Ship Electrical System Simulation

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***Abstract* — Several ship systems were evaluated as part of the "HTS Benefits to Ship System" study funded by the U.S. Office of Naval Research (ONR) in 2004. A commercially available power system simulation software application called PSCAD™ was used to evaluate the dynamic response of the selected ship electrical systems. The generic, large combatant ship electric systems reported here consist of the following:**

- **Two 36.5 MW propulsion motors with their variable speed drives (VSDs)**
- **Two 36 MW generators with gas turbines**
- **Two 4 MW auxiliary generators for auxiliary loads.**

Each system studied employed rotating machines that were built using high-temperature superconductor (HTS) wires. The PSCAD software enabled modeling of electrical systems with full transient details to study the dynamic response of the electric system over a wide frequency range. The default models and standard features available in PSCAD served all the requirements. A number of fault and load scenarios were studied. The goal of this simulation work was to develop a model for studying the dynamic behavior of the ship electrical system. This goal was successfully achieved.

***Index Term* — ONR (U.S. Office of Naval Research), PWM (pulse width modulation), VSD (variable speed drive), HTS wire, transient simulation, PSCAD, ship electric system, modeling**

I. Introduction

Recent advances in the development of all electric ships for the U.S. Navy indicate that the total power requirements on large surface ships could approach 100 MW. New technologies and techniques are emerging that manage the generation and utilization of the anticipated power level. As the power level and the number of critical electrical components on the ship increase, so does the complexity of analyzing the system. Traditionally, naval ships had relatively low electric power and simple electric systems, which could be analyzed using simple calculations. As a result, the experience in the application of advanced dynamic tools to analyze power systems of large combatant electric ships is limited. This paper shows how a power system simulation tool could be used to study the ship electrical system dynamics.

The experience reported in this paper was a part of a study [1] initiated by ONR to examine the benefits of high-temperature superconductor (HTS) electric machines. There have been significant advancements in the design of HTS electric motors and generators that can now be utilized for propulsion and power generation in the large electric ships. Based on the advantages unique to HTS technology, this study [1] was initiated by ONR with the intent of evaluating factors that optimize HTS component weights, sizes, and efficiencies in various ship-system configurations. Detailed results of this study are presented in a companion paper [2]. As part of this study, several power system technologies and configurations under consideration were simulated in order to evaluate their dynamic behavior. This paper reports the details of the dynamic simulation of one of the configurations that used HTS motors and generators. It shows how a power system simulation tool could be effectively employed to study the ship electrical system dynamics as the ship power system design and technology evolves.

II. Electrical System Simulation

A. The Simulation Tool

PSCAD power system simulation software is used to model the electrical ship system. PSCAD simulates electromagnetic transients and can capture a wide range of frequency response - DC to several kHz. All of the controls were modeled in detail. The PSCAD simulation algorithm is well suited for modeling the power electronic systems, such as PWM inverters, motors, generators, transformers, and loads in an integrated power system environment. The software uses interpolated switching to accurately represent switching instances, even with relatively large time steps (50µsec.). This feature allows for the modeling of larger systems without making the simulation time prohibitively long. PSCAD is a totally graphical, interactive, modular, hierarchical and customizable power system simulator. Models developed in C, FORTRAN and MATLAB® can be interfaced with PSCAD. It allows unlimited network size and control modeling capability. PSCAD can run on any modest personal computer with the Windows operating system.

B. The Power System

PSCAD cases were created for four different electrical system configurations.

- 6.6 kV, 60 Hz without transformers – baseline system
- 13.8 kV, 60 Hz system with transformers
- DC distribution
- 6.6 kV, 60 Hz without transformer for the small, high-speed ship.

The baseline case topology for a large combatant type ship is shown in Figure 1. Although small high-speed ships [3] were also modeled only large ship model is presented for illustrating the approach. The baseline case is the 6.6 kV system without transformers. The top-level layout shown in Figure 1 is composed of sections of hierarchical components

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shown with a grey background. By double-clicking on any of these sections the level below it opens to reveal additional details. For example, opening the generator icon G1 will reveal the detailed representation of the generator, turbine, governor, and exciter system. Other hierarchical modules are: motor (M), variable speed drive (VSD), frequency converter (FC) and breaker configurations (A, B and C).

