Energy Storage Systems for Energy Management of Renewables in Distributed Generation Systems

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Additional information is available at the end of the chapter

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Abstract

Distributed generation (DG) systems are the key for implementation of micro/smart grids of today, and energy storages are becoming an integral part of such systems. Advancement in technology now ensures power storage and delivery from few seconds to days/months. But an effective management of the distributed energy resources and its storage systems is essential to ensure efficient operation and long service life. This chapter presents the issues faced in integrating renewables in DG and the growing necessity of energy storages. Types of energy storage systems (ESSs) and their applications have also been detailed. A brief literature study on energy management of ESSs in distributed microgrids has also been included. This is followed by a simple case study to illustrate the need and effect of management of ESSs in distributed systems.

Keywords: energy storage, distributed generation, energy management, renewable, battery

1. Introduction

Distributed generation (DG) and electricity market liberalization have been the key drivers for the evolution of the concept of small-scale energy sources. Growing concerns about climatic changes further encouraged the use of renewable energy sources to ensure energy conservation and sustainability. But integrating renewable energy is turning out to be a real challenge for the smooth operation of DGs. Renewable power especially faces concern regarding power quality. Grid operators face immense issues in scheduling the generated power from the DGs, especially due to renewables and heat-driven energy sources which are difficult to be forecasted. DG may be the key to implement the much talked about micro grids and smart grids of today to ensure a clean and green energy portfolio. However, many issues as listed above need to be addressed to enable successful integration of DGs in the power grid. Thus, an effective management of the generating resources in the DG network is very essential.

Energy storages can be incorporated for energy management in many ways. Conventional usage of energy storage devices was mostly for long-term storage applications. But now they can be used for power storage and delivery from few seconds to days and months. Energy storage systems (ESSs) can act as spinning reserves for providing short-term power supply to manage instant variability in DG-generated power. They can compensate for the intermittency and variability of renewable resources and improve the power quality and reliability. ESSs can also provide ancillary services to enable quality power delivery to the end users. Optimized selection, sizing and siting of ESS will be critical for design engineers. Efficient management of energy generated in a DG system can enhance the performance of the system, thereby enabling quality and reliable power delivery. Market prices and other economic dynamics have great impact on the operation of DGs, in which case storage systems can act as added assets to achieve better economic dispatch solutions. Storage systems have proved to improve voltage stability, to smoothen wind power variations, to incorporate peak shaving and load leveling features. The main drawback of storage is its maintenance issues and life cycle failures. Effective implementation and usage of energy storages in the distributed grid requires intelligent and flexible energy management strategies capable of handling the dynamics of distributed systems, while ensuring effective and efficient usage of the storage device. The simplest energy management strategy avoids over charging/discharging of the storage. However, further implementation of hardware-in-loop simulations, optimization algorithms and other intelligent tools and techniques have now been attempted to propose advanced energy management scheme strategies to improve storage lifetime and operability.

2. Growth of renewable power generation

Energy crisis emerging from the early 1970s with increased environmental concern was the key factor for setting the foundation for development of renewable sources for electric power generation. Countries like Denmark, Germany and the United States led the green energy mission by creating critical markets and policy targets for development of renewable energy. Awareness on climatic change and its adverse effects further fueled this tremendous drive to reduce emissions and generate environment-friendly energy. Renewable power generation has seen accelerated growth in the developing countries, as it provided a means to reduce dependability on imported nonrenewable fuels. In the earlier days, renewable power was only advocated by scientists and environmentalists but with declining costs and expanding markets it eventually emerged as an implementable solution to improve energy security and diversify the energy portfolio of nations. The overall energy supply from renewables has grown to 76 EJ with a total investment amounting to 214.4 billion USD in 2013 which is a 30% increase from the scenario in 2004 [1]. Fastest growth of renewables has been recorded in the power sector with 560 GW being generated from renewables in 2013.

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Solar photovoltaics (PV) grabbed the highest growth rate of about 38% (average growth every year) in these 10 years. Wind power saw rapid expansion all over the world with many countries beginning to join in every year. Though China and the United States saw a mild decline in the wind market, it is still expanding due to technological improvements and fall in prices. Hydropower also increased in the last decade with many joint-venture large-scale projects being implemented. At the same time with microturbines installed on small streams and waterfalls, micro hydropower is also viewed as being a good complementary source to other renewables like wind and solar. Ocean energy is still in developmental stage, with France being the only country to have a functional tidal power plant with rated capacity of 240 MW.

