Controls for Minimizing Ship Power System Frequency Fluctuations

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ABSTRACT

The application of large load steps to the power system of an all-electric ship raises power quality issues since sudden changes in electrical loading on synchronous generators can cause their output frequency to fluctuate widely as the prime mover adjusts to meet the demand. This paper explores three control strategies for minimizing the fluctuations of generator frequency during load-step disturbances. These strategies include reducing propulsion motor power demand, accessing propulsion motor regenerative power, and applying regenerative power from a dedicated capacitor energy storage device to the generator bus. The performance of each control strategy was examined using a large-scale, real-time digital simulation model of a notional ship system. The simulation results demonstrate the control strategies' effectiveness in eliminating load-step frequency disturbances as well as limiting their magnitude to the level of military standards for shipboard systems.

***Index Terms*— IPS, energy storage, shipboard power systems, modeling and simulation, load steps, RTDS;**

INTRODUCTION

One of the design challenges for the next generation integrated power system (NGIPS) is the integration of various sources of electrical power to meet a growing ship power requirement in the most efficient manner possible. The power sources include large synchronous generators, hundreds of mega joules of dedicated energy storage for pulsed loads, and over 100 MJ of total energy in battery-operated uninterruptible power supplies (UPS) distributed throughout the ship's load centers (NAVSEA, 2007).

The functions of an integrated energy storage system are identified by the Naval Sea Systems Command (NAVSEA,2007) as supporting some loads during a loss of power generation, mitigating the system effect of a large load step, and enabling the provision of a large pulse of power to a pulsed load without applying that pulse to the overall power system. The second function addresses sudden changes in generator output power demand, such as during the charging of pulse-load energy storage systems for electromagnetic weapons or aircraft launchers, propulsion motor power reversal during ship crash astern maneuvers and the tripping offline of generators due to AC system faults.

Power quality issues are brought into play in considering the system effects of load steps since sudden changes in electrical loading on the synchronous generators can cause their output frequency to fluctuate widely as the prime mover adjusts to meet the demand. The maximum load acceptance rate per second for typical gas turbines is estimated by NAVSEA (2007) to be 20%. Fig. 1 shows the simulated load acceptance response of a 45 MVA synchronous generator (inertia constant of 4.0 MWs/MVA) with an aero-derivative, gas turbine prime mover. One measure of acceptable generator frequency fluctuation are the ±4% limits for transient frequency tolerance specified in MIL-STD-1399 (NAVSEA, 1987) and mirrored in IEEE-STD-45 (IEEE, 2002). They offer a potential performance benchmark for energy storage integration schemes that address load-step disturbances.

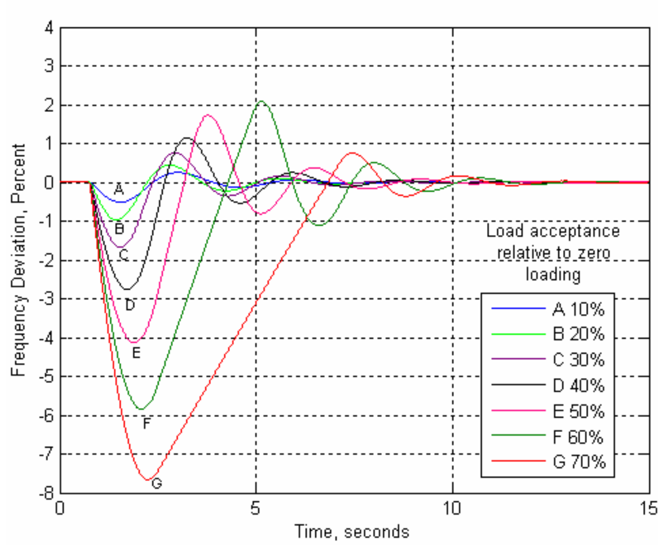


Fig. 1 Gas Turbine-Synchronous Generator Load Acceptance Frequency Response

Terrestrial power systems achieve bus frequency control through the application of a “large inertia” power generation grid. Holdsworth, Ekanayake, and Jenkins (2004) demonstrated the use of inertia in wind turbine generators of large wind farms to control the frequency response of utility power systems. However, for the shipboard power system, the total effective inertia is limited by the fact that individual load step changes can be a large percentage of the total installed power. Mission requirements can also reduce the effective inertia for frequency control further by forcing the islanding of generation resources as a result of reconfiguration responses to battle damage.

Total shipboard power generation system inertia can be effectively augmented during a sudden load demand by rapidly and dynamically decreasing the loading on the generators for the duration of the load disturbance’s most severe rate of change. This occurs during the initial onset and final release of load steps, corresponding to generator load acceptance and load rejection periods, respectively.

