EFFECT OF EM WEAPONS REQUIREMENTS ON THE ELECTRIC SHIP POWER SYSTEM

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The electric ship research effort at the University of Texas, Center for Electromechanics, is presently focusing on the development of a comprehensive model of ship power system. The model will allow the study of various architectures and power system configurations. The power system performance is assessed under prescribed scenarios that include representative mission profiles, advanced technologies in various system components, and fault mitigation. Particular attention will be given to the interaction of EM weapons with the whole power system and their effects on system stability. The potential benefits of an auxiliary energy storage system for EM weapons will be investigated. Initial analyses results will be presented.

INTRODUCTION

The electric ship research program at the University of Texas involves researchers from several departments and addresses several topics including power train technology, electrical distribution, electrically driven actuators for ship systems, thermal management, and control architectures. The Center for Electromechanics focuses on power train technology development. Our initial effort in this program was directed towards understanding issues associated with an electric propulsion power train. Results of a study which included the design and analysis of a 20 MW propulsion power train system were summarized in a recent paper [1]. Our present effort is a continuation of that work and is focused on the development of a comprehensive power system model that reflects the power system architectures envisaged for future electric ships. The goal of this model is to predict the behavior of the integrated power system under prescribed conditions and to assess the effects of individual components on the overall power system, as well as the performance of the technologies they encompass. High-power pulsed loads such as railgun systems will be given particular attention since their effective implementation on board Navy ships requires a very careful management of available energy.

The advent of the all-electric ship and recent advances in electromagnetic launch technology prompted a growing interest in the development of long-range naval railgun systems [2, 3, 4]. In addition to the benefits an integrated power system brings in terms of fuel savings, performance, redundancy, and many others, the level of installed electric power on new naval ships makes the integration of high power electric weapons, such as electromagnetic railguns, feasible. Advantages of this weapon system include range, lethality, improved time-of-flight, smaller and safer magazines, and cost. A high-firing-rate EM gun system (~10 rounds/minute), with a 200-500 km range, would require installed prime power in the range of several tens of MW, which is commensurate with the 80 MW power level projected for DDX ships. For the aforementioned range, the projectile's muzzle energy of ~50-100 MJ requires a power supply that can deliver several mega-amperes of currents to the rails in few milliseconds, and at medium voltages (several kV). This translates in *pulsed* power supplies of the order of tens of gigawatts. This requirement, clearly, shows that some sort of energy storage on board ships is necessary in order to satisfy the needs of high pulsed power railgun systems. The amount of stored energy depends on the railgun firing rate and the maximum number of shots that can be stored. Potential energy storage systems include flywheels, capacitors, batteries, fuel cells, and super-conducting magnetic energy storage systems. Some of these technologies are mature and well tested with improving performance, while others are still under development.

Authors' biographies

Dr. Joe Beno has BS and MS degrees in engineering physics and a PhD in electrical engineering. He is an Associate Director at the U.T Center for Electromechanics where he leads programs in electric vehicles, electric ship technology, and advanced vehicular suspension systems.

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Dr. Hamid Ouroua obtained his PhD, MS, and BS degrees in physics from the University of Texas, University of California at Los Angeles, and University of Algiers respectively. His work concentration is in EM design and analysis of electric machines.

Among these candidates, flywheels are the most promising energy storage systems. In this particular application they operate as high-power pulsed alternators that can provide several mega-amperes of pulsed current necessary to accelerate the projectiles to the desired hypersonic velocities (~ Mach 5-7). The advantages of a high-speed flywheel energy storage system are particularly attractive if additional constraints, such as high power density and efficiency, are imposed. A discussion on energy storage needs and requirements can be found in another paper presented at this conference [5].

POWER SYSTEM MODEL

A power system model that reflects the notional DD power system architecture was built in the Matlab/Simulink programming environment. Power electronics blocks and other components such as electric machines and transformers from Matlab/(Power System Blockset) toolbox were used whenever possible. While these pre-programmed blocks are useful in terms of ease of modeling, they are often limited in scope and flexibility and do not always run as expected. Simulation errors are often attributed to blocks with no means to correct the problem since one does not have access to them. A fact that often requires modifications of the model in order to get around the difficulties. This is a typical drawback for all pre-packaged programs to which Simulink and the Power System Blockset toolbox are not immune. Nevertheless, by introducing the necessary complexities to the model, such as adding more components, increasing switching frequencies, simulating faults, etc., in a gradual manner, progress towards completing the overall model can be made.

