Christopher A. Haller, *Student Member, IEEE* Gregory M. Hand, *Student Member, IEEE*

Dynamic Energy Management using Flywheel Energy Storage Systems: Design & Applications

***Abstract*—This paper reviews both the design and application of electrical energy storage in flywheels often referred to as a Flywheel Energy Storage System (FESS). FESS design considerations will be presented followed by both common and more specialized FESS's of the past, present, and future.**

***Index Terms*—Flywheels, Space vehicle power systems, Uninterruptible power systems, Power system dynamic stability**

I. Introduction

ENERGY usage and consumption in the world today is considered to be a growing problem. This problem is caused by a combination of human population growth currently at 6.7 billion (2008) and the technological advances of society demanding more energy to improve quality of life [1]-[2]. With increased energy demand, engineers of the world are finding innovative, new methods to create and deliver energy. The challenge is to generate and distribute that energy in ways which will not negatively impact the environment. One of the largest means of energy generation and distribution today is via electricity [3].

Electricity is easily generated from a number of sources, most of which involve turning an electric generator to produce power. Chemical means such as batteries provide a stored source of electricity. Both of these methods generally rely on non-renewable sources for electricity generation. In the United States electricity is generated in a variety of methods such as coal at 49%, natural gas at 20%, nuclear at 19%, petroleum at 2%, and renewables at 10% [4]. Power sources such as chemical batteries will eventually wear out and can potentially damage the environment. Moreover, the first 90% of electrical energy producers listed above are not considered long term sustainable sources.

There are many long-term but not commonly used sustainable/renewable sources for both high and low power applications. These sustainable sources could eventually replace their fossil fuel and chemical counterparts for electricity production. The drawback to renewable sources is that they are subject to random environmental factors such as sunlight being blocked from solar arrays or intermittent wind conditions at wind turbine farms. Satellites orbiting the earth are powered from solar panels and encounter an extended period of time in the Earth's shadow where they need stored energy to operate. As a result of their low capacity factors renewables are not considered reliable enough to guarantee power delivery to the grid at all times [5]. To help renewables play a larger role in the worlds electrical needs, given these kinds of operating conditions, better intermittent and long term energy storage methods are needed [6].

Both large and small scale electrical energy storage is limited by technological, environmental or economic drawbacks. Small scale energy storage options such as batteries often contain heavy metals which can damage the environment while large scale options such as superconducting magnetic energy storage have high material cost and refrigeration energy requirements. [7].

Small scale energy storage is most easily achieved with batteries. Large scale energy storage methods can range from electrochemical such as in batteries, to chemical such as hydrogen, to mechanical such as in flywheels, to thermal such as molten salt [8]. One of the oldest of these energy storage methods is the flywheel.

Two early forms of the flywheel are the potter's wheel used to make clay jars, and the Neolithic spindle used to spin wool [9]. However, with an electric motor/generator attached to a flywheel an old means of storing rotational energy can be used in present day as a storage method for electrical energy. The energy storage capability of a flywheel is given in Equation 1 where E equals energy, I is equal to the moment of inertia for the flywheel, and ω is equal to the rotational speed of the flywheel.

$$E = \frac{1}{2} I\omega^2 \tag{1}$$

In the simplest of terms, a system comprised of a rotating flywheel coupled with a motor/generator is known as a flywheel energy storage system (FESS). The FESS's are known by other names as well, such as flywheel generators, flywheel batteries, or just simply as flywheels.

Manuscript delivered on December 4, 2008. This work was developed for the Electrical Engineering and Computer Science Course ECE 530.

C. Haller is a graduate student at Oregon State University, School of Electrical Engineering and Computer Science, 1148 Kelley Engineering Center, Corvallis, OR 97331 USA. (phone: 971-404-9783; e-mail: chrishaller@ieee.org).

G. Hand is an undergraduate student at Oregon State University, School of Electrical Engineering and Computer Science, 1148 Kelley Engineering Center, Corvallis, OR 97331 USA. (cell phone: 541-740-3539; e-mail: gregmhand@ieee.org).