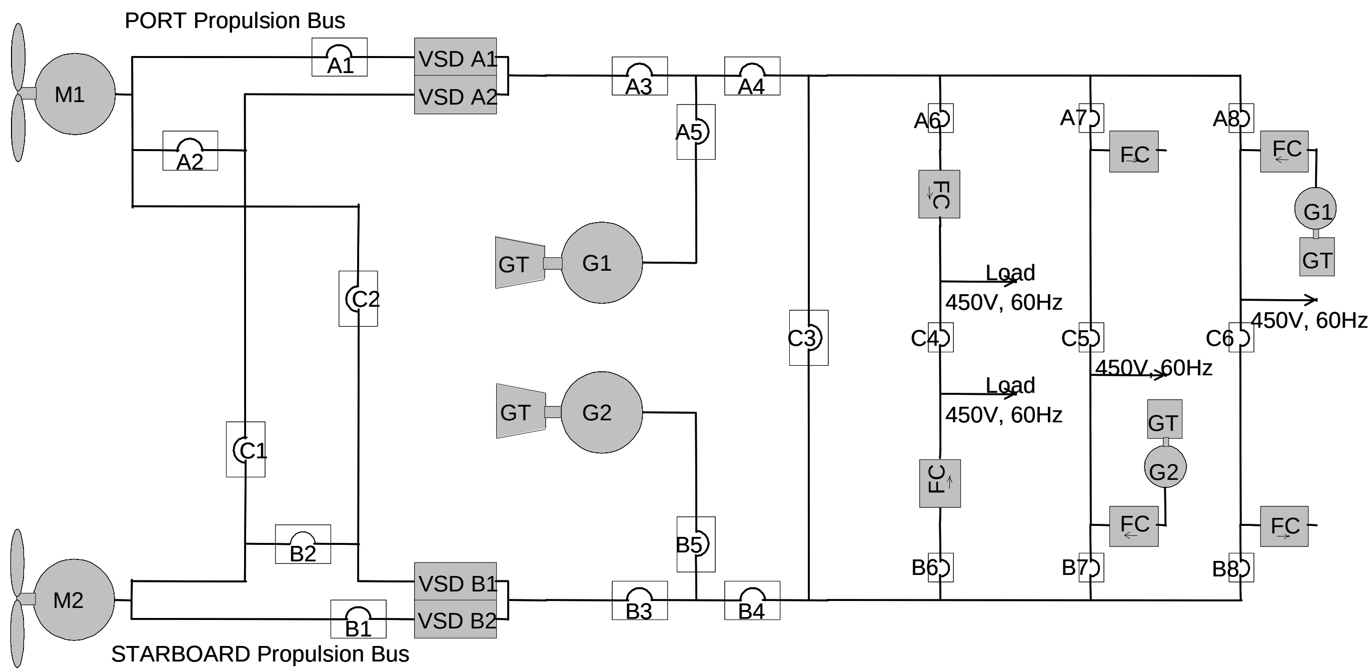

Figure 1: Top Level of 6.6 kV System Baseline Topology with Complete Ship Electric System

The simulation case also consists of control panels that can be used to monitor and adjust simulation parameters. A typical control panel is shown in Figure 2. This panel has a slider and two meters (motor speed and speed ordered.)

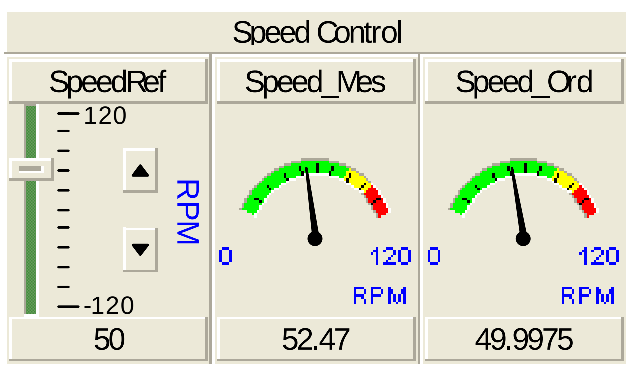

Figure 2: Typical Control Panel

Different types of controls available in PSCAD are listed in Table I.

Table I: Control Panel Controls

Controls	**Function**
Switches	Operate breakers
Push Buttons	Operate faults
Sliders	Change motor speed
Rotary Dial	Not used

C. Simplified Ship Electric System

While the complete ship electrical system that is necessary to study various system configurations is shown in Figure 1, a simpler equivalent circuit can be used for testing one drive at a time. This approach helps to speed up the simulation. The equivalent circuit of the 6.6 kV system for a dynamic test of the motor and drive while being fed by the main generator is shown in Figure 3.

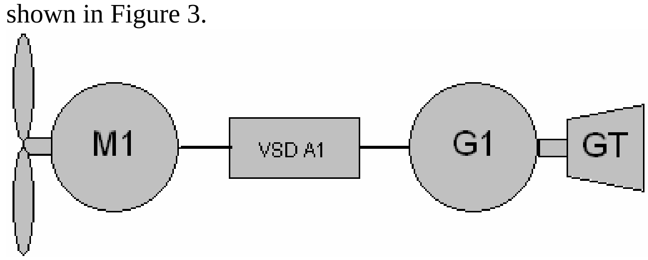

Figure 3: Equivalent Active Circuit of 6.6 kV System without the Auxiliary Generator

D. Main and Auxiliary Synchronous Generators

The details of the main power generator are shown in Figure 4.

