Model Design Document

System Model for RCPC Demonstration 1

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Prepared by

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1.1	June 21, 2021	**JL**: Corrections were made to the power ratings of components described in the text of the introduction.
1.0	June 18, 2021	**HR, JL, and KS**: Initial version.

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1 Introduction

This document describes modeling of a notional integrated power and energy system (IPES), generally based on that described in [2], intended for use in demonstrating concepts related to robust combat power and energy controls (RCPC) and derived from requirements established in [3]. This notional system is illustrated in Figure 1.1. The system is powered by two main gas turbine generators (MTG), each rated for 28 MW, and two auxiliary gas turbine generators (ATG), each rated for 4.0 MW. Power is distributed through port and starboard longitudinal medium voltage (MV) (13.8 kV AC) buses. Port and starboard propulsion motor modules (PMM) comprise the largest loads on the system, at 25 MW each, but these typically operate at much lower power levels during normal operation. There are multiple mission loads (ML) in the system which are interfaced to the MV level through the EMs or power conversion module (PCM). The mission loads represent DC loads that exhibit periodic and/or stochastic power pulsations, some of which may draw up to 2 MW in power. Most mission loads are supplied from the six energy magazines (EM) included in the system. These EMs are sized to be able to supply the full power demand for a designated amount of time, and the EM active front ends (AFE) are sized to draw the full power of the load demand. The system also includes a number of low voltage load centers (LC), from which non-vital and vital ship service loads are supplied. The ship service loads in this system are on the order of several MW. System-level controls for the plant include generator load sharing and system load shedding controls, along with the energy management control (EMC). Nominal power ratings for the primary components are summarized in Table 1.1.

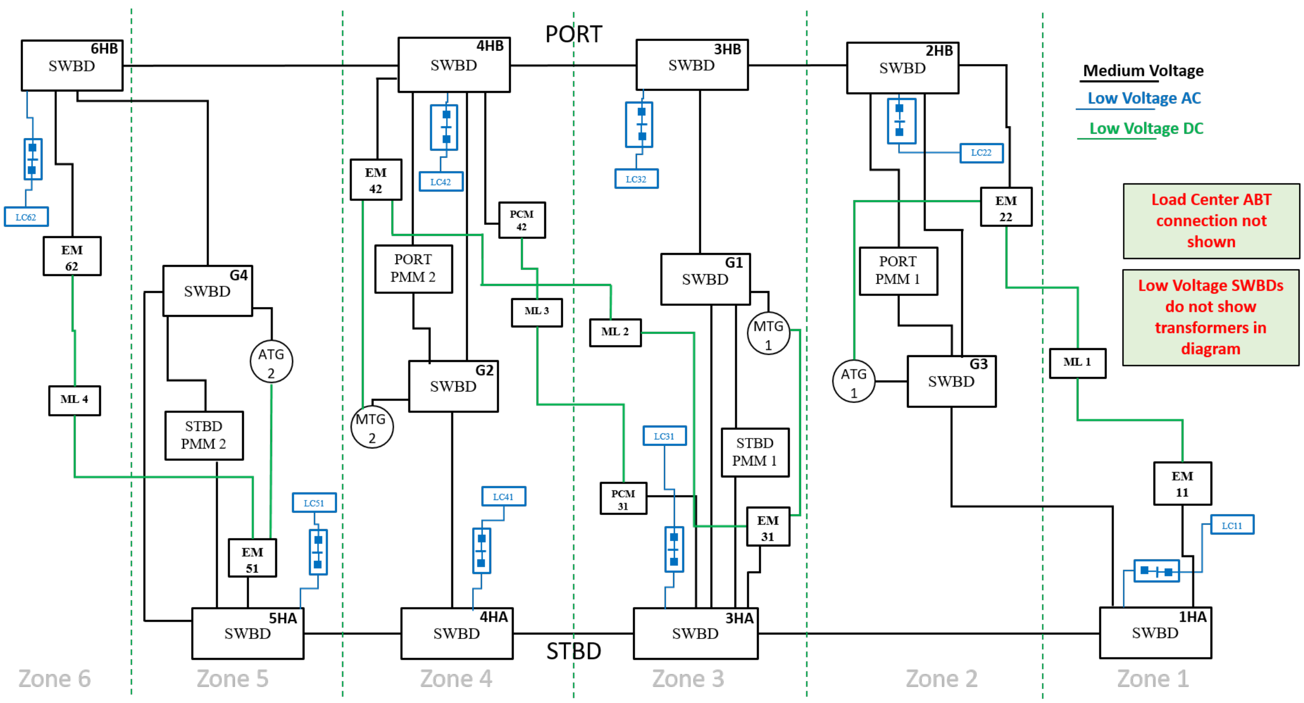

Figure 1.1: System Topology

Modeling of components and subsystems is described in more detail in Section 2. Modeling of the PGMs and power sharing controls are described in Sections 2.1, 2.2, and 2.3, with load shedding controls described in Section 2.4. Modeling of the EMs is described in Section 2.5, with the EMC being described in Section 2.6. Loads including the PMMs, mission loads, aggregate AC loads, and generator auxiliary loads are described in Sections 2.7, 2.8, 2.9, and 2.10 respectively. Other components, including switchboards and cables, are described in Sections 2.11 and 2.12, respectively. Circuit protection systems are described in Section 2.13.

Concluding remarks are given in Section 3.

Table 1.1: Nominal Power Ratings for Components

Component	Rated Load (MW)
MTG 1	28.0
MTG 2	28.0
ATG 1	4.0
ATG 2	4.0
Port PMM	25.0
Starboard PMM	25.0
Secondary PMM	2.0
ML 1 (periodic)	2.0
ML 2 (stochastic)	0.5
ML 3 (scheduled)	1.5
ML 4 (periodic)	2.0
LC 11	1.25
LC 22	1.34
LC 31	1.75
LC 32	1.85
LC 41	2.25
LC 42	2.2
LC 51	1.0
LC 62	1.17
MTG1 Auxiliary load	0.250
MTG2 Auxiliary load	0.250
ATG1 Auxiliary load	0.100
ATG2 Auxiliary load	0.100

Table 1.2 provides load center information. A detailed description of the loads is given in Section 2.9. The transferable motor load is modeled through ABT system. The Non-vital load includes ZIP and motor loads which will be shed if stage 1 load shed command becomes active. While The Semi-Vital load is a transferable load that will be shed in case of a stage 2 load shed command. The load shed commands are described in Section 2.4.

Table 1.2: LVAC Zonal Load Summary

Load Center	Max Operating (kW)	Vital (kW)	Semi-vital (kW)	Non-vital (kW)	Motor (%)	Constant-Z (%)	Constant-I (%)	Constant-P (%)
LC11	1250	810	110	330	20	60	0	20
LC22	1340	870	120	350	20	60	0	20
LC31	1750	1280	120	350	15	65	0	20
LC32	1860	1360	120	380	15	65	0	20
LC41	2250	1790	115	345	20	60	0	20
LC42	2200	1750	110	340	20	60	0	20
LC51	1000	700	75	225	10	70	0	20
LC62	1180	830	90	260	10	70	0	20

2 Descriptions of System Components

This section provides descriptions of the models employed for components within the system.

2.1 Main Turbine Generator (MTG)

The MTG model comprises a notional gas turbine–governor, an excitation system, and a synchronous machine. An AC breaker is used to interface to the MVAC system. The gas turbine–governor model is the IEEE GGOV1 as can be found in [4]. The excitation system model used is the IEEE AC8B as given in [5]. Table 2.4 provides parameters for the synchronous machine model, while Tables 2.5 and 2.6 provide parameters for the turbine and excitation models, respectively.

Figure 2.1 shows the MTG components and its interface to the rest of the system. Figure 2.2 depicts the control scheme for the MTG system. The MTG system control scheme is augmented from its default scheme to accommodate additional functionalities such as load sharing between generators and generator synchronization. Table 2.1 describes signals in the model, and Table 2.2 describes model parameters.

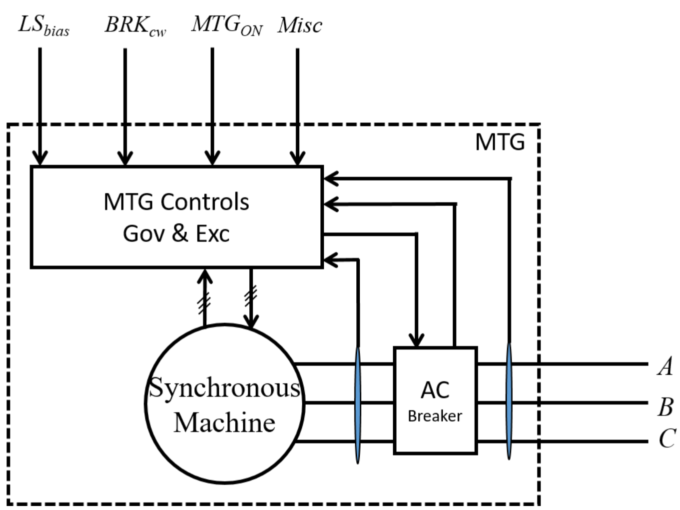

Figure 2.1: MTG Components and Interface

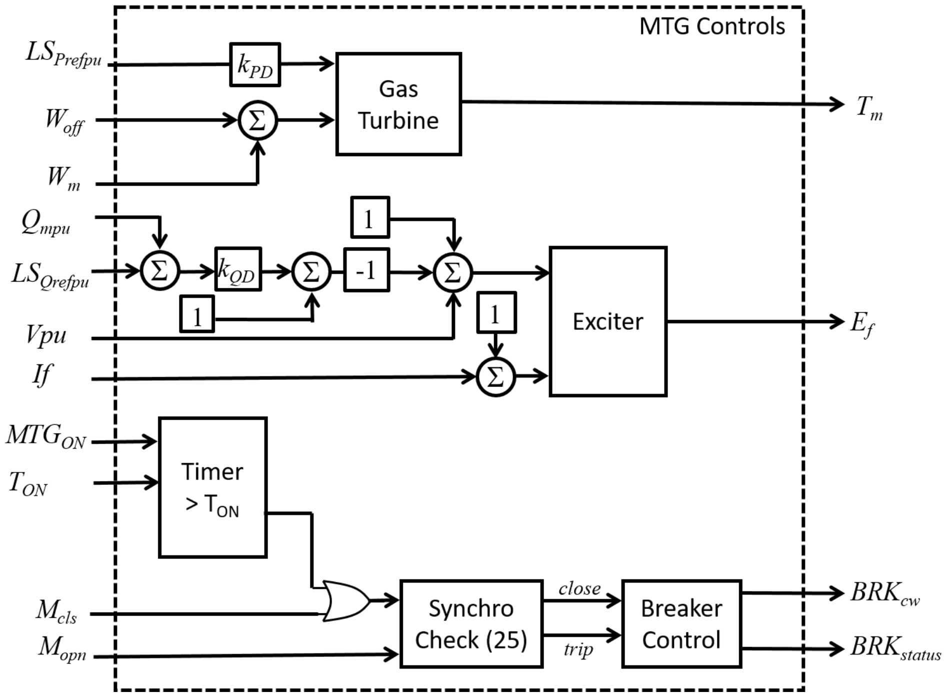

Figure 2.2: MTG Controls

Table 2.1: Signals for MTG Controls

Parameter	Description	Unit
LS_{Prefpu}	Real power load share command	p.u.
W_{off}	Speed offset for generator synchronization	rad/s
W_m	Measured rotor speed	rad/s
LS_{Qrefpu}	Reactive power load share command	p.u.
V_{pu}	Machine terminal voltage	p.u.
I_f	Field current	p.u.
MTG_{ON}	Command to startup MTG	NA
M_{cls}	Manual close command for MTG AC breaker	NA
M_{opn}	Manual open command for MTG AC breaker	NA
T_m	Mechanical torque input to machine	p.u.
E_f	Exciter output field voltage	p.u.
BRK_{cw}	MTG AC breaker control word	NA
BRK_{status}	MTG AC breaker status	NA

Table 2.2: Parameters for MTG Controls

Parameter	Description	Value	Unit
kPD	Active Power Droop	0.03	p.u.
kQD	Reactive Power Droop	0.03	p.u.
T_{ON}	Time needed to bring MTG online	5	min

Table 2.3: MTG Synchro Check (25) Parameters

Parameter	Value	Unit
Maximum angle difference	15	degree
Maximum slip frequency (pickup)	1	Hz
Maximum voltage difference	10	%
PT ratio for generator terminal	72.5	NA
PT ratio for bus terminal	72.5	NA
Minimum generator voltage	60	volt
Minimum system voltage	60	volt
Enable dead bus check	YES	NA
Dead bus undervoltage check	50	volt
Enable breaker advance close	YES	NA
Breaker close time	50	ms

Table 2.4: Parameters for MTG Synchronous Machine

Parameter	Value	Unit
Rated MVA	35	MVA
Rated RMS line-line voltage	13.8	kV
Base Frequency	60	Hz
Inertia Constant	6	MWs/MVA
Stator Leakage Reactance (Xa)	0.130	p.u.
D-axis Unsaturated Reactance (Xd)	1.79	p.u.
D-axis Unsaturated Transient Reactance (Xd')	0.169	p.u.
D-axis Unsaturated Sub-Transient Reactance (Xd") ()	0.135	p.u.
Q-axis Unsaturated Reactance (Xq)	1.71	p.u.
Q-axis Unsaturated Transient Reactance (Xq')	0.228	p.u.
Q-axis Unsaturated Sub-Transient Reactance (Xq") ()	0.228	p.u.
Stator Resistance (Ra)	0.002	p.u.
D-axis Unsaturated Transient Open Time Constant (Tdo')	4.3	s
D-axis Unsaturated Sub-Transient Open Time Constant (Tdo")	0.032	s
Q-axis Unsaturated Transient Open Time Constant (Tqo')	0.85	s
Q-axis Unsaturated Sub-Transient Open Time Constant (Tqo")	0.05	s
Machine Zero Sequence Resistance	0.002	p.u.
Machine Zero Sequence Reactance	0.13	p.u.
Neutral Series Resistance	1.0E5	p.u.
Neutral Series Reactance	0.0	p.u.

