Development of a Differentially Balanced Magnetic Bearing and Control System for Use with a Flywheel Energy Storage System

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ABSTRACT

The purpose of a magnetically suspended flywheel energy storage system for electric utility load leveling is to provide a means to store energy during times when energy is inexpensive to produce and then return it to the customer during times of peak power demand when generated energy is most expensive. The design of a 20 kWh flywheel energy storage system for electric utility load leveling applications involves the successful integration of a number of advanced technologies so as to minimize the size and cost of the system without affecting its efficiency and reliability. The flywheel energy storage system uses a carbon-epoxy flywheel, two specially designed low loss magnetic bearings, a high efficiency motor/generator, and a 60 cycle AC power converter all integrated through a microprocessor controller. This paper will discuss in detail the basic design of each of the components that is utilized in the energy storage design.

THE ENERGY STORAGE SYSTEM

At present, electric power utilities face a shortage in meeting their current consumer peak demands in addition to under-utilizing their baseline generating capacity at off peak times. The purpose of the energy storage system is to provide a means to save energy during times when energy is cheap to purchase and inexpensive to produce and then return the energy at times when energy is expensive to purchase and costly to generate. Typically, an energy storage device operates cyclically. For electric utility load levelling applications, a typical daily cycle is 8 hours of charge time, followed by an 8 hour float period, a 4 hour discharge time, and then a second 4 hour float period. It is expected that these systems will have a lifetime in excess of 10 years. Thus the system must be capable of withstanding at least 4000 cycles. Regardless of the application, the principle of operation of the flywheel energy storage system is the same:

- Take energy in and convert it to an easily stored form.
- Store the energy with minimal losses until it is needed.
- Convert the energy back to a suitable output form and return it to the system for use.

To illustrate the advantages of the flywheel energy storage (FES) system, a comparison is made between the flywheel energy storage system and an energy storage system that is currently available commercially, namely thermal energy storage. The FES system delivers energy to the residence in the form of 220/110 volt alternating current. Thermal energy storage delivers a less useful form of energy, viz: heat. Additionally, the FES system may be used year round, whereas thermal energy storage is primarily effective during the months of the year when heating of the residence is required. In addition, interfacing the FES with existing residences can be a straightforward process by simply working through the existing residential electrical panel. The final benefit of the flywheel energy storage system that will be discussed is that it can be located external to the residence, eliminating the need for useable space within the home.

Electric utilities in the greater Washington D.C. area were surveyed in order to size the energy storage capacity of the flywheel energy storage system. Of primary concern to these utilities was the top 10-20% of the residential power users. This group of utility consumers used a peak power of 7.5-8.5 kW, on average, over a 4-6 hour time period. As a result of our survey of these electric utilities, a system size of approximately 20 kWh was found to satisfy the energy requirements of these high end electricity users.

The flywheel energy storage system is composed of five components and is shown in block form in Figure 1. These components are

1. Flywheel and Enclosure
2. Differentially Balanced Magnetic Bearing
3. Differentially Balanced Magnetic Bearing Control System
4. Motor/Generator
5. Smart Microprocessor Power Conditioner

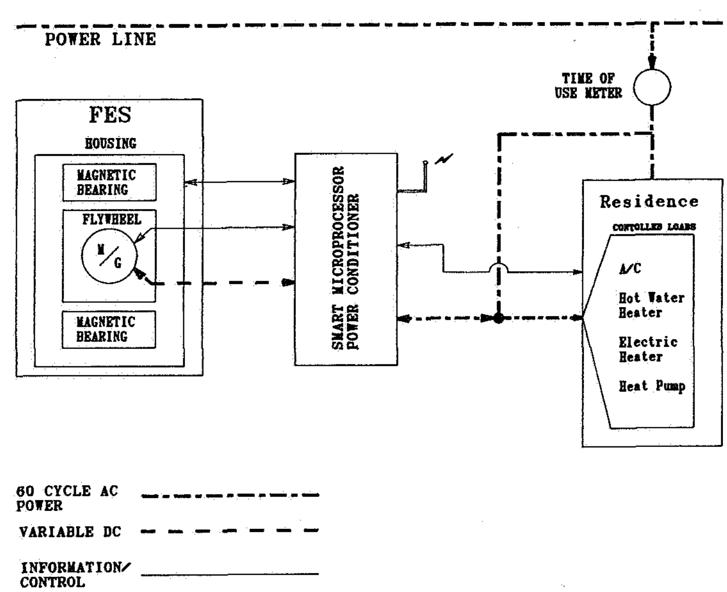

Figure 1. Flywheel Energy Storage System

In the FES system, shown in Figure 2, the flywheel (rotor) is composed of a number of composite material rings which are filament wound and interference assembled to form a multi-ring pierced disk. The rotor is filament wound and interference assembled to improve performance. Two differential balanced magnetic bearings (a new innovative feature) are present in the system, one at each end of the rotor. Two back up bearings are located immediately outboard of the two differential balanced magnetic bearings. Sandwiched between the two magnetic bearings, in the center section of the stator, is a high efficiency brushless motor/generator. The rotor and stator are housed within a vacuum enclosure. The smart microprocessor power conditioner is located external to the flywheel enclosure and provides the necessary power conditioning functions to deliver useful electricity to the customer. The design of the smart microprocessor power conditioner is based upon the state of the art resonant converter technology.

