SOME BENEFITS OF PULSED ALTERNATORS AS ELECTROMAGNETIC GUN POWER SUPPLIES ON POWER SYSTEMS FOR FUTURE ELECTRIC SHIPS

By:

R.E. Hebner
J.A. Pappas
J.R. Kitzmiller
K.R. Davey
J.D. Herbst
A. Ouroua
J.H. Beno

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Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

Some benefits of pulsed alternators as electromagnetic gun power supplies in power systems for future electric ships

R E Hebner[1], J A Pappas, J R Kitzmiller, K R Davey, J D Herbst, A Ouroua, J H Beno

University of Texas at Austin

SYNOPSIS

An electromagnetic gun provides a new component to be integrated into the power system of an electric ship. Electromagnetic guns have been fired successfully using either capacitors, inductors, or rotating machines to store the energy for the shot. Because capacitors trail rotating machines by more than an order of magnitude in the stored energy density, fielded systems will likely use rotating machines even though other approaches are used in laboratory experiments. An interesting topology for the power supply is a set of pulsed alternators with sufficient energy stored in the kinetic energy of the rotors to power a sequence of shots. In this configuration, when no shot is required, which historically has been most of the life of the system, the machine topology is analogous to that of a flywheel battery used to provide ride-through capability and improve power quality in land-based power systems or to provide load leveling in hybrid vehicles. This similarity raises the possibility that the power supply could be designed to serve multiple roles under conditions of ship operation. The conceptual design of such a power supply of eight alternators storing a total of 800 MJ has been completed. Megawatt-level motor-generators operating at speeds up to 15,000 rpm have been designed, constructed, and tested. Simulations of future electric ship power systems show the utility of this storage for load leveling. In addition, these components provide storage for an uninterruptible power supply for critical ship loads in the case of the loss of a generator. An important unresolved problem is the design of bearings that will operate at high speeds reliably for long periods and survive the high levels of shock and vibration that will be encountered.

INTRODUCTION

Future electric ships will likely incorporate energy storage in their power systems. Important reasons storage is needed include:

- Emergency "ride-through" power to maintain operation in the event of the failure of a gas turbine. The stored energy can be used to continue operations until a gas turbine can be started.
- Load leveling. The stored energy can be used to accommodate short-term variations in the load so that the gas turbines can be used at nearly constant speed and near the peak of their efficiency.

Author's Biography

All authors are with the University of Texas Center for Electromechanics. The Center develops and commercializes advanced energy technology. This work focuses on electric ship technology. Dr. Robert Hebner is the Center Director and an IEEE fellow. Previously he was acting Director of NIST and program manager at DARPA. Mr. John Pappas is a Research Engineer and program manager for the Center's Railgun Pulsed Power program. Dr. Jon Kitzmiller is an Associate Director. His expertise lies in prototype pulsed rotating machinery design, manufacturing, and testing. Dr. Kent Davey is a Senior Research Scientist, an IEEE fellow, and editor of IEEE Trans. on Magnetics. His background spans topics in electromechanics, field theory analysis, and optimization, in which he has focused over the past 27 years, specializing at MIT in continuum electromechanics. Mr. John Herbst is a Senior Engineering Scientist and has been with the Center since 1985. He currently is the program manager for the $30M Advanced Locomotive Propulsion System Program. Prior to this assignment, Mr. Herbst served as Project Engineer on the 9 MJ Electromagnetic Range Gun System Program. Dr. Hamid Ouroua is a Research Associate and a member of the Center's Electric Ship program team. Dr. Joe Beno is an Associate Director and program manager for the Center's Electric Vehicle program.

- Support for high power, short duration loads. With energy storage, the power system does not need to be designed to supply high power, short duration loads. These can be fed using the stored energy. This design approach reduces the weight of the power system and so its efficiency.

Currently, the highest power load anticipated in a future electric ship is an electromagnetic gun. It is very likely that electromagnetic guns will incorporate storage as a way to reduce the size of the overall system. These storage systems will not be small, however. The amount of energy needed is hundreds to thousands of megajoules. Today's storage technology allows the construction of storage systems, which do not involve combustible fuels, that are in the range of 1-100 kJ/kg. Technologies in this range include capacitors, room temperature and superconducting inductors, batteries, fuel cells, and flywheels.

Not only would the electromagnetic gun be the highest power load, but it is a load that is seldom used over the life of the ship. This raises the possibility of using the storage needed by the electromagnetic gun as beneficial storage for the remainder of the ship. This would put the storage system in continuous use.