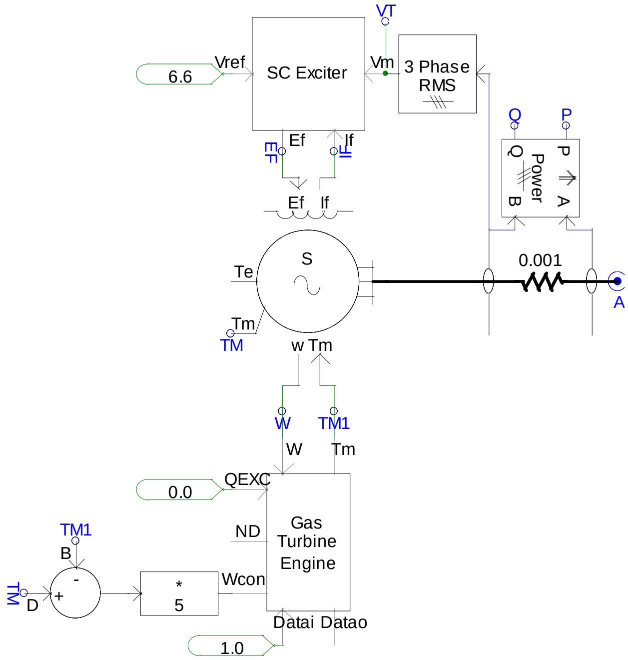

Figure 4: Details of Generator, Exciter and Turbine System

The synchronous generator model is written in the D-Q-0 reference frame and interfaces to the network using compensated current sources. The generator can model transient and sub-transient reactance on both axes. It can also model the saturation effects. The HTS machine is modeled using this generalized machine model with equivalent circuit parameters derived for the HTS machine. All generators are modeled as 3-phase machines. The exciter and governor models are simulated using basic control blocks in a hierarchical module.

E. Synchronous Motor

The circuit connections of the motor are shown in Figure 5.

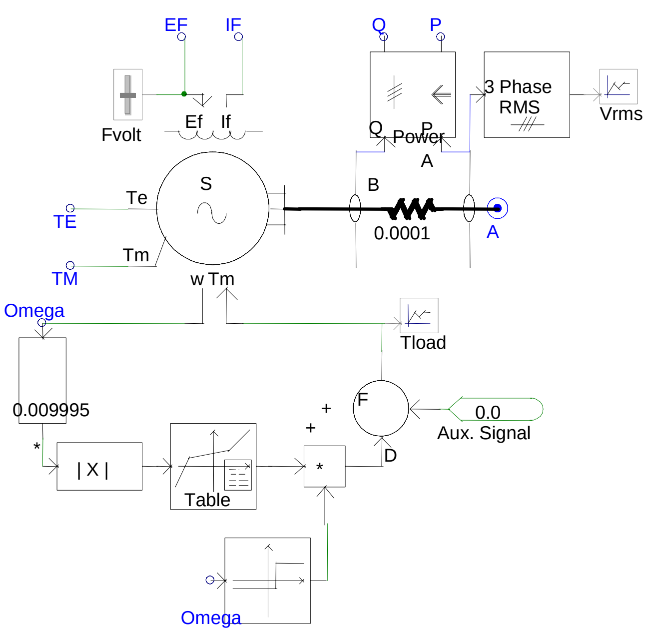

Figure 5: Details of Motor and Load Connections

The synchronous motor model is the same as the synchronous generator model, except that the mechanical torque is applied in the opposing direction. All motors are modeled as 3-phase machines.

The speed torque characteristics of the ship load are implemented as a look-up table with the torque direction changing with a speed reversal. This arrangement does not take into account the effect of the linear moment of inertia of the ship (acceleration and deceleration) and the random effects of waves and currents. These effects can be added as auxiliary signals to the mechanical torque inputs to the motor. Alternately, the speed torque table can be replaced with a composite function of speed that takes all effects in to account. The load models developed in MATLAB® can also be interfaced directly into PSCAD.

F. Variable Speed Drive

The VSD used to control the synchronous motor speed is implemented as a vector-controlled current referenced PWM inverter. The criterion for selecting this technology is discussed in a separate paper [4]. The input to the inverter is a diode-bridge rectifier fed by the main AC bus. A simplified version of the VSD was also modeled to improve the simulation speed. The simplified VSD, which uses a current source interface instead of PWM inverter, is shown in Figure 6. The complete PWM implementation is too large to show here.

G. Frequency Changer

The frequency changer is implemented using a diode-clamped multi-level PWM inverter. A three-level converter and a simplified frequency converter with source interfaces are shown in Figures 7 and Figure 8, respectively. The three-level converter can be used for a detailed study of the switching effects. The simplified model is faster to simulate and is useful for a more general system study.

