Model Description Document – Notional Four Zone MVDC Shipboard Power System Model

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Notional Four Zone MVDC Shipboard Power System Model

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ESRDC Team

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MISSION STATEMENT

The Electric Ship Research and Development Consortium brings together in a single entity the combined programs and resources of leading electric power research institutions to advance near- to mid-term electric ship concepts. The consortium is supported through a grant from the United States Office of Naval Research.

REVISION HISTORY

Personnel

VERSION NUMBER	DATE	COMMENTS
1.0	10/20/17	Initial Version of the document

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Terminology and Acronyms

MVDC	Medium Voltage DC
SPS	Shipboard Power System
DRTS	Digital Real Time Simulator
RTDS™	Real Time Digital Simulator from RTDS Technologies, Inc.
CHIL	Controller Hardware-in-the-loop
PHIL	Power Hardware-in-the-loop
ESRDC	Electric Ship Research and Development Consortium
DC	Direct Current
AC	Alternating Current
DRTS	Digital Real Time Simulator
CHIL	Controller Hardware-in-the-Loop
PGM	Power Generation Module
PCM	Power Conversion Module
PMM	Propulsion Motor Module
PCC	Point of Common Coupling
MMC	Modular Multi-level Converter
TCR	Thyristor Controlled Rectifier
RoS	Rest of System
NA	Not Applicable

1 Introduction

The following document provides information regarding documentation of the ‘Notional Four Zone MVDC Shipboard Power System Model’. The notional model is based on the IEEE-1826 zonal architecture utilizing MVDC breakerless shipboard power system (SPS) and as presented in [1][2][3][4]. Under previous grant funding through the ESRDC, a notional two zone 12 kV MVDC SPS model was implemented in DRTS platform, RSCAD/RTDS which was primarily intended for use in system fault management studies [5].

To broaden the scope of study and provide a common platform for ESRDC team members for input, discussion and collaboration between various entities in order to achieve the goals laid out by ESRDC, a simulation model working group titled, ‘ESRDC Time Domain Electric Model Simulation Working Group’ was realized. The goal of the group is to arrive at a common SPS model with its characteristics defined such that implementation of the SPS model in various simulation platforms can be mapped, verified and validated. The model zonal structure provided here is a direct mapping of the 10k ton ship model available in S3D under the ESRDC initiative [6]. The base architectural system data provided here is also derived from the S3D platform. Any dynamic data that is not available through S3D has been derived through discussion at the ESRDC Time-Domain Electrical Simulation Model Working Group. Only electrical characteristics have been considered in this document. Implementation of the power system model on various simulation platforms will be included as a subsidiary document.

Section 2 of this document lists the purpose of the document and the model. Section 3 provides an overview of the zonal architecture as envisioned by the Navy and the ESRDC team. Section 4 highlights the various modules and components that make up the next generation naval warship. While previous sections focus on the architecture of the system model and its components, section 5 provides information regarding the data required for implementation of modules, their inherent functionality, performance metrics, and also lays out information regarding electrical coupling of modules, their interface features such as control signal exchange and monitoring to an external control system that is tasked to perform a specific function to SPS such as power management, energy management, fault management and so on. Section 6 of this document lays out test cases intended for the SPS model that can be used to cross verify and validate models implemented across various simulation platforms.

The data and information provided in this documentation will be used for implementation of the SPS model in various simulation platforms such as RSCAD/RTDS, OPAL-RT, Matlab-Simulink.

2 Purpose

- The notional four zone MVDC SPS model described in this document is intended to be implemented on various simulation platforms with the intent to run in real time on various DRTS platforms such as RSCAD/RTDS, OPAL-RT
- The suggested characteristics/requirements of the system model described herein should be incorporated into various simulation platforms
- The model described in this document will support controls evaluation. More specifically, the model design will allow efficiently interfacing a diverse set of controls through a well-defined interface in a modular manner. Such controls may be in various forms including software only or a given hardware controller with embedded control logic. Controls can be evaluated by modifying model parameters and observing system responses.
- The characterized system model presented here in will aid in various efforts under the ESRDC project aiming to study areas such as control architecture, advanced control algorithms and strategies, stability analysis, fault management, energy storage, power and energy management, electric plant load analysis and more

- The information, data and characteristics provided in this document should help with traceability, verification and validation of the SPS model implementation across various simulation platforms since their implementation may vary between different simulation platforms and also on type of model implementation

3 Four zone shipboard power system architecture

Figure 1 shows the proposed notional four zone system architecture. The architecture is derived directly from the 10k ton ship study in S3D and can be mapped directly to it [6]. MVDC at 12 kV will be the primary means of power distribution with a SPS power rating of 100 MW. Each zone will consist of modules such as power generation module (PGM), power conversion module (PCM-1A), integrated power node center (IPNC), propulsion motor module (PMM), energy storage module (ESM). Special loads designated as mission loads such as electromagnetic rail gun (EMRG), LASER, SONAR, VLS are also represented in the SPS. Table 1 lists the salient features of the proposed shipboard power system model.

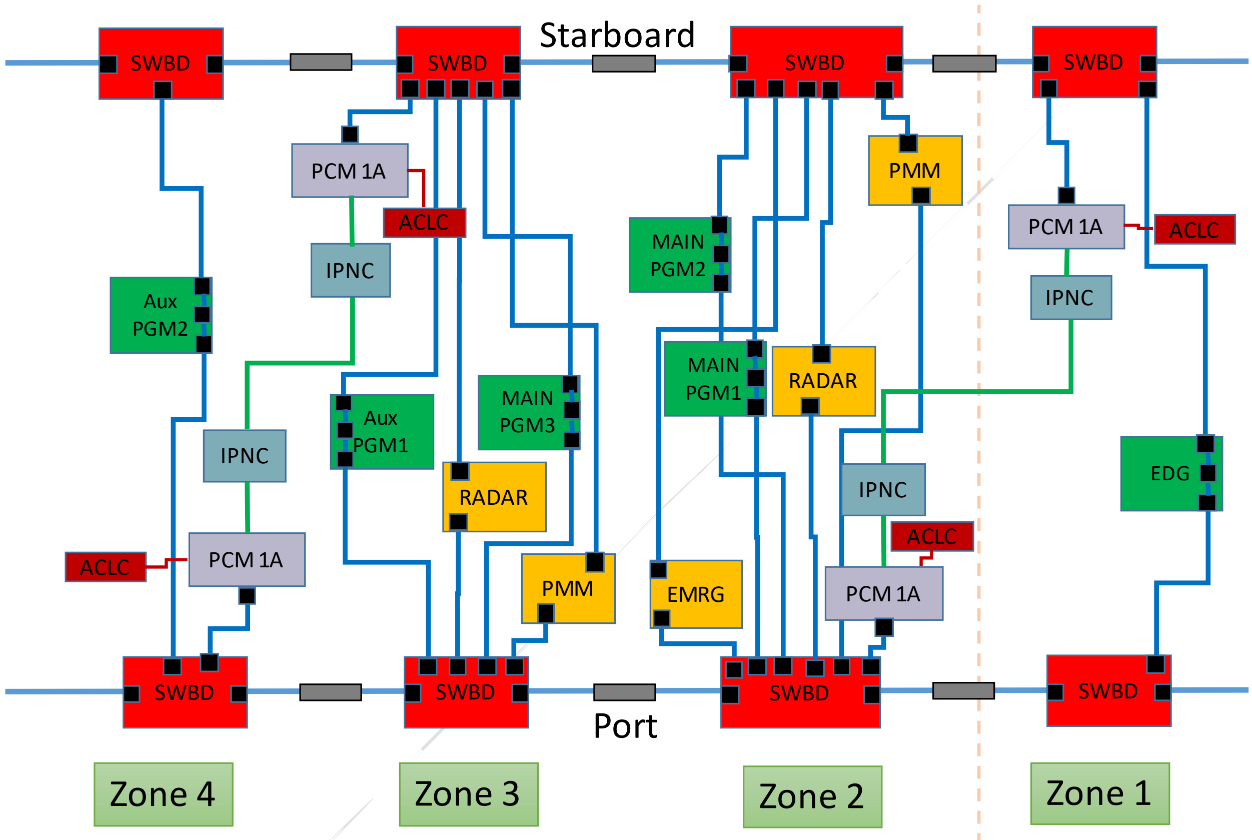

Figure 1 Notional four zone MVDC SPS architecture

Table 1 12 kV, 100 MW shipboard power system model overview

Distribution voltage class		12 kV
Shipboard power generation		~100 MW
Propulsion		72 MW
Mission Loads		29.4 MW
Zonal Loads	Hotel	6.31 MW
	Cooling	6.3 MW
Energy Storage		TBD

Salient features and advantages of the zonal architecture of the SPS are described below:

- Zonal architecture of SPS that can support increased reliability and serviceability of loads

- Dual output feed PGMs that when configured can power port and starboard bus simultaneously and independently
- PGMs with generators running at frequency higher than 60 Hz (120/240 Hz) and the ability to limit fault current through use of power electronic converters
- Special mission loads modeling such as EMRG, LASER, RADAR, VLS, SONAR, ADS
- Energy storage modules that can support un-interruptible loads and aid in mission load applications
- Cross zone interconnection of PCM-1A/IPNC for increased serviceability of vital loads through 450 V, 60 Hz AC or 1 kV DC
- The SPS implementation should adhere to the DC voltage interface standards as provided and listed in [7]
- DC disconnect switches implemented throughout the SPS to allow for various system configurations

Table 2 provides breakdown of modules by zones in the SPS model. The SPS model will consist of 3 main PGMs (rated to 30 MW each) and 2 auxiliary PGM (rated to 4 MW each). One PCM-1A will be modeled in each zone. Mission loads will be modeled separately from the aggregated zonal loads. Zonal loads will be further classified into Hotel loads and cooling loads. Hotel loads are further categorized as vital and non-vital hotel loads.

