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Pulsed Power Loads Support and Efficiency Improvement on Navy Ships

ABSTRACT

This paper addresses the use of energy storage and high speed power generation to support high power loads and at the same time reduce fuel consumption of DDG51 Arleigh Burke class destroyers. Energy storage can supply pulsed energy loads, and can be used to improve reliability and power quality by stabilizing the grid. It can also serve to improve ship efficiency by acting as an uninterruptible power supply, enabling single generator operation with a single gas turbine operating closer to its peak efficiency, rather than running constantly two generator sets at light load. In case of failure, the energy storage unit provides power for critical loads until a second generator set can be brought online.

Based on system modeling, fuel savings projections, and ship integration studies, a flywheel energy storage system was found to be a viable approach to realizing significant fuel savings on the DDG51 ship service generation system. Using a typical load profile, fuel savings in excess of $1M per year per ship can be expected. The particular flywheel energy storage system of this study can mitigate system transients and provide up to 10-minute ride-through to enable multiple start attempts on the second gas turbine generator set.

INTRODUCTION

The Navy is facing increasing demand for reliable, efficient electric power aboard ships, while concurrently having to support a variety of transient high power loads. At the same time, rising fuel and logistics costs have increased interest in reducing fuel consumption. The objective of this paper is to evaluate the impact of advanced power generation and energy storage technologies on ship electric power systems.

Specifically, a flywheel energy storage system is proposed for the support of intermittent duty loads. Furthermore, advances in gas turbines, high-speed generators, power electronics, and energy storage have enabled low volume, light weight power generation solutions in the 3-5 MW power range. The basic concept for an advanced Megawatt Power Module (MPM) of this type is shown in Figure 1.

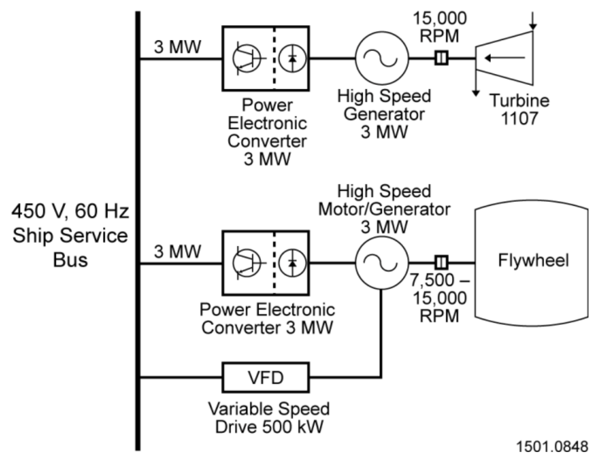

Figure 1. Notional 3 MW Power Module

Much of the weight and volume benefits of these systems accrue because the technology has been developed to operate megawatt-level generators at rotational velocities around 15,000 rpm, so they can be directly coupled to a gas turbine. Furthermore, advances in solid-state power conversion allow the designer to decouple the power generation frequency from the 60 Hz distribution frequency. This removes the need for a high-speed gear box, significantly reduces the size of the generator and enables variable speed operation to optimize gas turbine specific fuel consumption (SFC) with load.

The incorporation of energy storage, as is increasingly done in high value land-based systems today, provides several benefits.

First, it allows the support of high power intermittent duty loads that would otherwise destabilize the system. Furthermore, this approach can reduce fuel consumption by power leveling so that some of the temporal variation in the loads is served from the storage system. In this way, the gas turbine can spend more of its life operating in its most efficient manner.

Second, it provides power quality improvement by adding stability to the ship's power system.

