Flywheel Energy Storage System

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Prepared By:

AFS Trinity Power Corporation

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"Research Powers the Future"

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Contract: Flywheel Energy Storage System, #500-98-036 conducted by AFS Trinity Power Corporation. The report is entitled Flywheel Energy Storage System. This project contributes to the Energy Systems Integration program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

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Executive Summary

AFS Trinity Power Corporation has completed its PIER contract No. 500-98-036: Flywheel Energy Storage System. The overall goal of this project was to identify the key performance elements of an advanced flywheel power system that can perform load following for a distributed generation system. The product demonstrated in this contract is a 100 kW flywheel power system that delivers power for 15 seconds. Prototypes of this system have been constructed, and tested. As a result of this effort, the key performance elements were identified and demonstrated. The demonstrated system shows good commercial potential, and AFS Trinity is continuing with additional development work to make the commercial product more responsive to the marketplace. The company is also seeking new equity investment to complete the steps to a full commercial product launch.

During this contract, AFS Trinity also learned much about the commercial application requirements for this product. The project started in 1998 with the goal of producing an energy storage flywheel that could be used with a residential photovoltaic system for load-shifting energy storage. As the project progressed, AFS Trinity and the Commission realized that this market application had a very low probability of commercial success and decided to shift to a more commercially viable application, that of supporting the increased market penetration of distributed generation systems. The project goal was changed to produce a high power, short duration flywheel power system with applications in distributed generation and power management. Development was then completed for this market application and a successful demonstration of AFS Trinity flywheel technology necessary to support this application was completed.

PIER Objectives

This project addresses two PIER Program objectives:

1. To improve the reliability of California's electricity system by developing a distributed generation enabling flywheel energy storage system technology that permits distributed generation technologies to be more easily integrated into the utility grid; and
2. To reduce environmental risks from California's electric system by providing a more environmentally friendly energy storage technology and enabling the increased use of environmentally responsive renewable distributed generation technologies.

The broad goal of this project was to develop and demonstrate an advanced flywheel system for power management and load following. We have succeeded in this, and have proven the feasibility of the AFS Trinity M3AM Flywheel Power System.

As a direct result of the lessons learned in executing this contract, the goals have changed over the course of the contract. Where initially the project proposed to demonstrate an "energy wheel" design, under this effort, we came to realize that a "power wheel" is what the commercial market required, and the Commission agreed. The specific characteristics of the system demonstrated in this effort will be discussed in detail in Section 3 of this report.

Outcomes

During this effort, AFS Trinity Power has achieved several significant milestones that have advanced the state of flywheel technology and moved closer to a commercially viable flywheel power system. These achievements were:

- Integration of active magnetic bearings
- Highest energy density and power density of any commercially available flywheel power system
- Advanced motor control software that exceeds the capabilities of any known third party product
- Extensive market analysis of flywheel commercialization opportunities

Conclusions and Recommendations

This effort has successfully identified and demonstrated the key performance elements an advanced flywheel power system needs to perform to provide load following for a distributed generation system. As a distributed generation load following device, it will facilitate customer acceptance of fuel cells, microturbines and natural gas combined heat and power systems.

In addition to the distributed generation load following application, AFS Trinity has identified commercialization requirements for three additional applications of its flywheel energy storage systems. These are: power quality, light rail power management and industrial power management. This wider variety of commercial applications identified in this effort will help AFS Trinity and other emerging flywheel energy storage companies accelerate the commercial acceptance of their products.

Furthermore, we continue to work with several business incubator services in our search for new equity investment that will assist AFS Trinity in launching its flywheel product line. Concurrently with this project, AFS Trinity developed a detailed business plan for the commercialization of this emerging technology.

AFS Trinity recommends the continuation of the product development and market development of this promising technology. The next key technology milestone is to demonstrate the successful operation of the flywheel system at an end user site. We will continue to seek both government agency funding and private investment to achieve that goal.

Benefits to California

The results of the research and demonstrations completed in this project have demonstrated that flywheel power systems can create both economic and environmental benefits for the state of California. Successfully fielded commercial flywheel technology will reduce business losses from power disturbances and increase industrial energy efficiency. Sales success of this emerging technology will also lead to California job creation and economic growth.

Environmental benefits include air quality improvements and reductions in solid waste generation. As an enabling technology for distributed generation, our flywheels will facilitate greater customer acceptance of these efficient, low emissions alternatives to utility grid power. As a battery replacement in distributed utility applications, or in the existing commercial UPS market, flywheel technology can directly eliminate environmentally unfriendly batteries systems from the solid waste stream.

With further testing, development and customer acceptance, the AFS Trinity flywheel power system can successfully complete the transition to a commercial product. It serves as an excellent example of the successful collaboration between government and industry.

Abstract

The broad goal of this project was the development and demonstration of a complete prototype Flywheel Power System (FPS) and successful proof of the feasibility of this energy storage technology. The AFS Trinity M3AM system, as demonstrated in this contract, can discharge at 100kW for 15 seconds, and recharge immediately at the same rate. The duty cycle is thus 30 seconds, and the available energy is 0.42kWh. A duty factor of 40% is sustainable for 100 successive discharges, and a duty factor of 23% is sustainable indefinitely. The system has a footprint smaller than 4 sq ft, and typically has 680V DC output. It is based on a Halbach array motor generator and a high strength all-carbon composite rotor. Proprietary motor control software and hardware implement a deadband control scheme to give good voltage regulation on the DC bus. Maximum design speed of the system is 40,800 rpm, and the verified factor of safety is greater than 2.0 based on rotor burst testing. The final laboratory prototype systems have undergone extensive functional testing. The next step in development will be final system modifications for the transition from laboratory to field testing, and interface engineering for a field experiment.

AFS Trinity plans to commercialize this system for applications in load-following of advanced distributed generation, power quality, and industrial power management.

In addition to the Energy Commission, the Federal Transit Authority (FTA), Defense Advanced Research Projects Agency (DARPA), Department of Energy (DOE), and equity investors in AFS TRINITY have co-funded this project.

Keywords: Flywheel, Composite, Rotor, Storage, Load Following, Distributed Generation, UPS

1.0 Introduction

1.1 Energy Storage Background and Overview

1.1.1 Energy Storage Applications and Solutions

Energy Storage technologies produce no net energy, but can provide electric power over limited periods of time. Affordable, compact, reliable energy storage, available in a range of powers and discharge durations, would dramatically alter the standard solutions for provision of electrical power. Its presence in a system can eliminate the voltage swings caused by rapid changes in load, spare system hardware from large transient currents, decrease demand charges, damp oscillations, or shift load from a time when energy is scarce and expensive, to a time when energy is plentiful and cheap. It can store energy that would otherwise be dissipated, prevent dropout of sensitive loads, and defer system upgrades. This broad range of claims for storage technologies invokes an equally broad range of technologies as solutions. Certain technologies are most appropriate for small applications, while others are better at large system sizes. Some technologies have long cycle lives and others are good for only a few charge/discharge cycles. Needless to say, each choice has economic and functional ramifications, so careful choices of an appropriate technology are important. These technologies have also proven difficult and costly to develop, and this expense has driven a wide range of developers from the field.

1.1.2 Energy Wheels, Power Wheels, and Cost

The cost of any electrical energy storage system has three components, one due to the amount of energy stored, one due to the power at which it must be discharged, and one from the balance of systems. These are nearly independent. In the case of flywheels, the first is the flywheel rotor, the second includes the motor generator elements and the power electronics, and the third includes the cabinet, cooling system and other ancillary systems. Considering the first two cost factors, we use the term “energy wheels” for flywheel power systems where the rotor cost is dominant, and the term “power wheels” for those systems where the cost of motor/generator and power electronics dominates. Energy wheels are optimized for long discharge time, and power wheels are optimized for short discharge time.

1.1.3 Characteristic Discharge times

There are really only two energy storage technologies that have long histories of successful use for times of a second or more. These technologies are chemical batteries and pumped hydro. Pumped hydro has been utilized at large system sizes for diurnal load matching of wind, or load leveling with geothermal or nuclear power generation. Pumped hydro is relevant for long charge/discharge cycles of hours. Chemical batteries have been used successfully in applications ranging from the tiny devices in hearing aids to the large batteries at Chino or Vernon, for example. Batteries have useful charge/discharge cycles of minutes to hours, though typically discharges of less than 10s of minutes require battery over-sizing to prevent degradation of cycle life.

There is a consensus view that the ability to charge and discharge energy over times of a few seconds to a minute has significant value. This value relates to improved reliability, efficiency, system stability, or other factors, and can require a modest amount of stored energy. For example, the Tacoma SMES (Superconducting Magnetic Energy Storage) stored only 30 MJ, yet it provided the energy necessary to stabilize a 3 second sub-synchronous resonance on a 500kV transmission line, charging and discharging a million cycles during the year's duration of the test in Tacoma, WA.

1.2 Flywheel Background and Overview

1.2.1 Flywheel Concept

There are many ways that energy can be stored; in chemical bonds (fuel), in the energy to separate ions (batteries), in gravitational potential energy (pumped hydro), or in kinetic energy (flywheels), for example. In a flywheel, the inertia of a rotating mass is used to store energy.