H. Load Scenarios

The load scenarios studied are as follows:

- Full-speed ahead – all generators and motors on
- Both motors operating from one 36.5 MW generator
- Both motors operating from two 4 MW generators
- Both motors operating from one 4 MW generator
- Both motors operating from 2 MW available power

These scenarios were studied by populating the appropriate modules as necessary (to improve simulation speed) and by operating the appropriate breakers.

I. Faults

The ship electrical system can experience a variety of faults. The kinds of faults configured are as follows:

- Any combination of 3-phase faults with or without ground
- Single-phase fault with or without ground
- High impedance faults
- Fault on wave

- Variable duration fault
- Fault clearing and re-closing

The control panel used to select these fault scenarios is shown in Figure 9. The fault parameters can be dynamically set using the selector switch and the sliders on that control panel.

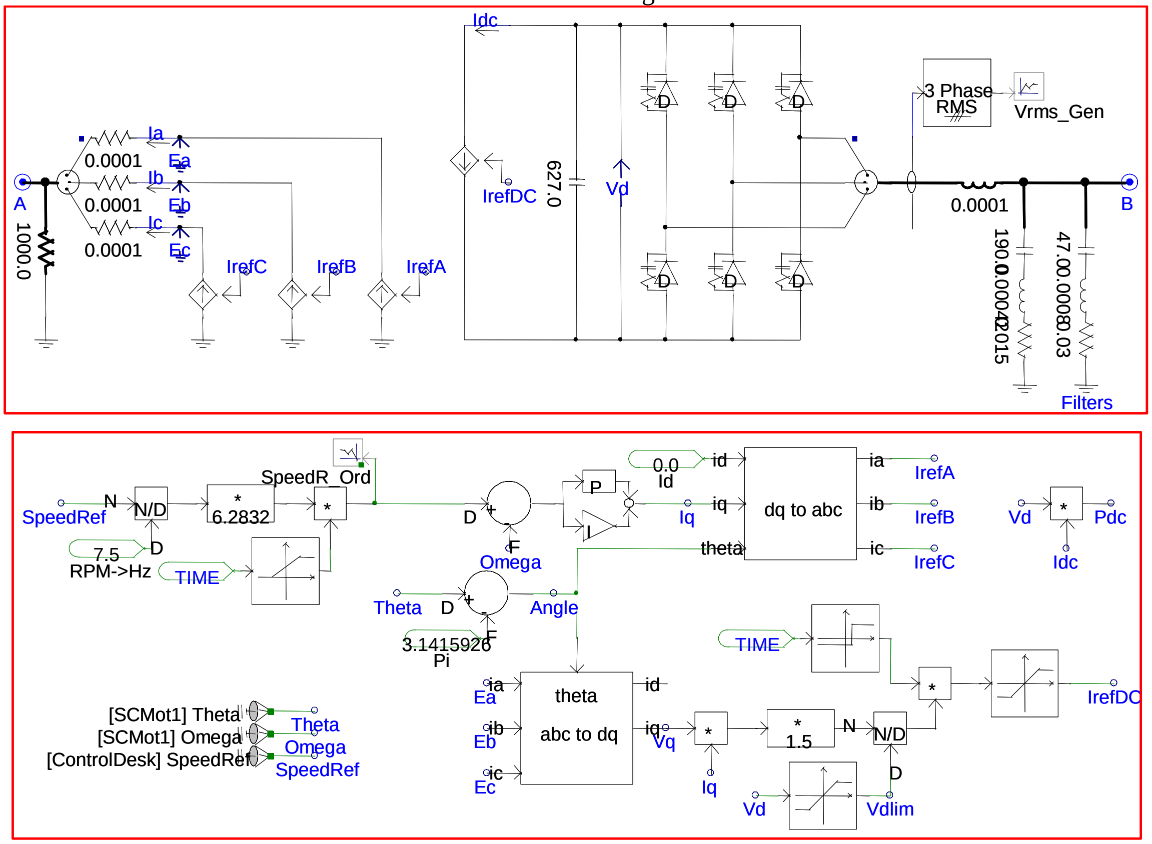

Figure 6: Simplified Variable Speed Drive with Current Source Interface

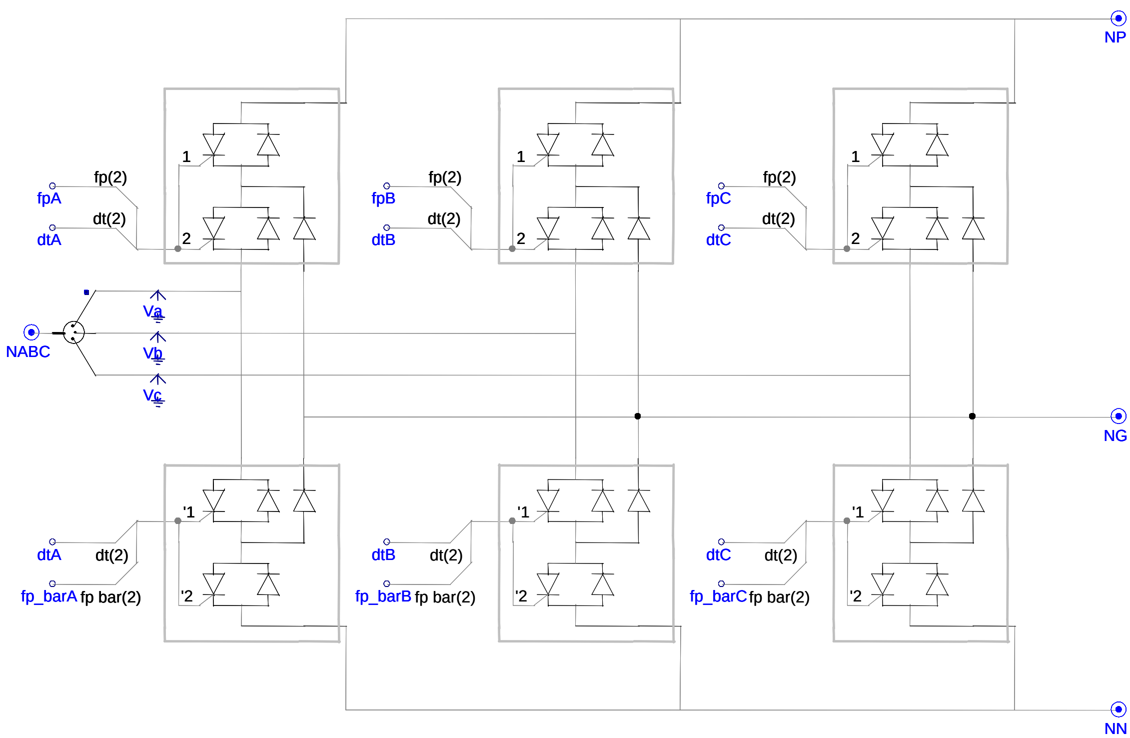