Third, the use of storage can reduce the number of hours of turbine operation and improve SFC. Although a typical class ship's base electrical load could be supported by a single 3 MW turbine/generator unit, today's practice is to operate two turbine generator sets, each supporting half of the power demand. This is done to avoid a single point of failure resulting in a "dark ship", namely, complete loss of electrical power. Operating two turbine generator sets maintains power system reliability by eliminating single point failures, but it effectively doubles the operational hours on the engines and results in increased SFC from operation of the turbines at partial load. In the envisioned system, the energy store is sized to support the ship's 2-3 MW base electrical loads and provide ample time to start another turbine if the primary operating unit fails for any reason. Thus, the incorporation of energy storage maintains power system reliability while permitting a single turbine generator set to manage the base electrical loads and operate in a higher efficiency region, reducing total fuel consumption.

And fourth, this mode of operation, in which the gas turbine maintains a more constant load, is beneficial to turbine life. The use of the storage system to minimize turbine load changes and thermal cycling reduces turbine maintenance and extends operational life. This both reduces the cost of ownership and enhances the reliability of the power plant.

Energy storage therefore offers many advantages and will likely be a high priority addition to future naval ships as well as retrofits. Although the potential benefits of such an approach have been recognized for some time, the challenge has been lack of appropriate technology for exploiting the potential benefits in high power systems. However, the required technologies are now available and have been evaluated.

ENERGY STORAGE OPTIONS

Energy storage for single generator set operations is challenging due to the combination of high power and required energy storage. Three major energy storage technologies were considered:

1. Capacitive storage
2. Battery storage
3. Flywheel storage.

The first option was soon abandoned, as it seemed clear that capacitive storage technology would be noncompetitive for this application from the standpoint of energy density. A competitive evaluation of advanced batteries and flywheels was then undertaken. A discussion of the relative merits and limitations of Li-ion batteries versus flywheels for a high power, high-energy naval power system application is presented here.

Technology Readiness Level (TRL)

Li-ion is the preferred battery chemistry for low power electronic consumer products. Electric vehicle batteries rated for a few kWh and tens of kW's are being developed, however Li-ion technology has not yet made significant progress into the automotive market. Complex integration and performance issues make it difficult to extrapolate cell-level parameters to predict the performance, size, and reliability of large high power battery arrays. No MW level Li-ion battery installations have been identified in the literature, suggesting that a MW level Li-ion battery array has a low TRL. In contrast, flywheel UPS systems at 0.5 to 1.0 MW levels are in commercial use today and plans for implementation of a 20 MW utility grid stabilization facility using flywheels are proceeding (Website 1).

Scaling

Integration of the large battery arrays needed by this application is a significant concern. While cell-level power and energy densities of Li-ion batteries reported in the literature are impressive, practical packaging considerations for a 2.5 MW, 5- or 10-minute battery bank make integration into an existing ship platform extremely challenging. With no MW level Li-ion battery installation for comparison, large-scale arrays of batteries of other chemistries at comparable power and energy levels were evaluated. The evaluation factored in differences in the energy and power densities of the different battery chemistries to project the size of comparable Li-ion systems. Two examples (valve regulated lead-acid – VRLA – and NiCd batteries) support the estimation that a practical and safe Li-ion battery bank could be prohibitively large for this application. The battery volume for a 2.5 MVA, 60-s VRLA system (Figure 2) is quite large – about 55 m^3. Even assuming a 3X higher energy density than VRLA batteries, a 2.5 MW, 10-minute Li-ion system would scale to 121 m^3.

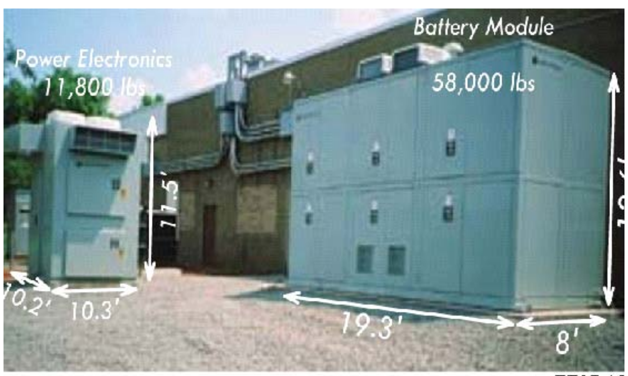

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Figure 2. S&C's PureWave 60-s UPS System (Website 2)