Because the application calls for hundreds of megajoules of stored energy, the choice was made to use a rotating machine for storage in this investigation. Rotating machines are in service with power and energy densities that are an order of magnitude larger than those of capacitors, and systems under development are approaching two orders of magnitude higher densities [1]. This makes the rotating machine solution significantly smaller and lighter than a capacitor solution.

Rotating machines and batteries have about the same stored energy density. However, the power density is somewhat better in a rotating machine. But the critical issue in this application is lifetime. While rotating machines show no degradation after more than 10^5 discharges [2], batteries have a much shorter lifetime.

It is also expected that the rotating machine storage solution would have a longer life than would a capacitor storage solution. Both capacitors and rotating machines are successful, long life components in ship power systems. The effort to increase the energy density of each adds stress to each that leads to life concerns. For rotating machines, higher energy density is typically associated with higher rotational speed, which leads to some reduction in bearing life. For capacitors, higher energy is typically achieved by operating at higher voltages, which reduces life.

This assessment of the state of the art led to an initial focus on rotating machines as the storage medium. It was necessary to make the choice of a specific storage medium to permit system modeling. If technology evolution leads to a different choice of storage medium, the analysis approach would be similar.

ELECTROMAGNETIC GUN

A conventional topology for a rail gun system is shown in Fig 1. The prime power for the system is provided from the ship's power grid. Conceptually, the drive motor uses the power from the grid to accelerate the rotor, storing the energy in the rotating mass. At this point, the system has the same active components as a flywheel energy storage system that is used to provide backup power to a factory or computer center [3]. So if the motor is designed properly, the mechanical energy in the spinning rotor can be extracted from the rotor and converted to electricity for such applications as improvement of power quality, ride through power for outages to permit an additional gas turbine to be brought on line, or supplemental power for large pulsed loads.

To provide power for the rail gun, a capacitor is discharged through the rotor winding. The induced current in the stator is then fed back to the rotor to bootstrap the system to full power. This process typically requires less than 30 ms. When full power is achieved, the alternator is discharged into the rails of the rail gun. The electrical energy stored in the barrel when the projectile leaves is then recovered and used to increase the rotational velocity of the rotor.

To determine some of the system performance characteristics, a preliminary design of a conceptual alternator set to fit ship systems was developed. The system is composed of eight alternators storing a total of 800 MJ. The selection of the stored energy helps to set the mass and rotational velocity of the rotor. This set of eight alternators, configured in sets of two for torque management as shown in Fig 2, requires a volume of about 18 m^3 and has a mass of almost 22,000 kg leading to a stored energy density of 36 J/gm and a specific energy density 44 MJ/m^3. The number of shots stored in the rotors, i.e., the maximum number of shots before re-motoring is necessary, is 5. In this design, the system efficiency, including the alternator, connecting cables, connections, and rails, is 41%. The system is designed to have about 20% more capacity than is expected to be necessary. This design is conservative. An important measure of the design conservatism is the stress in the outer banding of the rotor. This banding provides the mechanical restraint for the rotor winding. The stress produced is a function of the mass and mass distribution of the rotor as well as the rotational velocity. The stress is below 1.6×10^9 Pa, which is one half to two thirds the ultimate strength of applicable composite materials.

