Documentation for a Notional Two Zone Medium Voltage DC Shipboard Power System Model implemented on the RTDS™

Version 1.0

Submitted to:
The Office of Naval Research

ONR GRANT NO # N00014-14-1-0198

Submitted by:
Harsha Ravindra, Mark Stanovich, Mischa Steurer
Center for Advanced Power Systems
Florida State University

December 2016

2000 Levy Avenue, Suite 140 | Tallahassee, FL 32310 | www.esrdc.com

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.

Table of Contents

List of Figures

LIST OF TABLES

Terminology and Acronyms

FSU	Florida State University
CAPS	Center for Advanced Power Systems
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

1 EXECUTIVE SUMMARY

The MVDC architecture with 12 kV DC distribution represents a shift from traditional 60 Hz AC shipboard power distribution system and has the potential to provide superior power density, power quality while being affordable. The report here in provides information on ‘the two zone MVDC shipboard power system model’.

The main contribution of this report is the development of shipboard power system model in digital real-time simulator (DRTS), RTDS^{TM}. The model is based on the zonal integrated power distribution system architecture proposed by N. Doerry in [1]. The purpose of the model described in this report is to aid the investigation of fault management (fault identification, localization and recovery) in MVDC shipboard power systems.

The individual modules implemented for model will allow the user to comprehensively test different methods of fault detection algorithms while providing useful insight into behavior of different modules. The two model versions described herein feature two distinctly different types of power generation modules (PGMs): a modular multi-level converter (MMC) based PGM and a thyristor controlled rectifier based PGM. Technical data for various modules modeled in the report have been provided along with simulation results depicting the performance of the two versions of the models.

The shipboard power system model provided in this report acts as a first pass for simulation assisted studies involving fault management in MVDC systems. The outcomes from the simulation could be useful in understanding and paving a path for controller hardware-in-the-loop (CHIL) and power hardware-in-the-loop (PHIL) testing.

2 INTRODUCTION

This document describes the baseline 'Notional Two Zone Medium Voltage DC Shipboard Power System' model developed at the Center for Advanced Power Systems (CAPS), Florida State University (FSU) under the Electric Ship Research and Development Consortium (ESRDC) funding from ONR. This model is derived from the zonal integrated power distribution system proposed by Doerry and Amy [2].

The 'Two Zone Notional MVDC Ship Power System Model' is modeled on one rack of RTDSTM. The MMC based PGM version of SPS model runs in real time with a 50 µs time-step. The TCR based PGM version of SPS model runs in non-real time with a 1 µs time-step. The shipboard power system (SPS) is rated for 72 MW with a 12 kV DC distribution system. Fig. 1 illustrates the topology of the notional two zone MVDC SPS, and Fig. 2 provides a legend for the components in the topology illustration. The power system model is comprised of two zones, Zone 1 and Zone 2. Zone 1 contains one power generation module (PGM) and a power conversion module (PCM). Zone 2 contains one power generation module PGM, one PCM and a propulsion motor module (PMM). Two different models were developed based on two different types of PGMs. One version of this model contains a modular multilevel converter (MMC) based PGM, the other a thyristor controlled rectifier (TCR) based PGM. Table 1 outlines the salient features of the power system models.

