AN ELECTROMAGNETIC GUN POWER SUPPLY AS A COMPONENT OF AN ELECTRIC SHIP POWER SYSTEM

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Abstract

An electromagnetic gun provides a new component that must be integrated into the power system of an electric ship. 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 the shot. In this configuration, when no shot is required, 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. This paper expands upon earlier published work showing worst case perturbation to the power system, in this approach, and the use of the pulsed alternators as high-energy active filters to improve power system performance.

Introduction

A conventional topology for a rail gun system is shown in Figure 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 [1]. 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.

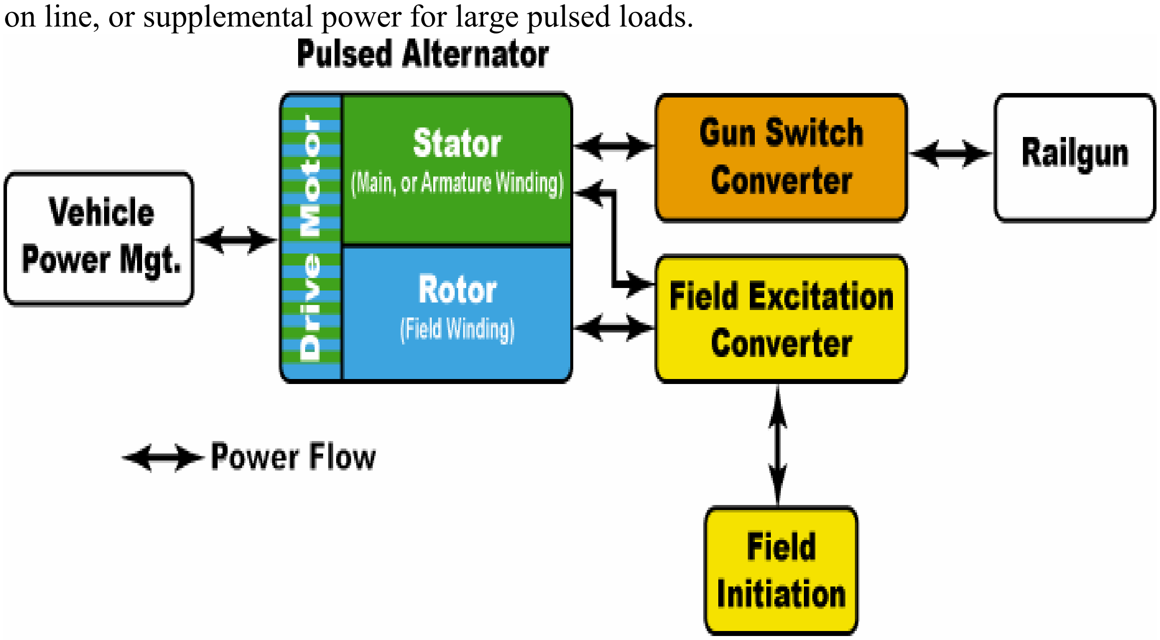

FIGURE 1 Block Diagram of Rail Gun Power System

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.

Alternator Characteristics

To determine some 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 Figure 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.

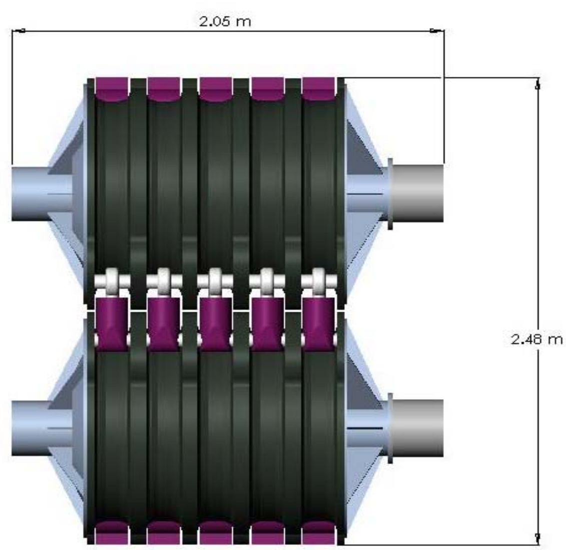

FIGURE 2 Drawings of a Set of Two of the Anticipated Pulsed Alternators (The alternators are configured in counter-rotating pairs for torque management.)