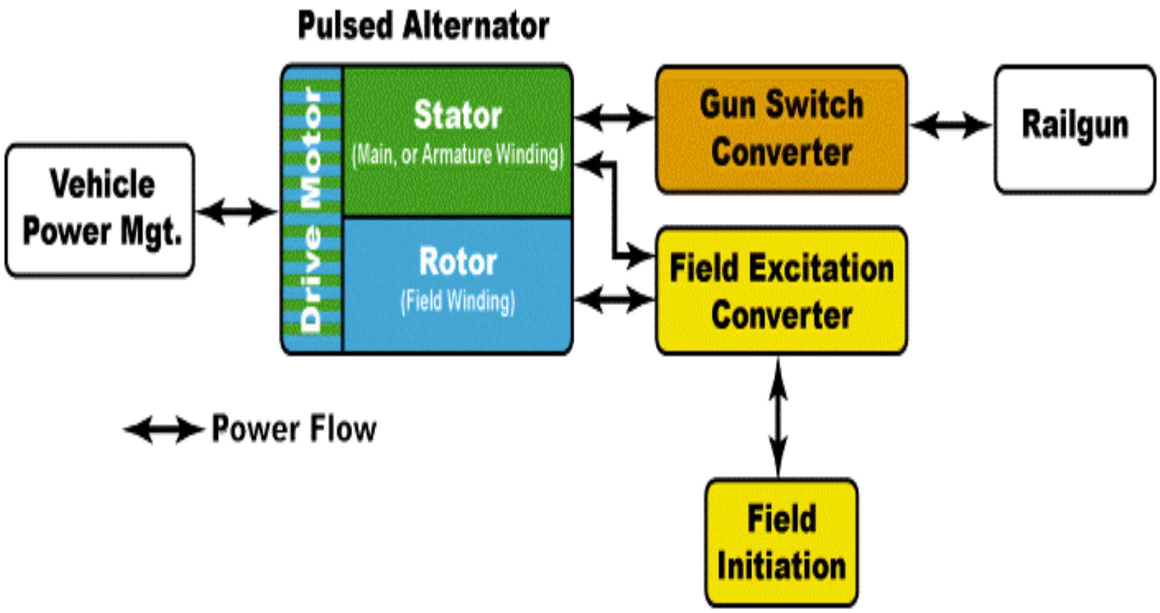

Fig 1 Block diagram of a rail gun power system

To underscore the conservatism of the design, alternators shown in Fig 2 constitute a quarter of the total system, storing 200 MJ. Fig 3 shows an energy storage flywheel under test that is designed to store more than 400 MJ. It is clearly more energy dense than the preliminary ship system design.

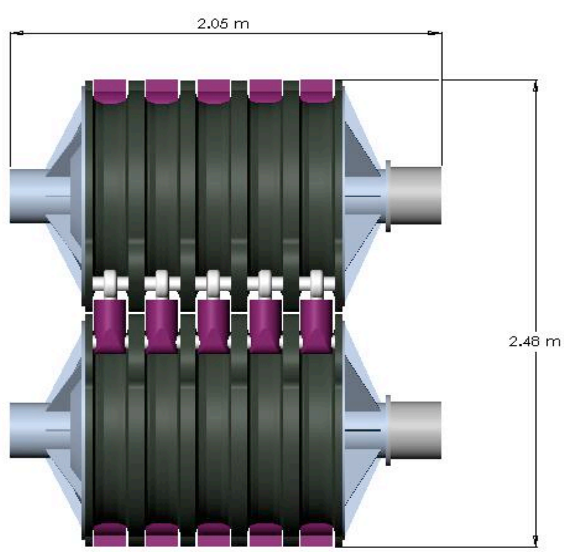

Fig 2 Drawings of a set of two of the anticipated pulsed alternators

Fig 3 Flywheel designed to store more than 400 MJ

Motor-generators

The design assumes each of the alternators is connected to a 5 MW motor-generator to deposit energy in and extract energy from the flywheel. These devices must operate at rotational velocities up to 15,000 rpm to eliminate the need for a high-speed gear box. The physical size of these components can be estimated by scaling from systems for similar applications. The basic scaling law is [4]

$$P = 2\pi J B_{gap} R^2 L t \omega, \tag{1}$$

where P is the electrical power, J is the current density in the stator, B_{gap} is the magnetic field in the air gap between the rotor and the stator, R is the air gap radius, L is the active length of the machine, t is the winding thickness, and ω is the mechanical rotational frequency of the rotor. The winding thickness, t, is the equivalent thickness of the stator winding spread over the air gap radius; it is approximately the slot depth times the conductor packing fraction times the ratio of slot span/(slot span + tooth span). This parameter is typically about ¼ of the slot depth.

The backiron behind the stator tooth is typically a fraction of the stator slot depth. Let βt represent the depth of the slot plus the thickness of the stator backiron. The index β is typically about 6. The volume, V, of the machine is

$$V = \pi\left(R + \beta t\right)^2 L \approx \pi\left(R^2 + 2R\beta t\right)L, \tag{2}$$

where the approximation applies when R is reasonably large compared to βt. In this same limit, the power per unit volume follows as

$$\frac{P}{V} = 2 J B_{gap} t \omega \left(1 - \frac{2\beta t}{R}\right) \tag{3}$$

From this expression, it is clear that trading (increasing) the working radius for length L (decreasing) is a better swap when volume is important. It is common to set the working radius as high as mechanical constraints allow given the operating speed as the first design decision. L is subsequently set by power demand. Equation (3) also highlights the limits available to the machine designer. J is set by thermal considerations, varying only to the extent that active cooling and shorter duty cycles are employed. B_{gap} is constrained by the saturation of the steel. While more formal optimization tools for sizing are available [5], they are not appropriate at this level of system definition.

Two examples are selected to help quantify the size of the motor-generator required for use in this application. One is a generator to produce prime power for a hybrid train. The power and speed ratings of the generator were selected to interface with 3 to 4 MW range gas turbines with output speeds ranging from 12,000 to 15,400 rpm, such as the Honeywell TF40/50 or the Pratt & Whitney ST40 engines [6, 7]. Table I provides a summary of the generator design parameters.