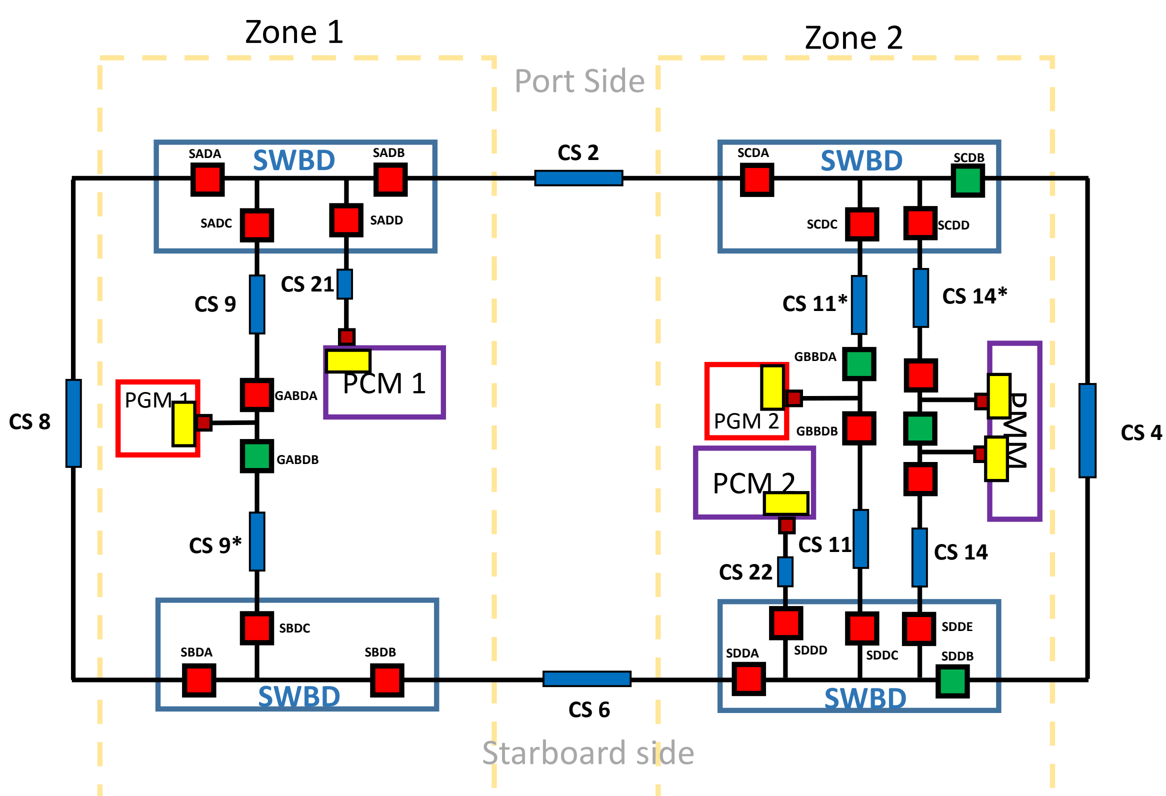

Fig. 1: Topology of notional two zone MVDC SPS

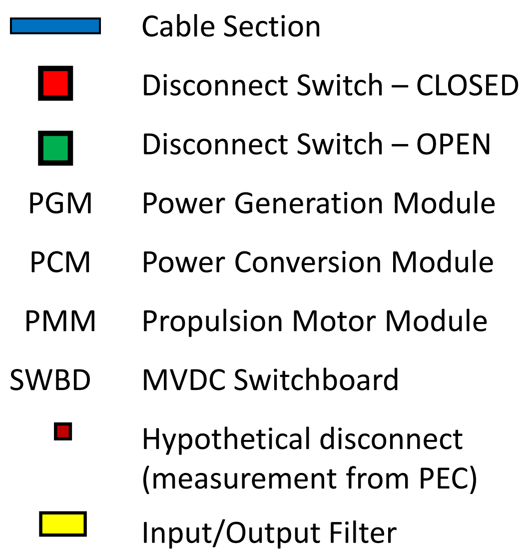

Fig. 2 Description of components in SPS model

Each zone has port and starboard side switchboards. The two zones are electrically connected on port and starboard side through cable sections CS 2 and CS 6 respectively. Port and starboard DC distribution busses can be connected through CS 8 and CS 4. In normal operation, the two zones are connected through CS 2 and CS 6 and either port or starboard DC distribution busses (through CS 4 or CS 8) are connected.

Table 1: Salient Features of notional two zone MVDC SPS model

Feature	**Common to both MVDC Architecture**	**MMC based PGM**	**TCR based PGM**
Generation Power	72 MW		
Distribution Voltage	12 kV		
Distribution Type	Radial (Optional Ring)		
PGM Generator	Synchronous wound-field cylindrical rotor		
PGM Generator Prime Movers	Gas Turbines 2 X 36 MW	2 X 36 MVA	2 X 45 MVA
PGM Rectifier		MMC	TCR
PMM	Resistive load 36 MW (2X18 MW)		
PCMs	Resistive load 2 X 10 MW		
Switch gear	DC disconnect switches		

3 SYSTEM MODELS

The section below describes the models used for each modules

3.1 MVDC distribution system

Fig. 1 also shows the zonal ring (two zone) topology of the MVDC distribution system. Table 2 provides information regarding cable names, corresponding connection ends, lengths and impedances. The cable impedance data is derived from data in [3].

Table 2. Cable Data

Cable Section #	Cable Routing	Length (m)	Resistance (in mΩ)	Inductance (in µH)
CS 2	Port Side Zone 1 to Zone 2	29.5	0.21	3.47
CS 4	Port to Starboard interconnect for Zone 2	29.5	0.21	3.47
CS 6	Starboard Side Zone 1 to Zone 2	29.5	0.21	3.47
CS 8	Port to Starboard interconnect for Zone 1	41.75	0.30	4.91
CS 9	Zone 1 Port to PGM 1	22.4	0.16	2.63
CS 9*	Zone 1 Starboard to PGM 1	22.4	0.16	2.63
CS 11	Zone 2 Starboard to PGM 2	45.2	0.32	5.32
CS 11*	Zone 2 Port to PGM 2	45.2	0.32	5.32
CS 14	Zone 2 Port to PMM	29.1	0.21	3.42
CS 14*	Zone 2 Starboard to PMM	29.1	0.21	3.42
CS 21	Zone 1 Port to PCM 1	18.2	0.26	4.30
CS 22	Zone 2 Starboard to PCM 2	20.1	0.28	4.73

The cable sections are modeled using the RTDS™ component 'RLBKR' [4]. The component model is a resistance-inductance section in series with the breaker. The reason for choosing the RLBKR is that it consumes fewer nodes (i.e., computation resources) than modeling the same characteristic with two components. The 'RLBKR' component is used to model the disconnect switches.

3.2 Disconnect switch

In addition to the RLBKR, the RTDS™ '1phbkr', a single-phase breaker, is also used to model disconnect switches. Table 3 lists the disconnect switch parameters used in the model. The disconnect switches on the cross connect cables (cables connecting the two zones or cables connecting between port and starboard distribution busses) can be configured such as to operate either port and starboard busses to operate independently or can be connected together by closing either one or both cross connect cables CS 4 and CS 8.

Table 3. Disconnect Switch Data

Disconnect Switch Parameter	Value		
	Default	Min	Max
OPEN Resistance	1e9 Ω	0.001 Ω	NA
CLOSED Resistance	0.001 Ω	0.001 Ω	NA

3.3 Power Generation Module

The power generation module consists of a gas turbine generator with a rectifier and an output filter. Two different PGM modules were developed based on the type of rectifier. **Error! Reference source not found.** is a block diagram of the PGM module.