Motor-Generators

The design assumes each of the alternators is connected to a 5 MW motor-generator. 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 [1]

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

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

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

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.

Three machines 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. Table 1 provides a summary of the generator design parameters.

TABLE 1. 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. Figure 3 shows a picture of the fully assembled generator in the laboratory at the University of Texas.

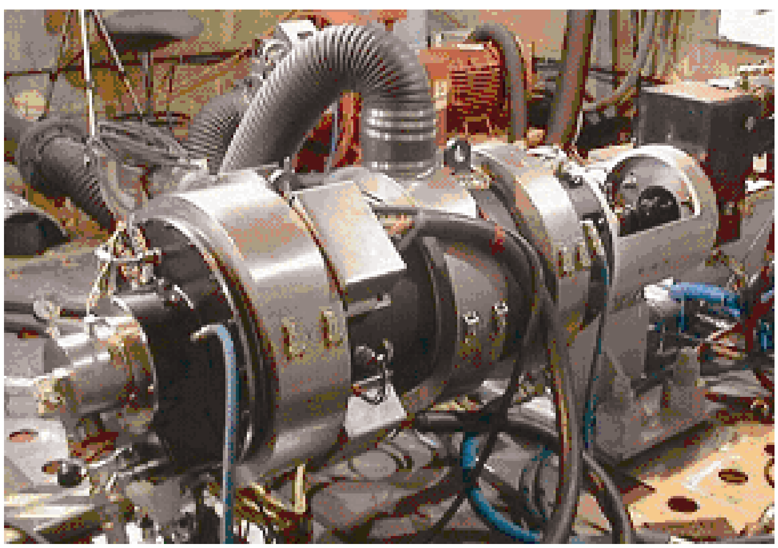

FIGURE 3 A 2.5 MW Continuous-Duty Generator with a Design Rotor Speed of about 15,000 rpm

The second comparison machine is a motor/generator sized to provide a 2 MW power rating for charging and discharging of a flywheel to meet the intermittent supplemental power demands of the 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 2. The stator for this machine is shown in Figure 4.

FIGURE 4 Stator of a 2 MW Motor/Generator Designed to Work with a Flywheel that Stores more than 400 MJ when Spinning at 15,000

TABLE 2. 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

The final generator was designed but is not yet under construction. It is a generator with a rotor employing high temperature superconductor (HTS) windings. The machine is a four pole, 6 phase design using YBCO field windings on the rotor. The baseline design is rated for 5 MW continuous duty at 15,000 rpm. The generator is approximately 0.53 m in diameter x 0.89 m in overall length and weighs 532 kg. A drawing of this conceptual design is shown in Figure 5.

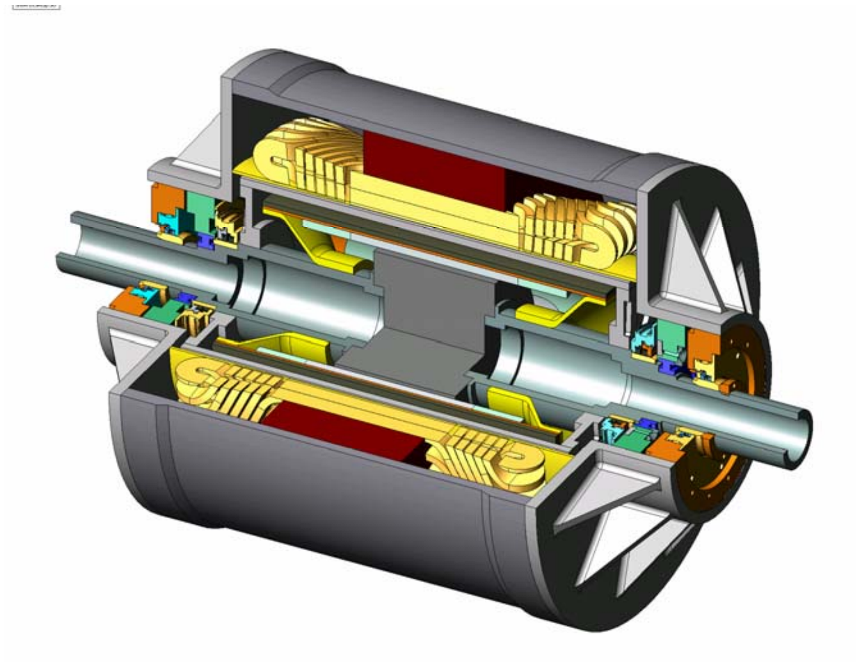

FIGURE 5 Conceptual Model of a Superconducting Motor-Generator that Operates at 15,000 rpm

Electrical Performance

A Simulink® model of a naval electromagnetic rail gun power supply was developed. The power supply was sized for projectiles with 64 MJ muzzle energy, 12 round/minute shot rate, and five stored shots. It 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 Figure 6. Figure 7 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. Figure 8 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.