In the following sections of the paper the proposed design methodology of the FES system will be presented as it pertains to each of the individual components listed above.

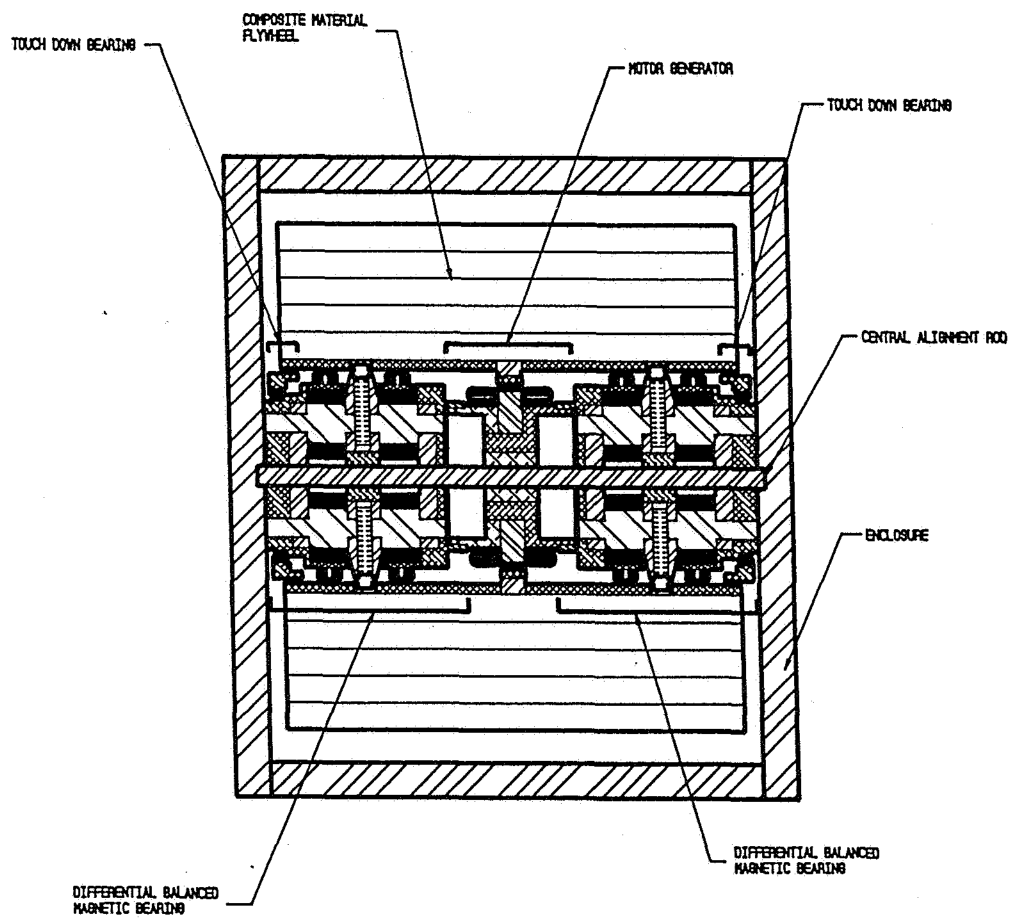

Figure 2. Cross Section of 20 kWh Energy Storage System

SYSTEM DESIGN

The Flywheel and Enclosure

One of the main components of the energy storage system is the flywheel (rotor). A typical figure of merit of a rotor is the amount of stored kinetic energy per unit of rotor weight [1,2]. This parameter is termed the specific energy density and is reducible to the following equation:

$$SED = K_S (\sigma/\gamma)$$

It is desirable to make the SED of the flywheel as high as possible [to minimize the weight and volume of the flywheel] thereby reducing the loads on the differentially balanced magnetic bearings.

It has been shown that composite materials, such as carbon/epoxy, are far superior to steel when used for high SED energy storage applications. The goal of maximizing SED, when using composite materials, is to achieve a uniform state of stress throughout the flywheel. This means that each point in the flywheel simultaneously reaches its working strength, in both the radial and tangential directions [3]. Because composite materials are either anisotropic or orthtropic, their strength can vary from 3,400 MPa [500,000 psi] or more in the tangential direction to 69 MPa [10,000 psi] or less in the radial direction. From a practical point of view, it is desirable to fabricate the flywheel using wet filament winding procedures, with the resultant flywheel having its highest strength in the tangential direction [stresses acting along the fibers] and its lowest strength in the radial direction [stresses acting transverse to the fibers]. A detailed comparison of rotors has been presented by Kirk et al. [4].

