FLYWHEEL ENERGY STORAGE TO IMPROVE THE ENERGY EFFICIENCY OF THE DDG-51 SHIP SERVICE ELECTRIC POWER DISTRIBUTION SYSTEM

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ABSTRACT

The Megawatt Power Module (MPM) for Ship Service Program modeled the use of energy storage and high speed power generation to reduce fuel consumption in the DDG51 class of ships. The MPM system modeling projected savings in excess of $1M/year per ship and provided the required reliability to enable single generator set operations. Energy storage is the enabling technology for the MPM concept. Flywheels and lithium ion batteries were originally evaluated based on available prototype information. The flywheel was selected for more detailed study as it was judged to be smaller, lighter, more reliable, and require less maintenance than lithium ion battery systems. With the recent emphasis on energy storage, both electrochemical battery and flywheel technologies have evolved. In parallel, improvements are now possible in the power and energy density of motors and generators and power conversion systems. This research highlights technology advances that increase efficiency and provide increased energy and power density relative to the state-of-the-art flywheel system designs of a few years ago. Important advances that are considered include rim arbor flywheel designs, advances in manufacturing and materials that permit higher speed operation, novel bearing technologies, and materials that make new generator topologies feasible.

INTRODUCTION

The University of Texas Center for Electromechanics (UT-CEM) and subcontractor Rolls-Royce (RR) conducted the Megawatt Power Module for Ship Service (MPM) program to evaluate the use of energy storage and high speed power generation to improve power generation efficiency by enabling safe operation on a single gas turbine generator set (GTG). Although a typical DDG 51 base electrical load could be supported by a single 3 MW GTG, current practice is to operate two units, each supporting half of the electric plant load. Operation at partial load results in increased specific fuel consumption (SFC) of the gas turbines, significantly reducing the efficiency of the ship service power generation system.

Energy storage is the enabling technology for the MPM concept and the reliable provision of uninterrupted power is a critical requirement for the ship service power system. Flywheels and lithium ion batteries were originally evaluated using available prototype information. Based on the initial trade studies, flywheel energy storage was selected for more detailed study as it was judged to be smaller, lighter, more reliable, and require less maintenance than lithium ion battery systems. Detailed *MATLAB Simulink* simulation models of the power system components were developed to enable performance studies of a variety of power system concepts and operational procedures. Initial designs of the major power system components were also developed to provide realistic performance, weight and dimensional data for the studies. Solid models were also created to develop general arrangements of the MPM package to ensure that the new system would fit within the AG9140 module footprint it was designed to replace. A range of MPM concepts was studied using different gas turbine prime movers, low speed and high speed generators and energy storage flywheel configurations.

The Office of Naval Research (ONR) subsequently issued BAA07-029 “Fuel Efficient and Power Dense Demonstrator for the USS Arleigh Burke (DDG 51) Flight IIA Class Ship”. The solicitation sought technologies capable of reducing fuel consumption, improving power conversion efficiency, and increasing installed power generation density on the USS Arleigh Burke (DDG 51) Flight IIA Class ships. The BAA required the power generation and energy storage systems developed for the MPM to be designed for retrofit into the existing DDG 51 Flight IIA class of ships with minimal modifications. The energy storage system was required to provide 10 minutes of uninterrupted power at the nominal rated power of 2,500 kWe to enable multiple start attempts on a second GTG. The requirements of this BAA eventually drove the final design of the MPM system that was presented to ONR. Table 1 shows projected fuel savings relative to current baseline dual-AG9140 performance with single shaft and twin shaft engines and 10 minutes of energy storage. It should be noted that the AG9140 Genset case features the current gearbox driven low speed generator.

Table 1. Projected DDG 51 fuel savings.

DDG 51 Fuel Saving Projections	
Case Description	Projected Fuel Savings*
AG9140 Genset	25.0%
Single Shaft Turbine + HSG	27.5%
Twin Shaft Turbine + HSG	34.8%

* Relative to baseline operation including 10 minute UPS.