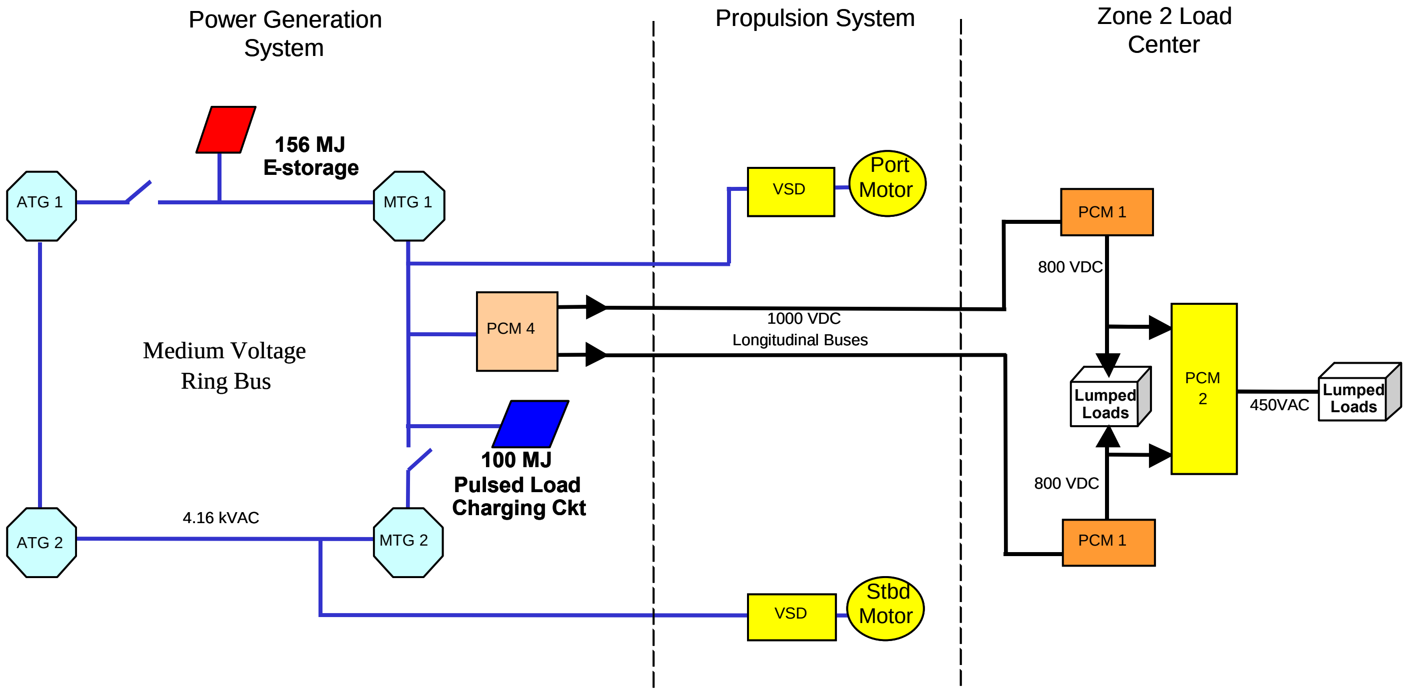
The ship’s forward momentum and combined rotational inertia of the propulsion motor rotors, drive shafts, propellers and entrained water provide a convenient source of kinetic energy for accomplishing this dynamic moderating of step loading. Depending on the velocity of the ship, power requested from the propulsion motors can be varied in direct response to a sudden fluctuation in speed of the gas turbines without significantly affecting the vessel’s forward motion. This is achieved through dynamic power control of the motor drive’s power/speed controller. The limitation of this approach is that the ship speed must be sufficient to cause the propulsion motors to draw at least as much power as would be required to reduce the frequency fluctuations from a load step to ±4%.

At slow ship speed the propulsion motors can still be used to moderate sudden load demands by operating them in regeneration mode. During crash astern maneuvers the electrical power generated by the motors is typically dissipated in braking resistors on the drives’ DC links. If the motor drive front-end converters have bi-directional power capability, the energy can also be passed directly to the power generation subsystem and absorbed by the ship’s loads. During slow-ahead ship motion, a bi-directional drive can be controlled by the same dynamic power controller mentioned above in order to request sufficient regenerative power from the motors to limit generator frequency fluctuations.

The use of dedicated energy (E-) storage devices to mitigate load-step disturbances requires control strategies that are unique to the design of the device and its specific implementation within the IPS. E-storage devices may utilize chemical batteries, capacitors, flywheels, fuel cells, super conducting magnets (SMES), or their combinations to realize systems for pulsed weapons, electromagnetic aircraft launchers (EMALs), and UPSs. These E-storage devices could be distributed throughout the IPS architecture, i.e., at the AC power generation-, longitudinal DC bus-, or load center levels. They will therefore require ship-wide power management controls, as well as local logic for controlling their regenerative power output to limit generator frequency fluctuations. In addition to these dedicated E-storage devices, high-speed micro-turbine generators operating in standby mode could also be brought online on an “as-needed” basis to compensate for load steps.

This paper discusses the control strategies for limiting the disturbing effects of load steps on the IPS through the reduction of propulsion motor power, the regeneration of power from the propulsion motors, and the regeneration of power from a capacitor E-storage device. The potential performance of each control scheme is examined using an elaborate computer model of a notional destroyer class IPS that was developed and implemented on the Real-Time Digital Simulator (RTDS) (Kuffel, et al., 1995) by the Center for Advanced Power Systems (CAPS).

The paragraphs that follow provide an overview of the RTDS E-ship model used in this study. The control strategies proposed are then presented, followed by simulation results. Finally, conclusions are drawn from the results.



Legend:

MTG1, MTG2	36 MW Main synchronous generators	PCM2	DC-AC 3-phase Converter	PCM 1	DC-DC Converter
ATG1, ATG2	4 MW Auxillary sync. Generartors	PCM4	AC-DC Converter	VSD	Variable Speed Drive

Fig. 2 Topology of the shipboard integrated power system model

RTDS IPS SIMULATION MODEL

CAPS has developed a large-scale, high-fidelity digital simulation of a notional destroyer IPS for conducting concept feasibility studies (Langston and Andrus, 2006). For hardware-in-the loop (HIL) experiments this model, or a suitable subset, can also be simulated in real-time on the same simulator hardware. The model is based on a concept developed in (Syntek, 2003). It represents a DC Zonal Electric Distribution System (DC ZEDS) architecture with the ship service loads distributed across five load center zones from bow to stern. For the study of this paper, the full detail of the large-scale model was not deemed necessary. Therefore, a subset was extracted which only represents the Zone 2 load center as depicted functionally in Fig. 2.