The potter's wheel is a low-tech example of this from antiquity. In a potter's wheel, the potter spins the wheel up from a stop by kicking it with her feet. Then when the potter molds the clay with her hands, she kicks the wheel occasionally to maintain the speed of rotation against the frictional forces that sap its energy and slow it down. Some of the friction is in the bearings of the wheel, and some is from working the clay. The purpose of the wheel is to keep the clay moving in a circular path so that it can be shaped into a vessel of cylindrical symmetry. The heavier the wheel the more uniform the velocity of rotation, and the more symmetrical the results. A second common example of a flywheel is found in an automobile. Its function is to smooth out the impulse torques provided by the firing of the engine's cylinders, into the uniform rotation of the drive shaft and wheels.

In a modern flywheel for storage of electrical energy there is also a rotating mass. Its purpose is to maintain the voltage of the attached lines at a constant value. This rotating mass is made of metal or composite, and it is spun up by being part of an electrical motor. To charge the flywheel with energy, pulses of electrical current are fed sequentially to fixed coils called the stator, and the magnetic fields from these currents exert forces on the rotor to spin it up, as the potter's kicking speeds up her flywheel. An electrical motor and an electrical generator are very similar, and the same hardware can be used for both functions. Whether the modern flywheel is being sped up, and thus storing energy, or whether it is being slowed down, and thus providing energy, is determined by the control system and the voltage of the system to which it is connected.

When the flywheel is not being sped up, it idles. It can maintain a very-nearly constant speed for a long time, because the losses (equivalent to friction) in the bearings are very small. The operation of a modern flywheel is somewhat like the heating system in your house, when operating under the control of a thermostat. It is sped up to its idling speed, it very slowly loses speed over some period of time, and then it is sped up to idling speed again. In the metaphorical comparison to home heating, your furnace brings the house up to the set temperature, the furnace turns off, the house slowly cools owing to the losses of heat through the walls, windows, and ceiling, and when the lower bound of the acceptable temperature range is reached, the furnace turns back on to raise the temperature to the top of the band again. In the modern flywheel for power applications, when the voltage supplied to the flywheel drops below a preset value, the flywheel discharges energy to maintain that voltage. When the voltage rises above another set value, the flywheel can absorb that energy to maintain the bus voltage in the desired range.

The main parts of the modern flywheel are a power converter, a controller, a stator, bearings, and a rotor. The rotor includes the rotating part of the motor generator, and the rotating part of the bearings. The stator is also a part of the motor generator. Figure 1 shows this schematically:

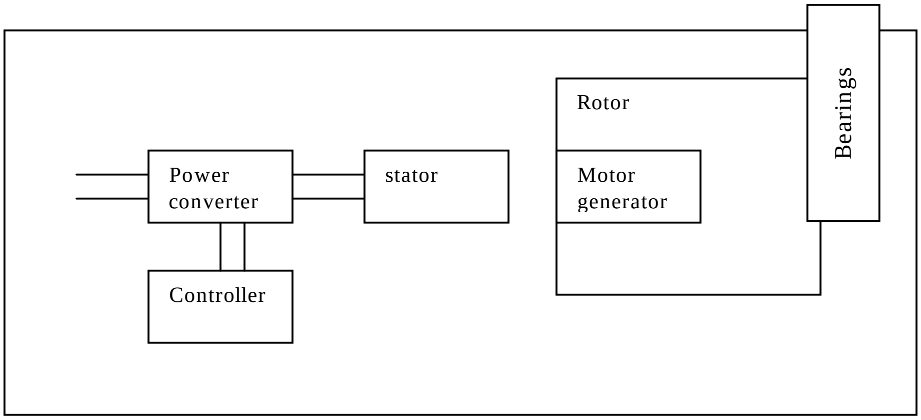


Figure 1. Schematic Diagram of Flywheel Subsystems

The power converter connects to a source of Direct Current (DC). It provides the current pulses to speed up the rotor. This is a current with variable frequency and variable voltage. The controller determines the frequency so that the flywheel receives the “kick” at just the right moment. The AFS Trinity flywheel uses a permanent magnet motor generator. The permanent magnets are embedded in the rotor. The bearings support the rotor with minimal drag. The stator is fluid-cooled. The entire system is contained in one cabinet, along with the necessary fuses, contactors, and cooling fans to support safe operation.

The system is used to provide extra energy when it is needed, or remove excess energy when it is present. This can be very important for the proper function of distributed generation sources when they are supporting variable loads.

1.2.2 Load Following for Distributed Generation

Three advanced generation technologies that are expected to play a large role in Distributed Generation applications are microturbines, natural gas engine generators, and fuel cells. Each of these generators operates best under constant load. If there is a significant change in the load on the generator, such as when a large motor turns on or off, it is likely that two things will happen for an interval after the load change: the voltage will sag or swell, and the efficiency of fuel consumption will drop. If the load has increased, the voltage will sag. If the load has decreased, the voltage will swell. It is as if the generator literally had inertia, and a tendency to continue to do what it had been doing in terms of generation.

Adding flywheel energy storage to a distributed generation system can provide four benefits. It can stabilize voltage for power users, improve generator fuel efficiency, reduce generator emissions and increase generator service life. Fuel Cells in particular, have a limited ability to raise or lower their electrical output quickly enough to follow rapid changes in electric load. For example, turning on an air conditioner or industrial motor will create a large step increase in load that may cause a voltage drop within the facility. Microturbines and natural gas engine generators are also known to run cleaner and more efficiently when their output power is adjusted gradually.

Figure 2 shows a step decrease in load followed by a step increase in load at a hypothetical distributed generation installation. When the load drops suddenly, as would happen if an industrial process were turned off, the flywheel can absorb power from the fuel cell or other generator for the few seconds it needs to reduce its output (first shaded triangle). If load is suddenly increased, the flywheel can discharge power for a few seconds while the fuel cell or other generator "catches up" with the electric load (second shaded triangle). In both cases, the flywheel also helps keep voltage constant, thereby eliminating power disturbances.

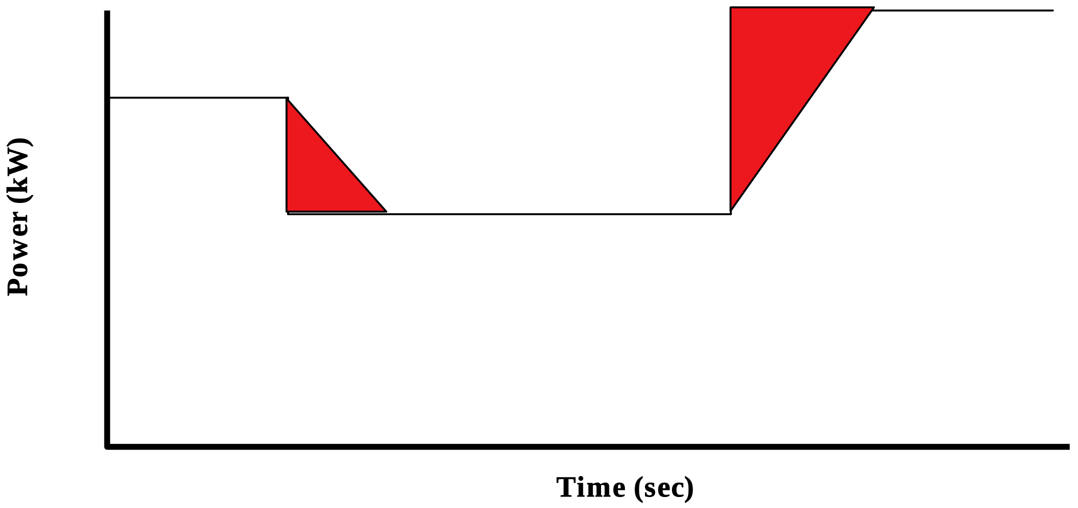


Figure 2. Shaded Areas Show "Fill-In" Energy Supplied by Flywheel

1.2.3 AFS Trinity System Applications

AFS Trinity System Applications require power for a duration of about 15 seconds. As mentioned earlier, these include load-following for distributed generation, industrial power management, or ride through of system disturbances. In part from work done under this Commission contract, we now know that inertial energy storage finds its "sweet spot" of discharge time in the range of 10 seconds to a couple of minutes, as shown in Figure 3. Prior to this contract we, and several other developers, believed that flywheels might also play a role at longer discharge times. As we developed a clearer picture of system costs for various technologies, we all realized that while batteries are unbeatable at long discharge times, and capacitors at short discharge times, flywheels have significant advantage in discharge time of 1 to 100 seconds, and discharge powers above 20kW, as illustrated below in blue.