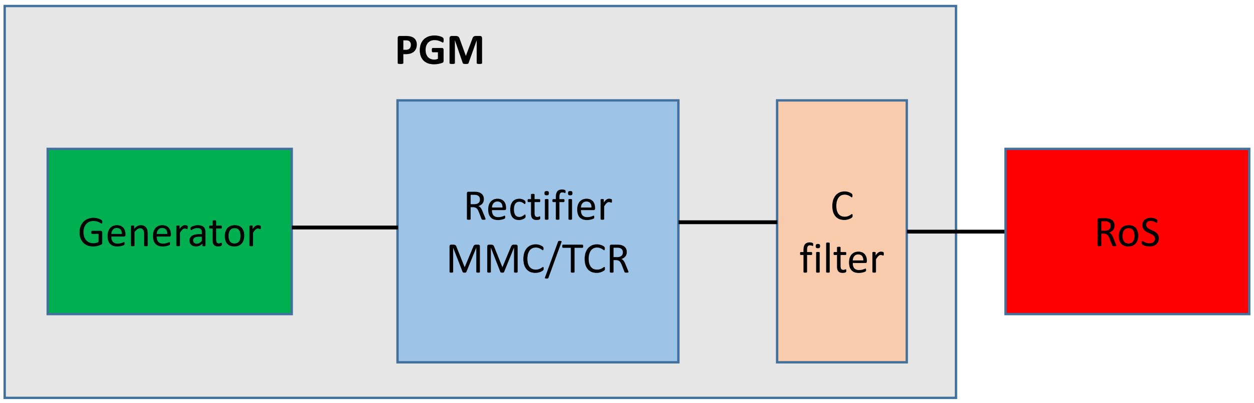

Fig. 3 Block Diagram of PGM Module

3.3.1 MMC based PGM

The MMC-based PGM module consists of a gas turbine generator rated at 36 MVA, 60 Hz with a 36 MW MMC as rectifier. Table 4 provides data for generator module including synchronous machine model, gas turbine, and its exciter module. RTDS^{TM} component for synchronous machine model 'RTDS_SHARC_MAC_V3' [4] is used while the RTDS^{TM} governor model '_rtds_GAST' [4] models the gas turbine governor characteristics. The exciter model in RTDS^{TM} '_rtds_ESAC1A' [4] is paired to the generator model.

The MMC based PGM version of the shipboard power system model runs in real-time with a time-step of 50 µs.

Table 4. Generator Module data for MMC based PGM

Parameter	Description	Default Value
	Synchronous Machine Model Parameters	
Mmva	Rated MVA of the Machine	36 MVA
cfqr	Number of Q-axis Rotor Windings	One
Vbsll	Rated RMS Line-to-Line Voltage	13.8 kV
HTZ	Base Frequency	60 Hz
H	Inertia Constant	4 MWs/MVA
D	Synchronous Mechanical Damping	0.04 pu/pu
Xa	Stator Leakage Reactance	0.08 pu
Xd	D-axis Unsaturated Reactance	1.352 pu
Xd'	D-axis Unsaturated Transient Reactance	0.296 pu
Xd"	D-axis Unsaturated Sub-Transient Reactance	0.148 pu
Xq	Q-axis Unsaturated Reactance	0.836 pu
Xq"	Q-axis Unsaturated Sub-Transient Reactance	0.122 pu
Ra	Stator Resistance	0.006 pu
Tdo'	D-axis Unsaturated Transient Open Time Constant	4.141 sec

Tdo”	D-axis Unsaturated Sub-Transient Open Time Constant	0.027 sec
Tqo’	Q-axis Unsaturated Sub-Transient Open Time Constant	0.184 sec
Gas Turbine Parameters		
R	Permanent Droop	1e-6 pu
T1	Governor Mechanism Time Constant	0.005 sec
T2	Combustion Chamber Time Constant	0.04 sec
T3	Exhaust Temperature Measurement Time Constant	0.01 sec
AT	Ambient Temperature Load Limit	0.9 pu
Kt	Temperature Limiter Gain	2.00
Vmax	Maximum Turbine Power	1 pu
Vmin	Minimum Turbine Power	0 pu
Dturb	Turbine Damping Coefficient	0.03
ESAC1A Exciter Parameters		
Tr	Filter Time Constant	0.001 sec
Tb	Lead-lag Denominator Time Constant	0.1 sec
Tc	Lead-lag Numerator Time Constant	0.2 sec
Ka	Voltage Regulator Gain	80
Ta	Voltage Regulator Time Constant	0.2 sec
VAmax	Maximum Control Element Output	15 pu
VAmin	Minimum Control Element Output	-15 pu
Te	Exciter Time Constant	0.2 sec
Kf	Rate Feedback Gain	0.03 pu
Tf	Rate Feedback Time Constant	1.49 sec
Kc	Rectifier Regulation Factor	1 pu
Kd	Exciter Internal Reactance	0.4 pu
Ke	Exciter Field Resistance Constant	1 pu
E1	Value of E at Se1	4 pu
Se1	Value of Se at E1	0.4
E2	Value of E at Se2	5 pu
Se2	Value of Se at E2	0.5
Cal	Saturation Constant ‘A’ Calculation Method	abs(A)
VRmax	Voltage Regulator Maximum Output	14.99 pu
VRmin	Voltage Regulator Minimum Output	-14.99 pu
Generator Transformer Parameters		
vtpri	Generator Transformer Primary L-L RMS	6.6 kV
vtsec	Generator Transformer Secondary L-L RMS	13.8 kV
TMVA	Transformer MVA rating	36 MVA
trpos	Positive Sequence Resistance	0.0 pu
txpos	Positive Sequence Reactance	0.02 pu