Table 2 SPS model summary by zone

	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
PGM	One (1-EPGM)	Two (2- MPGM)	Two (1- MPGM, 1-APGM)	One (1-APGM)
PCM-1A	One	One	One	One
PMM	-	One	One	-
ESM	TBD	TBD	TBD	TBD
Mission Loads (MW)	VLS (0.5) SONAR (0.4)	Integrated topside (4) EMRG (17) RADAR (3.3) ADS (0.6)	RADAR (1.7) VLS (0.5)	LASER (1.2) Sonar (0.15)
Total Hotel Load (MW)	1.47	1.65	1.65	1.54
Cooling Load (MW)	1.26	2.52	1.26	1.26

The sections below provide information on SPS modeling specifically on modeling of modules. Functional, performance, interface, and states of operation for each module represented in the SPS is described below.

4 Components and Modules in SPS

While section 3 provides information regarding the architecture in the SPS, the modules that are be implemented in the SPS model are described below. Information regarding their requirements have been described in section 5.

4.1 MVDC Distribution System

The MVDC distribution voltage will be 12 kV. Table 17 provides information regarding cable sections and their proposed lengths using data provided in [6].

4.2 Power Generation Module

The PGM will consist of generator/s with rectifiers and filtering systems. The generators can either be two different machines or dual wound machines or any other configuration. The generator should be configurable to run either at 60, 120 or 240 Hz. Each set of 3 phase AC output from the generator is connected to a rectifier that provides a 12 kV output physical interface to RoS thereby PGM will should dual independent output with each rectifier rated roughly to half the rating of the PGM. The rectifier in the PGM can either be thyristor controller rectifier or MMC based. The PGM provides two output interfaces at 12 kV which connect to rest of the system through either disconnect switches or DC breakers. With PGM having dual output option, the breakers can be configured such that the outputs feed port and starboard independently or both feeds can feed the same bus. Filtering systems will be incorporated into PGM based on type of rectifier used. Figure 2 shows the block diagram of a PGM with a dual wound machine option.

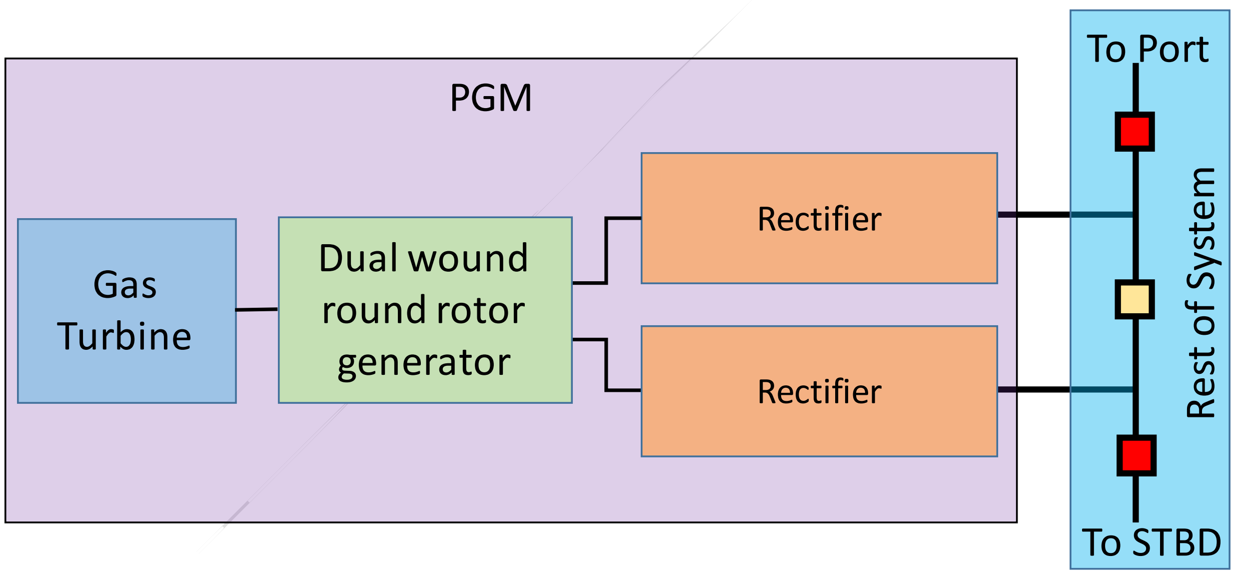

Figure 2 Block diagram of PGM

If the PGM rectifier is MMC based, generators can be designed to run at 60 Hz. If PGM rectifier is based on thyristor controlled rectifier (TCR) based systems, a six pulse TCR with a 120 Hz generator PGM will be used. Table 3 lists ratings of each PGM in the zonal SPS along with its rectifier ratings in case of a TCR based PGM.

Table 3 PGM rectifier and generator ratings based on TCR based PGM

	Zone	Prime Mover	Frequency (Hz)	Generator Power Rating (MW)	Total Rectifier Power Rating (MW)
Em PGM	1	Diesel	60	0.55	0.66
Main PGM 1	2	Gas turbine	120	29	34.8
Main PGM 2	2	Gas turbine	120	29	34.8
Main PGM 3	3	Gas turbine	120	29	34.8
Aux PGM 1	3	Gas turbine	120	3.7	4 .48
Aux PGM 2	3	Gas turbine	120	3.7	4 .48

4.3 Power Conversion Module

The power conversion module (PCM-1A) consists of converters that distribute the 12 kV MVDC power to loads at appropriate voltage levels (1 kV DC, 450 V AC). The PCM-1A can be rated up to 11 MW. Figure 3 shows the block diagram of PCM-1A with the IPNC module. Each PCM-1A will have one input module (dc-dc converter) that convert 12 kV MVDC power to 1 kV DC voltage level to which several output modules will be interfaced. An optional energy storage module (ESM) can also be present at the 1 kV DC level. MW class loads are connected directly to 1 kV DC bus. One set of output modules (DC-AC) supply power to AC load center loads (ACLC). A 1 kV DC supplies power to the IPNC module. Table 4 provides information regarding the ratings of the four PCM-1A in the SPS model.

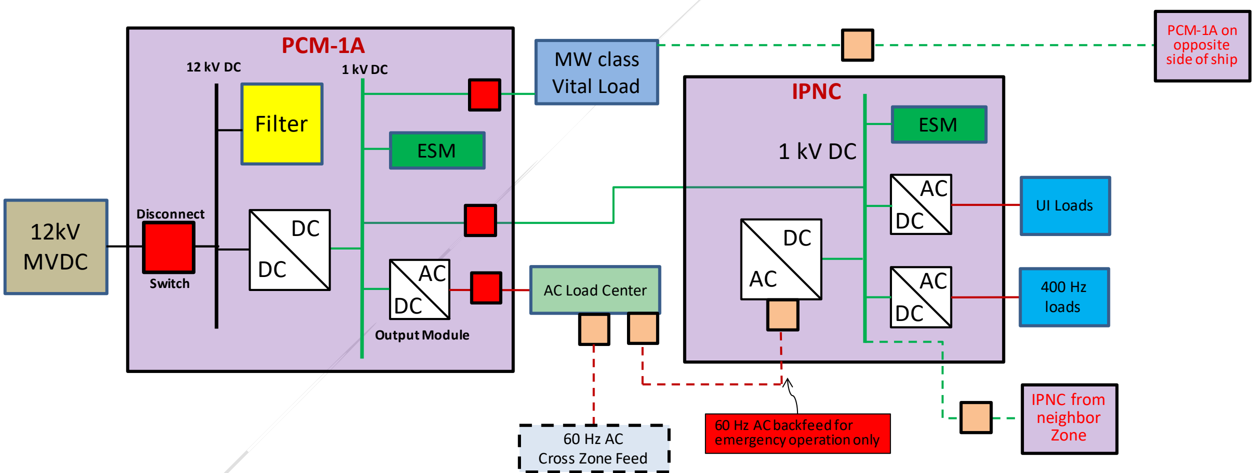

Figure 3 Block diagram of PCM-1A with IPNC

Table 4 PCM-1A ratings in SPS model

	Location	Power rating (MW)
PCM-1A - 1	Zone 1	10.64
PCM-1A - 2	Zone 2	10.64
PCM-1A - 3	Zone 3	9.17
PCM-1A - 4	Zone 4	9.17

4.4 Integrated Power Node Center

Integrated power node centers will consist of specific loads that require high power quality needs and uninterruptible loads (UI). IPNC can be powered directly through PCM-1A using a 1 kV DC interface. Energy storage module will be integrated into IPNC and will be sized such that UI loads can be served for at least 1 second after service interruption from PCM-1A before reconfiguration occurs such that neighboring zone IPNC can supply power to IPNC loads. Figure 3 shows block diagram of IPNC model and Table 5 provides the power rating of each IPNC in the SPS model.

