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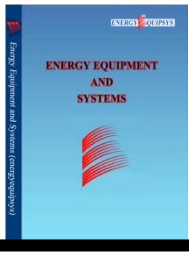

Review, Analysis and Simulation of Different Structures for Hybrid Electric Energy Storage

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ABSTRACT

Output power in a hybrid power system is constant while the input power with variable characteristics that is generated by different sources. Using Hybrid Electric Energy Storage (HEES) systems, is growing rapidly since there is an obvious need for clean energy. This paper introduces different parts of a HEES system and then proposes HEES systems which employ battery, ultracapacitor and flywheel as main energy storage devices. The behavior of a hybrid electric energy storage including battery as the main energy storage device and a diesel generator as auxiliary energy source, also battery/flywheel and battery/ultracapacitor hybrid energy storage system with purpose of supplying load with constant power is analyzed. Results of the simulation show how well ultracapacitor and flywheel can replace battery in maintaining the load with continuous power.

Keywords: Hybrid Source, Energy Storage, Battery, Ultracapacitor, Flywheel.

1. Introduction

Continuous and reliable power supply situations are vital for power systems. Sometimes, unwanted outages or using an energy source with low reliability can be harmful for consumer's power quality. Due to incremental fuel cost, shortage of reliability in power sources, increasing demand and harmful effects of fossil fuels on environment, renewable energy has found a better place in industry [1], [2]. Wind farms and photovoltaic arrays power generated is a function of different parameters such as radiation intensity, temperature and wind speed that makes the system to be variable in nature [3]. Combining renewable energy sources with fossil fuels can lower this variable nature of renewable resources to achieve a controllable power supply [4].

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Main parts of an HEES system are energy storage devices and energy sources. For example ref [5] introduces a system consisting of energy devices such as Engine–Generator/Battery/Ultracapacitor and concentrates on energy management of the system. Many researches have used fuel cells along with other storage devices [6]–[9]. Most of the efforts have been done on the control and energy management of such systems.

HEES benefits from economic properties as well as energy saving characteristics. Many researchers have gone into these aspects of HEES systems and investigated the economic side of using such system [10], [11]. In this paper modelling and operation of HEES are carried out. The paper is organized as follows: In section 2 main purposes and scientific justification of using HEES systems are investigated. In section 3 different sections of a HEES are introduced and advantages and deficits of them are analyzed. This section is based on main renewable energy sources such as solar cells and wind turbines and also devices for saving energy including battery, ultracapacitor and flywheel and also their characteristics are compared in order to use a proper device for any specific application. In section 4 principals of hybridization of energy devices are investigated and trending models are introduced. Finally in section 5 simulation of two HEES systems, including battery/ultracapacitor and battery/flywheel systems validates the proposed designs for such systems.

2. Purposes of hybrid electric energy systems (HEES)

The main purpose of a HEES system is to achieve a controlled output power while input energy sources happen to be variable in nature. To increase the availability of hybrid energy sources, using auxiliary power sources such as diesel generator and fuel cell would be possible. Figure 1 shows a hybrid system in which a renewable energy source works with energy storage to supply the load. Power electronic interface (such as DC-DC converters) must control the current between load and energy source and output power [12]. This type of converters is designed to work in maximum ranges of power that lead to high cost and complexity of the system.

HEES is a system that consists of multiple energy sources or different devices for storing energy. For example the main source can be made of a wind turbine, photovoltaic or a DC electric source where storage devices can be battery, flywheel or ultracapacitor. Using a HEES can decrease the cost of consumed energy; also increase the reliability and controllability of the system. For example, a wind/photovoltaic hybrid energy system can be a good option for isolated places [13] however sometimes supplying the power from main network is more economic due to high costs of required equipment or administrative costs [14].

A number of studies and simulations have been carried out that show the comparative costs of renewable energy systems as well as their competitiveness with conventional energy options, including diesel based power systems and the extension to the grid, as shown in Figs. 2 and 3 [15]. It can be observed that total cost for a hybrid system is less than diesel systems for more than 5 years and 4 years in Tanzania and India respectively; meaning using hybrid systems is more economically for long terms. It also can be seen that investment cost is decreased if PV panels are used instead of public grids for short distances.

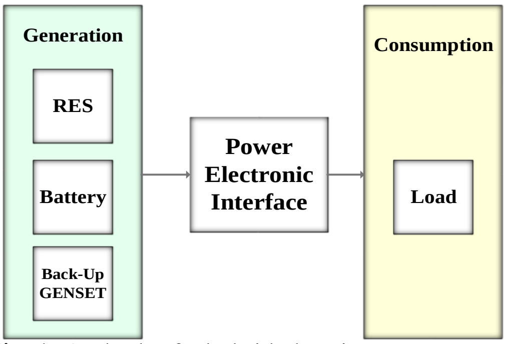

Fig. 1. Outlook of a hybrid electric energy system

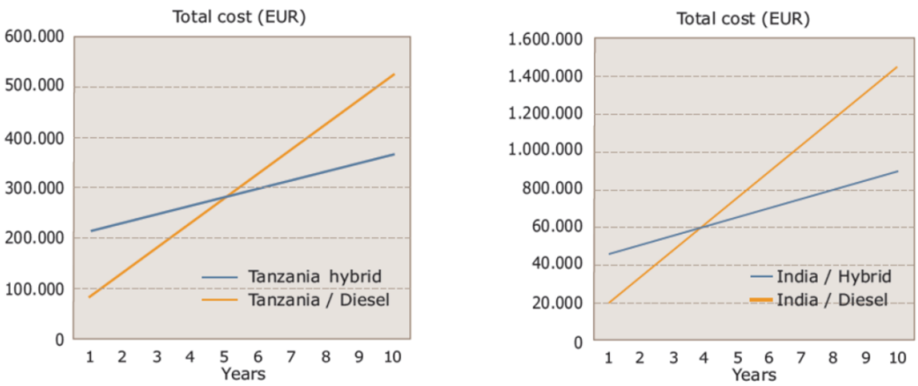

Fig.1. Economical comparison of diesel vs. hybrid systems in Tanzania and India (life cycle costs)

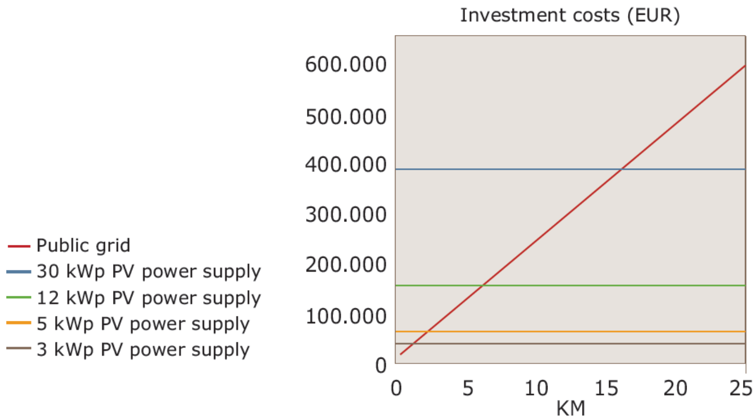

Fig.2. Economical comparison of grid extension vs. hybrid systems (investment costs)

Hybrid energy sources can play an important role in power systems with advantages like:

- Spinning reserve, for instant support of the generation unit, unifies load profile and avoids the system from effects caused by dynamic responses of the generation unit.
- Voltage regulation for generation units which are off-grid
- Frequency stability
- Procrastination capacity of an installing generation unit

3.Hybrid electric energy storage system parts

3.1. Renewable energy sources

Renewable energy resources are the main sources of clean energy which can be utilized in hybrid energy systems. Continuous energy can be supplied by a renewable energy source and also stored in an energy storage device such as battery and ultracapacitor. The role of renewable energy source is to provide the system with clean energy to supply the load or to be stored in storage system.