An average value model of modular multi-level converter (MMC) is used as a rectifier in the MVDC system. That is, the individual switching elements of the MMC are not included in the system model. The arm inductance (L_{arm}) and cell capacitance ($Cell_{cap}$) values for the 36 MW, 12 kV MMC-based PGM are derived from the information listed in Table 5. The equations used to derive the model of MMC is given in [5] and detailed discussion of the average value model can be found in [6]. The MMC average-value model has been compared with a 1MW, 5kV MMC controller hardware-in-the-loop (CHIL) simulation and represents the behavior of the CHIL MMC simulations satisfactorily with respect to normal operating conditions and current limiting function (i.e., similar peak current and steady state current limiting characteristics). Table 5 lists the parameters of the average-value MMC model. The MMCs can operate at unity power factor (pf=1) thereby reducing the sizing of generators. Thus the generator rating can be set to 36 MVA as opposed to 45 MVA for thyristor controlled rectifier. The MMC model is nominally current limited to 1.1 pu of nominal operating current but is a user-configurable setting that can be adjusted as desired. Fig. 4 shows the CHIL simulation with 1 MW MMC for a bolted fault on the DC side. It can be noted that the current from the MMC, once the fault is applied, peaks to about 4 pu for a short duration and then settles out and current limits to 228 A (200 A nominal operating current).

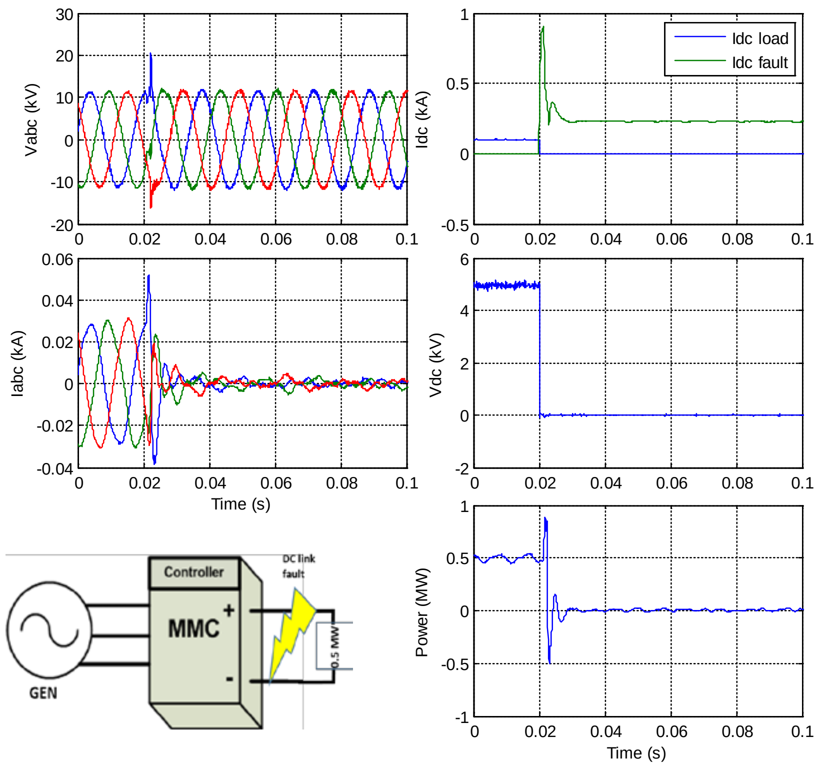

Fig. 4 CHIL simulation results for 1 MW MMC bolted fault

The MMC based PGM module does not require oversizing of generator since the MMCs can operate with unity power factor. The MMC based PGM modules also do not have any filtering on the 12 kV DC side. Table 6 shows the filter parameters for the MMC based PGM module.

Table 5. MMC data for PGM Module

Parameter	Description	Default Value
MMCmva	MMC Rating	36 MW
Vin	MMC AC Input L-L Voltage	6.6 kV
Vout	MMC DC Output Voltage	12 kV
$Cell_{cap}$	Cell Capacitor	2.1 mF

$Cell_{volt}$	Capacitor Cell Voltage	2 kV
$N_{cell/arm}$	Number of cells per arm/phase	6
L_{arm}	Arm Inductance for 5% current ripple	5.3 mH
f_{sw}	Switching Frequency	12 kHz

Table 6. Output filter parameters for MMC based PGM module

Parameter	Description	Default value
Rp	Filter Capacitor Resistance	6 Ω
Cp	Filter capacitance	10 µF

3.3.2 Thyristor Controlled Rectifier based PGM

A separate PGM module based on a thyristor controlled rectifier (TCR) was built, which provides an alternative option to the MMC-based PGM module. The TCR-based PGM module consists of a gas turbine generator rated at 45 MVA and a 45 MVA, 240 Hz, 6-pulse. The generator is operated at 240 Hz and its apparent power rating is increased to 45 MVA to manage the reactive power required by the TCR. Table 7 provides details of the generator module including synchronous machine model, gas turbine, and its exciter module. The RTDS™ component for synchronous machine model 'RTDS_SHARC_MAC_V3' is used while the RTDS™ governor model '_rtds_GAST' models the gas turbine governor characteristics. The RTDS™ exciter model '_rtds_ESAC1A' is paired to the generator model. The TCR is modeled using the RTDS™ component 'If_rtds_sharc_sld_VGRP6', which is a six-pulse valve group.

TCR based PGM model can also be adapted as necessary to have generators at various frequencies. The thyristor controlled rectifier can also be modified to run as a diode rectifier by disabling the firing angle controls on the rectifier.

To accurately capture the behavior of the thyristor controlled rectifier based power generation module for which a 240 Hz generator is used, the model is set to run in non-real time with a time-step of 1 µs.

