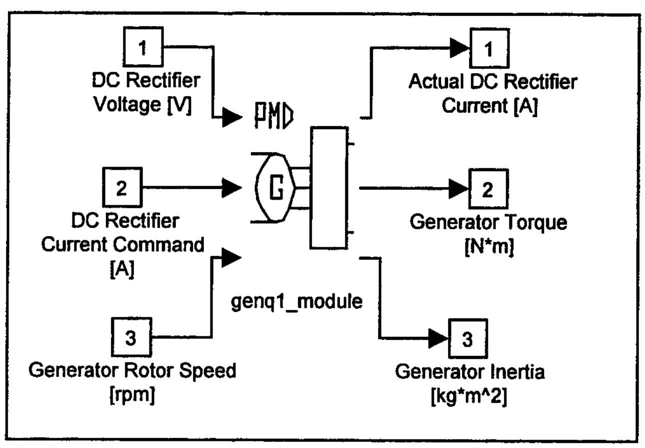


Figure 39. Inputs and Outputs of genq1_module

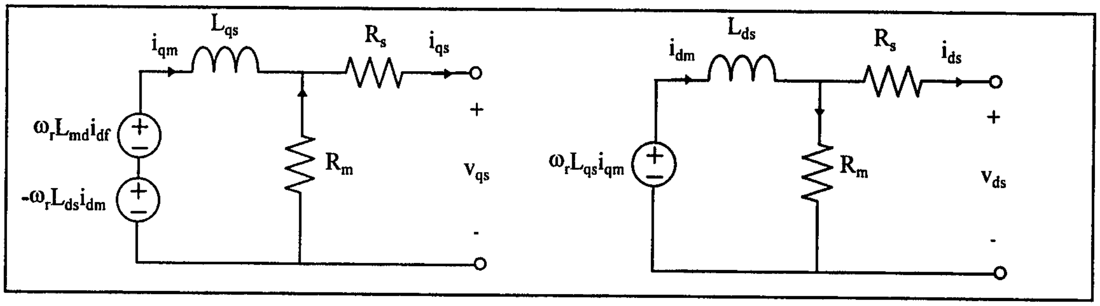


Figure 40. Dynamic Generator dq-Equivalent Circuits

The generator is controlled using conventional synchronous reference frame field orientation (i.e., "brushless dc" control) such that $i_{dm} = 0$. The q-axis current, i_{qm}, is controlled in the synchronous reference frame through a standard PI current regulator. The PI gains are user-definable.

3.0 ENERGY STORAGE LIBRARY

3.1 Lead Acid Battery

Figure 41 shows the circuit diagram used to develop the dynamic model of the lead-acid battery. A single battery cell is described by the following parameters:

$r_i[\Omega]$:	Internal resistance of cell i
E_i [V]:	Open circuit voltage of cell i
c_i [F]:	Capacitance of cell i
K_i [Ω]:	Polarization Resistance of cell i
SOC_i:	State of charge of cell I

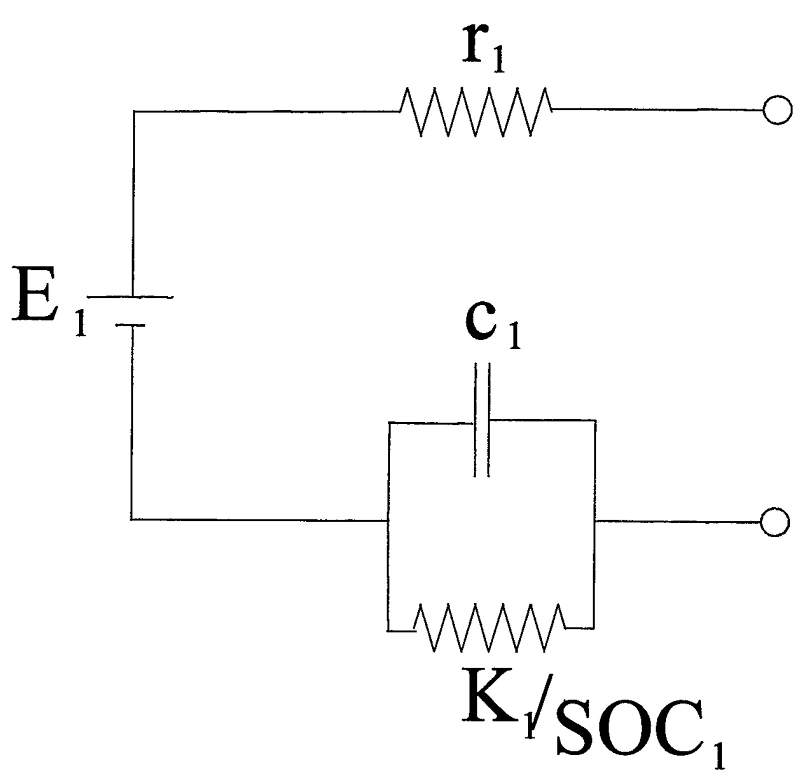


Figure 41. Circuit Diagram for a Single Cell of a Lead Acid

In a battery with multiple cells, the circuit will consist of N single cells in series with a terminal resistance R_T [Ω] and capacitance C_T [F]. Figure 42 shows 2 single cells in series, a terminal resistance R_T [Ω] and capacitance C_T [F]. Positive current I is shown by the direction of the arrow in Figure 41. Referring to Figure 41, and assuming that $c_1 = c_2$, $E_1 = E_2 = E$, $K_1 = K_2$, Kirchoff's voltage law can be formulated as follows:

$$N(Vc) + N(E) + N(I_r r) + I_r R_T = V_T \qquad [1]$$

where:

Vc: The voltage across the capacitor c_1 [V]

N: The number of cells in the battery [ ]

I_r: The portion of the current I that flows into the internal resistance r [A]

V_T: The terminal voltage [V]

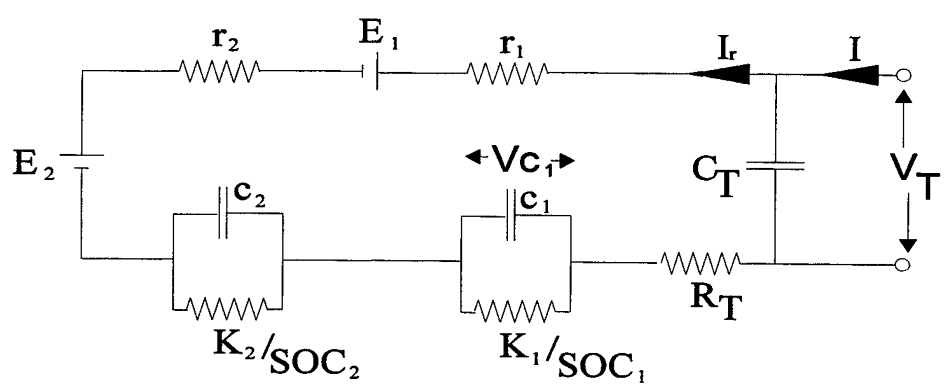


Figure 42. __Circuit Diagram for a Lead Acid Battery with Two Cells__

The above lead acid battery model has two states: Vc and V_T. Therefore, this is a second order battery model. Assuming, $SOC_1 = SOC_2 = SOC$, the above equation can be combined with Kirchoff's current law to determine these two states as follows:

$$I = C_T \frac{dVT}{dt} + I_r \qquad [2]$$

$$Ir = c\frac{dVc}{dt} + \frac{Vc}{K/SOC} \qquad [3]$$

Solving for Ir in equation (11) and substituting it in equations (12) and (13) yield the following for the two states Vc and V_T

$$\frac{dVT}{dt} = \left[I - \frac{(V_T - N(E) - N(Vc))}{N(r) + R_T}\right]\left(\frac{1}{C_T}\right) \qquad [4]$$

$$\frac{dVc}{dt} = \left\{\left[\frac{(V_T - N(E) - N(Vc))}{N(r) + R_T}\right] - \frac{Vc}{K/SOC}\right\}\frac{1}{c} \qquad [5]$$

Assuming positive current (charging) is in the direction shown in Figure 41, the state of charge SOC of the battery can be calculated as a function of the battery capacity. The battery capacity can be expressed as a function of temperature and discharge current Id as follows:

$$C(I,T) = C_5\left(\frac{Id}{I_5}\right)^{-0.325}[1 + 0.008(T - 30)] \qquad [6]$$

where:

C_5: Internal battery capacity [A-h]

I_5: Discharge current at 5 hour rate for the battery

Id: Discharge current

T: Temperature at which the battery operates [Deg C]

During the discharge,(Id < 0), the SOC can be calculated as follows:

$$\frac{dSOC}{dt} = \frac{100}{C(Id,T)} Id\left(\frac{1}{\eta_d}\right) \qquad [7]$$

where:

η_d: Discharge efficiency [ ]

During charge (Ic > 0), the SOC can be calculated as follows:

$$\frac{dSOC}{dt} = \frac{(100 - SOC)\eta_c Ic}{Q} \qquad [8]$$

where:

η_c: Charge efficiency [ ]

Ic: Charge current [A]

Q: Total Quantity missing in the battery over the entire operating time t

Q is calculated as follows:

$$Q = \left| \int_0^t I \, dt \right| \qquad [9]$$

3.2 Flywheel Battery

There are numerous possible flywheel energy storage system configurations. One of these configurations is shown in Figure 43.

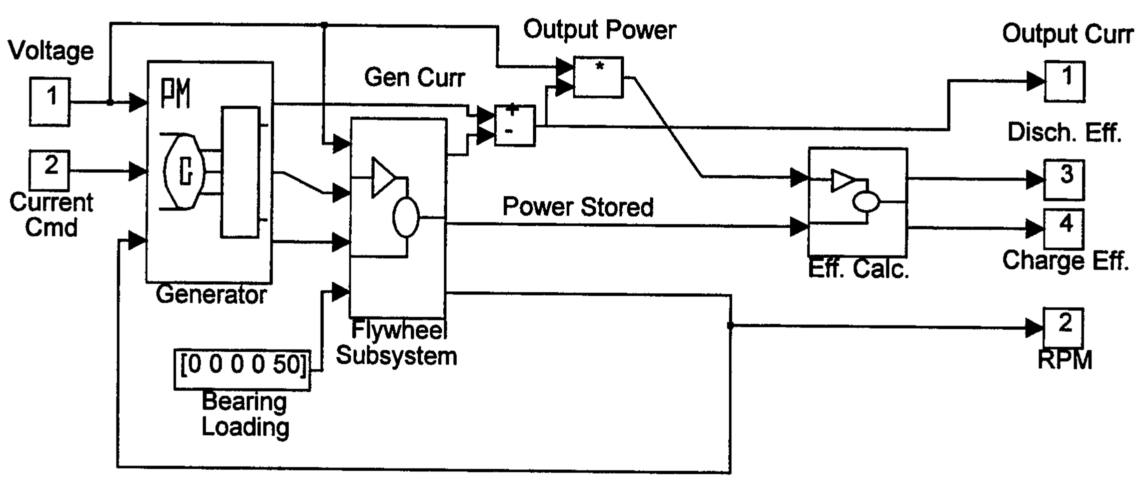


Figure 43. <u>Flywheel Energy Storage System Configuration</u>

Units

Voltage:	Volts
speed:	RPM
current:	Amps

Notes

inputs:	2(voltage, current command)
states:	1+(speed and generator states)
outputs:	4(output current, speed, discharge & charge eff)
direct feedthrough :	yes

There are two major components and one auxiliary component of this system:

1. Motor/Generator and Converter
2. Flywheel
3. Efficiency Calculation

This subsystem uses a permanent magnet generator. The 'Current Command' is the current command provided to the generator controller. The 'Output Current' is the actual current output to the DC Bus. Inputs for the 'Flywheel Subsystem' are the DC voltage, generator torque, generator inertia and bearing loads. The 'Flywheel Subsystem' has outputs of auxiliary current draw, stored mechanical power, and rotor speed.