The rotor used in this application possesses the following characteristics:

- The geometry is that of a constant thickness disk, with a hole in the center.
- The disk is magnetically levitated so that no spokes or shafts are required; thus, there are no stress concentrations.
- The disk is itself the rotor of a motor/generator set.
- Energy input is electrical and results in the acceleration of the flywheel with the flywheel running as a motor.
- Energy output is electrical and results in the deceleration of the flywheel with the flywheel running as a generator.

In this system, the rotor is composed of nine composite material rings which are filament wound and interference assembled to form a multi-ring pierced disk. In addition, a tenth, iron material ring, is attached to the inside of the composite rotor. This iron ring carries the necessary differential balanced magnetic bearing and motor/generator parts.

The FLYANS [FLYwheel ANalysiS] and FLYSIZE [FLYwheel SIZE] computer programs, developed at the University of Maryland [3] were used to perform a preliminary sizing for the composite rotor configuration. For flywheel applications, optimizing a rotor consists of maximizing the specific energy density. To maximize the specific energy density of the rotor entails obtaining the optimum ID/OD ratio of the rotor, determining the optimum percent interference allowed between rotor rings, determining the operating speeds of the rotor, and minimizing the flywheel weight [1,2]. The optimal ID/OD ratio was found to be 0.45. The flywheel will be prestressed using interference assembly techniques. This interference results in favorable stresses in the rings of the flywheel. The optimal amount of interference that should be developed between the rings during assembly was determined to be 0.6%. This amount of interference greatly increases the useable stored energy density, thereby reducing the flywheel weight. It was determined that this amount of interference could be achieved using conventional presses, without damaging the ring during assembly. The operationg speed range of the flywheel was designed to cycle between 95% of its maximum speed to 23.8% of its maximum speed [a 4:1 speed range]. Since the rotor stresses are proportional to the square of the speed, the stresses will be cycling between 90% of their maximum to 6% of their maximum. Table 1 summarizes the flywheel specifications.

Inner Diameter	0.254 m (10 in)
Outer Diameter	0.564 m (22.2 in)
Thickness	0.553 m (22 in)
Flywheel Weight	172.8 kg (380 lbs)
Burst Speed	46,345 rpm
Min. Operational Speed	11,610 rpm
Max. Air Gap Growth	0.134 cm (0.053 in)

TABLE 1: Flywheel Specifications

As stated previously, both the stator and rotor portions of the FES will be housed in a vacuum chamber to minimize the windage losses associated with rotation. Three methods of calculating the power loss due to aerodynamic drag loss on the spinning rotor were analyzed. The first method was based on the premise that the the thickness of the rotor was negligible when compared to the outer diameter. The second method was similar to the first in that it modeled the rotating wheel as a disk with negligible thickness. The third and final method modeled the drag on the ring as a result of skin friction which occurs on both the inside and outside diametral surfaces (a disk with a hole in the center), as well as on the top and bottom ring faces [5]. Since the third method of computation most closely resembled the flywheel rotor in this application, it was used as the basis to estimate the drag losses. A plot of the various losses for different operational pressures is given in Figure 3. During the design analysis it was determined that an operational pressure of 10^{-4} Torr will be sufficient to keep the rotational losses of the flywheel negligible. Furthermore, this pressure can be achieved cheaply and efficiently using conventional vacuum pumps, thus eliminating the need for more costly diffusion pumps.

The Differentially Balanced Magnetic Bearing

Magnetic bearings are used to suspend the composite flywheel because of the high rotational speeds and the need to eliminate contact friction and maximize the operational life of the system. The magnetic bearings used are called differentially balanced magnetic bearings, and incorporate both permanent magnets (PMs), and electromagnets (EMs), that are sandwiched between ferromagnetic plates. The permanent magnets provide a biasing flux in the air gap between the stator and the return ring while the electromagnets provide a control flux to stabilize the flywheel radially. Both the PM's and the EM's are located on the stator portion of the bearing. A high permeability return ring is attached to the inside diameter of the flywheel and is positioned concentrically around the stator. Sensors located in an orthogonal orientation to the flywheel sense the position of the rotor relative to the stator and provide a feedback signal to the magnetic bearing control system [6].