Table 7. Generator data for TCR based PGM Module

Parameter	**Description**	**Default Value**
	Synchronous Machine Model Parameters	
Mmva	Rated MVA of the Machine	45 MVA
cfqr	Number of Q-axis Rotor Windings	One
Vbsll	Rated RMS Line-to-Line Voltage	9.8 kV
HTZ	Base Frequency	240 Hz
H	Inertia Constant	4 MWs/MVA
D	Synchronous Mechanical Damping	0.04 pu/pu
Xa	Stator Leakage Reactance	0.08 pu
Xd	D-axis Unsaturated Reactance	1.352 pu
Xd'	D-axis Unsaturated Transient Reactance	0.296 pu
Xd"	D-axis Unsaturated Sub-Transient Reactance	0.148 pu
Xq	Q-axis Unsaturated Reactance	0.836 pu

Xq”	Q-axis Unsaturated Sub-Transient Reactance	0.122 pu
Ra	Stator Resistance	0.006 pu
Tdo’	D-axis Unsaturated Transient Open Time Constant	4.141 sec
Tdo”	D-axis Unsaturated Sub-Transient Open Time Constant	0.027 sec
Tqo’	Q-axis Unsaturated Sub-Transient Open Time Constant	0.184 sec
Gas Turbine Parameters		
R	Permanent Droop	1e-6 pu
T1	Governor Mechanism Time Constant	0.005 sec
T2	Combustion Chamber Time Constant	0.04 sec
T3	Exhaust Temperature Measurement Time Constant	0.01 sec
AT	Ambient Temperature Load Limit	0.9 pu
Kt	Temperature Limiter Gain	2.00
Vmax	Maximum Turbine Power	0.8 pu
Vmin	Minimum Turbine Power	0 pu
Dturb	Turbine Damping Coefficient	0.03
ESAC1A Exciter Parameters		
Tr	Filter Time Constant	0.001 sec
Tb	Lead-lag Denominator Time Constant	0.1 sec
Tc	Lead-lag Numerator Time Constant	0.2 sec
Ka	Voltage Regulator Gain	80
Ta	Voltage Regulator Time Constant	0.2 sec
VAmax	Maximum Control Element Output	15 pu
VAmin	Minimum Control Element Output	-15 pu
Te	Exciter Time Constant	0.2 sec
Kf	Rate Feedback Gain	0.03 pu
Tf	Rate Feedback Time Constant	1.49 sec
Kc	Rectifier Regulation Factor	1 pu
Kd	Exciter Internal Reactance	0.4 pu
Ke	Exciter Field Resistance Constant	1 pu
E1	Value of E at Se1	4 pu
Se1	Value of Se at E1	0.4
E2	Value of E at Se2	5 pu
Se2	Value of Se at E2	0.5
Cal	Saturation Constant ‘A’ Calculation Method	abs(A)
VRmax	Voltage Regulator Maximum Output	14.99 pu
VRmin	Voltage Regulator Minimum Output	-14.99 pu

The MVDC SPS with the TCR-based PGM has only been simulated in non-real time and is generally run with a 1 µs time step. A 790 µH DC reactor is attached at the DC side of the rectifier. Table 8 provides the data for the TCR parameters. The DC side of the PGM also has a filter capacitor. Parameters for the filter capacitor are given in Table 9 and were derived from those used in [7]. The firing angle for the rectifier is chosen to maintain a 12 kV output on the DC side. A bias signal ‘V_{bias}’ and measured voltage at DC terminal is used for load sharing when the PGM is operated in parallel with another PGM. The RTDS™ component 'rtds_sharc_ctl_FPGEN', which is a firing pulse generator, is used to generate firing pulse sequences that are fed to the 6-pulse rectifier block.

Table 8. TCR data for TCR based PGM

Parameter	Description	Default Value
TMVA	TCR Rating	45 MVA
Vbspr	Rated RMS L-L Primary Voltage	9.8 kV
Freq	Rated Frequency	240 Hz
Rp	Positive Sequence Resistance	0.0 pu
Lp	Positive Sequence Reactance	0.01 pu
Sn_R	Valve Snubber Resistance	1000 Ω
Sn_C	Valve Snubber Capacitance	25 µF
R_{ON}	Valve ON Resistance	0.001 Ω
R_{OFF}	Valve OFF Resistance	1e9 Ω
R_{Ldc}	Output Reactor resistance	0.075 Ω
L_{Ldc}	Output Reactor Inductance	790 µH

Table 9. Output filter for TCR based PGM

Parameter	Description	Default value
Rp	Filter Capacitor Resistance	0.075 Ω
Cp	Filter capacitance	835 µF

3.4 Power Conversion Module

There are two power conversion modules, PCM 1 and PCM 2, modeled in zone 1 and zone 2 respectively. Fig. 5 shows the block diagram of the PCM. Each PCM is rated for 10 MW. The PCMs are modeled as constant impedance type with a resistive load connected directly to 12 kV bus. An output filter was designed for the PCM, which results in a current ripple of 1.5% with observed voltage ripple of 65V (while using the TCR-based PGM SPS model).