3.1.1. Wind energy

In 2010, global rated capacity of electric power generated by wind turbines was 197 GW. Nowadays, this capacity is 430 TW that is equal to 2.5% of the total global energy consumed by people [16]. Power generation capacity of the wind turbines in the world is 73904 MW where European Union generates 65% of the total generated energy in the world. Generated wind power had the most development among all other technologies in 21th century that generation of power by wind has grown four times between the years of 2000 and 2006 [17]. In a system based on wind power, there must be an appropriate energy storage device. Flywheels are the best options in most cases to absorb the wind power. Figure 4 shows a wind turbine utilizing an energy storage device [18].

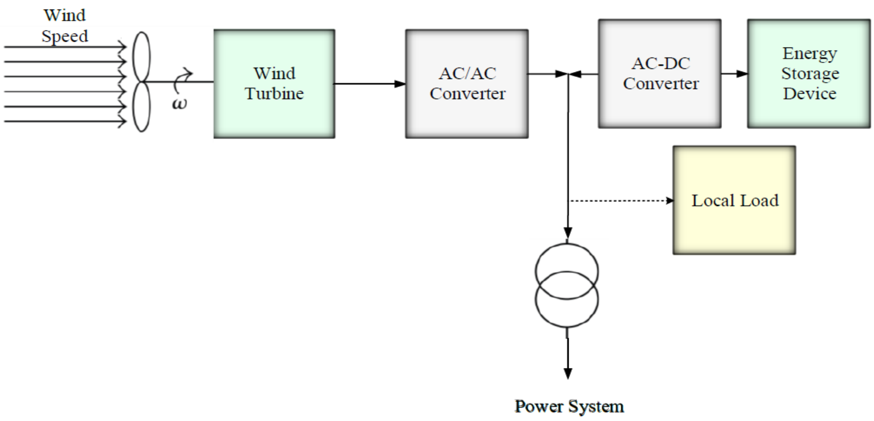

Fig.3. A wind turbine utilizing energy storage device

3.1.2. Photovoltaic energy

According to international standards, using solar energy is one the best ways of generating power and transferring it to isolated places and villages compared to other current technologies. If the average value of solar energy radiation is higher than 3.5 kWh/m2, using solar energy modules such as photovoltaic systems will be economic to supply the system's energy [19]. Photovoltaic arrays can also be used along with wind turbines [20]. Figure 5 shows a hybrid system utilizing photovoltaic arrays and wind farm to supply the load [21]. In this system both AC and DC loads are supplied via wind and photovoltaic arrays and also these energy resources are able to help each other.

3.2 Energy storage devices

Thermal energy, compressed air energy, hydro pump, chemical battery, ultracapacitor, magnetic super conductor, flywheel and fuel cell are the most important technologies for storing energy. Performance indexes of an energy storage system are including main costs, cycle efficiency, life cycle, self-discharging rate, power density and energy density [22]. The role of these systems in HEES is to store the energy provided either by a renewable energy source or by any other kind of fossil fuel.

3.2.1. Chemical Battery

Batteries possess some preponderance such as high energy density, low rate of self-discharging, low cost, long lifetime and some deficiencies including low power density and high relativity to temperature. A vital parameter that can affect the lifetime of batteries is the way that they are charged [22]. Figure 6 shows equivalent circuits for a battery that are proposed in literature.

Table 1 compares four different models for chemical battery presented in Fig. 6. The dynamic model has the best overall performance over other models. This model [23] is capable of forecasting voltage-current characteristics of battery under transient conditions.

The model shown in Fig. 6d is fully dynamic and its conditions are based on SOC that is calculated according to Eq. (1):

$$SOC = SOC_{initial} + \frac{1}{C}\int i(t) \quad (1)$$

In which SOCinitial is battery's initial SOC, C is battery nominal capacity and i(t) indicates battery charging current. Other parameters of battery are based on SOC and for a Polymer Lithium-Ion type battery calculated according to Eqs. (2) – (7).

$$V_{OC}(SOC) = -1.031e^{-35.SOC} + 3.685 + 0.2156.SOC - 0.1178.SOC^2 + 0.3201.SOC^3 \quad (2)$$