MPM System Overview

To minimize the cost and complexity of the DDG51 retrofit, the MPM power generation and energy storage systems were designed to fit within the footprint of the existing AG9140 Gas Turbine Generator Sets supplied by Rolls-Royce. To free volume for the energy storage and power conversion systems, the MPM used a high power density primary power generation system consisting of a high speed PM generator driven by a twin shaft gas turbine at approximately 15,000 rpm. The twin shaft engine is significantly more efficient than the older Allison 501 engine in the AG9140 GTG. Solid-state power conversion allows the system to decouple the power generation frequency from the 60 Hz distribution frequency and provides the interface to the energy storage system. This removes the need for a reduction gear box, significantly reduces the size and weight of the generator and enables variable speed operation to optimize gas turbine specific fuel consumption (SFC) with load. The high power density primary generation system enabled the integration of the baseline energy storage system within the AG9140 footprint. Figure 1 shows a solid model of one variant of the MPM system package with two 1.25 MW energy storage flywheel modules; other module designs featured four flywheels per skid.

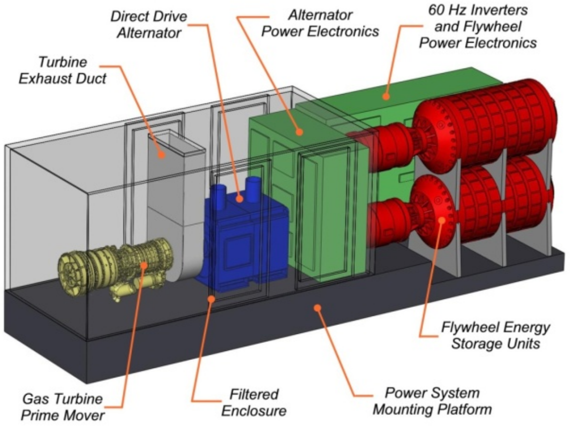

Figure 1. Proposed MPM general arrangement

Energy storage enables single generator set operations which provides three significant benefits:

- Reduced operational hours on the GTG’s
- Improved specific fuel consumption – load & speed optimization
- Load leveling to minimize transients and reduce turbine thermal cycling

Operating two GTG’s maintains power system reliability by eliminating single point failures but it effectively doubles the operational hours on the engines. The current mode of operations also results in significantly higher specific fuel consumption from operation of the turbines at partial load. The MPM system runs a single turbine at near rated load – the optimum efficiency point – and can modulate the gas turbine shaft speeds to further optimize efficiency at a given load. The reduction in operational hours on the GTG significantly reduces the life cycle cost of power generation for the DDG 51. Energy storage can also reduce thermal cycling and engine load transients by leveling the power system loads. Fewer engine thermal cycles can reduce turbine maintenance and extend operational life. This both reduces the total cost of ownership and enhances the reliability of the power plant.

MPM Energy Storage Trades

Energy storage is the enabling technology for the MPM concept. At the time of the study, flywheels and lithium ion batteries were evaluated based on available data and the flywheel system was selected for detailed study as it was judged to be smaller, lighter, more reliable, and require less maintenance than lithium ion battery systems. Flywheels also offer the ability to independently select the energy and power capability of the system and provide unequivocal indication of state-of-charge.

Technology Readiness Level: At the time of the study, no MW level Li-ion battery installations were documented in the literature, suggesting that a MW level Li-ion battery array has a low TRL. In contrast, flywheel UPS systems at MW levels were in commercial use at that time.

Scaling: While cell-level power and energy densities of Li-ion batteries are impressive, practical packaging considerations (bus work, mounting, maintenance access) for a 2.5 MW, 10-minute battery bank must be considered for installation into an existing ship platform. Using available information, the volume of two MW-scale battery installations (one lead-acid and one nickel cadmium) were scaled by cell-level power density to project the volume of a comparable Li-ion system. This comparison resulted in a projected volume of approximately 120 m^3 for the 10 minute battery system. Based on this comparison, Li-ion systems do not offer significant savings in storage volume over flywheel systems in this power and energy range.