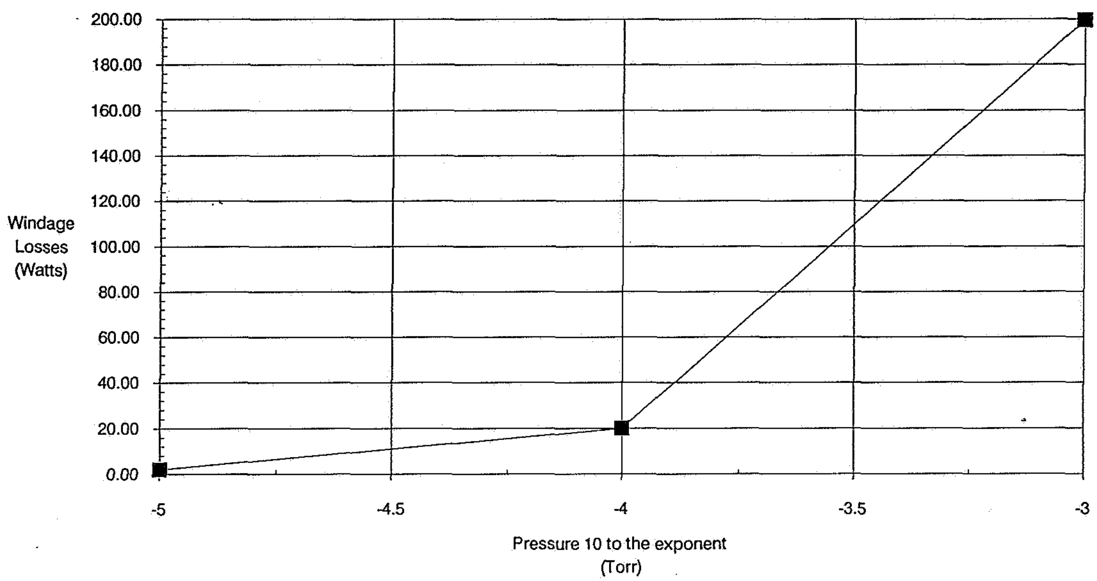

Figure 3. Plot of Pressure vs. Windage Losses for 20 kWh System

A possible orientation for the bearing stack is to align the axis of the bearing with the earth's gravitational field. In this orientation, with the flywheel weight in the axial direction, the suspension control of the pancake bearing is passive, meaning that the permanent magnets alone must be able to provide enough axial support to maintain the flywheel in suspension. Since the flywheel used in this application weighs approximately 172.8 kg (380 lbs.), a new and unique method of suspending the wheel was developed.

The 20 kWh flywheel is suspended by orienting the axial axis of the flywheel, and that of the bearing, parallel to the earth's surface (and thus perpendicular to its gravitational field). The weight of the wheel will then be suspended by the magnetic forces generated in the radial direction. As a result of using both EMs and PMs in the differential magnetic bearing design, a linear restoring force is generated in the radial air gap that acts to restore the rotor to its center position. In order to accomplish this task differential size permanent magnets are used. The permanent magnet located in the southern quadrant is larger than the permanent magnet in the northern quadrant so that the attractive forces due to the lower PM are larger than the magnetic attractive forces generated in the upper PM. Thus, a net restoring suspension force is achieved which suspends the flywheel as a result of the magnetic forces generated by the permanent magnets alone.

If the flywheel is horizontal, then the flux from the permanent magnets passively supports the assembled flywheel weight. Figure 4 shows in detail the flux paths of one of the axes. Path A, the solid line, is created by each PM. Flux flows from each PM and travels up into the top magnet plate across the air gap into the return ring then into the bottom plate and completes the loop by returning to the PM. Path B, the dashed line, is created by the EM coils. As noted above, a transducer is positioned interior to the rotor and senses all radial gap displacements. When the position transducer detects movement of the flywheel relative to the stator, a control flux is introduced as shown in Figure 4. This control flux adds to the PM generated flux on the side of the increasing gap and subtracts from the PM generated flux on the side of the decreasing air gap, thus furnishing a net force to restore the flywheel to its central position.

The magnetic bearing has active control in the radial direction of the flywheel and passive control in the axial direction. The stack is resistant to axial movements because of the passive stiffness of both magnetic bearings in the axial direction. If you consider the flywheel to have six degrees of freedom, three for translation and three for rotation, then the stack controls four of these degrees of freedom with two magnetic bearings. The two radial translation motions are controlled actively by both magnetic bearings. The two rotation motions (commonly called pitch and yaw) are also controlled by the two magnetic bearings. Axial translation is controlled by the static passive stiffness of the bearing and finally the motor/generator controls rotation about the spin axis of the flywheel.