Table 2.5: Parameters for MTG Turbine–Governor IEEE GGOV1

Parameter	Description	Value	Unit
Fq	Base Frequency	60	Hz
R	Permanent droop	0.04	p.u.
Tpelec	Electric power transducer time constant	0.1	s
Maxerr	Maximum value for speed error signal	0.05	p.u.
Minerr	Minimum value for speed error signal	-0.05	p.u.
Kpgov	Governor proportional gain	10	NA
Kigov	Governor integral gain	2	NA
Kdgov	Governor derivative gain	0	NA
Tdgov	Governor derivative controller time constant	1	s
Vmax	Maximum valve position limit	1	NA
Vmin	Mainimum valve position limit	0.15	NA
Tact	Actuator time constant	1	s
Kturb	Turbine gain	1.5	NA
Wfnl	No load fuel flow	0.2 p.u.	
Tb	Turbine lag time constant	0.1	NA
Tc	Turbine lead time constant	0	NA
Teng	Transport lag time constant (diesel engine)	0	s
Tfload	Load limiter time constant	3	s
Kpload	Load limiter time constant	2	s
Tfload	Load limiter integral gain	0.67	s
Ldref	Load limiter reference value	1	p.u.
Dm	Speed senstivity coefficient	0.0	p.u.
Ropen	Maximum valve openning rate	0.3	p.u./s
Rclose	Minimum valve closing rate	-0.3	p.u./s
Kimw	Power controller (reset) gain	0	NA
Aset	Acceleration limiter setpoint	1	p.u./s
Ka	Acceleration limiter gain	1e6	NA
Ta	Acceleration limiter time constant	0.1	s
Trate	Turbine MW Base	31.2	MW
db	Speed governor deadband	0.0	NA
Tsa	Temperature detection lead time constant	4.0	s
Tsb	Temperature detection lag time constant	5.0	s
Rup	Maximum rate of load limit increase	99	NA
Rdown	Miniimum rate of load limit increase	-99	NA
Flag	Fuel source characteristic	Speed dependent	NA

Table 2.6: Parameters for MTG Exciter IEEE AC8B

Parameter	Description	Value	Unit
Fq	Base Frequency	60	Hz
Tr	Regulator input filter time constant	0.0	s
Kpr	Regular proportional gain	80.0	p.u.
Kir	Regular integral gain	5.0	p.u.
Kdr	Regular derivative gain	10.0	p.u.
Tdr	Regular derivative block time constant	0.1	s
Vpidmax	PID maximum limit	7.6	p.u.
Vpidmax	PID minimum limi	-7.6	p.u.
Ka	Voltage regulator proportional gain	1	p.u.
Ta	Voltage regulator time constant	0.1	p.u.
Vmax	Regulator output maximum limit	8	p.u.
Vmin	Regulator output minimum limit	-8	p.u.
Kc	Rectifier loading factor	0.55	p.u.
Kd	Exciter regulation factor	1.1	p.u.
Ke	Exciter field proportional constant	1.0	p.u.
Te	Exciter field time constant	1.2	s
VFEmax	Exciter field current limit (>0)	6.0	p.u.
VEmin	Minimum exciter output voltage	-1	p.u.
E1	Field voltage Value 1	6.5	p.u.
Se1	Saturation factor at E1	0.3	p.u.
E2	Field voltage Value 2	9.0	p.u.
Se12	Saturation factor at E2	1.1	p.u.
Cal	Saturation constant 'A' calculation method	abs(A)	NA

2.2 Auxiliary Turbine Generator (ATG)

The ATG model comprises a notional gas turbine–governor and an excitation system. An AC breaker is used to interface to the MVAC system. The gas turbine governor model used is the IEEE GGOV1, which is based on [4]. The excitation system model used is the IEEE AC8B, based on [5]. Table 2.10 provides parameters for the synchronous machine model, while Tables 2.11 and 2.12 provide parameters for IEEE GGOV1 and IEEE AC8B models, respectively.

Figure 2.3 shows the ATG components and interface to the rest of the system. Figure 2.4 depicts the control scheme for the ATG system. The ATG system control scheme is augmented from its default scheme to accommodate additional functionality such as load sharing between generators and generator synchronization. Table 2.7 describes signals in the model, and Table 2.8 describes model parameters.

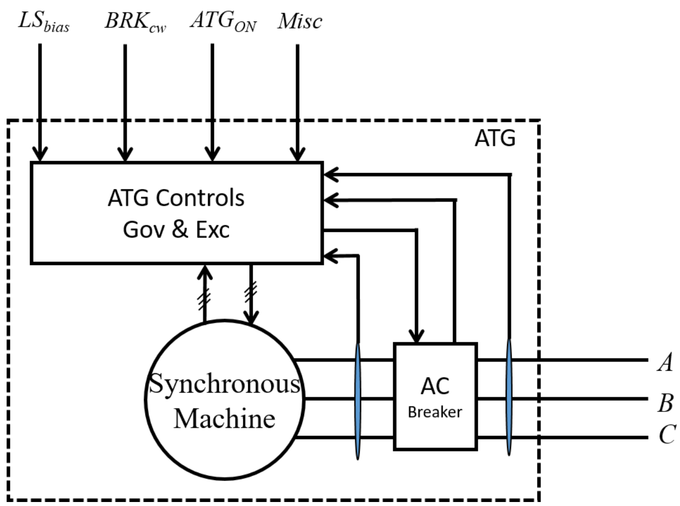

Figure 2.3: ATG Interface

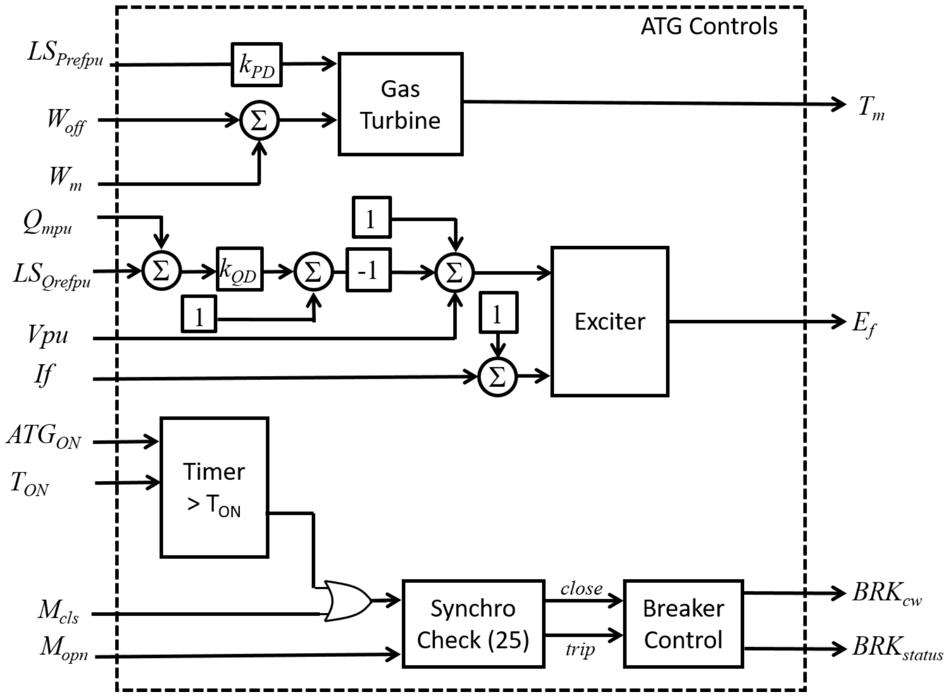

Figure 2.4: ATG Controls

Table 2.7: Signals for ATG Controls

Parameter	Description	Unit
LS_{Prefpu}	Real power load share command	p.u.
W_{off}	Speed offset for generator synchronization	rad/s
W_m	Measured rotor speed	rad/s
LS_{Qrefpu}	Reactive power load share command	p.u.
V_{pu}	Machine terminal voltage	p.u.
I_f	Field current	p.u.
ATG_{ON}	Command to startup MTG	NA
M_{cls}	Manual close command for ATG AC breaker	NA
M_{opn}	Manual open command for ATG AC breaker	NA
T_m	Mechanical torque input to machine	p.u.
E_f	Exciter output field voltage	p.u.
BRK_{cw}	ATG AC breaker control word	NA
BRK_{status}	ATG AC breaker status	NA

Table 2.8: Parameters for ATG Controls

Parameter	Description	Value	Unit
kPD	Active Power Droop	0.03	p.u.
kQD	Reactive Power Droop	0.03	p.u.
T_{ON}	Time needed to bring ATG online	5	min

Table 2.9: ATG Synchro Check (25) Parameters

Parameter	Value	Unit
Maximum angle difference	15	degree
Maximum slip frequency (pickup)	1	Hz
Maximum voltage difference	10	%
PT ratio for generator terminal	72.5	NA
PT ratio for bus terminal	72.5	NA
Minimum generator voltage	60	volt
Minimum system voltage	60	volt
Enable dead bus check	YES	NA
Dead bus undervoltage check	50	volt
Enable breaker advance close	YES	NA
Breaker close time	50	ms

Table 2.10: Parameters for ATG Synchronous Machine

Parameter	Value	Unit
Rated MVA	5.0	MVA
Rated RMS line-line voltage	13.8	kV
Base Frequency	60	Hz
Inertia Constant	6	MWs/MVA
Stator Leakage Reactance (Xa)	0.130	p.u.
D-axis Unsaturated Reactance (Xd)	1.79	p.u.
D-axis Unsaturated Transient Reactance (Xd’)	0.169	p.u.
D-axis Unsaturated Sub-Transient Reactance (Xd”) ()	0.135	p.u.
Q-axis Unsaturated Reactance (Xq)	1.71	p.u.
Q-axis Unsaturated Transient Reactance (Xq’)	0.228	p.u.
Q-axis Unsaturated Sub-Transient Reactance (Xq”) ()	0.228	p.u.
Stator Resistance (Ra)	0.002	p.u.
D-axis Unsaturated Transient Open Time Constant (Tdo’)	4.3	s
D-axis Unsaturated Sub-Transient Open Time Constant (Tdo”)	0.032	s
Q-axis Unsaturated Transient Open Time Constant (Tqo’)	0.85	s
Q-axis Unsaturated Sub-Transient Open Time Constant (Tqo”)	0.05	s
Machine Zero Sequence Resistance	0.002	p.u.
Machine Zero Sequence Reactance	0.13	p.u.
Neutral Series Resistance	1.0E5	p.u.
Neutral Series Reactance	0.0	p.u.

Table 2.11: Parameters for ATG Turbine–Governor GGOV1

Parameter	Description	Value	Unit
Fq	Base Frequency	60	Hz
R	Permanent droop	0.04	p.u.
Tpelec	Electric power transducer time constant	0.1	s
Maxerr	Maximum value for speed error signal	0.05	p.u.
Minerr	Minimum value for speed error signal	-0.05	p.u.
Kpgov	Governor proportional gain	10	NA
Kigov	Governor integral gain	2	NA
Kdgov	Governor derivative gain	0	NA
Tdgov	Governor derivative controller time constant	1	s
Vmax	Maximum valve position limit	1	NA
Vmin	Minimum valve position limit	0.15	NA
Tact	Actuator time constant	1	s
Kturb	Turbine gain	1.5	NA
Wfnl	No load fuel flow	0.2 p.u.	
Tb	Turbine lag time constant	0.1	NA
Tc	Turbine lead time constant	0	NA
Teng	Transport lag time constant (diesel engine)	0	s
Tfload	Load limiter time constant	3	s
Kpload	Load limiter time constant	2	s
Tfload	Load limiter integral gain	0.67	s
Ldref	Load limiter reference value	1	p.u.
Dm	Speed senstivity coefficient	0.0	p.u.
Ropen	Maximum valve opening rate	0.3	p.u./s
Rclose	Maximum valve closing rate	-0.3	p.u./s
Kimw	Power controller (reset) gain	0	NA
Aset	Acceleration limiter setpoint	1	p.u./s
Ka	Acceleration limiter gain	1e6	NA
Ta	Acceleration limiter time constant	0.1	s
Trate	Turbine MW Base	31.2	MW
db	Speed governor deadband	0.0	NA
Tsa	Temperature detection lead time constant	4.0	s
Tsb	Temperature detection lag time constant	5.0	s
Rup	Maximum rate of load limit increase	99	NA
Rdown	Miniimum rate of load limit increase	-99	NA
Flag	Fuel source characteristic	Speed dependent	NA

Table 2.12: Parameters for ATG Exciter IEEE AC8B

Parameter	Description	Value	Unit
Fq	Base Frequency	60	Hz
Tr	Regulator input filter time constant	0.0	s
Kpr	Regular proportional gain	80.0	p.u.
Kir	Regular integral gain	5.0	p.u.
Kdr	Regular derivative gain	10.0	p.u.
Tdr	Regular derivative block time constant	0.1	s
Vpidmax	PID maximum limit	7.6	p.u.
Vpidmax	PID minimum limit	-7.6	p.u.
Ka	Voltage regulator proportional gain	1	p.u.
Ta	Voltage regulator time constant	0.1	p.u.
Vmax	Regulator output maximum limit	8	p.u.
Vmin	Regulator output minimum limit	-8	p.u.
Kc	Rectifier loading factor	0.55	p.u.
Kd	Exciter regulation factor	1.1	p.u.
Ke	Exciter field proportional constant	1.0	p.u.
Te	Exciter field time constant	1.2	s
VFEmax	Exciter field current limit (>0)	6.0	p.u.
VEmin	Minimum exciter output voltage	-1	p.u.
E1	Field voltage Value 1	6.5	p.u.
Se1	Saturation factor at E1	0.3	p.u.
E2	Field voltage Value 2	9.0	p.u.
Se12	Saturation factor at E2	1.1	p.u.
Cal	Saturation constant 'A' calculation method	abs(A)	NA

2.3 Generator Power Sharing Controls

The generator active and reactive power sharing controls are based on proportional sharing by the online generation, as illustrated in Figure 2.5. Each of the generators employs droop control with explicit power reference for the both the frequency (with explicit active power reference) and voltage magnitude (with explicit reactive power reference) control loops, as illustrated in Figure 2.6. The use of droop control allows parallel generators to simultaneously regulate the voltage magnitude and frequency of the common bus, while sharing active and reactive power. Slower, outer-loop power sharing controls are used to provide the active and reactive power references to the generators in order to bring the voltage magnitude and frequency back to nominal at steady-state.