Two different versions of PCM-1A with IPNC are envisioned. One version of the IPNC provides 1 kV DC as interface to neighboring zone during emergency operation while the other version consists of a 450 VAC as interface to neighboring zone. The documentation here in assumes the 1 kV DC version as the default and describe its functionality.

Table 5 IPNC power rating by zones

Zone	**Power rating (MW)**
1	2.77
2	3.13
3	3.95
4	1.99

4.5 Propulsion Motor Module

Two PMMs, one in zone 2 and zone3 with each rated to 36 MW will be implemented in the model. PMMs will be powered through both port and starboard busses simultaneously. PMMs will be implemented such that balanced power drawn from both busses. Figure 4 shows the block diagram of PMM.

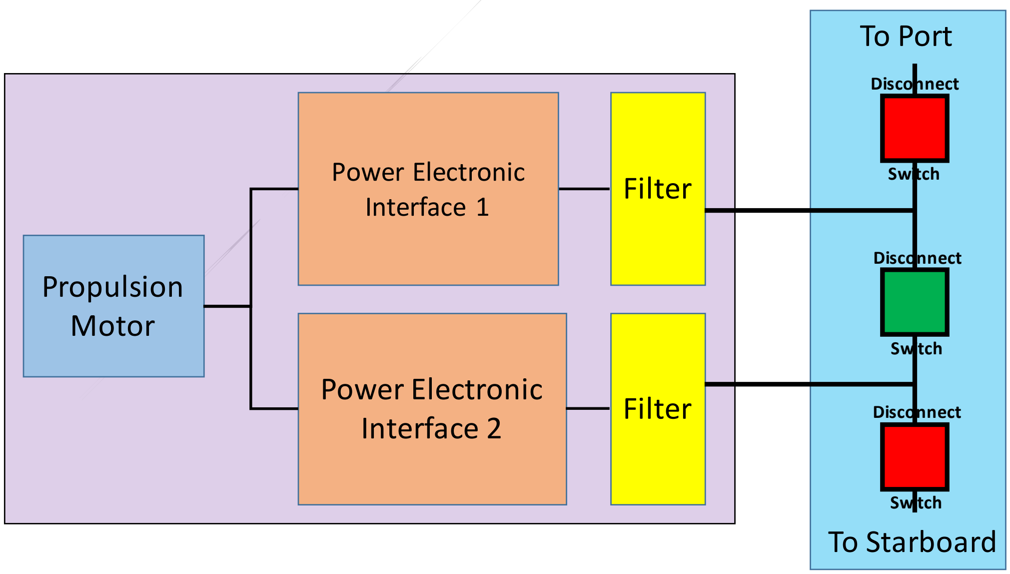

Figure 4 Block diagram of PMM

4.6 Energy Storage Module

The energy storage module is an important aspect in the SPS model and will be implemented at various locations in the SPS. Figure 5 shows the block diagram of generic ESM to be implemented. The energy storage system should support several key functions such as providing power to un-interruptible loads during power outages, support mission loads, provide system stability.

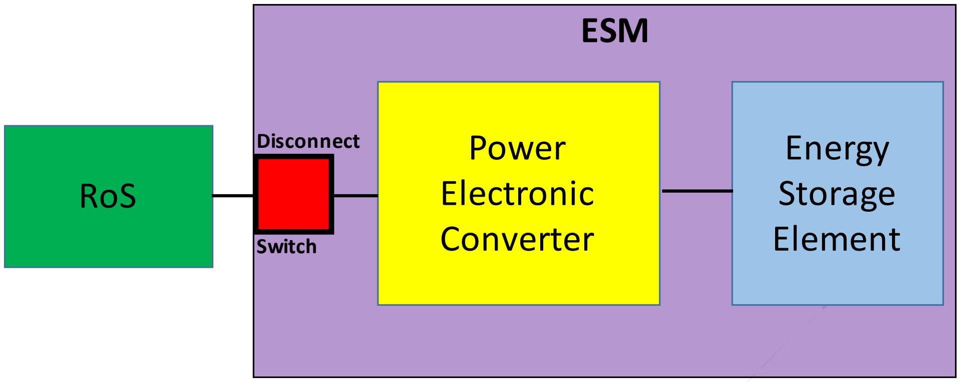

Figure 5 Block diagram of ESM

4.7 System Loads

Loads in the model are categorized into mission loads and zonal loads. Mission loads include armament and command and surveillance loads. Zonal loads are further categorized into hotel loads and cooling loads.

While mission loads will be modeled explicitly, zonal loads will be aggregated based on voltage class. Provisions will be made to categorize loads as vital, non-vital, and un-interruptible loads for load management.

Table 6 provides list of mission critical payload electrical power demand in MW at battle condition as provided in [6].

Table 6 Mission load electrical power demand in battle conditions [6]

Equipment	Maximum Electrical Power Demand (MW)
Armament	
EMRG	17
LASER	1.2
Active Denial System	0.6
VLS	0.98
Command and Surveillance	
Multi-Function Phased-Array Radar	5
Hull Mounted Sonar, Towed-Array Sonar	0.75
Total Ship Computing Environment (Integrated weapons, sensor, machinery and navigation control systems)	6
Helicopter/UAV	0
Small Boats/USV	0

Table 7 lists the aggregate hotel loads and is further categorized into vital and non-vital hotel loads by their rating. The loads could be modeled as single vital and non-vital loads with assigned power levels based on priority and mission conditions. Table 8 provides information regarding cooling equipment details and their power rating. Note that Zone 2 contains two chillers.

Table 7 Hotel load information

	Hotel Vital Load (MW)	Hotel Non-Vital Load (MW)
Zone 1	1.43	0.03
Zone 2	1.61	0.04
Zone 3	1.61	0.04
Zone 4	1.51	0.03

Table 8 Cooling equipment load information

	Chiller (MW)	Seawater pump (MW)	Chilled water pump (MW)
Zone 1	1.1	0.08	0.08
Zone 2	2.2	0.16	0.16
Zone 3	1.1	0.08	0.08
Zone 4	1.1	0.08	0.08

4.8 Electromagnetic Rail Gun

The EMRG model will consist of two PCM-1Bs each rated to 10 MW with a peak power rating of 20 MW. Energy storage on the order of 30 MJ will be incorporated into the EMRG model such that a 1000 round storage with a rep rate of 10 shots per minute can be accomplished. Figure 6 shows the block diagram of proposed EMRG system.