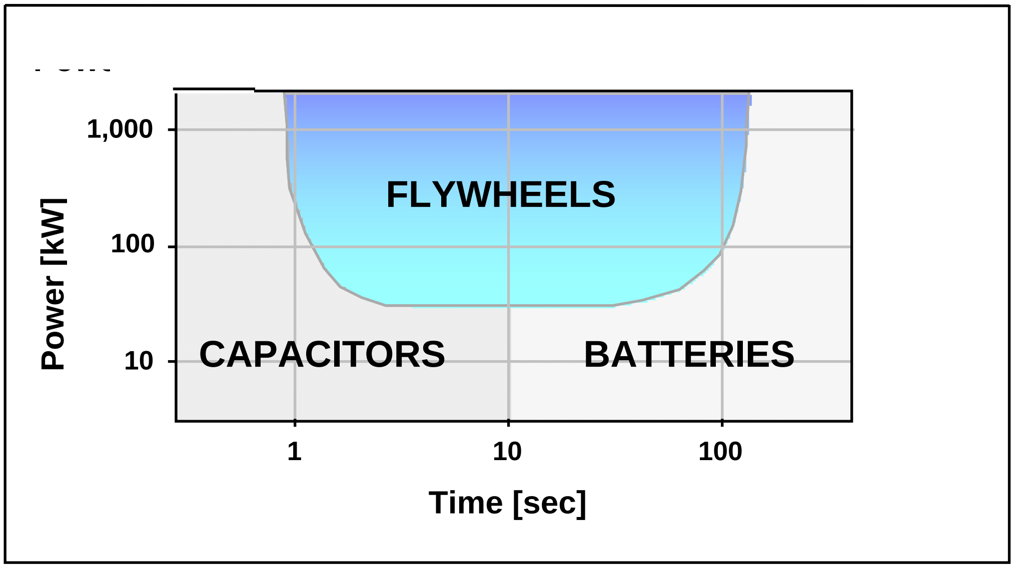


Figure 3. Suitability of Various Energy Storage Technologies

At the time that PIER II awarded this contract to Trinity Power, there was still a belief that there would also be economic applications of flywheels at low power and longer times, and this project was expected to culminate in a demonstration of flywheels for load shifting of residential photovoltaic power generation. Since 1998 several developers have ceased activity on flywheels with low ratio of power to energy (long discharge times) and AFS Trinity similarly came to the conclusion that the markets for broad commercialization all lie in applications whose characteristic times are of the order of 15 seconds. The Commission accepted this, and the direction of development was reoriented to shorter discharge time and higher power.

In addition to the distributed generation load following application, AFS Trinity has identified commercialization requirements for three additional applications of its flywheel energy storage systems. These are: power quality, light rail power management and industrial power management. This wider variety of commercial applications identified in this effort will help AFS Trinity accelerate the commercial acceptance of their products.

From the standpoint of its engineering physics, inertial energy storage holds great promise for applications in this discharge time regime of a few seconds to a minute. The challenge is to bring enough funding, creativity, and engineering expertise to bear, to succeed in the design, fabrication, and test of a reliable unit. Like any other hardware development project, there are many stages along the path.

1.2.4 AFS TRINITY Stage of Development

In 2001 the Commission published a reference document describing a process called Stages and Gates. This document is available on the Internet at:
http://www.energy.ca.gov/research/innovations/STAGES_AND_GATES.PDF

This process defines the Stage of a development program according to several criteria, and poses hurdles or Gates that a program must meet before advancing to the next Stage. While this process postdated signing of the present contract, it may be instructive to describe where AFS Trinity falls on this scale of maturity.

First, a brief summary of the Stages and Gates:

- Stage 1: Idea Generation and Work Statement Development
- Stage 2: Technical and Market Analysis
- Stage 3: Research and Bench Scale Testing
- Stage 4: Technology Development and Field Experiments
- Stage 5: Product Development and Field Testing
- Stage 6: Demonstration and Full-Scale Testing
- Stage 7: Market Transformation
- Stage 8: Commercialization

Stage 3, which we are just completing, culminates in a proof-of-feasibility test (Gate 3), while Stage 4, on which we propose to embark, includes a detailed field test plan, with reliability, availability, maintainability, and durability testing. Stage 4 also includes selection of field-test sites, construction of the field prototype, and initial field experiments.

Stage 2 for our program was completed by Lawrence Livermore National Laboratory (LLNL), when they conducted a technical and patentability analysis for the Halbach Array flywheel motor generator prior to granting a development license to Trinity Flywheel in 1993. AFS Trinity development of the LLNL technology has involved solution of problems in a wide range of engineering disciplines from rotating machinery to advanced materials, power electronics, microprocessor control, and system integration. The engineering work for the past 5 years, under PIER II funding, has been solidly in Stage 3, Research and Bench Scale Testing. We have advanced through multiple generations of technology in each major area: the rotor, the bearings, the control system, and the power electronics.

We have prepared a preliminary plan for our first field experiment, a Stage 4 activity. It shows that the System will require certain modifications for the transition from laboratory to field testing, interface engineering, and a final set of functional and reliability testing before the first field experiment. These activities are also Stage 4, and this final report marks the Gate between Stages 3 and 4.

1.2.5 Other Commission Flywheel work

At the time of this writing, in 2004, a high-strength composite flywheel power system from URENCO in Great Britain is available for purchase. http://www.urenco.com/flycylinder/. It has been deployed in the US particularly in trackside application for rapid transit systems. URENCO has been building high-speed composite centrifuges for uranium isotope separation for 25 years. Flywheel and centrifuge development have many common elements. URENCO displayed early prototypes of their DC flywheel system even before this contract was signed, and since then, they have brought their DC systems to market. They have conducted many demonstrations of their systems in a variety of applications, from trackside, to leveling of wind power, to backup power. The URENCO system is larger than the AFS Trinity system, at 3kWh, and optimized for somewhat longer charge-discharge cycles. In 2004, the Commission awarded a contract to URENCO for a demonstration of their flywheel on the MUNI system in San Francisco http://www.energy.ca.gov/contracts/2003-12-05_500-03-501_NOPA.PDF.

1.3 Project Goals and Objectives

The broad goal of this project was to develop and demonstrate an advanced flywheel system for power management and load following. We have succeeded in this, and have proven the feasibility of the AFS Trinity M3AM Flywheel Power System.

As a direct result of the lessons learned in executing this contract, the goals have changed over the course of the contract. Where initially the project proposed to demonstrate an “energy wheel” design, under this effort, we came to realize that a “power wheel” is what the commercial market required, and the Commission agreed. The specific characteristics of the system demonstrated in this effort will be discussed in detail in Section 3 of this report.

1.4 Report Organization

The remainder of this report is organized to three primary sections: **Project Approach**, **Project Outcomes**, and **Conclusions and Recommendations**. The sections become increasingly technical as they progress, and a reader who prefers only the broad non-technical view may wish to segue straight to the section on Conclusions and Recommendations. In the Project Approach section, we give the background of the PIER Project, a description of the system we developed, a breakdown of major subsystems, and a brief description of system testing. We conclude that section with a brief listing of the co-funding for this project. In the Project Outcomes section the first subsection describes the outcomes of the project related to the original contract objectives, and the second subsection takes a broader view of outcomes in general. In the Conclusions and Recommendations section we first address technical conclusions, then commercialization potential, and finally recommendations for further work. The primary appendix to the report is a more technical account of system testing that amplifies on the brief account under Project Approach.

2.0 Project Approach

2.1 PIER Project Background

Trinity Flywheel Power was created when two entrepreneurs negotiated a license agreement with Lawrence Livermore National Laboratory for exclusive rights to produce flywheels under the patents of Richard Post and LLNL. These patents concerned especially the use of the Halbach Array Motor Generator, and the FPS developed under this PIER II contract contains an FMG based on that concept. In 2001 Trinity Flywheel Power merged with American Flywheel Systems to become AFS Trinity Power Corporation.

At the time this contract was granted, Trinity Flywheel Power had assembled prototype flywheel power systems. We had rotors whose inner layers were fiberglass, and whose outer layers were carbon composite. Rotors were suspended on mechanical bearings. Operation was possible only at low speed and low power, and for short periods of time. The limitations of the power electronics and controls were difficult to overcome with the short run times that were possible with the mechanical bearings. While Trinity had planned to build the systems and to outsource the rotor fabrication, we had not planned to design and create our own power electronics, motor drive software, and controls hardware. But shortly after the award of this contract, when it became evident that the third vendor to attempt the task was failing, we made the decision to do these tasks ourselves, and this contract made it possible to successfully plan and execute that control system work. The task took 18 months, and at that point we had a fully functioning breadboard version of the control software, control hardware, and power electronics.

This achievement permitted us to test the rotating hardware at higher speeds, with higher power discharges, and over longer times, than had previously been possible, and we learned that to achieve the maintenance-free life that we sought would require that we successfully transition to active magnetic bearings (AMB). In the ensuing year, we achieved that goal, and in June of 2001 had a fully functioning system that included active magnetic bearings in place of the rolling element bearings. In the same time frame that we redesigned the system to accommodate AMB, we also designed and built a new cabinet which integrated all the parts of the system safely and compactly. The transition to AMB was a major milestone in our development, and permitted us to move to the next set of issues. We began, under DOT funding, a major effort to measure, analyze, and correct system runout, and to measure and then decrease on-rotor losses so that we could operate continuously within the thermal limits of the rotor composite.

Early in the program we had the benefit of DARPA funding of rotor advances, and transitioned from a glass/carbon rotor to an all carbon design. In 2002, under DOE funding, we began a program to qualify a rotor with higher thermal capability, one that would give us additional margin even under stringent operating regimes, or high ambient temperatures. This program concluded in the final quarter of 2003. Meantime, we tested the system extensively.

2.2 System Description

The M3AM Flywheel Power System is an energy storage and power management device that requires less than four square feet of floor space. Its applications were described in the introductory sections of this report. The flywheel, power electronics, and all other subsystems are housed in a floor-mounted cabinet. The application interface is a DC link with connection points located within the cabinet. The M3A system is shown in Figure 4 and the subsystems are described in Section 2.3.

Figure 4. M3 Flywheel Power System

2.3 Major subsystems

The major subsystems of the flywheel power system are (1) the FMG (Flywheel Motor-Generator) comprising a composite rotor, permanent magnet motor-generator, magnetic bearings, and housing, (2) a control system with DSP implementation of space vector control and a touch pad user interface, and (3) a power converter and associated electrical equipment.