3. Microgrids and DG

Growing power demand is predicted to be highly devastating for our environment as power generation is the highest contributor to greenhouse gas emissions. Also, rapid depletion of conventional energy resources and increasing fuel prices are crippling the economy of many countries. With technological advances, many renewables are now competing as alternative energy sources to conventional fossil fuels. Conventional power generation was highly centralized due to geographical concentration of energy sources. It also faced many issues like need for extraction infrastructure of generated power, losses in transmission and distribution and lacked the flexibility of being set up at desired locations. This led to conceptualization of DG, wherein the power generation takes place at/near the load centers by many small grid-connected power generating sources called distributed energy resources (DERs) which are mostly renewable in nature. Due to abundance of availability of natural renewable sources like solar and wind, these DERs could be set up anywhere making the DGs flexible, decentralized and modular. They are capable of capturing renewable power and minimizing losses occurring in transmission. This concept has gained a lot of interest due to many reasons as defined by the International Energy Agency [2]. They are congestion on centralized transmission lines, growth of renewables, increased customer demand, electricity market liberalization and environmental awareness. The benefits of DGs are listed below:

1. *Flexibility*: DGs are flexible in planning, installation, operation and modularity. They can also be started and stopped much more easily as opposed to conventional plants which need startup and shutdown time and costs. Hence they can be easily modulated as per market norms.

2. *Reliability:* In electrical power systems, it simply means uninterruptible supply to the consumers. This needs high maintenance of transmission network with increased costs for the utility grid. Industrial consumers demand uninterrupted power and hence are more willing for investing in backup and/or local generators. Fuel cells and microturbines are vastly viewed as being excellent small-scale generators for improving system reliability.

3. *Power quality*: In many developing countries, grid power is still marred with number of power quality issues like voltage sags and frequency deviations. These problems need to

be addressed to make the systems reliable and improved. DGs can easily be brought into play to improve the power quality and deliver reliable power to the consumer.

4. *Green power*: As most DERs can be renewables, DGs can be setup to promote green energy and reduce GHG emissions. Emissions omitted or reduced are now being viewed as amounting to energy saved. Many nations have now drafted environmental policies which encourage installation of DGs and urge adoption of green energy.

5. *Reducing grid congestion*: In order to provide power to remote areas which are located far from generation facilities leads to heavy congestion of transmission lines. Hence setting up of DGs in vicinity of such areas prevents burdening of the grid and avoids investment costs for setting up of new lines.

6. *Additional benefits:* DG also serve some additional purposes like deferral of upgrades from T&D, loss reduction in transmission lines, network support and ancillary services.

Thus DG can benefit power system delivery and mobilize new markets. They can be completely decentralized, serving a localized consumer independent of the grid or operate with the grid to address a part of the local load. Thus any DG which exhibits controllability on its connectivity interface can act as a microgrid. The control of microgrid poses many difficulties and needs extensive strategies to command operability based on grid conditions and customer requirements. They also need unique protection strategies to address any issues arising internally to not affect the power grid. Hence, a DG can be implemented with any combination