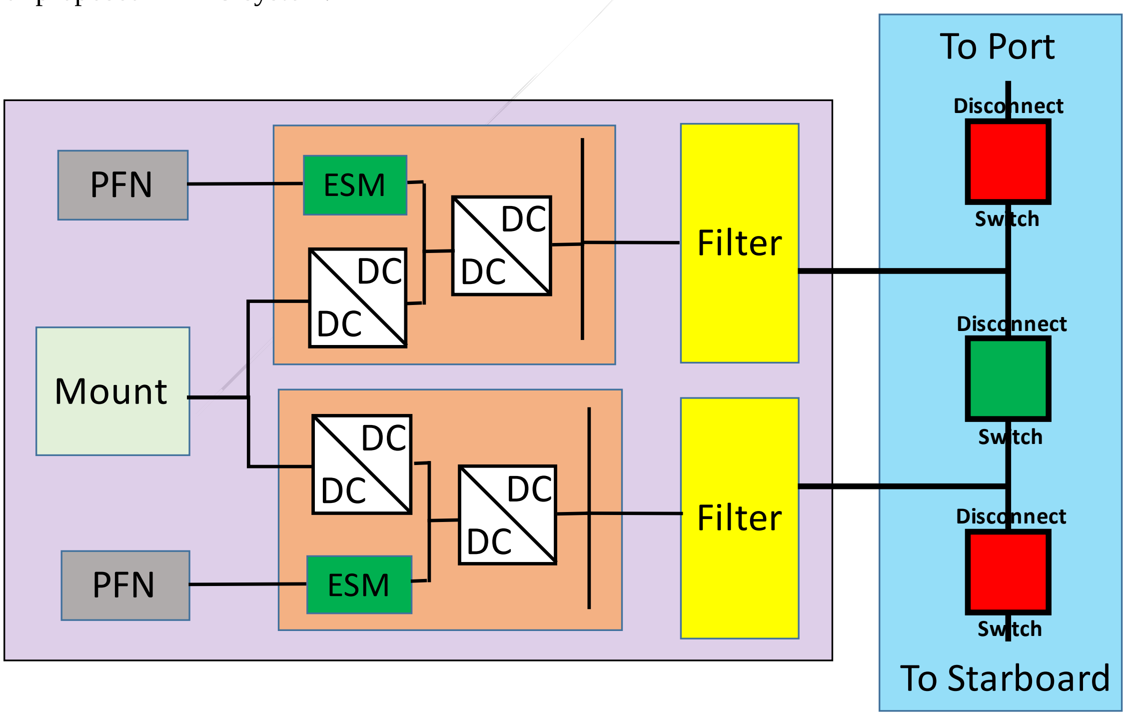

Figure 6 Block diagram of notional EMRG system

5 Requirements and Characteristics

The system requirements provided in this section aims to describe the desired characteristics from each module w.r.t implementation and operation. The requirements are classified into

- Functional: Intended purpose of the module/component and its scope of study
- Performance: capability of the module/component
- Interface: physical and control interfaces required to accomplish the purpose of the module/component. The interface characteristics provide a digital link to the control system to exchange data and information between the module and control system to enable the control of module. While certain desired power system characteristics can be controlled through the use of interface signals, certain characteristics are inherent to module implementation and can be set using the configurable parameters of the model
- States/mode: default and fault behavior of module/component. There can be multiple normal modes of operation for a specific module out of which one such mode should be selected as default

In order to distinguish different types of signals and interfaces described in the document, a nomenclature has been provided that aids in differentiating the various signals. Table 9 describes the nomenclature used for the section below to highlight signals and their types. Physical coupling signal refers to the interconnection of power system components to RoS such as rectifier output terminals connecting to a 12 kV MVDC distribution bus. Configurable inputs refer to model parameters that can be made configurable for certain desired power system characteristics and also aid in repeatability of experiments in a parametric space. The subsections below describe the requirements for the modules in the SPS model.

Table 9 Signal descriptions

Signal Type	Suffix	Interface style	Description
Physical Coupling	P		All physical coupling will be designated in black text with solid line connection
Control signal	CA-CZ		Control signals will be designated in blue text with long dash style connection
Monitoring signals	MA-MZ		Monitoring signals will be designated in red text with round dot style connection
Configurable parameters	YA-YZ		Configurable parameters will be designated in green text with dash dot style connection

The nomenclature provided here can be applied to any module/component in the system. Furthermore, a second character is included for signal description to identify sub-components within the module. Numbering of signals following ascending order for each sub-component for a module. Using control signal designated as 'CA1' and 'CB2' as an example, 'C' denotes the signal is of type control. 'A' and 'B' denote that control signal is of sub-component 'A' and 'B' while the numbers, '1' and '2', denote the first and second signal of each control sub-component.

5.1 DC disconnect Switch

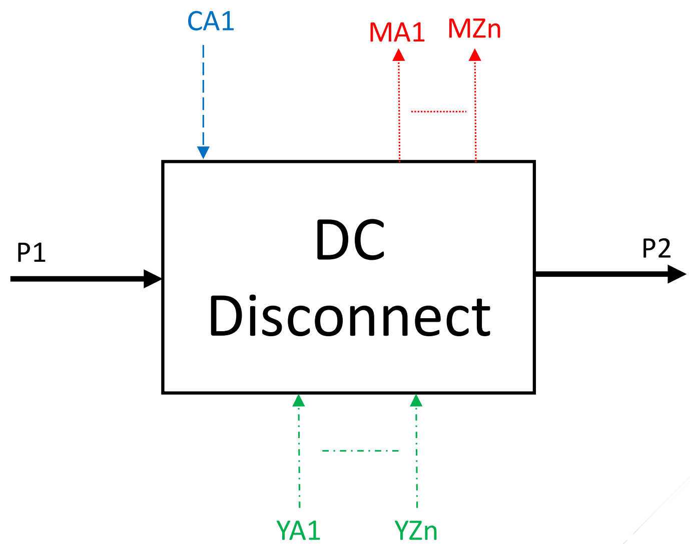

Figure 7 DC disconnect switch signal diagram

DC disconnect switches will be assumed as the primary type of interruption devices for 12 kV and 1 kV DC unless specified as a DC breaker. Figure 7 shows the signal block diagram of a DC disconnect switch depicting various signals in and out of the component. Table 10 provides information regarding the signal type, their functions, range and description of the signal.

5.1.1 Functional requirements

The DC disconnect switch is intended to provide isolation between various modules in the system for normal operation and for the ability to provide system reconfiguration. The switches in the system are not intended to be used for studies related to degradation of switch performance and internal breakdown/malfunction of switches.

5.1.2 Performance characteristics

NA

5.1.3 Interface requirements

Table 10 provides a list of signals for interface requirements pertaining to control and monitoring signals.

5.1.4 States and Modes of Operation

- The disconnect switch can only be in one of two states, either CLOSED or OPEN
- The default mode can be either one of the states based on desired system configuration
- If disconnect switch is requested to OPEN/CLOSE under non-zero voltage or current, the action will not result in change of status of the switch

Table 10 Disconnect switch signal descriptions

Signal Type	Name	Description	Unit	Range	Default	Remark
Physical Coupling	P1	Terminal 1	-	-	-	
	P2	Terminal 2	-	-	-	
Control Signals	CA1	Control word	Binary	0 - 1	-	0 = 'OPEN' 1 = 'CLOSED'
Monitoring Signals	MA1	Switch status	Binary	0 - 1	-	0 = 'OPEN' 1 = 'CLOSED'
	MB1	Terminal 1 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MB2	Terminal 2 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
Configurable parameter	YA1	Switch Closed resistance	Ω	0 - 2%	100	Zb = System impedance
	YB1	Switch operation time	μs	50 - 1000	200	Time to open/close switch after receiving status

5.2 Power Generation Module

Figure 8 shows the signal block diagram of a power generation module depicting various signals in and out of the component. PGM module shown above consists of a dual wound generator with two rectifiers (with incorporated filtering system), and AC breakers Table 11 provides information regarding the signal type, their functions, range and description of the signal.

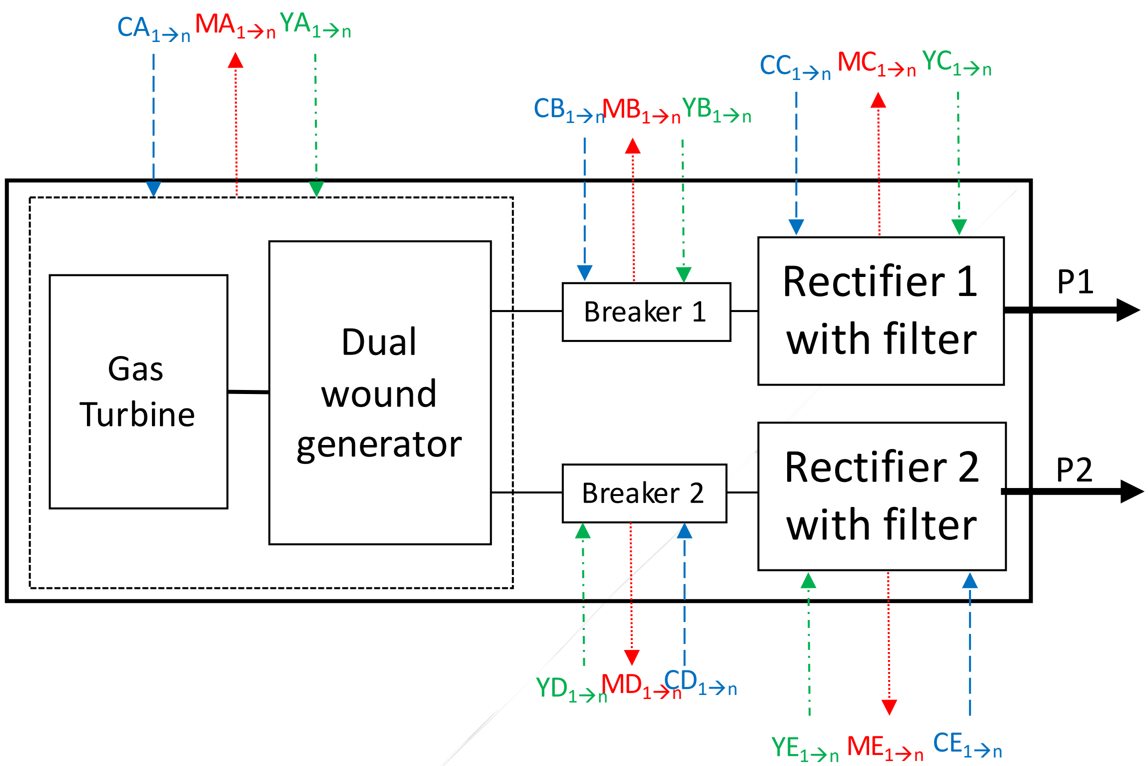

Figure 8 PGM signal diagram

5.2.1 PGM Functional requirements

The following functional requirements are applicable to all main and auxiliary PGMs:

- The PGM is required to provide power to the MVDC distribution at 12 kV while maintaining DC voltage interface standards
- The generators are required to be within operational limits for frequency and voltage
- Be available for system load sharing function
- Assist in fault management in the system in case of fault at MVDC level or at generator side AC
- Provide self-protection capability in case of malfunction of fault management system
- Although real time simulations are not advisable for long term SPS fuel efficiency cost studies, provisions in the model should be available to accommodate such studies

5.2.2 PGM Performance characteristics

The desired performance characteristics for PGMs are described below. Table 11 provides list of signal names that aid in accomplishing said performance characteristics.

- Generator real power ramp rate should be controllable by the user and can be set specific to a certain study
- Generator efficiency curve should be made accessible if necessary
- Provisions to set rectifier maximum power ramp rate
- Able to control current limiting capability of rectifiers
- Control (block) of firing pulses of rectifiers where modeled using switching converters
- The PGM module should be able to assist load sharing control with proper inputs and be able to accept the load share command request (voltage/current bias) based on the mode of operation. For any PGMs operating in voltage source mode (VSM), a voltage bias signal will be required and for any PGM operating in current source mode (CSM), a current bias signal is to be provided. In most case studies, the PGMs will be operated in VSM mode as opposed to CSM

5.2.3 PGM Interface requirements

Table 11 provides a list of signals for interface requirements pertaining to control and monitoring signals.

5.2.4 PGM States and Modes of Operation

- Under normal mode of operation, PGMs should be able to provide dual output for interfacing to MVDC system
- In the event of a fault on the 12 kV DC side, the PGM rectifiers should act accordingly and be able to block firing pulses if requested by the fault management system. Voltage and current levels requested by the fault management systems should also be adhered to
- In the event of a fault on the AC bus between generator and rectifiers, the PGM should power down and disconnect from RoS.
- Fault management in the system should be able to detect fault on the MVDC system in less than 2 ms. In case of undetected fault in the system or miss-operation of fault management system, PGM should go into self-protection mode and if observed current limitation is observed by PGM for more than 3 ms, it should ramp down voltage and current and disconnect from RoS

Table 11 PGM signal descriptions

Signal Type	Name	Description	Unit	Range	Default	Remark
Physical Coupling	P1	Output Terminal 1	-	-	-	
	P2	Output Terminal 2	-	-	-	
Control Signals	CA1	Generator Real power ramp rate	pu/sec	0.2 - 4	1	
	CB1	AC Breaker 1 Control word	Binary	0 - 1	NA	0 = 'OPEN' 1 = 'CLOSED'
	CC1	Rectifier 1 real power ramp rate	pu/sec	0.2 - 4	1	
	CC2	Rectifier 1 current limiting value	pu	1.05 - 2	1.1	Current limiting capability could also be influenced by design
	CC3	Rectifier 1 Block/de-block of firing pulse	Binary	0 - 1	-	0 = 'De-block' 1= ' Block'
	CC4	Rectifier 1 voltage bias signal	Pu	0 - 1	-	Aid in load sharing when in VSM
	CC5	Rectifier 1 current bias signal	Pu	0 - 1	-	Aid in load sharing when in CSM
	CD1	AC Breaker 2 Control word	Binary	0 - 1	NA	0 = 'OPEN' 1 = 'CLOSED'
	CE1	Rectifier 2 real power ramp rate	pu/sec	0.2 - 4	1	
	CE2	Rectifier 2 current limiting value	pu	1.05 - 2	1.1	Current limiting capability could also be influenced by design
	CE3	Rectifier 2 Block/de-block of firing pulse	Binary	0 - 1	-	0 = 'De-block' 1= ' Block'
	CE4	Rectifier 2 voltage bias signal	Pu	0 - 1	-	Aid in load sharing when in VSM
	CE5	Rectifier 2 current bias signal	Pu	0 - 1	-	Aid in load sharing when in CSM

Monitoring Signals	MA1	Generator terminal 1 voltage	kV	-	-	
	MA2	Generator terminal 1 current	kA	NA	NA	
	MA3	Generator terminal 1 frequency	Hz	60 - 400	-	
	MA4	Generator terminal 2 voltage	kV	NA	NA	
	MA5	Generator terminal 2 current	kA	NA	NA	
	MA6	Generator terminal 2 frequency	Hz	60 - 400	-	
	MB1	AC breaker 1 status	Binary	0 - 1	-	0 = 'OPEN' 1 = 'CLOSED'
	MB2	AC Breaker 1 current	kA	-	-	Iin = 'Positive' Iout = 'Negative'
	MC1	Rectifier 1 DC output voltage	kV	0 - 15	-	
	MC1	Rectifier 1 DC output current	kA	0 – 3	-	
	MD1	AC breaker 2 status	Binary	0 - 1	-	0 = 'OPEN' 1 = 'CLOSED'
	MD2	AC Breaker 2 current	kA	-	-	Iin = 'Positive' Iout = 'Negative'
	ME1	Rectifier 2 DC output voltage	kV	0 - 15	-	
	ME1	Rectifier 2 DC output current	kA	0 – 4	-	
Configurable parameter	YA1	Generator Efficiency Curve	-	-		Fuel efficiency curve of generator
	YB1	Breaker 1 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YB2	Breaker 1 operation time	μs	500-10000	2000	Time to open/close breaker after receiving status

	YB3	Breaker 1 self-protect time threshold	µs	500-10000	4000	Time to open/close breaker after receiving status
	YC1	Rectifier 1 efficiency curve	-	-	-	
	YD1	Breaker 2 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YD2	Breaker 2 operation time	µs	500-10000	2000	Time to open/close breaker after receiving status
	YD3	Breaker 2 self-protect time threshold	µs	500-10000	4000	Time to open/close breaker after receiving status
	YE1	Rectifier 2 efficiency curve	-	-	-	

5.3 Power Conversion Module

Figure 9 shows the signal block diagram of a power conversion module depicting various signals in and out of the component. PCM-1A shown below consists of several converters that serve loads at two different voltages. The input DC-DC converter converters 12 kV MVDC power to 1 kV DC which forms the primary distribution voltage for loads in PCM-1A. Certain mission loads and large high power DC loads will be serviced through the 1 kV DC MW class load bus. Another 1 kV DC output feeds the integrated power node center that serves vital un-interruptible loads. A DC-AC converter serves as the interface to AC load center (ACLC) that serves zonal loads in the system at 450 V, 60 Hz AC.

