DESIGN AND ANALYSIS OF FLYWHEEL ENERGY STORAGE SYSTEM WITH DIESEL ENGINE

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Abstract: Energy can be stored in the form of chemical, thermal, electromagnetic and mechanical form. The applications of mechanical energy storage devices include compressed gas facilities, pumped hydroelectric storage and flywheels. A flywheel stores energy in the form of kinetic (rotational) energy. Whereas each energy storage system has its inherent advantages and disadvantages compared to the others, it is the overall system performance and simplicity of flywheels that make them especially attractive for a variety of applications. This thesis is based on Design simulation and analysis of dynamic UPS with diesel engine & flywheel. The UPS is composed of an AC/DC rectifier, a DC/AC inverter, a permanent magnet brushless DC motor, a motor converter and a flywheel energy storage unit. Firstly, main power circuit of the UPS and its flywheel energy storage unit are introduced. Then the control strategies of the flywheel charging, discharging and DC/AC converter are discussed in detail. In charging mode, the AC/DC rectifier and motor converter are used for brushless DC motor driver. In discharging mode, motor converter is for boosting the dc link voltage. In both modes, UPS can work in on-line or off-line mode. The flywheel energy storage unit, which takes place of the conventional chemical battery unit, has the advantages of free maintenance, long life and no pollution. Finally the experiment results testify the Dynamics UPS has better character and dynamical response.

Keywords: Diesel rotary UPS, Flywheel energy storage, Kinetic Energy, rotary UPS.

I. INTRODUCTION

Efficient regenerative energy storage is one of the great technical challenges of our time. Energy can be stored in the form of chemical, thermal, electromagnetic and mechanical form. Applications of mechanical energy storage devices include compressed gas facilities, pumped hydroelectric storage and flywheels. A flywheel stores energy in the form of kinetic (rotational) energy. Whereas each energy storage system has its inherent advantages and disadvantages compared to the others, it is the overall system performance and simplicity of flywheels that make them especially attractive for a variety of applications. With the introduction of frictionless magnetic bearings, the efficiency of flywheels for energy storage could be increased to an economically useful level. The main drawback of active magnetic bearings is the elaborate control system which is required to keep them operational. Increasing the reliability and reducing the complexity and cost of the system are still points of major concern in the field. For applications which are exceptionally critical concerning friction, such as flywheel systems for regenerative energy storage, active control is unwanted, because it contributes to intrinsic bearing drag. The Flywheel also act as a buffer against power spikes and sags, since such short-term power event snot able to appreciably affect the rotational speed of the high-mass Flywheel, Flywheel-based UPS systems typically provide 10 to 20 seconds of protection before the Flywheel has slowed and power output stops. [3]. An important task for the Flywheel design is to determine power and energy storage requirements and the location of the storage device [13]. In this paper simulation investigation relating to static UPS and rotary UPS system is discussed with eddy current coupling and Flywheel model and the results have been reported.

II. FLYWHEEL DYNAMIC UPS SYSTEM

The consideration flywheel Dynamic UPS System is illustrated in fig. 3.23Schematically, it consists of:

- An isolating choke (of high inductance value) between the supply side and the load side.
- A synchronous machine connected on the load side of the above choke through a MV/LV transformer, depending on the system, a small coupling inductance may also be connected in series on the feeder between the connections point of the synchronous machine and the load side.
- A kinetic energy storage system, this may be a flywheel, or a special a synchronous machine with a very heavy rotor or whatever type of system able to store kinetic energy and to restitute whenever needed.
- Finally a diesel engine that provides the required mechanical power in the case of long duration power cut or any detecting fault condition, power is provided to the load.