II. Design Overview

A. Motor/Generator Comparison

1) Induction Motor/Generators

Induction motors can achieve high speeds through flux weakening while permanent magnet motors are limited in their flux weakening capabilities due to the permanent magnets on the rotor [10]. A fall back to induction motors is that they have high rotor losses due to rotor currents [11] which cause them to generate heat that is difficult to evacuate in vacuumed conditions. The other major fall back for induction motors is that their power to weight ratio is much less than that of a permanent magnet motor, which would give it fewer feasible applications.

2) Switched Reluctance Motor/Generators

Switched reluctance motors (SRM) operate on the principle of achieving minimal magnetic resistance, or 'reluctance', during operation [12] (see Figure 1 for cross-sectional view) and produce high torque densities [11]. The SRM employs a simple iron laminate rotor and is a strong candidate for flywheel applications due to its robustness and reliability. The advantage of using a SRM motor over a permanent magnet motor is that no rotor magnets or windings are needed for charging and discharging the flywheel making demagnetization a non-issue [13]. In addition electromagnetic spinning losses are eliminated during no torque situations because the wheel can be allowed to free wheel without the need of a stator excitation field. The major disadvantage to using a SRM in a flywheel application is the essential need for a laminate rotor [11].

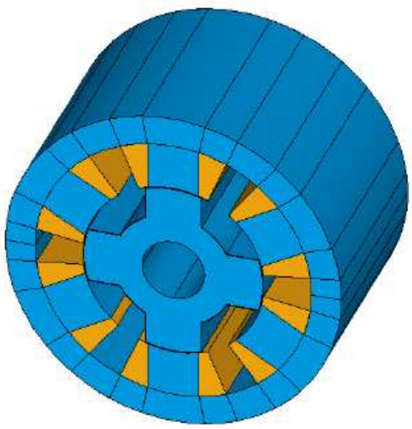

Fig. 1. Cross-sectional view of a Switched Reluctance Motor. [12]

3) Permanent Magnet Motor/Generators

Permanent Magnet AC (PMAC) or Brushless DC (BLDC) motors are the most common motor/generator used in flywheel applications. PMAC synchronous motors are well suited for ultra high speed flywheel applications because they have low rotor loss and high torque densities [11]. Low rotor loss is easily associated with low rotor heat which is important when operating in a vacuumed space where system heat dissipation is very difficult. A fall back to PMAC motors is that they employ magnets that will demagnetize over time. Due to the constant field produced by the magnets on the rotor a free wheel mode is only possible when a stator magnetic field is present which amounts to extra system loss.

B. Flywheel Rotor Design

Flywheel design is essential in establishing both the energy storage capacity and maximum power delivery of the flywheel system. There are four main topics of discussion in flywheel design; they are wheel shape, wheel material, magnetic bearing selection and active magnet bearing control.

1) Wheel Shape

The goal when designing the shape of a flywheel is to accomplish a uniformly distributed stress over the entire wheel [14], such that all parts of the wheel would be capable of the same max speed. This technique would allow the flywheel to store the most optimal amount of energy. Many have done their best to simulate flywheels to determine what the most optimal shape would be including G.R. Kress at the Swiss Federal Institute of Technology in Zurich, Switzerland [15]. Kress implemented a two dimensional Finite Element Method (FEM) and a one dimensional analytical method "inspired by Stodola's solution for an evenly stressed turbine disk without central bore." [15] It was found that the circumferential stress increases with decreasing distance to the center of the wheel and that the shape of the wheel is dependent on the desired radius. It was confirmed by both methods used that the general shape of an optimally distributed stressed flywheel would radially look like Figure 2. The clear conclusion that was made from Kress's observations was that "The specific energy storing capacity of the evenly stressed flywheel according to the closed-form solution of the simplified model equals the specific strength of the material being used."

2) Wheel Material

Flywheel material is important in determining how much energy can be stored in the system. Since energy storage increases with the angular speed squared it is desirable to use a material that can spin at high speeds without coming apart. Another point to consider is that the lighter a flywheel is the more applications it can be applied in and for that reason flywheels have found their way into cars and even satellites [14].