Performance Degradation and Life: One issue with all battery technologies is the reduction of energy storage capacity over time and with charge/discharge cycles. 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 multiple 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. Future Navy needs for pulsed loads or sensors may further exacerbate this problem. In contrast, flywheels have been demonstrated to show no discernible degradation after more than 100,000 deep discharge cycles. The flywheel can be designed to meet the 35-year design life without replacement.

Reliability**:** Due to the low Li-ion cell voltage (nominally ~3.6 V per cell), it is necessary to connect many cells in series to achieve the minimum voltage required on the ship service grid. Many of these 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 (with thousands of electrical connections) for a typical ship service system application. Li-ion cells can fail catastrophically if they are overcharged so it is necessary to individually monitor and control the charging of each cell in the battery array. Reliability is a significant issue in installations requiring thousands of cells since the failure of a single cell can impact an entire series-connected string and can potentially affect other cells as the load shifts to parallel strings and increases their effective discharge rate.

*Safety***:** Monitoring and maintenance requirements are also high for Li-ion cells because of their catastrophic failure mode. A complex battery protection circuit is required for each cell in the array to avoid thermal runaway. However, upon failure, any protection system removes that cell from the array and compromises the performance of the entire series string.

Outcomes: Based on these considerations, the final MPM system design consisted of a twin shaft gas turbine driving a permanent magnet generator, a system of eight energy storage flywheels and the required power conversion and control modules. The number of flywheels was driven by the DDG 51 retrofit design constraint because the maximum envelope and weight of individual components was severely restricted. This favored designs using a larger number of smaller flywheels.

Energy Storage Technologies

Recent emphasis on energy storage means that both electrochemical battery and flywheel technologies have evolved, along with improvements in the power density of motor/generators and power converters. A rigorous comparison of current state-of-the-art battery and flywheel designs is beyond the scope of this paper; however, an updated study of current energy storage technologies for the DDG51 application would be valuable and is recommended for future study. This study should also include similar comparisons for other naval energy storage applications including advanced weapons and sensors. This paper presents some of the recent advancements in flywheel energy storage to illustrate the potential impact of technology developments. The concept presented does not represent a fully optimized design for the DDG 51 application – it was intended only to show how these new technologies and capabilities could be applied in a focused design effort.

To illustrate the potential impact of new flywheel materials and rotor topologies on the size and weight of the energy storage flywheels, a comparison between the baseline 210 MJ flywheel rotor used in the MPM study and current state-of-the-art flywheel designs is useful. The MPM flywheel design was based on a solid, radially preloaded rotor design first developed at this scale for the Advanced Locomotive Propulsion System (ALPS) program[1,2]. The rotor consists of a hollow steel shaft supporting multiple cylindrical composite rings assembled with radial interference. The rotor assembly is mounted in a set of five-axis active magnetic bearings and an independent motor/generator is used to input and extract energy from the flywheel. The rotor size and aspect ratio for the MPM design were driven by rotor dynamics considerations and the constraints imposed by the DDG 51 retrofit – the maximum OD of the flywheel module was limited to only 1.05 m (41.5 in) to enable installation through existing passageways. The MPM flywheels are extremely robust and are designed for infinite cycle life using intermediate modulus graphite fibers and a conservative maximum tip speed (angular velocity multiplied by radius) of only 825 m/s. Figure 2 shows the general arrangement and major components of the MPM flywheel.