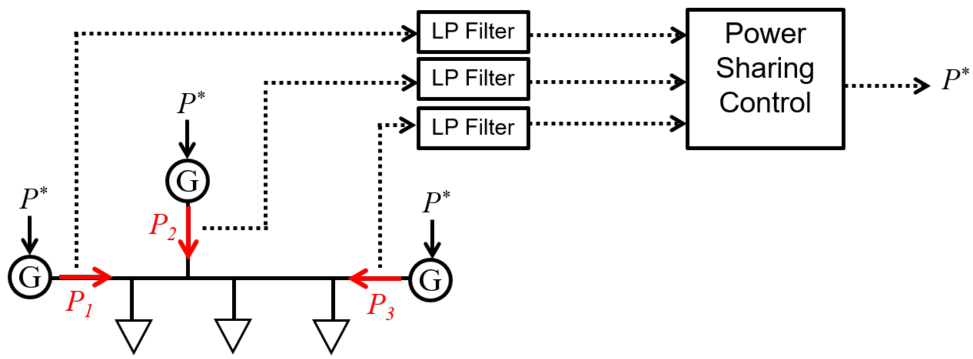

Figure 2.5: Approach for Proportional Generator Power Sharing

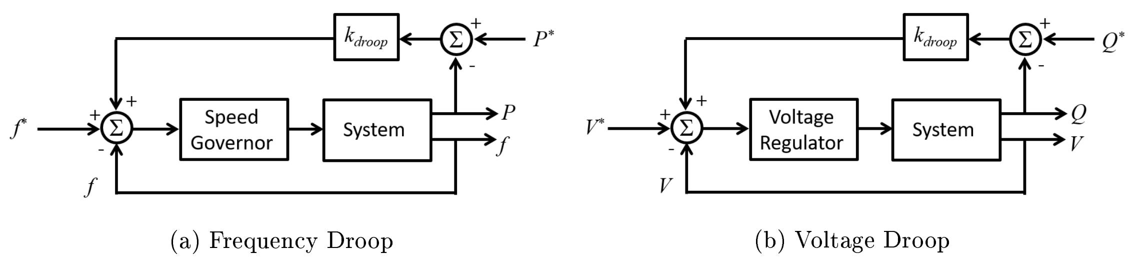

Figure 2.6: Droop Control with Explicit Power Reference

For the active power sharing, the power measured out of each generator, P_i, is passed through a low-pass filter, to obtain the filtered power for each generator, P_{i-f}, as given in (2.1).

$$P_{i-f} = \frac{1}{\frac{s}{2\,\pi\,f_c} + 1} P_i \tag{2.1}$$

The filters effectively slow the response of the power sharing controls to avoid interaction with the local controls of the generator. The proportional power request (in pu) to each of the generators, P^*, is then given by (2.2).

$$P^* = \frac{\sum_i u_i\, P_{i-f}}{\sum_i u_i\, P_{capacity-i}} \tag{2.2}$$

Here, u_i indicates the status (a value of 1 for online or a value of 0 for offline) of generator i, and $P_{capacity-i}$ indicates the power capacity of generator i.

The reactive power reference, Q^*, is similarly obtained through (2.3) and (2.4), where Q_i and $S_{capacity-i}$ are the reactive power supplied by generator i and the apparent power capacity of generator i, respectively.

$$Q_{i-f} = \frac{1}{\frac{s}{2\,\pi\,f_c} + 1} Q_i \tag{2.3}$$

$$Q^* = \frac{\sum_i u_i\, Q_{i-f}}{\sum_i u_i\, S_{capacity-i}} \tag{2.4}$$

Parameters of the model are given in Table 2.13.

Table 2.13: Parameters of EM Power and SoC Management

Parameter	Description	Default Value
f_c	Cutoff frequency for low-pass filter.	1 Hz

2.4 System Load Shedding Scheme

In order to prevent prolonged overloading of generators, a load shedding scheme is implemented. The load shedding scheme is a two-stage approach which monitors the individual generator loading. Figure 2.7 shows logic for the load shedding scheme, which applies to both the MTG and ATG. Table 2.14 describes control signals, while Table 2.15 describes control parameters.

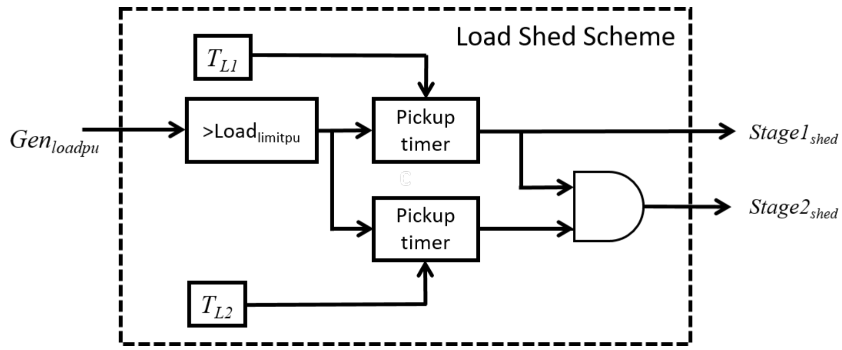

Figure 2.7: Load shedding scheme logic

Table 2.14: Control Signals for Generator Load Shedding Scheme

Parameter	Description	Unit
Gen_{loadpu}	Generator loading in pu.	pu
$Stage1_{shed}$	Flag to shed stage 1 loads	NA
$Stage2_{shed}$	Flag to shed stage 2 loads	NA

Table 2.15: Parameters of Generator Load Shedding Scheme

Parameter	Description	Value	Unit
T_{L1}	Pickup timer for stage 1 load shed	250	ms
T_{L2}	Pickup timer for stage 2 load shed	2.5	s

2.5 Energy Magazines

The energy magazine concept, described in [6, 7, 8, 9, 10], generally involves a power converter with energy storage, which interfaces to the shipboard power system through an AFE and exposes one or more output ports from which loads can be supplied. An example of an EM is illustrated in Fig. 2.8, in which the energy storage medium (in this case, a battery) is directly connected to the internal DC bus of the EM. In this case, the AFE is operated in a power control mode, accepting a power reference (P_{AFE-r}) from the power and state-of-charge (SoC) management controller. As illustrated in Fig. 2.8, the load power (P_{Load}) is filtered by a low-pass filter (Filter 1), and then used as a feed-forward component for the AFE power reference. The filter is used to remove high frequency components in the load power, so that these are supplied by the internal energy storage of the EM, rather than being drawn from the upstream system by the AFE (providing for the load buffering functionality of the EM). To this feed-forward power component is added a power demand from the SoC control, here modeled as a simple proportional control based on the SoC of the energy storage medium. This total power demand is passed through a rate limiter (to enforce the power ramp rate limits of the AFE) and then through a hard limiter (to enforce the power limits of the AFE). The signal resulting from hard limiter 1 becomes the power demand of the AFE (P_{demand}) that is supplied to the EMC. The power limit from the EMC (P_{limit}) is then applied in hard limiter 2, such that the reference AFE power signal, P_{AFE-r}, is limited thereby. The DC/DC converters used at the output ports simply regulate the ouput (load) voltage. With this configuration, the EM serves as an energy reservoir between the power generation system and the loads served by the EM, affording a degree of flexibility to the system-level controls to manage power flow to the EM without affecting the loads served by the EM.

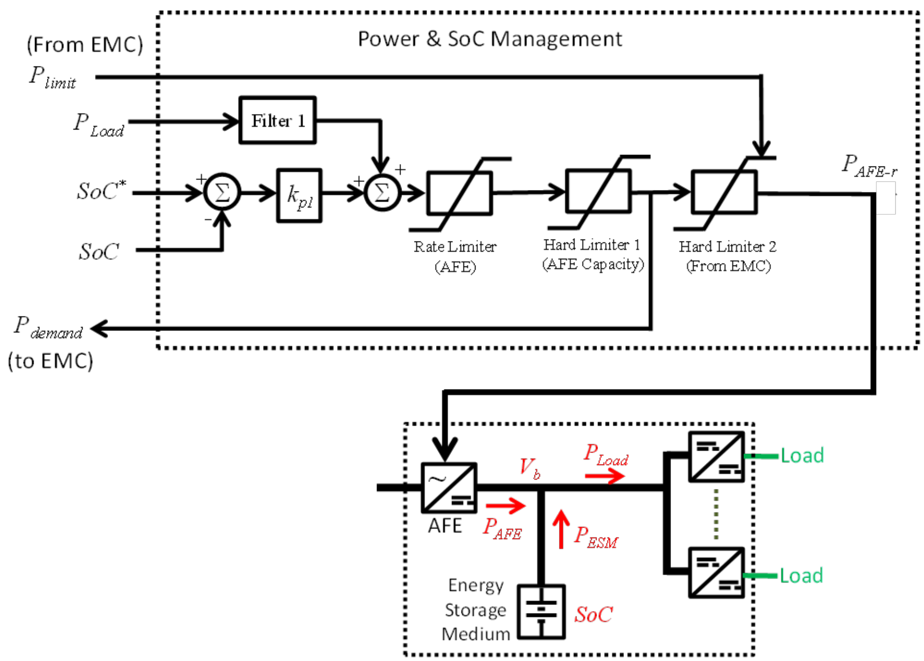

Figure 2.8: Energy Magazine, Power and SoC Management Controls, and Interface to EMC

$$G_1(s) = \frac{1}{\frac{s}{2\pi f_{c-G1}} + 1} \tag{2.5}$$

The models employed for the AFE, DC/DC converters, and battery are described in Sections 2.5.1, 2.5.2, and 2.5.3, respectively.

Table 2.16: Parameters of EM Power and SoC Management

Block	Parameter	Description	Value
Filter 1	f_{c-G1}	Feed forward branch power filter cutoff frequency.	1 Hz
k_{p1}	k_{p1}	SoC control proportional gain.	1
Rate Limiter (AFE)	R_D	Maximum rate of decrease of power reference.	1 p.u./s
Rate Limiter (AFE)	R_I	Maximum rate of increase of power reference.	-1 p.u./s
Hard Limiter 1	P_{max-1}	Maximum power reference.	1 p.u.
Hard Limiter 1	P_{min-1}	Minimum power reference.	-1 p.u.
Hard Limiter 2	P_{max-2}	Maximum power reference.	EMC-Plimit p.u.
Hard Limiter 2	P_{min-2}	Minimum power reference.	-1 p.u.

There are six energy magazines modeled in the system. The storage within each EM is sized to handle mission loads being served for a specified amount of time. Table 2.17 provides information on the six EMs in the system

Table 2.17: EM Ratings

EM Name	AFE Rating (MW)	ES size (MJ)	Mission Loads Served
EM 11	2	500	ML1
EM 22	1	500	ML1, ATG1
EM 31	0.5	100	ML2, MTG1
EM 42	0.5	100	ML2, MTG2
EM 51	1	500	ML4, ATG2
EM 62	2	500	ML4

2.5.1 AC/DC Converter

The AC/DC converter model is implemented as illustrated in Figure 2.9 [1]. This model is employed for a converter controlling the voltage on the secondary side, and, thus, employs a three-phase current injection (I_{r-abc}) on the primary side and a voltage source (V_r) on the secondary side. The controls for the model, illustrated in Figure 2.10, are based closely on those of the DC/DC converter described in Section 2.5.2. In the case of the AC/DC converter model, a phase-locked loop (PLL) is used to track the voltage angle, θ. This angle is used to convert the three-phase voltages (V_{1abc}) and currents (I_{1abc}) to DQ-frame quantities V_{1dq} and I_{1dq}, respectively. From these, the magnitudes of the voltage ($|V_1|$) and current ($|I_1|$) are computed, and used in place of the instantaneous primary side voltage and current employed in the DC/DC converter model. Similarly to the DC/DC converter model, the secondary side DC voltage reference, V_r, is computed through the multiplication of the turns ratio, n, with the filtered primary side voltage magnitude, $|V_1|$. The primary side current injections, I_{r-abc}, are computed based on the measured secondary-side power, P_2, and primary-side voltage magnitude, $|V_1|$. These are generated using θ in order to be in phase with the primary side voltages for unity power factor.