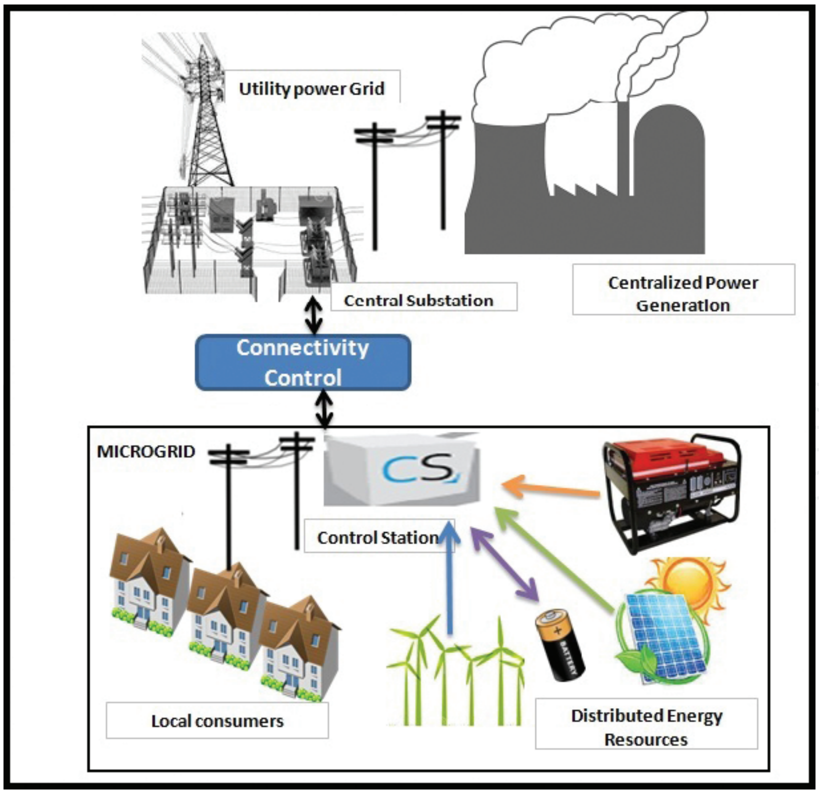

Figure 1. Distributed generation vs conventional centralized generation.

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of generating sources renewable or conventional with/without storage as shown in **Figure 1**. Thus, many nonrenewable small-scale generators like fuel-cell, diesel-based generators and microturbines are also incorporated into DGs to meet consumer demand [3].

3.1. Issues and options for integrating renewables in DGs

Integration of renewable power sources poses many challenges during operation and scheduling of DGs. Intermittency, power quality and price of electricity generated are some of the issues which are being currently addressed in the distributed power scenario. DGs facilitate the power system by providing voltage support and power factor correction applications. However, increased penetration of renewables and extensive decentralization of power sources may cause problems in its voltage profile, making it unstable and unreliable. The major issues which need to be addressed for enabling increased implementation of DGs are explained in detail below:

i. *Costs and investments:* DGs require installation of different power generating technologies at the load centre, each of which is characterized by a different energy cost. Energy costs include costs for investing in installation, operation, maintenance and replacement costs and are generally coined as cost per kilowatt hour of energy generated. Most of the DERs especially the renewable systems are very expensive compared to existing fossil fuel-based generating systems. As per status reports by REN21 [1], solar PV costs have declined by 50% in the past 4 years due to widespread awareness and learning towards conceptualization of grid parity. Now, introduction of concepts like microturbines and biomass generation is proving to be cheaper. Also costs of investments can be reduced during planning a DG by selecting the optimal combination of DERs so as to yield maximum energy at lowest costs and adapting optimal operating conditions.

ii. *Unpredictability ofrenewable energy system (RES):* A dispatchable power is defined as a power source whose output can be regulated to match the demand so as to ensure power balance. Renewables depend on nature and are considered to be nondispatchable due to their continued unavailability and intermittency. Solar power is available only as long as the sun shines and wind is ever varying in both speed and direction. The planning committee must ensure that any intermittency or variability caused in the generation side by these DERs is balanced before being fed to the consumers (or the power grid) to avoid any damage to consumer appliances and to ensure quality. Usually, any party generating power using DGs signs a contract with its local power system operator called the access responsible party (ARP) to ensure stability and operability of the grid as per the grid codes. Grid code encompasses the technical specifications and rules to be abided by the transmitting party to ensure grid safety and security. Any discrepancy henceforth is penalized. Forecasting studies have come a long way in order to enable better planning of renewable power scheduling especially in the wind power sector. Every plant owner, grid operator and energy trader demand high accuracy in forecasting techniques to ease management of DGs and to improve system reliability.

iii. *Power quality issues:* Frequency variations and voltage drops and deviations may impact on the quality of power delivered to the consumer. The microgenerators in DG systems lack speed governors and spinning reserves and hence may not be able to provide frequency regulation. In islanded mode of operation the DG becomes more sensitive to variations in voltage profile caused by any variations in load. Additional variations fed in from renewables will further impact the frequency and voltage profile of the system. The main power quality problems faced by DG systems are harmonic distortions and voltage deviations introduced by the many inverters installed to integrate the various DERs like PV panels. Thus, connection of large number of DERs into the DG system requires meticulous planning and control to establish load-frequency and power quality.

iv. *Connectivity issues:* As explained before, DGs are capable of operating with and without the grid, ensuring reliable power delivery to the consumer. However, the decision to stay connected or operate in isolation requires extensive sensing equipments and intelligent control systems. In the case of voltage faults or grid failure, the microgrid needs to immediately get into islanding the system from the faulty portion of the grid. Similarly, they also must engage in smooth transition from islanded to grid-connected mode after fault clearance. Switching between connected and stand-alone modes needs to be highly synchronized and safe. Any bidirectional flow of current due to imbalances of voltages at higher renewable penetration needs to be controlled and managed [4, 5].