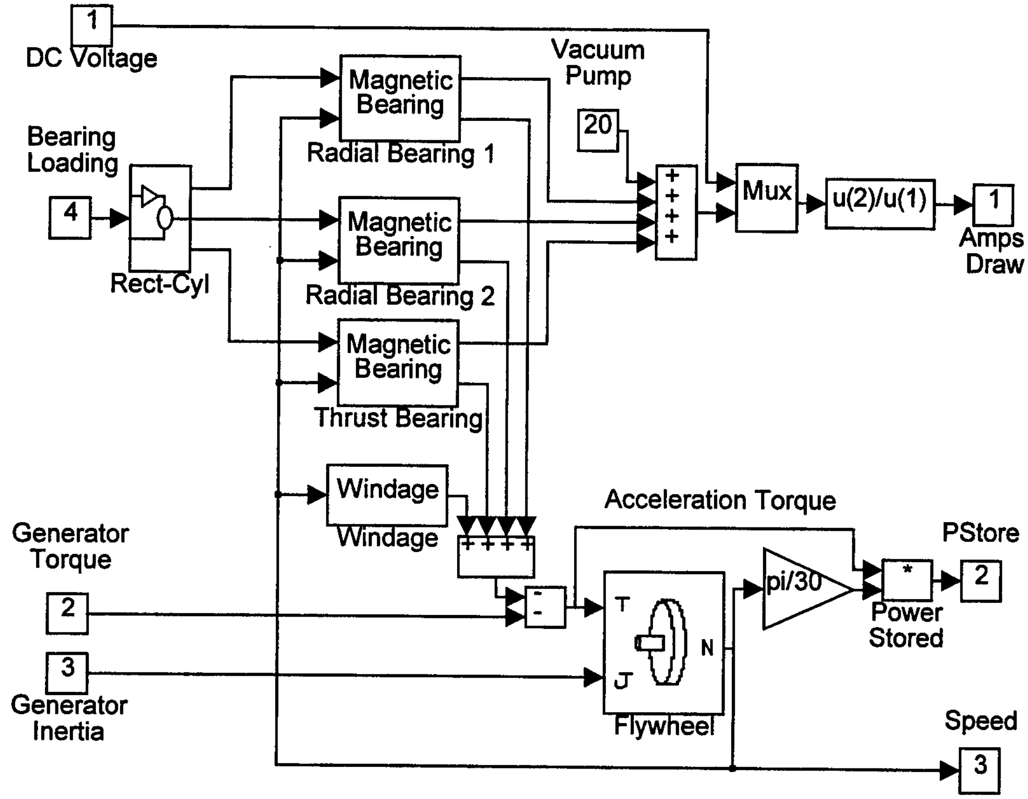


Figure 44. <u>**Flywheel Subsystem with Magnetic Bearings**</u>

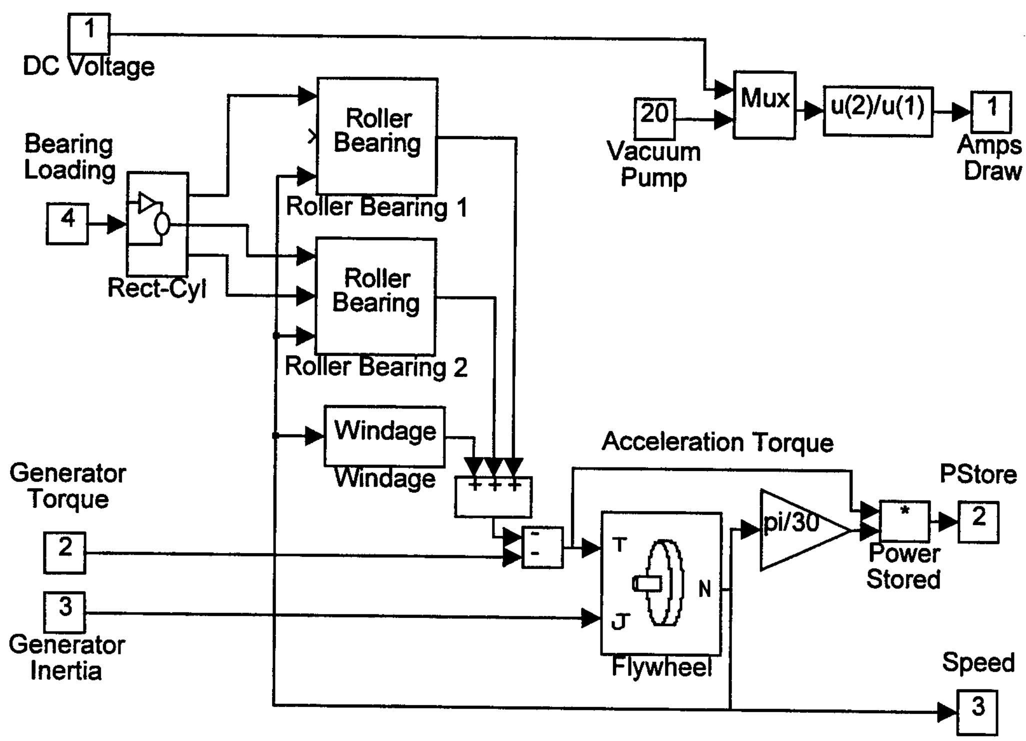


Figure 45. <u>**Flywheel Subsystem with Roller Bearings**</u>

The vacuum system is assumed to have a constant electrical power draw specified by the user. The inputs to the bearings are the forces on the bearings. These forces will be highly dependent on the mounting, with particular attention to whether gimbal mounting removes gyroscopic effects. The torque, which must be reacted by the bearings as radial forces to overcome gyroscopic effects, follows the following form:

$$\tau = J\omega_{rotor}\dot{\theta}$$

where

t: reaction torque to rotate the flywheel (N-m)

J: moment of inertia of the rotor (Kg-m)

w_{rotor}: rotor speed (rad/sec)

$\dot{\theta}$: rate of change of rotor position (rad/sec)

Because of the fairly high rotor speeds, a fairly low rate of change of rotor angle can generate a large gyroscopic torque. If a small bearing span is used this could generate large bearing forces. The equations to translate vehicle accelerations from the six degrees of freedom (X, Y, Z, yaw, pitch and roll) into bearing forces will be mounting dependent and is left to the system integrator.

3.2.1 Efficiency Calculation for Flywheel Energy Storage System

Inputs for the efficiency calculation subsystem 'Eff. Calc.' are the power going into stored energy and the power going into electrical energy. The efficiency calculation subsystem uses the following equations.

$$E_{out,discharge} = \int_{P_{elect>0}} P_{elect} \qquad E_{out,charge} = \int_{P_{mech>0}} P_{mech}$$

$$E_{in,discharge} = \int_{P_{elect>0}} P_{loss} + E_{out,discharge} \qquad E_{in,charge} = \int_{P_{elect<0}} P_{loss} + E_{out,charge}$$

$$\eta_{discharge} = \frac{E_{out,discharge}}{E_{in,discharge}} \qquad \eta_{charge} = \frac{E_{out,charge}}{E_{in,charge}}$$

There is a case where electrical power flows into the flywheel energy storage system but stored energy also decreases. With the above equations, these losses are included in the efficiency calculation by counting them as charging losses.

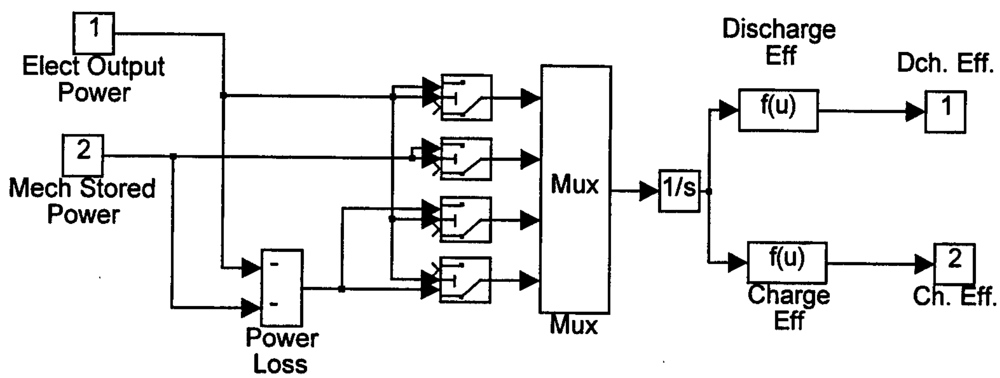


Figure 46. Flywheel Energy Storage Efficiency Calculation

3.2.2 Flywheel Battery System

A flywheel battery system can be defined as a flywheel energy storage system with an associated filter capacitor and controller to regulate a DC bus voltage. The relationship between the DC voltage and input current could be similar to a lead-acid battery, but a control scheme that maintains a fairly constant voltage can be used. A flywheel battery system with a simple feed-forward control and low gain feedback is shown. The feed-forward signal exactly balances the input current. There is a low gain feedback to keep the bus voltage near it's reference (300 volts in this case) to adjust for losses.

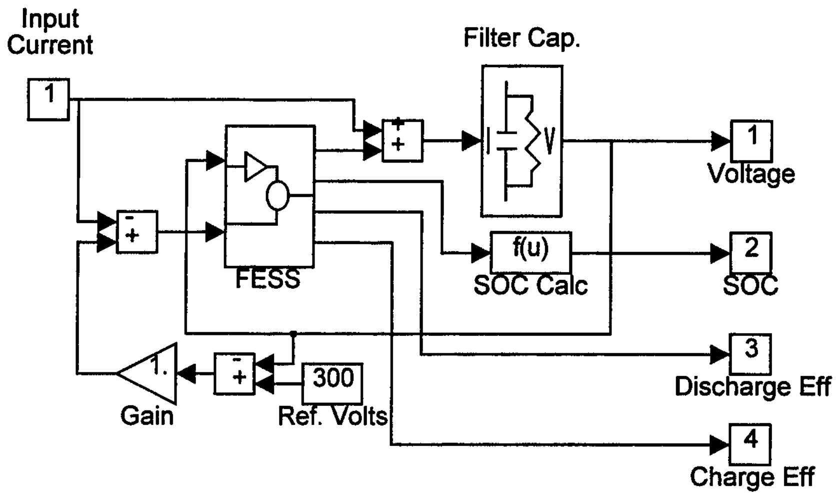


Figure 47. Simple Flywheel Battery System

3.3 Capacitor

Mathematical Model

$$I - \frac{V}{R} = C\frac{dV}{dt}$$

Units

current:	Amps
voltage:	Volts
resistance:	Ohms
capacitance:	Farads

Notes

inputs:	1 (current)
states:	1 (Voltage)
outputs:	1 (Voltage)
direct feedthrough:	no

4.0 VEHICLE LIBRARY

4.1 Wheeled Vehicle (Version 1)

This wheeled vehicle model calculates all the load forces acting on the vehicle. The total load force is as follows:

$$F_{Load} = F_{aero} + F_{roll} + F_{grade}$$

where:

F_{load} [N]:	Total resistance force acting on the vehicle
F_{aero} [N]:	Aerodynamic load on vehicle
F_{roll} [N]:	Rolling resistance from the tires on the vehicle
F_{grade} [N]:	Resistance as a result of the slope of the road (road grade force)

The aerodynamic drag force F_{aero} is expressed as a function of the vehicle frontal area (A), aerodynamic drag coefficient (C_d), the air density (r), the coefficient of yaw sensitivity (a), the normal (V_n) and parallel (V_p) wind velocity component, and the vehicle velocity (V) as follows:

$$F_{aero} = 0.5\rho C_d A(V - V_p)^2 (1 + \alpha \tan^{-1}(\frac{V_n}{(V - V_p)})) \qquad 1$$

where:

F_{aero} [N] :	Aerodynamic drag force
ρ [kg/m^3]:	Air density
Cd [ ]:	Aerodynamic drag coefficient
A [m^2]:	Vehicle frontal area
V [m/s]:	Vehicle velocity
V_n [m/s]:	Normal wind velocity component
Vp [m/s]:	Parallel wind velocity component
α[ ]:	Coefficient of yaw sensitivity