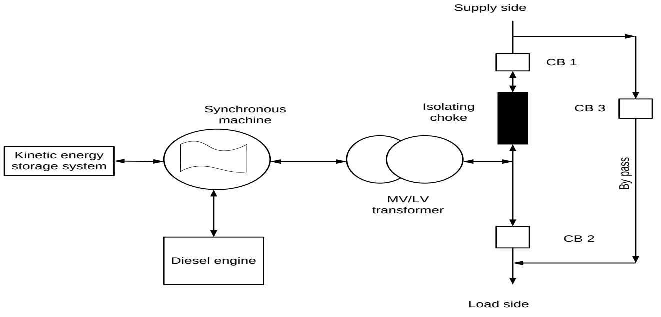

Fig. 1 Flywheel Dynamic UPS System

In fig. 1 normal operating condition, circuit breaker CB1 and CB2 are closed and CB3 is open. The power supply is provided by the HV network through the HV/LV substation and the isolating chock. In case of disturbance on the supply side (limited voltage dips or very short power cuts), the voltage and frequency on a HQ feeder are regulated by the dynamic flywheel UPS system. When severe voltage dips or power cut occur on the supply side, CV1 opens. The UPS system is disconnected from the main network and operates in islanded condition on its HQ feeder. For the first few second, the mechanical power is supplied to the UPS synchronous machine by the kinetic energy storage system. Depending upon the configuration chosen by the manufacturer, the diesel engine is then started and progressively pickup the load. A part of produced power is used to reconstitute the kinetic energy reserve. After the disturbance has disappeared, the UPS system synchronizes itself with the supply side and then reconnects to the main network (CB1 closes).

III. MATHMATICAL MODULATION

A. 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.

B. Wheel Shape

The goal when designing the shape of a flywheel is to accomplish a uniformly distributed stress over the entire wheel, 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. Kress implemented a two dimensional Finite Element Method (FEM). 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 radically look like Fig.4.1. 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."

C. 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.

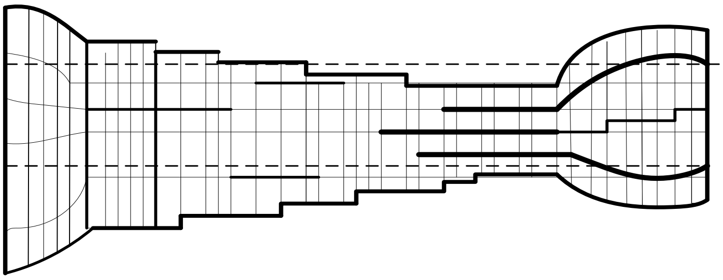

Fig. 2 Size of flywheel

Carbon composites have the greatest specific energy storing capacity due to its high specific strength. 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. 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.

IV. FES MODELING AND SIMULATION TOOL

A. Overview of the FES Simulation Tool

The simulation tool is developed in the MATLAB/SIMULINK® environment with a user friendly GUI. Several commercially available flywheels have been modeled as a part of the proposed FES simulation tool. Users have two choices for FES simulation, either to use commercial FES models in the developed flywheel library or to customize their own FES. Fig.4 illustrates the generic block diagram of the FES model developed in MATLAB/SIMULINK®. As shown, the FES model is composed of two subsystems, namely the flywheel subsystem and the generator/motor subsystem. Inputs to the FES simulation tool are: voltage and current measurements at the load bus which are the signal to control flywheel power output. For a customized flywheel model, additional flywheel characteristics are required as user-defined inputs, including flywheel maximum and minimum rotating speeds (rad/sec), power capacity (kW), energy capacity (kW*sec), efficiency, charging duration, discharge duration at maximum power (sec), and discharge duration at half of maximum power (sec). Outputs of this model are the flywheel power output (kW), energy output (kW-sec) and rotating speed (rad/sec).