v. *Market regulation:* Most countries have a monopolistic electricity market where the utility is the sole regulator of electricity distribution to consumers. In such cases, the power generated by the DGs is purchased by the utility under authoritative drafted agreements. Hence, for further penetration of DGs and microgrids a more liberalized market is needed where the DG power could be directly sold to consumers. Some countries only implement marginal norms for purchase and sales of green power which is not sufficient to justify the investment costs of newer technologies. However, liberalization alone is not the solution for this. It may also lead to increased complexity and prices which adversely affect small DGs and renewable generators in meeting scheduled dispatches and buying of backup power.

vi. *Regulatory frameworks:* Microgrid and DG operators face most problems due to lack of appropriate regulatory frameworks to support and govern investments and operations both in isolated and grid connected scenarios. A fitting legal design for microgrids with market liberalization is very much essential. Proper framework for costing and economic analysis needs to be structured which should recognize value of reliable and nonintermittent power supply.

DGs and microgrids are and will play a pivotal role in meeting future energy challenges. However, the issues discussed above need to be addressed by DG operators, planners and policy makers. Combining energy storage in the portfolio of DERs of a DG will effectively address many of these issues and enable the DG system to operate reliably and securely.

3.2. Need for ESS

ESSs can aid in improving the operation and power delivery of the DG and can help in elimination of uncertainties in the system. Conventional power systems only depended on rotational generators for spinning reserves and ancillary services. But most micro sources in a DG, especially renewable generation units lack this facility and hence depend on external storage to fulfil these requirements. Some of the needs of ESS in DG systems are listed below:

i. *Spinning reserve and short-term backup:* Fuel-powered plants usually are held at stand by to provide for the spinning reserve and yet, they need considerable time (in minutes) to respond. In the absence of spinning reserve in the case of renewable systems, the ESS can aid in ramping up of power delivery in times of need. Recent advanced storage systems are capable of ramping up in terms of seconds to few minutes. Thus, an effectively managed ESS can replace a much larger spinning reserve. They can also store energy for delivering short-term backup power. They are slower to respond but can be brought into commissioning in about an hour.

ii. *Load levelling and peak shaving:* Usually utilities operate peak resources and generators to deliver the peak demand power. They are usually combustion engines and gas-fired plants which are characterized with lower efficiencies and higher emissions. Efforts are being initiated to reduce the peak of the demand curve by improving the end-user energy efficiency, educating on demand response measures and implementing peak pricing strategies. Energy storage is an attractive option for managing the peak of the demand curve. They are capable of storing energy at low peak times and then discharge it at peak time. Thus it acts as a very responsive and flexible peak reserve. Storage is essential for demand response programs too which will enable a consented and co-ordinated direct control on end users' demand. ESS employed for peak shaving will result in reduced emissions also.

iii. *Integration of renewable sources in DG:* Wind power is generated mostly at night when the demand is low. Hence, storing this energy and delivering it at demand times enhance the efficiency of the DG system. If the same storage systems are provided at the end-user side, then all the excess wind energy can be transmitted at night time (time of low congestion) and stored near to delivery point. This will also reduce the congestion of T&D lines at peak times, causing lesser faults and outages. Similarly, solar power is available only as long as the sun shines and hence can be stored at times when generation exceeds demand and discharged at evening peak hours. Increased penetration of solar power resulted in a critical situation called the duck curve in California. This created a huge difficulty for the system providers to ramp up other generators to meet the sudden shift in demand. ESS can help in such scenarios to level the demand curve and aid in ramping up of supply at peak times. They can also help in improving the penetration of renewable generators by eliminating their variability and intermittency.

iv. *Power quality support:* Integration of renewables poses many power quality issues ranging from flickers to fluctuations and spikes, swells and sags. Then storage systems capable of responding rapidly to system fluctuations like flywheels and ultra capacitors can be implemented to maintain power quality standards as per grid codes. Eliminating harmonics, LVRT and transient response can also be managed with an ESS. Flywheels, super capacitors and fast-responding batteries are extensively applied for frequency and voltage control and power quality improvement in DGs.

v. *Ancillary services:* Ancillary services are those which are needed by the grid operators to sustain stable and reliable operation of the grid. Frequency regulation is an important aspect of ancillary services including load following and energy arbitrage. Future deregulation of markets and introduction of time-based tariffs will create a platform for energy arbitrage. It involves charging of storage with cheap energy at off-peak times and delivering at a higher price at peak times. It goes hand in hand with peak shaving concept but focuses on commercializing the saved energy for maximum profit. However, it is important to note that storage systems used for regulation and load following purposes need to be highly responsive and efficient, else the losses occurring in ramping up/down the storage will outweigh the advantages. Usually conventional generators used for ancillary services are operated at below the rated capacities and hence have lower efficiencies and high emissions. ESS can hence be the emission-free cheaper option for ancillary services thus freeing generators to operate at maximum efficiencies.