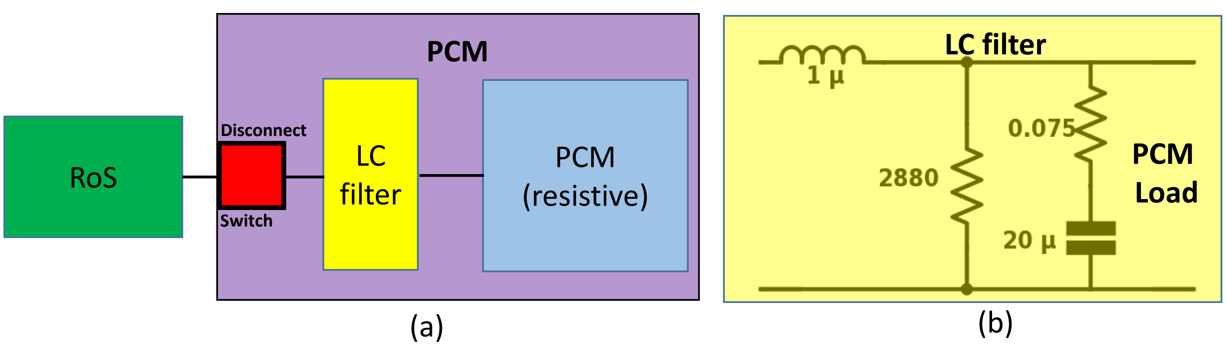

Fig. 5: (a) Block Diagram of PCM, (b) PCM - LC filter with its parameters

3.5 Propulsion Motor Module

A propulsion motor module (PMM) is implemented in zone 2. Fig. 6 shows the block diagram of PMM implementation in RTDS™. The PMM is split into two 18 MW units. The disconnect switches that feed the PGM can be configured such that all PMM (36 MW) can be fed solely through either the port or starboard side; or fed equally from port and starboard sides. The PMMs are modeled as constant impedance type with resistive load connected directly to 12 kV bus.

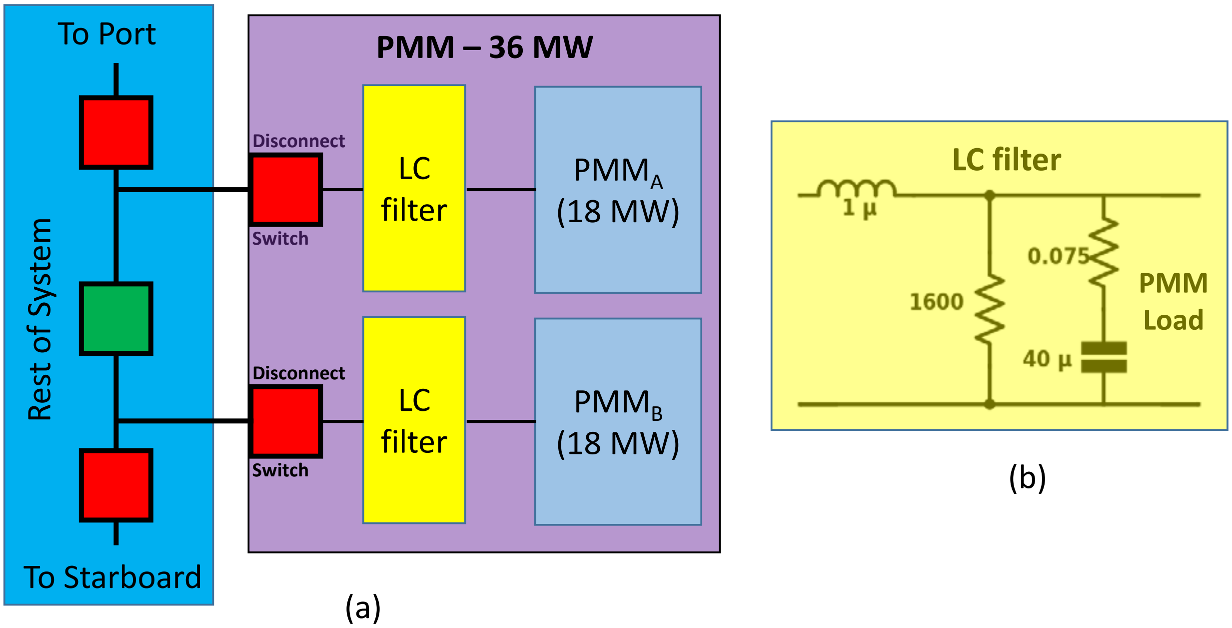

Fig. 6: (a) Block Diagram of PMM, (b) PMM - LC filter with its parameters

3.6 System Controls

The control schemes implemented in the model are described below.

3.6.1 Load Sharing Scheme

When the PGMs are paralleled together by closing the disconnect switches to the port and starboard side cross-connect cables (either or both CS 4 and CS 8), the load sharing scheme becomes active and allows the user to control load sharing between generators. The user can set percentage of load shared between PGMs as desired. The default setting is for the generators to share load equally.

3.6.2 Fault Control Block

To allow for system fault studies, fault controls have been implemented in the model. Faults can be applied at any point on the 12 kV DC distribution system (switchboards, cable sections). The inception of fault is in reference to Phase A of generator on PGM 1; the generator is feeding port side connected in zone 1. Fault impedance, angle, duration can be set by the user for simulation studies.

4 VERIFICATION OF OPERATION

As mentioned in the preface for the report, the model was developed for testing and analyzing of fault management in MVDC SPS. The section below shows the performance of the two version of the shipboard power system model for a bolted fault near PCM 1 on CS 21. The fault is applied with respected to Phase A of the PGM 1 generator with a fault angle of 90 degrees. Fig. 7 shows the location of fault at PCM 1 on the shipboard power system model. The two PGMs in the simulation are paralleled by closing of disconnect switches SADA and SBDA (cross connect cable CS 8 in operation).