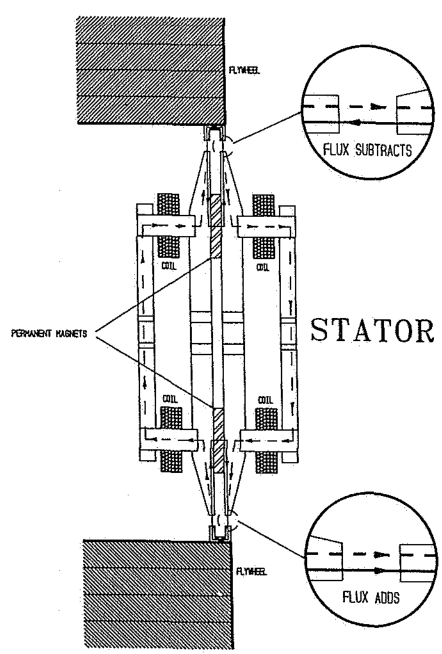

Figure 4. Flux Paths of Magnetic Bearing

Radial Stiffness	1143 kN/m (6527 lbf/in)
Axial Stiffness	146 kN/m (831 lbf/in)
Turns/Electromagnetic Coil	750 turns
Max. Operating Current	2.69 amperes
Gap Operating Range	±0.097 cm (±0.038 in.)
Nominal Gap Distance	0.254 cm (0.100 in.)
Stator Radius	1.27 cm (5 in.)
Pole Face Thickness	8.79 cm (3.46 in.)

TABLE 2: Magnetic Bearing Specifications

The important parameters that need to be determined for a specified bearing are the radial stiffness (K_X) of the permanent magnets across the air gap, and the current force sensitivity (K_I) of the coils [7]. These parameters must be determined prior to an in-depth design to determine whether or not the pancake bearing stack will support the flywheel assembly. They are also necessary to the design of the magnetic bearing control system. Table 2 summarizes the preliminary design specifications for the differential balanced magnetic bearings.

The Differential Balanced Magnetic Bearing Control System

The generic control system shown in Figure 5 is composed of a number of blocks which are used to control the physical plant, in this case the flywheel itself. The control system is driven by transducer sensors which determine the instantaneous position of the flywheel. The control system is a simple linear system with lead/lag compensation and a low-pass filter. The corrective force to the plant is provided by the electromagnetic coils whose gain is K_I. The coil is driven by the current amplifier whose maximum calculated output was determined to be approximately 2.7 amps. As long as the plant excursions are small (i.e. in the linear range) the current amplifier operates in the linear mode. If, however, the excursions become large, the amplifier saturates and acts as a limiter. This, and the fact that the electromagnetic coil has inductance, and a small non-linearity, provides the principal reason for non-linear behavior. The control system, therefore, has been carefully designed to operate in the linear region while the inductance of the coil is minimized.

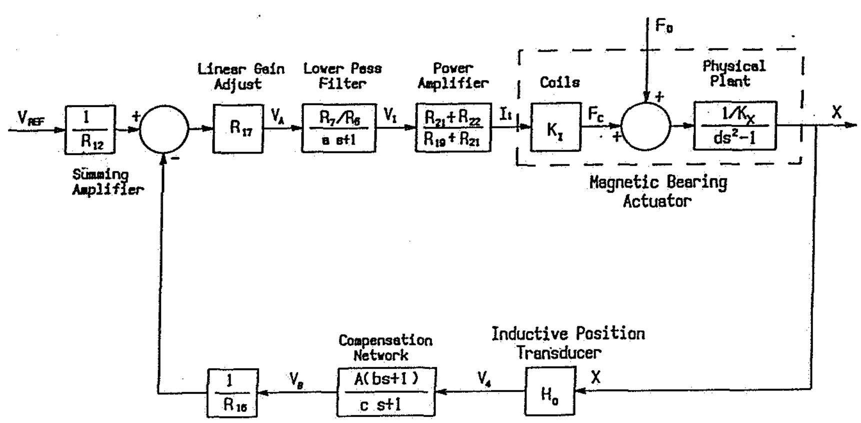

Figure 5. Magnetic Bearing Control System

Two design tools are used in the design and simulation of the stack bearing control system. JEYCAD [8], a computer program for the IBM PC, allows the user to input the component data of the control system and computes the transfer functions and active stiffness of the design. Classical Control, CC, is then utilized to analyze the proposed control system. The CC program plots the frequency and time responses of the control system. These plots can then be analyzed and compared to the specifications in the original parameter design.

The design goals of the differential balanced magnetic bearing control system were defined to be:

1. A maximum excursion of the flywheel should be less than the mechanical touchdown bearing gap.
2. Linear operation with maximum relative stability.

The first requirement is the displacement limit of the flywheel, because the mechanical bearings are built to prevent any damage due to the failure of the magnetic bearing components. The maximum transient overshoot of the control system is designed to be less than the touchdown gap of the mechanical bearing. Mechanical back up ball bearings are located outboard of the differentially balanced magnetic bearings should touchdown occur in the unlikely event of magnetic bearing failure. It also defines a minimum active radial stiffness for a step input of the external disturbing force. The second requirement is met with a gain margin of at least 6 dB and a phase margin of about 45 degrees.