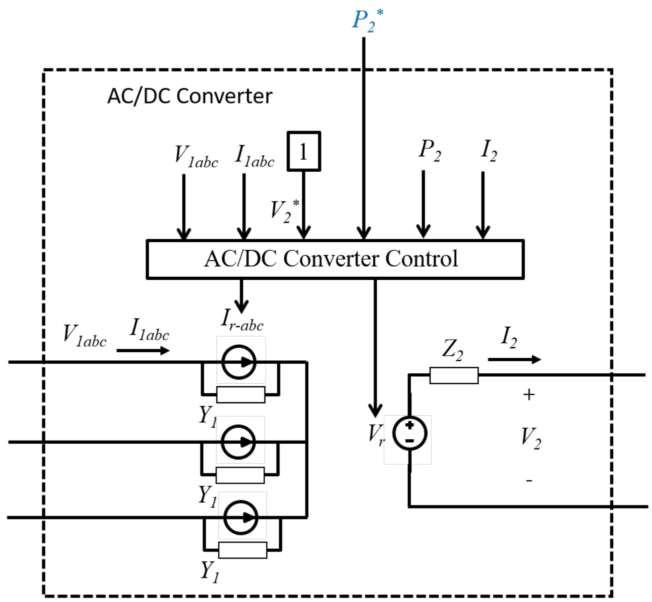

Figure 2.9: Model for AC/DC Converter [1]

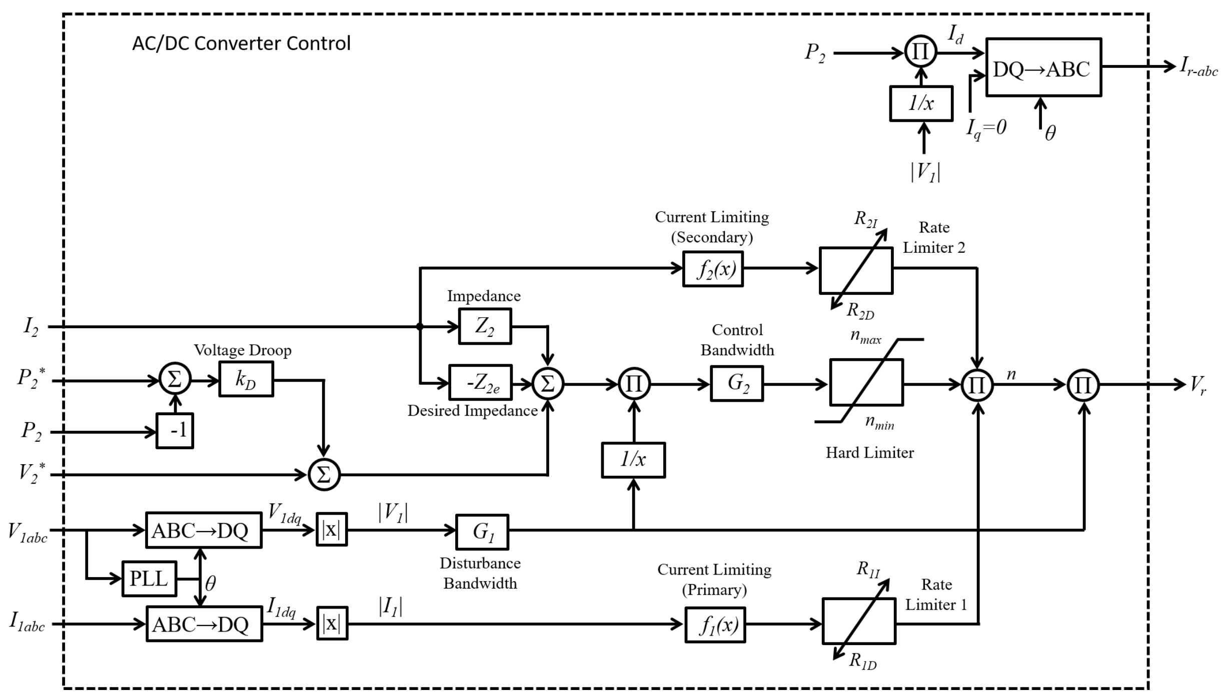

Figure 2.10: Model for AC/DC Converter Control [1]

Table 2.18: Parameters of AC/DC Converter

Block	Parameter	Description	Value
N/A	S_{rated}	Converter apparent power.	1 MVA
N/A	P_{rated}	Converter rated power.	1 MW
N/A	$V_{1-rated}$	Converter primary side rated voltage.	13.8 kV
N/A	$V_{2-rated}$	Converter secondary side rated voltage.	1 kV
N/A	f_b	Base frequency for purposes of computing reactive components.	60 Hz
N/A	Z_{b-1}	Base impedance on primary side.	43.56 Ω
N/A	Z_{b-2}	Base impedance on secondary side.	1 Ω
Y_1	R_{1-Y1}	Converter input admittance resistive component (see (2.6)).	100 pu
Z_2	R_{1-Z2}	Converter output impedance resistive component (see (2.7)).	0.01 pu
Z_2	X_{1-Z2}	Converter output reactance component (see (2.7)).	0.05 pu
Voltage Droop	k_D	Voltage droop factor.	0.1
Desired Impedance	R_{Z2e}	Resistive component of desired impedance (see (2.8)).	0 pu
Disburbance Bandwidth	f_{c-G1}	Cutoff frequency for primary-side disturbances (see (2.9))	800 Hz
Control Bandwidth	f_{c-G2}	Cutoff frequency for representing the control bandwidth (see (2.9))	250 Hz
Current Limiting (Primary)	$f_1(x)$	Scale factor function for primary side current limiting (see Table 2.19 and Figure 2.11).	N/A
Current Limiting (Secondary)	$f_2(x)$	Scale factor function for secondary side current limiting (see Table 2.19 and Figure 2.11).	N/A
Rate Limiter 1	R_{I1}	Limit for rate of increase.	10 pu/s
Rate Limiter 1	R_{D1}	Limit for rate of decrease.	−100 pu/s
Rate Limiter 2	R_{I2}	Limit for rate of increase.	10 pu/s
Rate Limiter 2	R_{D2}	Limit for rate of decrease.	−100 pu/s

$$Y_1(s) = \frac{1}{R_{1-Y1}} \tag{2.6}$$

$$Z_2(s) = R_{1-Z2} + s\frac{X_{1-Z2}}{2\,\pi\,f_b} \tag{2.7}$$

$$Z_{2e}(s) = R_{1-Z2e} \tag{2.8}$$

$$G_i(s) = \frac{1}{\frac{s}{2\pi f_{c-Gi}} + 1} \tag{2.9}$$

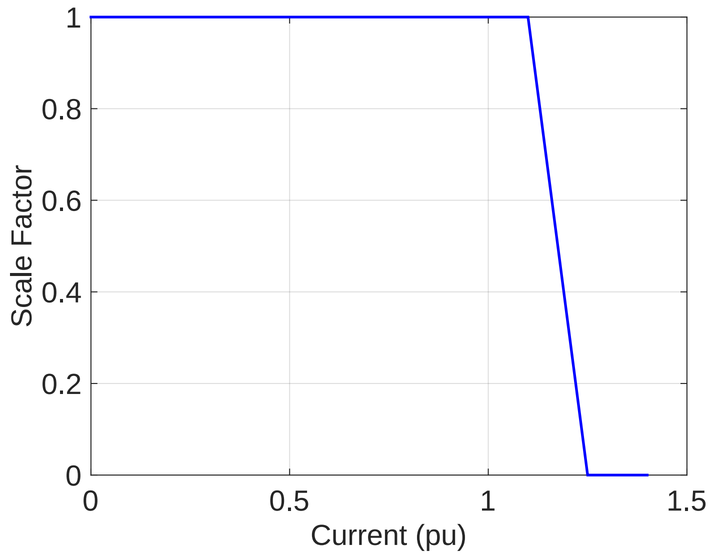

Figure 2.11: Scale Factor Function Current Limiting

Table 2.19: Scale Factor Function for Current Limiting

Current (pu)	Scale Factor
0.000	1.000
1.100	1.000
1.250	0.000
1.400	0.000

2.5.2 DC/DC Converter

The DC/DC converter model is implemented as illustrated in Figure 2.12 [1]. This model is employed for a converter controlling the voltage on the secondary side, and, thus, employs a current injection (I_r) on the primary side and a voltage source (V_r) on the secondary side. The controls for the model are illustrated in Figure 2.13, in which all input and output quantities are taken in per unit values. This model is intended to serve as an average-value model through representation of the performance characteristics of the DC/DC converter, rather than through explicitly modeling the converter control structure. The model is based around the concept of an ideal transformer with adjustable turns ratio, n. The controls accept a reference secondary side voltage, V_2^*, which is biased through the droop characteristic affected by the difference between the reference power (P_2^*) and the actual output power (P_2). This voltage reference is further augmented by the term $I_2 Z_2$ to compensate for the secondary side voltage drop across Z_2. The voltage reference may be further augmented by the term $-I_2 Z_{2e}$ in order to include voltage drop for an emulated impedance, Z_{2e}. These contributions combine to form the effective voltage reference, V_e^*. This voltage reference is divided by the primary side voltage, V_1, after applying the filter of $G_1(s)$ to this voltage measurement, resulting in the reference turns ratio, n^*. Here, $G_1(s)$ is intended to represent a restriction in the bandwidth of disturbances on the primary voltage that may propagate through to the secondary side. The filter $G_2(s)$, representing the control bandwidth of the converter, is then applied to n^*, and the hard limiter is then applied to enforce limits on the minimum and maximum values of the turns ratio. Two other branches are employed to represent the current limiting behavior of the converter. The current limiting functions f_1 and f_2 provide gains as functions of the primary (I_1) and secondary (I_2) currents, respectively. These gains are typically unity within the current limits of the converter, and these tend to zero as the the current limits are approached. Rate limiters 1 and 2 allow these multiplicative factors to ramp down very quickly, but ramp back to unity more slowly in order to avoid rapid oscillations when current limiting. The result of multiplication with these current-limiting factors is the actual turns ratio, n. This factor is multiplied by the filtered primary side voltage to produce the secondary voltage reference, V_r, and it is multiplied by the secondary current to provide the primary side current reference, I_r. Parameters of the model, along with default values, are given in Table 2.20.

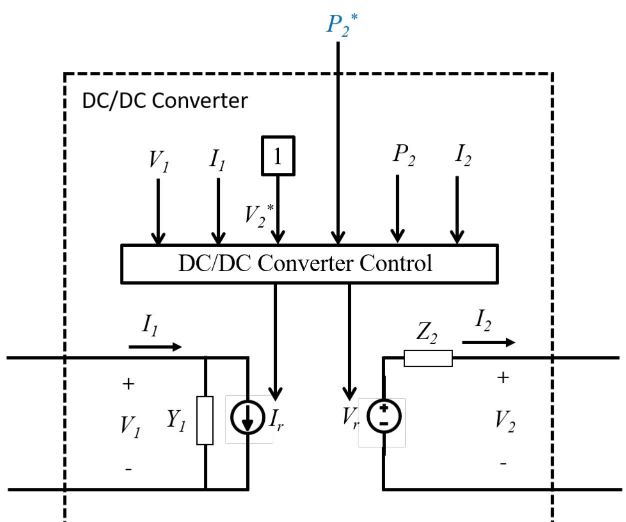

Figure 2.12: Model for DC/DC Converter [1]

$$Y_1(s) = \frac{1}{R_{1-Y1}} \tag{2.10}$$

Table 2.20: Parameters of DC/DC Converter

Block	Parameter	Description	Value
N/A	P_{rated}	Converter rated power.	1 MW
N/A	$V_{1-rated}$	Converter primary side rated voltage.	1 kV
N/A	$V_{2-rated}$	Converter secondary side rated voltage.	1 kV
N/A	f_b	Base frequency for purposes of computing reactive components.	60 Hz
N/A	Z_{b-1}	Base impedance on primary side.	1 Ω
N/A	Z_{b-2}	Base impedance on secondary side.	1 Ω
Y_1	R_{1-Y1}	Converter input admittance resistive component (see (2.10)).	100 pu
Z_2	R_{1-Z2}	Converter output impedance resistive component (see (2.11)).	0.01 pu
Z_2	X_{1-Z2}	Converter output reactance component (see (2.11)).	0.05 pu
Voltage Droop	k_D	Voltage droop factor.	0.1
Desired Impedance	R_{Z2e}	Resistive component of desired impedance (see (2.12)).	0 pu
Disburbance Bandwidth	f_{c-G1}	Cutoff frequency for primary-side disturbances (see (2.13))	800 Hz
Control Bandwidth	f_{c-G2}	Cutoff frequency for representing the control bandwidth (see (2.13))	250 Hz
Current Limiting (Primary)	$f_1(x)$	Scale factor function for primary side current limiting (see Table 2.21 and Figure 2.14).	N/A
Current Limiting (Secondary)	$f_2(x)$	Scale factor function for secondary side current limiting (see Table 2.21 and Figure 2.14).	N/A
Rate Limiter 1	R_{I1}	Limit for rate of increase.	10 pu/s
Rate Limiter 1	R_{D1}	Limit for rate of decrease.	−100 pu/s
Rate Limiter 2	R_{I2}	Limit for rate of increase.	10 pu/s
Rate Limiter 2	R_{D2}	Limit for rate of decrease.	−100 pu/s