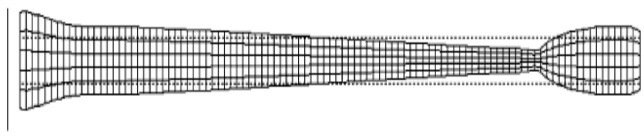

Fig. 2. Radial distribution of an evenly stressed distribution w/center bore on the left and tip on the right. [15]

Carbon composites have the greatest specific energy storing capacity due to it's high specific strength as can be seen from the composites in Table 1. In fact carbon fiber composites can rotate at tip speeds of 1000 m/s while metals are only capable of tip speeds of 200-300 m/s [16]. Carbon fiber is clearly the new material of choice in the flywheel world and has allowed flywheel energy storage to become more energy dense by weighing less and taking up less space.

3)Magnet Selection

The relative strength of the permanent magnets used on the rotor is directly related to the amount of power that can be drawn from the flywheel in the generator mode [14]. NASA's Glenn Research Center compared four strong permanent magnets for space flywheel applications and as can be seen in Figure 3 researchers found that the NdFe permanent magnets provide the greatest power delivery. It was noted that although NdFe magnets provided greater power delivery the SmCo magnets had better thermal characteristics.

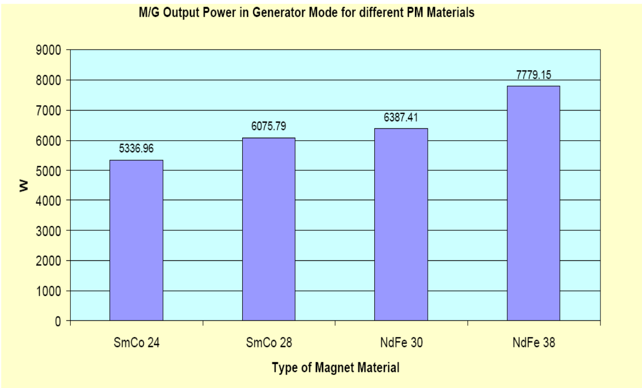

Fig. 3. Output power in generator mode for different permanent magnets. [14]

4)Magnet Control

The magnetic bearings of the flywheel are usually comprised of rare-earth permanent magnets (PM) and because the specific strength of these magnets is much less than that of the carbon composite flywheel they must also rotate at lower tip speeds. For this reason the magnets are placed near the hub of the flywheel [17]. The permanent magnets are called homopolar permanent magnets because their bias flux is oriented uniformly outward from the shaft [16]. The advantage of using homopolar PM is that they significantly reduce rotor eddy current losses.

One particular design has focused on a magnetic bearing that is actually comprised of two magnetic systems, the active magnet bearings (AMB's) and the superconducting magnetic bearings (SMB's) [18]. The SMB's are used for the levitation of the flywheel while the AMB's detect extra gaps between the rotor and electromagnets and compensate for instability of the wheel at high rpm's. The layout of this design can be see in Figure 4. The testing results revealed that the addition of AMB's to the design did in fact help to suppress rotor vibrations at high speeds.

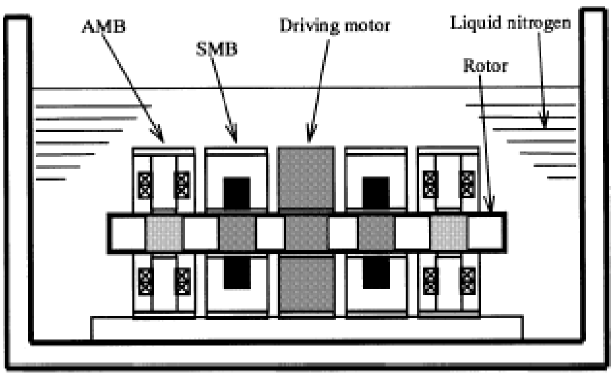

Fig. 4. Superconducting and Active Magnetic Bearings for Flywheel Applications. [18]

C.Heat Dissipation in a Vacuum

Ultra high speed flywheels significantly suffer losses due to drag at high speeds, to counteract these losses the wheel is actually operated in a partial vacuum. Heat dissipation in a vacuumed space is quite difficult due to the absence of air flow. Currently the best ways to deal with heat problems is to minimize the heat generated in the system and to make sure the materials used in construction can withstand high temperatures. NASA's approach to flywheel design was to ensure high thermal endurance of both the rotor and stator. [14] All but the carbon composite wheel was designed to withstand heat exceeding 200 degrees Celsius. In addition, NASA's flywheel, like many other high speed flywheels, employed a permanent magnet motor which introduces very little loss into the rotor, thus eliminating heat issues.