The Motor/Generator

Figure 6 shows a cross-section of a motor/generator system that has been shown to be a viable design for flywheel applications [9,10]. This motor/generator is a brushless permanent magnet device that incorporates optical infra-red sensors for electronic commutation. The absence of brushes on the motor/generator, coupled with magnetic bearings for suspension, eliminates mechanical friction thus making a more efficient energy storage device.

The motor/generator contains an outer ring assembly that is attached to the flywheel and rotates with it as shown in Figure 6. This assembly is composed of several permanent magnets that are attached and evenly spaced around the perimeter of the soft iron backing ring. The north and south poles of the magnets face the coils of the stationary ironless armature (attached to the stator) and create a magnetic field through the control coils. When current from a power supply is pumped through the control coils a torque is generated that causes the flywheel to accelerate. The power supply is shut off, when the flywheel attains its maximum operational speed, and the flywheel spins down to its lowest operational speed, generating a current through the armature coils. The power conditioning electronics yield a voltage that is directly proportional to the flywheel speed. This is the generator mode or discharge cycle of the device. During the motor mode of the device, the coil current is monitored and varied by the electronic commutation mentioned previously. The optical sensors are used to determine the position of the flywheel (as well as the position of the permanent magnets with respect to the coils) by sensing the position of the commutation markings located on the outside of the flywheel. The commutation logic found in the electronics of the device causes the coil current to be varied in order to accelerate the flywheel or keep it spinning at a constant speed [9].

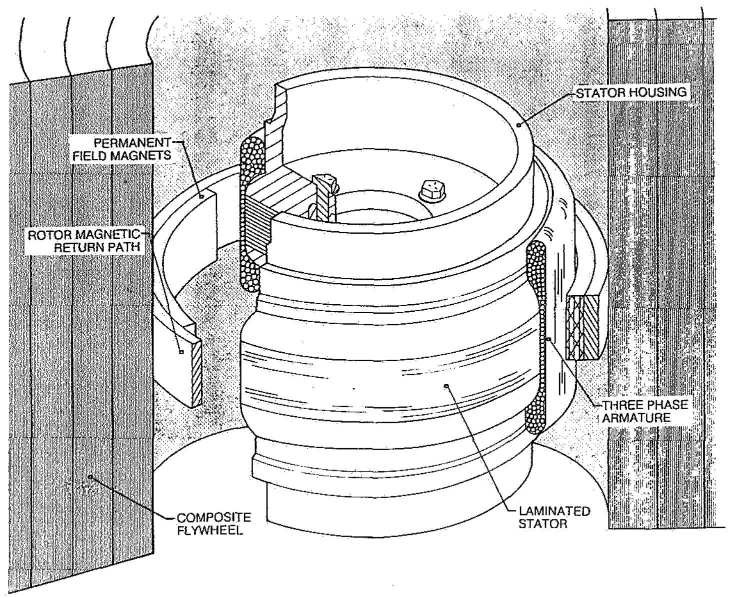

Figure 6. High Efficiency Brushless Motor/Generator

The motor/generator was designed using detailed calculations based on design goal data, flywheel specifications, and magnetic bearing specifications. The first step in the design process was to determine the power, voltage, and armature current variation during the charge cycle of the motor and the discharge cycle of the generator. It was assumed that the bus of the motor receives a constant power of 2.5 kW from the utility grid at 240/110 V ±2% AC. This happens during the charge cycle time of eight hours. Since motor voltage is proportional to flywheel speed and flywheel speed was determined to vary over a four to one ratio using FLYSIZE, a motor voltage profile varying from 680V to 170V was used in the design. Armature current variation (per phase) was determined by dividing the time equation of power by the time equation of voltage. At the beginning of the charge cycle, the armature current/phase was computed to be 29.3 amps and at the end it was computed to be 7.33 amps. A proportional discharge cycle was assumed based upon previous work that has been conducted in this area at the University of Maryland [11]. Over the eight hour peak period the generator discharges a power, on average, of 2.5 kW. Altogether the generator delivers 2.5 kW over eight hours, or 20 kWh of useable stored energy. The voltage variation of the generator is linear from 680V to 170V, with the discharge rate varying as power is delivered to the residence.

Of importance is the maximum current in the armature per phase which is given by $I = P/3V$ or 4.90 amps/phase. This maximum current is used to design the coils in the armature. Table 3 summarizes the preliminary design parameters of the motor/generator.Of final interest was the determination of energy losses within the armature and the power electronics of the device. Armature losses were computed to be 22 watts while the loss due to the ferrite ring was determined to be negligible. Heat generation within the motor/generator was also investigated. The losses seen in the motor/generator would be generated in the form of core heating. Since the system is contained in a vacuum environment, convection within the system is not possible. To eliminate this problem the central aligning rod is used as a heat sink to conduct the heat generated in the motor/generator to the outside environment (external to the vacuum enclosure).