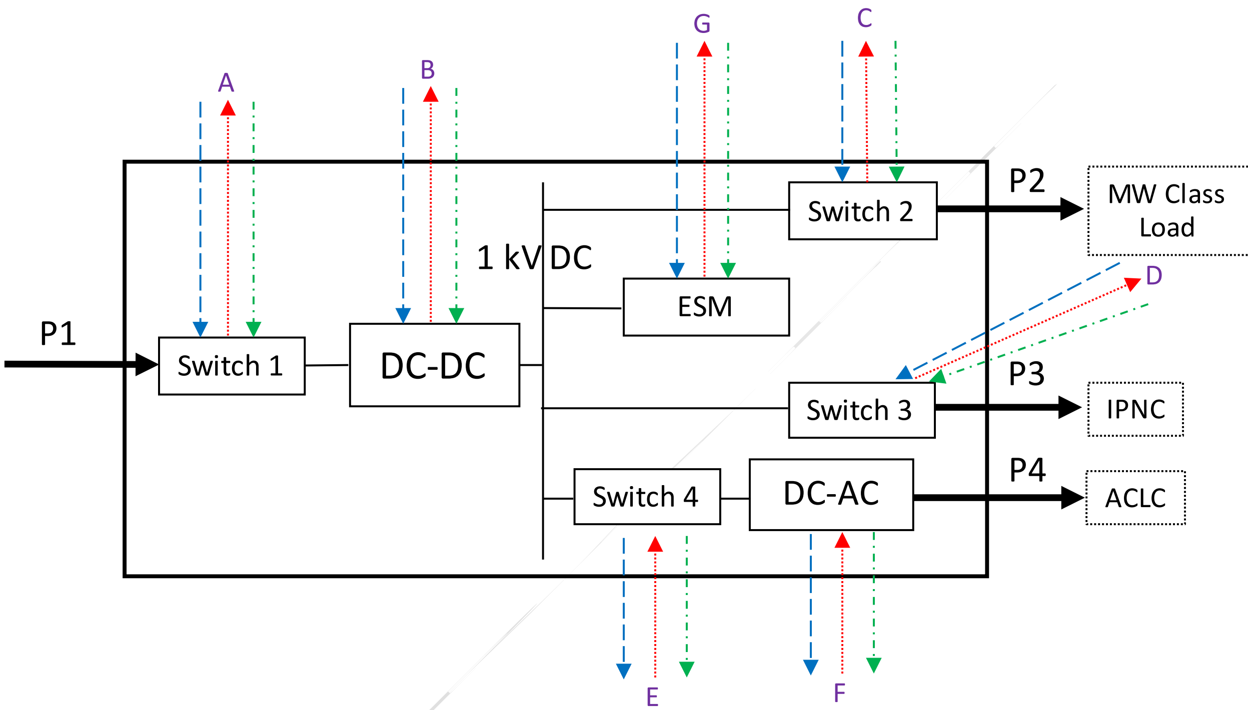

Figure 9 PCM-1A signal diagram

5.3.1 PCM-1A Functional requirements

The following functional requirements are applicable to PCM-1A:

- PCM-1A is required to service all loads connected through it while maintain AC and DC voltage interface standards
- Provide self-protection capability in case of malfunction of fault management system
- Optional energy storage module if present in the system should be set such that default mode of operation is to improve system stability by reflecting the PCM-1A load on 12 kV DC side observable as constant impedance type
- Support system level power and energy management by providing appropriate interfaces

5.3.2 PCM-1A Performance characteristics

- PCM-1A should be able to provide current limiting functionality for each converters modeled in the module
- Converters within PCM-1A should be able to support adjustable power ramp rate

- Efficiency modeling of converters should be supported
- Disconnect switches and breakers within PCM-1A should be able to support the fault management system. In case of non/miss-operation of FMS, self-protection of PCM-1A should be required

5.3.3 PCM-1A Interface requirements

Table 12 provides a list of signals for interface requirements pertaining to control and monitoring signals.

5.3.4 PCM-1A States and Modes of Operation

- Under normal mode of operation of PCM-1A, all loads will be served as requested by PCM-1A
- Self-protection modes of PCM-1A is described below:
  - For a fault on 1 kV DC bus of PCM-1A, all disconnect switches within PCM-1A open
  - For a fault on 450 V AC bus of ACLC, appropriate switches open to isolate fault
  - For a fault on 1 kV DC bus supplying MW class load, appropriate switches open to isolate fault
  - For a fault on 1 kV DC bus supplying IPNC, appropriate switches open to isolate fault

Table 12 PCM-1A signal descriptions

Signal Type	Name	Description	Unit	Range	Default	Remark
Physical Coupling	P1	12 kV DC input	-	-	-	
	P2	1 kV DC input to MW class load	-	-	-	
	P3	1 kV DC input to IPNC	-	-	-	
	P4	450 V AC input to ACLC loads	-	-	-	
Control Signals	CA1	Switch 1 control word	Binary	0 – 1	1	0 = ‘OPEN’ 1 = ‘CLOSED’
	CB1	DC-DC converter current limit value	pu	1.05 - 2	1.1	Also influenced by converter type and design
	CB2	Block/De-Block of firing pulses	Binary	0 – 1	0	0 = ‘Block’ 1 = ‘De-Block’
	CC1	Switch 2 control word	Binary	0 – 1	1	0 = ‘OPEN’ 1 = ‘CLOSED’
	CD1	Switch 3 control word	Binary	0 – 1	1	0 = ‘OPEN’ 1 = ‘CLOSED’
	CE1	Switch 4 control word	Binary	0 – 1	1	0 = ‘OPEN’ 1 = ‘CLOSED’
	CF1	DC-AC converter current limit value	pu	1.05 - 2	1.1	Also influenced by converter type and design
	CF2	Block/De-Block of firing pulses	Binary	0 – 1	0	0 = ‘Block’ 1 = ‘De-Block’
	CG1	ESM charge/discharge enable	Binary	0 – 1	-	0 = ‘Disable’ 1= ‘Enable’
	CG2	ESM Charge/discharge command	kVA	TBD	TBD	‘+ value’ = ‘Charge’ ‘- value’ = ‘Discharge’
Monitoring Signals	MA1	Switch 1 status	Binary	0-1	-	0 = ‘OPEN’ 1 = ‘CLOSED’

	MA2	Switch 1 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MB1	DC-DC converter output voltage	kV	1	1	
	MB2	DC-DC converter 1 kV DC side current	kA	-	-	
	MC1	Switch 2 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	MC2	Switch 2 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MD1	Switch 3 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	MD2	Switch 3 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	ME1	Switch 4 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	ME2	Switch 4 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MF1	DC-AC converter output voltage	kV	0.450	0.450	
	MF2	DC-AC converter 1 kV AC side current	kA	-	-	
	MG1	ESM State of Charge	-	0 – 1		0 = 'Fully discharged' 1 = ' Fully Charged'
	MG2	ESM full charge/discharge cycle count	-	-	-	
	MG3	ESM partial charge/discharge count				
Configurable parameter	YA1	Switch 1 Closed resistance	Ω	0-2%	100	Zb = System impedance

	YA2	Switch 1 operation time	µs	50-1000	200	Time to open/close switch after receiving status
	YB1	DC-DC converter efficiency curve	-	-	-	
	YC1	Switch 1 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YC2	Switch 2 operation time	µs	50-1000	200	Time to open/close switch after receiving status
	YD1	Switch 1 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YD2	Switch 3 operation time	µs	50-1000	200	Time to open/close switch after receiving status
	YE1	Switch 1 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YE2	Switch 4 operation time	µs	50-1000	200	Time to open/close switch after receiving status
	YF1	DC-aC converter efficiency curve	-	-	-	
	YG1	ESM full charge/discharge cycle count limit set	-	-	-	
	YG2	ESM partial charge/discharge count limit set	-	-	-	

5.4 Integrated Power Node Center

Figure 10 shows the signal block diagram of an integrated power node center (IPNC) with various signals in and out of the component. The goal of PNC in the SPS is to provide power to vital un-interruptible (UI) loads and special loads. An energy storage module exists within IPNC to serve UI loads in case of power interruption before system reconfiguration can happen.

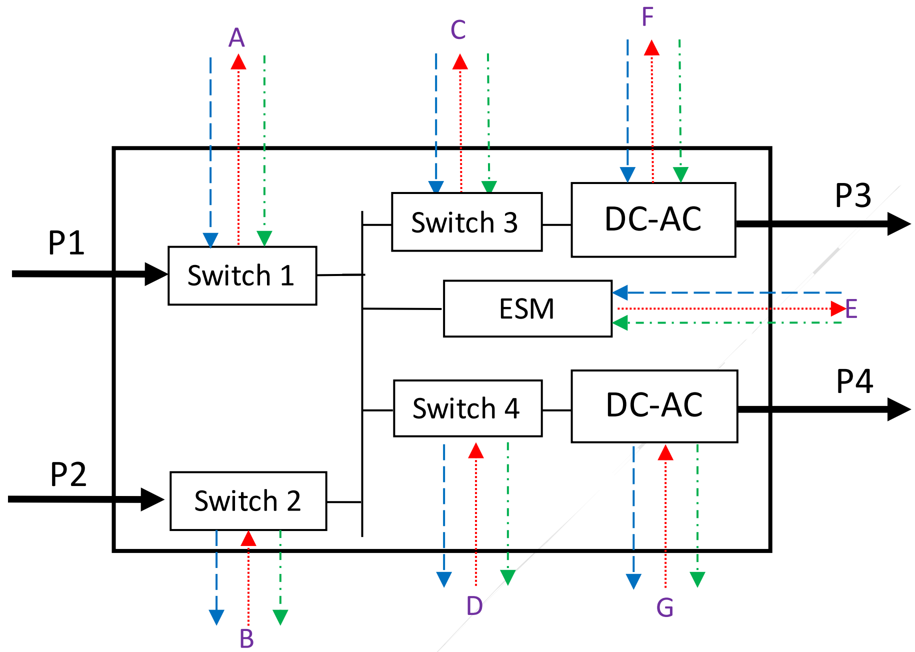

Figure 10 IPNC signal diagram

5.4.1 IPNC Functional requirements

The following functional requirements are applicable to IPNC:

- IPNC is required to service all loads connected through it while maintain AC and DC voltage interface standards
- IPNC should serve all UI loads even under power interruption from PCM-1A
- ESM should be able to support UI loads for the duration of reconfiguration of system

5.4.2 IPNC Performance characteristics

- IPNC should be able to provide current limiting functionality for each converters modeled in the module
- Converters within IPNC should be able to support adjustable power ramp rate
- Efficiency modeling of converters should be supported
- Disconnect switches and breakers within IPNC should be able to support the fault management system. In case of non/miss-operation of FMS, self-protection of IPNC should be required

5.4.3 IPNC Interface requirements

Table 13 provides a list of signals for interface requirements pertaining to control and monitoring signals.