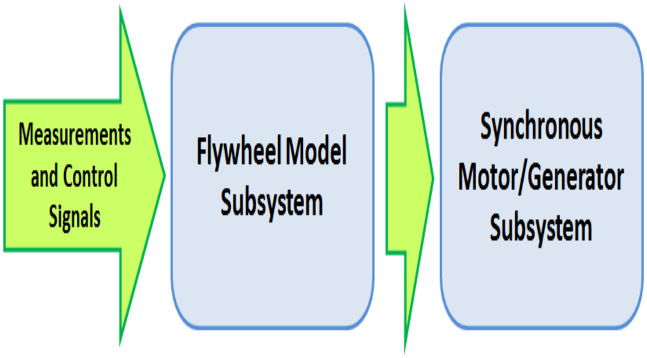

Fig.3. Generic block diagram of the proposed FES model in MATLAB/SIMULINK.

B. The Flywheel Subsystem

The typical discharge time of a flywheel ranges from 10 to 30 seconds [27]-[29]. Flywheel charging from the totally discharged point to the totally charged point needs 1 to 10 minutes, depending on FES technologies and manufacturer designs [29]- [30]. The control of FES is based on the balance of power supply and demand. If the available power is more than the load, flywheel starts charging to absorb the excess power. During a utility disturbance or lack of power, the flywheel is discharged to handle critical loads. Then, after diesel generators start and the system voltage and frequency are stabilized (ramp-in time), flywheels are recharged from the diesel generators. Fig.4 depicts flywheel charging and discharging cycles.

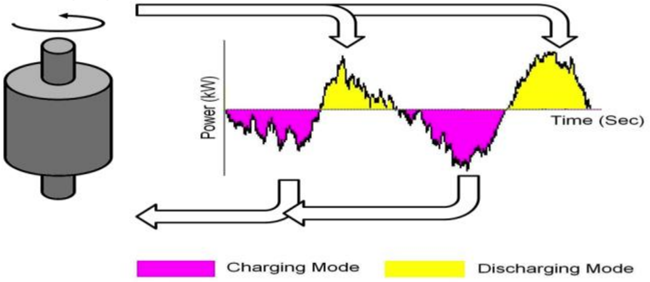

Fig. 4. Flywheel control signal for charging and discharging modes.

The flywheel subsystem consists of the discharge and charge sections. The exponential function shown in is the basis for the calculating the charging and discharging power. Fig. 5 and Fig. 6represent the implementation of power discharging and charging functions, respectively, in the MATLAB/SIMULINK® environment. The discharging section consists of the mathematical function in and a switch that is controlled by the external signal from the load bus. The discharging of FES is activated when the voltage and current measurements on the load bus indicate shortage of power.

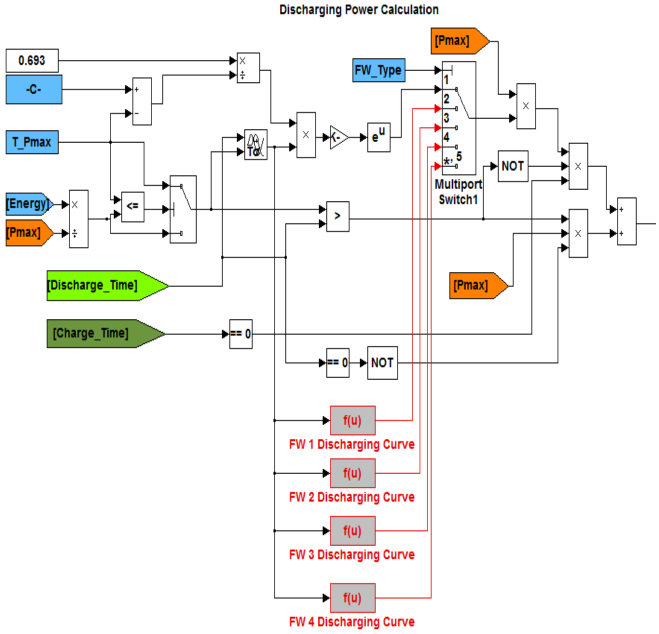

Fig. 5 Discharging section of the flywheel model.