Another recent example is a 27 MW, 15-minute NiCd battery backup system with a net battery volume of 3,800 m^3. The batteries actually occupy a space of 12,500 m^3 (Figure 3), indicative of a practical installation with allowance for interconnections, cooling, accessibility, monitoring, and other auxiliary equipment. Scaled down to 2.5 MW for 10 minutes, this system would yield a net NiCd battery volume of 232 m^3, which scales to a 116 m^3 Li-ion installation, comparable to the preceding estimate.

Practical integration factors (bus work, mounting maintenance access) likely drive the overall battery package size more than the energy density of the individual cell, so practical battery systems may remain relatively large despite advancements in battery chemistry. A conclusion drawn from this analysis is that Li-ion systems do not offer significant savings in storage weight or volume or in auxiliary systems over flywheel systems in this power and energy range.

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Figure 3. Alaska Golden Valley Cooperative Project: One Aisle of 27 MW Battery Backup for 15 Minutes (Website 3)

Performance Degradation Issues

Several factors influence the useful life and performance of batteries in high power, high-energy applications. One issue with all battery technologies is the reduction of energy storage capacity over time and with cycles (capacity fade) requiring an increased number of cells to meet energy requirements at the end of the battery's useful life. Capacity fade is dependent on battery temperatures and the depth of the discharge cycles.

The internal heating and energy capacity of batteries is strongly dependent on the discharge rate, with higher discharge rates increasing internal heating and reducing the available capacity. The energy capacity of batteries is typically based on the 1C discharge rate – with the rated energy delivered over a 1-hour discharge time. The UPS duty cycle of the ship service application represents a relatively high 6C discharge rate for a 10-minute discharge and a 12C rate for 5-minute discharge. Li-ion batteries also have an internal resistance approximately 20 times that of aqueous solution electrolytes, leading to higher internal heating in high power applications. The impact of discharge rate on capacity and internal temperatures also drives the designer to increase the number of cells to limit the effective discharge rate and heating in each cell.

Battery Life

Even under best case conditions, Li-ion batteries have a short useful life relative to a typical ship service application, likely requiring replacement of the battery array three to four times during the 35-year design life. Battery life can be further decreased by cycling, with high depth of discharge cycles having the greatest impact on life. Load leveling of the gas turbine to extend life and maintenance intervals will require frequent charge/discharge cycles. Future Navy needs for pulsed loads or sensors may also demand more frequent cycling from the energy store. Furthermore, the power capability of batteries is not symmetric; they typically cannot be charged at the same rate that they can be discharged, which may limit the flexibility of the energy storage system for load leveling or future functions.

By contrast, flywheels can be charged and discharged at the same rate and NASA-funded testing by the University of Texas at Austin Center for Electromechanics (UT-CEM) showed no discernable degradation after more than 110,000 deep discharge cycles. The flywheel can be designed to meet the 35-year design life without replacement.

Reliability

Energy storage system reliability is of paramount importance to any critical ship service application. Due to the low Li-ion cell voltage (nominally ~3.6 V per cell), it is necessary to connect at least 188 cells in series to achieve the minimum 680 Vdc voltage required to produce 450 Vac power on the ship service grid. Because the cell voltage will drop with load and state of charge, additional series connections are needed to supply the required voltage. Many series "strings" must then be connected in parallel to provide the required power and energy, resulting in an array of at least several thousand cells for a typical ship service system application. Reliability is a significant issue in installations requiring thousands of cells since the failure of a single cell can fail an entire series-connected string and can lead to a cascade failure of other cells as the load shifts to parallel strings and increases their discharge rate.