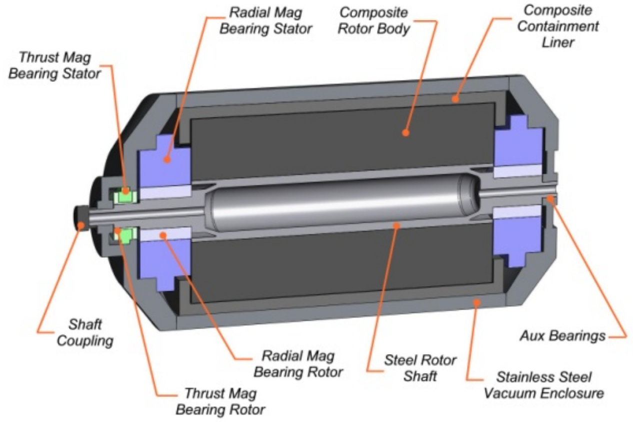

Figure 2. MPM flywheel cross section.

Recent advances in composite materials and manufacturing techniques for complex composite structures lead to significant improvements in flywheel rotor performance. UT-CEM developed and implemented a high modulus graphite fiber/resin laminate construction that increases the allowable tip speed of the rotor while maintaining robust design margins relative to ultimate strain. This material enables operational strains over 1% and has been successfully demonstrated at tip speeds over 1,350 m/s in a NASA flywheel program[3]. UT-CEM also pioneered new analytical and composite manufacturing techniques that enable the design and construction of strain matching composite arbors that bridge between the rotor shaft and an annular flywheel rim. The development of the rim/arbor flywheel design is supported by a unique suite of custom software codes called CEMWIND. This unique design tool allows simulation and visualization of the complex filament winding process to evaluate non-geodesic winding patterns and assess manufacturing issues such as bridging or tow slippage. Once the baseline winding pattern is established, the code generates a finite element mesh and exports a set of custom material property definitions for each element based on fiber orientations at that location; structural and thermal analyses can then be solved in an external solver such as ABAQUS. Once satisfactory structural and physical properties have been achieved, the code then generates the G-codes for programming of the 5 axis filament winding machine. Using CEMWIND, strain-matching arbors can be designed to track the radial deflection of the inner surface of the rim at the OD and to match the limited radial growth of the shaft at the ID. This enables the designer to concentrate the rotor mass at a larger radius to maximize the moment of inertia and energy storage.

For comparison with the solid MPM flywheel, a notional rim/arbor flywheel design was developed based on demonstrated rim-ring and arbor performance characteristics. The rotor stores 350 MJ and is designed to operate with a nominal 1,200 m/s tip speed at a maximum operating speed of 20,000 rpm. Figure 3 shows a cutaway section of the advanced rim/arbor flywheel.

Table 2 provides a comparison of the original MPM flywheel with this advanced flywheel design.

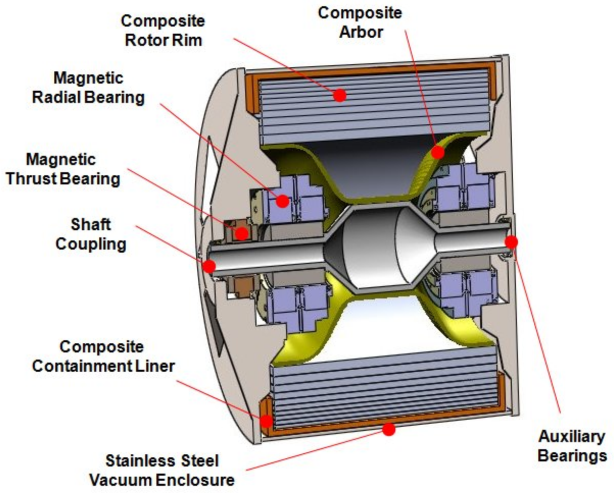

Figure 3. Rim/arbor flywheel cross section.

Table 2. Flywheel rotor topology comparison.

Parameter	Solid Rotor	Rim/Arbor Rotor
Stored Energy	210 MJ	335 MJ
Delivered Energy	160 MJ	250 MJ
Rotor Outer Diameter	0.82 m	1.13 m
Rotor Length	1.44 m	0.79 m
Max shaft speed	19146 rpm	20,000
Composite mass	1,114 kg.	690 kg

A logical extension of the rim/arbor rotor design is a “shaftless” rotor topology – effectively a rim supported on inside-out bearings. This rotor topology maximizes the effectiveness of the composite materials and is best suited for fully integrated topologies where the motor/generator is integrated into the flywheel structure.