Figure 7: Three-Level Diode-Clamped PWM Inverter for Frequency Converter

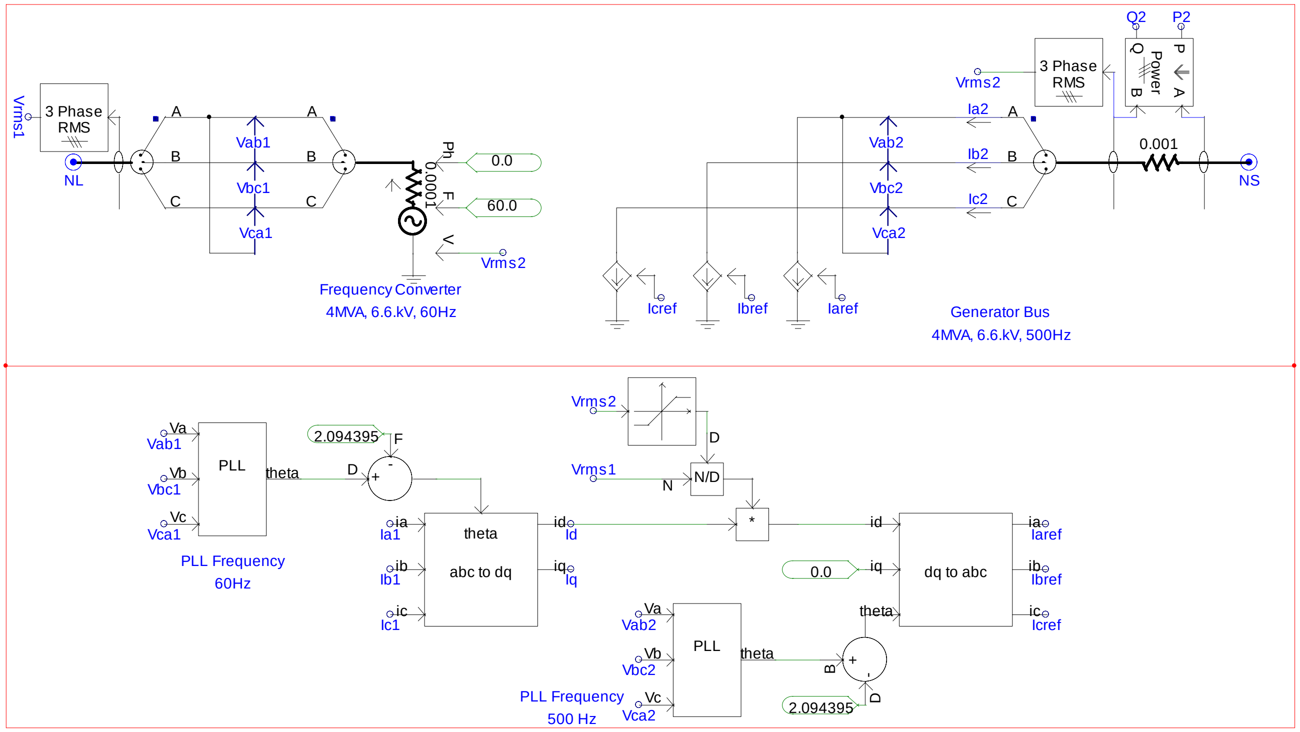

Figure 8: Simplified Frequency Converter with Current Source Interface

The graph in the lower left-hand corner of Figure 9 indicates that a Phase A to ground fault (FType_A1 = 1) was applied to the Port Bus (Fault_A1) at about 0.5 seconds. This was done by manually pressing the corresponding push button (Fault_A1) during the simulation. These faults can also be set based on predefined timers. For studying worst case scenarios, many faults can be applied in an automated batch mode. The simulation results, along with the value of the pre-selected criterion (maximum over-voltage), would be available as a batch output file.

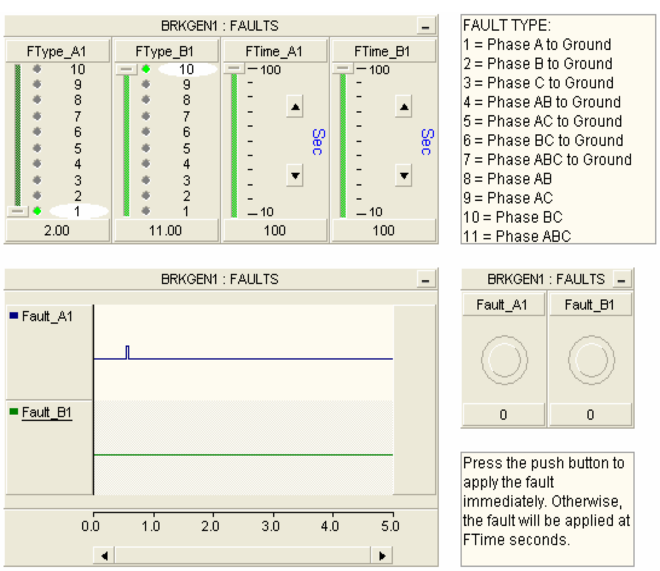

Figure 9: Control Panel for Fault Application

J. *Load Transients*

The case is set up to study the following load transients:

- Sudden load ON
    - Startup from zero load
    - Step increase in load
- Sudden load OFF
    - Step change of speed to zero
    - Step decrease in load
- Crashback
    - Change of speed from positive to negative
    - Change of speed from negative to positive

K. *Transient Simulation Results*

To demonstrate the dynamic response of the motor, generator and variable speed drive, simulation results of two transients are presented.

- Speed order change (refer to Figure 10, Figure 11, and Figure 12)
- AC bus fault (refer to Figure 13 and Figure 14)

The simulation was first run to steady state and a snapshot was taken. The case was restarted from the steady state snapshot to perform dynamic tests. The time axis in the plots is relabeled to start from 0.0 seconds at the time of the snapshot. At about 0.6 seconds, the speed[2] order was changed from 50 rpm to 80 rpm. Rated speed of the motor is 120 rpm. At about two seconds, the motor speed order was changed from positive (+) 80 rpm to negative (-) 80 rpm. The transient

[2] Motor speed in the plots is labeled as Omega and is a fraction of rated speed (120 rpm)

response of the motor is shown in Figure 10. Values plotted against time (sec) are as follows:

- Pmot, Qmot (real and reactive motor power)
- Tload, Te (load and motor torques)
- Omega (motor speed as a fraction of 120 rpm – the rated speed)
- Vrms (motor terminal voltage – rms)
- Ef, If (field winding voltage and current).