Table I Generator design parameters

Power	2.5 MW continuous
Voltage	963 V L-N / 1668 L-L
Current	910 A
Power Factor	95%
Speed Range	12,000-15,400 rpm
Max. Ambient Temp.	50° C
Altitude	Sea Level to 2400 m
Temperature Rise	170° C

Operating the generator at the power turbine output speed eliminates the need for a speed reducing gearbox and significantly reduces the operating torque, and therefore, size and weight, of the generator. The speed reducing gearbox for the existing turbine-electric locomotive weighs approximately 985 kg and each of the two 4,000 rpm alternators weighs approximately 1,460 kg. In contrast, this generator only weighs 980 kg. The generator is approximately 0.71 m in diameter x 1.37 m in overall length. Fig 4 shows a picture of the fully assembled generator.

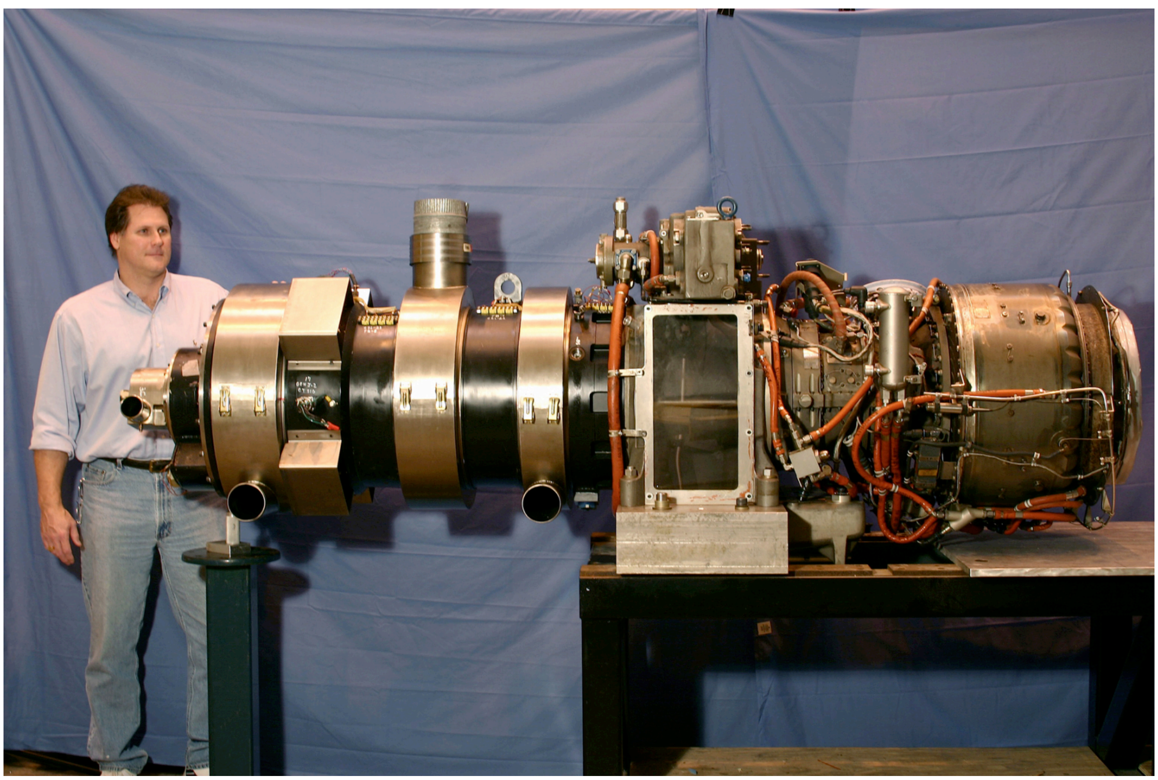

Fig 4 A 2.5 MW continuous-duty generator (attached to a gas turbine) with a design rotor speed of about 15,000 rpm

The second comparison machine is a motor/generator sized to provide a 2 MW power rating for charging and discharging a flywheel to meet the intermittent supplemental power demands of a locomotive. The operating speed range of the motor generator is 7,500-15,000 rpm to match the flywheel. A two pole, three phase squirrel cage induction machine topology was chosen for this application for its relative simplicity and high reliability. The motor/generator is approximately 0.86 m in diameter x 1.04 m in overall length and weighs 1,900 kg. The characteristics of this machine are summarized in Table II. The stator for this machine is shown in Fig 5.