4. Types of ESSs

Storage and conservation of energy has been practiced by mankind for many decades. Hydro storage and electrochemical batteries have been the traditional face of electricity storage. Based on the technology used, the different ESSs can be classified as shown in **Figure 2**. **Figure 3** shows the share of different energy storage technologies worldwide based on installed capacity.

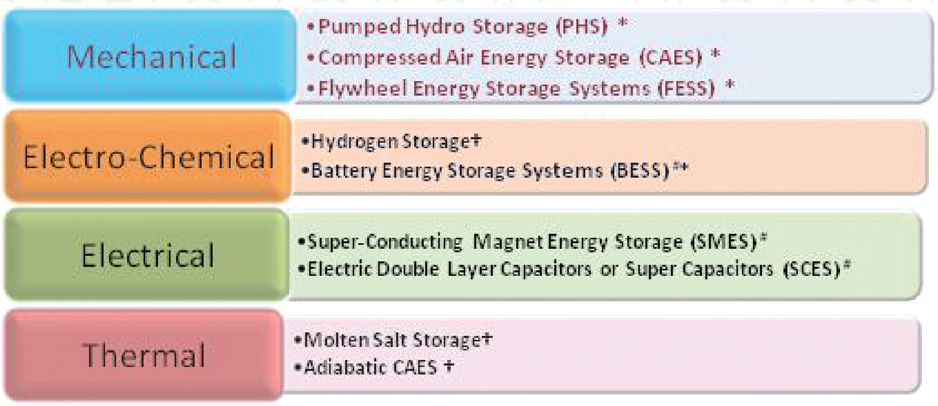

Figure 2. Energy storage technologies. *, Deployed and operational; #, under demonstration; and †, early stage.

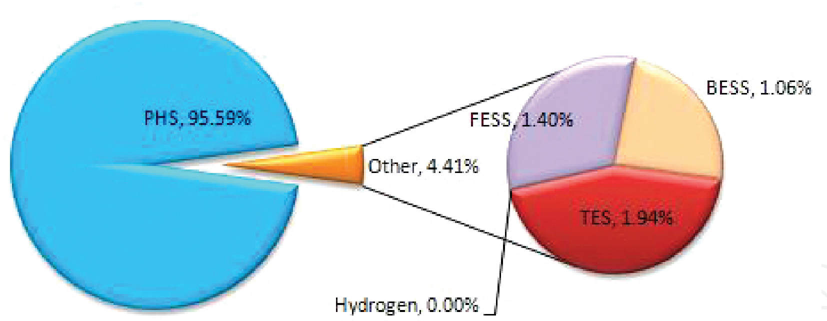

Figure 3. Worldwide operational energy storage technology share based on installed capacity. (Source: DOE database 2015 [6]).

4.1. Pumped hydro storage (PHS)

They are commercially installed and most widely operated grid-scale form of storage. PHS employs two reservoirs situated at different heights and pumps water from lower reservoir to upper reservoir using off-peak cheap electricity from the grid. When required the stored water is released to the lower reservoir and electricity is generated through rotating turbines. They are capable of storing huge capacities of energy for many months and have long life times of about 50–60 years. Their efficiency lies in the range of 70–80% depending on plant capacity, height difference and type of turbine used. They need extensive investments and long gestation and planning periods. New developments in pumped hydro include features like speed pumping which further improves the system response times for ramping applications.

4.2. Compressed air energy storage (CAES)

Compressed air is stored as a form of potential energy in large underground caverns and mines. When needed they are mixed with natural gas and burnt and passed through expansion turbines to generate electricity. This type of CAES has usually low efficiency value of about 50% and is called as diabatic CAES. If the heat generated during compression is stored as some form of thermal energy and reused to heat air in the discharging process, it is termed as an adiabatic CAES. Such systems are still being explored and when developed will give a very high efficiency of about 75%. They are being used in many places like North America and Australia. Advantages of CAES include large energy capacities with long duration storage. But they also need huge investments and are site-dependent with low round-trip efficiency.