III.FESS CONFIGURATIONS

A.Serial and Parallel Dynamic Power

Another name for a series connected FESS is a Dynamic Voltage Restorer (DVR). The main function of a DVR is to boost the line voltage when the line voltage sags below the desired system voltage level.

Figure 5 gives an example of a FESS used as a DVR. The figure shows a load being powered from a power source with a FESS-DVR monitoring system voltage at node 2. If a low voltage condition is detected the FESS-DVR will act as a generator to boost the voltage between the power source and load. This series connection between the power source and load will help to maintain full power delivery to the load. Once the voltage level can be maintained by the power source the flywheel will stop delivering power to the load and begin motoring the flywheel to store kinetic energy until it is needed again [12]-[19]. One possible application example for a FESS-DVR would be in industrial areas which draw large intermittent loads but are not located near their generating power sources.

Parallel connection of a flywheel into an electrical system is another possible FESS configuration. The FESS would act to source power for peak demand intervals while other system power sources are at their limits. The FESS discharges power during peak demand and when peak demand has subsided it recharges the flywheel from the primary power source. This FESS power demand is similar in nature to many hybrid cars on the road today which use an electric assist motor to provide brief boosts of power for the vehicle to allow greater output torque and faster acceleration [20]. Hybrid vehicles with electric assist could be considered an applicable area for a parallel dynamic FESS.

B.Uninterruptible Power

Another common functional configuration of a FESS listed in this paper is that of the Uninterruptible Power Supply (UPS). As a UPS, the flywheel ensures that a load never experiences a power loss.

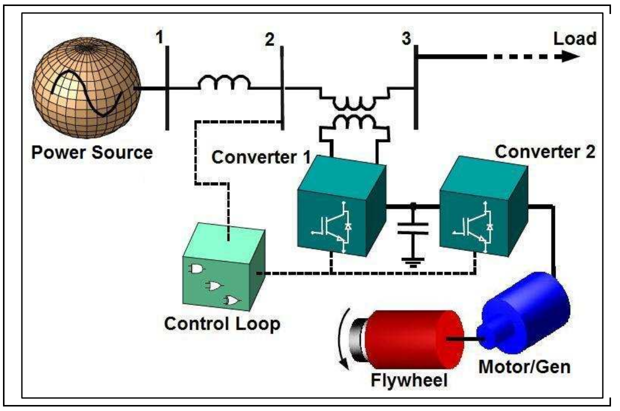

Fig. 5. Dynamic Voltage Restorer (DVR) Flywheel Energy Storage System is energized using power from ‘Electrical Generation’ in top left. ‘Control Loop’ manages FESS, ‘Converter 1’ and ‘Converter 2’. The converters are comprised of power electronics which either deliver power to the flywheel or the grid. The ‘Motor/Gen’ is used as a motor to add energy to the flywheel, or as a generator to remove energy from the flywheel [12].

Figure 6 is an example of a FESS configured as a UPS for a given load. If the load stops receiving power from the power source, either by power source failure, or by failure of the transmission line between node 1 and 2, then the FESS will start delivering power to the load such that the load will never see a change in supplied power. These systems can be used both in unexpected conditions such as temporary power failure at a computer data center, or expected conditions such as a solar powered satellite temporarily passing into Earth’s shadow as it completes an orbit [12].