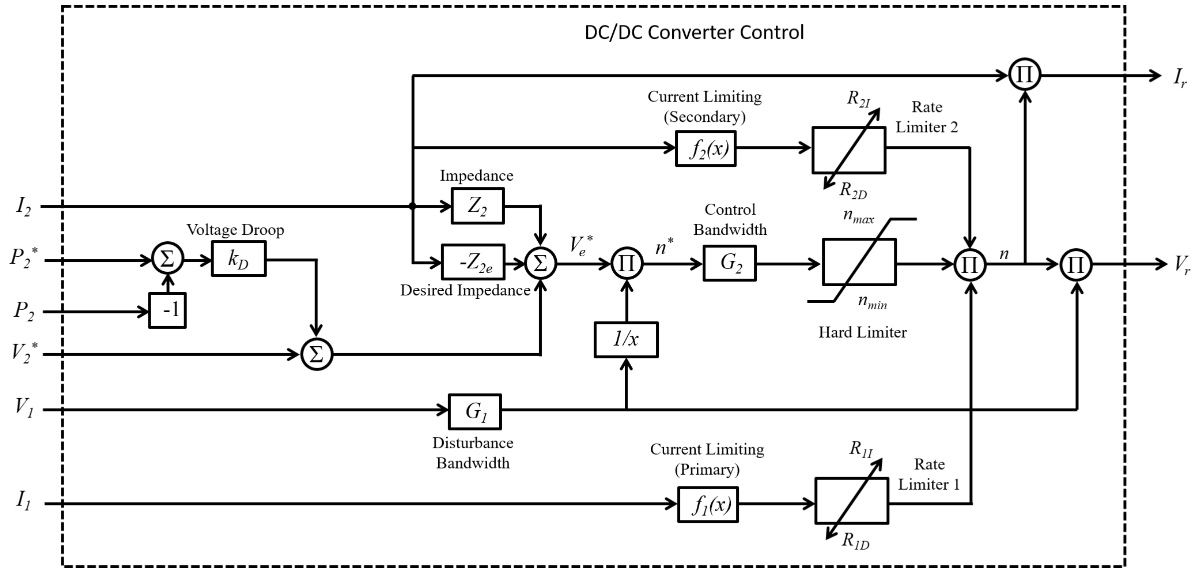

Figure 2.13: Model for DC/DC Converter Control [1]

$$Z_2(s) = R_{1-Z2} + s\frac{X_{1-Z2}}{2\,\pi\,f_b} \tag{2.11}$$

$$Z_{2e}(s) = R_{1-Z2e} \tag{2.12}$$

$$G_i(s) = \frac{1}{\frac{s}{2\pi f_{c-Gi}} + 1} \tag{2.13}$$

Table 2.21: Scale Factor Function for Current Limiting

Current (pu)	Scale Factor
0.000	1.000
1.100	1.000
1.250	0.000
1.400	0.000

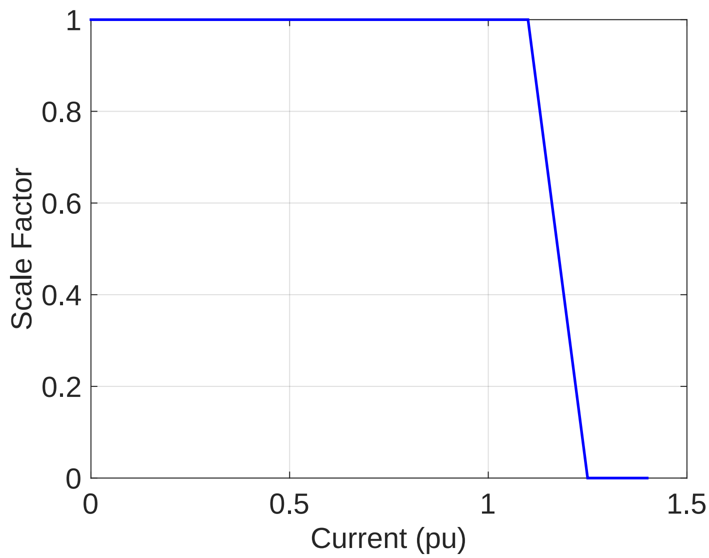

Figure 2.14: Scale Factor Function Current Limiting

2.5.3 Battery System

The battery system model is based on that for a Lithium-ion based system. The battery model dynamics are based on the Huria/Ceraolo/Gazzarri/Jackey model, as described in [11]. The battery model takes into account the effects of temperature on dynamics. The internal battery model parameters, such resistance and capacitance, are functions of temperature. The model uses a 2-dimensional interpolation to calculate the resistance and capacitance based on the state of charge (SoC) and temperature of the cells. Figure 2.15 shows the equivalent circuit of the battery model. Table 2.22 provides information on the basic battery parameters which are provided in [12].

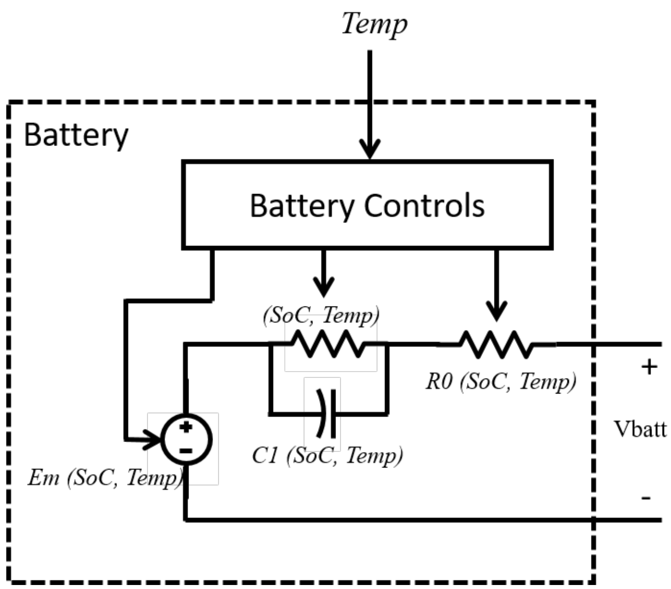

Figure 2.15: MTG Interface

Table 2.22: Li-ion Battery Parameters

Parameter	Value	Unit
Number of entries for temperature	3	–
Number of entries for SoC	7	–
Cell capacity	1	Ah
Heat capacitance (C_t)	2.04e6	J m^{-3} K^{-1}
Convection resistance	5.0	W m^{-2} K^{-1}
Temperature array	[5 20 40]	°C
SoC array	[0 10 25 50 75 90 100]	%
E_m	See Table 2.23	V
$R0$	See Table 2.24	Ω
$R1$	See Table 2.25	Ω
$C1$	See Table 2.26	F

Table 2.23: Battery Voltage Data

SoC (%)	Em (V)
0.0	3.508
10.0	3.562
25.0	3.624
50.0	3.724
75.0	3.921
90.0	4.106
100.0	4.187

Table 2.24: 2-D Table for $R0$ (Ω)

SoC (%)	Temp (5 °C)	Temp (20 °C)	Temp (40 °C)
0	0.01169	0.00905	0.008567
10.0	0.01099	0.009033	0.00855
25.0	0.01139	0.009175	0.008642
50.0	0.01076	0.008808	0.008267
75.0	0.01068	0.0091	0.008317
90.0	0.01128	0.008875	0.008467
100.0	0.01156	0.0089	0.008508

Table 2.25: 2-D Table for $R1$ (Ω)

SoC (%)	Temp (5 °C)	Temp (20 °C)	Temp (40 °C)
0	0.011	0.00295	0.00133
10.0	0.00689	0.00246	0.00124
25.0	0.00473	0.00257	0.00133
50.0	0.0034	0.00165	0.00105
75.0	0.00334	0.00227	0.00143
90.0	0.00332	0.0018	0.00107
100.0	0.00284	0.00171	0.00103

Table 2.26: 2-D Table for $C1$ (F)

SoC (%)	Temp (5 °C)	Temp (20 °C)	Temp (40 °C)
0	1.88e3	1.29e4	3.07e4
10.0	4.84e3	1.84e4	3.34e4
25.0	2.32e4	4.06e4	4.74e4
50.0	1.11e4	1.9e4	2.68e4
75.0	1.81e4	3.31e4	4.81e4
90.0	1.24e4	1.88e4	2.7e4
100.0	9.22e3	2.33e4	3.03e4

2.6 Energy Management Control

The EMC makes use of the control approach described in [2]. In the this system, the EMC serves as a system-level controller used to limit the power draw of the EMs during scenarios in which the power demand is higher than the capacity of the online generation. In these cases, the EMs continue to fully support their respective loads, but the balance of power is pulled from the energy storage.[1] The interface between the EMC and the system is illustrated in Fig. 2.16. The EMC receives loading and capacity[2] information from each of the PGMs, along with the power draw of each of the EMs. The EMC may make use of additional information from the EMs, such as the power demand and state-of-charge (SoC). The EMC may also make use of similar status information from other curtailable loads. In turn, the EMC provides a power limit to each of the EMs and curtailable loads, and may optionally provide load shed signals to short-term interruptible loads. In this way, the EMC regulates the maximum loading of the generators, while attempting to avoid (or minimize) impacts to loads. This function may be important in situations in which the total power demand exceeds the generation capacity, such as in the sudden loss of a PGM or during engagements requiring the simultaneous use of several high power mission loads.

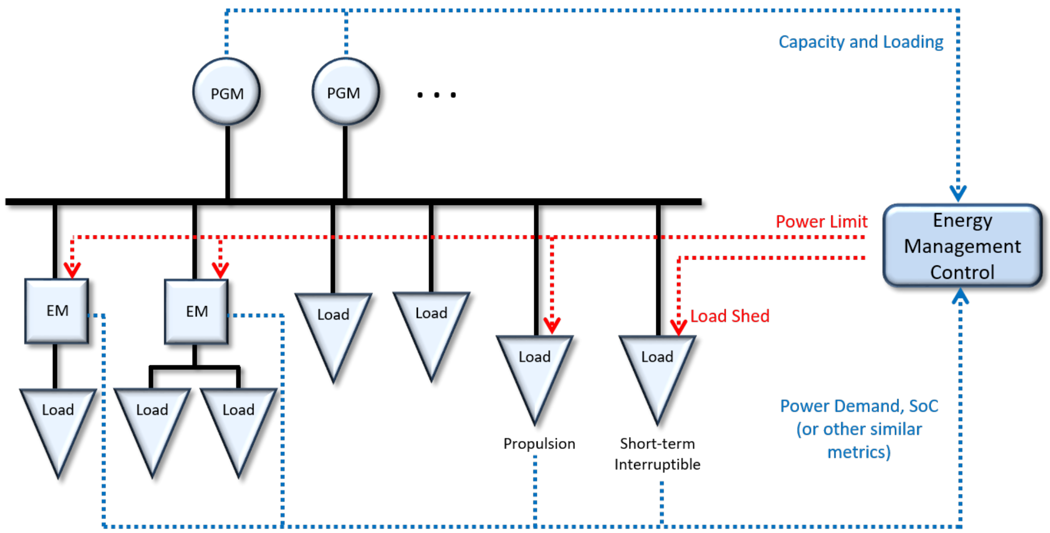

Figure 2.16: EMC Interface

In this work, the EMC is decomposed into a small number of modules, as illustrated in Fig. 2.17. The EM priority computation module is used to assign an instantaneous priority for each of the EMs based on status information of the EM and priority weighting information. The priority of EM j (y_j) is given by (2.14), where x_j^* is the target value of the status quantity (e.g. target SoC) for EM j, x_j is the actual value of the status quantity (e.g. actual SoC) for EM j, and w_j is the priority weight for EM j.

$$y_j = w_j \left(x_j^* - x_j\right) \tag{2.14}$$

The priority weight reflects the relative importance of an EM, based the loads served, the current mission,

[1]In general, this approach may be taken with any load for which the power can be temporarily curtailed without loss of functionality. For example, the power draw for a propulsion load could be curtailed for a short time. This would result in a slowing of the shaft speed, but the inertia of the system inherently provides energy storage. Another example may be short-term interruptible loads, such as freezers.

[2]Here, it is allowed that the generation capacity of a PGM may change dynamically, depending on operating conditions.

and the operating conditions.[3] The normalized priority is computed for each of the EMs from (2.15)

$$\tilde{y}_j = \frac{y_j}{\sum_j y_j} \tag{2.15}$$

These normalized priority values, which are always between zero and one, are the values that are subsequently used by the power allocation module.

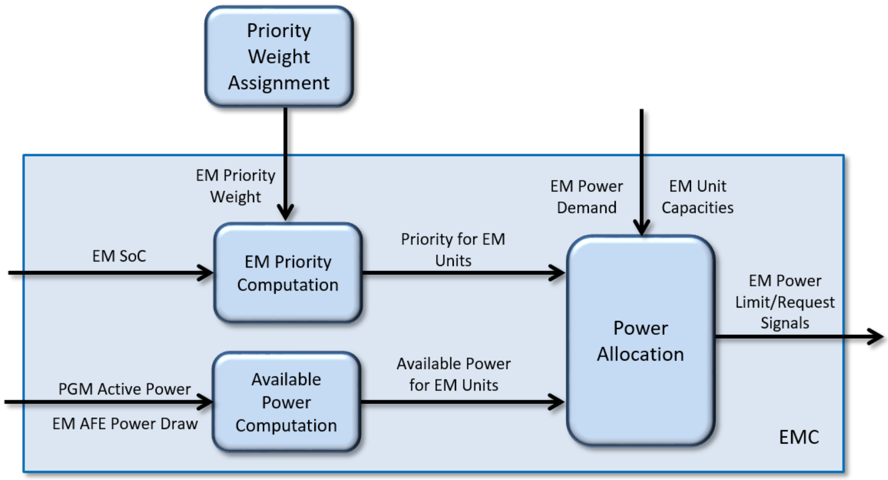

Figure 2.17: Modules of the EMC

The available power is computed by (2.16), where P_{cap-i} is the generation capacity for PGM i, P_{out-i} is the power supplied by PGM i, P_{AFE-j} is the power drawn by the AFE of EM j, and P_{margin} is a power margin that can be requested by higher level controls.

$$P_{av} = \sum_i P_{cap-i} - \sum_i P_{out-i} + \sum_j P_{AFE-j} - P_{margin} \tag{2.16}$$

Thus, P_{av} effectively conveys the generation capacity that is available to the EMs, after other loads (which cannot be curtailed without affecting performance) are served, potentially allowing for a specified power margin.