The shaftless rotor topology is very challenging for high power continuous duty applications due to the difficulty in managing the losses in the motor/generator but it is ideal for UPS applications where the motor/generator discharge losses can be absorbed adiabatically. Figure 3 shows this topology for a small scale, 25 kWh, 25 kW flywheel design developed for another application.

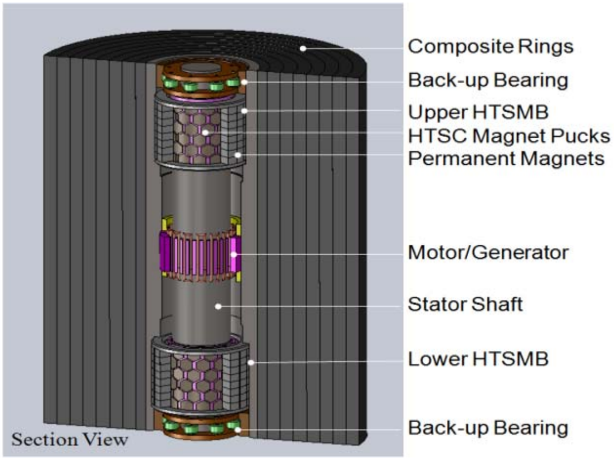

Figure 4. Shaftless rotor design.

High Temperature Superconducting Trapped Field Magnets

The flywheel rotor represents only one element of the overall energy storage system. UT-CEM is also conducting research with bulk yttrium-barium-copper-oxide (YBCO) high temperature superconducting (HTS) materials for magnetic bearing and motor/generator applications[4]. When exposed to magnetic fields at temperatures below their transition temperature, the YBCO “pucks” can trap or pin magnetic flux. The activated materials -- referred to as Trapped Field Magnets (TFM) – then behave like permanent magnets as long as the temperature remains below the critical point.

The power of a rotating electric machine is directly proportional to the magnetic flux density in the air gap:

$$P \propto B \times J \times L \times D^2 \qquad [1]$$

where,

P = power, W
B = airgap flux density, T
J = stator line current density, A/m
L = active length, m
D = airgap diameter, m

Figure 4 illustrates the potential benefits of this technology – TFMs have demonstrated a peak magnetic flux density greater than 17 T at the surface of the puck and can achieve flux densities over 8 T at 46 Kelvin[4]. Trapped field magnets offer the potential for significant increases in the airgap flux density of rotating machines which can lead to a corresponding increase in the power density of the machine.

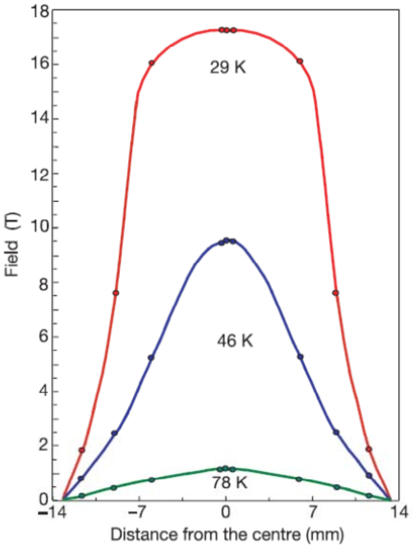

Figure 4. Trapped fields in bulk YBCO superconductors.

Due to their inherently low losses, HTS magnetic bearings are actively being developed for energy storage flywheels [5, 6, 7]. HTS magnetic bearings can also benefit from TFM technology. When TFMs are activated in a magnetic circuit they exclude magnetic flux and subsequently resist any relative motion with respect to the magnetic field. (The magnetic field is typically generated by permanent magnets located on the rotor of the machine.) The resulting restoring forces generated in response to deflections form the basis for HTS magnetic bearings. The magnitude of the restoring force is proportional to the airgap flux density so higher strength TFMs offer the potential for higher force density bearings. UT-CEM is developing novel analytical approaches to characterize the behavior of HTS bearings along with specialized damping and control systems for high speed rotating machine applications.