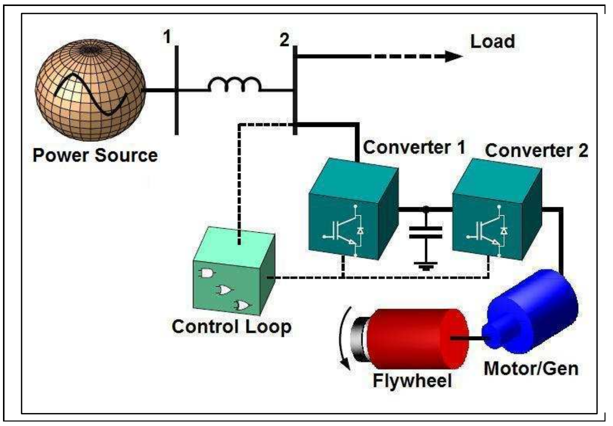

Fig. 6. Uninterruptable Power Supply (UPS) Flywheel Energy Storage System is energized using power from ‘Electrical Generation’ in top left. ‘Control Loop’ manages the FESS through ‘Converter 1’ and ‘Converter 2’. The converters are comprised of power electronics which either deliver power to the flywheel or the grid. The ‘Motor/Gen’ is used as a motor to add energy to the flywheel, or as a generator to remove energy from the flywheel If a failure occurs from either ‘Electrical Generation’ or the transmission line between nodes 1 and 2, then the flywheel acts as a

IV.PAST AND PRESENT APPLICATIONS

A.Stellarator AC Flywheel Generator

A typical FESS found in plasma physics research will be used to deliver power pulses to a device called a stellarator. A stellarator is “a device used to confine hot plasma with magnetic fields in order to sustain a controlled nuclear fusion reaction” [21].

The FESS used in this application is a so called “AC Flywheel Generator” which receives its charge from the local utility grid. Once enough kinetic energy is stored in the spinning flywheel the power is pulsed at a high rate through thyristors to the stellarator load. One of the main stellarator power loads consists of a large copper bar that has been bent toroidally around the hot plasma chamber to create a magnetic field winding. The magnetic field acts in two ways to contain and heat the plasma [21]. The FESS pictured in Figure 7 is rated for 0.8 gigajoules of energy, and 200 megawatts of power delivery [22].

A stellarator of this size could conceivably be adapted to assist in handling electrical grid conditions such as dynamic voltage sag correction, or used as a UPS to sink or source electricity on demand when generated supply elsewhere is not able to meet immediate demand needs.

Fig. 7. FESS also known as AC Flywheel Generator used in Ukraine for operation of Stellarator power source. FESS is rated for 0.8 gigajoules of energy and maximum power delivery at 200 megawatts. For scale note the person standing near the center junction point of the flywheel and motor/generator connection [22].

B.Regenerative Electric Train Flywheel Storage

A large power scale application of flywheels currently in use is for capture and delivery of power for electric trains at train stations. Traditionally trains *and many other vehicles* have used friction brakes for stopping. When friction brakes are used, all kinetic energy of the train motion is converted into heat energy. Instead of wasting this braking energy by converting it into heat, the electric train could convert this energy of motion into electricity when braking. With some relatively simple power electronic switching, these trains can regenerate back to a storage source, or in this case their power source.

Problems can develop from the large bursts of braking power entering the train power source supply though, as their may not be another source to absorb the power from the train properly.

Flywheel energy storage installed at common places which trains are most likely to stop such as train stations are able to store this temporary burst of power that the braking electric train generates. The flywheel held energy is then released back to the train power supply system when the train accelerates. This energy storage will smooth out total system power of a multiple train electrical system [20].

C.Space Flywheel Research

The National Aeronautics and Space Administration (NASA) has been doing flywheel research for space applications. Currently many of the projects they support such as the International Space Station (ISS) and various satellites use batteries. The ISS uses nickel-hydrogen batteries, and many satellites use lead-acid batteries which have fixed life spans typically around 5 years [23]-[24]. The "mechanical batteries" they have been developing will provide power to objects in orbit around the Earth which spend a portion of their time in the shadow of the Earth. Figure 8 shows an example of satellites experiencing the shadow of the earth while in orbit.

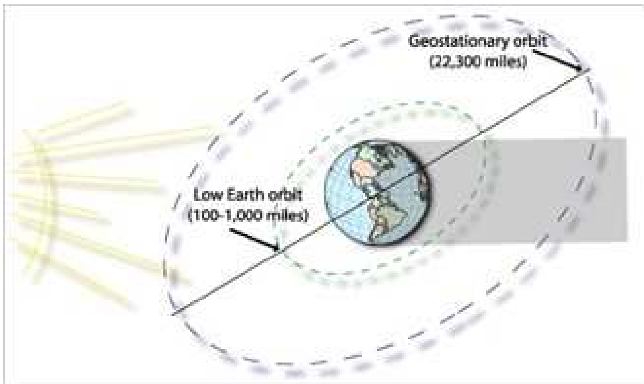

Fig. 8. As solar powered satellites orbit the earth, a portion of their orbit takes place in the shadow of the earth. Low Earth orbit satellites can spend as much as approximately 1/3 of their time in shadow, with no solar power production. This keeps most satellites out further in geostationary orbit which extends battery life of the satellite. With a flywheel energy storage system more satellites could fly in low earth orbit, which would allow faster communication times [25].