Safety

Since safety is another significant concern in shipboard systems, monitoring and maintenance requirements are also high, as Li-ion cells have a demonstrated catastrophic failure mode. Li-ion cells are extremely sensitive to charging voltage – the overcharge voltage is typically within 3 to 4% of the full charge voltage – so a complex battery protection circuit is required for each cell in the array. Overcharging, over-discharging, or failure of a cell protection circuit can lead to thermal runaway. Recently, nonflammable electrolytes have been introduced in $LiFePO_4$ Li-ion batteries, but this chemistry reduces the power and energy capacity of the battery by as much as 30% relative to the current chemistry. Internal protection incorporated in some manufacturers' cells may eliminate catastrophic failures; however, the protection system effectively removes that cell from the array and compromises the performance of the entire series string. The high initial cost, capacity fade, and potential catastrophic failure mode require complex battery management techniques to ensure safe and effective use of Li-ion cells over their useful life. The required monitoring and protection circuits further increase the complexity of the battery control system and impact the reliability of the overall system. While these monitoring and protection circuits may reduce the risk of catastrophic failure, Li-ion batteries still represent a significant safety hazard in the ship environment.

Based on these considerations, the Li-ion battery technology does not appear to be competitive with flywheels for the energy storage requirements of this application at this time, due to the unresolved questions of maturity, scaling, capacity fade, reliability, life, and safety.

FLYWHEEL ENERGY STORAGE

One critical benefit for retrofit integration of energy storage into the DDG-51 class ships is the ability to package the energy storage flywheel system in the current volume of modified AG9140 power systems. Space can be made available for this addition by removing the gear box and low speed generator, and replacing them with a compact, direct drive generator and 60 Hz inverters. These modifications free the needed volume to package the flywheels within the existing volume.

Another option for adding energy storage to naval ships, without the need to upgrade the main generators, is to integrate independent energy storage modules into the existing power system. This approach would use modular, standalone flywheel packages to facilitate integration into the ship platform. Such packages could include the energy storage flywheel, a direct coupled motor generator, auxiliaries, and power electronics required to interconnect the electrical output of the flywheel transparently to the 450 V, 60 Hz service grid.

Standalone flywheel energy storage can be implemented in a variety of scales – from one large flywheel, to many small power system modules distributed throughout the ship, all interconnected by the service grid. Previous flywheel design studies for comparable MW-level energy storage applications conducted by UT-CEM indicated that the most economical approach is to minimize the number of units and maximize scale. On the other hand, distributing multiple flywheels increases fault tolerance and redundancy, and may offer distinct integration advantages for retrofit applications which may not have large unoccupied volumes.

For a retrofit application, our recommendation is to balance these considerations by selecting the largest flywheel unit size which can be installed without major impact to ship structure, and using multiple flywheels of this scale to meet the total energy need, providing a favorable combination of flywheel capital costs, ship integration costs, performance, and reliability/redundancy.

To quantify the baseline flywheel sizing, a preliminary evaluation of the installation of a flywheel was conducted, considering the maximum flywheel size that can be feasibly installed with minimal impact to the ship structure during retrofit. For the study, it was assumed that the major pieces of the flywheel system (flywheel, motor/generator, power electronics) would be individually brought into the ship, and assembled in place. This study found that a flywheel unit size of approximately 90-inch length by 41-inch outer diameter (corresponding to a system of four flywheels to supply the total energy for a five-minute discharge, eight flywheels for a 10-minute discharge) could be installed with minimal impact to the ship structure, while flywheels larger than this may require more significant ship modifications. The flywheel unit size was therefore selected around this criterion, and a system package concept for a single flywheel unit was developed. Depending on the final locations selected for integration of the energy storage components, the flywheel packages could be expanded to two, three, or four flywheel modules.