The rolling resistance force is expressed as follows:

$$F_{roll} = \mu \text{Weight} \cos(\tau)$$
$$\mu = f_0 + 3.24 f_s \left(V/_{100} \right)^{2.5} \tag{2}$$

where:

V [mph]:	Vehicle speed
m [ ] :	Coefficient of friction
Weight [N]:	Total vehicle weight
f_0 [ ]:	Coefficient of rolling resistance [ ]
f_s [ ]:	Speed dependent coefficient of friction

The road grade force is expressed as follows:

$$F_{grade} = \text{Weight} \sin(\alpha) \tag{2}$$

where:

Weight [N]:	Total vehicle weight
α [rad]:	Road gradient

4.2 Wheeled Vehicle (Version 2)

In this model, the vehicle is modeled as a single mass, whose acceleration is computed using Newton's second law of motion:

$$m_{eq} \ddot{x} = F_{driving} - F_{load}$$

where:

m_{eq} [kg]: Equivalent mass of vehicle

$\ddot{x}$ [rad/sec2]: Vehicle acceleration

$F_{driving}$ [N]: Total driving force on vehicle

F_{load} [N]: Total resistance load on vehicle

The mass of vehicle takes fuel consumed mass (as fuel is consumed, total fuel mass decreases) into consideration. The vehicle acceleration is integrated once to determine vehicle speed, and again to determine vehicle position. The computation of F_{load} is the same as described in the wheeled vehicle version (1), with the exception of including Fbrake, which is provided by the driver model. Therefore, Fload is computed as follows:

$$F_{Load} = F_{aero} + F_{roll} + F_{grade} + F_{brake}$$

4.3 Wheel Model (Version 1)

Figure 48 shows the physical model of the vehicle and the driven wheel, along with all forces acting on the vehicle. The following is an explanation of all forces acting on the vehicle:

F_{load} [N]: Sum of all load forces opposing the motion of the vehicle. This force comprises the Aero dynamic load and the gradient load.

F_f [N]: The friction force acting on the surface of the tires as a result of the friction coefficient between the tires and the road.

m [Kg] : The total mass of the vehicle (including the wheel mass)

x [m] : The linear displacement of the vehicle

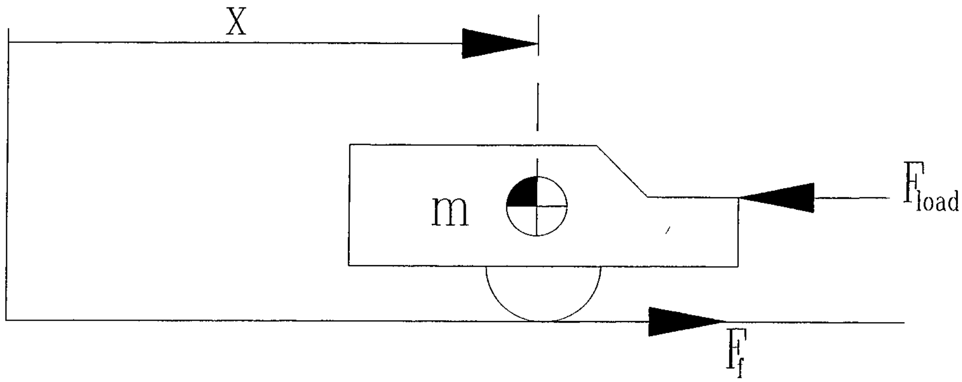


Figure 48. <u>Physical Model of the Vehicle and Wheel</u>

For the system shown in Figure 48, Newton's law can be formulated as follows:

$$m\ddot{x} = F_f - F_{load} \quad (1)$$

Figure 49 shows the physical model of the wheel. The following is an explanation of the forces and moments acting on the wheel:

T_d [Nm]:	The driving torque on the wheel delivered from the axle
F_f [N] :	The friction force acting on the surface of the tires as a result of the friction between the tires and the road.
J_W [kg m^2]:	The mass moment of inertia of the wheel
q [rad]:	The rotation in radians of the wheel

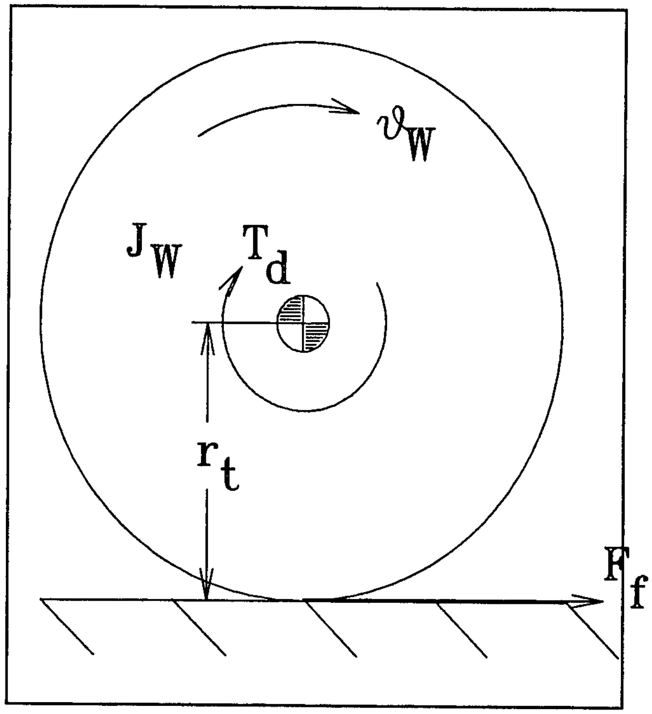


Figure 49. Physical Model Of The Wheel

Assuming a constant tire radius, Newton's law can be formulated for the wheel as follows:

$$J_W\ddot{\theta} = T_d - F_f r_t \quad (2)$$

From Equation (1), F_f can be expressed as follows:

$$F_f = m\ddot{x} + F_{load} \quad (3)$$

Combining equations (2) and (3), it follows:

$$J_W\ddot{\theta} = T_d - m\ddot{x}r_t - F_{load}\,r_t$$

$$\ddot{x} = r_t\ddot{\theta}$$

$$J_W\ddot{\theta} = T_d - mr_t^2\ddot{\theta} - F_{load}\,r_t \quad (4)$$

$$(J_W + mr_t^2)\ddot{\theta} = T_d - F_{load}\,r_t$$

$$\ddot{\theta} = \frac{T_d - F_{load}\,r_t}{J_W + mr_t^2}$$

4.4 Wheel Model (Version 2)

This wheel model converts the vehicle velocity into the rotational speed of the wheel, which is equal to the rotational speed of the output shaft of the axle. The axle or coupler connects the electric motor to the wheel.

$$\omega_{wheel} = V / r_{wheel}$$

where:

ω_{wheel} [rad/sec]: Rotational speed of the wheel

r_{wheel} [m]: Wheel radius

V [m/s]: Vehicle linear velocity

The driving torque acting on the wheel is converted to driving force as follows:

$$F_{driving} = \frac{T_{axle\_out}}{r_{wheel}}$$

where:

$F_{driving}$ [N]: Total driving force acting on vehicle

T_{axle_out} [Nm]: Total output torque delivered from axle

r_{wheel} [m]: Wheel radius

If the entire mass of the vehicle is regarded as concentrated at the wheel mass center, then the total inertia of the wheel can be computed as follows:

$$m_{eq} * r_{wheel}^{2} = (1/2 * mwheel * rwheel^{2} + Jaxle\_out$$

where:

meq [Kg]: Equivalent vehicle mass

rwheel[m] : Wheel radius

Jaxle_outpt [kgm^2]: Output Inertia of axle

5.0 COUPLINGS LIBRARY

5.1 Motor Wheel Coupling (Version 1)

Figure 50 shows the physical model of the motor wheel coupling as well as the free body diagram for each gear. The following is an explanation of all forces and moments shown in Figure 50:

T_1 [Nm]:	Torque at the input side of the coupler model
T_2 [Nm]:	Torque at the output side of the coupler model
F [N]:	The contact force between gear 1 and gear 2
q_1 [rad]:	The rotation of the shaft at the input side of the coupler model
q_2 [rad]:	The rotation of the shaft at the output side of the coupler model
J_1 [kgm^2]:	Inertia at the input side of the coupler model
J_2 [kgm^2]:	Inertia at the output side of the coupler model
r_1 [m]:	Radius of input gear of the coupler model
r_2 [m]:	Radius of output gear of the coupler model
G [ ]:	Gear ratio of the coupler
η[]:	Coupler efficiency

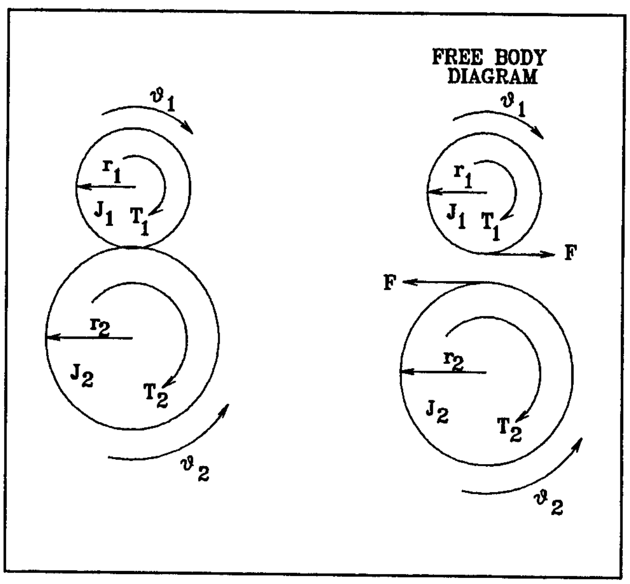


Figure 50. The Coupler Physical Model

Newton's law can be formulated for both gears as follows:

$$
\begin{aligned}
\ddot{\theta}_1 &= \frac{T_1 - Fr_1}{J_1} \\
\ddot{\theta}_2 &= \frac{Fr_2 - T_2}{J_2} \\
\frac{\ddot{\theta}_1}{\ddot{\theta}_2} &= \frac{\dot{\theta}_1}{\dot{\theta}_2} = \frac{r_2}{r_1} = G \qquad (1) \\
\therefore F &= \frac{(J_2\ddot{\theta}_2 + T_2)}{r_2} \; ; \; \ddot{\theta}_1 = \ddot{\theta}_2 G
\end{aligned}
$$

1

From equation (1), the coupler model can be formulated as follows (traction):

$$
\begin{aligned}
\ddot{\theta}_2 G J_1 - T_1 &= -\frac{1}{G}(J_2\ddot{\theta}_2 + T_2) \\
T_2 &= [T_1 - (G J_1 + (\frac{1}{G}) J_2 \ddot{\theta}_2)] G \eta
\end{aligned}
$$

The output torque T2 of the coupler in regen mode is then:

$$T_2 = [T_1 - (GJ_1 + (\frac{1}{G})J_2\ddot{\theta}_2]G(\frac{1}{\eta})$$

5.2 Motor Wheel Coupling (Version 2)

This model computes the total inertia as seen by the wheel as follows:

$$(J_{in} + J_{ingear})G^2 + J_{outgear} = J_{wheel}$$

where:

J_{in} [kgm^2]:	Inertia of the rotor of the motor
J_{ingear} [kgm^2]:	Inertia of the input side of the gear coupler between the motor and wheel
G [ ]:	Gear ratio of coupler

$J_{outgear}$ [kgm^2]: Inertia of the output side of the gear coupler between the motor and wheel

J_{wheel} [kgm^2]: Total inertia that the wheel has to accelerate

The gear ratio is defined as follows:

$$G = \frac{N_{in}}{N_{out}}$$

where:

N_{in} [rpm]: Rotational speed at the input side of the coupler

N_{out}[rpm]: Rotational speed at the output side of the coupler

The torque output of the coupler is computed as follows (traction mode):

$$T_{out} = T_{in} G \eta$$

The torque output of the coupler is computed as follows (regen mode):

$$T_{out} = T_{in} G(\frac{1}{\eta})$$

where:

Tout [Nm]: Torque to drive wheel

Tin [Nm]: Torque inputted into coupler from motor

G [ ]: Gear ratio

η [ ]: Coupler efficiency

6.0 MISCELLANEOUS LIBRARY

The equations used in this library are briefly discussed in the User's manual. Therefore, the reader is referred to the User's Manual for the equations describing the models of the miscellaneous library.