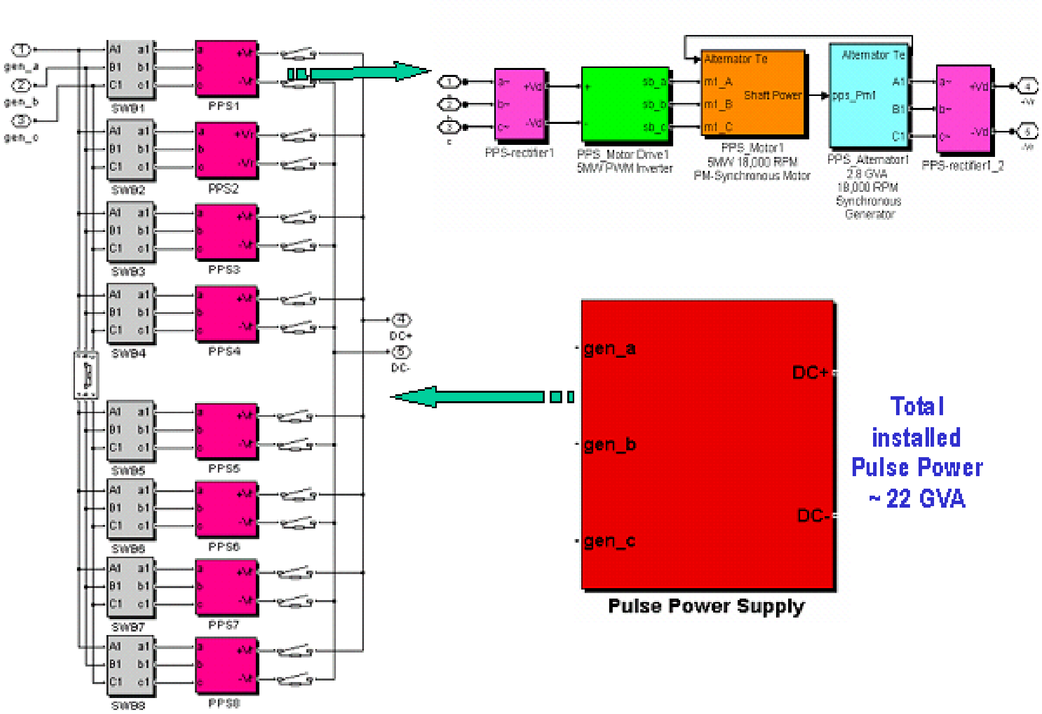

FIGURE 6 Circuit Model of a Ship Power System with Pulsed Load

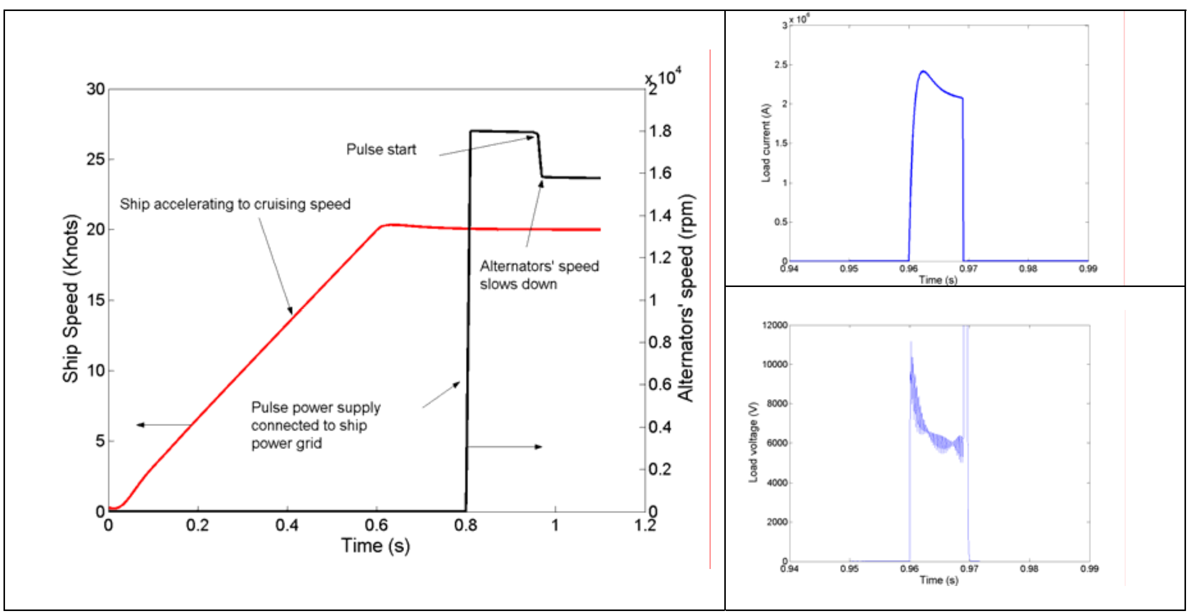

FIGURE 7 Example of an Electromagnetic Gun Firing at a Speed of 20 Knots

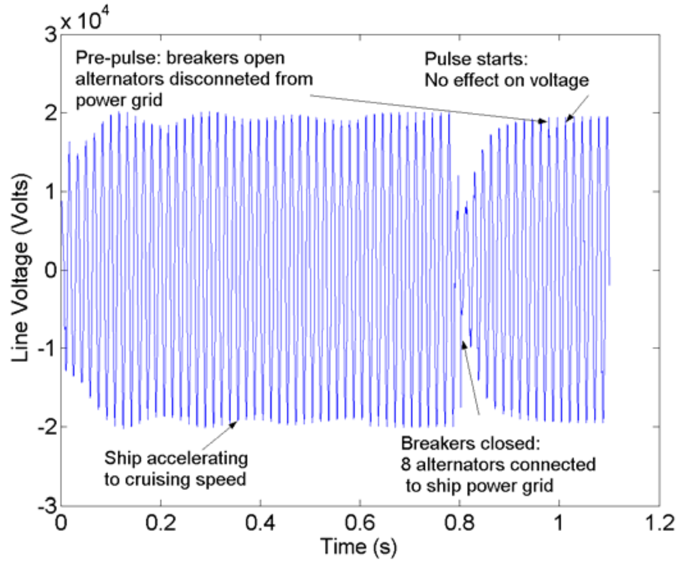

FIGURE 8 Maximum Effect of Charging of Electric Gun System and Gun Firing on a Ship's Bus Voltage (It is maximum in the sense that no efforts in power management were made.)

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.

It may also be possible to use this stored energy to power other loads, but that application requires further study. To demonstrate the feasibility of this dual-function, a Simulink® model of a propulsion power train, with an integrated pulse power supply and active filter, was developed. Figure 9 shows the top level model where, for simplicity, only a single propulsion power train and a single 36 MW generator were used. The energy storage block and an inverter were explicitly extracted out of the pulse power supply to clearly show their dual use with the help of the various switches shown.