It is estimated that while a set of chemical nickel-hydrogen batteries will last approximately 5 years on the ISS, a flywheel energy storage system could last approximately 20 years. These satellites have a high density of energy storage as well while spinning at angular velocities in the range of 50 to 100 thousand rotations per minute [24].

D.Power Grid Regulation

Power grid regulation containers (PGRC) are currently available from a company called Beacon Power. These PGRCs are the size of a standard shipping container and house a set of 10 flywheels. Each flywheel has a capacity of 25 kilowatt-hours which gives a total shipping container energy capacity of 250 kilowatt-hours. They have a maximum output power rating of 2 megawatts. With a cycle life of 20 years, or 300,000 operating cycles, they easily exceed normal battery operation time periods [25].

Two of these PGRCs have been installed, one in California, and one in New York. The company Beacon Power is also selling combination plants which hold 5 megawatt-hours of energy with a delivery rate of 20 mega-watts for 15 minutes [26].

Their product lines are built on a single flywheel design in which each flywheel is made out of carbon/glass fiber composite rim which spins at 22,500 rotations per minute when fully charged with kinetic energy.

V.Conclusion

As can be seen from this paper, flywheel energy storage systems are a viable option for many high performance applications. As time and the economy begin coming into play the cost of flywheels, like most technology, is expected to come down. Because ultra high-speed flywheels are still new in development their use will most likely be limited to well funded research entities such as NASA. Other high speed flywheels are already being tested for viability in grid support. With the stability of the grid in question due to unforeseen renewable energy growth, flywheels may be the answer to balancing power delivery between generating sources.

References

[1] World Population. (2008, December 2). [Online]. Available: http://en.wikipedia.org/wiki/World_population

[2] World Energy Resources and Consumption. (2008, December 3). [Online]. Available: http://en.wikipedia.org/wiki/World_energy_resources_and_consumption

[3] Energy and Environment at Lawrence Livermore National Laboratory. (2004 June). [Online]. Available: https://eed.llnl.gov/flow/

[4] Electricity Generation. (2008, December 1). [Online]. Available: http://en.wikipedia.org/wiki/Electricity_generation

[5] Capacity Factor. (2008, November 25). [Online]. Available: http://en.wikipedia.org/wiki/Capacity_factor

[6] Solar vs. Wind vs. Hydro Power. [Online]. Available: http://www.solaralaska.com/primer/solvs.htm

[7] Superconducting Magnetic Energy Storage. (2008, November 18) [Online]. Available: http://en.wikipedia.org/wiki/Superconducting_magnetic_energy_storage

[8] Grid Energy Storage. (2008, December 3). [Online]. Available: http://en.wikipedia.org/wiki/Grid_energy_storage

[9] Flywheel Energy Storage. (2008, November 30). [Online]. Available: http://en.wikipedia.org/wiki/Flywheel_energy_storage

[10] Z. Yen, "Flywheel Energy Storage System for Vehicle Application", unpublished.

[11] P. Acarnley, B. Mecrow, J. Burdess, J. Fawcett, J. Kelly, P. Dickinson, "Design Principles for a Flywheel Energy Store for Road Vehicles," *IEEE Transactions on Industry Applications*, vol. 32, no.6, Nov. 2006.

[12] R. de Andrade jr, G. G. Sotelo, A. C. Ferreira, L.G.B. Rolim, *Flywheel Generator with Switched Reluctance Machine* (Paper Style). Rio de Janeiro, Brazil: Federal University of Rio de Janeiro.

[13] E. Darie, E. Darie, *The Control of Switched Reluctance Drives*, (Paper Style), [Online], http://snet.elth.pub.ro/snet2004/Cd/circ/circ_P23.pdf.