The model's components and their parameters are based, when available, on the published data related to the projected power system for DDX ships. The model consists of four gas turbines, four synchronous generators, switchboards, two propulsion transformers, two propulsion rectifiers, two PWM drives, and two permanent-magnet propulsion motors. The ship service section of the model has two load-center transformers, two rectifiers, a ship service transformer, an inverter, a DC-DC converter, several switches and breakers, and eight different loads. The pulsed power supply, which taps power from the main high voltage bus that connects the four generators, consists of a transformer, a rectifier, a PWM drive, and a five megawatt permanent-magnet motor that accelerates the rotor of a high power alternator to the desired speed. At the time of this writing, the pulsed power supply model has been completed up to the charging motor, while work on the alternator is continuing. A top-level representation of the actual Simulink model is shown in figure 1.

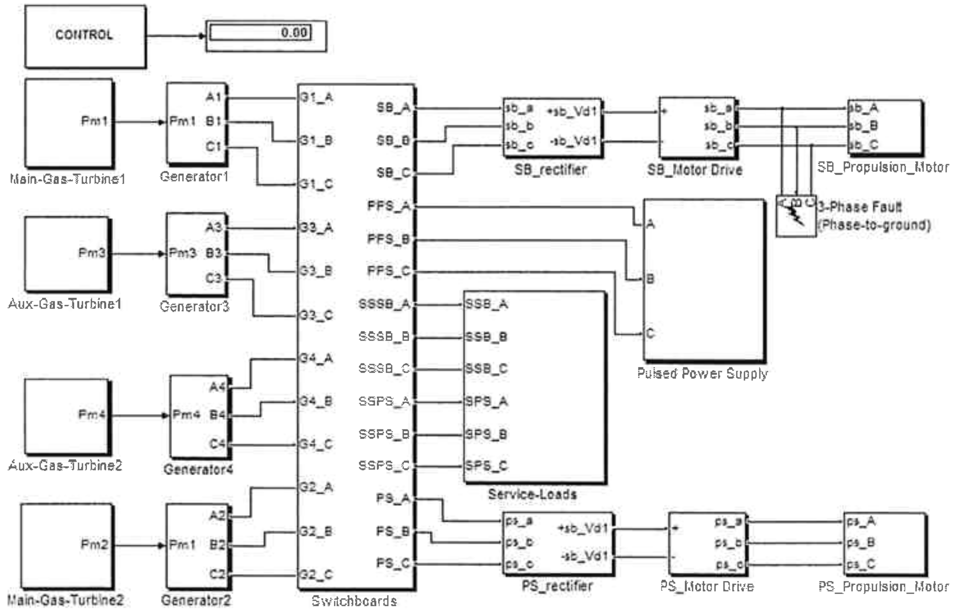

Figure 1: Top level Simulink model of power system.

The two main gas turbines and the two auxiliary gas turbines are rated respectively at 36 MW and 4 MW, giving a total installed prime power of 80 MW. These gas turbines reflect Rolls-Royce MT30 and MT5 engines which run at 3600 rpm. Consequently, the corresponding generators are also chosen to run at 3600 rpm, assuming that there are no gear boxes between the gas turbines and the generators. The generators' output voltage and frequency are, respectively, 13.8 kV and 60 Hz. This implies that the generators are 2-pole machines; a factor that affects machine size considerably, considering that high power density is a premium for future electric ships. While this direct connection between the turbines and the generators, and the choice of 60 Hz as generation frequency, seem to be the preferred choice in the Navy community, it is not obvious, however, that this is the optimum prime power generator-set in terms of power density and efficiency.

The windings of all AC components in the system are three-phase windings. The actual, high-torque, low-speed, propulsion motors will probably have a higher number of phases. We assumed a three-phase radial-flux permanent-magnet motor for simplicity during the initial development stage of the power system model. Propulsion motor models with the appropriate motor parameters will be developed once the correct number of phases, motor topology, and other parameters are known, and the overall power system model is more robust. The PWM inverters were chosen as motor drives for their proven effectiveness and continuing improvement in performance. The eight ship service loads include vital and non-vital loads for one zone when the zonal distribution concept is considered. Although some of the loads are controlled loads which include reactive power, we used only resistive loads for simplicity. The nature and magnitude of these loads were chosen to reflect typical loads in current Navy ships. An expanded version of the model presenting the various loads along with the prime movers and the propulsion power trains are shown in figure 2. The pulsed power model components are omitted for clarity.