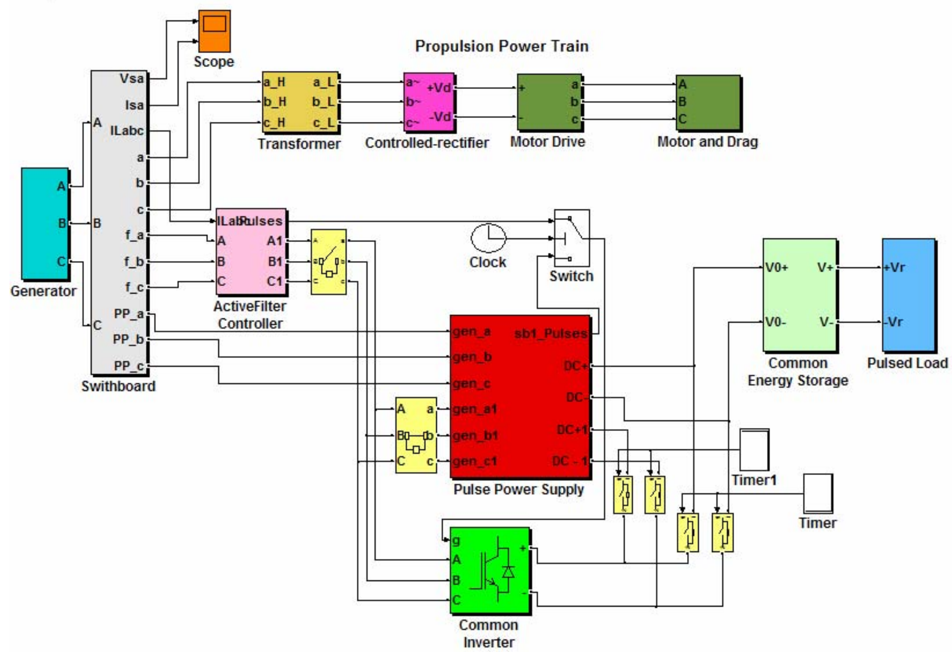

Figure 9 Circuit Model for Active Filtering

The active filter works by injecting currents into the distribution lines to eliminate harmonic currents, or reduce their detrimental effects, on sensitive loads. The energy storage components are the rotors of the eight alternators of the naval EM rail gun power supply, as mentioned earlier, and the DC link capacitors to which they are connected. The control block consists of a calculation block, a hysteresis control block, and an LC filter to reduce inverter switching harmonics.

When separate energy storage elements and inverters are used in the model, i.e., filter and pulse power supply components are independent, the simulation runs relatively well given the complexity of the model. In this example, the propulsion power train is consuming ~11 MW to keep the ship moving at cruising speed of 20 knots. Active filtering results are shown in Figures 10 and 11 where the total harmonic distortions in the voltage and current are reduced from 6.7% to 4.2% and from 28.5% to 8.2%, respectively. While the voltage and current signals are improved, the filtering is not perfect because, in part, the filter parameters are not optimized. Also, the presence of high frequencies in the resulting signals is due to the fact that only a single inverter is modeled, thereby requiring very high switching frequencies (> 30 kHz). Using additional inverters, from the eight available, should reduce the required switching frequency considerably and improve signal quality.

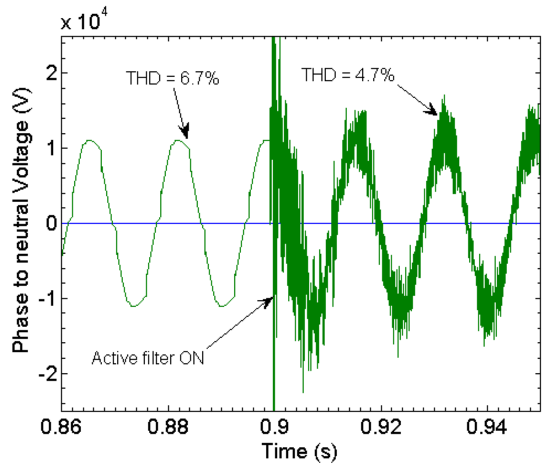

FIGURE 10 Voltage With and Without Active Filtering

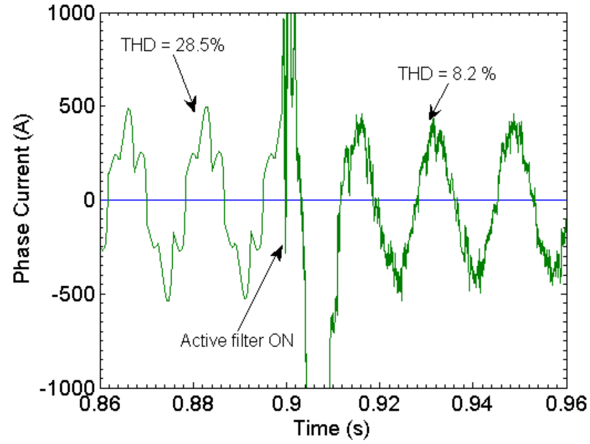

FIGURE 11 Current With and Without Active Filtering

Conclusion

While significant development work is needed to reliably capture the potential benefits highlighted here, it appears that there may be important advantages to incorporate 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.

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Acknowledgements

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