2.3.1 Motor Generator

The AFS TRINITY M3AM incorporates a novel permanent magnet motor–generator invented at Lawrence Livermore National Laboratory and licensed to AFS Trinity. The rotor portion of the motor-generator consists of an array of permanent magnets lining the bore of the rotor. The magnets are oriented to produce a dipole field aligned across the bore of the rotor. The stator consists of turns of finely stranded wire where each strand is insulated (Litz wire). Litz wire is used to minimize eddy current losses in the stator. In discharge operation the rotating dipole field of the permanent magnets intercepts the windings and induces a voltage in the windings. Conversely, when the machine is charging, the currents impressed on the stator windings create magnetic fields that exert forces on the magnet array in the bore of the rotor, causing it to spin up.

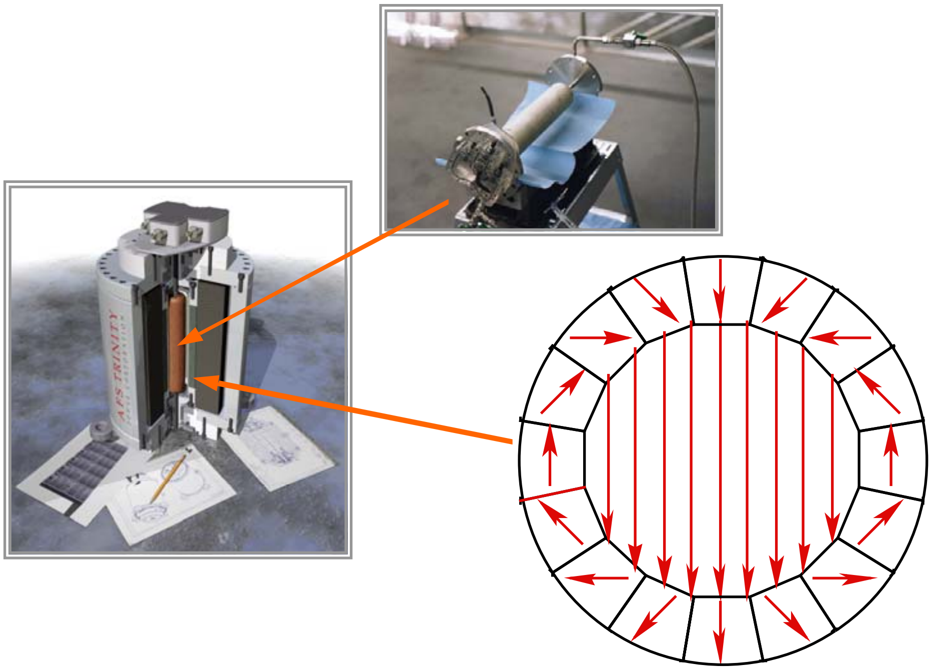


Figure 5. Ironless Permanent Magnet Motor Generator, Litz Wire Stator (top), and Halbach Magnet Array (right)

The power density and efficiency of the AFS TRINITY motor-generator are exceptionally high and undesirable thermal loads are substantially avoided.

2.3.2 Bearings

The AFS TRINITY M3AM uses active magnetic bearings (AMB). The M3AM AMB set comprises (1) a stator with radial and axial actuators and radial and axial position sensors; (2) rotor components including laminations, thrust disks, and sensor targets; and (3) a controller system including AMB controller hardware and embedded software.

2.3.3 Composite Rotor

The M3AM rotor is about 14 inches long and 10 inches in diameter and operates with a maximum surface speed of about 550 m/s. The rotor material is carbon fiber in an epoxy matrix. Prior to use in a flywheel system a number of rotors are produced and spin tested to destruction in order to substantiate the safety factor used in the design. Rotors have also been subjected to cycle testing and spin testing at elevated temperature.

2.3.4 Control System

The M3AM system controller is separate and distinct from the AMB controller discussed above. The M3AM control system comprises (1) a DSP and associated motherboard, (2) interface components and PCBs for sensors and other communication, (3) fiber optic communication with the power converter, (4) a user interface with an LCD display and touch pad, and (5) AFS TRINITY designed software driving motor control, voltage regulation, and the user interface. The controller hardware and software represent proprietary AFS TRINITY designs.

2.3.5 Power Electronics

The power electronics comprises a three-phase H-bridge power converter using IGBTs. The power converter is liquid cooled and the assembly is surrounded by an enclosure to provide EMI shielding. The power converter communicates with the controller through fiber optic links to minimize transmitted EMI. The maximum power of the M3AM under normal operating conditions is about 120kW.

2.3.6 Ancillary systems

The M3AM incorporates all required subsystems within the flywheel power system enclosure. These include a vacuum system and a liquid cooling system for the stator and power converter. The cooling system uses an electrically non-conducting oil to cool the stator windings directly. Heat from the cooling system is dissipated in heat exchangers located at the top of the M3AM cabinet.

2.3.7 Switchgear

In addition to the power converter and ancillary subsystems, the M3AM flywheel power system also incorporates switchgear that protects both the flywheel system and the application from various types of fault conditions. A DC bus contactor connects the power converter to customer equipment. Relays in series in the system controller open the bus contactor under fault conditions. These contactors disconnect the flywheel from the power converter and connect the flywheel to the dump resistor. The dump resistor is located on top of the cabinet and is sized to safely decelerate the rotor to rest. This configuration assures that the kinetic energy of the flywheel can be dissipated safely even in the event of a total failure of the system controller and power converter.

2.4 System Testing

Extensive system testing was conducted at every stage in the program. For a flywheel, the degree of integration and interdependence between the various subsystems is great. Typically, the performance of a subsystem can only be evaluated when the subsystem is built into the flywheel system. For example, a bearing cannot be completely characterized unless it is being used to support a flywheel operating at full speed and full power, and the control system cannot be fully characterized and debugged without being able to test it with a fully functioning flywheel.

During the first several years of the program, flywheel system testing was performed in support of subsystem development. From 1998 to 2002, system testing was used to prove innovations in power electronics, controls, rotors, bearings, and thermal management. During this period, characterization of system performance was conducted in a way that went beyond subsystem development.

In 2003 and 2004 the operating envelope of the system was explored comprehensively. This activity concluded in February 2004 with System Demonstration Testing. System Demonstration Testing characterized the following attributes of system performance.

1. *Output Voltage.* The DC bus voltage is settable by the customer. In discharge mode, the flywheel system regulates the DC bus voltage to this value. Output Voltage testing demonstrated precise voltage control for an output power range from 0 to 100 kW, 50% speed to 100% speed, and bus voltage settings ranging from 580 VDC to 680VDC. After recovery from an initial transient, the flywheel system regulated bus voltage to better than ±0.75% under all operating conditions.

2. *Step Load Transient Response.* Immediately after a step change in load, DC bus voltage will momentarily droop below the user-selected value. Transient response measurements were conducted to determine the magnitude of the transient and the duration of the transient for a wide range of operating conditions. Detail is given in later sections of this report.

3. *Start-up and Charging Time.* The amount of time required for the system to attain a state of full charge after beginning from a dead stop was measured for a range of charge conditions. For representative available charging power (a property of the facility, and not of the FPS), the M3 can reach full charge from a dead stop in less than 4 minutes.

4. *Power Vs. Time.* During discharge, the flywheel system delivers power to the load until extractable energy is depleted. The discharge duration was measured into various loads. Voltage regulation was maintained over the time interval at each power level. The results are summarized in Table 1 and Figure 6.

Table 1. Voltage Regulated Output Power vs. Discharge Time

Power (kW)	Discharge Time (sec)
122.1	10.26
115.6	11.46
108.7	13.06
102.1	14.50
67.6	26.00
33.7	58.50
13.5	150.60

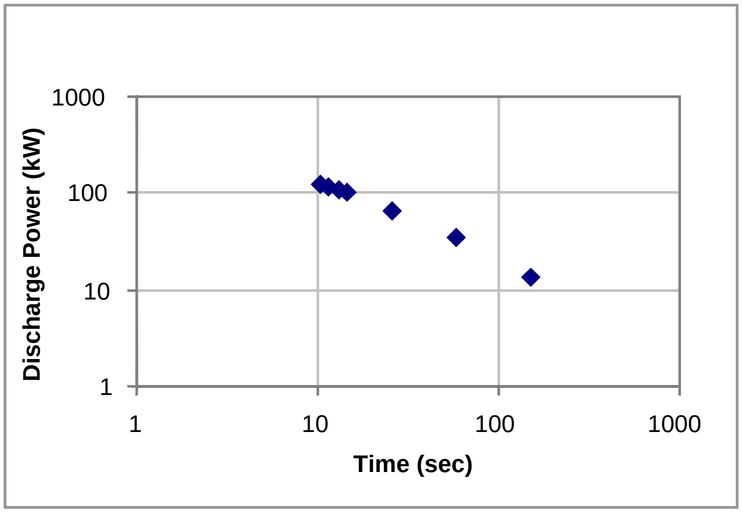


Figure 6. Voltage Regulated Output Power vs. Discharge Time

5. *Standby Power Consumption.* Standby power is the sum of two terms; power consumed to overcome drag and maintain the flywheel rotor at a particular state of charge, and power that is used by the auxiliary systems. The power consumed by the auxiliary system and within the power electronics is distinct from losses that exert drag on the rotor. We measured the various loss components separately. We determined that total standby power consumption for the present system is 931 Watts and that this value will be reduced considerably through straightforward design modifications that are presently planned for the next phase of development.