The following model subsystems are described below:

- Power generation
- Propulsion systems
- Hydrodynamics
- Non-propulsion loads

Power Generation

A 4.16 kV medium voltage (MV) ring bus is supplied by two 36 MW/45 MVA main gas turbine, synchronous generators (i.e., MTG 1 and MTG 2), and two 4 MW/5 MVA auxiliary gas turbine generators (i.e., ATG 1 and ATG 2) as shown in Fig. 2. The alternators are each implemented in the system using a model component native to the RTDS which employs a DQ axis synchronous machine model. This model accounts for mechanical aspects, such as inertia and damping, as well as the typical electrical characteristics. By including all four generators in this scaled-down system model we account appropriately for the total effective inertia of the power generation system during sudden load changes. This is because the power demand of the load step is met by all four generators, which reduces the percentage of load acceptance/rejection for any one generator.

A twin-spool, aero-derivative gas turbine model is employed as generator prime mover that includes details of the governor, combustion chamber, and exhaust gas temperature measurement time constants

(Hannett, Jee, and Fardanesh, 1995). The voltage regulator is a generic model employing proportional-integral (PI) control. A load sharing routine monitors the real and reactive powers supplied by each generator and provides control signals to equally divide the loads between connected generators as a fraction of each generator's capacity. Although generic models are currently employed, the simulation is capable of providing a reasonable representation of the voltage and frequency variations that would be displayed by a shipboard power generation plant of limited capacity in response to a wide range of transient events and time varying loads. This is in contrast to many terrestrial power system studies in which the generation often can be modeled as a stiff source coupled through a transmission line. For shipboard systems such a simplification will lead to skewed results by failing to account for the reactions of controls to the frequency deviations exhibited by a finite inertia system.

Propulsion Systems

The ship propulsion is provided by two 36.5 MW motors, each currently implemented in the simulation using a DQ axis induction machine model. Again, this model captures mechanical behavior, such as inertia and damping, as well as electrical characteristics including magnetic saturation. Each motor drive consists of a 6-pulse front-end active rectifier and a two-level voltage source converter type inverter bridge. Both the rectifier and inverter valve groups employ PWM firing controls with a 1 kHz switching frequency. Vector control is used for the motor, and the drive front-end utilizes passive filtering to minimize the harmonic distortion produced on the generator bus. The drive front-end is also regenerative, providing a bi-directional power flow capability.

It should be noted that the required computation time could be significantly reduced by employing averaged models for the motor drives. However, in addition to losing the detail of time-varying harmonic bus voltage distortion, such simplification may also neglect some of the effects caused by the controls which could be sensitive to the frequency and voltage deviations on the bus. Correctly capturing such interactions is of paramount importance as the drives represent such a significant proportion of the load connected to the system (over 90% at full power).

Hydrodynamics

As it is important to accurately model the behavior of the propulsion motors and drives, the torque load applied to the motors from the propellers must also be modeled to a reasonable degree of accuracy in order to assess the effect of ship maneuvers on the power system. The hydrodynamic model is largely based on the model provided by Lecourt (1998), but the empirical data for the propeller torque and thrust coefficients, along with the hydrodynamic resistance of the ship, have been replaced with data more representative of a destroyer class ship. Such a model accounts for the inertia of the propeller and entrained water as constants, the torque exerted on the motors by the propellers and the thrust exerted on the ship by the propellers as functions of the ship speed and propeller speeds, and the hydrodynamic resistance of the ship as a function of the ship speed. The model restricts the simulation to one-dimensional motion of the ship, but allows for both positive and negative values of the ship speed and angular velocities of the propellers.

Non-propulsion Loads

The MV subsystem also supplies a charging circuit for a 100 MJ energy storage system designated for a pulsed weapon load, which is described in more detail below, and an AC-DC power conversion module (labeled PCM4). The PCM4 rectifies 4.16 kV AC to 1 kV DC for powering port and starboard DC buses. The longitudinal DC buses feed 1 kV DC power to the load centers, represented here by only one zone (Zone 2). At the zonal level, port and starboard DC-DC power conversion modules (labeled PCM1) step the DC bus voltage from 1 kV down to 800 V. In each zone these converters simultaneously feed one 800 V bus through auctioneering diodes to allow for a seamless power transfer between the two 1 kV DC buses in case of a fault occurring on one of them. Some equipment, such as a large motor drive, operates directly from this 800 V bus. Generic AC loads are supplied through a DC-AC inverter (labeled PCM2) that converts 800 V DC to 120/208 V AC or 450 V AC, depending on the AC load requirements. All power conversion modules are modeled as switched converters, not average models. PCM4 rectifiers are 12-pulse thyristor modules with (PI) voltage control. PCM1 DC buck converters switch at 1 kHz and employ PI voltage control. PCM2 inverters are sinusoidal PWM hard-switching voltage source converter modules with voltage control. The ship service loads are represented in the RTDS E-ship model as lumped resistive loads of different categories (e.g., Type 1 AC, non-vital Type 1 AC, DC) at the 800 V DC bus level based on Syntek (2003).

Pulse load Charging Circuit

A generic pulsed power charging circuit, modeled at the switched-power electronic device level, is used for representing the interface between the pulsed load energy storage system and the prime power system. It addresses both low and high energy charging pulsed loads in order to represent loads that range from pulsed radars to electromagnetic launchers. It is used in this study to set up a pulsed load step on the power generation system, which causes the system frequency to deviate from steady state due to generator load acceptance and load rejection.

The pulsed load model, shown in Fig. 3, includes a diode rectifier, a passive filter on the DC bus (comprised of L_f and C_f) and a variable resistor to represent different load demands on the DC side. By adjusting this resistance over time according to $R_L(t) = V^2/P(t)$, the effects of a time varying power profile P(t) during charging, and a (near complete) disconnect from the power system during discharge of the pulse power energy storage (not modeled here), can be studied. The DC side filter has a resonance frequency of 120 Hz.