The power allocation module is tasked with apportioning the available power, P_{av}, to the EMs through use of the power limit signals. In the current implementation of this module, this is accomplished by apportioning the available power on a "first come, first served" basis, where the highest priority loads are generally served first. However, if done based solely on instantaneous priority, this can lead to oscillations in power limits between EMs with equal priority. To avoid these oscillations, a ranking system is used, in which power is apportioned in order of ranking, as illustrated in Fig. 2.18. The rankings of the EMs are influenced by priority, but the rankings do not correspond directly to instantaneous priority. The rankings may be arbitrarily initialized, with rankings thereafter being determined through the logic illustrated in Fig. 2.19. For every rank k, the logic of Fig. 2.19 is used to facilitate a swap in the ranks of k and $k+1$ when warranted. In Fig. 2.19, the difference between the normalized priority of the EM in rank k ($\tilde{y}_k$) and that of the EM in rank $k+1$ ($\tilde{y}_{k+1}$) is used as input to an integrator. If this difference is less than zero (i.e. the priority of the EM in rank $k+1$ is higher than the priority of the EM in rank k), the integrator is reset, in order to maintain the appropriate current ranking of the EMs. However, when $\tilde{y}_k$ is higher than $\tilde{y}_{k+1}$, the difference between the two is integrated over time. If the output of the integrator exceeds the threshold

[3] The priority weight would be assigned by a higher-level module, but the details of the priority weight assignment module are not considered in this work.

set by parameter z_{th}, the ranks of the two EMs is swapped, so that the higher priority EM is elevated in rank. The approach avoids oscillations when the priority of one EM rises above that of another (as the power allocation is not immediately changed based on instantaneous priority). This method also has advantages over using a simple pickup time, in that an EM with a much higher priority than its ranking superior can very quickly be swapped in rank, without waiting through the set pickup time at each rank stage. This allows an EM which suddenly becomes high priority (e.g. due to change in mission or operating conditions), to very quickly propagate up the ranking structure to quickly be apportioned power.

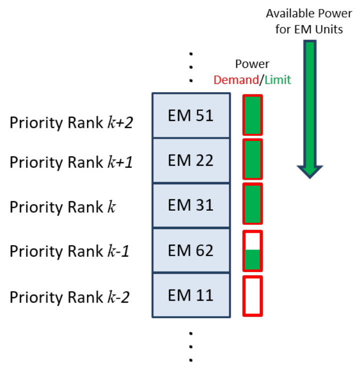

Figure 2.18: EM Power Allocation

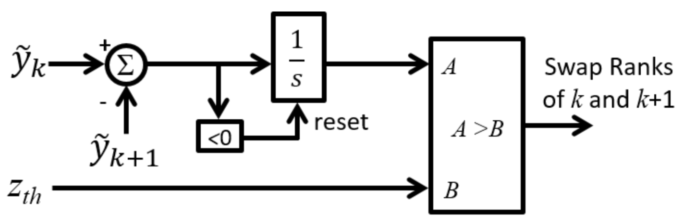

Figure 2.19: Logic for Swapping Rankings of Elements k and $k+1$

Proceeding from the EM with highest ranking to the EM with the lowest ranking, the power allocation module sets the power limit signal of the EM based on the EM's power demand and the available generation capacity that has not yet been allocated. The power available to be allocated, P_{pool}, is initialized to the available generation capacity, P_{av}. The power limit signal of the first EM is set to its power demand, up to the amount of P_{pool}, and this amount of power is subtracted from P_{pool}. This process is repeated for the each of the EMs, progressing from the highest to the lowest rank. If the available generation capacity is sufficient to meet the power demand of all of the EMs, the power limit for each EM is set to its demand level, such that there is not power curtailment of the EMs. If the available generation capacity is not sufficient to supply the power demand of all of the EMs, the EMs with highest rank are allowed to draw power from the system, and the EMs with lower rank are curtailed. However, an EM which is curtailed and heavily loaded will eventually rise to higher priority as its SoC, allowing it to propagate up the rankings and obtain power allocation. Thus, this system allows normal power draw by EMs when sufficient power generation capacity is available, but attempts to intelligently allocate power resources when these are scarce.

If the EM units have bi-directional AFEs, the EMs may be able to also provide support to the system in conditions in which the generators become overloaded by non-curtailable loads (i.e. $P_{av} < 0$). The EM power limit signal can be used to indicate a request to push power upstream to the system if a negative power value is specified. In these conditions, the same approach can essentially be used for the power allocation, but the order of progression is reversed. In this way, the power deficit (P_{av}) is requested first from the EMs with lowest priority until the power deficit is met. All other (higher priority) EMs are limited to zero power draw, in this case, but are not required to supply power to the upstream system. This mode of operation can be useful to avoid shedding loads until additional power generation capacity can be brought online. Parameters of the EMC are described in Table 2.27.

Table 2.27: Parameters of EMC

Block	Parameter	Description	Default Value
Power Allocation	z_{th}	Threshold for integrated priority above which ranks of units are swapped.	1.0

2.7 Propulsion Motor Modules (PMM)

A port and starboard propulsion system is modeled in the system. Each propulsion system contains two motors driving the same shaft, with each PMM rated for 12.5 MW. A simplified representation of the PMMs is used in this system model. The PMMs are modeled as current injections at the medium voltage AC level. Figure 2.20 shows the PMM interface.

Figure 2.21 depicts the PMM control scheme. The PMM model has the option to select between speed or power as the control input to the system. If speed is selected, the commanded speed is processed through a speed to power curve for each PMM. For power input selection, the real power at the MVAC bus is directly commanded to the system. The real power command is used to compute a real current request, I_d. The voltage used to compute I_d and I_q contains a rate limiter as well as a hard limiter such that the PMM behaves as a constant-power load within the voltage band as specified by hard limiter and acts as a constant-current load beyond the limits of the voltage band. Based on the real power output of the PMM, the reactive power is computed using a P-Q curve. The real current I_d and reactive current I_q are then used to compute the 3 phase instantaneous current injection request I_{r-abc} using a DQ to ABC conversion. An under-voltage check logic is included in the system so that if the voltage on the bus is lower than the specified value, the PMM is requested to shut off. As illustrated in Figure 2.22, hysteresis logic is implemented to avoid oscillations in the enable signal, u_{st}. Table 2.28 describes the control signals in the model, while Table 2.29 gives the PMM model parameters.

$$G_1(s) = \frac{1}{\frac{s}{2\pi f_{c-G1}} + 1} \tag{2.17}$$

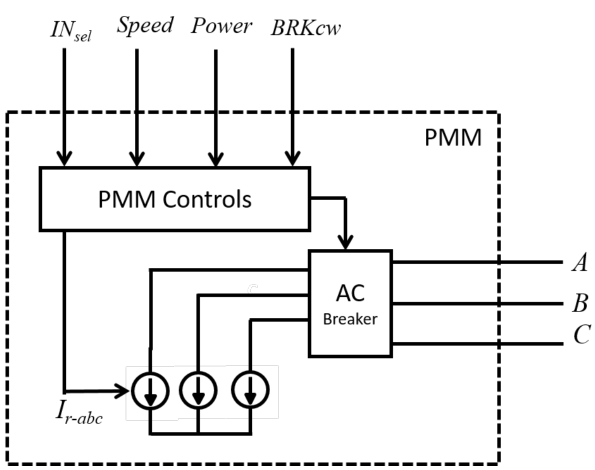

Figure 2.20: PMM Interface

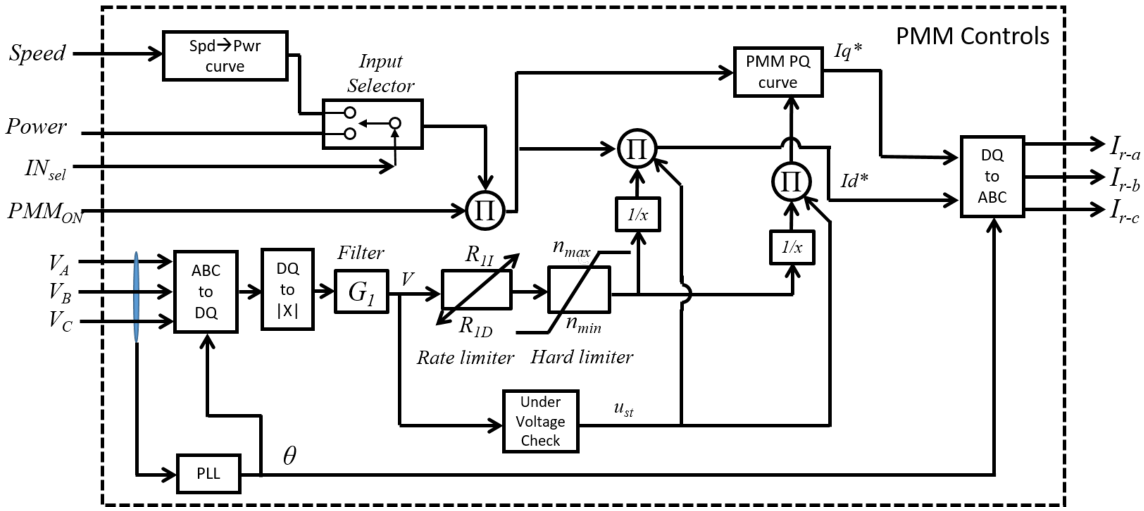

Figure 2.21: PMM Controls

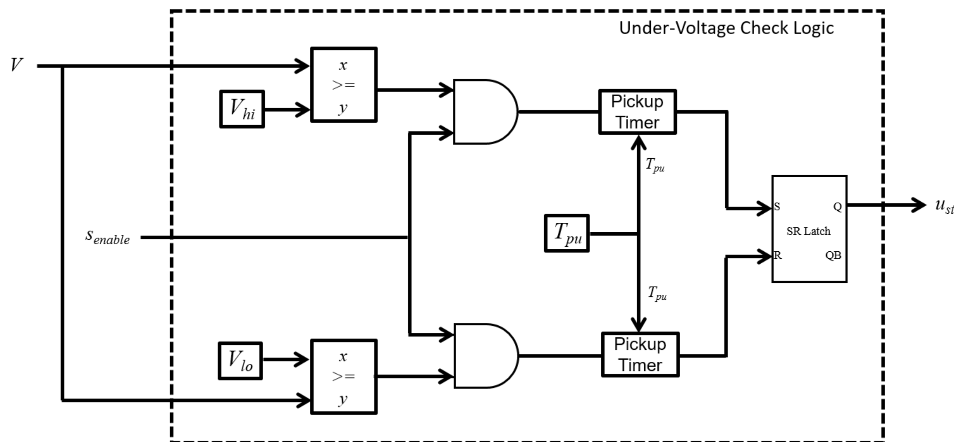

Figure 2.22: PMM Under-Voltage Check Logic

Table 2.28: Control Signals for PMM

Parameter	Description	Unit
PMM_{ON}	Enable/disable PMM	NA
IN_{sel}	Speed or Power Input Select	NA
Speed	Desired ship speed	knots
Power	PMM power draw on MVAC bus	MW
V_A, V_B, V_C	Instantaneous AC voltage at PMM terminal	kV
I_{r-a}, I_{r-b}, I_{r-c}	Instantaneous 3 phase current request for PMM current injection	kA

Table 2.29: Parameters for PMM Controls

Parameter	Description	Value	Unit
f_{c-G1}	Cutoff frequency for voltage measurement (see (2.17)).	300	Hz
R_{1I}	Limit of rate of increase	10	pu/s
R_{1D}	Limit of rate of decrease	-10	pu/s
n_{max}	Upper limit of voltage	1.15	pu
n_{min}	Lower limit of voltage	0.85	pu
V_{hi}	Under-voltage check threshold above which to enable the PMM.	0.9	pu
V_{lo}	Under-voltage check threshold below which to disable the PMM.	0.8	pu
T_{pu}	Pickup time for under-voltage check logic.	0.1	s

2.8 Mission Loads (ML)

The mission load model is intended to be used to represent loads with constant, periodic, or stochastic loading, or a combination thereof. The mission load is modeled as a constant-power characteristic, using a current injection at the supply bus. Figure 2.23 shows the mission load components and interface, while Figure 2.24 shows the mission load control structure. The model includes a base load (P_{base}) and a dynamic load input (P_{base}), both of which are rate limited by Rate Limiter 1. A stochastic load generator is modeled in the system that can generate a stochastic profile that can be added to the base and dynamic load where needed. The mission load control scheme also implements an option to have an under-voltage check as well as rate and peak limiters for input voltage to calculate the current injection. The mission loads are fed through dual auctioneering diodes, each of which is from the output port of an EM. Table 2.30 describes control signals in the model while Table 2.31 describes model parameters.