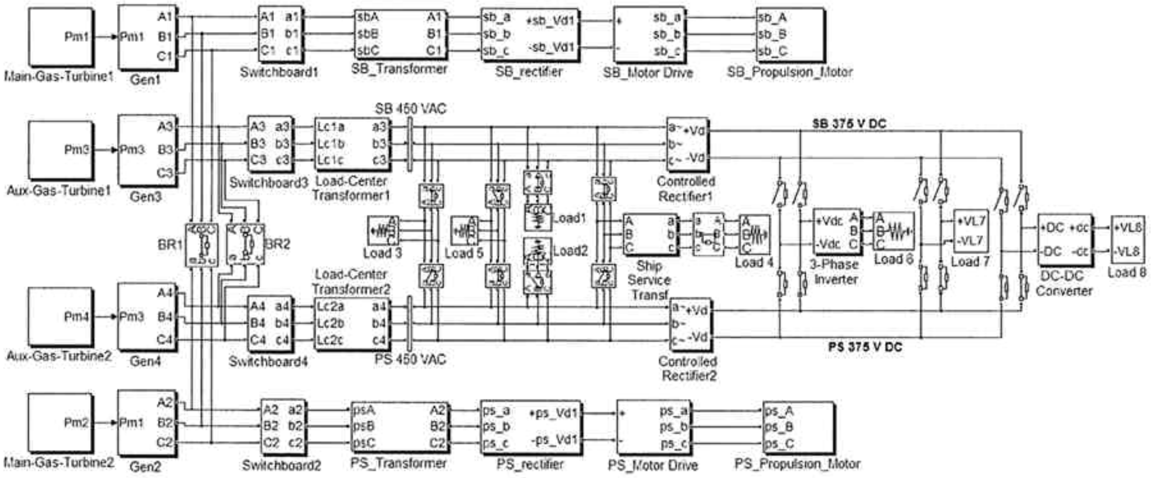

Figure 2: Ship service loads and their connections.

As can be seen in figure 2, vitals loads, 3, 4, and 5 are connected to two equivalent 60 Hz /450 VAC buses, while loads 6, 7, and 8 can take power from either 375 VDC buses. Breaker BR2 connects the two 4 MW auxiliary generators, Gen3 and Gen4, and breaker BR1 connects the two 36 MW main generators, Gen1 and Gen2. To this point the 36 MW generator-set and the 4 MW generator-set have not been connected together yet. In this power distribution configuration the main generators provide power to the propulsion power trains, while the auxiliary generators supply the ship service loads. All the generators will, eventually, be connected together to allow power to move from each source to any load when needed or when a power re-configuration scenario is considered.

SIMULATION EXAMPLES

To exercise the model, two examples simulating fault scenarios are presented. In the first example, one of the propulsion power train sections of the model was isolated from the overall power system model and ran independently. This is to illustrate the possibility to test smaller sections of the model, when it is not necessary to run the whole system. In this scenario, the ship is assigned a mission profile in which it is accelerated from rest to a speed of 30 knots, holds this speed for a short period, then, decelerates to a cruising speed of 20 knots. During this period a ground fault at one of the propulsion motor terminals is initiated then removed 20 milliseconds later. The effects of this fault are observed by monitoring currents and voltages at relevant places in the model. The following figures show some results of the events just described. Figure 3 shows the ship's speed profile and the corresponding motor speed command and actual motor speed. The motor speed command is calculated using motor power and ship speed data that are relevant to DDX ships. The torque command and the electromagnetic torque of the propulsion motor that was subjected to the ground fault are shown in figure 4. The response of the electromagnetic torque to the ground fault can be clearly seen. Motor currents profiles for the three phases are in figure 5. The results show the currents increasing and decreasing during the acceleration and deceleration segments of the mission, while they remain steady during the two cruising periods. The currents response to the ground fault is interesting in that they recover their equilibrium after several oscillations. It is important to note that in this example and the ones that follow, ship speed rates and simulation times were adjusted in order to run the full mission in a reasonable amount of time. Obviously, it takes a much longer time to accelerate the ship from rest to full speed. The goal of these exercises is to demonstrate the capabilities of the model and point out its shortcomings when appropriate.