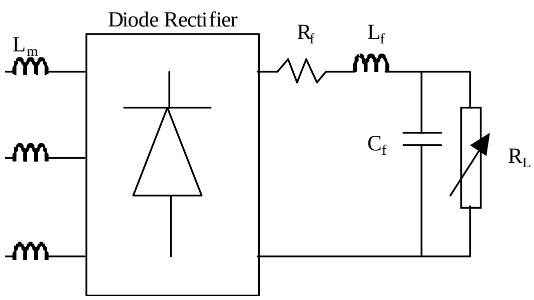


Fig. 3 Circuit diagram of the pulse load charging circuit model

Dedicated E-storage Device

Fig. 2 shows a dedicated 156 MJ energy storage device attached to the MV ring bus. The electrical circuit for this device is shown in Fig. 4. A six-pulse thyristor valve group supplies charging power at 5 kV DC to a 12.5 F capacitor bank. At present, this capacitor bank is modeled by a single ideal capacitor. A separate six-pulse thyristor valve group converts energy from the capacitor bank back to 3-phase AC power in order to allow the energy storage to supply power back into the MV ring bus.

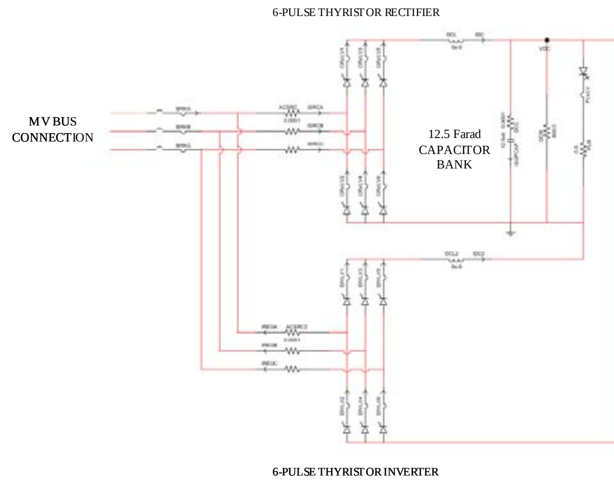


Fig. 4 Circuit diagram of the E-storage device model

CONTROL STRATEGIES

Bus Frequency Control Through Propulsion Motor Power Control

The use of the propulsion motors to control disturbances in the ship electrical system has been employed in electric drives for marine vessels for many years. At CAPS, Woodruff (2006) and Woodruff et al. (2005) demonstrated the use of this technique to effectively eliminate the transfer of sea-state variations in propeller loading to the notional electrical ship system described above. A follow-on hardware-in-the-loop (HIL) study (Woodruff, Qi, and Sloderbeck, 2007) demonstrated the use of propulsion motor power control, applied to laboratory type 2.5 MW testing motors, to minimize power level disturbances on a notional ship MV bus introduced by a pulse load charging circuit.

This present study builds upon these earlier studies by augmenting the motor speed and power controller with a frequency control loop as shown in Fig. 5. In this control scheme, the difference between the actual bus frequency (f_{bus}) and a steady-state reference frequency (f_{ref}) of 60 Hz (i.e., 376.99 rad/sec), is input to a proportional-integral-derivative (PID) controller, which modifies the error input to the drive back-end, i.e. the motor speed and power controller. The frequency error signal (ε_{error}) is passed to the controller by a dead-band switch when it is outside of the ±4% MIL-STD-1399 limits. Since bus frequency is measured by a phased-lock loop (PLL), the design of the PLL's controls can limit the maximum rate of