HYBRID ELECTRIC VEHICLE
SIMULINK TOOLBOX

(Commercial Vehicle Version)

PATHS Validation
Draft Copy

Version 1.1

EXECUTIVE SUMMARY

The following report summarizes the efforts to validate PATHS, a modeling and simulation software for electric and hybrid vehicles. Due to time and budget constraints, it was impossible to validate all the components of the PATHS software. Therefore, only key components of PATHS were validated. The APU, AC induction motor, lead acid and driver-axle-wheel-vehicle combined models were validated. These are the components that are principally used to model a commercial hybrid vehicle.

Validation was performed by first developing a computer model of a 22-foot series hybrid shuttle bus, followed by comparing its output to data collected from the same bus on a dynamometer. Section 1 describes the series hybrid bus and the driving profiles used during validation.

Section 1.1 describes the results of the APU model validation. Fuel consumption and CO (Carbon Monoxide) and NOx (Nitrogen Oxide) emissions were measured and compared with model predictions. Model and measured data agreed with each other to within less than 5%, while considerably larger deviations up to 100% were observed between measured and model predicted CO and NOx emissions. This can be largely attributed to insufficient emissions data obtained from the manufacturer.

Section 1.2 describes the validation of the AC induction motor model. The consumed motor current in motor mode and regenerated current in generator mode were compared with data collected from the motors of the bus. The model predicts transient and steady-state operations of the motor within 10%, except for measured motor current spikes in current draw and regeneration.

Section 1.3 describes the validation of the lead acid battery model. Battery state of charge and voltage predicted by the model were compared with measured data from the hybrid bus. The model predicted battery state of charge compared within 5% to the measured data of the same. Larger deviations were observed with the comparison of the model predicted and measured battery voltage.

Section 1.4 describes the validation of the combined driver-axle-wheel-vehicle model.

Finally, Section 2.0 describes the hybrid bus model of the 22-foot series hybrid shuttle bus that was used to validate PATHS.

Section 3.0 provides concluding comments on this validation report.

1.0 INTRODUCTION

This document comprises the validation and testing of the main components of PATHS. The reader is referred to the User's Guide and Technical Notes for a more detailed description of PATHS. The validation includes the following main models of PATHS. These are the models that are used at a minimum to model a general series hybrid vehicle.

- APU model from the engine library
- AC induction motor model (including inverter) from the electric machine library
- Lead acid battery model from the energy storage library
- Driver-axle-wheel-vehicle combined model

The data for the validation of the above components was obtained from a 22-foot series hybrid shuttle bus developed by the Electricore consortium. This bus has a 35-kW, CNG-fueled Auxiliary Power Unit (APU) with two battery packs, each containing 26 lead-acid batteries. The vehicle is propelled by two 70-kW (peak), AC-induction wheel motors, one on each side of the rear wheels. A fixed ratio speed reducer of 20:1 is integrated into the motor before the output to the wheels.

The hybrid bus was placed on a heavy-duty chassis dynamometer at Southwest Research Institute (SwRI) and operated on two driving cycles: the CBD and EPA schedule D driving cycles. Figure 51 shows the CBD driving profile, and Figure 52 illustrates the EPA schedule D driving profile.

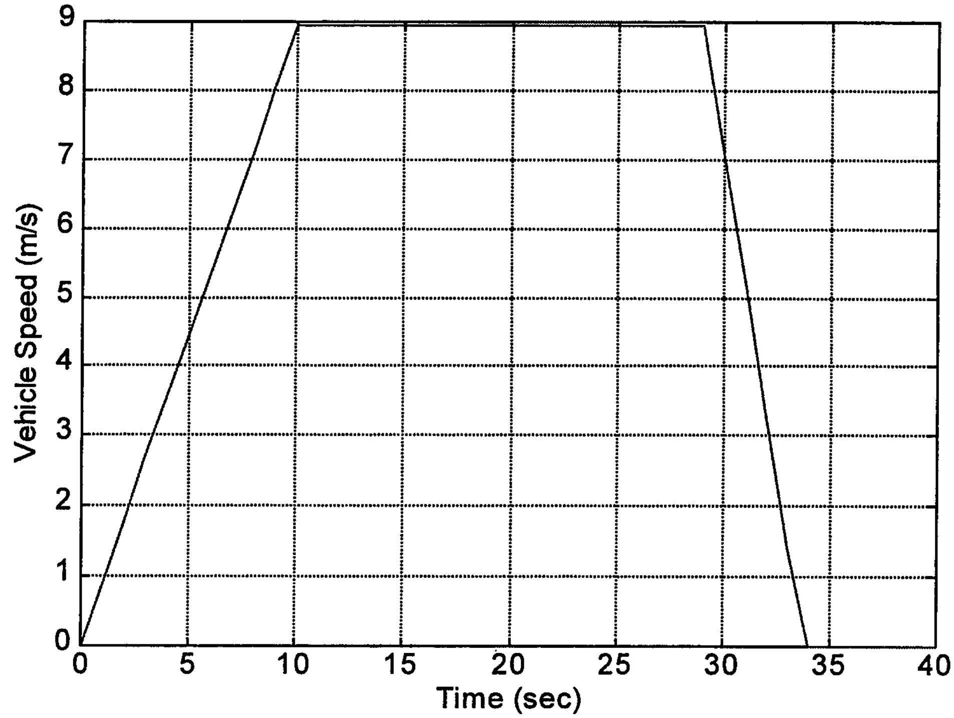


Figure 51. CBD Driving Profile

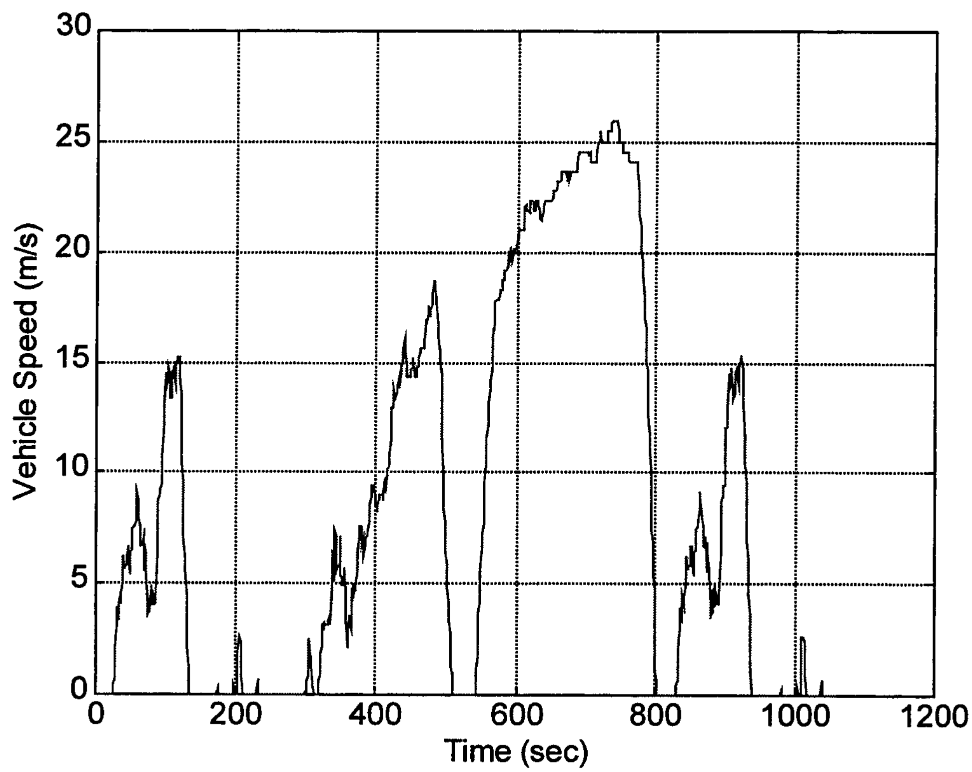


Figure 52. Schedule D Driving Profile

Data was collected over six consecutive EPA schedule D and ten CBD-14 driving cycles respectively. A CBD-14 driving profile consists of 14 consecutive CBD segments (see Figure 50 for one CBD driving segment). For each of the aforementioned driving cycles, the following data was collected on a second-by-second basis:

- Bus voltage (volts)
- Vehicle speed (miles per hour)
- APU engine speed (rpm)
- Accelerator pedal position (0-1)
- Brake pedal position (0-1)
- Current into and out of left motor inverter (DC amps)
- Current into and out of right motor inverter (DC Amps)
- Current into and out of left battery pack (DC Amps)
- Current into and out of right battery pack (DC Amps)
- Generator current (DC Amps)
- Battery pack state of charge (%)

The following sections describe the validation results of the main components of PATHS.

1.1 APU Model Validation

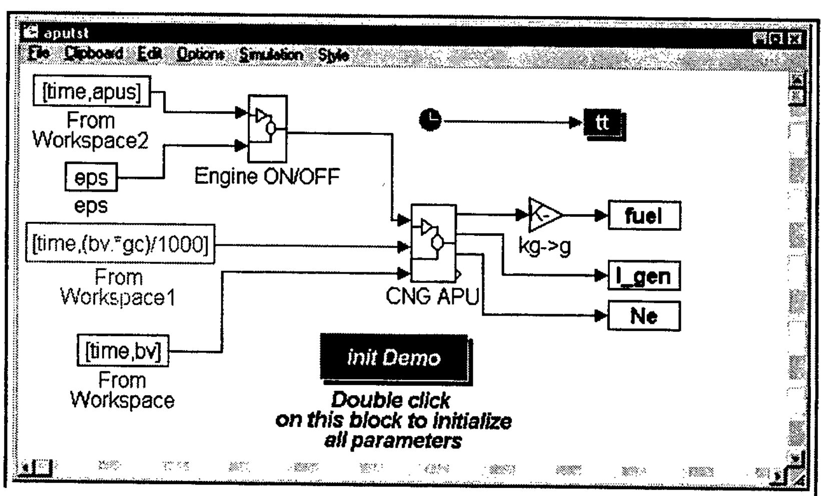


Figure 53. APU Model Validation

The APU model shown in Figure 53 is of the table look-up type and models a 35 kW CNG engine, coupled to a permanent magnet generator. Table 27 describes the inputs and outputs of the APU model.

Table 27. APU MODEL	
INPUTS	**OUTPUTS**
Engine on/off state	Mass of fuel consumed (kg)
Desired electric power (kW)	Generator current (DC Amps)
Battery voltage (volts)	Engine speed (rpm)
	APU inertia (kgm^2)

The APU model was tested by providing collected test data on bus voltage and generator current (the electric power is equal to the product of the bus voltage and generator current) as inputs to the model and comparing the model outputs of fuel consumed and engine speed with measured data of the same. Figure 54 shows a comparison of fuel consumed as predicted by the APU model and measured fuel consumption data. Figure 55a and 55b illustrate a comparison of the APU emissions (HC and Nox) predicted by the model and the collected data.