Table II Motor/generator design parameters

Power	2.0 MW
Voltage	1,100 V L-L / 250 Hz
Current	1,200 A rms
Efficiency	96.5%
Speed Range	7,500-15,400 rpm
Max. Ambient Temp.	50° C
Altitude	Sea Level to 2400 m
Temperature Rise	135° C

Fig 5 2 MW motor/generator designed to work with a flywheel that stores more than 400 MJ when spinning at 15,000 rpm

Ship Modeling

In our initial modeling and simulation effort, a power system model that reflects a notional ship power system architecture was built in the MATLAB®/Simulink® programming environment. The ship power system is shown schematically in Fig 6.

The MATLAB®/Simulink® environment was selected for this task due to its widespread use and compatibility with the Virtual Test Bed (VTB), a programming environment specially developed by the research staff at the University of South Carolina for naval applications [8]. Power electronics blocks and other components, such as electric machines and transformers from MATLAB®/Power System Blockset toolbox, were used. The model's components and their parameters were based, when available, on the published data related to the projected power systems for ships. The model consists of four synchronous generators, switchboards, two propulsion transformers, two propulsion rectifiers, two PWM drives, and two permanent-magnet propulsion motors. Realistic models for the projected prime movers, which consist of four gas turbines, were not yet completed. 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 top level MATLAB®/Simulink® model of the initial power system, without the storage, is shown in Fig 7.