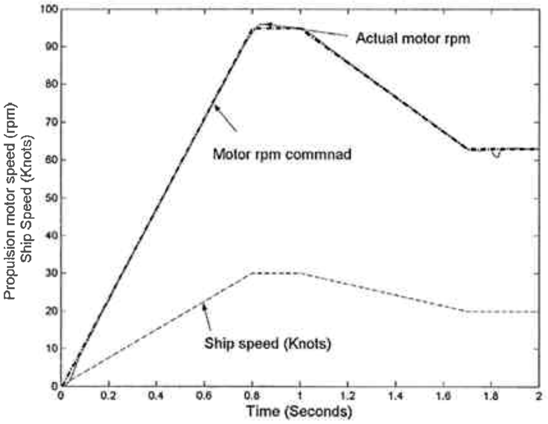

Figure 3: Ship speed profile and motor speeds.

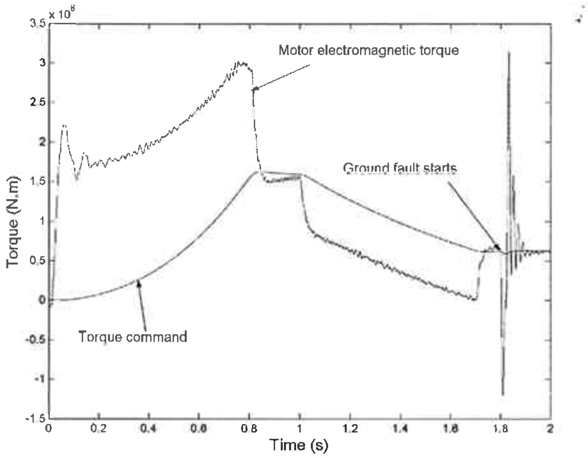

Figure 4: Motor torque command and electromagnetic torque.

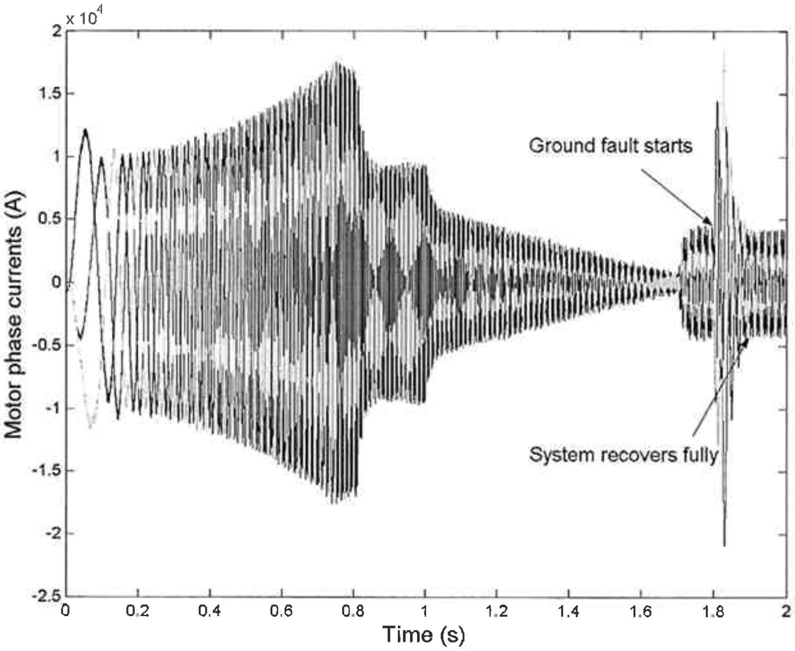

Figure 5: Motor three-phase currents

In the second example all components of the power system model, as shown in figure 1, are used. A similar mission profile was run with top and cruising speeds reduced to 26 and 15 knots respectively. While the ship is steady at 26 knots, power to one of the 450 VAC buses is lost. This fault is simulated by opening a breaker in switchboard3. To maintain or restore power to vital loads 3 and 4, the faulty bus is isolated by opening breaker BR2, and power to all non-vital loads 1, 2, 6, 7, and 8 is switched-off, to insure that enough power from the working bus is available for all vital loads. Finally, power from the second 450 VAC bus is switched-on to vital loads 3 and 4. During this part of the exercise the different breakers were closed and opened at different time intervals, from instantaneous switching to several milliseconds intervals, to observe the response of the power system to the disturbance.