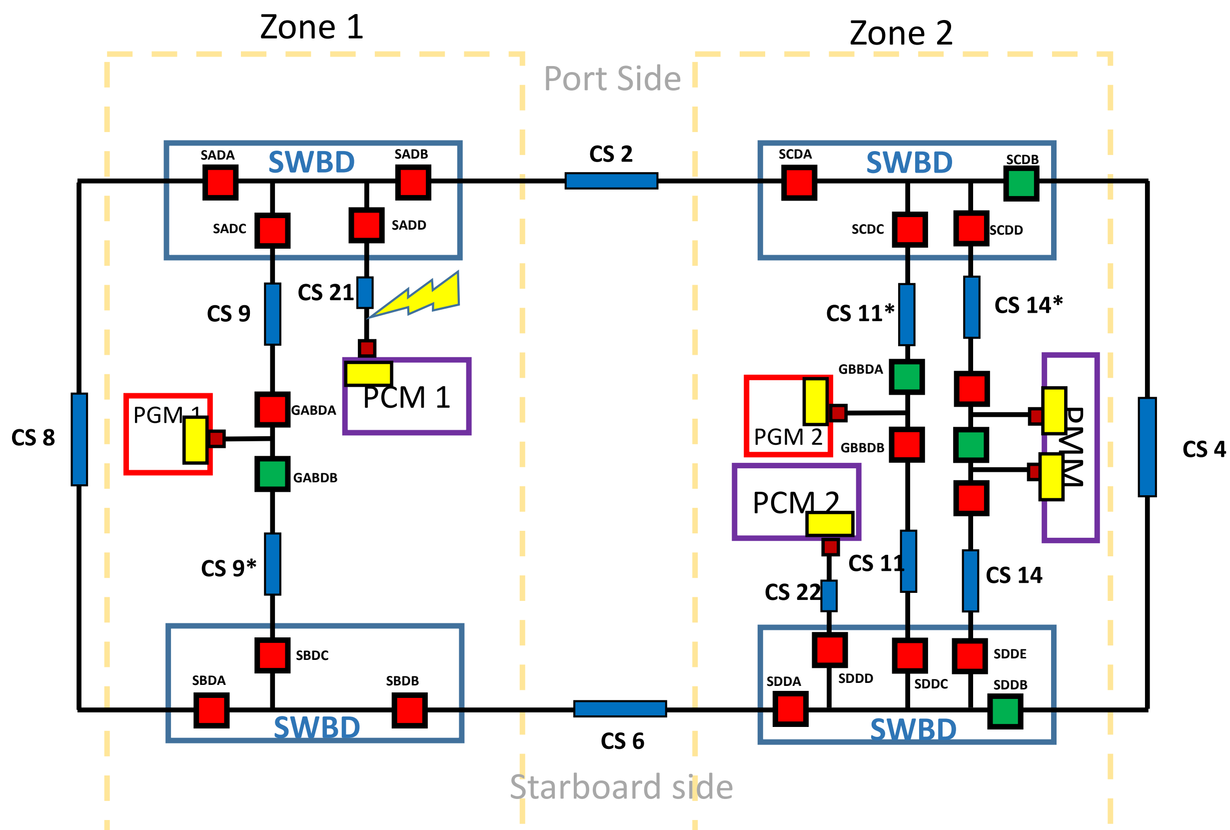

Fig. 7: Location of fault for case studies on SPS

4.1 MMC based PGM version

Fig. 8 shows the current through disconnect switch SADD while Fig. 9 shows plots DC current at PGM 1 terminal, PGM 2 terminal, and the voltage at 12 kV distribution bus. The current through disconnect switch SADD in Fig. 8 is the sum of fault current contribution from PGM 1 and PGM 2. From Fig. 9, it can be observed that at the inception of fault, current through MMC peaks to about 2.5 pu, and then the current limitation function of MMC takes over and current limits to 3.3 kA (10% of nominal operating current). The DC bus voltage drops to zero due to the bolted fault applied. The fault current contributions observed from MMC based PGMs will be significantly lower than that of thyristor controlled rectifier based PGM due to the inherent ability of MMCs to current limit their operation.

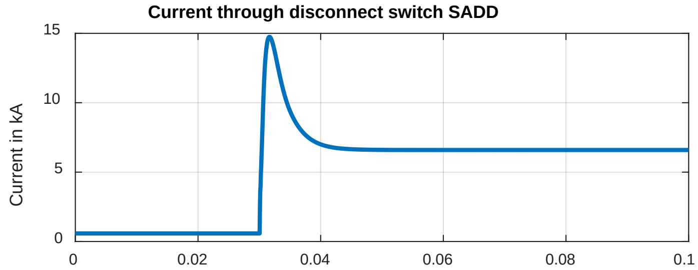

Fig. 8: MMC based PGM – Current through disconnect switch SADD

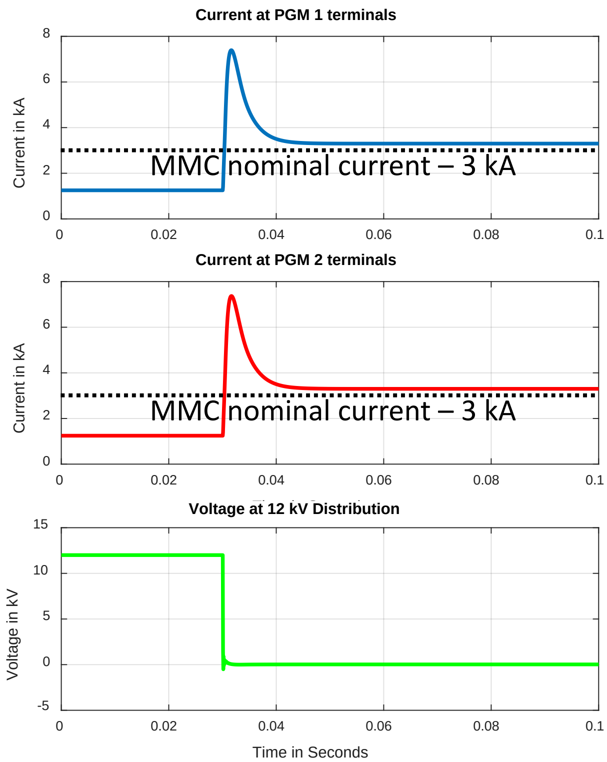

Fig. 9: MMC based PGM – currents and voltages at PGM, PGM 2 and distribution bus

4.2 Thyristor controlled rectifier based PGM

Fig. 10 shows the currents through disconnect switches in switchboard A (SADA, SADB, SADC and SADD), current and voltage at two PGM generator terminals. The current through disconnect switch SADD is the fault current which is the sum of current contributions from PGM 1 and PGM 2. The current through SADA is the fault current contribution of PGM 2 routed through cable section CS 8 which ties the port and starboard busses together through zone 1, current through disconnect switch SADC is the fault current contribution from PGM 1. It can be observed that the steady state fault current levels with a TCR based PGM can be significantly higher than that of a MMC based PGM system.