6. *Duty Factor.* A duty cycle is defined as a discharge followed immediately by a recharge. A duty cycle is characterized by the rate of discharge, the depth of discharge, and the rate of recharge. The duty factor characterizes the frequency with which this charge-discharge cycle is repeated.

   Here we define duty factor for high power energy storage:

   - The full rated power of the flywheel is 100 kW.
   - Delivered energy corresponds to a 15 second discharge at rated power (1.5 MJ = 100 kW x 15 seconds).
   - The cycle comprises three steps
     1. Discharge from full speed.
     2. Recharge from minimum speed to full speed.
     3. Dwell at full speed.
   - A *Duty Factor of 100%* is defined as:
     1. 100kW, 15 second discharge from full speed.
     2. 100kW, 15 second recharge.

3. No dwell at full speed.
By this definition, operation at a Duty Factor of 100% corresponds to a repetition of the full power charge-discharge cycle at intervals of 30 seconds.

- Duty Factor is defined as a ratio of:
  (30 seconds)/(actual charge-discharge cycle duration)
- A Duty Factor of 50% corresponds to a charge-discharge cycle repeated at intervals of 60 seconds where the cycle begins with a 1.5MJ discharge from full speed. The remainder of the cycle comprises an arbitrary combination of recharge and dwell.
- Duty factor = 33% implies cycle duration = 90 seconds.
  Duty factor = 25% implies cycle duration = 120 seconds.
  Duty factor = 10% implies cycle duration = 5 minutes.

Testing conducted under this program demonstrated a sequence of more than 100 consecutive charge discharge cycles at a duty factor of 40%. Operation at higher duty factor was precluded by facility limitations limiting our maximum charge rate to about 50kW.

7. *Energy Recovery Efficiency*. Energy is lost during the charge-discharge process due to the efficiency of energy conversion of the power converter and the motor. Energy lost in the charge and discharge processes is separate and distinct from standby power consumption and needs to be accounted for separately.

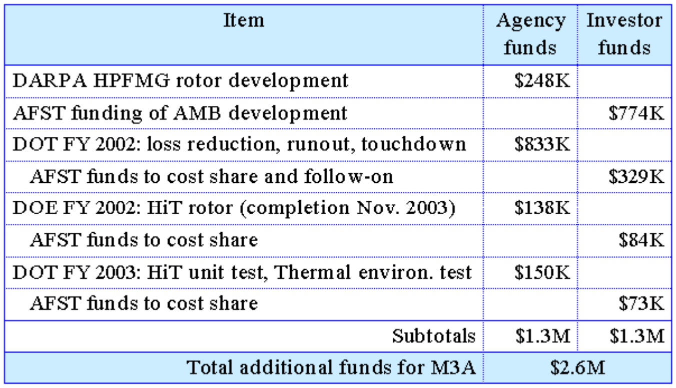
   Energy recovery efficiency is defined as the fraction of input electrical energy that is retrieved from the flywheel and delivered as output electrical energy. For high power cycle testing performed under this program, energy recovery efficiency typically exceeded 85%.

2.5 Project Financing

Commission Contract #500-98-036 was for the amount of $1,057,406 in state funding. This was to be matched by $1,062,494 from investors and other sources, for a project total of $2,119,900. Expenditures to date on the project have exceeded $4.6M, so in fact the match has been >78% rather than the ~50% promised. Of the additional $2M in funding, half has come from equity investors, and half has come from a variety of federal sources, including DOE, DOT/FTA, and DARPA.

Table 2 gives a summary of these inputs to the M3A development.

Table 2. Summary of Project Financing



Item	Agency funds	Investor funds
DARPA HPFMG rotor development	$248K	
AFST funding of AMB development		$774K
DOT FY 2002: loss reduction, runout, touchdown	$833K	
AFST funds to cost share and follow-on		$329K
DOE FY 2002: HiT rotor (completion Nov. 2003)	$138K	
AFST funds to cost share		$84K
DOT FY 2003: HiT unit test, Thermal environ. test	$150K	
AFST funds to cost share		$73K
Subtotals	$1.3M	$1.3M
Total additional funds for M3A	$2.6M	

While these amounts are large, they are similar to or smaller than the amounts spent by other entities in development of prototype-stage units.

3.0 Project Outcomes

3.1 Outcomes based on Contract Objectives

This section will begin with the objectives of the contract, and describe the outcome that relates to each of them. Each contract objective is shown as a bulleted item.

- Produce a 2 kWh Flywheel Motor Generator (FMG) with a rotor diameter not to exceed 16 inches, and having a length not exceeding 32 inches.

We have produced an FMG that stores 0.42kWh of usable energy in a carbon composite rotor 10”D x 14”L. The size objective was intended to constrain the rotor to high strength composite material, and away from steel.

- Test and demonstrate a Flywheel Power System (FPS) installed within a cabinet not to exceed 48 inches wide, 36 inches deep, and 80 inches high. The performance objectives of the FPS are: usable storage of not less than 2 kWh; maximum output power greater than or equal to 5 kW; and a rated output of 2 kW.

The dimensions of the cabinet demonstrated are 24 x 22 x 78 inches. While the demonstrated deliverable energy is 0.42kWh at 100 kW, it is 0.55kWh at 15kW. Our rated output is 100kW rather than the 2kW prescribed, because we believe that the markets in which the unit is cost justified will be in the higher power/shorter discharge sector. While we have tested the unit to an output power of 120kW, the machine will not be warranted for customer use above 100kW. The higher power testing simply establishes our operating margins.

Table 3. Contract Objectives and Achievements Related to Cabinet Size

Parameter	Contract	Achieved	Ratio of Achieved to Original Contract	Exceeds Goal
Cabinet Size, inches	48 x 36 x 80	24 x 22 x 78	0.3	Yes
Cabinet volume, ft^3	79.2	23.8	0.3	Yes
Energy/volume	0.025	0.017	0.66	No
Rated Power/volume	0.025	4.2	166	Yes

Table 3 presents the contract technical objectives related to cabinet size, and the outcomes we achieved. It shows that we exceeded the goal in three areas. This completes the discussion of the specific technical and economic objectives stated in the contract. What follows is a discussion other project outcomes, on topics not called out explicitly in the contract objectives.

3.2 Other Outcomes

During the course of the company's history of flywheel development, three major configuration changes were implemented as part of or in parallel with the CEC program. These changes include transitioning to (1) in-house power electronics and controls, (2) an all carbon fiber rotor, and (3) magnetic bearings.

1. *In-House Power Electronics and Controls.* Prior to 1998 Trinity had attempted to obtain power converter and system controller technology from appropriate vendors. Up to this point we had attempted to incorporate drives from two different manufacturers who each had conducted development funded by Trinity for this purpose. The combination of technical requirements including high machine frequency (680 Hz rather than 60 Hz), large speed range, and seamless transition between various machine states proved daunting and both vendors failed to produce operable systems. At this time, Trinity initiated in-house development of a power converter and system controller. Within 18 months we had constructed a power converter of our own design and implemented a system controller with code written in-house.
2. *All-Carbon rotor.* Prior to 1999 Trinity rotors were built in a single piece by filament winding glass fiber with successive overwrap layers of medium stiffness carbon fiber and high stiffness carbon fiber. This construction had two significant deficiencies. First, the relatively large thickness of the part required numerous intermediate cure stages and the length of the curing process was not readily scalable to low production cost. Second, the low elastic modulus of the glass fiber at the bore of the rotor allowed considerable dilation of the bore during operation, which resulted in amplified unbalance, shortened bearing life, and cracking of the magnets. (The NdFeB magnets are mounted in the bore of the rotor and strain follow the material on the bore of the rotor as it grows from centrifugal force during high-speed rotation.) In 1999 we committed to transition to an all-carbon construction where press fit assembly replaced a gradient in elastic modulus as a way of mitigating matrix material stresses. We continue to use the configuration that we developed at that time. While the economic benefit of shorter curing time was offset by the increased cost of finishing the press fit rings, all of the technical objectives of this construction have been realized. Bore dilation during operation was reduced, unbalance growth was reduced, and magnet cracking was eliminated.
3. *Active Magnetic Bearings.* Prior to 2000 all AFS Trinity flywheel systems used high performance ball bearings. While magnetic bearing research and development had been conducted in parallel with flywheel system development, none of the bearing effort prior to 2000 proved fruitful. By 2000 we determined that ball bearing performance was unacceptable and in September 2000 we committed to a transition to magnetic bearings. We incorporated what we believe to be the most appropriate magnetic bearing technology for terrestrial flywheel systems. In June 2001 we demonstrated full speed, full power operation of an M3 rotor levitated on active magnetic bearings just nine months after initiating this effort.

4.0 Conclusions and Recommendations

AFS Trinity Power has achieved many technical advances in its flywheel products during the period of this program. These are summarized in section 4.1. The product is now at a stage where it can be brought to market within about one year of receiving significant new investment. It can also be used for further development and research. AFS Trinity, the CEC and the energy industry have learned many valuable lessons from this flywheel development effort that have been presented in prior progress reports and at industry conferences. We have performed the system integration work necessary to build and test complete flywheel power systems. In particular, we have converged on an optimal set of performance targets that meet customer requirements and are feasible for manufacturing.