$$G_1(s) = \frac{1}{\frac{s}{2\pi f_{c-G1}} + 1} \tag{2.18}$$

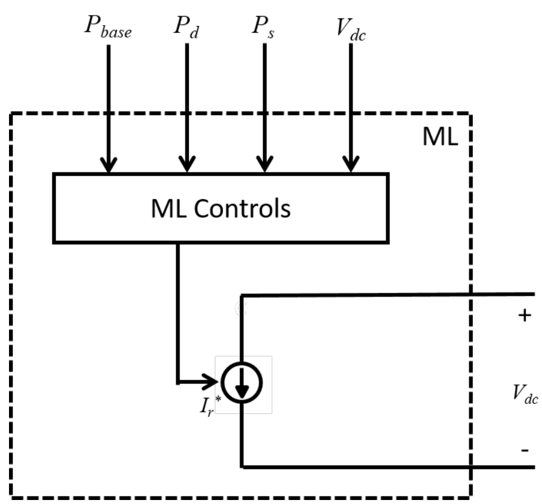

Figure 2.23: ML Components and Interface

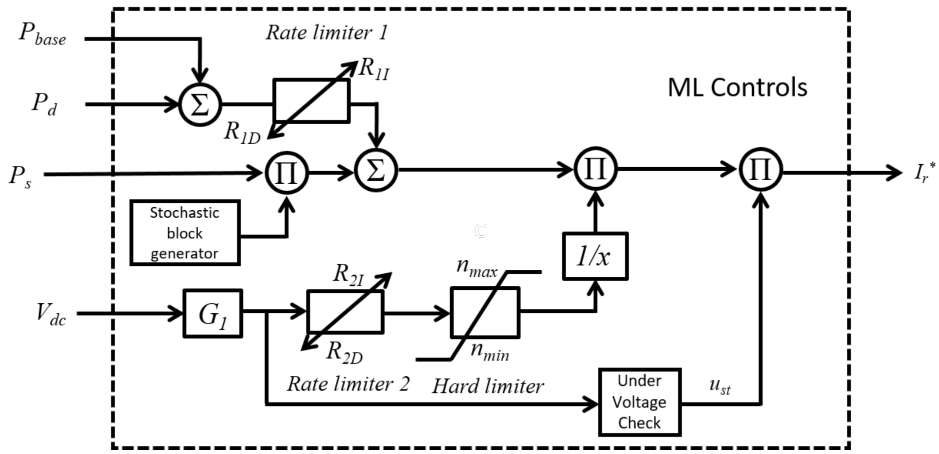

Figure 2.24: ML Controls

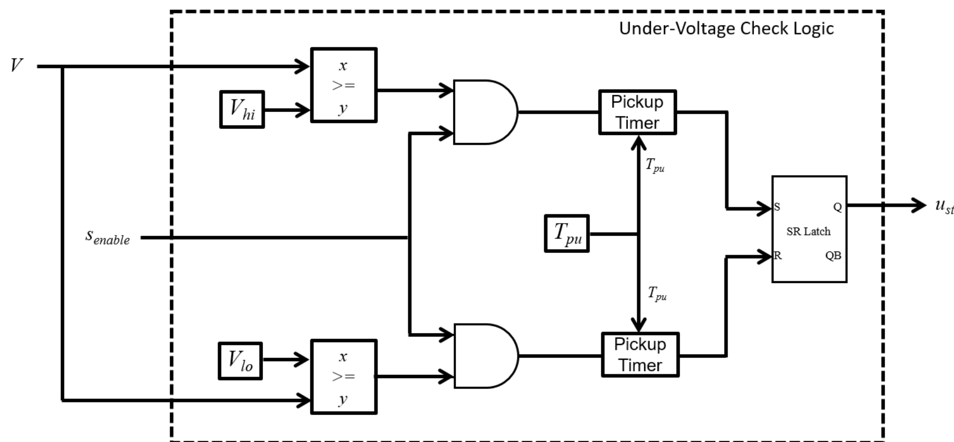

Figure 2.25: ML Under-Voltage Check Logic

Table 2.30: Signals for Mission Load Controls

Parameter	Description	Unit
P_{base}	Base load	MW
P_d	Dynamic load.	MW
P_s	Stochastic load power	MW
V_{dc}	Measured dc voltage at mission load terminal	kV
I_r	DC current injection reference	kA

Table 2.31: Mission Load Control Parameters

Parameter	Description	Value	Unit
f_{c-G1}	Cutoff frequency for voltage measurement (see (2.18)).	300	Hz
R_{1I}	Limit of rate of increase	200	MW/s
R_{1D}	Limit of rate of decrease	-200	MW/s
R_{2I}	Limit of rate of increase	100	pu/s
R_{2D}	Limit of rate of decrease	-100	pu/s
n_{max}	Upper limit of voltage	1.15	pu
n_{min}	Lower limit of voltage	0.85	pu
V_{hi}	Under-voltage check threshold above which to enable the PMM.	0.9	pu
V_{lo}	Under-voltage check threshold below which to disable the PMM.	0.8	pu
T_{pu}	Pickup time for under-voltage check logic.	0.1	s

2.9 Aggregate AC Load (RTDS Implementation)

This model is intended to represent an aggregation of AC loads at a bus for a shipboard power system facilitating primary and alternate supply connections. The basic implementation of the model is illustrated by Figure 2.26. All loads are aggregately represented by a mix of constant power, constant current, constant impedance, and induction machine loads. All constant power, constant current, and constant impedance loads, are represented by module A (ZIP). Non-vital induction machine loads are represented by module B, and vital (including semi-vital) induction machine loads are represented by module C. Induction machines are modeled using the "_rtds_INDM" native scalable induction machine component within RSCAD, described in [13]. Common parameters used for the machine models are given in Table 2.36. Module C is connected through circuit breakers to both a primary and an alternate supply bus, with the breaker to the primary bus being normally closed and the breaker to the alternate bus being normally open. The automatic bus transfer (ABT) logic module is used to transition the vital (and semi-vital) loads from the primary to the alternate supply bus in the event of an under-voltage on the primary bus. For the induction machine loads, this is accomplished by first opening the breaker to the primary bus, and then closing the breaker to the alternate bus. In order to conserve simulation resources (nodes, switching elements, etc.), the loads represented by the ZIP module are not physically connected through breakers to both buses. Rather, this model is intended to be used in conjunction with a counterpart instance representing the primary load for the associated alternate bus, as illustrated by Figure 2.27. If an ABT switching event occurs, a power reference, P_a, is sent from one load module to the counterpart module, such that the vital portions of the ZIP loads are removed from one module and added to the ZIP power of the counterpart module.

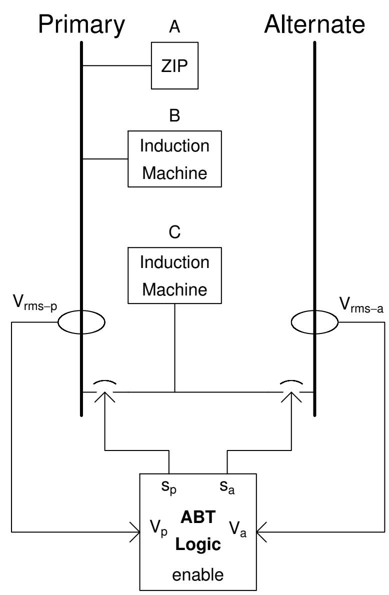

Figure 2.26: Basic Implementation of Aggregate Load Model

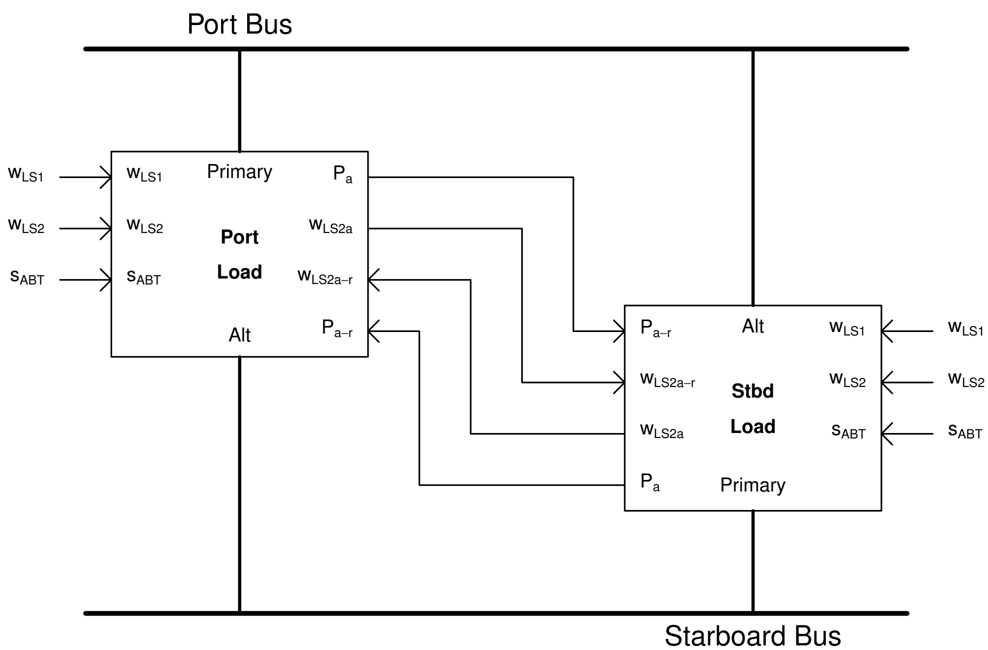

Figure 2.27: Use of Counterpart Load Modules to Represent the Loads within a Distribution Zone

The ABT logic module is implemented as shown in Figure 2.28. The three-phase RMS voltage at the primary bus, V_p, and the alternate bus, V_a, are supplied as inputs to the module. If the voltage at the primary bus drops below a specified threshold (parameter V_{th}) for a specified duration (parameter T_{pu}), while the voltage at the alternate bus remains above the specified threshold, an ABT switching event is initiated. Immediately upon initiating the switching event, the status signal for the primary bus, s_p, is set to zero. This causes the breaker connecting the load to the primary bus to the opened, and the vital loads to be removed from this bus. After a specified duration, T_{del}, the status signal for the alternate bus, s_a, is set to one. This results in the breaker connecting the load to the alternate bus to be closed, and the load to be applied to the alternate bus. In general, this logic only supports shifting loads from the primary to the alternate bus, and does not support logic to switch loads back to the primary bus from the alternate bus if an under-voltage subsequently occurs on the alternate bus. An enable input signal is used to enable and reset the logic, however. This is primarily intended to disable the logic during the initialization of a transient simulation, in order to prevent ABT switching before steady state is reached.

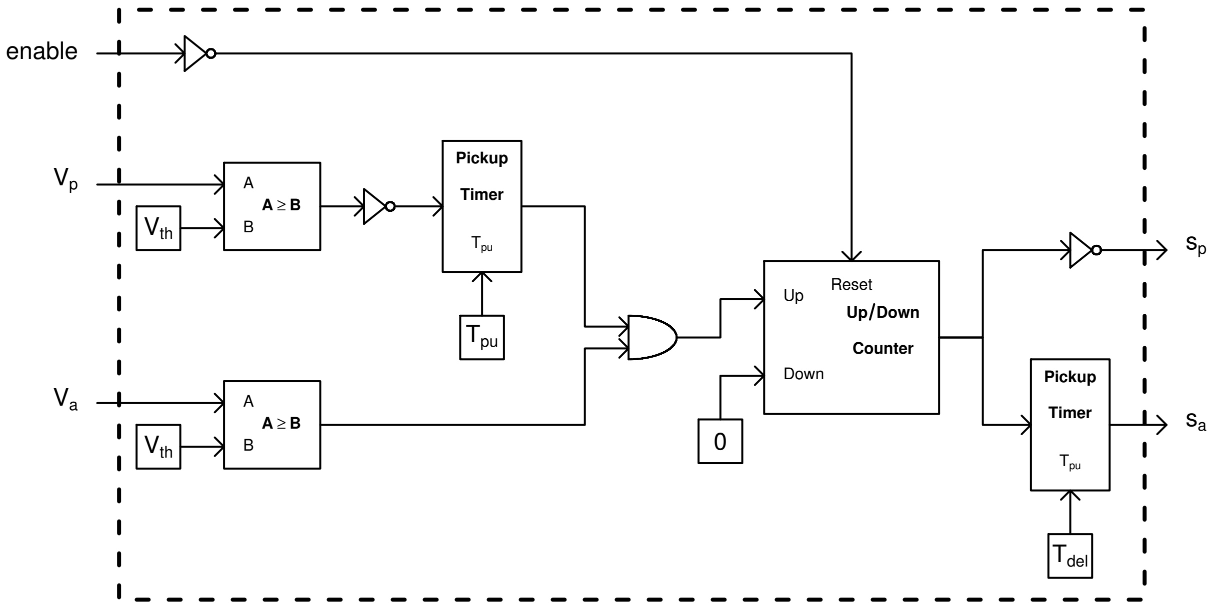

Figure 2.28: ABT Logic

Model parameters, inputs, outputs, and exposed electrical nodes are described in Tables 2.32, 2.33, 2.34, and 2.35, respectively. The model parameters are used to configure the rated voltage for the load, the power factor for the load, and the total power for the vital, semi-vital, and non-vital portions of the aggregate load. Additionally, the parameters are used to configure the fractions of the load to be represented as constant power, constant current, constant impedance, and by induction machines.