5.4.4 IPNC States and Modes of Operation

- Under normal mode of operation of IPNC, loads within IPNC should be served by in-zone PCM-1A with energy storage in standy by state
- If 1 kV DC bus from in-zone PCM-1A is unavailable, ESM should support the vital UI loads until reconfiguration occurs thereby which neighboring zone IPNC supplies power to UI loads
- If any non-vital interruptible loads, are modeled in IPNC, load shedding must take place such that only UI loads are served through ESM
- Self-protection modes of IPNC is described below:
    - For a fault on 1 kV DC bus of IPNC, all disconnect switches within IPNC open
    - For a fault on 60 Hz, UI load, switch connecting the said load opens thereby isolating the fault
    - For a fault on 400 Hz load, switch connecting the said load opens thereby isolating the fault

Table 13 IPNC signal descriptions

Signal Type	Name	Description	Unit	Range	Default	Remark
Physical Coupling	P1	1 kV DC input from in-zone PCM-1A	-	-	-	Normal operation feed live and corresponding switch closed
	P2	1 kV DC input from neighboring zone IPNC	-	-	-	Only used in case of power interruption of in-zone PCM-1A. Corresponding switches normally open
	P3	450 V AC, 60 Hz UI load input	-	-	-	
	P4	450 V AC, 400 Hz UI load input	-	-	-	
Control Signals	CA1	Switch 1 control word	Binary	0 – 1	1	0 = 'OPEN' 1 = 'CLOSED'
	CB1	Switch 2 control word	Binary	0 – 1	0	0 = 'OPEN' 1 = 'CLOSED'
	CC1	Switch 3 control word	Binary	0 – 1	1	0 = 'OPEN' 1 = 'CLOSED'
	CD1	Switch 4 control word	Binary	0 – 1	1	0 = 'OPEN' 1 = 'CLOSED'
	CE1	ESM charge/discharge enable	Binary	0 – 1	-	0 = 'Disable' 1= 'Enable'
	CE2	ESM Charge/discharge command	kVA	TBD	TBD	'+ value' = 'Charge' '- value' = 'Discharge'
	CF1	DC-AC converter current limit value	pu	1.05 - 2	1.1	Also influenced by converter type and design
	CF2	Block/De-Block of firing pulses	Binary	0 – 1	0	0 = 'Block' 1 = 'De-Block'
	CG1	DC-AC converter current limit value	pu	1.05 - 2	1.1	Also influenced by converter type and design
	CG2	Block/De-Block of firing pulses	Binary	0 – 1	0	0 = 'Block' 1 = 'De-Block'

Monitoring Signals	MA1	Switch 1 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	MA2	Switch 1 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MB1	Switch 2 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	MB2	Switch 2 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MC1	Switch 3 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	MC2	Switch 3 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	MD1	Switch 4 status	Binary	0-1	-	0 = 'OPEN' 1 = 'CLOSED'
	MD2	Switch 4 current	kA	NA	NA	Iin = 'Positive' Iout = 'Negative'
	ME1	ESM State of Charge	-	0 – 1		0 = 'Fully discharged' 1 = ' Fully Charged'
	ME2	ESM full charge/discharge cycle count	-	-	-	
	ME3	ESM partial charge/discharge count	-	-	-	
	MF1	DC-AC converter output voltage	kV	1	1	
	MF2	DC-DC converter 1 kV DC side current	kA	-	-	
	MG1	DC-AC converter output voltage	kV	1	1	
	MG2	DC-DC converter 1 kV DC side current	kA	-	-	
Configurable parameter	YA1	Switch 1 Closed resistance	Ω	0-2%	100	Zb = System impedance

	YA2	Switch 1 operation time	μs	50-1000	200	Time to open/close switch after receiving status
	YB1	Switch 2 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YB2	Switch 2 operation time	μs	50-1000	200	Time to open/close switch after receiving status
	YC1	Switch 3 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YC2	Switch 3 operation time	μs	50-1000	200	Time to open/close switch after receiving status
	YD1	Switch 4 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YD2	Switch 4 operation time	μs	50-1000	200	Time to open/close switch after receiving status
	YE1	ESM full charge/discharge cycle count limit set	-	-	-	
	YE2	ESM partial charge/discharge count limit set	-	-	-	
	YF1	DC-AC converter efficiency curve	-	-	-	
	YG1	DC-AC converter efficiency curve	-	-	-	

5.5 Energy Storage Module

Figure 11 shows the signal block diagram of an energy storage module. ESM should be able to serve several functions within the SPS model such as power UI loads, mission loads, aid in power and energy management. Specific function of ESM can be dictated by required control system.

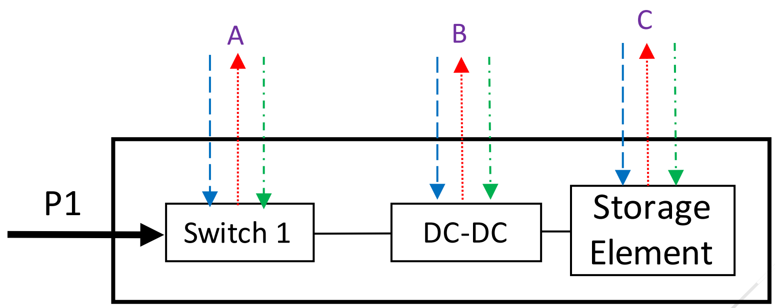

Figure 11 ESM signal diagram

5.5.1 ESM Functional requirements

The following functional requirements are applicable to ESM:

- ESM is required to support SPS in case of power interruption, serves mission loads that require pulsed power characteristics
- Although charge/discharge cycle count can be monitored, degradation studies of ESM are not applicable to this model

5.5.2 ESM Performance characteristics

- ESM should be able to provide State of Charge (SoC) information at all times
- ESM should be able to provide adjustable power ramp rate to satisfy loads as required

5.5.3 ESM Interface requirements

Table 14 provides a list of signals for interface requirements pertaining to control and monitoring signals.

5.5.4 ESM States and Modes of Operation

- ESM should be either be in standby mode or in operation based on the intended use
- During a fault on the internal ESM bus, the appropriate disconnect switch should operate to isolate the fault

Table 14 IPNC signal descriptions

Signal Type	Name	Description	Unit	Range	Default	Remark
Physical Coupling	P1	1 kV DC output from ESM to RoS	-	-	-	
Control Signals	CA1	Switch 1 control word	Binary	0 – 1	1	0 = ‘OPEN’ 1 = ‘CLOSED’
	CB1	DC-DC converter current limit value	pu	1.05 - 2	1.1	Also influenced by converter type and design
	CB2	Block/De-Block of firing pulses	Binary	0 – 1	0	0 = ‘Block’ 1 = ‘De-Block’
	CC1	ESM charge/discharge enable	Binary	0 – 1	-	0 = ‘Disable’ 1= ‘Enable’
	CC2	ESM Charge/discharge command	kVA	TBD	TBD	‘+ value’ = ‘Charge’ ‘- value’ = ‘Discharge’
Monitoring Signals	MA1	Switch 1 status	Binary	0-1	-	0 = ‘OPEN’ 1 = ‘CLOSED’
	MA2	Switch 1 current	kA	NA	NA	Iin = ‘Positive’ Iout = ‘Negative’
	MA3	Switch 1 voltage	kV	-	-	
	MB1	DC-DC converter output voltage	kV	1	1	
	MB2	DC-DC converter output current	kA	-	-	
	MC1	ESM State of Charge	-	0 – 1		0 = ‘Fully discharged’ 1 = ‘ Fully Charged’
	MC2	ESM full charge/discharge cycle count	-	-	-	
	MC3	ESM partial charge/discharge count	-	-	-	
Configurable parameter	YA1	Switch 1 Closed resistance	Ω	0-2%	100	Zb = System impedance
	YA2	Switch 1 operation time	μs	50-1000	200	Time to open/close switch after receiving status

	YB1	DC-AC converter efficiency curve	-	-	-	
	YC1	ESM full charge/discharge cycle count limit set	-	-	-	
	YC2	ESM partial charge/discharge count limit set	-	-	-	

5.6 Propulsion Motor Module (TBD)

5.7 Electromagnetic Rail Gun (TBD)

5.8 Active Denial Service (TBD)

5.9 VLS (TBD)

5.10 LASER (TBD)

5.11 SONAR (TBD)

6 Model Implementation API

This section describes …

7 Test Cases

The test cases to be described in this document will aid in verification and comparison of SPS model implementation across various simulation platforms. The test cases will comprise of static, dynamic, and fault scenarios. Long term quasi-static scenarios are not preferred to be implemented on real time platforms. Table 15 provides example static mission conditions; Table 16 provides example dynamic scenario as provided in [6]. Data pertaining to power quality, state of ESMs, power flow should be recorded in order to aid in cross validation of simulation models.