The charging power calculation is presented in Fig.6 this part of the model consists of the mathematical function and a switch that is controlled by the signal from the load bus. The charging of FES is activated when the voltage and current measurements on the load bus indicate excess power.

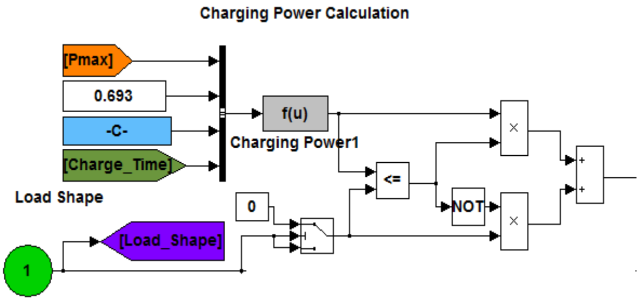

Fig. 6. Charging section of the flywheel model.

C. Motor Generator Subsystem

Different types of electric machines can be used in an FES. The most common types are induction machines [31], and permanent magnet synchronous machines (PMSM) [32]. In this paper PMSM is used for the FES model. To model the motor-generator subsystem of the FES in MATLAB/SIMULINK®, the synchronous machine (SM) excitation system is performed by the standard excitation block provided in the MATLAB/SIMULINK® library. The model of diesel engine is presented in Fig. 7.

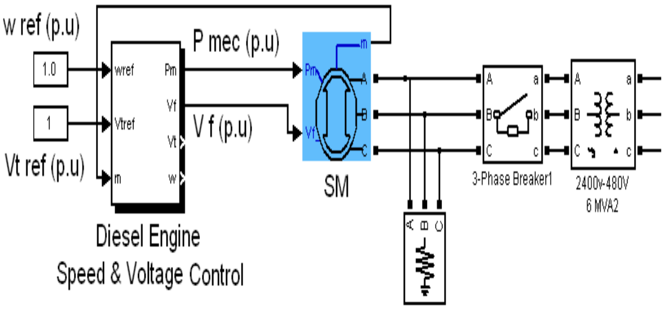

Fig. 7. MATLAB/SIMULINK model of a synchronous motor/generator unit.

D. FES Simulation Results and Model Validation

To validate the proposed FES model, authors have developed four flywheel models of different sizes, following the specifications of four commercial flywheels available from different manufacturers: (i) a 120kW flywheel unit, (ii) a 150kW flywheel unit, (iii) a 160kW flywheel unit, and (vi) a 250kW flywheel unit. The model outputs are compared with the manufacturers' data as presented in Fig. 6. The dashed lines are the manufacturers' data, while the solid lines are the simulation results. Fig. 9 indicates that simulation results are consistent with the flywheel's experimental data from the manufacturers. These four flywheel units are built-in into the flywheel library as mentioned earlier. Based on (11), flywheel discharging has two operation regions. In the first region, output power is constant. In the second region, output power has exponential decreasing trend.

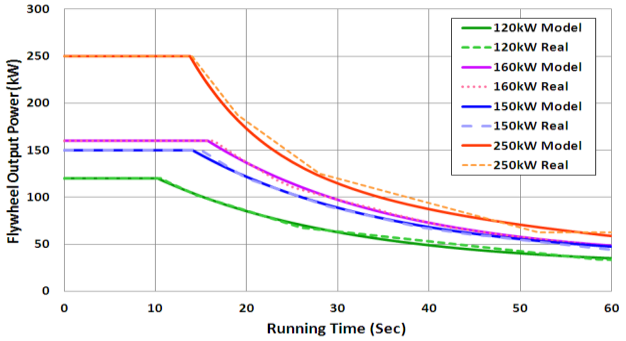

Fig.8. Flywheel discharging characteristics for four different flywheel units.