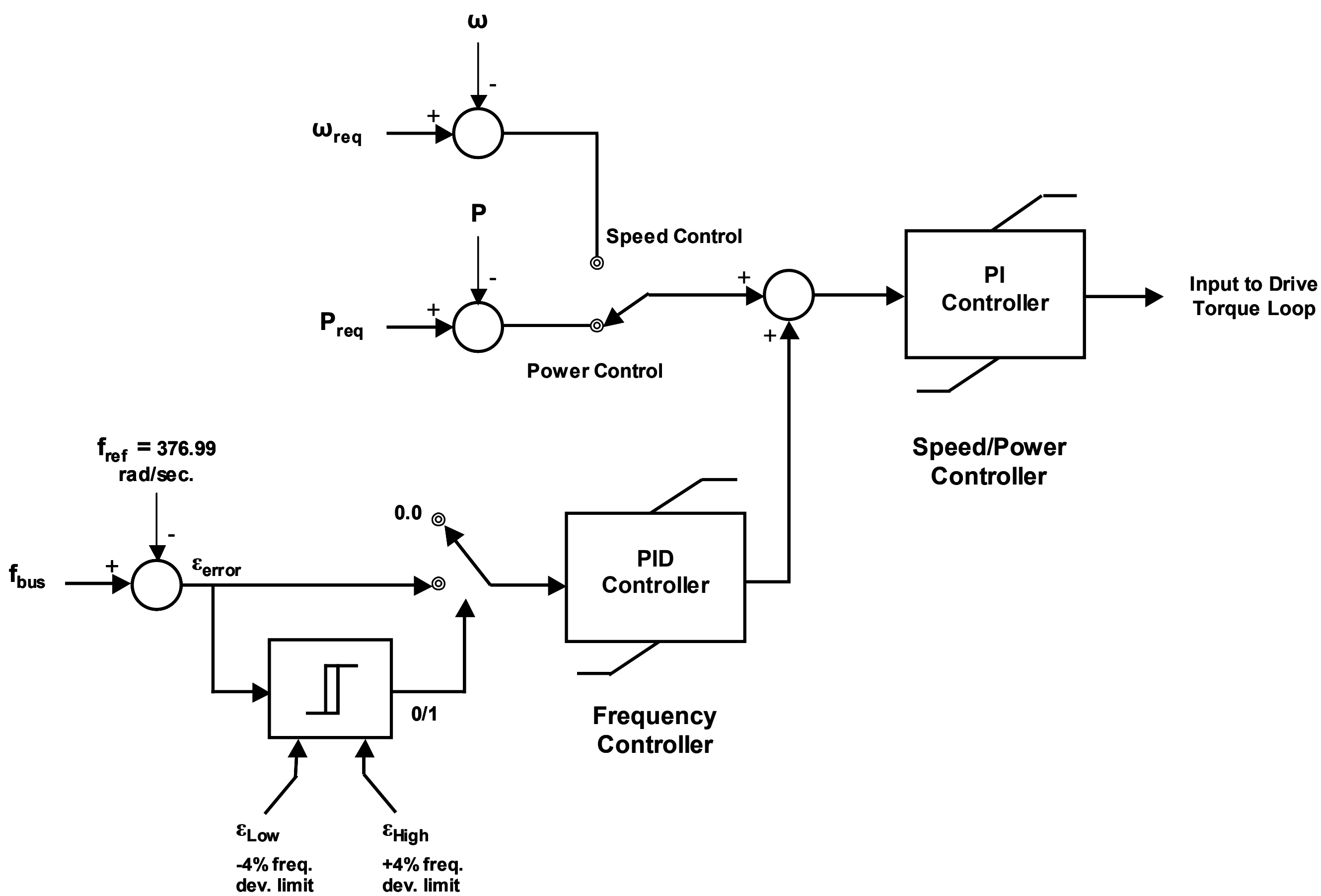


Fig. 5 Propulsion Motor Bus Frequency Controller

change of bus frequency that the controller of Fig. 5 can accommodate during a load step disturbance.

The actual motor speed or power, and the required motor speed or power are identified in Fig. 5 as ω\P and ω_{req}\P_{req}, respectively. When the bus frequency decreases due to increased generator loading, the frequency loop introduces a negative offset to the requested motor torque. This reduces the requested torque and effectively provides an additional level of power control to the drive. Correspondingly, positive frequency overshoots beyond the limit cause the requested motor torque and power to increase in order to compensate.

Bus Frequency Control Through E-storage Device Power Control

The control of dedicated energy storage devices within the IPS is a system-level controls study since implementation concepts can involve the integration of multiple E-storage devices at various locations on the ship. This study focused on the use of a single, generic, 156 MJ capacitor E-storage device on the MV ring bus. As with the previous propulsion motor frequency control scheme, the goal was to use the E-storage device to limit frequency fluctuations on the AC bus due to a load-step to within MIL-STD-1399 standards, i.e., ±4%.

Fig. 6 shows how the power controller for the E-storage device was augmented to control its regenerative power output in response to frequency deviation. The difference between the actual bus frequency and the reference bus frequency is input to a PID controller through the control of a dead-band switch, as was done in the propulsion motor frequency control strategy. The output of the PID controller alters the firing angle of the thyristor inverter valves so that the energy required to meet a sudden bus load demand is drawn from the storage capacitor.

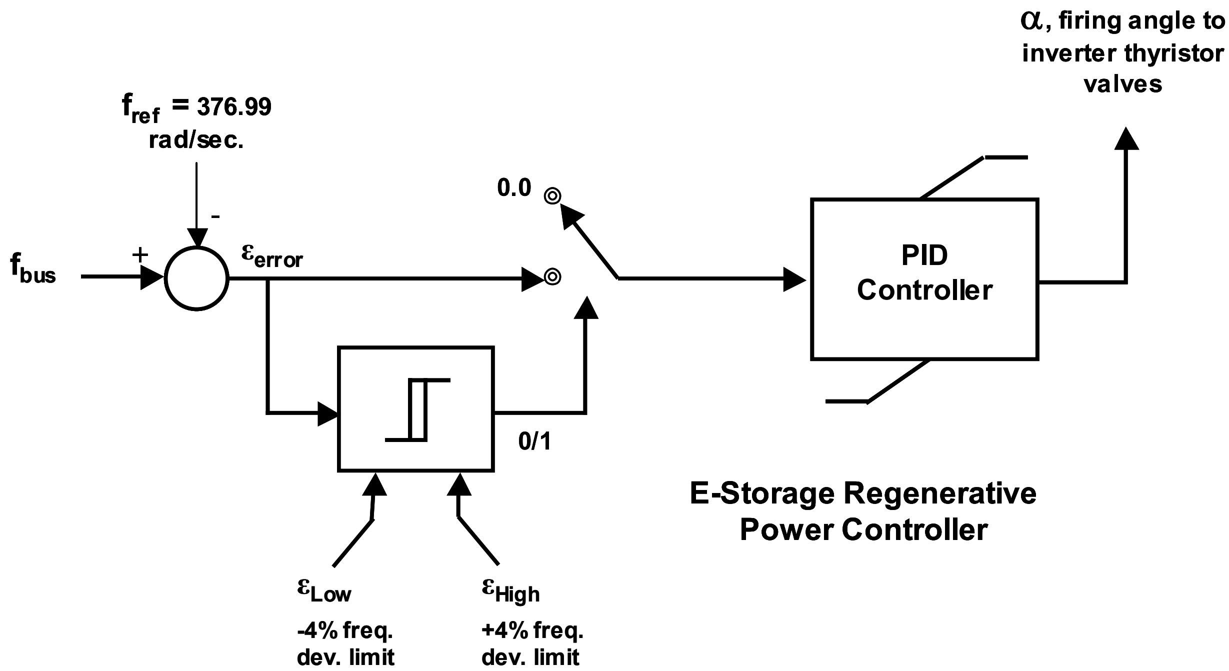


Fig. 6 E-storage Device Bus Frequency Controller

SIMULATION RESULTS

The RTDS E-ship model described earlier was employed to evaluate the effectiveness of the control strategies proposed above. Three simulation cases are reported here. They are identified in **Table 1** along with their corresponding initial simulation conditions.

The propulsion motor bus frequency control scheme was evaluated at both high ship speed (28 knots) and low ship speed (15.3 knots) to demonstrate how both a reduction in motor loading and the creation of motor regenerative power can be used to limit or even eliminate bus frequency fluctuations.

