Abstract— Energy storage is needed to fill the gap when variable power energy production systems are offline. This project is to study an energy storage device using high temperature superconducting (HTS) windings. The design will store energy as mechanical and as electrical energy. Mechanical energy will be stored as inertia in the mass of the spinning rotor. This inertial energy storage is very similar to a flywheel. Magnetic energy will be stored in the motor's rotor windings and possibly in the field windings. Energy stored in these windings will create a magnetic field to store energy proportional to the current and number of turns in the coils and will also spin the flywheel / rotor. This design study is to determine the amount of energy that can be stored in the device and estimate the losses resulting from the spinning mass of the rotor and the peripheral devices needed for operation.

Keywords - hts; superconductor; motor; flywheel; magnetic; bearings; energy; storage

I. INTRODUCTION

Energy storage is becoming a critical component of the smart grid as more time varying power production sources are integrated into the system. Furthermore; demand response and demand side management schemes require improved storage capability for the grid. Schainker [1] discusses the advantages and disadvantages of energy storage methods including batteries, capacitors, pumped—stored hydroelectric and compressed gases. Two common disadvantages are energy density and geographical limitations. This work focuses on developing a design for an energy storage option that can be co-located with wind turbines. Wind energy is a non-polluting resource however the amount of energy produced varies greatly from day to day [1].

Two methods of storing energy have been investigated in the literature explored in this paper to improve storage capacity. In this work flywheel energy storage and superconducting magnetic energy storage are combined to determine the possibility of creating a more energy dense device.

A. Inertial Energy Storage

Flywheel energy storage has been researched significantly in the literature investigated for this paper. Some of the more recent work was to design a small 25 kW composite flywheel energy storage system using high temperature superconducting bearings to levitate the rotating flywheel [2]. Rotational speeds of 82,000 rpm in air and 130,400 rpm in a vacuum were achieved in their work.

Researchers in Japan investigated the use of 3 different flywheel materials; carbon reinforced polymer, chrome molybdenum steel, and magnesium alloy in their energy cache system [3]. A prototype design was created using conventional bearings. The total energy accumulated in the flywheel was 1.53 MJ.

Haruna et al. [3] developed a prototype capable of supplying 5.4 kW with losses amounting to 1.16 kW. Most of these losses, 1 kW, were from auxiliary equipment used to run an oil pump and blow a vacuum in the case. There were also 160 W of windage and mechanical losses. Further research will be needed to determine the amount of energy that will be lost in the design described in this paper.

McGrath et al. [4] are developing a 100 kWh flywheel energy storage system. Their design uses a "flying ring" and magnetic levitation bearings to deliver much more energy than other flywheel energy storage devices.

B. Magnetic Energy Storage

Magnetic Energy Storage is the second energy storage method studied in this paper. This method is known as superconducting magnetic energy storage (SMES).

Energy storage applications using SMES devices have been installed and tested. A large 1.4 MVA / 2.4 MJ SMES was installed in the Brookhaven National Laboratory [5]. Particle physics researchers at Brookhaven use this storage device to compensate for power sags and momentary power interruptions to prevent beam loss in their synchrotron source. The technology uses pancake shaped coils to create sections of magnets. The sections are arranged in a toroid configuration to store the magnetic energy. The objective of this research is an SMES in the 2 MJ class capable of a 25 Tesla magnetic field when cooled to 4.2K [6].

Design of a 2.5 MJ SMES for microgrid operations is under development [6]. The intent of their research is to improve SMES design methodology and to meet the Army's requirements for a tactical microgrid. They also intend to develop robust quench protection and switching components and to investigate the possibility of using superconductor tape designs to reduce AC losses.
C. Inertial and Magnetic Energy Stored in a Motor

One aspect the study in this paper focuses on is storing mechanical or inertial energy in the spinning mass of the flywheel / rotor similarly to those inertial energy storage methods mentioned in Section I.A. A simplified prototype study model will be described in Section III.D.