$$R_{Series}(SOC) = 0.1562e^{-24.37SOC} + 0.07446 \quad (3)$$

$$R_{Transient\_s}(SOC) = 0.3208e^{-29.14SOC} + 0.04669 \quad (4)$$

$$C_{Transient\_s}(SOC) = -752.9e^{-13.51SOC} + 703.6 \quad (5)$$

$$R_{Transient\_L}(SOC) = 6.603e^{-155.2SOC} + 0.04984 \quad (6)$$

$$C_{Transient\_L}(SOC) = -6056e^{-27.12SOC} + 4475 \quad (7)$$

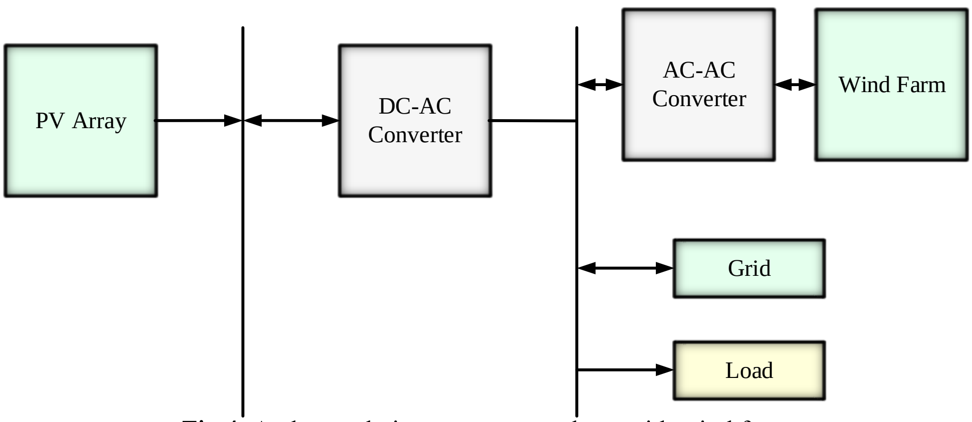

Fig.4. A photovoltaic array system along with wind farm

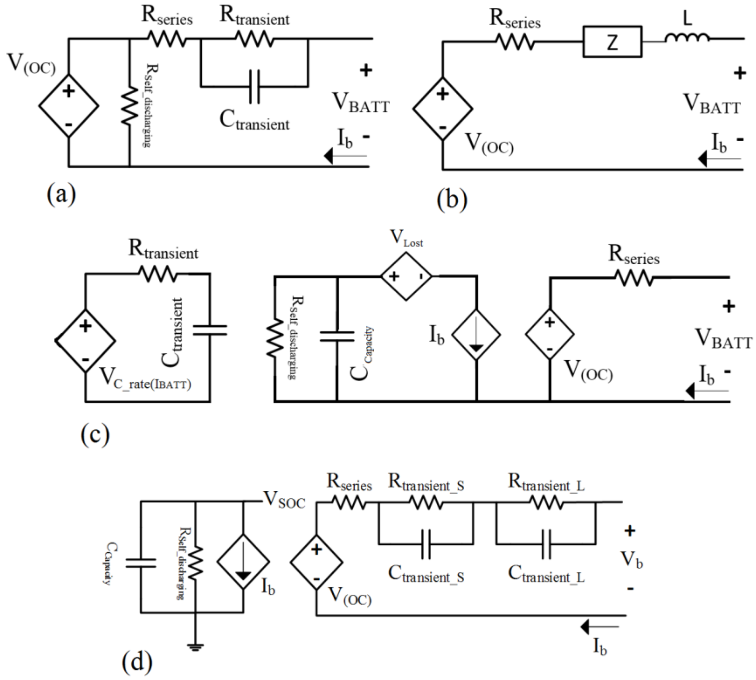

Fig. 5. Equivalent circuit of battery: a) Thévenin model, b) Impedance based model, c) Runtime-based model d) Dynamic model

Table 1. Comparison of three model of chemical battery

Prediction Capability	**Thavnan model**	**Impdance based model**	**Runtime based model**	**Dynamic model**
DC	No	No	Yes	Yes
AC	Limited	Yes	No	Yes
Transients	Yes	Limited	Limited	Yes
Runtime	No	No	Yes	Yes

3.2.2. Flywheel

Flywheels are unique among the energy storage devices because of their ability to supply very high power. In fact, the rate at which energy can be recharged into or drawn out of the flywheels is limited only by the motor-generator design that can be very high [24]. The main advantage of a flywheel is that it can store a high mass of energy in a very short period of time, an aspect which batteries lack. Therefore if flywheel is taken into account in a HEES along with battery, system's efficiency and performance can be dramatically increased. Figure 7 shows an electromagnetic relationship model of flywheel [25].

Flywheel has to work as a device that response quickly. Flywheel is able to work 2 to 5 times of its rated power in short operations. Since there is a need that there must be an acceleration and deceleration in a short period, controlling the torque and minimizing the losses and axial-force stress are very important. The rotational energy stored in the flywheel is defined as:

$$E_{(rot)} = \frac{1}{2} I \omega^2 \tag{8}$$

where I is the moment of inertia that is directly proportional to the mass of the rotor as a constant that depends on the shape factor of the device. ω is the angular velocity. For a cylinder flywheel, the moment of inertia is dominated by:

$$I = \frac{1}{2} \pi h \rho (r_0^4 - r_i^4) \tag{9}$$

where the outer diameter and inner diameter are represented by ro and ri, respectively. h is length and ρ is mass density. Thus:

$$E = \frac{1}{4} \pi h \rho \omega^2 (r_0^4 - r_i^4) \tag{10}$$

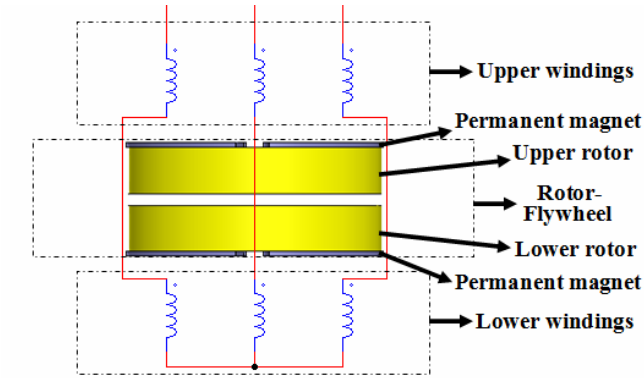

Fig.6. Electromagnetic relationship model of flywheel

According to Eq. (10), a flywheel with a larger angular velocity (ω) is able to save much more energy.

Flywheel's applications can differ depending on the load and its needs. For example flywheel can be used as energy storage for a static var compensator (SVC) system. In a SVC, flywheel must supply the critical load and compensate voltage sudden drops. Figure 8 shows SVC system utilizing flywheel [26].

3.2.3. Ultracapacitor

Capacitors are devices that store energy in the most direct and literal way. The speed of charging and discharging in capacitors are faster rather than batteries and they also are able to work tens of thousands times cycles with a better efficiency. However the main problem considering capacitors is low energy density. Therefore when there is a need for large capacity, dielectric area should be large. This fact makes the use of large capacitors uneconomical and often cumbersome. This is particularly true in stationary HEES applications [27]. Ultracapacitor behavior is something between battery and flywheel. Fig 9 shows three different model of an ultracapacitor.

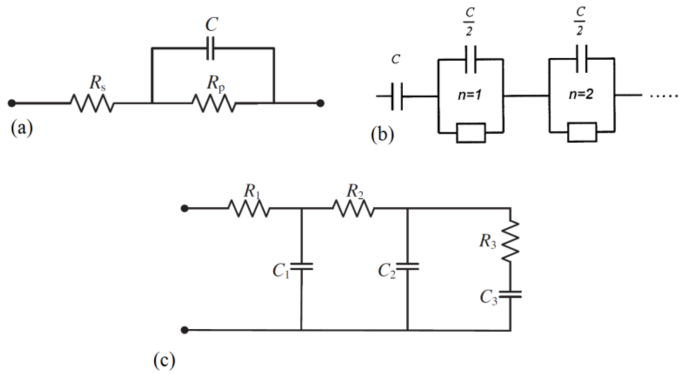

Fig.7. Eqvivalant circuits of a ultracapacitor: a) Classical model, b) Dynamic model and c) Multi-stage ladder model

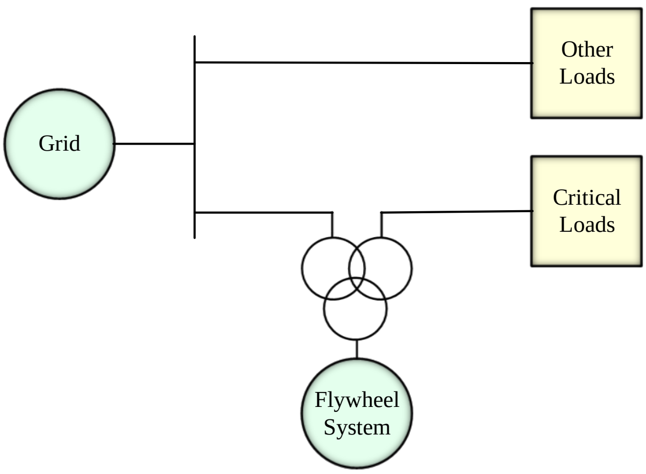

Fig.8. Application of flywheel in static var compensator

Table 2 shows the comparison of models shown in Fig. 9. From this table it can be concluded that classical model has better overall performance over other models.