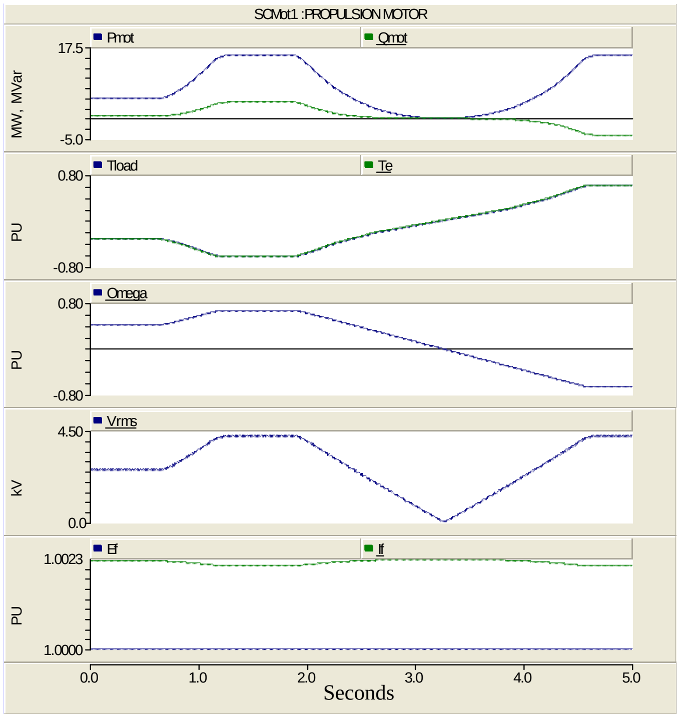

Figure 10: Motor Transient Response

The transient response of the VSD to changes in motor speed order is shown in Figure 11. The rate of change of speed reference is limited to 60 rpm/second through a rate limit function. The motor speed (Speed_Mes) follows the ordered speed (Speed_Ord). The motor current and voltage amplitudes change with speed to meet the load demand. The frequency also changes with synchronous speed.

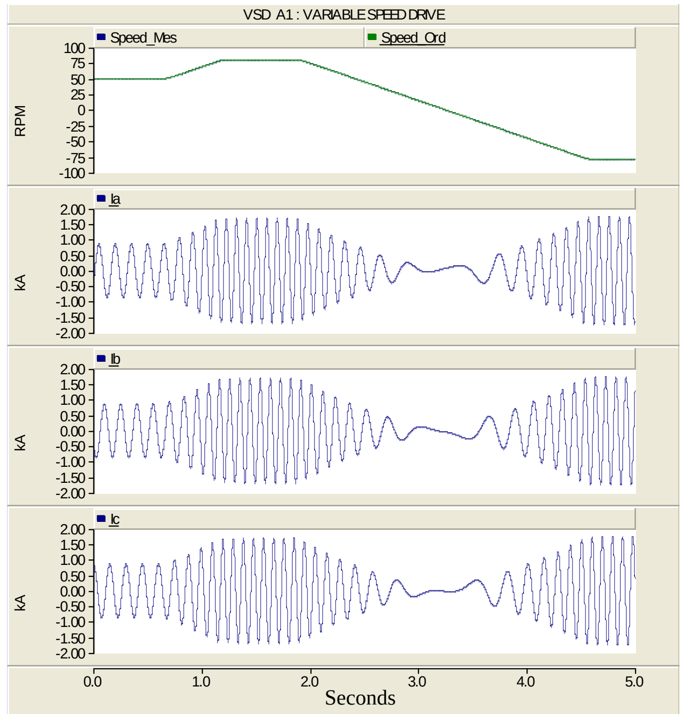

Figure 11: VSD Transient Response

The transient response of the main generator to changes in speed order is shown in Figure 12. The generator power output and its terminal voltage change with speed. The exciter maintains the steady-state voltage at 6.6 kV before applying the speed change. The exciter action to decrease the terminal voltage can be seen between 2.5 seconds and 4.0 seconds, when the terminal voltage is high.