The other energy storage method studied in this paper is magnetic energy. A preliminary set of equations as described in the Magnetic Energy Storage Formulas Section II.B were used to determine the SMES energy storage capabilities of this motor.

II. ENERGY STORAGE METHODS

Research is being done to create innovative methods of storing energy in a flywheel. Estimates of one such design are that it can deliver 400% as much energy as other flywheel energy storage systems. Flywheel energy storage could become very important in wind and solar power installations [4].

The design in Figure 1 uses a steel or iron flywheel as the mechanical part of the energy storage system. Mechanical bearings will be assumed to avoid the complications of a control system needed for the use of magnetically levitated bearings. The expense and use of composite materials will also not be a part of this study. Both of these techniques could be added to a more advanced design study in the future.

A. Inertial Energy Storage Formulas

The inertial energy storage capabilities of this design study can be found by determining the flywheel mass and angular velocity. The flywheel mass will be found using the density for soft iron. It will be assumed the flywheel is capable of rotating at 10,000 rpm with an angular velocity (\(\Omega\)) of 1047 radians per second.

Kinetic energy stored in the flywheel can be found using inertia (\(I\)) and \(\Omega\). The formula below is used to find the amount of energy that could be stored in the flywheel.

The kinetic energy (\(KE_r\)) available for use in the flywheel / rotor is:

\[
KE_r = \frac{1}{2} I \Omega^2
\]  

Note the \(\Omega^2\) angular velocity used in the kinetic energy equation above means the amount of energy stored in the spinning flywheel mass is exponentially related to the angular velocity. This relationship between energy and angular velocity is the impetus for research into higher speed flywheel designs perhaps as high as 1 million revolutions per minute to increase the amount of energy stored [2].

To increase flywheel rotational speed the use of composite materials for their construction has been proposed in the literature. One such example is a composite flywheel that achieved a rotational speed of 130,400 rpm [2].

B. Magnetic Energy Storage Formulas

This energy storing motor design will use superconducting coils in the rotor or flywheel to store SMES energy. The prototype study design shown in Figure 1 could be used to study the techniques. This prototype design will be discussed further in Section III.C.

A preliminary set of calculations was performed to determine the SMES energy storage capabilities of this motor. These calculations will use optimistic values for the current capability of the superconducting wire and the magnetic field capability of the coils. The rotor coils will be an air or vacuum core design to overcome the saturation limitations of using iron or other ferrous material. Using a coil size of 0.1 m diameter (\(d\)) and 0.2 m long (\(L\)) it was
found that 40 turns of 4 mm wide HTS wire could be wound on each layer and up to 600 layers will fit in this space. The total number of turns \((N)\) that could be wound in this coil is 24,000. Metal Oxide Technologies Inc. is working to create advanced HTS materials able to carry one million Amperes per square cm \([8]\). A value of 600 Amperes \((i)\) will be used for the current in this estimate. In addition the calculations done in Section III will be done using a rotor with twelve coils to obtain higher energy storage.

The inductance \((L_c)\) of the coil will be found from:

\[
L_c = \frac{\mu_0 N^2 \pi (d/2)^2}{L} \tag{2}
\]

The magnetic energy \((U_c)\) that can be stored in each rotor coil is:

\[
U_c = \frac{1}{2} L_c i^2 \tag{3}
\]

Magnetomotive force \((F_m)\) can be found using:

\[
F_m = i N \tag{4}
\]

Magnetic field strength \((H)\) is found using the formula:

\[
H = \frac{F_m}{L} \tag{5}
\]

The magnetic field \((B)\) is found with the following equation:

\[
B = \mu_0 H \tag{6}
\]

The total amount of energy \((KE_{tot})\) stored in this example will be the sum of the flywheel / rotor kinetic energy \((KE_r)\) and the electrical or magnetic energy \((U_c)\) stored in all twelve rotor coils.