In all of these models SOC of ultracapacitor is calculated as [28]:

$$SOC = \frac{V_{UC}}{V_{UC\_nom}} \tag{11}$$

3.2.4. Comparison of different energy storage devices

Table 3 compares three energy storage devices used in hybrid energy systems [29]. In a hybrid application an energy storage with high energy density and another energy storage with high power density can be used, therefore battery/ultracapacitor and battery/flywheel are good examples of a hybrid energy storage system.

4.Modelling and technologies of hybrid energy storage

The main purpose of a hybrid energy system is to achieve a power source having both high power density and high energy density. With hybridization of different energy storage devices, one can have all advantages and increase the system's reliability and optimization. Figure 10 shows the simplified structure of a ultracapacitor/battery hybrid energy storage system [30].

An HEES system should be carried out for some special applications such as operating in regenerative braking energy in electric vehicles since an energy storage source with high power density and high energy density is required. Table 4 compares these parameters for different energy saving devices [31].

4.1. Load's states

Electric loads are required to have either high power, or low power. As it is shown in Fig. 11 when load needs low power, the source with high energy density is on top of priorities. When load needs high power, both sources supply the load together. In some special applications such as absorbing regenerative braking energy in electric vehicles,

Table 2. Comparison of different models of ultracapacitor

Model	Accuracy	Complexity
Classical model	Good	Good
Dynamic model	Good	Normal
Multi-stage ladder model	Normal	Normal

Table 3. Comparison of four energy storage devices in hybrid energy systems

Characteristics	Battery	Flywheel	Ultracapacitor
Power density (w/kg)	To 400	1-200	1-10
Energy Density (wh/kg)	To 650	100-900	1-5
Lifetime (cycle)	To 1000	10000	10000
Self-Discharging rate	Up to 30% in month	Low	50% in month

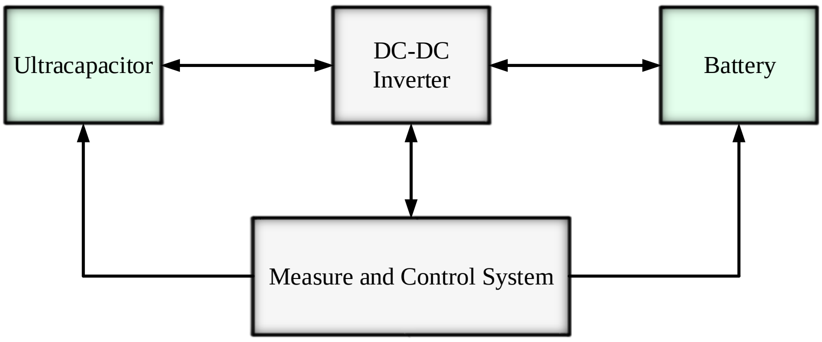

Fig.9. Structure of a ultracapacitor/battery energy system

regenerative braking first is stored in the storage device with high power density and then it is delivered to storage devices with high energy density [27], [31].

4.2. Battery / Ultracapacitor Hybrid System

Battery has high energy density whereas ultracapacitor has high power density. Combining battery and ultracapacitor will give a source with high power density and high energy density. Connections of battery and ultracapacitor are including non-active connection or direct connection and active connection or controlled connection. Non-active connection as shown in Fig. 12 is when battery and ultracapacitor have parallel connection without any interface of control block. In non-active connection, ultracapacitors limit the highest value of drawn current from the battery. In this structure, when the load is connected to hybrid source, initial response to load's current is carried out by capacitors and then due to their voltage drop, load's current.
To stop power flow between sources and causes capacitor's power to become usable completely DC-DC converters can be used. In active or controlled connection, according to control circuits, the control unit sets how sources supply the loads [32].

4.3. Flywheel / Battery Hybrid System

Battery has high energy density and flywheel has high power density as shown in Table 4 and one can use them together as a hybrid system. The advantage of using flywheel in a hybrid system is fast dynamic response of the device. For building the flywheel energy storage system (FESS) an electrical machine is required that converts electrical energy into mechanical and mechanical to electrical whenever required. The best choice is a permanent magnet synchronous machine [33], [34].

4.4. Flywheel / Ultracapacitor Hybrid System

As shown in Fig.13 since flywheel's behavior is similar to battery, one can replace it with battery in previous structure to achieve a flywheel/ultracapacitor hybrid source [35]. Similar to previous structure, a flywheel/ultracapacitor hybrid

Table 4. Qualitative values of energy storage devices

Device	Specific energy	Specific power
Chemical battery	high	low
Ultra-capacitor	low	high
Flywheel	low	High

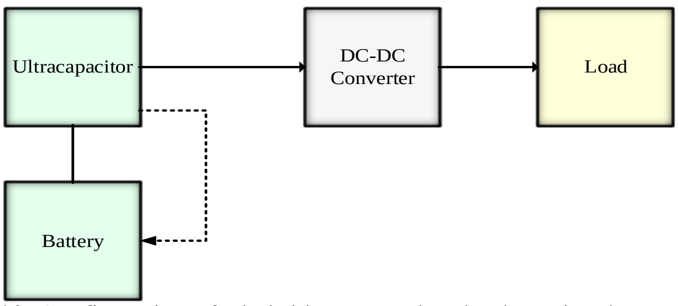

Fig.10. Configuration of a hybrid system when load requires low power

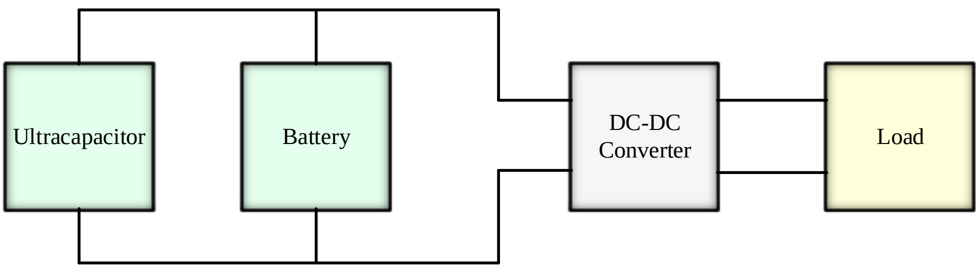

Fig. 11. Non-active connection of battery / ultracapacitor

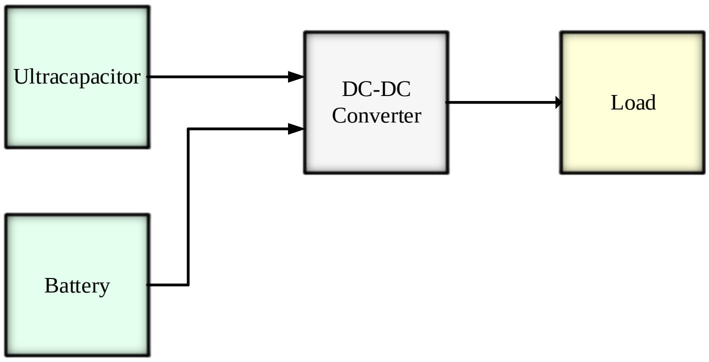

Fig.12. Active connection of flywheel / ultracapacitor hybrid system

system includes two kinds of active and non-active energy storage. The main advantages of this system are high temperature capability and low maintenance. These characteristics are very important for military vehicles [36].

4.5. Connection to Grid Capability

Hybrid power systems are divided into two categories as off-grid and grid-connected systems.