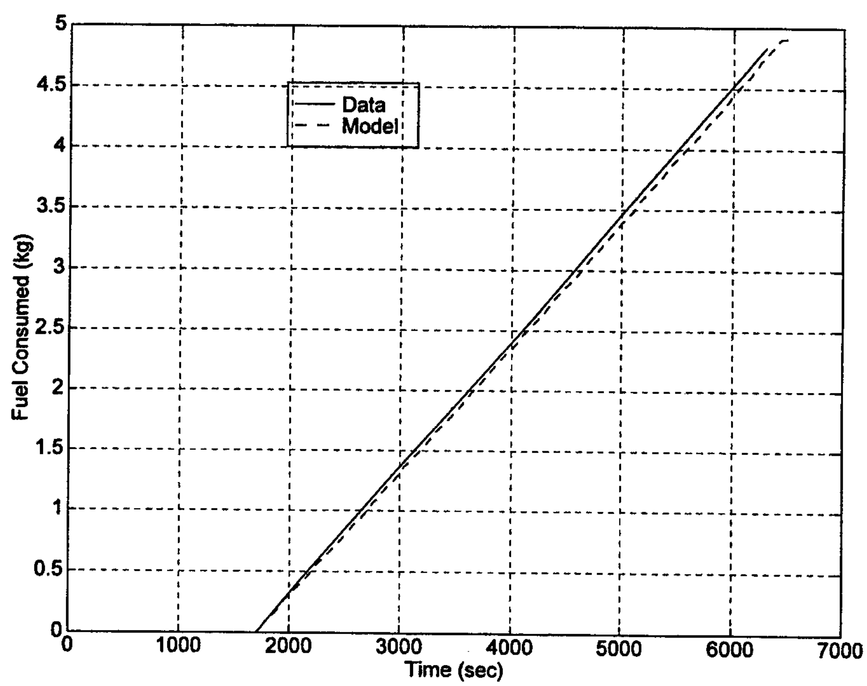


Figure 54. APU Validation – 6 EPA Schedule D

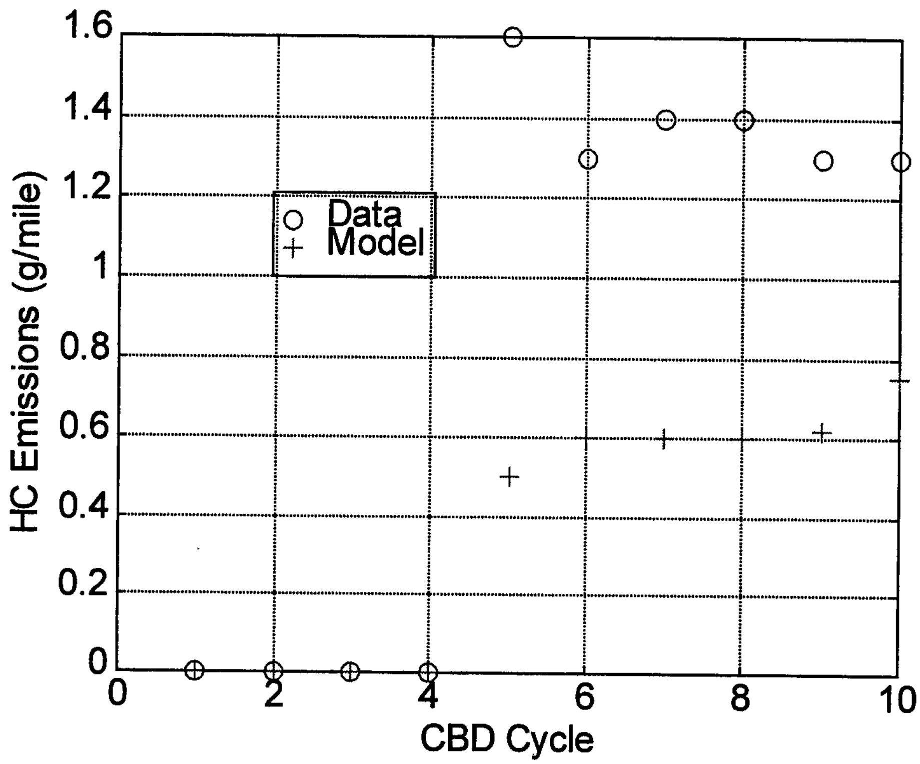


Figure 55a. <u>**APU Model Validation –10 CBD Driving Cycles (HC Emissions)**</u>

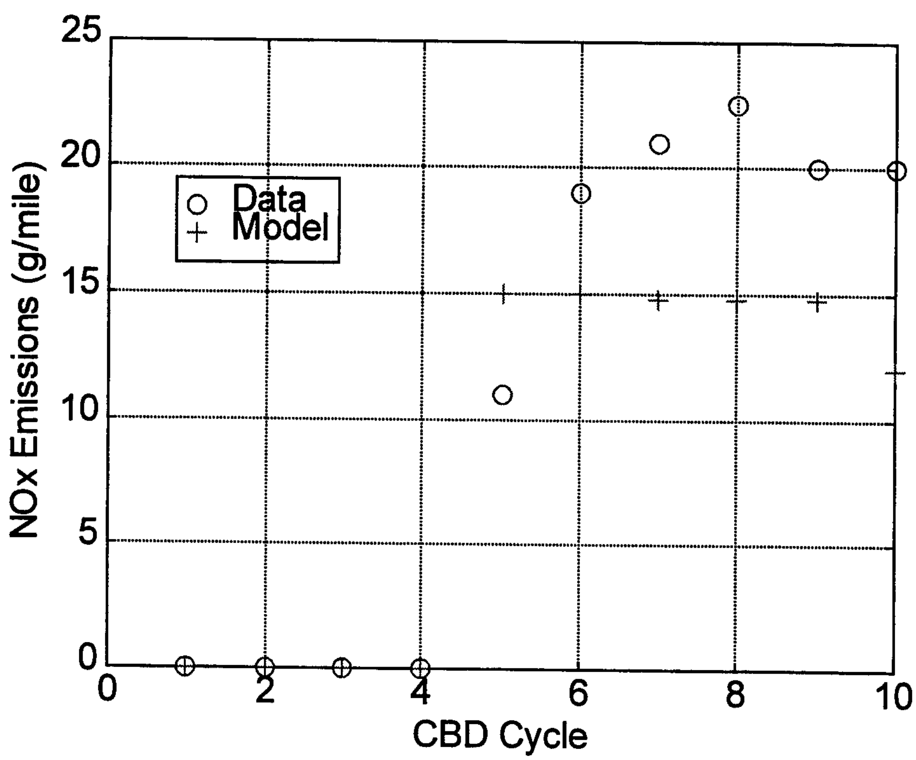


Figure 55b. <u>**APU Model Validation –10 CBD Driving Cycles (NOx Emissions)**</u>

1.2 AC Induction Motor Model

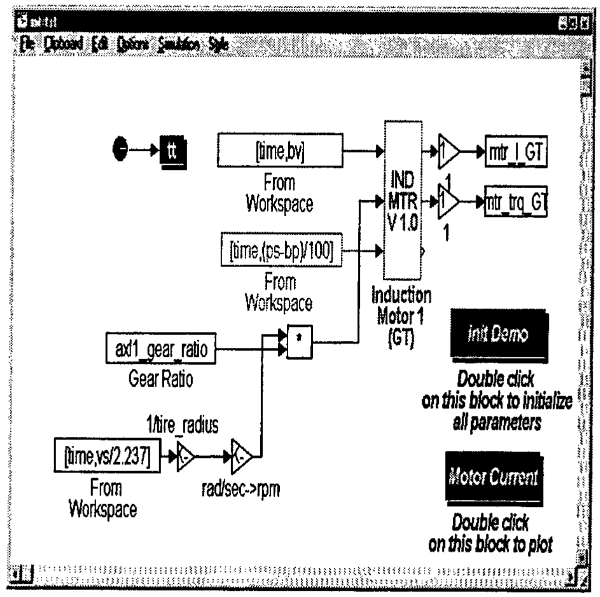


Figure 56. AC Induction Motor

The AC induction motor model must have several parameters defined prior to integration into a hybrid vehicle simulation model. The essential motor model parameters are described in Table 28.

Table 28. AC INDUCTION MOTOR MODEL PARAMETERS	
P (hp):	Rated power of motor
V (volts)	Rated operating voltage
f (Hz)	Rated operating frequency
n(rpm)	Rated speed
CL(hp)	Core losses at rated voltage and speed
SLL(hp)	Stray load losses at rated voltage and speed
Rs(Ω)	Per phase stator resistance
Rr(Ω)	Per phase rotor resistance
Lls(H)	Per phase stator leakage inductance
Llr(H)	Per phase rotor leakage resistance
Lm(H)	Per phase magnetizing inductance
η (-)	Inverter efficiency
I(kgm^2)	motor inertia
sample_N	Number of samples saved to workspace
sample_T	Time between each saved sample

The above parameters must be matched for an individual motor by means of the full-throttle torque speed curve of the motor. The full throttle and part throttle torque speed curves for the 70 kW AC induction motor are illustrated in Figure 57. An iterative procedure was used to match the motor parameters to produce the torque speed characteristics shown in Figure 57. Figure 58 shows the motor model predicted torque speed characteristics superimposed on that of Figure 57. The final motor parameters that were used to simulate the hybrid bus are defined in the model mask, illustrated in Figure 58.