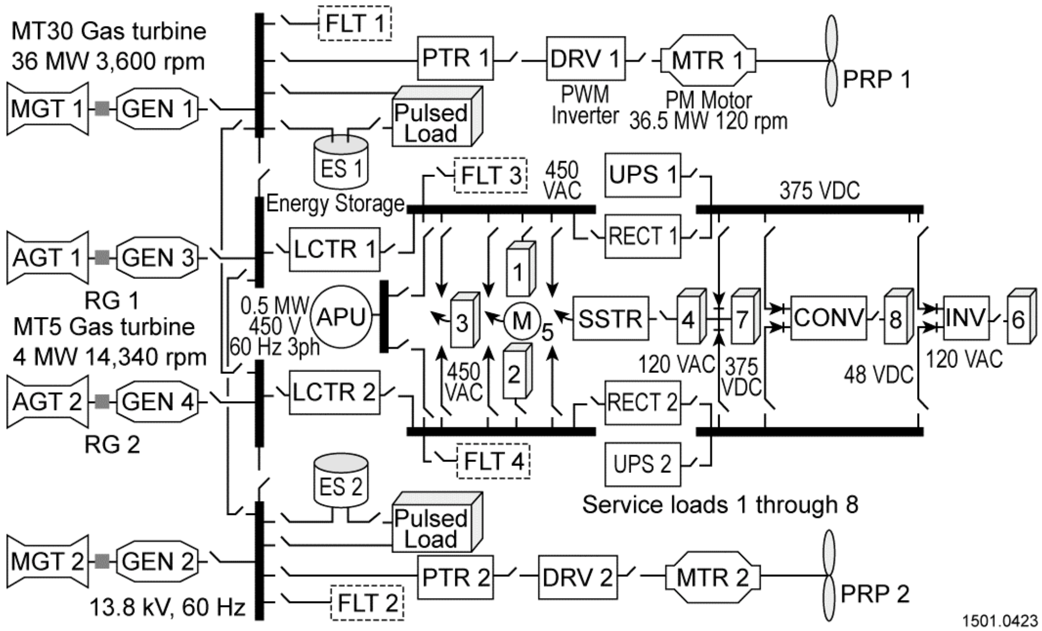

Fig 6 Summary of the notional power system that was used for the analysis

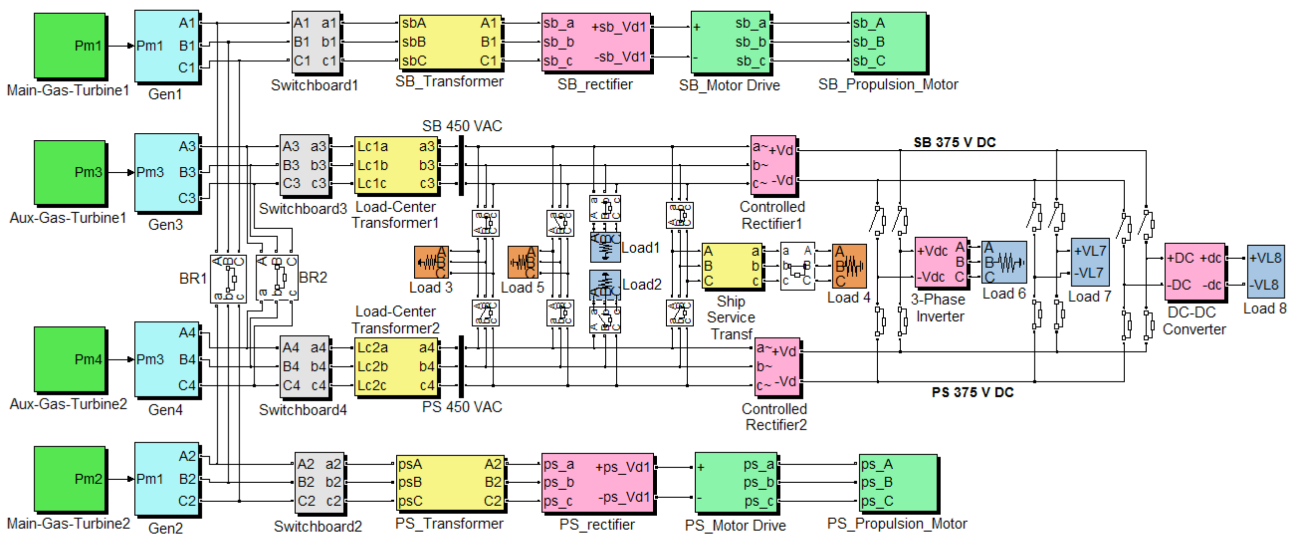

Fig 7 Top-level MATLAB®/Simulink® initial power system model

To illustrate the use of the model, an example simulating a fault scenario is presented. 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 of time, 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 the fault are observed by monitoring currents and voltages at relevant places in the model. Figs 8 and 9 show some results of the event just described. Fig 8 shows the ship's speed profile and Fig 9 shows the motor current profiles for the three phases. 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, as expected. The current's response to the ground fault shows a gradual recovery after several oscillations. It is important to note that in this example, 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 this exercise was to demonstrate the capabilities of the model and point out its shortcomings when appropriate. As previously mentioned, this model used component models from the Power System Blockset toolbox. While these pre-programmed blocks are useful in terms of ease of modeling, they are often limited in scope and flexibility. This is not a particular problem with this software, but a limitation of all pre-packaged programs.

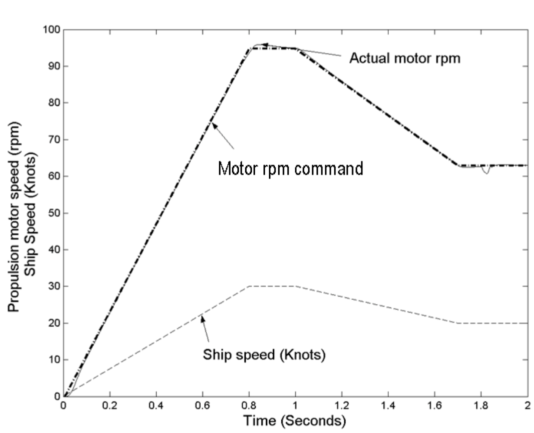

Fig 8 Ship mission (speed) profile

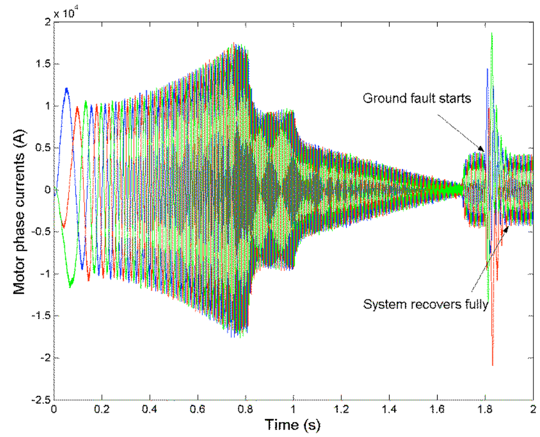

Fig 9 Motor current with ground fault

In order to improve the model performance and capabilities, the electric ship power system model was rebuilt without the use of the preprogrammed components from the commercial toolbox. In addition to MATLAB®/Simulink®, other programming environments were investigated. These were ACSL, another commercial software, and the VTB. This effort was driven by the desire to find a programming environment that has better simulation capabilities and faster execution time. The two commercial codes and the VTB proved to have little difference in execution time or in ease of use for this particular application.

The Simulink® model built with only native library components (Fig 7), i.e., not the pre-built commercial blocks, was used to analyze a power transfer scenario involving the loss of a main generator supplying one of the propulsion power trains while the ship is at full speed, and transferring power from the other generator supplying the second power train. Results describing the effect of the fault and the power transfer process and the ship speed and motor voltage are shown in Figs 10 and 11.