4.3. Flywheel energy storage systems (FESSs)

These store energy in the form of electromechanical kinetic energy in a rotating part like an accelerated rotor or rotating cylinder. The concept is based on the usage of stored mechanical inertia of a rotating object. When charging, the flywheel is accelerated and while discharging the reverse process takes place with the flywheel acting as a brake to extract the stored energy. Advanced FESS has high-speed rotors made of light-weight high-strength carbon materials spinning at twenty to fifty thousand rpm under vacuum. They are capable of supplying high power rating at minimum response times and are very suitable for ramping and spinning reserve applications. Other attractive features of a FESS include high efficiency, high power rating and long life with minimum to no maintenance. The major drawback is the high self-discharge, occurring due to deceleration and resistive losses at bearings.

4.4. Hydrogen storage

Electricity is used to split water into hydrogen and oxygen in an electrolyzer, and the hydrogen generated is stored under pressure in separate tanks. On requirement, this hydrogen is passed with oxygen/air into a fuel cell to generate electrons and water (a reverse electrolysis process). Thus, it is truly a form of very clean energy as water and heat are the only byproducts of the entire process. This is also called as a regenerative fuel cell (RFC). They possess high modularity, scalability, energy and power capacities. But they have low-to-medium efficiencies of 50% and suffer from self-discharge.

4.5. Battery energy storage systems (BESSs)

These are the most widely implemented and commercially used storage systems in power system applications. The basic idea is to convert electricity into some electrochemical form and save it as electrolytes inside a cell. While discharging, the electrolytes react with the electrodes in the cell and reverse reaction generates electric current. Over the years, many types of batteries have been developed each having a varied range of characteristics thus making the battery storage technology highly versatile and multipurpose. Nonrechargeable batteries are known as primary batteries and they are mostly used in military and medical applications. A hierarchy of rechargeable/secondary batteries is shown in **Figure 4**.

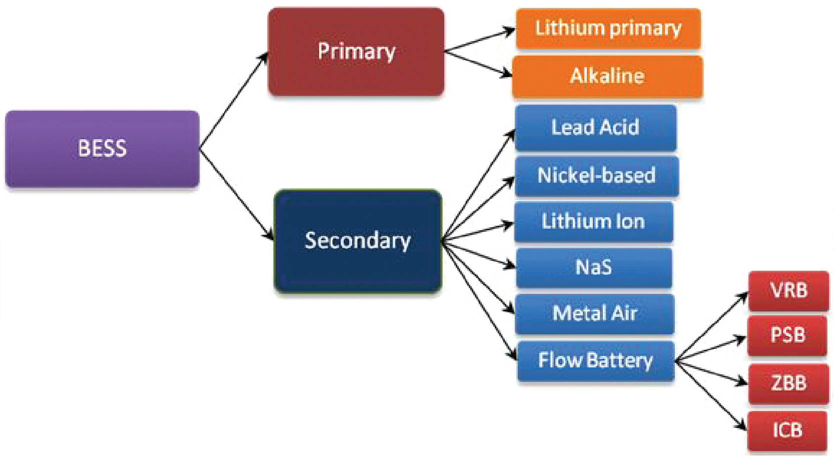

Figure 4. Battery storage systems' hierarchy.

Lead-acid batteries are in usage since the 1890s and recent advancements like valve-regulated batteries, absorbent glass mat batteries are being proposed to improve battery performance and reduce maintenance. Nickel cadmium batteries have been used in applications for stabilizing wind energy but have been discouraged due to environmental hazards from

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cadmium disposal. Lithium-ion batteries have very high energy density and find extensive applications in portable electronic systems. Recent lithium–polymer systems are also being developed with excellent features for renewable integration. NaS batteries are finding increased applications in renewable systems with high power density and efficiency. Metal–air batteries are recently being explored. Lithium–air batteries are most attractive with high-specific energies and zinc–air batteries are also feasible. But metal–air batteries are extremely prone to risk of fire due to high reactivity between metals and air/humidity. Flow batteries are rechargeable batteries which store the liquid electrolytes externally in separate tanks. This helps in increasing their energy capacity by many folds. They are highly modular and scalar as their power capacity can be added by adding up of electrode cells. Instant recharging can be done by simply replacing the electrolytes in the tank. Recyclable electrolytes make the system highly efficient and they are capable of operating for many thousands of cycles. They are also called redox batteries as reduction–oxidation reactions occur in the battery during charging/discharging process. Some types of flow batteries are vanadium redox battery (VRB), polysulphide bromide battery (PSB), zinc–bromide battery (ZBB) and iron–chromium battery (ICB). A detailed exploration of battery storage systems and their characteristics have been presented in [7].