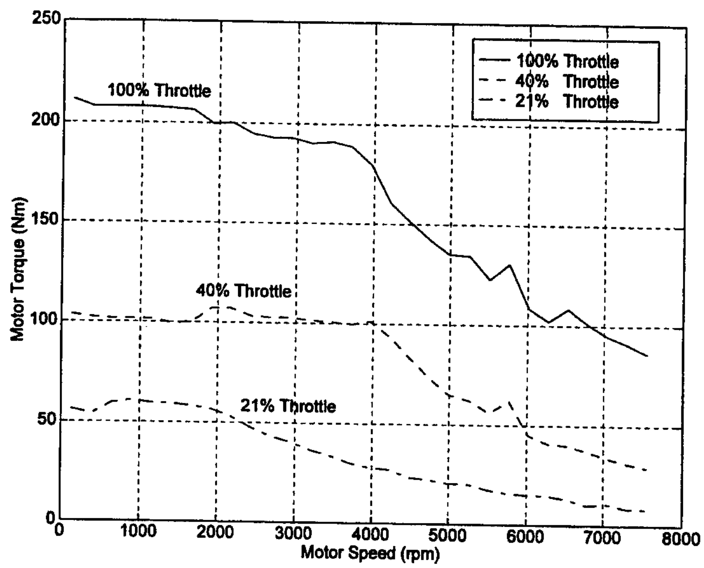


Figure 57. <u>**System Voltage =312V – Measured Motor Data**</u>

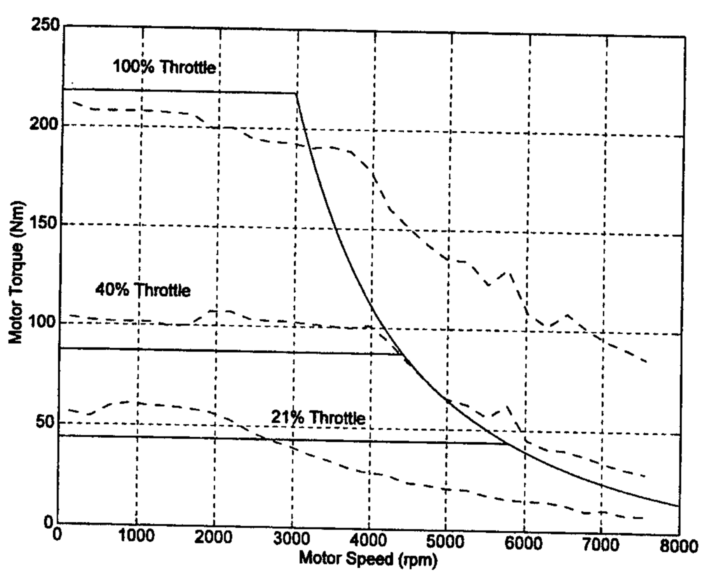


Figure 58. <u>**System Voltage = 312 V – Measured Motor Data vs. Model**</u>

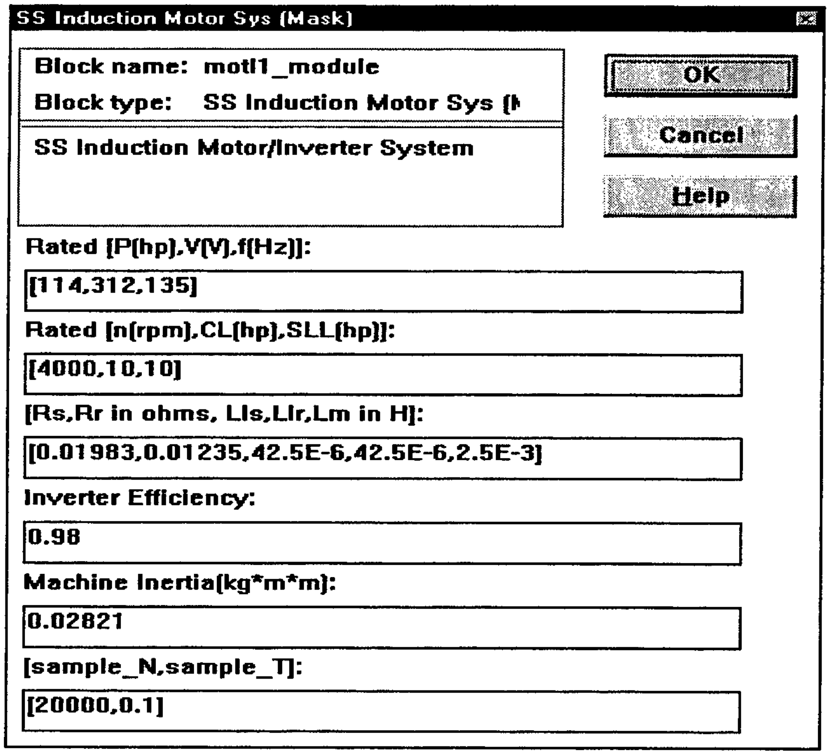


Figure 59. SS Induction Motor Sys (Mask)

Table 29. AC INDUCTION MOTOR MODEL	
INPUTS	**OUTPUTS**
Bus voltage (V)	Motor current (DC Amps)
Motor speed (rpm)	Motor torque (Nm)
Torque command (0-1)	Motor inertia (kgm^2)

The motor model was validated by providing collected test data on bus voltage, torque command from driver accelerator and brake pedal, and vehicle speed as inputs to the model and comparing the model outputs of current and torque with measured data of the same. Figure 60 shows a comparison of the model predicted current and measured data for the first 500 seconds of the EPA schedule D driving profile . Figure 61 shows the same comparison for the last 500 seconds of the same driving profile.

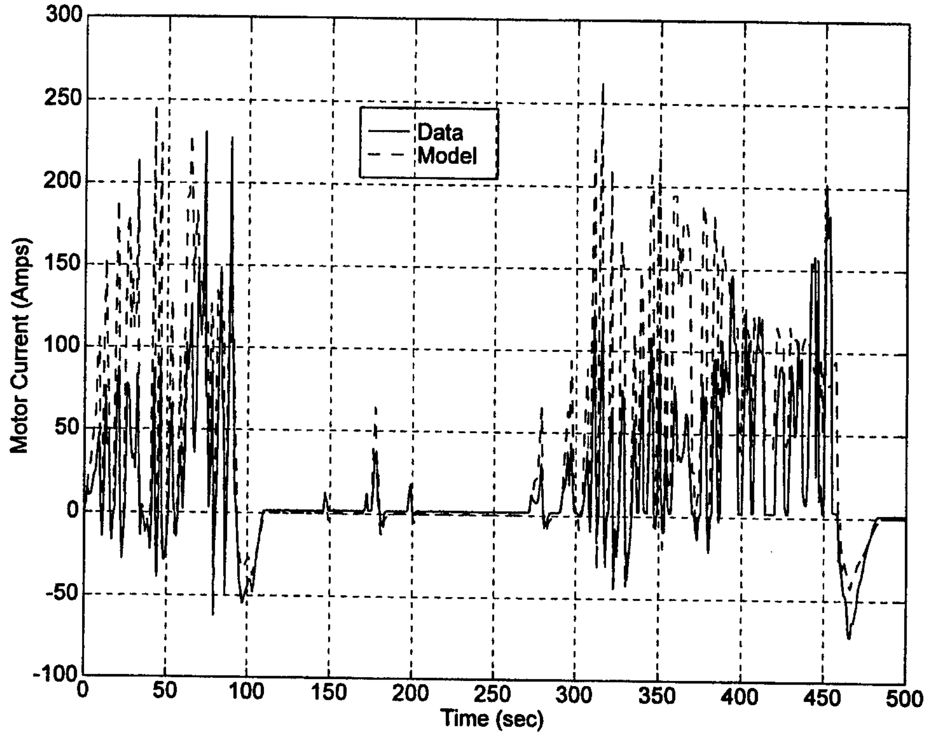


Figure 60. <u>**Motor Model Validation – 1 EPA Schedule D (first 500 seconds)**</u>

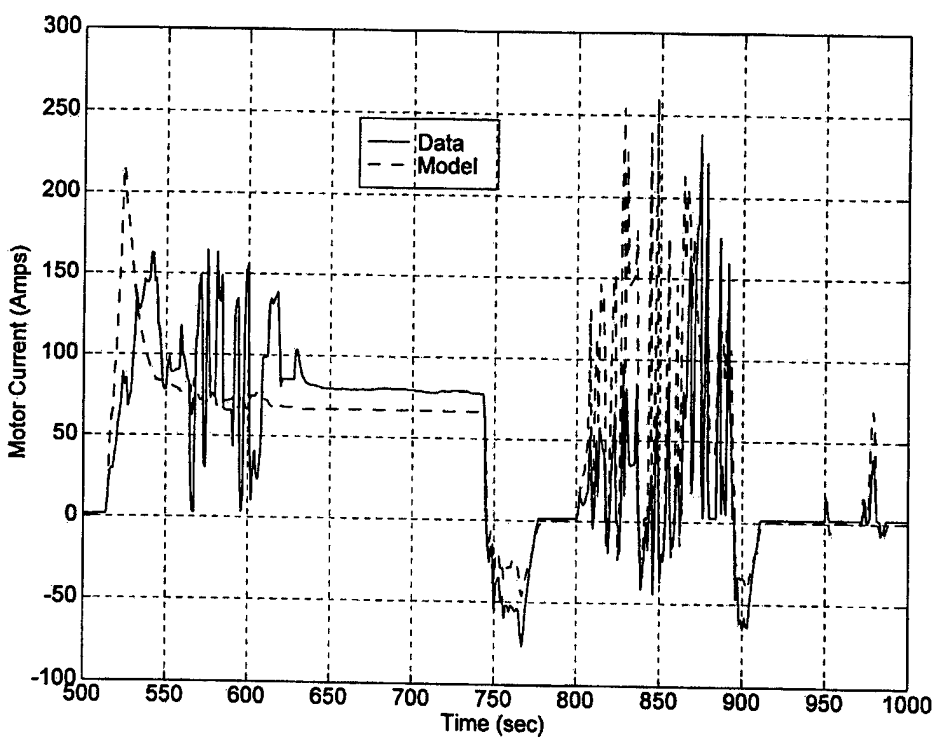


Figure 61. <u>**Motor Model Validation – EPA Schedule D (last 500 seconds)**</u>

1.3 Lead Acid Battery Model

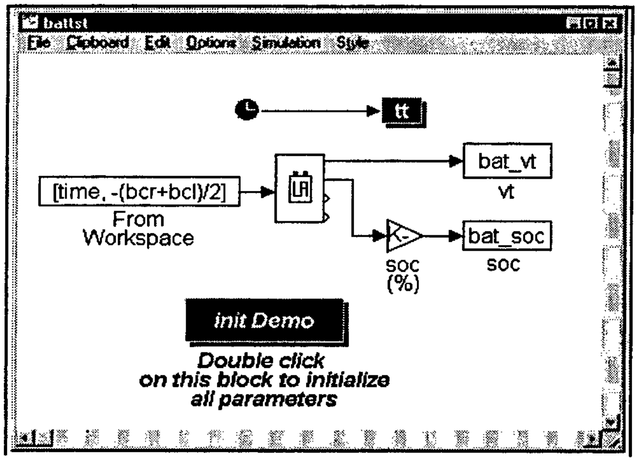


Figure 62. Lead Acid Battery Model

The lead acid battery model parameters are presented in Table 30.

Table 30. LEAD ACID BATTERY MODEL PARAMETERS	
Number of batteries	(-)
Open circuit voltage of a battery	(volts)
Internal resistance of the battery	(Ω)
Polarization resistance of the battery (Ω)	(Ω)
Battery capacitance	(F)
Terminal battery resistance	(Ω)
Terminal battery capacitance	(Ω)
Discharge capacity at a 5 hour rate and 30° Celsius	(A-hr)
Discharge current at a 5 hour rate and 30° Celsius	(A)
Charge efficiency	(0-1)
Discharge efficiency	(0-1)
Operating temperature	(° C)
Initial polarization voltage	(V)
Initial state of charge	(0-100)

The hybrid bus is equipped with two battery packs, each containing 26 batteries. The above parameters needed for the model were obtained from the battery manufacturer and are entered into the model mask, illustrated in Figure 63. Note the mask represents a battery pack containing 26 batteries.

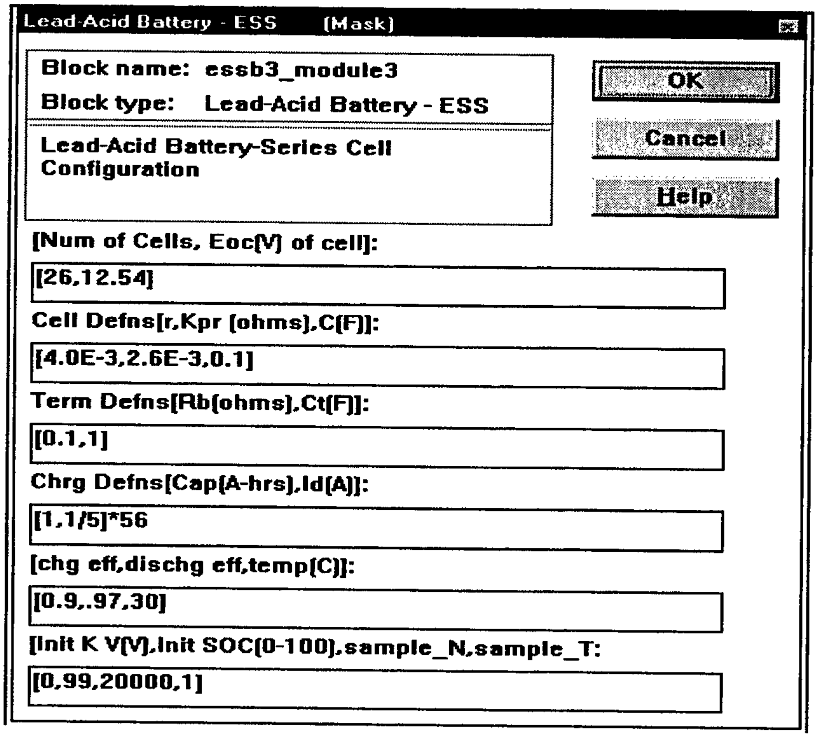


Figure 63. Lead-Acid Battery – ESS (Mask)

The input and outputs of the battery model are described in Table 31.

Table 31. BATTERY MODEL

Inputs	Outputs
Charge/discharge current (DC Amps)	Battery voltage (volts)
	State of charge (0-1)

The battery model was validated by supplying to the battery model input the measured charge/discharge current and comparing the model predicted battery pack state of charge and voltage with measured data. Figure 64 shows a comparison of the battery state of charge as predicted by the model and measured on the bus. Figure 65 shows a comparison of the battery voltage as predicted by the model and measured on the bus using the EPA Schedule D test.