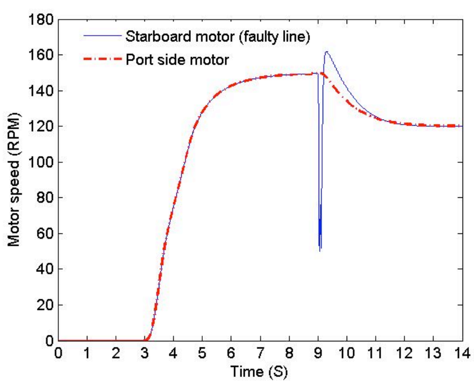

Fig 10 Propulsion motor speeds

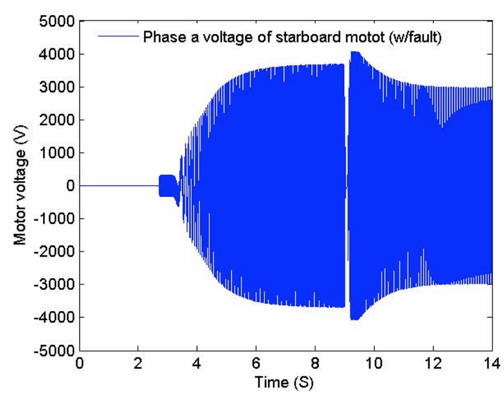

Fig 11 Motor phase voltage with fault

The Simulink® model was recently expanded to include pulse power systems, mainly, an EM rail launcher (EML) and a free electron laser system (FEL). The energy storage system was sized for projectiles with 64 MJ muzzle energy, 12 round/minute shot rate, and the energy needed for five consecutive shots was stored in the rotating mass. The model consists of eight high-speed pulsed alternator sets. Each set includes two rectifiers, a pulse-width-modulated motor drive, a 5 MW charging motor, and breakers and switches. A top level schematic is shown in Fig 12.

Fig 13 shows an example, including pulse current and voltage traces, in which an EM gun shot is taken while the ship is cruising at 20 knots. Fig 14 shows the response of the bus voltage to the high power pulse. This simulation suggests that, while uncontrolled rapid charging of the system could distort the power grid for a few cycles, the discharge has no effect. It is likely the charging effects can be mitigated by better management of power demands, including, as an extreme measure, diverting power from propulsion for a fraction of a second.