Each flywheel unit has a specific running time. If there is a need for a longer running time, more flywheel units can be paralleled. The tool developed and presented in this paper also helps the user to find a sufficient number of flywheels for a specific running time. The tool can demonstrate the output of multiple flywheel units connected in parallel. It calculates the running time for each case. Fig.9 illustrates how additional flywheels in parallel can meet the load for a longer time. In this case, to achieve 750 kW power for 20 seconds, at least three 250 kW flywheels should be paralleled. Four 250 kW flywheels can serve the 750 kW load for 33.4 seconds.

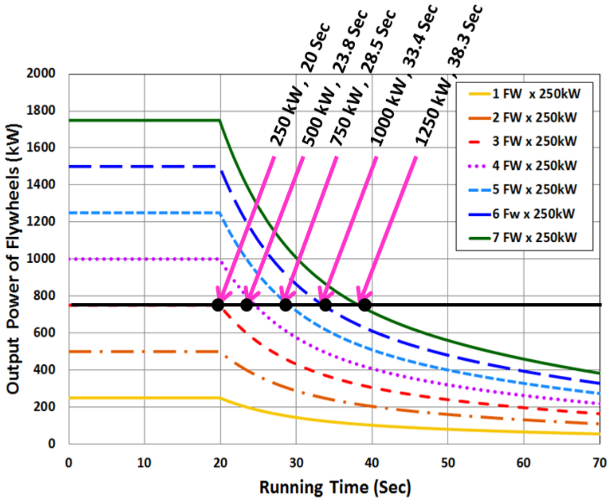

Fig 9. Different running times for different numbers of 250 kW flywheel units connected in parallel.

V. SIMULATION RESULTS

Fig. 10 illustrates the simulation results, showing the operation of the flywheels and the diesel generator when a utility outage occurs at t=0 sec. The solid line is the total load of the system (kW) and the dashed line is the diesel generator power output (kW). At the time of the power outage (t=0), flywheels operate to provide ride-through capability for the critical loads (750kW). Since the outage is longer than 5 seconds, the diesel generator starts (t=5 sec). After the diesel generator has synchronized with the system (t=17 sec), the rest of the data center loads are served, and the flywheel changes from its discharging mode to its charging mode.

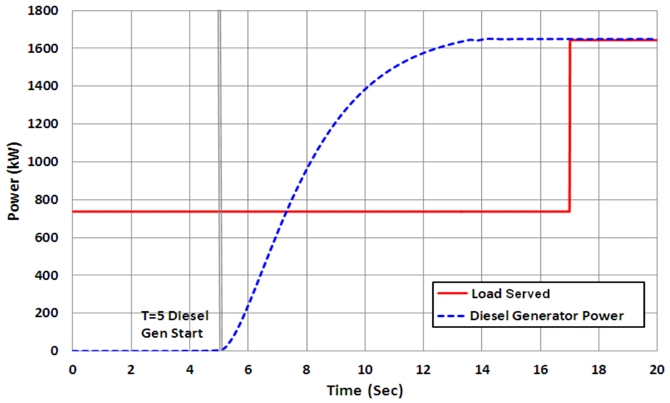

Fig. 10. Snapshot of electrical power (kW) at the load bus after the outage.

At this time, the load served (the solid line) is the total data center load plus the flywheel charging. The generator output (dashed line) matches both the data center load and the flywheel charging load. Once the flywheel is fully charged (t > 190 sec – not shown), the diesel generator output will decrease to the total data center load level.

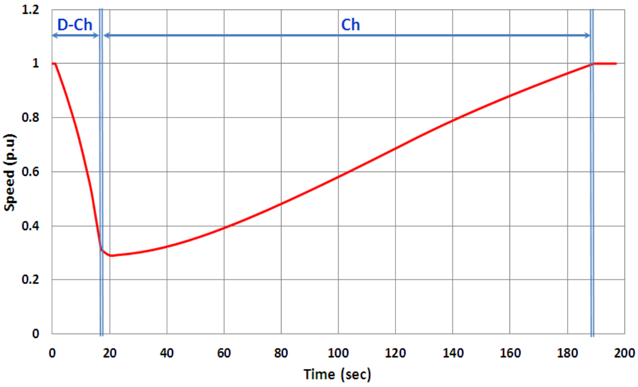

Fig. 11. Flywheel speed during charging and discharging periods: D-Ch and Ch indicate flywheel discharging and charging periods, respectively.