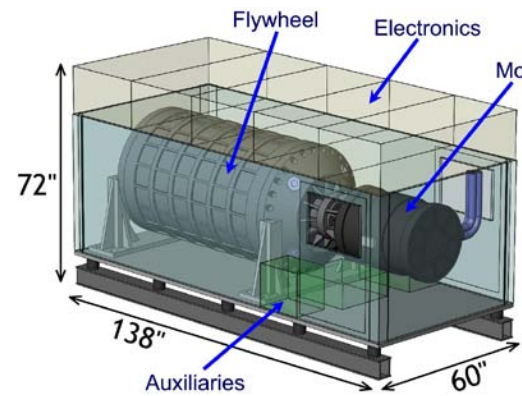

Figure 4. Concept Flywheel Package for Standalone Ship Energy Storage System

The concept standalone flywheel energy storage system package includes the flywheel and direct coupled motor generator, lubrication, vacuum, and controls auxiliary modules, and power electronics and switchgear to connect the flywheel's output to the 450 V, 60 Hz, three-phase ship service grid. This equipment is mounted in an enclosure with a shock isolated base. For the five-minute discharge system, four of these modules would be distributed through the ship, as space allows, to supply the energy and power demands. For the 10-minute discharge system, eight flywheels of this size would be needed. In each case, one backup unit may be desired for redundancy so one unit may be taken out of service at any time for maintenance. The nominal dimensions of this concept for a single flywheel energy storage module are shown in Figure 4.

The significant physical parameters of the flywheel energy storage system, including the dimensions, weight, center of gravity, electrical input and output, cooling requirements, and ship interface are presented in Tables 1 and 2, itemized separately for the flywheel and the motor generator.

Table 1. Physical Characteristics for 2.5 MW, 10-minute UPS Energy Storage System

Physical Characteristics	Flywheel	Flywheel Motor/Generator
Length, Width, Height	90" L, 41.5" W, 41.5" H	33.1" L, 25.8" W, 25.8" H
Maintenance Envelope (L x W x H)	130" L, 81.5" W, 81.5" H	73.1" L, 65.8" W, 65.8" H
Weight, Center of Gravity	14715 lb, COG*: 45.75"x, 0"y, 0"z	2368 lb, COG*: 16"x, 0"y, 0"z
RPM	9573-19146 rpm	9573-19146 rpm
Equipment Rating	52 kWh/FW deliverable (208 kWh per skid)	625 kW/MG (2.5 MW per skid)
Thermal Cooling Fluid, Type, Volume, Pressure	water, 10 gpm, 60 psi/skid	water, 28 gpm, 60 psi/skid
Thermal Discharge Fluid, Type, BTUs, Vol, Press, Temp	water, 20 kW (1137 BTU/m), 10 gpm, 60 psi, 42°C outlet/skid	water, 56 kW (3185 BTU/m), 28 gpm, 60 psi, 42°C outlet/skid
Expected Mounting Location of Components – include Type of Mount	Pedestal mounted to modified AG9140 skid, shock isolated	Flange mounted to FW on modified AG9140 skid
Number of Units	4 FWs per skid	4 MGs per skid

* Origin is on rotational centerline at mating end of shaft

Table 2. Electrical Characteristics for 2.5 MW, 10-minute UPS Energy Storage System

Electrical Characteristics	Flywheel	Flywheel Motor/Generator
Time to full power from standby	500 ms	500 ms
Time to full power from secured	1245 s (21 min)	1245 s (21 min)
Noise Frequencies and Level (dB)	160-319 Hz, 75dB (est)	160-638 Hz, 85 dB (est)
Operating Temp Range: Internal and External	100°C int., 49°C ext.	140°C int., 49°C ext.
Electrical Power Input	up to 10 kW control power & auxiliaries	up to 19 kW charge maintenance/5 kW excitation, and auxiliaries
Input Volts, Amps, Phases, Freq	220 V, 45.5 A, 1 ph, 60 Hz	460 V, 23.8 A, 3 ph, 60 Hz 220 V, 22.7 A, 1 ph, 60 Hz
Input Harmonic Limits	MIL-1399	MIL-1399
Backup Source	Battery UPS for controls and bearings	Battery UPS for field excitation
Electrical Power Output	N/A	625 kW/MG (2.5 MW per skid)
Voltage, Amperage, Frequency, Phase	N/A	600 Vl-lrms, 1402 Arms, 0-638 Hz, 3 phase
Output Harmonics	N/A	MIL-1399 Compliant at 60 Hz bus
Backup Source	N/A	N/A
Applicable Spec or MILSTD	N/A	MIL-1399