4.6. Super-conducting magnet energy storage (SMES)

Each SMES unit has a superconducting coil maintained at low temperature, a power conditioning equipment and a cooling system. Existence of electricity in an electromagnetic form has been discovered ages before when supercooled metals were found to exhibit superconductivity. Employing this feature for storing electric energy began in the late 1960s when strong magnetic fields formed by superconducting coils at extreme low temperature such as 4 Kelvin were explored. Recent research has led to development of materials which can function at 100 Kelvin also. The system has high efficiency but lower energy capacity and power ratings. Also, cooling systems increase the costs and maintenance of the system and it is still in the early stages of demonstration.

4.7. Electric double layer capacitors or super capacitors

These store electric current in the form of electrostatic charges. Usually it is made of a parallel plate structure with dielectric between them which stores the charge. This is the technology which bridges the gap between conventional dielectric capacitors and batteries as they can store large capacity of energy, comparable to batteries. Since they do not involve any conversion process (as in batteries) they are very fast and capable of rapid charge and discharge cycles. They are highly efficient (<90%), environmentally safe, easily recyclable and suitable for frequency support applications. However, they suffer from very high self-discharge and find increased applications in electric vehicles and traction systems.

4.8. Thermal energy storage (TES)

With increased solar power penetration, thermal storage has gained a lot of perspective. Excessive heat energy can be stored for later usage in buildings or in externally stored secondary energy carriers. Ice-based and Molten salt technologies are being developed and once under operation are expected to share a huge part of electric demand for heating purposes. Ice-based thermal storage includes latent heat storage and when used with solar power generation is claimed to achieve exemplary efficiencies.

5. ESSs for energy management of DGs

Section 3 detailed the various issues faced in integrating renewable systems and the subsequent need for ESSs. It provided a general understanding on the various applications for which ESSs can be used. Some applications like power smoothing and frequency regulation require storage systems capable of charging/discharging high power in short duration. Whereas, arbitrage and peak shaving applications need more energy capacity to withhold the stored energy with low self-discharge. Depending on these applications, appropriate type of storage needs to be selected and sized to be integrated with the DG. As storage systems are quite expensive, they need to be managed effectively to ensure their longevity and performance, else they may cause O&M issues, reduced performance and premature failure. A proper management of both the storage as well as the generating units is necessary to ensure effective utilization of the DERs. Hence, energy management has been a key topic of interest to renewable energy researchers and developers. **Figure 5** depicts the components of an energy management system.

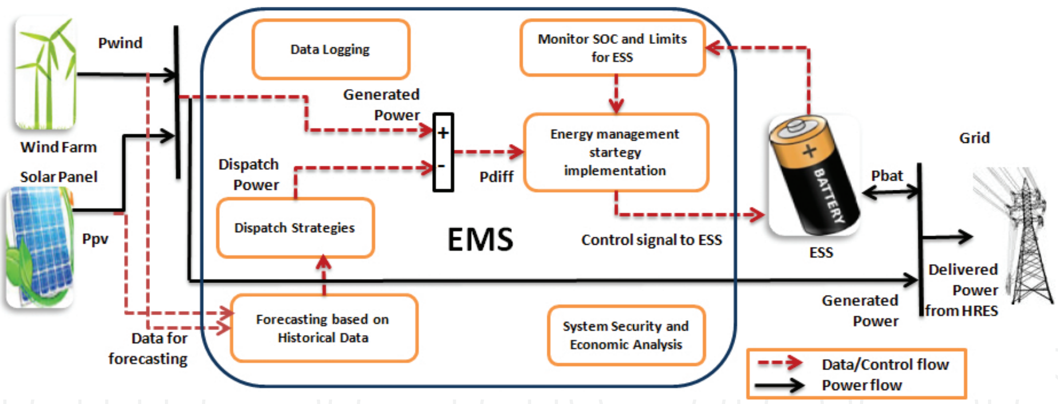

Figure 5. Components of an energy management system.