4.1 Conclusions

1. **Scalability:** At the inception of the contract we believed it would be a feasible task to create a design that was scalable over a wide range of sizes. This expectation is captured in one of the summary goals of the project: "The FPS design will be scalable..." We no longer believe that there is a fully predictable path for scalability. While one can preserve general system architecture, there will be many details that must be worked out afresh at each new size, and as the percentage increase in size becomes larger, the general expectation is that the level of difficulty will increase in the scaling. The greater the scale step, the more iterations will be required before the new design meets requirements. So definition of the term "scalable" is difficult, and the word may imply that the process is easier than in fact it is. We consider the primary uncertainties to arise in rotor fabrication, and consider the scale-up of the controls and power electronics to be more predictable in budget and schedule.
2. **System Storage:** The system we have designed, fabricated, and tested delivers 0.42kWh at rated power (and somewhat more energy at lower power ratings). Our market research indicates that the resulting ride-through time of 15 seconds is well matched to the needs of several applications, including load following for distributed generation, ride through for voltage sags and standby generator startup, and heavy hybrid electric vehicles.
3. **System Power:** The system power rating is 100kW. We have determined that an FPS is unlikely to be economically feasible compared to batteries for long discharge times, such as the one-hour discharge time inherent in the original contract objectives. Although several development groups were seriously engaged in addressing this market in 1998 when we wrote the proposal, all the private companies engaged in this endeavor have now come to the same conclusion, and ceased development of such a machine. It is at the relatively short discharge times of seconds to a few minutes that most technologists now expect flywheels to play an important role. One of the difficulties in customer understanding of energy storage is that the conclusions on appropriate technology change with the characteristic discharge time of the application: there is no "one size fits all" solution.

4. **System Cost:** Initial cost estimates have been compiled on the basis of existing small quantity purchases for the pre-production M3 and labor to assemble the components in a non-production shop. The cost of the Flywheel is comprised of approximately 60% electronics and packaging, and 40% for the flywheel motor/generator. Approximately 80% of the total cost is in material and 20% in labor. Initial cost of the M3 will be high in comparison to the mature cost, which should be reduced by 60%. The cost reduction will be achieved systematically on three major fronts: 1) labor will decrease by 50% due to the learning curve of the work force as volume and experience increase, 2) material costs will be reduced by 50% as a result of the volume increase and supplier rationalization, and 3) a cost reduction program will focus on lean manufacturing and design for manufacturability and assembly to further reduce labor and material costs to meet the mature cost target.
5. **System Volume:** The integrated FPS is in a cabinet whose outer dimensions are smaller than the Commission contract objective. Energy per unit volume is comparable to, though fractionally smaller than, the objective. Power per unit volume is dramatically higher than its objective. We now believe that within a certain range, system volume is not a strong driver of customer acceptance.
6. **System electrical performance:** The FPS is designed to connect to a DC bus. Our system controller uses a deadband control scheme. The flywheel charges when the voltage rises to the top of the deadband, and discharges when the bus voltage drops to the lower setting. The width of the deadband, allowed voltage droop on discharge, and voltage recovery time are adjustable to customer requirements. We continue to believe that this approach is generally consistent the technical requirements for nearly every power management application of which we are aware.
7. **System response time:** In response to a step change in load, the DC bus voltage regulated by the flywheel system will droop momentarily and then recover to the voltage level that existed prior to the application of the load. The droop will be on the order of 10s of volts and will have a duration of 10s of milliseconds with exact values depending on the magnitude of the step load change and the settings entered into the user interface. Response characteristics can be tailored to the application requirement.
8. **System efficiency:** Depending on the application, system efficiency may matter a great deal, or not at all, in the energy budget of the installation. System roundtrip efficiency acts as a discount on energy only when the system is required to discharge, and while some applications require very frequent discharge, others do not. Otherwise, the system standby power consumption is what imposes energy costs on the user.
9. **System standby power consumption:** In light of our extensive system testing, we now expect that we will dramatically reduce system standby power consumption in the next round of upgrades of the ancillary systems.
10. **Ancillary system maturity:** The ancillary systems that we use in the engineering prototypes are industrial products with good reliability and would be suitable

for use in field test units and commercial products. The cost of this equipment comprises a significant part of the total system cost and development work on ancillary systems will seek to reduce cost by combining functions (rotor system that also performs vacuum pumping) and reduce capacity (less expensive heat exchangers). Ancillary systems are also the only portions of the system that require routine scheduled maintenance and future development will seek to eliminate required maintenance to the greatest practical extent.

11. **Interface issues:** The DC bus and keypad interface provide good basic operability. Many applications will benefit from relatively high bandwidth communication between the flywheel system and the application and individual flywheel units when multiple units are operated in parallel. We are addressing this by designing subsequent generations of system controllers to incorporate CAN bus communication capability.
12. **System lifetime:** We expect that the existing system would demonstrate a cycle life exceeding 10^5 cycles and possibly 10^6 cycles but are unable to execute a program to demonstrate this due to the prohibitively cost of high-cycle spin testing. There is no firm design life limit to the primary flywheel components and a 20-year life is believed to be a conservative expectation. In practice, power electronics and ancillary systems are expected to have much shorter service lives than the flywheel itself and life improvement will be part of continued engineering of ancillary subsystems.

4.2 Commercialization Potential

AFS Trinity has completed Stage 3, Research and Bench Testing, in the Stages and Gates model used by The Commission. The M3AM FPS developed under this contract has undergone an extensive testing program over the past two years. This is described in Appendix I.

Remaining development work consists of: design modifications for reliability and manufacturability, regulatory certification with UL, FCC and others and field evaluation testing. These tasks fall into Stages 4 – 8. AFS Trinity has already begun work on Stage 4 and plans to move through the remaining stages during the coming two years.

During the course of this project significant progress has been made towards commercializing the M3AM flywheel power system. While the CEC PIER funded work has focused on research and lab testing, AFS Trinity has also developed marketing, sales and distribution plans. One major commercialization milestone was AFS Trinity Power's presentation at the National Renewable Energy Lab (NREL) 16th Annual Industry Growth Forum in Austin, TX on November 17th – 19th, 2003. AFS Trinity worked with two small business incubator services, the Environmental Business Cluster (EBC) and Technology Ventures Corporation (TVC), to refine its presentation for this event. We continue to work with EBC and TVC to pursue the new equity investments we will need to fully commercialize our flywheel product.

AFS Trinity defines commercial potential as the sales revenues we can realistically achieve with our flywheel products. Our revenue from the M3AM FPS, and units derived from it, comes from the following four application areas:

- Power Quality / UPS
- Distributed Generation Load Following
- Industrial Pulsed Power
- Light Rail Power Management

For each application, we have identified target customers, studied their product requirements and calculated the market potential (unit sales and revenues). We have published specifications for the M3AM on our web site and in a widely distributed data sheet. Customer reaction has been positive, with many requests to test or purchase a unit as soon as it is available. The following paragraphs describe our four applications and projected revenues for each.

Our first commercial launch application is Power Quality / UPS. In this application, the flywheel replaces lead-acid batteries in an uninterruptible power supply (UPS). We will first offer a DC battery replacement FPS, and later a fully integrated AC flywheel UPS. The DC product will connect to most commercial UPS power converters in place of the standard battery cabinet. Our market research indicates a total addressable market (TAM) for this application of $2.5 billion by 2008. We believe that after five years of sales growth, we will achieve a 15 percent market share in the UPS application. We have selected the UPS application for our initial product launch because it is a large, existing market and we offer a unique product with significant customer benefits compared with battery-based UPS systems.

The distributed generation load following application enables fuel cells, microturbines and natural gas engine generators to operate in both grid-connected and islanded modes with greater reliability and power quality than they could achieve alone. AFS Trinity's flywheel technology is uniquely suited to this application because it can recharge as quickly as it discharges. The resulting duty cycle capability matches the need for a power management device to source or sink power for step changes in load, and we believe AFS Trinity flywheels will facilitate greater customer acceptance of distributed generation. We project a 2008 TAM of $3.3 billion for the distributed generation market. (Load following will be a small part of the total distributed generation market.) Our market share projection for the total distributed generation market is 1 percent after 5 years.

The industrial pulsed power application meets the needs of a variety of process industries whose machinery creates highly variable or erratic power demands on the grid or a local generation source. Silicon wafer production, arc welding, mining, printing, paper milling, textile milling and lumber production are examples of these industries. The AFS Trinity flywheel will meet the brief high power requirements for machinery in such industries, thereby avoiding both voltage sags and high utility demand charges. The 2008 TAM for this application is $3 billion. AFS Trinity projects a 4 percent market share within five years.

Light rail power management is similar to the industrial pulsed power and hybrid vehicle applications. Uniquely, it requires many flywheels installed trackside at key points in a municipal light rail system. The flywheel provides acceleration power for trains leaving stations or climbing inclines, and it captures regenerative braking energy when trains approach stations or descend grades. A competing flywheel company, URENCO, has validated this application with flywheel installations at over ten light rail lines around the world, and the Commission will co-fund a demonstration of the URENCO flywheel on the MUNI system in San Francisco over the next three years. The 2008 TAM for light rail power management is $1 billion. AFS Trinity expects to capture a 10 percent market share after five years.

AFS Trinity plans to manufacture its own products, with certain components outsourced to other manufacturers. Sales will be conducted through a direct sales force in some markets and through partnerships with other companies for the UPS and vehicle applications. We have several potential partner firms for these applications and will form partnership agreements after we have been able to conduct further field evaluations of our products.