[14] A.Nagorny (Ph.D.), "High Speed Permanent Magnet Synchronous Motor/Generator Design for Flywheel Applications", (Powerpoint) NASA Glenn Research Center, National Research Council.

[15] G.R. Kress, "Shape Optimization of a Flywheel", New York: Springer-Verlag, 2000.

[16] L. Hawkins, B. Murphy, J. Kajs, "Application of Permanent Magnet Bias Magnetic Bearings to an Energy Storage Flywheel", Center for Electromechanics, Univ. of Texas.
[17] J.C. Whitaker, AC Power Systems Handbook, [Online]. Available: http://books.google.com/books, 2006, pp. 196
[18] M. Komori, C. Shiraishi, "A Levitated Motor with Superconducting Magnetic Bearings Assisted by Self-Sensing AMB's," *IEEE Transactions on Applied Superconductivity*, vol.13, no.2, June 2003.
[19] S. Samineni, B. Johnson, H. Hess, J. Law, *Modeling and Analysis of a Flywheel Energy Storage System with Power Converter Interface* (Lecture Style) ECE529, Dept. Elect. Eng., Idaho Univ., Moscow, ID, 2008.
[20] Energy Efficiency Technologies for Railways. (2004, April 16). Networks (2nd ed.) [Online]. Available: http://www.railway-energy.org/tfee/index.php?TECHNOLOGYID=195&ID=220&SEL=210
[21] Stellarator. (2008, June 7). [Online]. Available: http://en.wikipedia.org/wiki/Stellarator
[22] V. I. Lapshyn. (2003). Development of Stellarator Research in NSC KIPT [Online]. Available: http://www.ipp.mpg.de/eng/for/veranstaltungen/workshops/stellarator_2003/papers/papers_pdf/Lapshyn_147_SWS.pdf
[23] International Space Station Nickel-Hydrogen Batteries Approached 3-Year On-Orbit Mark. (2004, September 24). [Online]. Available: http://www.grc.nasa.gov/WWW/RT/2003/6000/6910dalton.html
[24] Solving a Satellite Power Problem. (2001, August). [Online]. Available: http://findarticles.com/p/articles/mi_qa3957/is_/ai_n8997538
[25] Space Research. (2003, May). [Online]. Available: http://spaceresearch.nasa.gov/general_info/flywheel_lite.html
[26] M. Lazarewicz, A. Rojas. (2004, February 26). *Grid Frequency Regulation by Recycling Electrical Energy in Flywheels.* [Online Paper Format]. Available: http://www.beaconpower.com/products/EnergyStorageSystems/docs/Grid%20Freq%20Reg%20White%20Paper.pdf
[27] Energy Storage (2008 November 12). [Online]. Available: http://en.wikipedia.org/wiki/Energy_storage
[28] Battery (electricity). (2008, December 2). [Online]. Available: http://en.wikipedia.org/wiki/Battery_(electricity)
[29] Hybrid Vehicle. (2008, Dec, 2). [Online]. Available: http://en.wikipedia.org/wiki/Hybrid_vehicle
[30] 20 MW Frequency Regulation Plant. (2008, July 23). [Online]. Available: http://www.beaconpower.com/products/EnergyStorageSystems/docs/SEM%2020MW.pdf

Christopher A. Haller (M'04) earned his bachelor of science in electrical engineering at Oregon State University in 2008. He is continuing into a master's of science degree in 2008 under a graduate teaching assistantship.

He worked as primary test and quality control technician for NW Rail Electric from 2002 to 2005. In 2006 he worked for Flextronics International as an Engineering Intern, and also for the Tekbot program at Oregon State in 2007 as a lead engineering intern.

Mr. Haller served as Webmaster for the OSU IEEE Student Group his 2005 to 2006 school year, and President of the group from 2006 to 2008.

Greg M. Hand currently attends Oregon State University with a coursework focus in energy systems and will earn his bachelor's degree in electrical engineering in April of 2009. During his college career Hand taught freshman level engineering labs and interned in area distribution engineering at Pacific Power. Hand will begin his career in application engineering at Eaton Corporation's Cutler-Hammer in July of 2009. His interests are in power electronics and motor control.