No. of Poles	8
No. of Conductors/Phase	16
No. of Turns/Phase	2
No. of Armature Coils	16
No. of Coils/Phase	2 (each parallel)
No. of Conductors/Slot	16
Slot Area	36 mm^2 (0.056 in^2)
Av. Length of Turn	0.018 m (0.71 in)
Operational Freq. Range	193.5 - 772.4 Hz

TABLE 3: Motor/Generator Specifications

The Smart Microprocessor Power Conditioner

The distribution of electric power in the FES system is accompanied by conversion of that power from one voltage form to another. In the case of the flywheel energy storage system, AC power from the utility is converted to DC power pulses and provided to the motor/generator (which is operating in a motor mode) during the charge cycle of the system. The motor during this charge cycle operates as a permanent magnet brushless DC motor. Power input to the motor is in the form of voltage pulses which are properly sequenced with respect to rotating magnets by a commutation sensor system. During the discharge cycle, the motor/generator is in a generator mode producing variable frequency, variable amplitude, alternating current. This current is produced from the generator as three phase power. The generator output must be converted back to AC power for use in the residence.

A generally accepted utility standard for AC power is that it must be delivered to the residence at a constant voltage of 240/110 volts rms $\pm 2\%$, at 60 Hz. This standard was used in the design so that the generated power (from the FES) is compatible with that delivered from the utility grid. To condition the output power from the FES a power converter or power conditioner is required. Electronic power conditioners contain no moving parts; they are comprised of solid state switches, filters, control circuits and diodes.

The power conditioning element of the flywheel energy storage system is a resonant converter. A block diagram of the converter is shown in Figure 7. This resonant circuit is in the direct path of power flow into and out of the system. Natural commutation is employed to control the flow of power into and out of the "resonant tank". This occurs when either the voltage or current passes naturally through zero. When this occurs the current or voltage is then switched on or off (in order to properly shape the output power to the residence) by a microprocessor that resides within the unit; thus the name smart microprocessor power conditioner. There is little dynamic power loss associated with natural commutation since either the voltage or current at the time of switching is equal to zero (power equals zero); therefore, the frequency of the resonance can be increased dramatically.

In the motor mode, the smart microprocessor power conditioner functions as a motor controller. Three commutation sensors are positioned 120 electrical degrees apart (on the inside of the flywheel and on the motor/generator) and sense the instantaneous position of the permanent magnets on the rotor. The signals from the commutation sensors are control signals to the resonant converter. The commutation signals determine the sequence of the DC pulses delivered to each phase of the three phase motor/generator. As the frequency of the motor increases the magnitude of the DC voltage pulse is increased to correspondingly increase the speed of the rotor. Scheduling of the required timing of the voltage pulses will be performed by a master controller which will govern both the control of the smart microprocessor power conditioner and the other components of the system.

In the generator mode, the smart microprocessor power conditioner will perform the function of an AC inverter. The three phase AC output (variable frequency and variable amplitude) from the generator will be captured in the resonant tank. This power is then processed in the resonant tank to shape the single phase, 60 Hz, 240/110 volt, alternating current power for use in the residence.