C. Loss / Operation of Analytical and Prototype Models

The prototype study design uses mechanical bearings. A more advanced design would use HTS magnetically suspended bearings to minimize frictional losses. The greatest source of losses in this design will be from the peripheral equipment required to refrigerate and circulate coolant needed to cool the HTS materials.

The design shown in Figure 1 uses magnetic fields to transfer energy from the field to the flywheel coils similarly to a transformer. Current pulses in the Field coils will induce currents into the flywheel / rotor coils and store it there. Some losses will result from this energy transfer. Energy will also be extracted from the rotor using the field coils once again causing losses. The final source of energy loss in this design will be external to the motor in the system that converts the energy to prepare it to be used on the grid. Losses of 30% were estimated using \([3]\) as an example and adding energy transfer losses. The result is 31.1 MJ wasted energy for the analytical model. Clearly effort is needed to overcome losses.

As can be seen in Figure 2 a current pulse flows into the field coil at the top (+) and out the bottom (-) of the field coil. This will induce a current into the rotor coil as it passes by each of the five field coils during the period of excitation for that particular rotor coil. More current can be induced into the rotor coil as it passes by each field coil.

The field coil pulses will also attract the rotor coils causing it to turn.

![Figure 2: Field Coil to Rotor Coil Induction](image)

III. RESULTS AND NUMERICAL ANALYSIS

The materials, specifications, and formulas in Section II can be used to determine the energy storage. Inertial energy from the flywheel and magnetic energy from the SMES part of the design are both found using the above formulae. The total energy was found by summing the inertial energy and magnetic energy. Results of those analytical calculations are shown below.

A. Inertial Energy Stored in This Motor

Flywheel cross sectional area \((A)\) is:

\[
A = \pi \cdot (D/2)^2 = \pi \cdot (1/2)^2 = 0.785 \text{ m}^2 \tag{7}
\]

Flywheel volume \((V)\) is:

\[
V = A \cdot W = A \cdot 0.1 = 0.0785 \text{ m}^3 \tag{8}
\]

Using the density \(\rho\) of soft iron as 78.7 kg/m\(^3\) the flywheel mass \((M)\) is:

\[
M = V \cdot \rho = 618 \text{ kg} \tag{9}
\]

Inertia \((I)\) is:

\[
I = \frac{1}{2} M \cdot (D/2)^2 = \frac{1}{2} \cdot 618 \cdot (1/2)^2 = 77.25 \text{ kg} \cdot \text{m}^2 \tag{10}
\]

From (1) the Kinetic Energy is:

\[
KE_r = \frac{1}{2} \cdot 77.25 \cdot 1.047^2 = 42.36 \text{ MJ} \tag{11}
\]

The total energy that could be extracted from the flywheel / rotor is 42.36 MJ.

B. Magnetic Energy Stored in ThisMotor

Using (2) Coil Inductance is:

\[
L_c = \frac{((4\pi \cdot 10^{-7}) \cdot 24,000^2 \cdot \pi \cdot (0.1/2)^2)/0.2 = 28.4 H}{12}
\]

From (3) Magnetic energy in a single coil is:

\[
U_c = \frac{1}{2} \cdot 28.4 \cdot 600^2 = 5.116 \text{ MJ} \tag{13}
\]
From (4) Magnetomotive force is:
\[ F_m = 600 \times 24,000 = 14.4 \times 10^6 \text{ Ampere-turns} \quad (14) \]

Magnetic field strength found using (5) is:
\[ H = 14.4 \times 10^6 / 0.2 = 72 \times 10^6 \text{ A/m} \quad (15) \]

Equation (6) gives the magnetic field as:
\[ B = 4 \times \pi \times 10^{-7} \times 72 \times 10^6 = 90.5 \text{ Tesla} \quad (16) \]

### C. Total Estimated Energy Storage

Combining the energy from both storage methods, inertial and magnetic, will result in a total energy that could be stored in this motor under ideal conditions. Flywheel storage is 42.36 MJ. The total amount of energy stored in the twelve rotor coils \((U_r \cdot 12)\) would be 61.9 MJ. Therefore total energy storage is found to be 103.7 MJ. This would result in the equivalent energy of 28.8 kWh of energy and would be enough to run a 5 horsepower home air conditioning system for nearly 8 hours.