Table 15 Static scenarios

Equipment	Peacetime Cruise	Sprint to Station	Battle	Anchor
Active Denial System	off	off	high	low
Laser	off	medium	high	off
Railgun	off	off	high	off
Vertical Launch System	off	off	high	off
Integrated Topside	medium	medium	high	medium
Radar	medium	high	high	low
Sonar	off	off	on	off
Towed-Array Sonar	off	off	off	off
Aggregated AC Non-vital Loads	high	medium	medium	high
Aggregated DC Vital Loads	medium	high	high	medium
Ship Speed	15 kts	31 kts	8 kts	0 kts

Table 16 Dynamic scenario example

<table>
<tr><th>Equipment</th><th>Initial state</th><th>Sequence of events</th></tr>
<tr><td>Active Denial System</td><td>standby</td><td rowspan="11">• Charge railgun (5 sec)
• Fire railgun (1 sec)
• Charge railgun (5 sec)
• Fire railgun (1 sec)
• Increase speed to 25 kts
• Fire laser (15 sec)</td></tr>
<tr><td>Laser</td><td>standby</td></tr>
<tr><td>Railgun</td><td>standby</td></tr>
<tr><td>Vertical Launch System</td><td>standby</td></tr>
<tr><td>Integrated Topside</td><td>high</td></tr>
<tr><td>Radar</td><td>high</td></tr>
<tr><td>Sonar</td><td>on</td></tr>
<tr><td>Towed-Array Sonar</td><td>off</td></tr>
<tr><td>Aggregated AC Non-vital Loads</td><td>medium</td></tr>
<tr><td>Aggregated DC Vital Loads</td><td>high</td></tr>
<tr><td>Ship Speed</td><td>8 kts</td></tr>
</table>

8 References

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Appendix A: Cable Data

Table 17 SPS model MVDC cable information

Cable No	Description	Length (m)
CS 1	Port side Zone 1 to Zone 2 switchboard	57.13
CS 2	Port side Zone 2 to Zone 3 switchboard	38
CS 3	Port side Zone 3 to Zone 4 switchboard	34.16
CS 4	Port to Starboard cross connection Zone 4	NA
CS 5	Starboard side Zone 1 to Zone 2 switchboard	15.11
CS 6	Starboard side Zone 2 to Zone 3 switchboard	43.33
CS 7	Starboard side Zone 3 to Zone 4 switchboard	50.65
CS 8	Port to Starboard cross connection Zone 1	NA
CS 9	EDG to Port Zone 1 connection	19.72
CS 10	EDG to Starboard Zone 1 connection	9.46
CS 11	MPGM 1 to Zone 2 Port connection	3.72
CS 12	MPGM 1 to Starboard Zone 2 connection	42.68
CS 13	MPGM 2 to Zone 2 Port connection	17.65
CS 14	MPGM 2 to Starboard Zone 2 connection	27.21
CS 15	MPGM 3 to Zone 3 Port connection	13.3
CS 16	MPGM 3 to Starboard Zone 3 connection	24.95
CS 17	APGM 1 to Zone 3 Port connection	29.63
CS 18	APGM 1 to Starboard Zone 3 connection	7.54
CS 19	APGM 2 to Zone 4 Port connection	4.89
CS 20	APGM 2 to Starboard Zone 4 connection	2.38
CS 21	Zone 1 PCM-1A to Starboard connection	3.77
CS 22	Zone 2 PCM-1A to Port connection	4.02
CS 23	Zone 3 PCM-1A to Starboard connection	2.57
CS 24	Zone 4 PCM-1A to Port connection	8.01
CS 25	Starboard PMM to Zone 2 Port connection	20.39
CS 26	Starboard PMM to Zone 2 Starboard connection	47.08
CS 27	Port PMM to Zone 3 Port connection	9.28
CS 28	Port PMM to Zone 3 Starboard connection	28.86
CS 29	IPNC to VLS Zone 1	9.19
CS 30	IPNC to ADS Starboard Zone 2	35.89
CS 31	Port Integrated topside to Port Zone 2 connection	19.43
CS 32	Port Integrated topside to Starboard Zone 2 connection	36.37
CS 33	Starboard Integrated topside to Port Zone 2 connection	31.07
CS 34	Starboard Integrated topside to Starboard Zone 2 connection	48.01
CS 35	RADAR to Port Zone 2 connection	21.75
CS 36	RADAR to Starboard Zone 2 connection	27.14
CS 37	EMRG to Port Zone 2 connection	27.04
CS 38	EMRG to Starboard Zone 2 connection	11.75
CS 39	RADAR to Port Zone 3 connection	22.32
CS 40	RADAR to Starboard Zone 3 connection	15.54
CS 41	Zone 4 IPNC to LASER connection	26.59

Appendix B: PGM data

Table 18. Parameters for Notional Synchronous Machine

Parameter	Description	Default Value	Source
S_r	Rated apparent power (MVA).	37.5	
V_r	Rated voltage (line-line, RMS) (kV).	4.16	
f_r	Rated frequency (Hz).	240	
R_s	Stator resistance (pu).	2.0e-3	
L_l	Stator leakage reactance (pu)	0.15	
L_{md}	D-axis unsaturated magnetizing inductance (pu)	1.5	
L_{mq}	Q-axis unsaturated magnetizing inductance (pu)	1.5	
R_{fd}	Field resistance (pu)	1.0e-3	
L_{lfd}	Field leakage inductance (pu)	0.09	
R_{kd}	D-axis damper resistance (pu)	0.01	
L_{lkd}	D-axis damper leakage inductance (pu)	0.045	
R_{kq1}	Q-axis damper resistance (pu)	0.01	
L_{lkq1}	Q-axis damper leakage inductance (pu)	0.045	
R_{kq2}	Q-axis damper resistance (2nd damper winding) (pu)	0.01	
L_{lkq2}	Q-axis damper leakage inductance (2nd damper winding) (pu)	0.045	
H	Inertia constant (MW*s/MVA)	6	
F	Friction factor (pu).	0	
p	Pole pairs	4	
$V_{sat}(I_{fd})$	Saturation curve.		

Table 19. Parameters for Notional Single-Shaft Gas Turbine Model

Parameter	Description	Default Value	Source
a	Valve positioner constant.	1	
b	Valve positioner constant.	0.05	
c	Valve positioner constant.	1	
k_{flma}	No-load fuel parameter.	0.2	
k_{flmb}	No-load fuel parameter (1- k_{flma}).	0.8	
$k_{\alpha\text{-limit}}$	Acceleration limit (pu/s).	0.01	
$k_{i\text{-}\alpha}$	Acceleration control integral gain.	100	
$L_{lower\text{-}Limit1}$	Lower limit for limit block “Limit 1” (fuel limit).	-0.1	

$L_{upper-Limit1}$	Upper limit for limit block "Limit 1" (fuel limit).	1	
T_c	Combustor delay time (s).	0.01	
W	Speed governor constant.	25	
X	Speed governor constant.	0	
Y	Speed governor constant.	0.05	
Z	Speed governor constant.	1	
τ_{FS}	Fuel system time constant (s).	0.4	
τ_{CP}	Compressor discharge volume time constant (s).	0.2	

Table 20. Parameters for Simplified IEEE Type AC8B Exciter

Parameter	Description	Default Value	Source
k_A	Voltage regulator gain.	1	
k_{DR}	PID controller derivative gain.	0	
k_{IR}	PID controller integral gain.	0.08	
k_E		1	
k_{EF1}	Saturation function coefficient.	1.0119	
k_{EF2}	Saturation function coefficient.	0.0875	
k_{PR}	PID controller proportional gain.	200	
T_A	Voltage regulator time constant (s).	0.0001	
T_e	Integration time constant (s).	1	
T_{DR}	Filter time constant for PID controller derivative branch (s).	0.001	
V_{EMAX}	Field winding excitation voltage upper limit.	∞	
V_{EMIN}	Field winding excitation voltage lower limit.	0	
V_{RMAX}	Voltage regulator upper limit.	5	
V_{RMIN}	Voltage regulator lower limit.	0	