Fig. 11 shows the flywheel speed during its operation. During the first 5 seconds, the flywheels discharge to serve the critical loads and the flywheels' speed decreases. The system waits for 5 seconds to confirm that it is the real power outage before starting the diesel generator. Once the generator starts at t=5 sec, it takes some time – as shown in the simulation results – before it can fully synchronize with the system and serve the loads at t=17 sec. After picking up the loads, the generator charges the flywheels until t=190 sec. The flywheels charging time is in accordance with the charging range, 2-3 minutes, indicated by the flywheel manufacturer [36]. During the charge period, the flywheels speed increases, as indicated in Fig. 10. In addition to providing continuous power supply, flywheels also stabilize the frequency at the load bus. Fig. 11 presents frequency deviation at the load bus during the simulation. The solid line represents frequency response of the system with flywheels. The dashed line shows frequency response of the diesel generator after it starts at t=5 sec. Note that the frequency is stabilized at around t=16 sec before the diesel generator synchronizes with the system at t=17 sec.

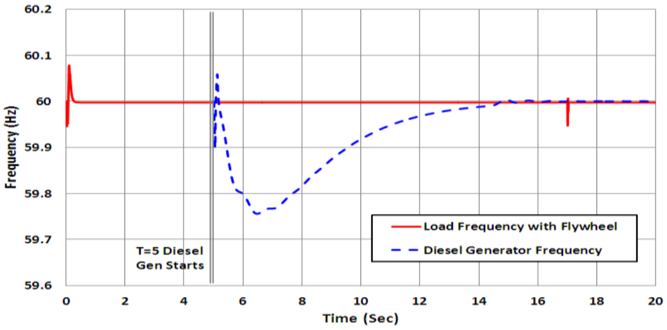

Fig. 12. The frequency deviations after the power outage with flywheels (solid) and without flywheels (dashed).

Fig. 12 indicates that flywheels can significantly decrease the system frequency deviation. During its startup (t=5-17 sec), the generator frequency goes down as low as 59.75 Hz. This results in the system frequency deviation of 0.25 Hz from the nominal frequency of 60Hz. With the flywheels, the maximum frequency deviation decreases to 0.06 Hz. This deviation meets the maximum allowable frequency deviation for sensitive loads of 0.12 Hz or 0.2% of the normal frequency [37].

VI. CONCLUSIONS

This paper presented a tool for modeling and simulation of a flywheel energy storage (FES) system in a micro grid environment. The FES model was validated by comparing simulation results with manufacturer supplied data. To demonstrate the use of the developed FES model, a case study of a facility micro grid based on a data center application was presented. This study showed the operation of the FES coupled with a diesel generator to serve the data center's critical loads during a utility outage. Results indicated that the FES, coupled with the generator, can deliver secure and resilient power to support critical loads during a utility outage. Since FES applications to provide power security and resiliency for a mission-critical facility are new on the horizon, there is a lack of experimental data for use in micro grid studies. The proposed software tool bridges this gap by enabling facility engineers and system designers to run several what-if analysis scenarios -- that is, to analyze the operation of a facility micro grid with the incorporation of a FES system coupled with traditional fuel-based generators as a backup power source.