Case 1 Propulsion Motor Load Reduction

With the ship moving ahead at 28 knots, all four synchronous generators were connected in a closed, ring-bus configuration. This involved closing the two circuit breakers shown in Fig. 2 that connect ATG1 to MTG1 and MTG1 to MTG2. The MV bus was then subjected to a load-step simulated by operation of the pulsed load charging circuit. A charging pulse of 100 MJ energy was setup by forming a load pulse of 30 MW for 3.33 seconds. These were the load-step parameters used in all three cases listed in **Table 1** and discussed below.

Table 1 Simulation Case Initial Conditions

Parameter Identification	Case 1	Case 2	Case 3
Control Strategy	Motor power demand reduction	Motor re-generative power	E-storage power
Ship speed	28 knots	15.3 knots	15.3 knots
MV ring bus configuration	Closed ring - Breakers closed	MTG1 islanded – Breakers Open	MTG1 islanded – Breakers Open
Pulsed Load Charging pulse peak power	30 MW	30 MW	30 MW
Step Load Duration	3.33 seconds	3.33 seconds	3.33 seconds
Generator Inertia Constant	2.0 s	4.0 s	4.0 s

The square-wave shape of the simulated load-step was selected in order to produce the generators' worst-case dynamic response. In practice, rise and fall times of pulsed load charging pulses would be shaped to limit their power quality impact. On the other hand, an unplanned load-step disturbance, such as a generator tripping off line, could approximate a square-wave-shaped load-step.

The generator load sharing controls distributed the 30 MW pulse load step proportionally between the two MTGs and two ATGs. As a result, MTG1 experienced a 14 MW increase in load demand, which drove it to a new operating point of 1.03 pu, or 37 MW during the pulse. This corresponds to 39% load acceptance and rejection, respectively. In order to maximize the generators' dynamic response to the load-step, their inertia constant was set to 2.0 s.

Fig. 7 shows the frequency response of MTG1 and its associated gas turbine as a result of the pulse load-step. The maximum frequency deviation from the reference frequency is 16.1 rad/sec, or 4.3%, which barely exceeds the MIL-STD-1399 limits of ±4%.

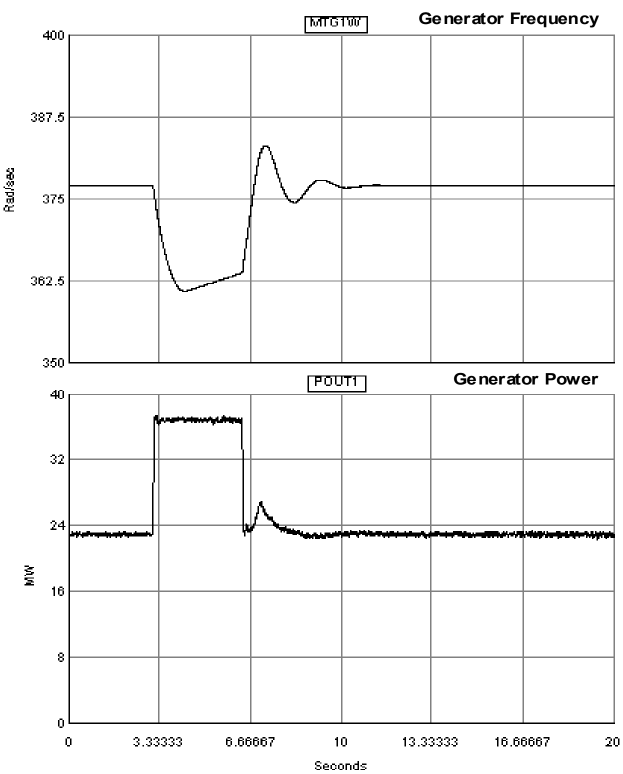


Fig. 7 MTG1 Load-step Frequency Response – Closed MV Ring Bus

The propulsion motor bus frequency controller was then engaged. In order to evaluate the capability of the control strategy to completely mitigate step load disturbances on the MV bus, the frequency deviation threshold was set to zero instead of ±4%. The simulation results shown in Fig. 8 demonstrate the effectiveness of the controller for limiting load-step disturbances. By reducing the power drawn by the propulsion motors, the load step was almost completely compensated for with a corresponding reduction in motor speed of 15% over the 3.33 seconds pulse duration. Also, the corresponding reduction in ship forward speed was only 0.6 knots. Although this speed reduction is relatively small, the maximum duration of load disturbance that one could totally compensate in this way would be limited by ship mission and operation considerations.

These results represent an upper bound on the usage of the control scheme to compensate for load- step disturbances. The following simulation results for Case 2 do not completely eliminate the frequency deviations but limit them to ±4% and hence require less compensation power.