4.5.1. Off-Grid Hybrid Power System

Due to hardships in installation of a new electric line in mountainous environments, using off-grid systems is a good option for isolated areas. In addition, high investment costs of installation new lines can be another reason to use these systems as shown in Fig.14 [16].

In a hybrid system, different sources supply the load in parallel. Power sharing between these sources is an important factor that can effect on system design [16].

4.5.2. Grid-Connected Hybrid Power System (GCHPS)

Many of the systems utilizing wind as main energy source works connected to grid. Figure 15 shows an example of these systems. An inverter has been used to connect solar arrays to the grid. Also since output voltage generated by photovoltaic cell is low, using a step-up transformer is inevitable. Another application of this transformer is that with changing its tap level, output voltage can be set on required amplitude [37]. In Fig. 15 due to variability of frequency, generated power by wind turbine is converted to DC by the rectifier and then turned into a specific power to be delivered to the grid.

5.Simulation of hybrid electric energy storage

5.1. Battery/Ultracapacitor System

Battery has high energy density whereas ultracapacitor has high power density. A hybrid system consisting battery and ultracapacitor is an energy storage system that includes both high power density and high energy density simultaneously. This hybrid system is a proper option for storing regenerative braking energy in electric vehicles

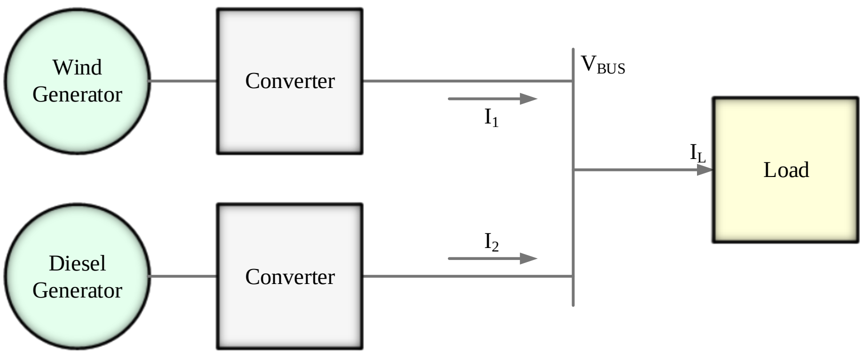

Fig.13. A hybrid system including a wind turbine and diesel generator

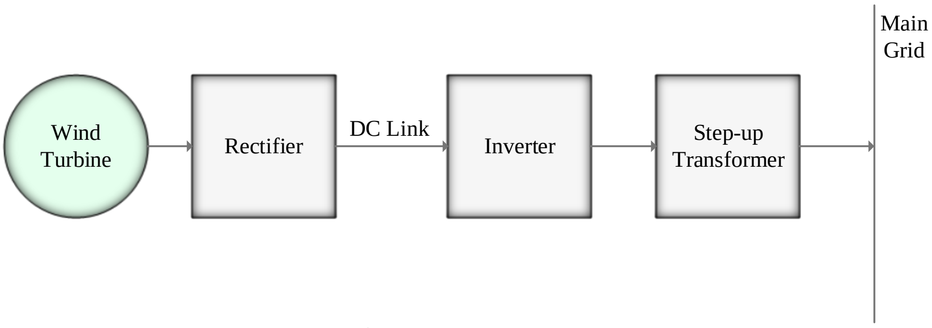

Fig.14. A sample of GCHPS

[38], [39]. There is a high amount of energy in a braking process in this case a storage device with a high power density must be utilized. Ultracapacitors have this capability, but have a high rate a self-discharging that deficit can be solved by using batteries along with ultracapacitors. Thus ultracapacitor charges the batteries after absorbing energy from the braking operation. The main purpose of this simulation is analysis of dynamic behavior of battery and ultracapacitor in an energy delivering cycle. In this system battery and ultracapacitor can be arranged in different ways which are shown in Fig. 16.

In this paper double converters in parallel configuration as Fig. 16d is chosen as case study. This system is designed to absorb regenerative braking energy and then deliver it to a constant load, the system strategy is:

- When load's current is negative (energy is flowing into system) battery is disconnected from the load and also battery and ultracapacitor must be separated. In this situation only ultracapacitor remains in the system to absorb regenerative braking energy.
- When load's current is zero or higher than zero, ultracapacitor is disconnected from the load and its energy charges the battery.

The simulation results are shown in Fig. 17. Load's current is zero until 15 seconds meanwhile ultracapacitor's energy discharges in battery with a very little current. From 15 to 19 seconds (4 seconds) load's current is -15 A that must be supplied mostly by ultracapacitor. From 19 to 22 seconds load's current is 0 again and ultracapacitor and battery current slowly attend to 0. After the second of 22, a constant 3 A load stands on the load and voltage is supplied by the energy stored in battery.

5.2. Battery / Flywheel system

The hybrid system including battery and flywheel is connected to a common DC bus. The main supply for this bus is an unidentified temporary renewable energy source like wind power system or photovoltaic power supply or anything else that is shown in Fig. 18. Figure 19 shown detailed system simulated in this paper including battery and flywheel.

The energy storage system connected to DC bus consists of a battery bank and a PMSM driven flywheel. The former is interfaced to the common DC bus through a one-leg bidirectional DC-DC convertor and the latter employs the inherent three-phase bilateral inverter as the interface owing to its voltage boosting capability from electric machine to DC link. A bidirectional single-phase three-wire load inverter is equipped to power the local home appliance loads with 60Hz 220V. In addition, a dump load is added to waste the extra energy and prevent batteries from overcharging. In emergency needs utility grid can support the energy bus through an inverter that is shown in Fig. 18.

First, the renewable energy system makes a 5 A current on DC bus. The battery was charged to avoid overcharging in batteries. Dump load drops a 420V voltage on DC bus. Meanwhile the flywheel energy storage system starts to store energy by gaining its speed to specific value. For insufficient energy for reaching the specific speed, battery release its energy to accelerate the rotor speed of flywheel. After renewable energy source is removed, energy storage system starts to discharge its energy until it is finished. For avoiding battery from overcharging, a dump load is equipped as shown in Fig. 18 to absorb the surplus energy with fixed voltage control (V_{dc}= 420 V).

Figure 20 shows measured waveform values of V_{dc} (bus voltage), i_{as} (power supply current), i_b (load current) and V_{ab} (load voltage). Figure 21 shows ω_r (velocity) and I_{fw} (flywheel current).

Figure 22 shows extended waveforms of Fig. 20 under flywheel system different modes.

From the figures it can be concluded that energy storages work cooperatively and states change at required moments.