Admittedly using the two values of 600 Amperes and 90 Tesla in the magnetic energy equations may be overly optimistic. Estimates found in the literature show that MetOX 2nd Gen HTS will be capable of carrying a current of one MA / cm² [8]. The coil winding calculations above were done using insulated HTS wire with a 5 mm by 80 μm cross section. This would seem to indicate MetOX 2nd Gen HTS conductors of the same size would be capable of carrying 4000 Amperes of current.

The maximum magnetic field of 90 Tesla in the rotor coils will be extremely difficult to obtain. Based on a relationship between current flow and magnetic field in a superconductor; when either the current or magnetic field reaches a certain level the superconducting properties of the HTS material fail. At that point the superconductor becomes a regular conductor with the resistance and power dissipation associated with conductors. All energy stored in the SMES device would dissipate or quench if the superconducting property fails; perhaps with destructive consequences.

A magnetic field of 90 Tesla is extremely high for a coil or solenoid. Very high stresses will occur on the coil supporting material or bobbin, between adjacent windings, and between coil layers. Designing the coils to support the stresses associated with such a high magnetic field will be challenging. Superconducting materials can enable extremely strong magnetic fields on the order of tens to hundreds of Tesla [9]. Wejers [10] shows that superconducting magnet coils with a field of 19.81 Tesla is possible through the model developed. It is hoped that higher field superconducting magnet designs will allow greater energy storage in the near future.

Research by Rembeczki [11] shows low temperature superconducting technology limits the magnetic fields to around 22 Tesla. His work goes on to explain a method of creating force reduced solenoid designs using conductors other than superconductors and mentions a magnetic field of nearly 100 Tesla should be possible.

### D. A Prototype for Design Study

To research the properties of this SMES device a relatively economical prototype motor could be constructed with a configuration similar to that shown in Figure 1. For testing purposes a cast steel core would be used for the rotor coils. This would provide a relative permeability (\(\mu_r\)) of around 100 and allow up to a 1.9 Tesla magnetic field in each of the rotor coils. Performing calculations similar to those above and using only a single layer of HTS material with 28 turns would give a magnetic field of 1.58 Tesla. With a current of 90 A flowing through the HTS windings nearly 16 J of energy could be stored in each coil or 64 J total in all four coils.

| Type        | \(KE_r\) (MJ) @ 10,000 rpm | \(U_r\) (MJ) per coil | \(B\) (Tesla) per coil | Total Energy \(KE_{tot}\) (MJ) | Power (kWh) |
|-------------|-----------------------------|-----------------------|------------------------|-----------------------------|-------------|
| Analytical Model\(^a\) | 42.364 | 5.116 | 90.5 | 103.7 | 28.8 |
| Prototype\(^b\) | 42.364 | 15.67 | 1.58 | 42.365 | 11.8 |
| Flywheel\(^c\) | 360 | - | - | - | 100 |
| SMES\(^d\) | - | - | 25 | 2 | 20 |

This 64 J of magnetic energy in the fully charged rotor coils would only allow the flywheel to rotate at 12 rpm. In order to spin the flywheel / rotor a motor will be required in addition to the peripheral devices needed to cool the HTS windings. A review of Table 1 shows the more affordable prototype design study model’s total energy storage is little more than the energy stored in the 10,000 rpm flywheel rotor. Table 1 also lists the power storage possible in other flywheel and SMES examples cited in this paper.

Note the magnetic energy as determined by (1) for \(L_2\) and (2) for \(U_r\) are primarily governed by the \(N^2\) and \(i^2\) terms. The lower current and less number of turns in the prototype explains the much lower magnetic energy stored in the prototype design.