In this example, the time between initiating the fault and restoring power to vital loads 3 and 4, by closing and opening the appropriate breakers, is one millisecond. The switching occurs at time t=0.95 s. Figure 6a and figure 7a, show the behavior of the voltages across vital loads 3 and 4 during the switching events. It is clear that just after the power is restored to loads 3 and 4, the voltages appear to be noisier. Power spectra of voltages across the loads taken just before and after the disturbance, shown in figures 6b-c, and 7b-c, indicate the level of noise generated by the switching exercise. So far, the model includes only a minimal complement of filters but we anticipate adding a more rigorous set as the model development progresses.

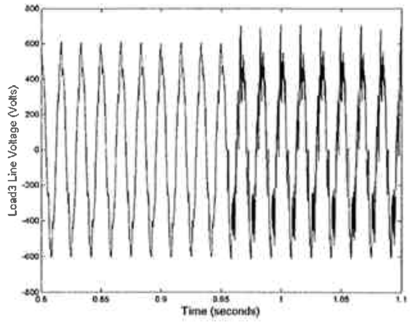

Figure 6a: Line voltage across load 3 before and after the switching event.

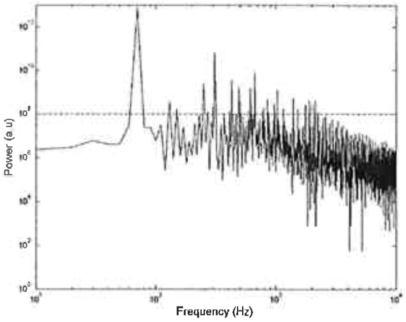

Figure 6b: Power spectrum of voltage oscillations in load 3 prior to the switching event.

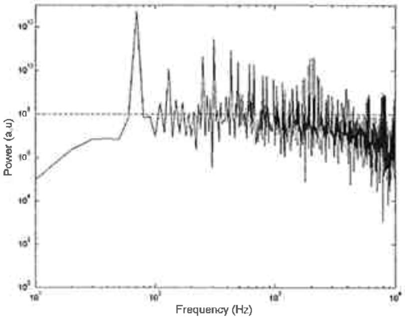

Figure 6c: Power spectrum of voltage oscillations in load 3 after the switching event.

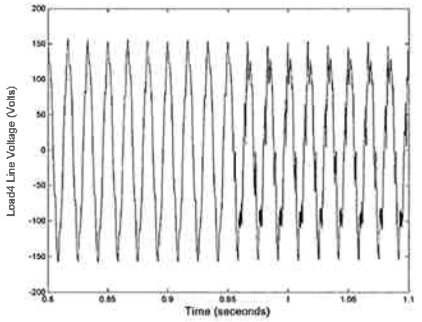

Figure 7a: Line voltage across load 4 during the switching event.

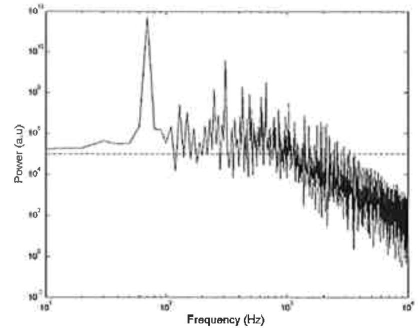

Figure 7b: Power spectrum of voltage oscillations in load 4 prior to the switching event.

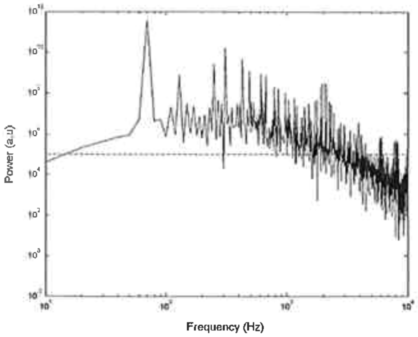

Figure 7c: Power spectrum of voltage oscillations in load 4 after the switching event.