Advanced Power Conversion

Power conversion systems are common to both flywheel and battery energy storage systems; however, flywheels typically require an additional ac/dc conversion step compared to battery systems. Any additional conversion losses for the flywheel system are typically offset by the higher internal losses in the batteries so flywheel systems still provide higher “round-trip” efficiencies. Recent advances in power conversion topologies and silicon carbide (SiC) semiconductor switches offer the potential for significant improvements in the efficiency of conversion systems. While this will benefit both energy storage technologies, it will further increase the round-trip efficiency advantage of the flywheel system.

UT-CEM is currently leveraging the successful demonstration of a multi-MW bi-directional power converter for high speed flywheel applications to develop and demonstrate an enhanced soft-switching power converter. A soft-switched converter is a more complex machine than its hard-switched counterpart, both from the standpoint of part count and the sophistication of the control system. Justification for its use is based on the desire to increase efficiency, reduce losses, and extend its rating by minimizing the switching losses in the main converter bridge.   The increased cost and complexity of soft switched converters have limited their acceptance by industrial users and commercial converter manufacturers, particularly for high power converters. However, in applications where temperature limits, the operating frequency, or constraints on physical size exceed the capabilities of conventional technology or results in significant savings elsewhere in the system, the projected advantages afforded by a resonant converter may not only justify its use but be the only way to solve the problem.

The novel converter topology being developed will result in significantly reduced switching losses relative to conventional hard-switched converters and provide increased robustness relative to the original resonant switching converter design. When coupled with the lower on-state conduction voltage drop of SiC switches, the new technologies offer the potential for a significant reduction in both of the primary loss components of solid state power converters.

There are several implications of reduced switching and conduction losses in the power semiconductors. Reduced switching losses may enable higher pulse width modulation (PWM) switching frequencies for the solid state devices. Higher switching frequencies can reduce the total harmonic distortion (THD) of the output waveforms and can potentially reduce the size and weight of circuit filters to provide the required power quality.

The lower conduction losses of the SiC semiconductors will further improve the performance and overall efficiency of the power conversion process and may enable a reduction in the capacity of the thermal management system for the converter. Alternatively, the reduced losses in the SiC systems may also allow higher operating current densities that will improve the overall power density of the power conversion system.

CONCLUSION

Recent emphasis on energy storage means that both electrochemical battery and flywheel technologies have evolved, along with improvements in the power density of motor/generators and power converters. Advancements in flywheel energy storage technologies were presented to illustrate their potential impact on the design of a flywheel energy storage system for the DDG 51 UPS application. The rim/arbor rotor topology presented in the paper provides an approximately 60% increase in the gravimetric energy density over the original solid rotor design developed for the original MPM flywheel study. The concept presented does not represent a fully optimized design for the DDG 51 application – it was intended only to show how these new technologies and capabilities could be applied in a focused design effort.

The performance of the flywheel can potentially be further enhanced through the use of low-loss HTS magnetic bearings. HTS technology also offers the potential for substantial increases in the power density of motor/generators needed to drive the flywheel. Finally, advances in power conversion topologies and the advent of high power SiC semiconductor switches offer the potential for reduced losses and increased power density for the power conversion system. Improvements in this technology have much broader implications for advanced naval electric power systems and continued research and development in this area is strongly encouraged.

A rigorous comparison of current state-of-the-art battery and flywheel designs was beyond the scope of this paper; however, an updated evaluation of current state-of-the-art energy storage technologies for the DDG51 application would be extremely valuable and is recommended for future study. Such a study should also include similar technology comparisons for other naval energy storage applications including advanced weapons and sensors.

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