SYSTEM MODELING AND SIMULATION RESULTS

To study the behavior of a ship's power system with multiple flywheel energy storage units, a simplified system with two flywheels was modeled using the MatLab/Simulink platform, as shown in Figure 5. This system configuration consisted of a high speed permanent magnet generator directly driven by a Rolls-Royce AE1107 twin shaft gas turbine coupled with two flywheels to provide system energy storage. The system featured a common dc bus with passive rectification of the permanent magnet generator output and active rectification for the flywheel motor/generators. Four parallel IGBT inverters were used to provide 450 V, 60 Hz three-phase power to an ac distribution grid.

Simulations of several MPM functions were performed to guide the system designs, including:

- Uninterruptible Power (UPS)
- Turbine Load Leveling
  - Block Load
  - Load Shedding
- Flywheel Charging and Balance
- Filtering Requirements
- System Stability
- Fault Management

Some results of the simulation studies in regard to the UPS function are reported below as examples.

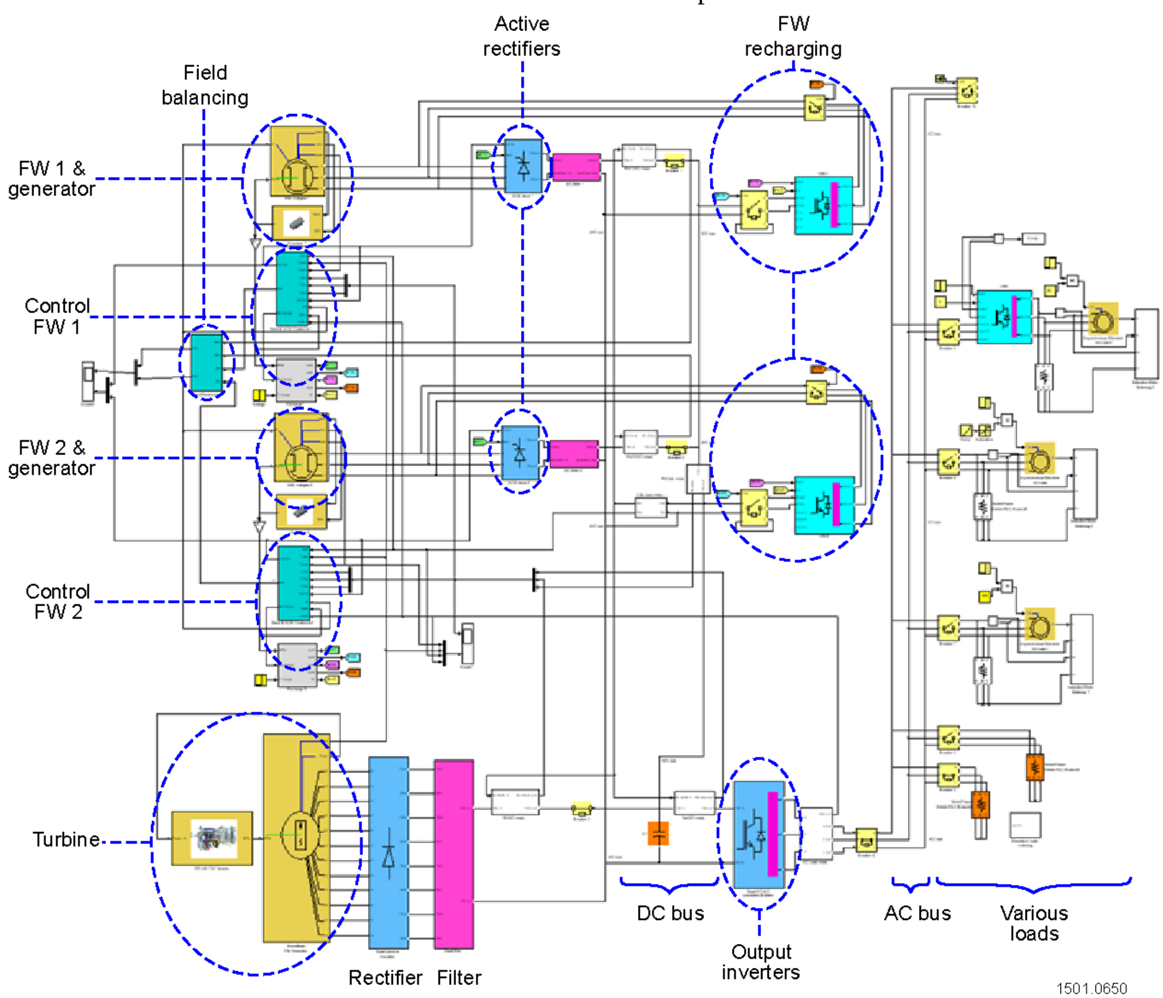

Figure 5. Overall Simulink System Model – the block of the output inverters contained four 750 kW inverter units in parallel

The ability to provide Mil-Spec quality uninterruptible power to the 450 V 60 Hz ac ship service distribution grid after failure of the primary turbine generator set is a principal goal of the MPM system. The UPS capability enables operation on a single gas turbine generator set which provides the majority of the fuel savings associated with the MPM power system concept.