EM GUNS AND SHIP POWER SYSTEM INTERACTIONS

As indicated in the introduction, electromagnetic railgun systems require pulsed power supplies in the gigawatt range. These pulsed supplies will need to be fed from the installed electric power on board. Consequently, there are concerns about a potentially detrimental interaction between the railgun and the ship power system. This concern would be totally legitimate if the railgun is kept connected to the ship power grid during the firing cycle. If, however, the railgun can be effectively isolated from the ship power grid during the firing cycle, then, the only interaction between the two systems would be during the charging cycle. This is a relatively slow process that, in principal, should not cause, or be subjected to, harmful transients. One of our immediate goals, in our modeling and simulation effort, is to address this railgun-power system interaction issue. We recently started working on a model of a railgun power supply as part of the ship power system model.

Based on CEM experience, for a 64 MJ muzzle energy, and a ~12 shots/minute rate, with 5 stored shots in the rotor of high-speed alternators, the required stored energy is ~ 800 MJ. For this application, approximately 8 CEM-type high-speed compensated pulsed alternators (compulsators [6, 7]) would be needed, with each storing 100 MJ with a power level of ~ 3 GW. In addition, each machine will need a charging motor, a motor drive, a transformer, a rectifier at the charging end of the supply, and a second rectifier at the output of the alternator. Usually, in CEM designs the charging motor and alternator are integrated within a single unit. However, in this initial study, the motor and alternator are modeled separately. Considering the shot rate and the stored energy discussed earlier, the charging motor power is ~ 5 MW (or ~ 6.5 MVA). Figure 8, is an expanded diagram of the pulsed power block shown in figure 1.

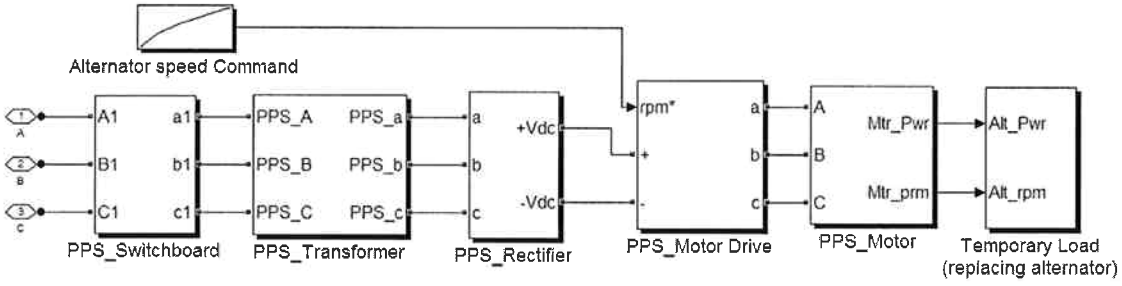

Figure 8: Model of the pulsed power supply for an EM gun.

The model shown in figure 8 represents only $1/8^{th}$ of the actual pulsed power supply for a railgun system with the parameters discussed earlier. The full model will contain eight sub-models similar to the model in figure 8, with outputs connected in parallel. This is obviously a very large model that will require large amount of computing resources, mainly simulation time and data storage.

The partial pulsed power supply model of figure 8 was integrated with the ship power system model and a simulation scenario was conducted. The components chosen for the pulsed power supply are as follows. The motor is a 5 MW, 18,000 rpm, 4-pole, permanent-magnet motor. The motor drive is a PWM drive similar to the ones used for the propulsion motors. A 13.8/4.16 kV, 7 MVA, Y/delta transformer; a diode rectifier, and a breaker connecting to the main high voltage bus complete the power train for the pulsed supply. The alternator is being modeled as a 2.8 GVA, 18,000 rpm, 4-pole synchronous generator. At the time of this writing, the model has not yet been completed. The scenario used in the second example was extended to include driving the pulsed power supply motor to its nominal speed and power. Spinning the 5 MW motor from rest to 18,000 rpm would take a very long time to run. Instead, the motor initial speed was set to a very high value, then, the motor is connected to the power grid and the rotor is accelerated until the desired speed is achieved. Once the motor achieves its rated speed, it is kept running at full power until the simulation ends. Some results of the simulation are shown in figures 9, 10, 11, and 12. Figure captions give a brief explanation of each. In summary, the charging of the pulsed power supply does not appear to cause any significant disturbance in the power system. However, in reality the pulse power motors will have to pull eight times as much power, and the response of the power system may be different. More runs and analyses are necessary to verify these observations.