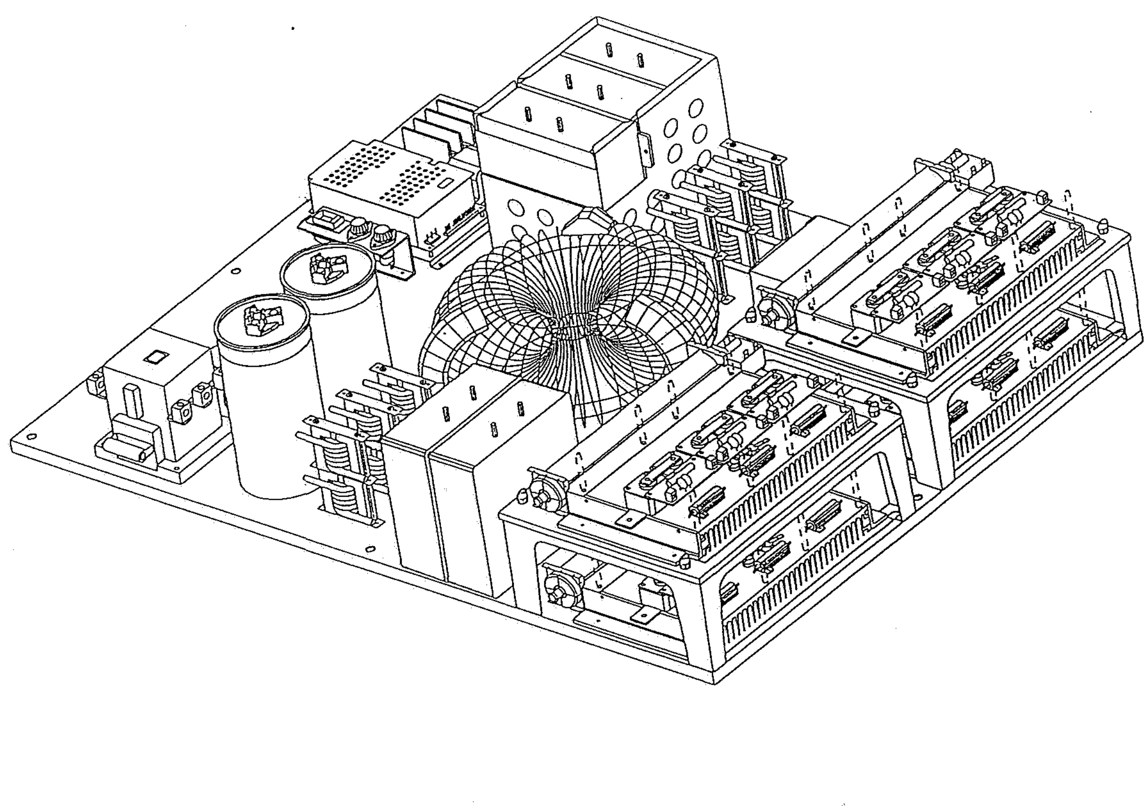

Figure 7. The Resonant Converter

SYSTEM CONSIDERATIONS

System Efficiency

In determining the overall system efficiency of FARE's 20 kWh flywheel energy storage system a typical charge and discharge cycle was assumed as shown in Figure 8. A power budget was prepared that estimated the losses present in the system over the typical 24 hour operational cycle. In order to return 20 kWh of useable energy to the residence, it was estimated that the system would have to store approximately 24.8 kWh of energy.

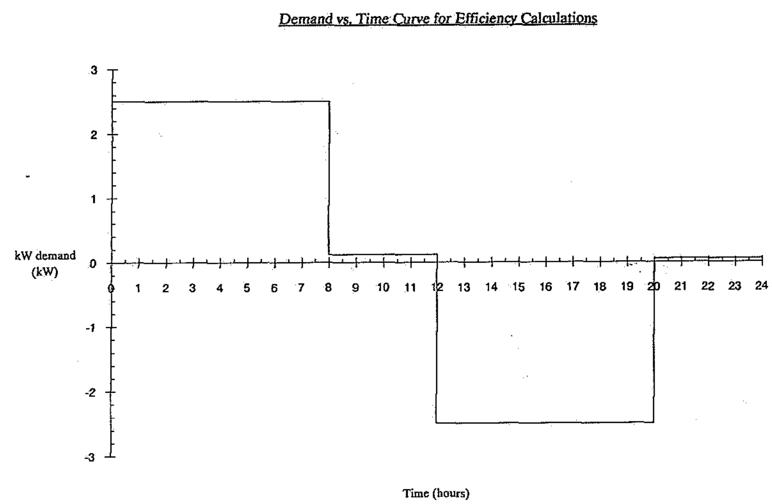

Figure 8. FES System Power Cycle

The round trip efficiency of the system is defined as the amount of useable energy delivered to the residence divided by the amount of energy stored by the system during the charge cycle . Thus system efficiency is:

$$\text{round trip efficiency} = \frac{20 \text{ kWh}}{24.81 \text{ kWh}} = 0.81$$

System Economics

In conducting an economic analysis of FARE's flywheel energy storage system, the up front cost of the system was determined to be $7500. In addition, the cost of generating power was associated with two different rates, one for off peak generation and the other for peak generation. The approximate savings per year was estimated to be $2000/year based upon the above rate differential. Knowing the estimated cost savings per year from utilizing the proposed system, and assuming an up-front utility rebate of $2000 to the consumer, the payback period of the system is calculated to be 3 years.

CONCLUSION

Magnetically suspended flywheel energy storage systems are a unique and superior alternative to other forms of energy storage for electric utility load leveling applications. By utilizing flywheel energy storage systems, utilities possess the capability to save energy and conserve vital fossil fuel resources. In addition, flywheel energy storage systems negate the need for utilities to construct new generating facilities to satisfy their current, as well as future, peak demands. The magnetically suspended flywheel energy storage system can be designed in modules of 24 kWh that deliver 20 kWh of energy to the residence at a constant voltage of 110/240 volts, alternating current. By using state of the art devices, a round trip efficiency of 81% is achieved. Finally, the economic feasibility of the flywheel energy storage system has been demonstrated to be competitive with other currently available commercial systems, with a payback period of 3 years.

ACKNOWLEDGEMENTS

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