Figure 6 shows the system response to loss of the turbine generator at time t = 0.75 s. The currents furnished to the dc bus by the three power sources are shown together with the total current. The initial 20 ms transient current rise is due to the interaction of reactive elements in the circuit with the flywheel currents and can be minimized by further refining the various interacting control parameters.

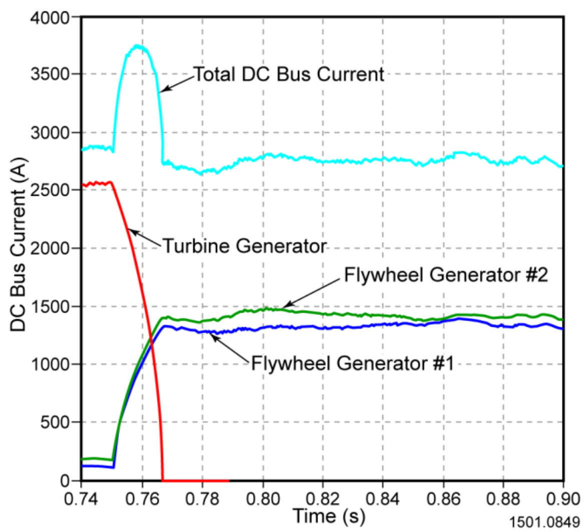

Figure 6. System Response to the Sudden Loss of the Turbine Generator when Carrying a 2 MW Load at *t* = 0.75 s

Figure 7 shows the response of the system at the ac output bus: the voltage across the load is hardly affected. A measurement of the RMS value of the load voltage before the transient of the turbine loss at t = 0.75 s yields a value of 456.23 V and after the transient a value of 443.33 V. This represents a change of 2.8%, well within the 7% allowed by MIL-STD-1399. Fourier analysis of the waveform before and after the transient shows no measurable change in harmonic content with THD values in both cases less than 0.1%. Thus, the flywheel and power conversion system response to the loss of the primary turbine generator set is essentially transparent to the 450 V ac distribution grid and power quality remains within the requirements of MIL-STD-1399, Section 300 throughout the transient event. The discharge and subsequent recharge of a flywheel is shown in Figure 8.