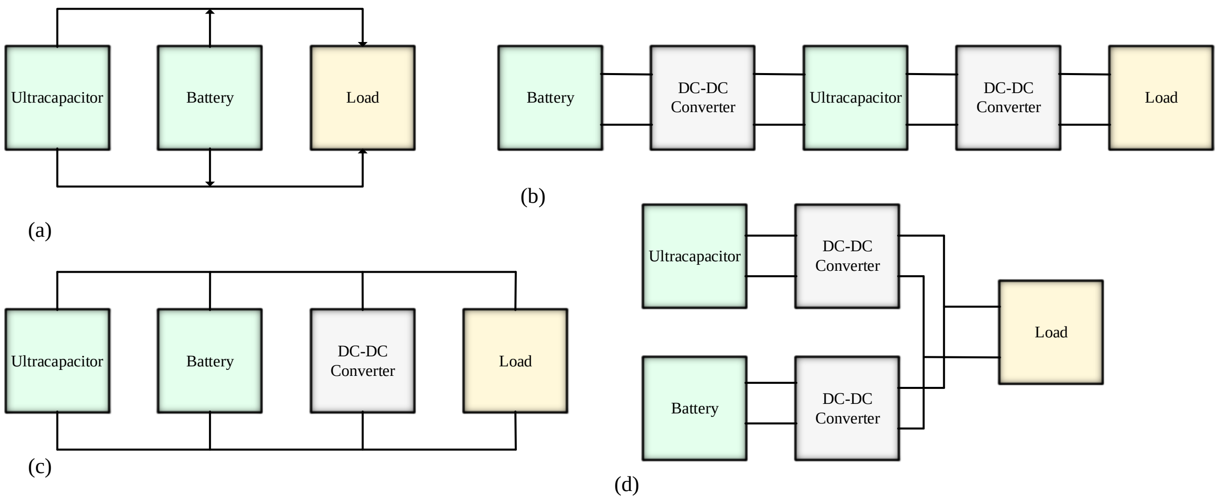

Fig.15. Different configurations of a hybrid battery/ultracapacitor system: a) direct parallel connection, b) double converters in series, c) dual input converter and d) double converters in parallel

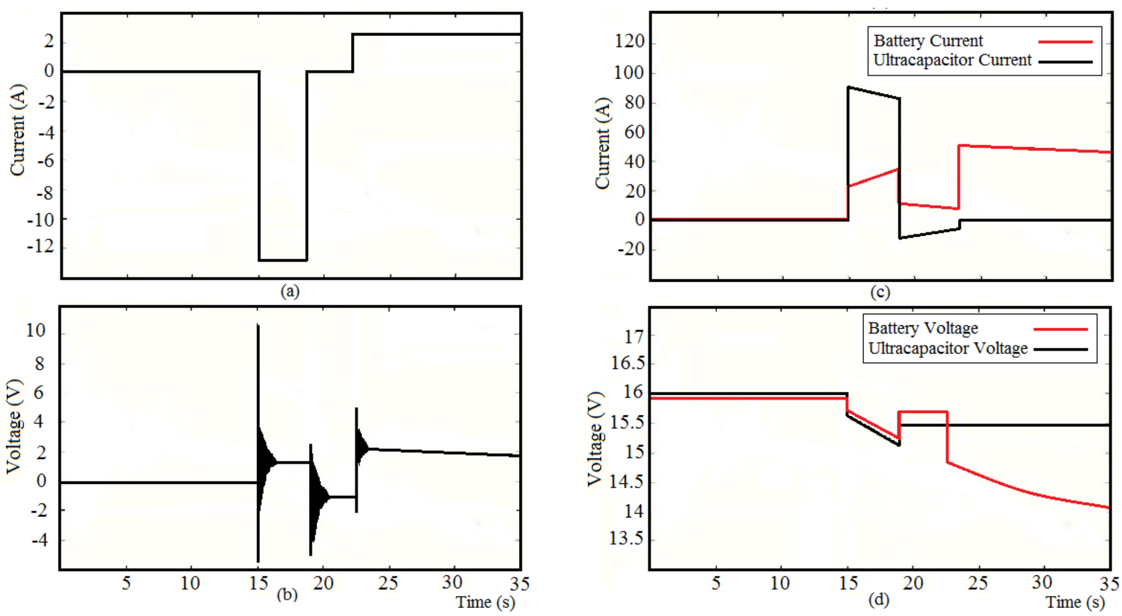

Fig.16. Simulation results for battery/ultracapacitor system: a) Load current, b) Load voltage, c) Battery and ultracapacitor current changes and d) Battery and ultracapacitor voltage changes