4.3 Recommendations

AFS Trinity Power must continue parallel efforts in product development and market development. The next major product development step is to conduct field experiments. In this phase we will deploy a few field prototype units in protected situations outside of our own facility. By this, we mean situations where the unit is not serving customer load, but instead is being tested, either alone or in conjunction with equipment from other manufacturers, in another laboratory or research facility. One likely choice of location for such early testing is the Distributed Utility Integration Test (DUIT) at the Modular Generation Test Facility (MGTF) in San Ramon, CA.

The experience we gain from this Stage 4 field experiment, and from similar testing at other locations, will allow us to make the final system changes necessary before we begin the stage 5 tasks of product development and field testing. In Stage 5 we will address issues of reliability, availability, maintainability, and durability (RAMD), and have trials of field prototype units at multiple sites.

The experience we gain in these series of tests will provide the necessary definition of any gaps that remain between system performance and application requirements. The final stage of full scale field-testing will be with a unit that has been reengineered for cost reduction and manufacturability

In the market development area, the Company should continue to work with business incubator services such as EBC and Technology Ventures Corporation (TVC) to identify potential investors and refine its presentations to them. In addition the Company should continue to seek government funding for R&D work from state and federal government agencies. The work done under these programs often advances the state of technology beyond what is required for commercial success – thereby achieving the valuable public policy goals that are described in Section 4.4.

AFS Trinity Power is pleased to have the CEC's support for its flywheel power system development work and is looking forward to continued growth as its products gain market acceptance.

4.4 Benefits to California

The flywheel commercialization program at AFS Trinity Power has created benefits to California in two important ways: economic and environmental. We are now a small business, but our business plan requires that we increase our California staff to over four hundred employees within 5 years of receiving the required equity investment. This staffing level is necessary to achieve our unit production and sales revenue goals. Our commercial success will also benefit California through sales taxes and secondary business we create as a consumer of supplies and services.

By reducing business losses from power disturbances and increasing industrial energy efficiency, our products will benefit the many California businesses we expect as customers. This will have direct benefits to the California economy.

Environmental benefits for California fall into two categories: improved air quality and reduced toxic solid waste. AFS Trinity flywheels are an enabling technology that makes distributed generation systems more cost effective and more reliable. As such, flywheels will facilitate greater customer acceptance of distributed generation with its known benefits in air quality and fuel efficiency. Distributed generation systems primarily use natural gas engine generators, fuel cells or microturbines. All three of these are highly efficient at converting fuel into electric power, particularly when part of a Combined Heat and Power (CHP) system. Furthermore, distributed generation eliminates power losses from long distance transmission lines and voltage conversion at substations along the way. Distributed Generation will have greater customer acceptance with flywheel energy storage instead of battery energy storage.

Every flywheel that replaces an energy storage battery in a UPS system will reduce the amounts of toxic lead, sulphuric acid and other toxic chemicals entering the waste stream in California and throughout the world. One 100 kW flywheel power system replaces batteries weighing between 2,000 and 3,000 lbs. These batteries have a typical life cycle of 2 – 4 years. Therefore a single flywheel will on average, eliminate over 800 lbs of toxic waste per year. AFS Trinity projects annual sales of 6,000 FPS in year five after commercialization. These systems alone will eliminate 4.8 million pounds of batteries from the waste stream per year.

5.0 Glossary

AC	Alternating Current
AMB	Active Magnetic Bearing
CHP	Combined Heat and Power
DC	Direct Current
DER	Distributed Energy Resources
DOD	Depth of Discharge
DOE	Department of Energy
DOT	Department of Transportation
DUA	Distributed Utility Associates
DUIT	Distributed Utility Integration Test
EMI	Electromagnetic Interference
FMG	Flywheel Motor Generator
FPS	Flywheel Power System
FTA	Federal Transit Authority
IGBT	Insulated Gate Bipolar Transistor
LLNL	Lawrence Livermore National Laboratory
MJ	Megajoule(s)
MUNI	San Francisco Municipal Railway
RAMD	Reliability, Availability, Maintainability and Durability
TAM	Total Addressable Market
UPS	Uninterruptible Power Supply
UUT	Unit Under Test

Appendix I: System Testing

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1.0 Test Process

1.1 Scope

Key results from flywheel system testing are summarized in this appendix.

1.2 System Description

The M3A Active Magnetic Bearing (AMB) Flywheel Power System (FPS) is a flywheel-based energy storage system that sources or sinks energy to or from a DC bus. The M3AM has three major subsystems: the Flywheel Motor / Generator (FMG), the Power Converter, and the Controller.

The FMG is the energy storage component. It is a motor generator with a three-phase stator and a high-speed rotor. Embedded in the rotor is a Halbach array magnet assembly that provides the magnetic field that rotates about the stator. The FMG rotor is suspended by an active magnetic bearing system that reduces mechanical friction in the FMG to zero.

The Power Converter converts DC power from the bus to increasing frequency AC that powers the FMG while in the charging mode and conversely converts decaying frequency AC of the FMG to regulated DC power during the discharge mode.

The Controller commands the Power Converter and FMG to perform speed control, voltage control, and other functions as dictated by the power environment and operator input.

The other FPS supporting sub-systems are the vacuum and cooling systems, the operator control pad, and the monitoring systems.

1.3 Modes of Operation

Charge Mode: The FMG draws and stores energy from the application when the terminal voltage exceeds a programmed set point. Current regulation is implemented to prevent current inrush when the FMG impedance is low. Charging does not exceed 100 kW.

Discharge Mode: Discharge is initiated by reduction of the voltage impressed across the terminals of the FMG. During discharge, the FPS regulates output voltage between settable upper and lower limits. Discharge does not exceed 100 kW under most operating conditions.

1.4 General Test Procedures

AFS Trinity conducted demonstration testing at the Trinity Engineering Center in Livermore, CA. The UUT (Unit Under Test) was attached to a floor mounted steel plate at test station #2. The AFS Trinity test engineer ensured all pre-test procedures were accomplished and the correct system test configuration was established. This included connecting and energizing the vacuum pump, establishing and verifying correct connection of all electrical wires and feeders, energizing the high voltage DC bus, energizing the 24 volt DC equipment, connecting the Data Acquisition System (DAQ) to the test article, and ensuring compliance with all safety procedures and precautions. Test engineers referred to the M3AM Installation and Operations Manual version current at the time of the test for detailed operational procedures.

The unit (or units) under test, the load bank, and the DC power supply all connect to a common DC bus. Most of the testing was accomplished by charging the M3AM at the voltage provided by the DC power supply and discharging it into the test load at the voltage called for by the test procedure.

After initial settings were made for each test, the test execution was for the most part executed by opening and closing contactors on the DC bus. For some of the shorter tests, these contactor activations were performed manually by the test engineers. However, for the longer tests and for the tests where contactor event timing was critical to the proper execution of the test, the contactors were sequenced automatically.

2.0 Test Results

2.1 Power vs. Time

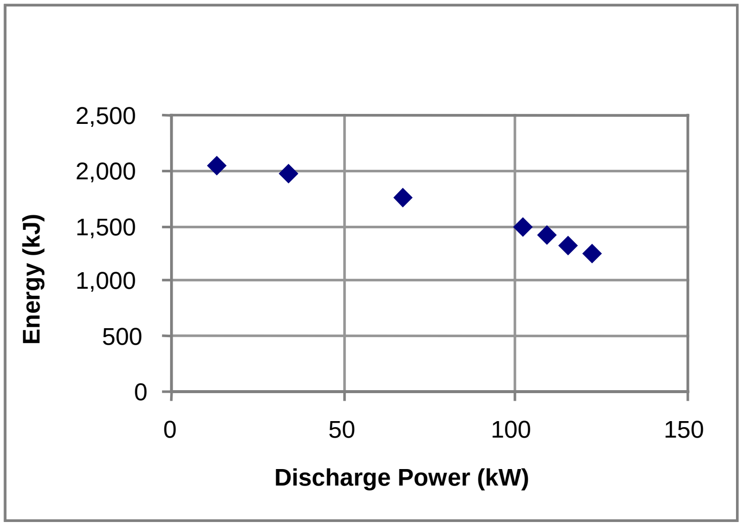
Requirement: Determine the power versus time profile at various output power settings and DC bus voltages.

Results: Discharge time was obtained for discharge power from 13.5 kW to 122.1 kW. The UUT regulated bus voltage at 650 VDC for the discharge times indicated in Table 1.

Table 1. Discharge Time vs. Output Power

Power (kW)	Discharge Time (s)	Min. Speed (RPM)	Extracted Energy (kJ)	Extracted Energy (kWh)
122.1	10.26	23,000	1,253	0.35
115.6	11.46	22,000	1,324	0.37
108.7	13.06	21,000	1,419	0.39
102.1	14.50	18,800	1,481	0.41
67.6	26.00	13,800	1,757	0.49
33.7	58.50	9,000	1,972	0.55
13.5	150.60	4,800	2,036	0.57

At lower power the UUT regulated bus voltage over a larger speed range. As a result, more of the stored energy is extractable at lower power. Figure 1 shows the relationship between energy extracted under bus voltage regulation and output power.



Note that: 2,000 kJ = 0.55 kWh (maximum extracted energy),
1,500 kJ = 0.42 kWh (rated extractable energy).