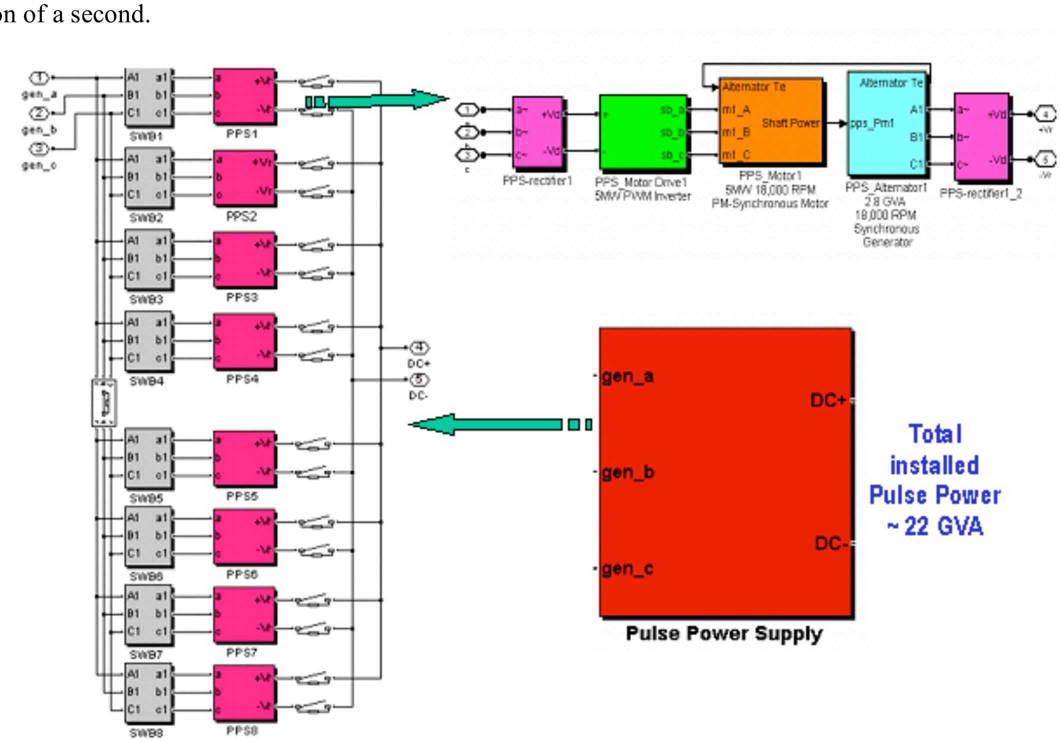

Fig 12 Circuit model of a ship power system with pulsed load

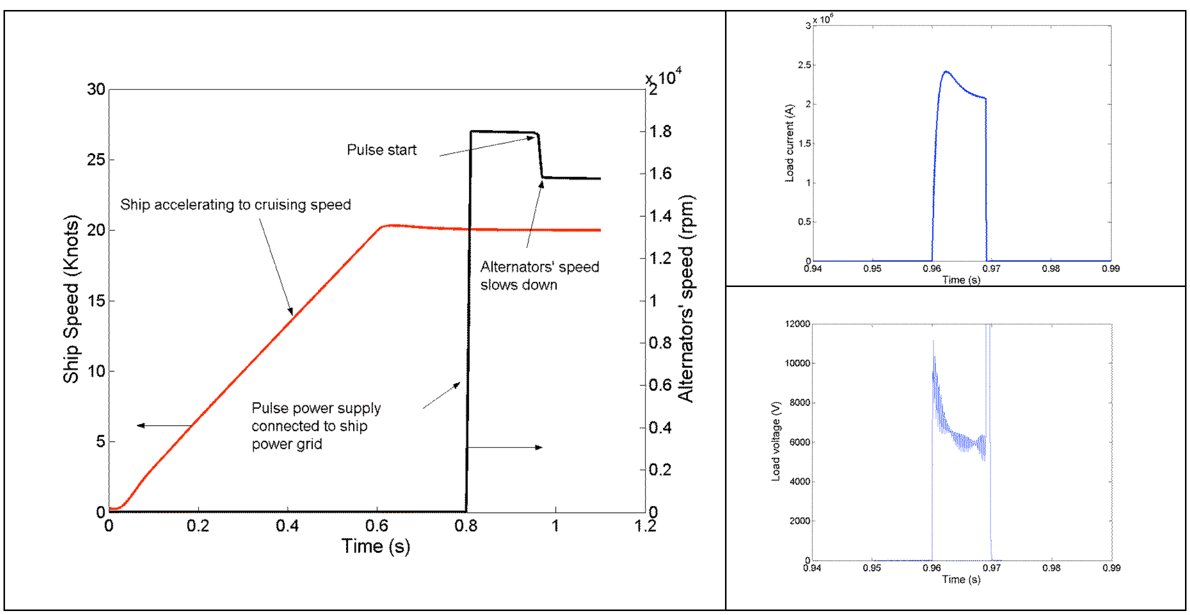

Fig 13 Example of an electromagnetic gun firing at a speed of 20 knots

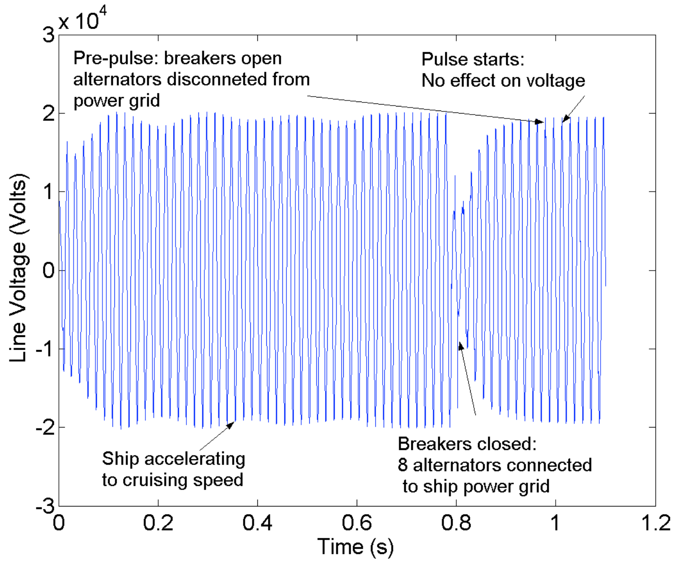

Fig 14 Maximum effect of charging of electric gun system and gun firing on a ship's bus voltage

CONCLUSION

The intermittent nature of high power pulse loads onboard future naval vessels makes the pulse power supply a highly inefficient subsystem, in terms of power density, if it is used solely for its primarily purpose. In order to enhance its functionality, this research explored the potential use of the energy stored in the rotors of high-speed alternators of a naval EM gun power supply, and its power electronics components, as an active filter to reduce harmonic pollution generated by various power conditioning equipments.

While significant development work is needed to reliably capture the potential benefits highlighted here, it appears that there may be important advantages to incorporating an electromagnetic rail gun, powered by advanced alternators, in a future electric ship. The energy storage required for the application shows promise for producing significant improvements in the efficiency, reliability, and quality of the ship's power system for the majority of the ship's life when the rail gun is not in use.

ACKNOWLEDGEMENTS

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