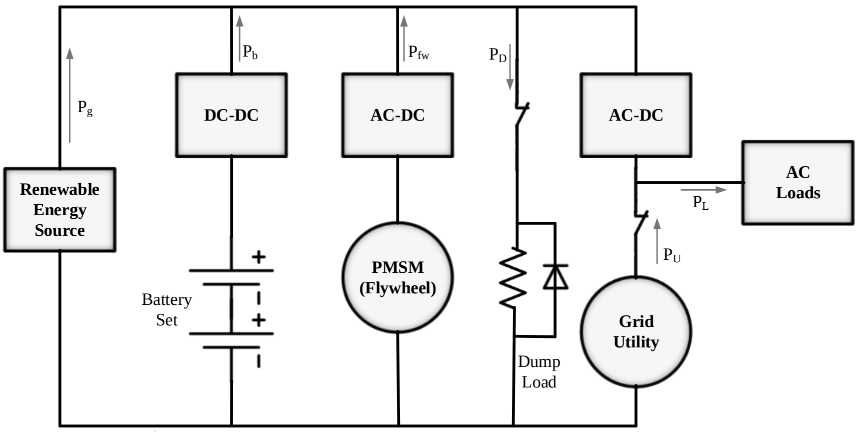

Fig.17. Flywheel/Battery hybrid system block diagram

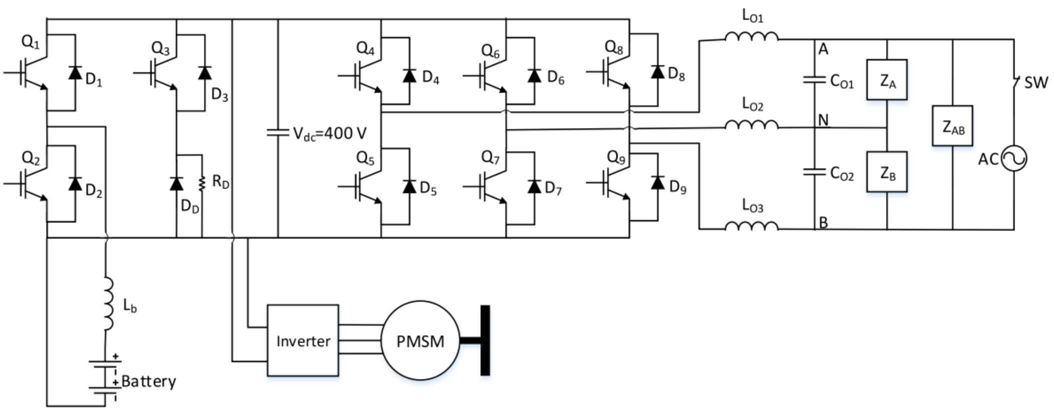

Fig.18. Flywheel/Battery hybrid system configuration

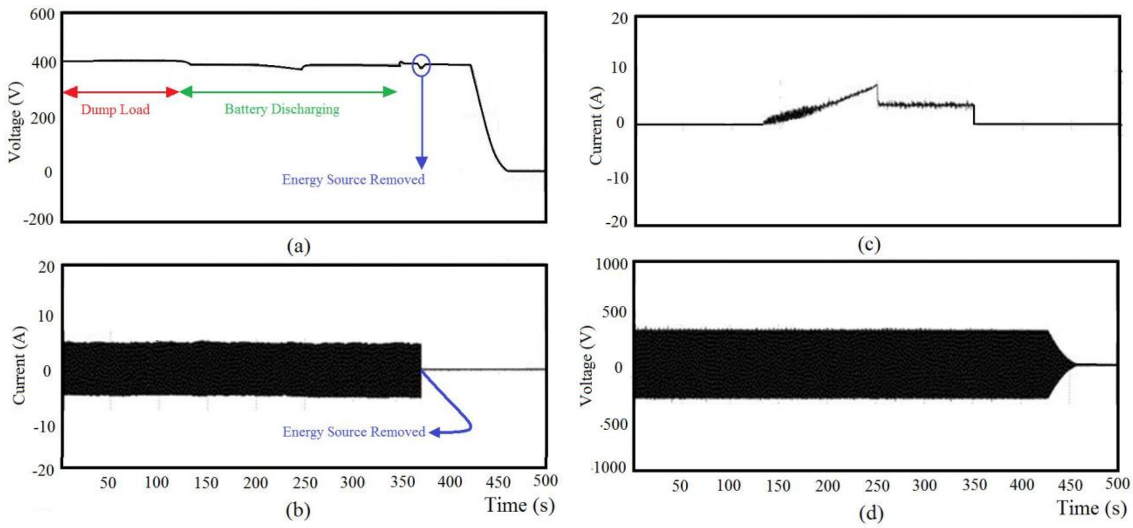

Fig.19. Simulation results for battery/flywheel system: a) Vdc (bus voltage), b) ias (power supply current) , c) ib (load current) and d) Vab (load voltage)

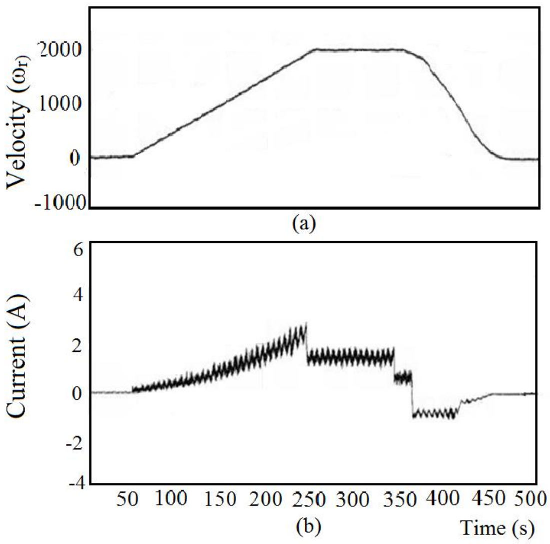

Fig.20. Simulation results for battery/flywheel system: a) ωr (velocity) and b) Ifw (flywheel current)

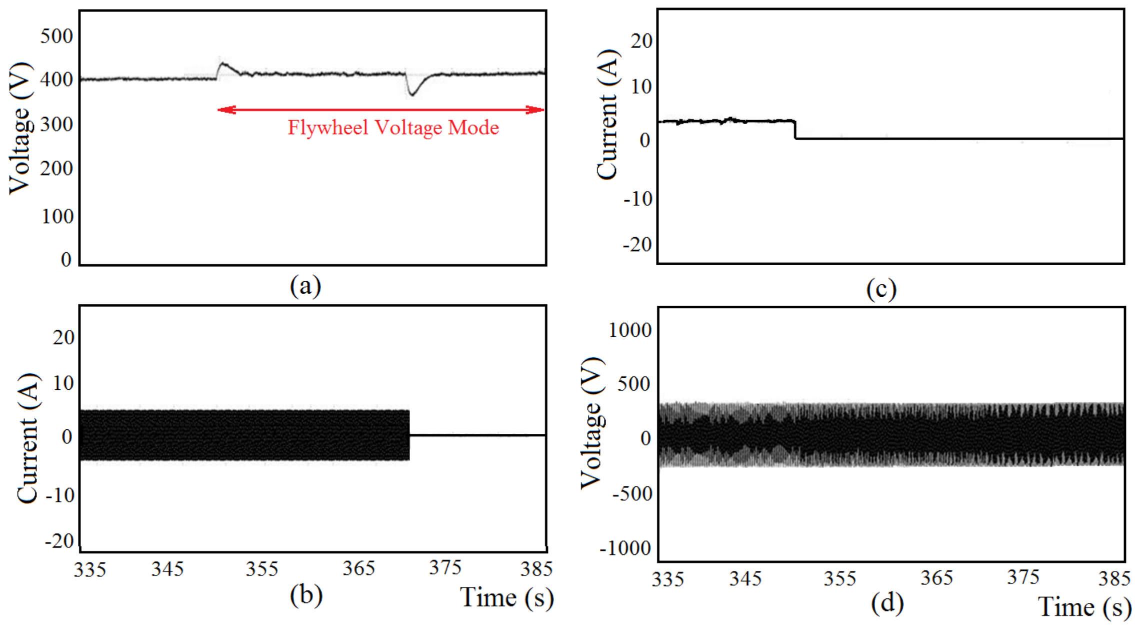

Fig.21. Extended waveforms under flywheel system different modes, a) Vdc (bus voltage), b) ias (power supply current), c) ib (load current) and d) Vab (load voltage)

6.Conclusion

In this paper the behaviour of HEES systems were investigated. Renewable energy sources can be helpful in HEES systems which add different advantages to the system. More energy and a more reliable system are the results of using renewable energy sources in a hybrid energy storage system. Different energy storage systems were modeled and their behavior in a hybrid system was analyzed. Battery/ultracapacitor and battery/flywheel HEES systems were modeled and simulated in MATLAB/Simulink and the results were presented. Simulation results show more reliable electric energy system with higher power compared to systems with only one electric energy storage.

References

[1] Shahinzadeh H., Gharehpetian G. B., Fathi S. H., Nasr-Azadani S. M., Optimal Planning of an Off-grid Electricity

Generation with Renewable Energy Resources using the HOMER Software, International Journal of Power Electronics and Drive Systems (2015) 6(1): 137–147.

[2] Gheiratmand A., Effatnejad R., Hedayati M., Technical and Economic Evaluation of Hybrid wind/PV/Battery Systems for Off-Grid Areas using HOMER Software, International Journal of Power Electronics and Drive Systems IJPEDS (2016) 7(1):134–143.

[3] Kuo Y.-C., Huang Y.-M., Liu L.-J., Integrated Circuit and System Design for Renewable Energy Inverters, The International Journal of Electrical Power & Energy Systems (2015) 64: 50–57.

[4] Paiva J. E., Carvalho A. S., Controllable Hybrid Power System Based on Renewable Energy Sources for Modern Electrical Grids, Renewable Energy (2013) 53:271–279.

[5] Yin H., Zhao C., Li M., Ma C., Chow M. Y., A Game Theory Approach to Energy Management of An Engine #x2013;Generator/Battery/Ultracapacitor Hybrid Energy System, IEEE Transactions on Industrial Electronics (2016) 63(7): 4266–4277.

[6] Gauchia L., Sanz J., A Per-Unit Hardware-in-the-Loop Simulation of a Fuel Cell/Battery Hybrid Energy System, IEEETransactions on Industrial Electronic s (2010) 57(4) 1186–1194.