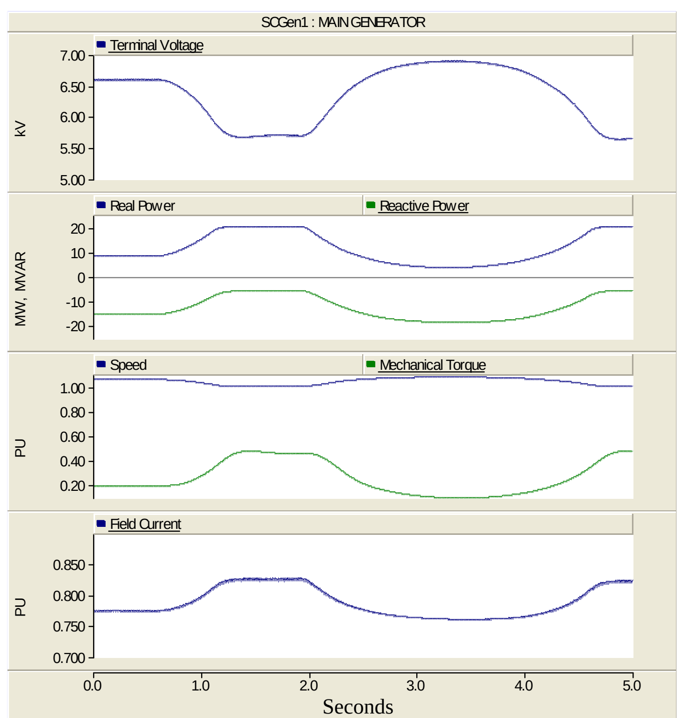

Figure 12: Main Generator Transient Response

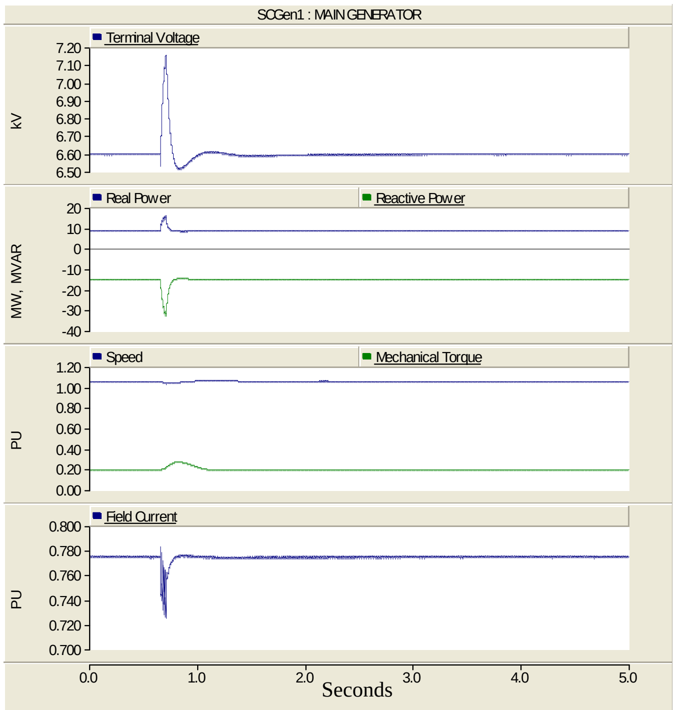

Figure 13: Simulation of Single Line to Ground Fault

The transient response of the main generator for a single-line to ground fault is shown in Figure 13. The fault is applied at the generator terminals for duration of 50 milli-seconds. A 3-phase to ground fault at the same location is shown in Figure 14.

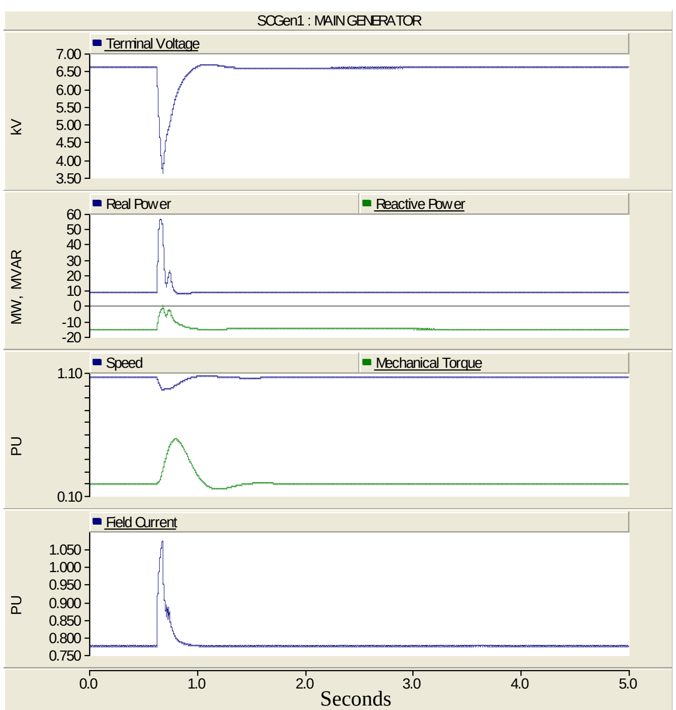

Figure 14: Simulation of a 3-Phase to Ground Fault

IV. Conclusions

The purpose of this simulation work was to develop a model for studying the dynamic behavior of the ship electrical system. PSCAD proved to be a suitable tool for this purpose. It enables modeling of electrical systems with full transient details. The default models available in the master library provided the entire model necessary to represent the ship electric system. The hierarchical modeling feature was very useful to design custom controllers such as exciters and governors using the control blocks included in default library. PSCAD also has convenient custom model interfaces to add models written in C, FORTRAN or MATLAB®. However, this study did not require the use of these advanced features. The PSCAD simulation tool is fast, flexible, modular and highly customizable.

IV. References

[1] Analysis of High-Temperature Superconductor Benefits for Ship Systems – Final Report, December 20, 2004. Work performed under ONR Contract No. N00014-04-C-0105

[2] S. S. Kalsi, N. Henderson, D. Gritter, O. Nayak and C. Gallagher, "Benefits of HTS Technology to Ship Systems", a paper to be presented at the IEEE Electric Ship Technology Symposium, Philadelphia, PA, July 2005.

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