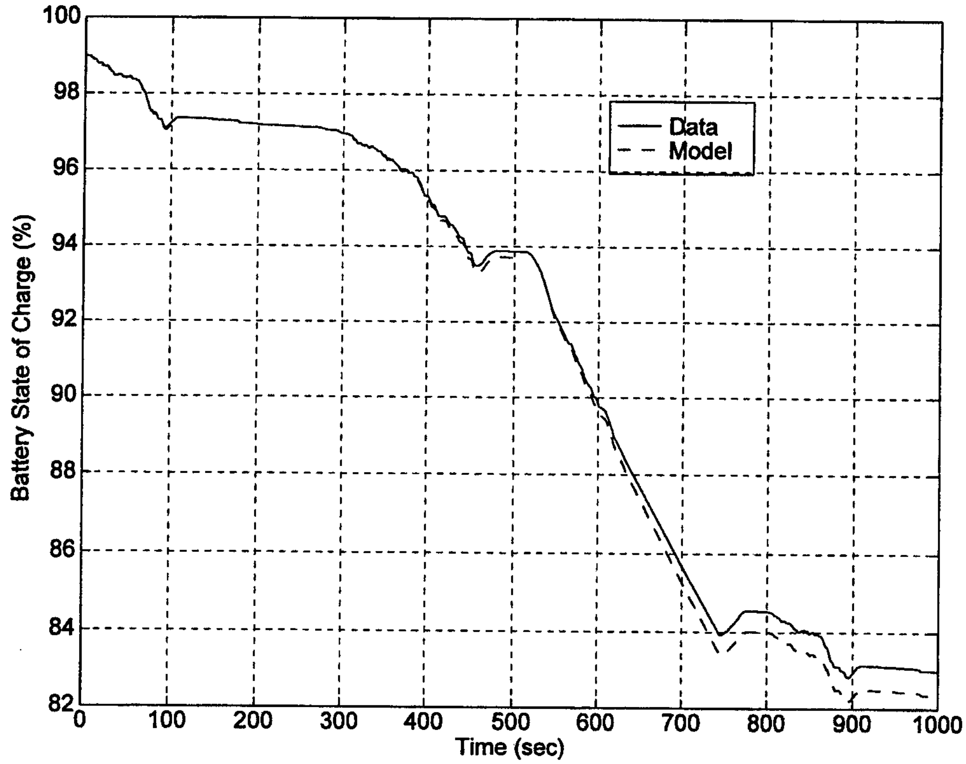


Figure 64. Battery Validation- EPA Schedule D

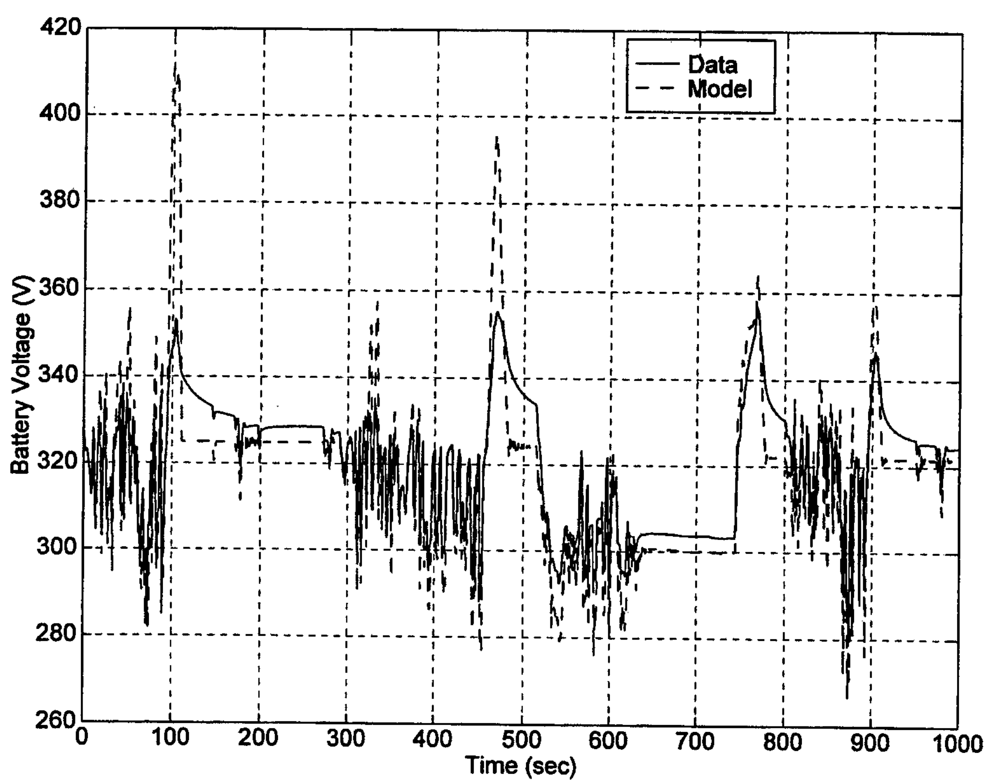


Figure 65. Battery Validation – EPA Schedule D

1.4 Driver-Axle-Wheel-Vehicle Combined Model

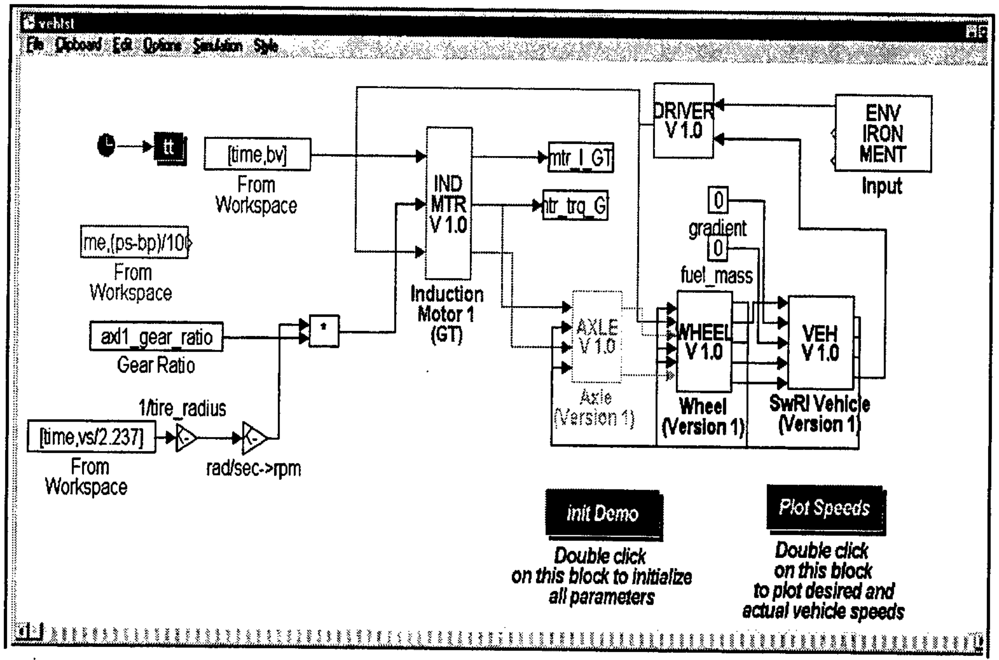


Figure 66. Driver-Axle-Wheel-Vehicle Combined Model

This combined model consists of four component models. The nature of the available test data required us to combine these four components into a single model for testing and validation purposes. The Tables 32-35 summarize the inputs and outputs of each of the component models.

Table 32. DRIVER MODEL

INPUTS	OUTPUTS
Desired vehicle speed (m/s)	Power demand (0-1)
Actual vehicle speed (m/s)	

Table 33. AXLE MODEL

INPUTS	OUTPUTS
Input torque (Nm)	Output torque (Nm)
Output shaft speed (rpm)	Input shaft speed (rpm)
Input inertia (kgm^2)	Equivalent output inertia (kgm^2)

Table 34. WHEEL MODEL	
INPUTS	**OUTPUTS**
Maximum traction force (N)	Rotational wheel speed (rpm)
Power demand from driver (0-1)	Vehicle speed (m/s)
Torque at input (Nm)	Vehicle acceleration (m/s^2)
Total resistive load (N)	Wheel moment of inertia (kgm^2)
Total vehicle mass (kg)	Service brake force (N)
Equivalent inertia (kgm^2) from axle	

Table 35. VEHICLE MODEL	
INPUTS	**OUTPUTS**
Vehicle speed (m/s)	Total load on vehicle (N)
Gradient (radians)	Maximum traction force (N)
Fuel mass consumed (kg)	Vehicle speed (m/s)
Vehicle acceleration (m/s^2)	Total vehicle mass (kg)
Service brake force (N)	

Figure 67 shows a comparison of the pedal and brake positions between the measured data and that predicted by the driver model, while following the EPA - schedule D driving profile.