Figure 1. Extractable Energy vs. Discharge Time

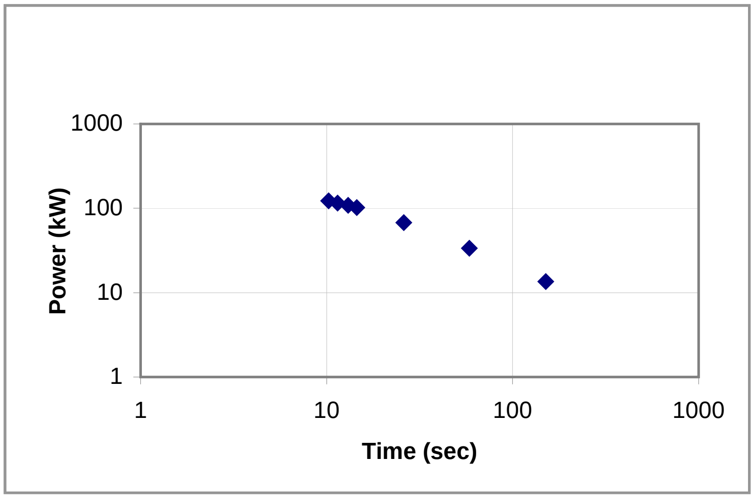


Figure 2. Power vs. Discharge Time

Figure 2 shows the output power as a function of discharge time on both linear and log scales.

2.2 Duty Factor

Requirement: Characterize thermal limits for sustainable operation under continuous cycling.

Assumptions and Definitions: A high power charge-discharge cycle is defined as a pulsed discharge followed immediately by a recharge. This cycle is characterized by the rate of discharge, the depth of discharge, the rate of recharge, and the frequency with which this charge-discharge cycle is repeated. For the purpose of this report, a particular type of high power duty cycle is used.

Definition of the UUT high power test cycle:

- The full rated power of the UUT is 100 kW.
- Delivered energy corresponds to a 15 second discharge at rated power (1.5 MJ = 100 kW x 15 seconds).
- The cycle comprises three steps
  1. Discharge from full speed.
  2. Recharge from minimum speed to full speed.
  3. Dwell at full speed.
- A *Duty Factor of 100%* is defined as:
  1. 100kW, 15 second discharge from full speed.
  2. 100kW, 15 second recharge.
  3. No dwell at full speed.

  Here, operation at a Duty Factor of 100% corresponds to a repetition of the full power charge-discharge cycle at intervals of 30 seconds.
- Duty Factor is defined as a ratio of:
  (30 seconds)/(actual charge-discharge cycle duration)
- A Duty Factor of 50% corresponds to a charge-discharge cycle repeated at intervals of 60 seconds where the cycle begins with a 1.5MJ discharge from full speed. The remainder of the cycle comprises an arbitrary combination of recharge and dwell.
  Duty factor = 33% implies cycle duration = 90 seconds, etc.

Alternative definition of duty factor:

- For more complicated operation over a specified test period:
  Duty Factor = (average power over test period)/(rated power).

Results: Duty factor results were obtained from recent and earlier operation of unit P5 and are summarized below in Table 2. A sample of data from recent operation is shown in Figure 3. In this example, P5B7 is repeating 100kW, 15-second discharge events at intervals of 75 seconds where recharge rate is limited by the facility power supply. This corresponds to a duty factor of 40%. The data indicate that the UUT can operate in thermal equilibrium of the motor and power electronics at a duty factor exceeding 40% and that the entire system operates in thermal equilibrium for a duty factor of up to at least 23%.

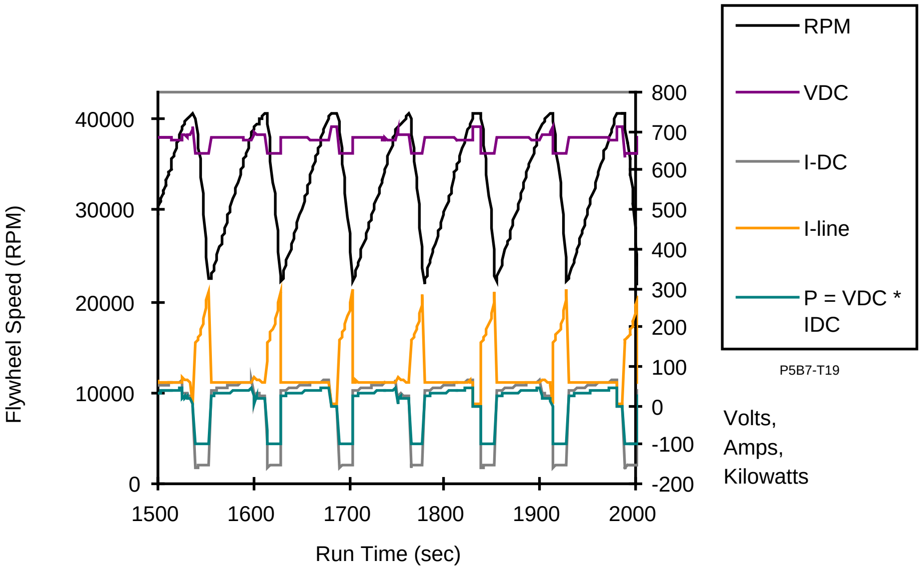


Figure 3. Sample of High Power Cycle Testing

Table 2. Duty Factor Test Results

Unit/Date/Test	Duty Factor	# of Cycles in Test	Thermal Condition	Reason for End of Test
P5B7 040225 T25	44%	100	Equilibrium (2)	End of programmed cycles
P5B7 040211 T19	40%	24	Nonequilibrium	Drive fault, inverter temp (1)
P5B3 020910 T04	30%	22	Nonequilibrium	End of programmed cycles
P5B3 020919 T11b	30%	22	Nonequilibrium	End of programmed cycles
P5B3 021115 T26g	23%	125	Equilibrium	End of programmed cycles
P5B3 021118 T26i (a)	20%	20	Equilibrium	Drive fault, cause unknown
P5B3 021118 T26i (b)	17%	144	Equilibrium	End of programmed cycles
P5B3 021119 T27/T27a	16%	251	Equilibrium	End of programmed cycles

Note (1): Low coolant flow rate setting: 33% of max flow to inverter during this test

Note (2): Electronics and stator in thermal equilibrium. Rotor thermal time constant is >4 hours so constant rotor temperature was not reached during this test.

2.3 Energy Recovery Efficiency

Requirement: Demonstrate energy recovery efficiency evaluated at DC bus.

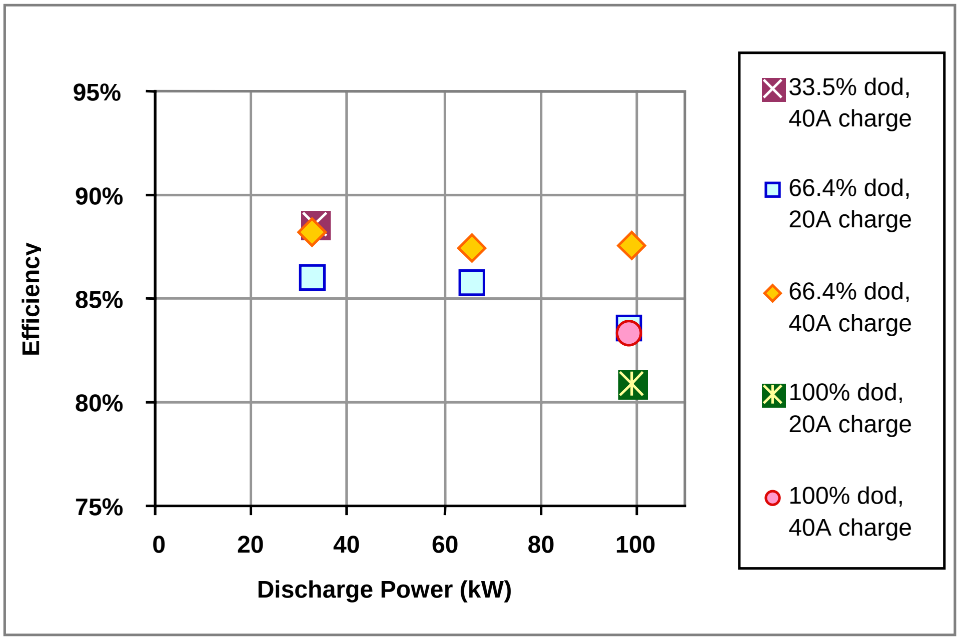
Results: Tests were conducted for discharge power ranging from 33kW to 100kW, discharge duration of 10s to 30s, and recharge current settings of 20A or 40A. Ten different operating conditions were tested. Twenty consecutive charge-discharge cycles were conducted for each operating point. Results are summarized in Table 6 and Figure 6 below. Data labels in the figure indicate discharge duration and charge current.

Total charge energy was calculated by time integrating charge current and bus voltage over the charge intervals. As standby (tare) losses are accounted for separately, tare losses were subtracted from total charge energy to yield net charge energy.

Two different methods were used to calculate total discharge energy. Method A integrates discharge current, voltage and time as recorded in the data spreadsheet. This method tends to underestimate discharge time duration due to the time increment of 1.2 – 1.5 seconds. Method B multiplies average bus current, average bus voltage, and a scope measurement of discharge time. These two analysis methods yield efficiency values that differ by about 1%. The average of these two values is plotted in Figure 4 below.

Energy recovery efficiency is a round trip efficiency calculated as (total discharge energy)/(total net charge energy).

Results varied from 80.8% to 88.6%. Higher efficiency (>87%) correlated with higher charge rate and total discharge energy of 1MJ or less. Efficiency varied weakly with discharge power.



Note: The efficiency is shown as measured for various depths of discharge (dod) and charging current.

Figure 4. Round Trip Energy Recovery Efficiency