REFERENCES

[1] J. Hayes," Data Center 2020", IET Magazine Engineering and Technology, pp: 54-57, Nov 7 2009.
[2] D. Hart, "Using AMI to realize the Smart Grid," in Proc. Power Energy Society General Meeting, Pittsburg, PA, 2008, pp. 1–2.
[3] F. Rahimi and A. Ipakchi, "Demand response as a market resource under the smart grid paradigm," IEEE Trans. Smart Grid, vol. 1, no. 1, pp. 82–88, Jun. 2010.
[4] F. Alvarez and H. Rudnick "Impact of energy efficiency incentives on electricity distribution companies," IEEE Trans on Power Systems, vol. 25, no. 4, pp. 1865–1872, Nov. 2010.
[5] L. An Thanh, "New UPS System Configuration that Will Improve Energy Efficiency," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, Issue: 4, pp. 829 – 834, 1985.
[6] R. Billinton, "Evaluation of Different Operating Strategies in Small Stand-Alone Power Systems," IEEE Transactions on Energy Conversion, Vol. 20 , Issue: 3, pp. 654 – 660, 2005.
[7] M. Ross, R. Hidalgo, C. Abbey, G. Jo s, "Energy storage system scheduling for an isolated microgrid," IET Renewable Power Generation, Vol. 5, Issue: 2, pp. 117 – 123, 2011.
[8] S. Samineni, B. K. Johnson, H. L. Hess, J. D. Law, "Modeling and analysis of a flywheel energy storage system for Voltage sag correction", IEEE Transactions on Industry Applications, Vol. 42, Issue 1, pp. 42 – 52, Jan.-Feb. 2006.
[9] Long Zhou, Zhi ping Qi, "Modeling and control of a flywheel energy storage system for uninterruptible power supply", in Proc. International Conference on Sustainable Power Generation and Supply, 2009, pp. 1 – 6.
[10] A. Rajapakshe, U. K. Madawala, D. Muthumani, "A model for a fly-wheel driven by a grid connected Switch Reluctance Machine", IEEE International Conference on Sustainable Energy Technologies, ICSET 2008, Singapore, 2008, pp. 1025 - 1030.
[11] T. T. Leung, "Concept of a modified flywheel for mega joule storage and pulse conditioning ", IEEE Transactions on Magnetics, Vol. 27, Issue 1, pp. 403 – 408, Jan 1991.
[12] M. Ahrens, L. Kucera, R. Larsonneur, "Performance of a magnetically suspended flywheel energy storage device", IEEE Transactions on Control Systems Technology, Vol. 4, Issue 5, pp: 494 – 502, Sept. 1996.
[13] R. F. Thelen, A. Gattozzi, D. Wardell, A. Williams, "A 2-MW Motor And ARCP Drive for High-Speed Flywheel", in Proc Applied Power Electronics Conference, IEEE APEC 2007, Anaheim, CA, 2007 , pp. 1690 – 1694.
[14] R. T. Doucette, M. D. McCulloch, "A comparison of high-speed flywheels, batteries, and ultra capacitors on the bases of cost and fuel economy as the energy storage system in a fuel cell based hybrid electric vehicle," Journal of Power Sources, Vol. 196, Issue 3, pp. 1163-1170, 1 February 2011.
[15] (2008), "Flywheel vs. battery for medical center IT infrastructure," Mazzetti Nash Lipsy Burch Company, San Francisco, CA, [Online] available: www.mazzetti.com/images/uploads/Flywheel_UPS.pdf
[16] "Reliability Assessment of Integrated Flywheel UPS vs. Double Conversion UPS with Batteries," Active Power Inc., Austin, TX, White paper # 103, 2008.