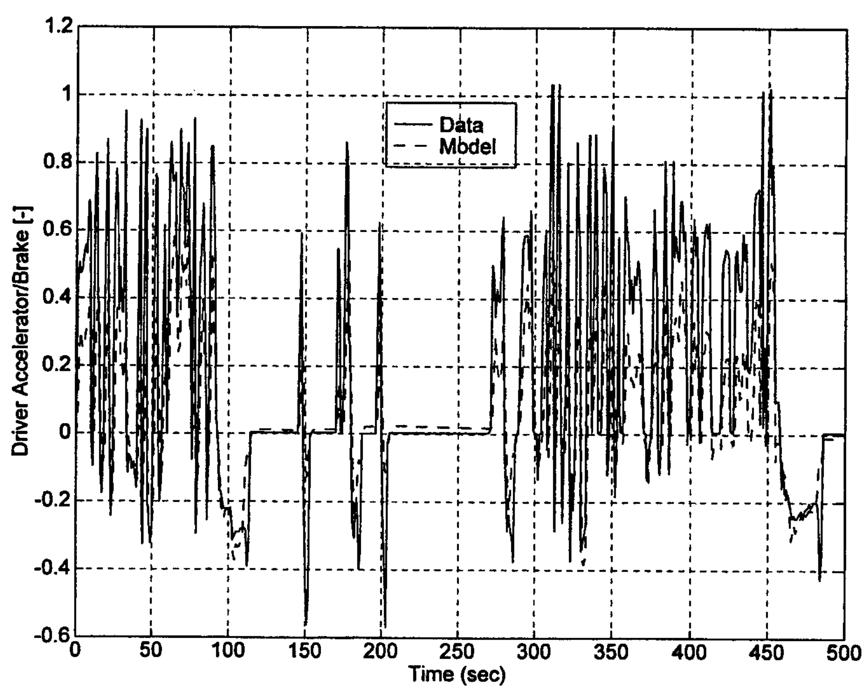


Figure 67. Driver Model Validation – EPA Schedule D

2.0 Hybrid Bus Model

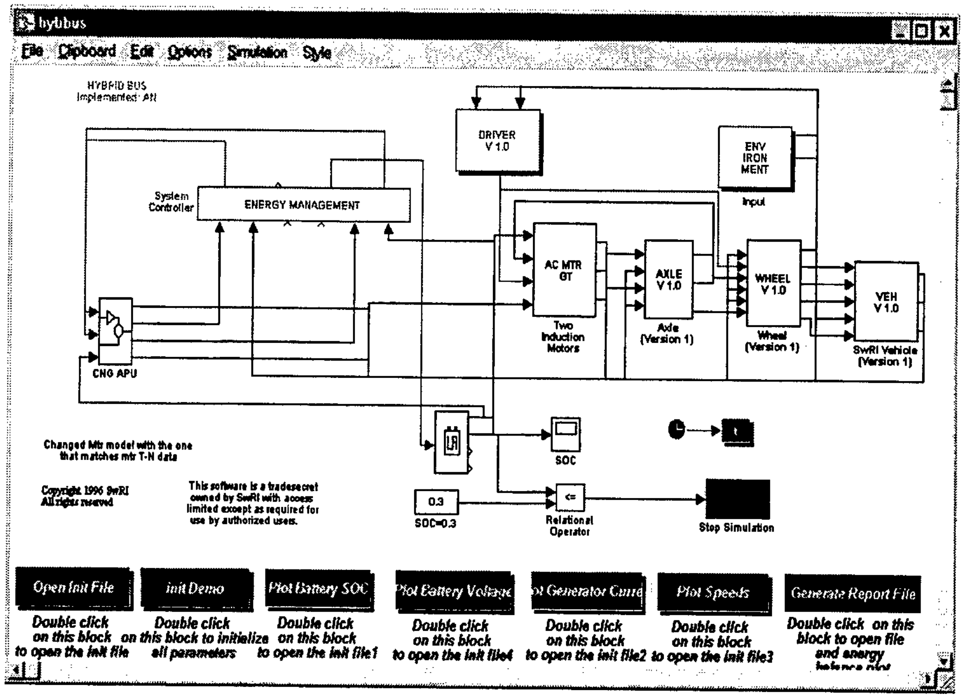


Figure 68. Hybrid Bus Model

The subcomponents described in Sections 1.1 to 1.4 were combined to model a 22-foot series hybrid shuttle bus developed by the Electricore consortium. As described in Section 1, this bus is equipped with two 70-kW wheel, AC-induction motors, a 35-kW CNG-fueled APU, and two battery packs, each containing 26 lead-acid batteries. The weight of the hybrid bus is approximately 14,600 pounds (empty weight plus an estimated 10 passengers). The inertia weight for the chassis dynamometer was computed from this estimate of the bus weight. Based on the frontal area and drag coefficient, the road load was estimated at 52 hp at a speed of 50 mph. The rolling resistance was computed to be 17 hp and the aerodynamic losses were computed as 35 hp. The power management controller turned the APU on when the battery state of charge fell below 75%, and turned the APU off when the battery state of charge increased above 85%. The electrical power requested from the APU was a function of state of charge, that is user modifiable. Figure 69 shows the model of the hybrid bus using the components described in Sections 1.1 to 1.4.

Figure 69 shows a comparison of the battery state of charge, while the hybrid bus was operated over 6 EPA-Schedule D driving profiles. Figure 70 shows the relative error of the model predicted battery voltage with respect to the measured data during operation over 6 EPA-Schedule D driving profiles. Figure 71 compares the vehicle speed predicted by the model with data measured on the dynamometer test stand.

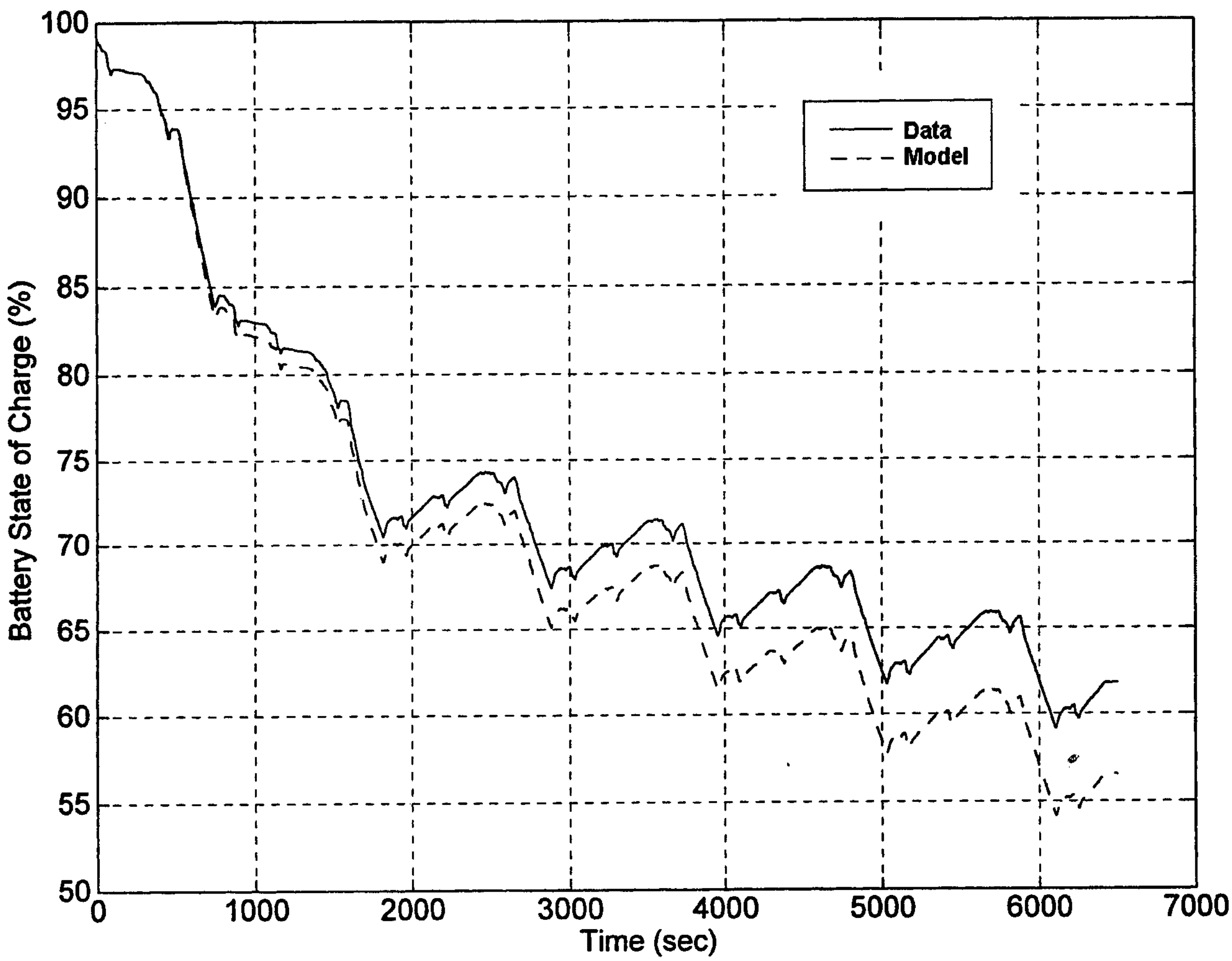


Figure 69. Hybrid Bus Model Validation – EPA Schedule D

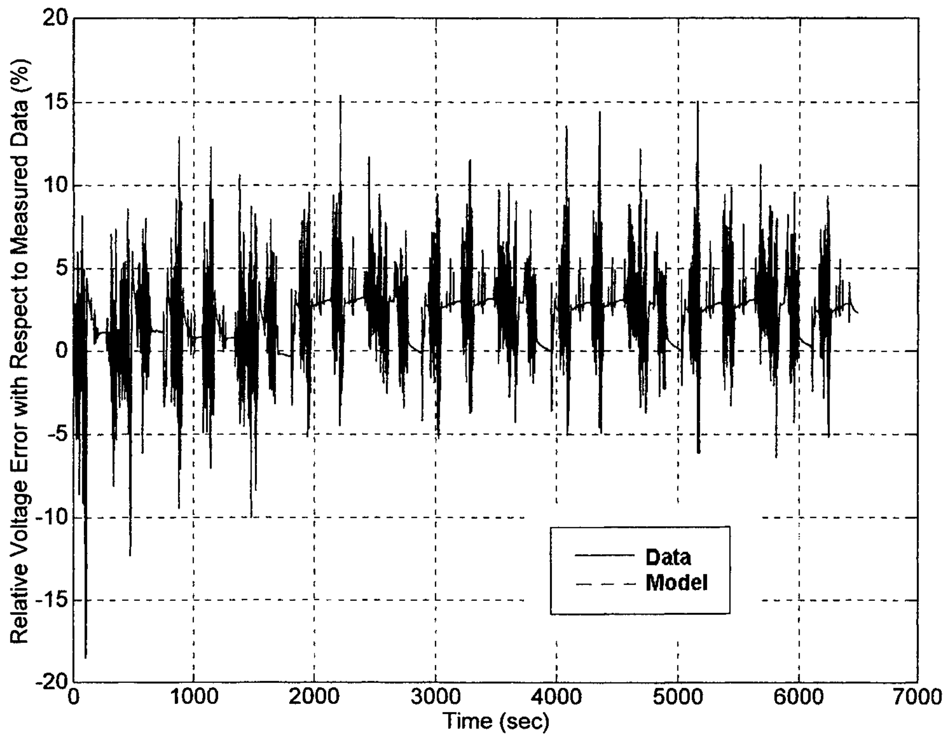


Figure 70. Hybrid Bus Model Validation – EPA Schedule D (Battery Voltage)

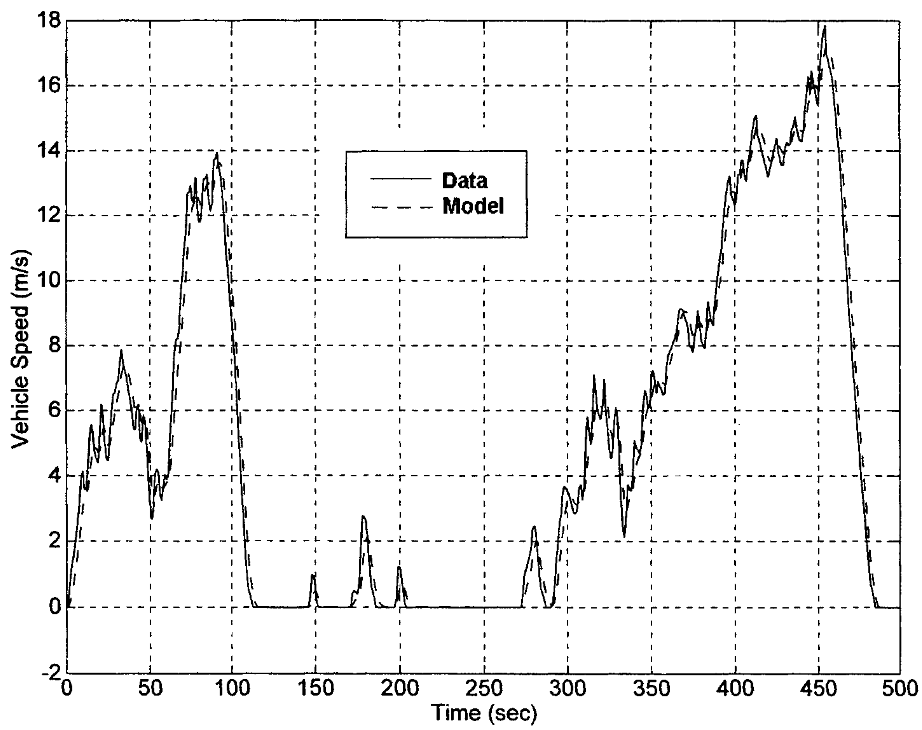


Figure 71. Hybrid Bus Model Validation – EPA Schedule D (Vehicle Speed)

3.0 CONCLUSIONS

This document describes the first attempt to validate PATHS. The validation exercise was limited to key components from the many libraries of PATHS. The validation was performed by comparing the model predictions with data collected from a hybrid bus operating on EPA and CBD driving profiles. The models that were validated appear to agree with the test data reasonably well. The results that are described in this report lend significant credibility in applying PATHS to designing and building hybrid vehicles.

It is apparent that some models compare very well with measured data, while others do not. For example, the APU model was able to predict fuel consumption to within 1% of the measured data, while predictions of the HC emissions were off by almost a 100%. Although the predicted battery state of charge compared quite well to the measured data (within less than 5%), the predicted battery voltage was sometimes much larger than what was measured. However, it was remarkable to observe the trends were duplicated throughout the driving profile.

Ideally, changes to the model would have to be made after performing the described validation exercise in order to refine and develop a better model. There were no funds remaining for this task, but we hope that funding will be available for this important task in the future.

The validation results have provided the much-needed confidence to use PATHS in designing and developing a hybrid or pure electric vehicle. We hope that it will find more widespread usage throughout the electric/hybrid vehicle industry and become an accepted design tool.