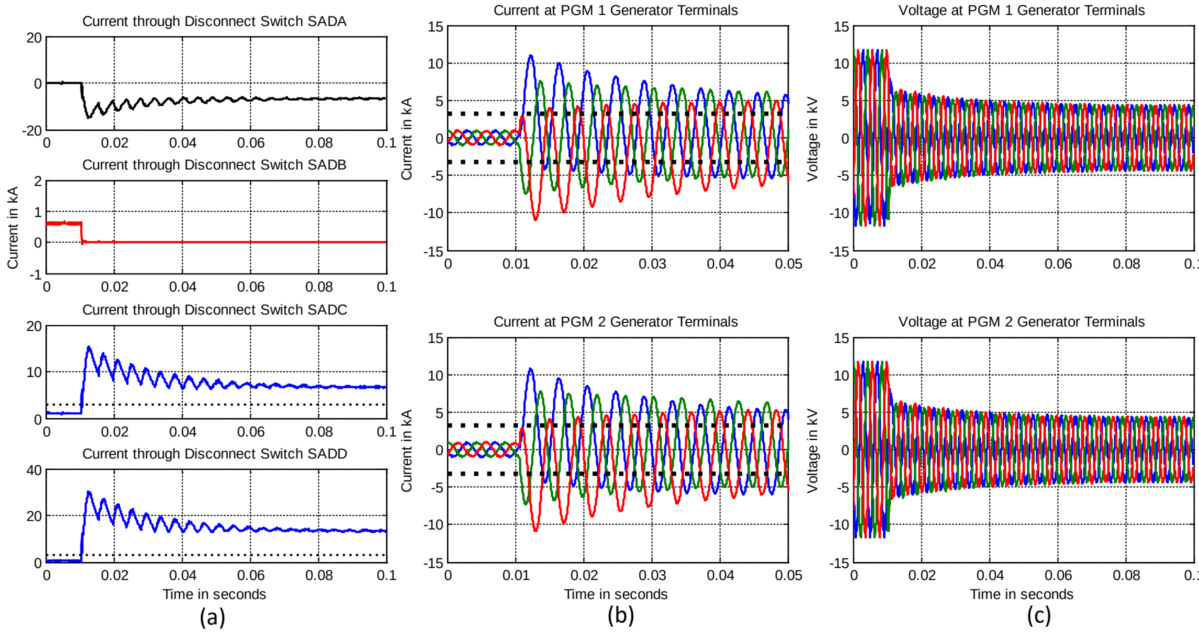

Fig. 10: (a) – Current through disconnects in switchboard A, (b) – Current at generator terminals of PGM 1 and PGM 2, (c) – Voltage at generator terminals of PGM 1 and PGM 2

5 FUTURE WORK

The shipboard power system model presented in this report was intended to run in a single-rack due to which only two zones were implemented with simplifications made to several modules (PCM, PMM). The future work given here represents an expansion to the existing model by incorporating the following features:

- Expansion of the current two zone model to six zones thereby going to a multi-rack RTDS model to include new modules
- Modifications to PGM to allow modeling of different rectifier and generator types/combinations, modeling of two independent active rectifiers for each PGM that power port and starboard busses independently and simultaneously
- Development of detailed models for power conversion modules, propulsion motor modules
- Development of models for pulsed power charging module
- Inclusion of energy storage modules in various zones
- Implementation of automatic load shedding schemes
- Implementation of realistic load profiles for PCM, PMM and pulsed power loads

6 References

[1] N. Doerry, 'Next Generation Integrated Power Systems for the Future Fleet', *Corbin A. McNeill Symposium, United States Naval Academy.* Annapolis, 2009.

[2] N. Doerry and J. Amy, Jr, "MVDC Shipboard Power System Considerations for Electromagnetic Railguns," in *Proceedings of the DoD Electromagnetic Railgun Workshop*, Laurel, MD, Sep. 2015.

[3] *Caledonian Medium Voltage Cables*, http://www.caledonian-cables.com/DdFls/Medium%20Voltage%20Cables.pdf, Caledonian.

[4] RTDS™ User Manual.

[5] K. Sun, D. Soto, M. Steurer and M. O. Faruque, "Experimental verification of limiting fault currents in MVDC systems by using modular multilevel converters," in *Proc. of the IEEE Electric Ship Technologies Symposium (ESTS)*, Alexandria, VA, 2015, pp. 27–33.

[6] *[In progress of conversion from Distribution D to Distribution A]* Center for Advanced Power Systems, Florida State University, Model Design Document, 'Modular Multi-level Converter Average Value Model', 2015.

[7] M. Bash, R. R. Chan, J. Crider, C. Harianto, J. Lian, J. Neely, S. D. Pekarek, S. D. Sudhoff, and N. Vaks, "A Medium Voltage DC Testbed for Ship Power System Research," in *Proc. of the IEEE Electric Ship Technologies Symposium (ESTS)*, Apr. 2009, pp. 560–567.