[7] Thounthong P., Raël S., Davat B., Control Strategy of Fuel Cell and Supercapacitors Association for a Distributed Generation System, IEEE Transactions on Industrial Electronics (2007) 54 (6) 3225–3233.

[8] Seyezhai R., Kalpana B., Design and Development of Hybrid Multilevel Inverter employing Dual Reference Modulation Technique for Fuel Cell Applications, International Journal of Power Electronics and Drive Systems IJPEDS (2011) 1(2):104–112.

[9] Seyezhai R., Design, Simulation and Hardware Implementation of a Multi Device Interleaved Boost Converter for Fuel Cell Applications, International Journal of Power Electronics and Drive Systems IJPEDS (2014) 4(3): 314–320.

[10] Som T., Chakraborty N., Studies on Economic Feasibility of an Autonomous Power Delivery System Utilizing Alternative Hybrid Distributed Energy Resources, IEEE Transactions on Power Systems (2014)29(1): 172–181.

[11] Gutierrez-Vera J., Use of Renewable Sources of Energy in Mexico Case: San Antonio Agua Bendita, The IEEE Transactions on Energy Conversion (1994) 9(3): 442–450.

[12] Addula S. R., Mahalingam P., Coupled Inductor Based Soft Switched Interleaved DC-DC Converter for PV Applications, International Journal of Renewable Energy Research IJRER (2016) 6(2): 361–374.

[13] Das H. S., Dey A., Tan C. W., Yatim A. H. M., Feasibility Analysis of Standalone PV/Wind/Battery Hybrid Energy System for Rural Bangladesh, International Journal of Renewable Energy Research IJRER (2016) 6(2):402–412.

[14] Saheb-Koussa D., Haddadi M., Belhamel M., Economic and Technical Study of a Hybrid System (wind–photovoltaic–diesel) for Rural Electrification in Algeria, Applied Energy (2009) 86(7–8): 1024–1030.

[15]http://www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/Position_papers/ARE-WG_Technological_Solutions_-_Brochure_Hybrid_Systems.pdf.

[16] Patel M. R., Wind and Solar Power Systems: Design, Analysis, and Operation, Second Edition. CRC Press (2005).

[17] Milano F., Power System Modelling and Scripting, 2010 edition. London: Springer, (2010).

[18] Tomczewski A., Tomczewski A., Operation of a Wind Turbine-Flywheel Energy Storage System under Conditions of Stochastic Change of Wind Energy, Operation of a Wind Turbine-Flywheel Energy Storage System under Conditions of Stochastic Change of Wind Energy, The Scientific World Journal(2014) 2014: p. e643769.

[19] 18914.Solar Photovoltaic Energy (Iet Renewable Energy) by Anne Labouret, Scribd. [Online]. Available: https://www.scribd.com/doc/236285422/18914-Solar-Photovoltaic-Energy-Iet-Renewable-Energy-by-Anne-Labouret. [Accessed: 22-Oct-2014].

[20] Aissou S., Rekioua D., Mezzai N., Rekioua T., Bacha S., Modeling and

Control of Hybrid Photovoltaic Wind Power System with Battery Storage, The journal Energy Conversion and Management (2015) 89:615–625, Jan. 2015.

[21] Al-Masri H. M., Ehsani M., Feasibility Investigation of a Hybrid On-Grid Wind Photovoltaic Retrofitting System, IEEE Transactions on Industry Applications (2016) 52(3):1979–1988.

[22] Vechiu I., Etxeberria A., Camblong H., Vinassa J. M., Advanced Power Electronic Interface for Hybrid Energy Storage System used for Microgrids.

[23] Chen M., Rincon-Mora G. A., Accurate Electrical Battery Model Capable of Predicting Runtime and I-V Performance, The IEEE Transactions on Energy Conversion (2006) 21(2): 504–511.

[24] Emadi A., Uninterruptible Power Supplies and Active Filters, 1 edition. Boca Raton: CRC Press (2004).

[25] Nguyen T. D., Tseng K. J., Zhang S., Nguyen H. T., On the Modeling and Control of a Novel Flywheel Energy Storage System, in 2010 IEEE International Symposium on Industrial Electronics (2010)1395–1401.

[26] Carrillo C., Feijóo A., Cidrás, Comparative Study of Jornal Flywheel Systems in an Isolated Wind Plant, Renewable Energy (2009) 34(3): 890–898.

[27] Chen H., Cong T. N., Yang W., Tan C., Li Y., Ding Y., Progress in Electrical Energy Storage System: A critical review, The journal of Progress in Natural Science, vol. 19, no. 3, pp. 291–312, Mar. 2009.

[28] Onar O., Khaligh A., Dynamic Modeling and Control of a Cascaded Active Battery/Ultra-Capacitor Based Vehicular Power System, in IEEE Vehicle Power and Propulsion Conference(2008):1–4.

[29] Gao Y., Moghbelli H., Ehsani M., Frazier G., Kajs J., Bayne S., Investigation of High-Energy and High-Power Hybrid Energy Storage Systems for Military Vehicle Application, SAE International, Warrendale, PA, SAE Technical Paper (2003).

[30] Li L., Sun L., Liu Z., Sun H., Ultra-Capacitor Control Strategy of EV with Energy Hybridization, in IEEE Vehicle Power and Propulsion Conference (2008):1–4.

[31] Ehsani M., Gao Y., Emadi A., Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design, Second Edition, 2 edition, Boca Raton, CRC Press (2009).

[32] Stepanovs A., Galkins I., Development of Supercapacitor Based Uninterruptible Power Supply, in Publication, EditionName (2007):136–141.

[33] Chou M.-C., Liaw C.-M., Development of Robust Current 2-DOF Controllers for a Permanent Magnet Synchronous Motor Drive With Reaction Wheel Load, IEEE Transactions on Power Electronics (2009) 24(5)1304–1320.

[34] Hu K. W., Liaw C. M., On the Flywheel/Battery Hybrid Energy Storage System for DC Microgrid, in Future Energy Electronics Conference (IFEEC), 2013 1st International (2013):119–125.

[35] Tokahashi I., Itoh Y., Andoh I., Development of a New Uninterruptible Power Supply Using Flywheel Energy Storage Techniques, in Proceedings of the IEEE Industry Applications Society Annual Meeting (1989): 711–716.

[36] Kusakana K., Vermaak H. J., Hybrid Renewable Power Systems for Mobile Telephony Base Stations in Developing Countries, Renewable Energy (2013) 51: 419–425.

[37] Ray P. K., Kishor N., Mohanty S. R., Islanding and Power Quality Disturbance Detection in Grid-Connected Hybrid Power System Using Wavelet and -Transform, The IEEE Transactions on Smart Grid (2012) 3(3): 1082–1094.

[38] Ito Y., Ishiguma S., Uninterruptible Power Supply with Function of Absorbing Regenerative Energy, in Power Electronics Conference (IPEC), 2010 International (2010): 1169–1173.

[39] Tsotoulidis S. N., Safacas A. N., Analysis of a Drive System in a Fuel Cell and Battery powered Electric Vehicle, International Journal of Renewable Energy Research IJRER (2011) 1(3): 140–151.