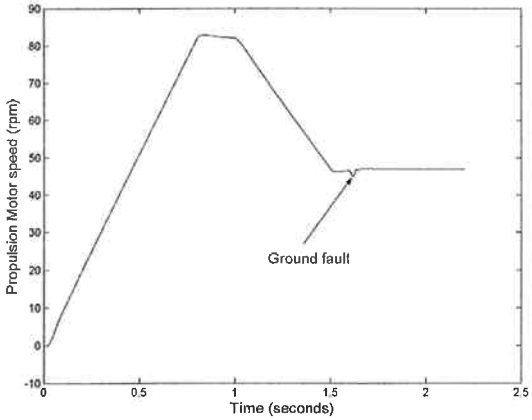

Figure 9: Propulsion motor speed is not affected during the charging of the pulsed power supply.

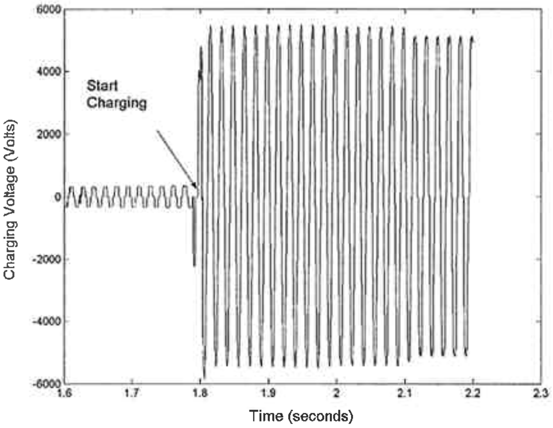

Figure 10: Charging voltage tapped from the main high voltage bus. Charging breaker closed at t = 1.8 s.

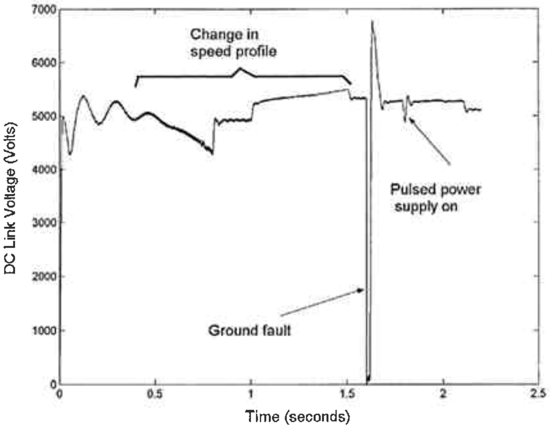

Figure 11: Propulsion motor PWM DC link voltage is not affected significantly during the charging process.

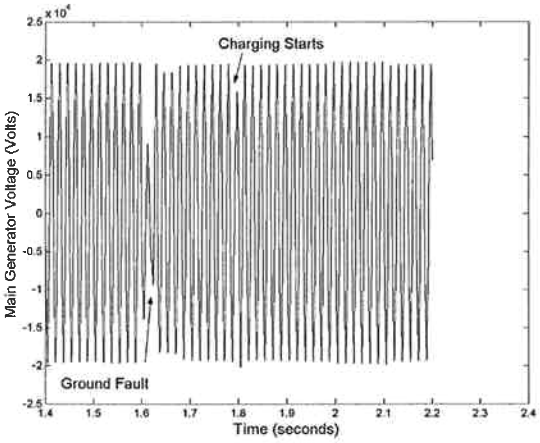

Figure 12: Main generator's voltage response to the ground fault and the charging event. No major disturbances observed.

SUMMARY

A Matlab/Simulink power system model for an electric ship was described and its goals and capabilities explained. The need for energy storage for pulsed power loads such as railguns was discussed and emphasized. The model was exercised by investigating fault scenarios including ground faults and switching events. A flywheel energy storage system–based pulsed power supply was described. Possible interactions between the power system and the pulsed power supply were discussed. A partial, component-based, model for the pulsed power supply was described and exercised concurrently with the power system. No major effects were observed when the pulsed power supply motor was pulling 5 MW out of the ship power grid.

ACKNOWLEDGEMENT

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