Table 2.32: Parameters for AC Aggregate Load Model

Symbol	Description	Range	Default
V_b	The rated line-line, RMS voltage (kV) for the load.	Positive Real	0.45 kV
P_{vital}	The total power (MW) drawn by the vital loads at nominal voltage.	Positive Real	0.1 MW
$P_{nonvital}$	The total power (MW) drawn by the nonvital loads at nominal voltage.	Positive Real	0.1 MW
pf	The nominal power factor of the loads.	[0 1]	0.8
FracZ	The fraction of the total load represented by constant impedance.	[0 1]*	0.2
FracP	The fraction of the total load represented by constant power.	[0 1]*	0.1
FracIM	The fraction of the total load represented by induction machines.	[0 1]*	0.7
FracSemiVital	The fraction of the vital load that is regarded as semi-vital (i.e. this fraction of the vital load is shed if a stage 2 load shed is requested.	[0 1]	0.1

Table 2.32: Parameters for AC Aggregate Load Model

Symbol	Description	Range	Default
LSMask	An integer representing a bitmask that is used to denote which load shed requests the load associated with this bitmask responds. For this model, generation units issue load shed requests and loads respond (by performing a load shed operation) to these requests. A bit value of one indicates that the associated load will respond to load shed requests from the generator associated with the respective bit position. A bit value of zero indicates the associated load will not respond to load shed requests. For example, assume bits (at positions) 0, 1, and 2 are associated with generation units G1, G2, and G3, respectively. If a load is being supplied by generators G1 and G3 (i.e. the load must perform a shed operation if G1 and/or G3 issue a load request), the mask value is 101 (binary) or 5 (decimal).	Positive Integer	31
V_{th-ABT}	The voltage threshold (pu) below which the ABT logic will transfer vital loads (the voltage on the alternate bus must also be above this threshold in order for the ABT switches to activate).	[0 1]	0.8
T_{pu-ABT}	The time (s) for which the voltage at the primary bus must drop below the specified threshold (given by V_{th-ABT}) for the ABT logic to initiate transferring vital loads to the alternate bus.	Positive Real	0.05 s
$T_{del-ABT}$	The amount of time (s) between vital loads disconnecting from the primary bus and re-connecting to the alternate bus.	Positive Real	1.0 s
*	Note: The values of FracZ, FracP, and FracIM must sum to a value less than or equal to 1. The remainder of the load (one minus the sum of these parameter values) is assumed to be represented by constant current loads.		

Table 2.33: Inputs for AC Aggregate Load Model

Symbol	Description	Range
P_{a-r}	Reference power (MW) for contant power, constant current, and constant impedance portions of load transferred through ABT switches from another set of loads for which this bus is the alternate supply.	Positive Real
s_{ABT}	Enable signal for ABT logic. A value of 1 enables the logic, and value of 0 disables the logic. This may be used, for example, during initialization to disable the ABT logic while the system reaches steady state.	{0,1}

Table 2.33: Inputs for AC Aggregate Load Model

Symbol	Description	Range
w_{LS1}	An integer bitmap representing the status of first stage load shedding controls. Each bit represents the status (1 - overloaded, 0 - normal) of an element, such as a generator. The load shed mask parameter (LSMask) is used to specify for which bits of this word the load should respond by shedding load. If the same bit is high (1) in both this input and the LSMask parameter, the load will respond by shedding all nonvital loads.	Positive Integer
w_{LS2}	An integer bitmap representing the status of second stage load shedding controls. Each bit represents the status (1 - overloaded, 0 - normal) of an element, such as a generator. The load shed mask parameter (LSMask) is used to specify for which bits of this word the load should respond by shedding load. If the same bit is high (1) in both this input and the LSMask parameter, the load will respond by shedding all semi-vital loads.	Positive Integer
w_{LS2a-r}	An integer bitmap representing the status of second stage load shedding controls, as affecting the alternate supply bus for this load. If ABT switches have transferred vital and semi-vital loads from the primary bus to the alternate bus, this signal is used to indicate if semi-vital loads should be shed (reflected in the P_a output). This signal would typically be supplied from a counterpart load on the alternate supply, and would represent the application of a bitwise AND operation with w_LS2 and the LSMask parameter for the counterpart bus.	Positive Integer

Table 2.34: Outputs for AC Aggregate Load Model

Symbol	Description	Range
P_a	The power (MW) representing the portion of the constant power, constant current, and constant impedance load being transferred through ABT switches to the alternate supply. This output is intended to be used as an input (P_{a-r}) to a counterpart load.	Positive Real

Table 2.34: Outputs for AC Aggregate Load Model

Symbol	Description	Range
w_{LS2a}	An integer bitmap representing the status of second stage load shedding controls affecting the primary bus. This output is intended to be used an an input (w_{LS2a-r}) to a counterpart load. In this way, if a counterpart load is adding load through alternate supply, those loads can be made aware of the load shed request in order to shed semi-vital loads. This signal would represent the application of a bitwise AND operation with w_LS2 and the LSMask parameter	Positive Integer

Table 2.35: Electrical Nodes for AC Aggregate Load Model

Symbol	Description
Primary	A three-phase (three-wire) electrical connection, representing a connection to the primary supply bus.
Alt	A three-phase (three-wire) electrical connection, representing a connection to the alternate supply bus.

Table 2.36: Common Induction Machine Parameters

Symbol	Description	Default
T_{scale}	MVA scaling factor smoothing time constant.	0.05 s
V_{base}	Rated line-line voltage (RMS).	0.450 kV
N_{rs}	Turns ratio, rotor over stator.	1.0
f_{base}	Rated frequency.	60.0 Hz
R_a	Stator resistance.	0.003 pu
X_a	Stator leakage reactance.	0.07 pu
X_m	Unsaturated magnetizing reactance.	2.0 pu
R_1	First cage rotor resistance.	0.03 pu
X_1	First cage rotor leakage reactance.	0.07 pu
H	Inertia constant.	1.0 MW s/MVA
D	Frictional damping.	0.0 pu/pu
	Saturation curve.	Linear

As noted above, the model is intended to be used in module pairs representing the loads of a shipboard distribution zone, as illustrated by Figure 2.27. Figure 2.27 shows two aggregate loads being supplied by a port and starboard bus. The module designated as the port load connects to the port bus as the primary supply and the starboard bus as the alternate supply. This is reversed for the starboard load module. Both modules accept the load shed bitmaps w_{LS1} and w_{LS2} (for load shed stages one and two, respectively), for which each bit indicates a load shed request status (e.g. one bit for each generation unit). However, the modules may interpret the load shed requests differently based on the module's LSMask parameter. As an example, consider a case in which bits 0, 1, and 2 of w_{LS1} and w_{LS2} represent the load shed request status for three generators, G1, G2, and G3, respectively. In a split plant configuration in which the starboard bus is supplied by G1 and G3, and the port bus is supplied by G2, the LSMask parameters for the starboard and port modules would be set to 5 (101 binary) and 2 (010 binary), respectively. In this case, if G1 became overloaded, resulting in a value of 1 (001 binary) for w_{LS1}, load would be shed by the starboard load module, but not by the port load module. Another point to note is that the P_a and w_{LS2a} outputs from each module are supplied to the P_{a-r} and w_{LS2a-r} inputs, respectively, of the counterpart modules. This facilitates shifting the ZIP loads from a module to the counterpart module in the event of an ABT switching.

2.10 Generator Auxiliary Load

The MTG/ATG auxiliary support load is load that is engaged when startup up an MTG or ATG. The auxiliary loads are the loads required to bring online the generator system. Each of these loads is modeled as a dc load that is fed from an EM. Table 1.1 provides ratings for the auxiliary loads of the MTG and ATG. Modeling of MTG and ATG auxiliary loads are similar and only differ in ratings. Figure 2.29 shows the auxiliary load interface while Figure 2.30 shows the auxiliary load controls. Table 2.37 provides control signals while Table 2.38 describes control parameters for generator auxiliary loads.

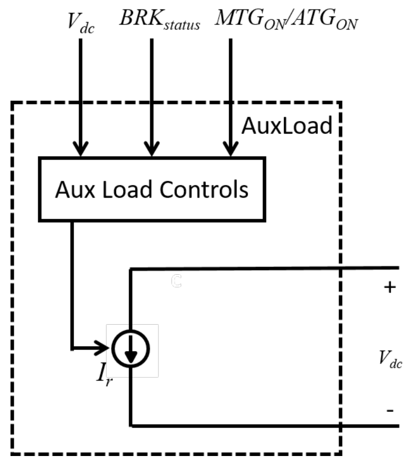

Figure 2.29: Generator Auxiliary Load Interface

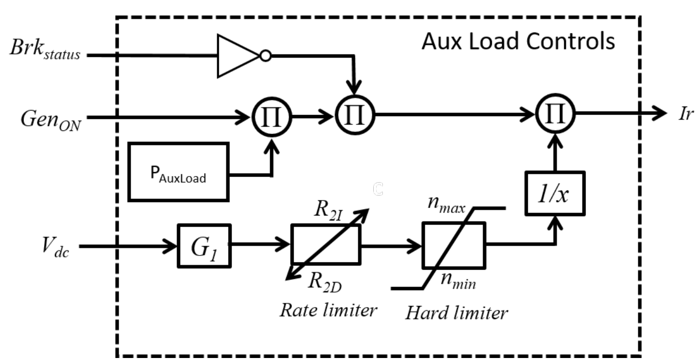

Figure 2.30: Generator Auxiliary Load Controls

Table 2.37: Generator Auxiliary Load Control Signals

Parameter	Description	Unit
Gen_{ON}	MTG or ATG turn on request	NA
Brk_{status}	Generator AC breaker status	NA
V_{dc}	DC voltage at load terminal	kV
I_r	Current request for aux load current injection	kA

Table 2.38: Generator Auxiliary Load Control Parameters

Parameter	Description	Value	Unit
R_{1I}	Limit of rate of increase	10	p.u./s
R_{1D}	Limit of rate of decrease	-10	p.u./s
n_{max}	Upper limit of voltage	1.15	p.u.
n_{min}	Lower limit of voltage	0.85	p.u.

2.11 Switchboards

Switchboards are modeled as assemblies of ideal circuit breakers. The current implementation of switchboards does not include any protection elements, but it is expected that future revisions will include switchboard protection logic. Table 2.39 summarizes switchboards modeled in the system.

Table 2.39: Medium voltage switchboard information

Switchboard Name	Description
1HA	Zone 1 starboard MV switchboard
2HB	Zone 2 port MV switchboard
3HA	Zone 3 starboard MV switchboard
3HB	Zone 3 port switchboard
4HA	Zone 4 starboard MV switchboard
4HB	Zone 4 port MV switchboard
5HA	Zone 1 starboard MV switchboard
6HB	Zone 1 port MV switchboard
G1	MTG 1 switchboard
G2	MTG 2 switchboard
G3	ATG 1 switchboard
G4	ATG 2 switchboard

2.12 Cables

Only MVAC distribution cables are modeled in the system. Parameters for the cable sections between various MV switchboards are provided in Table 2.40.

Table 2.40: Cable Parameters

Cable No.	From	To	Length (m)	R_1 (Ω)	X_1 (Ω)	L_1 (µH)	C_1 (MΩ)	R_0 (Ω)	X_0 (Ω)	C_0 (MΩ)
1	ATG1	G3	32.0	0.0031	0.0038	10.0785	0.0027	0.0380	0.0259	0.0187
2	MTG1	G1	32.0	0.0006	0.0008	2.1218	0.0136	0.0076	0.0052	0.0934
3	MTG2	G2	32.0	0.0006	0.0008	2.1218	0.0136	0.0076	0.0052	0.0934
4	ATG2	G4	32.0	0.0031	0.0038	10.0785	0.0027	0.0380	0.0259	0.0187
5	2HB	G3	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
6	1HA	G3	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
7	3HB	G1	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
8	3HA	G1	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
9	4HB	G2	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
10	4HA	G2	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
11	6HB	G4	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
12	5HA	G4	38.0	0.0007	0.0009	2.3870	0.0162	0.0090	0.0062	0.1109
13	2HB	3HB	70.0	0.0014	0.0017	4.5088	0.0298	0.0166	0.0113	0.2043
14	3HB	4HB	12.0	0.0004	0.0003	0.7957	0.0079	0.0032	0.0024	0.0553
15	4HB	6HB	68.0	0.0025	0.0020	5.3045	0.0446	0.0183	0.0138	0.3134
16	1HA	3HA	90.0	0.0034	0.0026	6.8958	0.0590	0.0243	0.0182	0.4148
17	3HA	4HA	45.0	0.0009	0.0011	2.9175	0.0192	0.0107	0.0073	0.1314
18	4HA	5HA	45.0	0.0009	0.0011	2.9175	0.0192	0.0107	0.0073	0.1314

Column Heading Descriptions:

Cable No. Cable number.

From Component from which cable originates.

To Component at which cable terminates.

Length (m) Cable length.

R_1 (Ω) Positive sequence resistance.

X_1 (Ω) Positive sequence reactance.

L_1 (µH) Positive sequence inductance.

C_1 (MΩ) Positive sequence shunt (capacitive) impedance.

R_0 (Ω) Zero sequence resistance.

X_0 (Ω) Zero sequence reactance.

C_0 (MΩ) Zero sequence shunt (capacitive) impedance.

2.13 Circuit Protection

No protection elements are currently implemented in the model.

3 Conclusion

This document describes modeling of a notional integrated power and energy system (IPES), generally based on that described in [2]. The model is intended for use in demonstrating concepts related to robust combat power and energy controls (RCPC). This document generally describes modeling of the system, but does not address implementation of the model on a specific platform. It is intended that specific implementations of the model should be described in separate model implementation documents.

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A Acronyms and Glossary

ABT Automatic Bus Transfer

AFE Active Front End

ATG Auxiliary Turbine Generator

CAPS Center for Advanced Power Systems, Florida State University

EM Energy Magazine

EMC Energy Management Control

ESM Energy Storage Module

FSU Florida State University

LC Load Center

LVAC Low Voltage Alternating Current

LVDC Low Voltage Direct Current

ML Mission Load

MPDU Main Power Distribution Unit

MTG Main Turbine Generator

MVAC Medium Voltage Alternating Current

MVDC Medium Voltage Direct Current

PCM Power Conversion Module

PEMC Power and Energy Management Control

PGM Power Generation Module

PMM Propulsion Motor Module

RCPC Robust Combat Power and Energy Controls

SLPM System Level Protection Module

SoC State of Charge

UPS Uninterruptible Power Supply