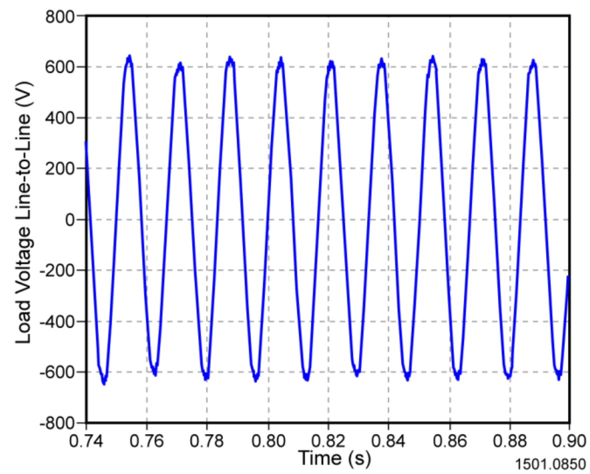

Figure 7. Response of AC Grid to Loss of Gas Turbine Generator Set at t = 0.75 s

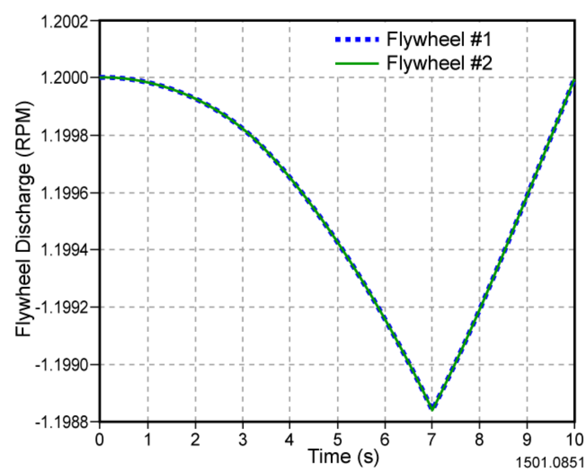

Figure 8. Flywheel Discharge and Recharge Cycles (Discharge (0-7 s) and Recharge (7-10 s))

In addition to the performance simulations, comparisons of fuel consumption at the macroscopic level were conducted to project potential fuel savings for various system configurations.

Estimates of the potential fuel savings of various DDG51 ship service power system configurations were developed. Baseline parameters for the estimates were taken from BAA07-029: 4,000 hours of operation per year with a ship service power of 2525 kW (electrical) and a fuel cost of $100 per barrel.

These figures do not necessarily reflect actual performance requirements or fuel costs (particularly the $100/bbl fuel cost), but allow for comparison between the various ship service system topologies and with other fuel saving concepts. Information on turbine specific fuel consumption for the engines used at specific power levels was provided by Rolls-Royce; this information is considered proprietary and cannot be disclosed. All fuel saving comparisons are relative to the baseline fuel consumption using current DDG51 CONOPS with two AG9140RF units providing the required 2525 kW of electrical power to the ship service distribution grid. The projected fuel savings resulting from these evaluations are $1.25 million per ship per year.

CONCLUSION

A conceptual design for supporting pulsed power loads aboard a DDG51 class destroyer was presented based on energy storage. Two options, Li-ion battery storage and flywheel energy storage, were compared and reasons for preferring the kinetic energy storage alternative were given. A conceptual design for flywheel-based energy storage modules suitable for retrofitting DDG51 ships was also presented.

A notional system with a high speed generator directly coupled to a turbine and two flywheel storage units feeding a common dc bus was considered and its simulation on the Matlab/Simulink platform was described.

A flywheel energy storage system allows the use of a single turbine close to full load instead of the current practice of running two turbines at less than half load. This opens the possibility for fuel savings which were also estimated.

The flywheel energy storage system is a mature technology and represents a natural extension of the Electromagnetic Launch System (EMALS), where the generator rotor is its own kinetic energy storage, which has been adopted by the Navy for aircraft launching. Therefore, it should be given serious consideration as a support for the new class of pulsed energy loads and as an enabler of potential fuel savings.

ACKNOWLEDGMENTS

This work was supported by ONR under Grant no. N00014-06-1-0886 and Contract no. N00014-07-C-0361.

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