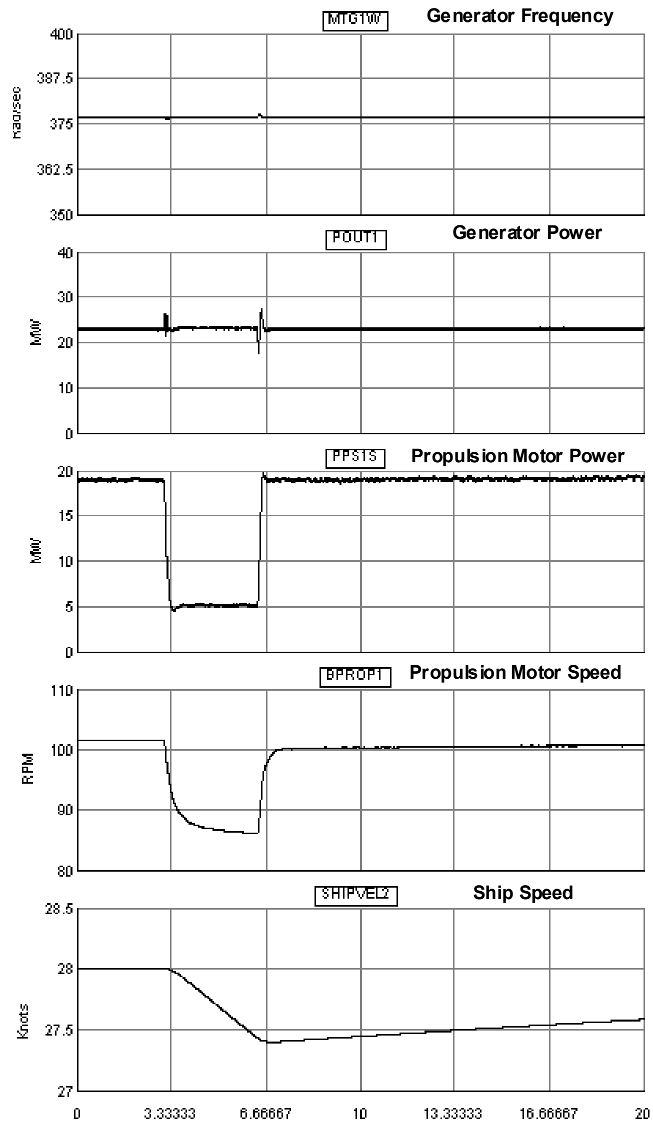


Fig. 8 Propulsion Motor Bus Frequency Controller Performance with zero frequency change allowance

Case 2 Propulsion Motor Regenerative Power Generation

A second case simulation was run to evaluate the controller's capability of using motor regenerative power to limit bus frequency deviation to the ±4% standard. In order to accomplish this, the ship speed was reduced to 15.3 knots. The MV ring was opened by opening the circuit breakers shown in Fig. 2.This created a power island with connections to main generator 1 (MTG1), the port propulsion motor, the PCM4 converter supplying Zone 2, the pulsed load charging circuit, and the dedicated E-storage device. The generator's inertia constant was increased to 4.0 in order to show the dynamic response of small MVA generators to load-step disturbances.

In the new configuration, a 30 MW load step subjects MTG1 to 83% load acceptance and rejection in this open ring bus configuration. As a result, without the compensation the frequency deviates in excess of MIL-STD-1399 limits by a maximum value of –5.7%, as illustrated in Fig. 9.

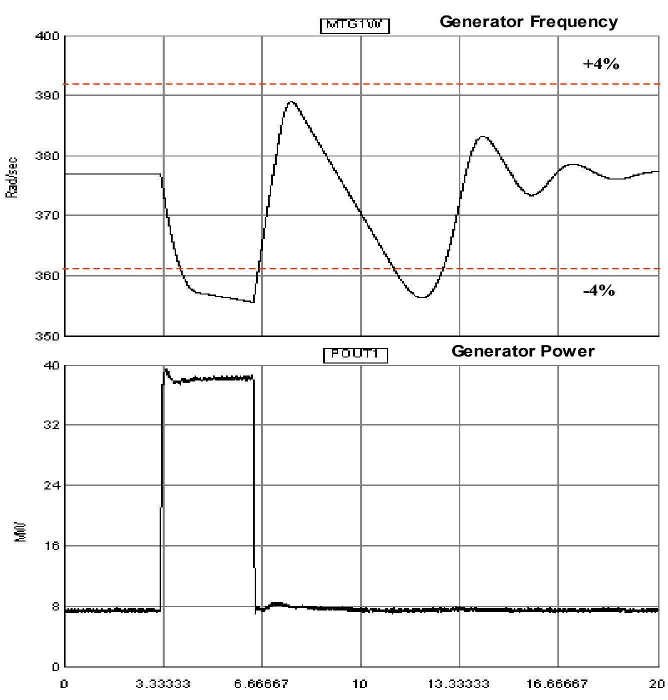


Fig. 9 MTG1 Load-step Frequency Response – Open MV Ring Bus

Error! Reference source not found. shows the effect of operating the frequency controller on the port motor only during the load step. The maximum frequency deviation input to the controller shown in Fig. 5 was set to ±4%.

These simulation results demonstrate that by driving the propulsion motors into regeneration in a controlled fashion, the energy that is passed to the MV bus through the motor drives can be used effectively to limit bus frequency deviations. By integrating the motor power curve below its steady-state value, the total energy required for frequency control is shown to be 10.9 MJ. Of this amount, 5.2 MJ can be attributed to reducing the motor power demand to zero, and 5.7 MJ results from operating the motor in regeneration (i.e., negative motor power).

The curves in Fig. 10 show that by limiting frequency deviation to ±4% through the use of regenerative motor power, the motor speed was briefly reduced by a maximum of 22.7 RPM, or 42%. However, the maximum reduction in ship speed was only 0.2 knots. The lower limit on the usefulness of this control strategy is set by the point at which the propeller speed is slowed to zero. Since this is a function of ship speed, a minimum ship speed can be defined for any given load-step amplitude and system configuration.

Case 3 E-storage Device Regenerative Power Utilization

The last simulation case studied was the use of the dedicated E-storage device to limit bus frequency deviation during an MV bus load step. This case used the same initial simulation conditions as in Case 2, therefore, the MTG1 load-step frequency response shown in Fig. 9 also serves as the comparison case. Fig. 11 shows the effect of the E-storage device based-bus frequency controller. Similarly to the previous case, a total of 10.8 MJ is extracted from the storage capacitor to keep the maximum bus frequency deviation within ±4%. However, in this case the energy was not taken from the moving ship, hence the ship velocity remained 15.3 knots.