[17] M. Zackrisson, L. Avellán, J. Orlenius , “Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues ,” Journal of Cleaner Production, Vol. 18, Issue 15, pp. 1519-1529, November 2010.
[18] “Cost Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant,” Technical Report, Beacon Power Corporation, Tyngsboro, MA, KEMA Project: BPCC.0003.002, September 2007.
[19] “Flywheel Energy Storage,” Federal Technological Alert, Department of Energy, Washington, D.C, Document number: DOE/EE-0286, September 2003.
[20] “2020 Strategic Analysis of Energy storage in California,” Public Interest Energy research (PIER) Program, Final Project report, California energy Commission, Sacramento, CA, Document number: CEC-500-2011-047, November 2011.
[21] M. Olsen, “15 Seconds vs. 15 Minutes”, NewsLink, The international magazine of 7x24 Exchange, pp: 16-17, spring 2008.
[22] “Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and recommended R&D strategy”, Technical Report, CCLRC-Rutherford Appleton Laboratory, Didcot, U.K, Storage Technology Report, ST6: Flywheel, 2003.
[23] “Understanding Flywheel Energy Storage: Does High Speed Really Imply a Better Design?”, Technical Report, Active power Inc., Austin, TX, white papers no 112, 2008.
[24] T. Siostrzonek, A. Penczek, S. Pirog,“ The control and structure of the power electronic system supplying the Flywheel Energy Storage (FESin Proc. 2007 European Conference on Power Electronics and Applications, Aalborg, Denmark, 2007, pp. 1-6.
[25] E. R. Furlong, W. Wiltsch, (2010), “Performance and Operational Characteristics of an Advanced Power System,” Electrical Maintenance Handbook, Vol 10, The electricity forum publisher, Geneva, NY, [online]. Available: http://www.meisterintl.com/PDFs/Electrical-Maintenance-Handbook-Vol-10.pdf.
[26] R. S. Weissbach, G. G. Karady, R. G. Farmer, “A combined uninterruptible power supply and dynamic voltage compensator using a flywheel energy storage system”, IEEE Transactions on Power Delivery, Volume 16, Issue 2, pp: 265 - 270, April 2001.
[27] S. Eckroad,“Flywheels for electric utility energy storage,” Technical Report, Electric Power Research Institute, Palo Alto, CA, EPRI report TR-108889, Dec 1999.
[28] (2011) ” UNIBLOCK UBR - Hybrid Rotary UPS from 150 kVA up to 1300 kVA”, Piller UPS Company, Osterode, Germany [Online]. Available: http://www.piller.com/site/dynamic/uniblockr.asp?nav_id=132.
[29] (2005) “Technical data sheet, UNIBLOCK UBT 1300”, Piller Company, Osterode, Germany [Online]. Available: www.cmbuck.com/images/PowerDivision/Piller/ubt_pb_1300_16mj.pdf
[30] I. Alan, T. Lipo, S. Sanders, “Induction machine based flywheel energy storage system,” IEEE Transactions on Aerospace and Electronic Systems, vol. 39, no. 1, pp: 151–163,2003.
[31] H. Hofmann, “High-Speed Synchronous Reluctance Machine for Flywheel Applications”, PhD thesis, University of California, Berkeley, 1998, pp.65-67.
[32] (2012), “Data Centers Specifications,” VAZATA Solutions, Plano, TX [Online]. Available: http://vazata.com/VirginiaOneDataCenter.aspx.
[33] “IEEE Std 493-2007”, Revision of IEEE Std 493-1997, IEEE, New York City, NY, 2007 , pp: 188 – 189.
[34] C. Rubens,(Sep 2008), “Flywheels Keep Data Centers Flying”, GigaOM webpage [Online]. Available: http://gigaom.com/cleantech/flywheels-keep-data-centers-flying/.
[35] (2012), “Unimatic PMS system”, DEIF Company, Skive, Denmark, Specification Sheet Ref Number 4189340188C, [Online]. Available: http://www.deif.com/Files/Filer/Documentation/Files/4189340188.pdf?typename=Unimatic&nav2_selector_dd.
[36] (2009), “Active Power, Cleans Source 250-2000kW datasheet”, Active Power Inc, Austin, TX [Online]. Available: http://www.activepower.com.
[37] (2008), “Caterpillar UPS 300 Series datasheet, Single Module Systems 60 Hz”, Caterpillar Company, Peoria, IL [Online]. Available: http://www.cat.com/cda/files/254634/7/LEHE4948-02%28P1%29.pdf.