While not able to store significant amounts of magnetic energy the prototype design would allow the study of energy transfer to the HTS material. Validation of the concepts used to put energy into and extract energy from the rotor coil windings could be done with the prototype design. Extracting energy will be done by applying a load on the field coils. Losses involved with energy transfer can also be studied using the prototype design. The techniques used to transfer energy through the motor, although derived from common electrical machinery, could be considered unique in this application and may provide other benefits as well.

### IV. Conclusion

Two energy storage methods were researched in this design study. The first method, flywheel energy storage, was presented with three examples showing medium to
high energy storage capabilities. The second method was magnetic energy storage and analytical calculations were done showing a very high energy storage capability. The methods used in the examples cited are similar to those used for this design study. The objective of this study is to determine the feasibility of using a combination of these two methods to increase the energy storage density of the example device.

Thus far, in research for this paper no examples of energy storage using both inertial and magnetic energy storage have been discovered. The use of HTS materials in flywheel energy storage designs has been limited to magnetically levitated bearings. Likewise none of the SMES examples researched use inertial energy storage. The analytical calculations done in Section III indicate a relatively high energy density could be achieved provided the high values for magnetic field and current can be achieved. At this time we have not been able to determine how high a current and magnetic field are possible using HTS materials cooled to very low temperatures would compare to the 22 Tesla maximum field mentioned in Section III.C for low temperature superconductors.

Authors of this paper feel the combined approach of using inertial and magnetic energy storage could be of immense benefit. Now is the time to develop novel and innovative solutions to help overcome the intermittent nature of many renewable energy sources and lessen our dependence on coal, petroleum products, and nuclear energy.

REFERENCES

[1] R. B. Schainker, “Energy storage technologies & their role in renewable integration,” IEEE SF Power & Energy Society Workshop, pp. 7-14, November 15, 2010.
[2] B. Li, D. Zhou, K. Xu, S. Hara, K. Tsuzuki, M. Miki, et al., “Materials process and Applications of single grain (RE)-Ba-Cu-O bulk high-temperature superconductors,” IEEE/CSC & ESAS European Superconductivity News Forum, No. 19, pp. 11-12, January 2012.
[3] J. Haruna, K. Murai, J. Itoh, N. Yamada, Y. Hirano, T. Fujimori, T. Homma, “Experimental evaluation of a high speed flywheel for an energy cache system,” International Symposium on Global Multidisciplinary Engineering 2011 (S-GME2011), IOP Publishing, pp. 2-6, January 2012.
[4] Dr. P. McGrath, R. Hockney, “Next-generation flywheel energy storage.” ARPA-E Online, March 6, 2012 <http://arpa-e.energy.gov/?q=arpa-e-projects/next-generation-flywheel-energy-storage>.
[5] P. Tixador, “Superconducting magnetic energy storage: status and perspective.” IEE/CSC & ESAS European Superconductivity News Forum, No. 3, pp. 9, January 2008.
[6] D. Hazeltone, “2G HTS conductor development at SuperPower for magnet applications,” SuperPower Inc. 2013 Spring MRS Meeting, San Francisco CA., pp. 22-23, April 2, 2013.
[7] SuperPower Inc., “Superconducting magnetic energy storage (SMES),” SuperPower Incorporated and ARPA-E, <http://www.superpower-inc.com/content/superconducting-magnetic-energy-storage-smes>.
[8] “High temperature superconducting wire (2nd generation HTS wire),” Center for Advanced Materials, University of Houston, and Metal Oxide Technologies Inc.
[9] P. Parfomak, “Energy storage for power grids and electric transportation: a technology assessment,” Congressional Research Service, 7-5700, R42455, pp. 132, March 27, 2012.
[10] H. Weijers, “High-temperature superconducting magnet cables reach a record current at a magnetic field of 20 T,” Mag Lab Reports, Vol. 19, No. 1, pp. 9, Spring 2012.
[11] S. Rembeczki, “Design and optimization of force-reduced high field magnets,” Florida Institute of Technology, pp. 11, pp 119, May 2009.