Regardless of the type of E-storage device that is employed in the power system, 10.8 MJ of energy must be injected into the bus over the duration of the frequency fluctuations if the performance of Fig. 11 is to be achieved. For this study, controls that accomplish this were developed for a generic, thyristor-switched, capacitor energy storage device. The interface circuitry and regenerative power controls for SMES, fuel cell and flywheel E-storage systems could be quite different and will require device-specfic design efforts.

CONCLUDING REMARKS

Control strategies for minimizing IPS MV bus frequency fluctuations during generator load steps have been presented. They include using frequency

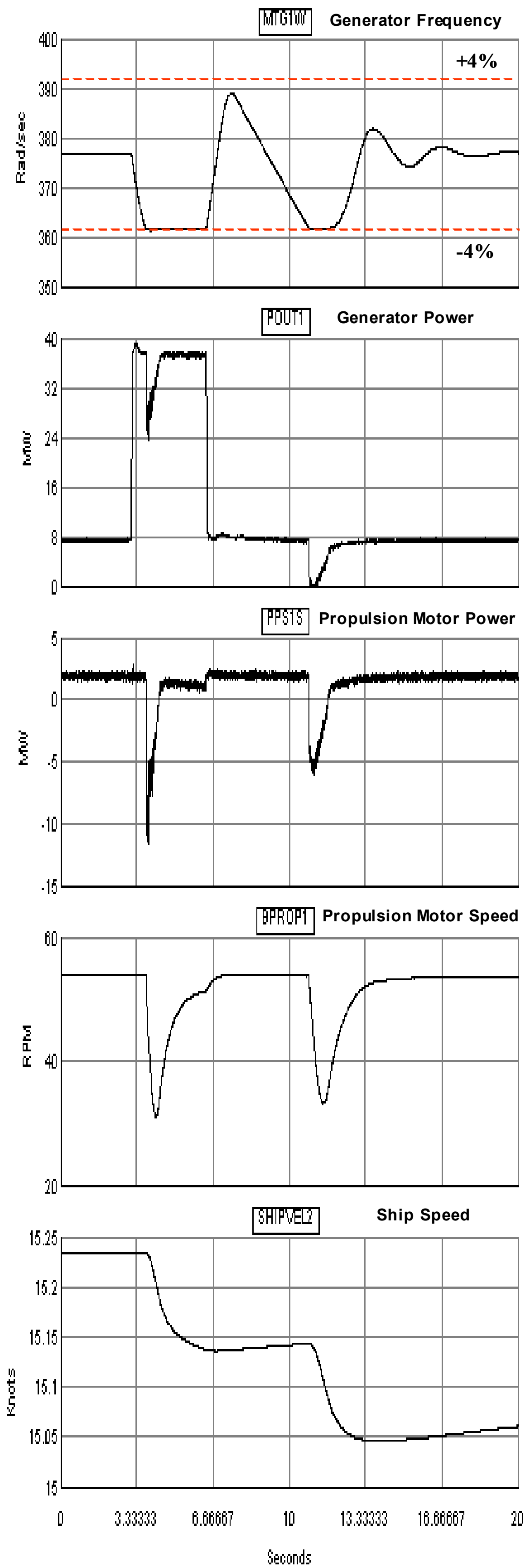


Fig. 10 Propulsion Motor Bus Frequency Controller – Regeneration Mode

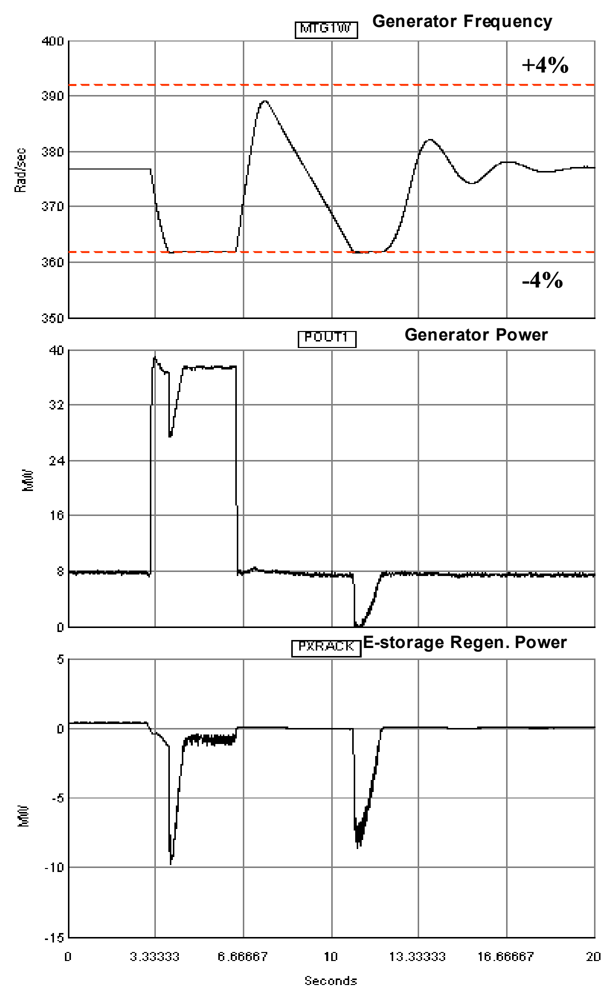


Fig. 11 E-storage Device Bus Frequency Controller Performance

deviation to control power demand of the propulsion motors, regenerative power output from the propulsion motors, and regenerative power output from a dedicated capacitor energy storage device. The RTDS E-ship model was used to simulate the performance of each control scheme. The results demonstrate how the momentum of the ship can permit reductions in propulsion motor power demand that dramatically reduce step load frequency disturbances. If the propulsion motor drives have a bi-directional power capability, then motor regenerative power can also be used to limit bus load-step frequency disturbances. Finally, simulation results demonstrate the use of regenerative power from a dedicated energy storage device to limit frequency deviation to within military standards. In the future, additional studies should explore the feasibility of utilizing distributed E-storage devices for pulse load leveling.

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