Energy management strategies are a crucial part of planning of autonomous and standalone power systems incorporating renewable power [8]. A storage system can be operated to address many applications as detailed before in a microgrid, and the management strategy will have to be proposed in view of attaining the predetermined objectives without affecting the system as well as the storage system. As Nykamp et al. [9] stated in their study, from a Distribution System Operator (DSO) perspective a storage system's usage is to be primarily oriented towards peak shaving and renewable integration applications. But, on the contrary, a private energy trader would want to utilize the storage system to maximize profits by arbitrage and ancillary services that would earn money. A vivid comparison of different

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applications of the same storage in a distribution grid has been accounted with simulation results in [9]. Generally, energy management is based on state of charge (SOC) of the energy storage devices so as to avoid any over/under charging issues [10–12]. Reihani et al. [13] simulated grid-scale battery storage to implement peak load shaving, power smoothing and voltage regulation of a distribution system. Tewari and Mohan [14] analyzed and managed a sodium-sulphide (NaS) battery to shift wind power generation from off-peak to peak-load times and explored market participation opportunities for the battery. Díaz-González [15] managed a flywheel-based storage device to achieve wind power smoothing for grid integration using a vector-controlled algorithm and Chandra et al. [16] used a battery system for frequency damping of system oscillations. Zhou et al. [17] investigated the sizing of a standalone PV-hydrogen system based on an optimized energy management strategy aimed at maximizing efficiency of operation of the hydrogen system. Garcia et al. [18, 19] proposed an intelligent energy management system to determine the power sharing between the hydrogen and battery storage based on operating costs in the hybrid standalone system and yielded better results as against the simple state-based energy management strategies. Cheng et al. [20] used PSO with roulette wheel redistribution mechanism to include power balance equality constraints in the energy management strategy. The energy management strategy considers the effects of depth of discharge of the battery storage and enables extending longevity by penalizing charging and discharging based on SOC levels.

Gamarra and Guerrero give a detailed overview of the different optimization techniques applied to microgrid planning and energy management. Wang et al. [21] presented a hierarchical energy management strategy for minimizing operation costs while optimizing the uncertainties in the wind and load and tested it on RT_Lab real-time platform. Mohammadi et al. optimized the management of a microgrid using Hong's estimation [22] and stochastic-based frameworks [23] to minimize costs and manage uncertainties. They also proposed a unit commitment formulation for the microgrid based on cuckoo search algorithm [24]. Chaouachi et al. [25] attempted an online energy management strategy involving intelligent and multi-objective optimization techniques for a hybrid microgrid to minimize costs and emissions. Chen et al. [26] employed intelligent fuzzy-based management of battery SOC in a DC microgrid integrating renewable source resulting in improved battery lifetime. Feroldi et al. [27] conceptualized control based on receding horizon strategy giving highest priority to wind generation and using hydrogen energy as the least priority source. The strategy enabled an improvement of about 88% in power supply delivery. R. Palma-Behnke et al. [28] employed the rolling horizon strategy to manage a wind-PV-diesel-storage hybrid system by evaluating set points for generating and storage units for optimized operation of the microgrid based on demand side management. Stochastic-based dynamic programming is employed in [29] to adapt to uncertainties of wind energy and market price variations.

ESSs also find applications in distributed systems for managing renewable power curtailment occurring due to transmission system constraints [30]. Fu [31] adapted a distribution feeder and operated it as a microgrid by integrating renewable sources and ESSs to measure and observe power quality issues. Silva-Monroy and Watson [32] addressed some core issues encountered while integrating energy storage devices for market management applications for the grid. Abdeltawab et al. [33] also proposed a market-oriented strategy for managing a wind-battery storage system with the aim of earning maximum profit in a deregulated market structure.

6. Energy management of energy storage for a hybrid renewable system – a case study

A hybrid renewable system consisting of a wind turbine with a solar panel is considered in the case study to understand the need for storage system and to simulate how management of the energy storage will help in improving the reliability and performance of the power system. The wind turbine produces wind power through an asynchronous induction machine at a rated power of 200 kW at 400 V. A 75 kW solar panel is connected to the power system through an inverter to convert the dc current into alternating current to deliver the load. The system is a grid-connected power generating system which delivers the power generated to the grid through a small substation. The hybrid system is simulated by modeling the wind and solar power models as detailed in equations (2) and (2) using Matlab coding software with wind speed and irradiation data fed from real-time measured data from a wind farm site.

a. Wind turbine modeling: The turbine generates power P_w depending on the wind speed v. If the speed is lesser than the cut-in speed (v_{ci}) or above the cut-off speed (v_{co}), then the turbine does not generate power. For wind speeds greater than v_c and rated speed of turbine v_r the power is proportional to cubic of wind speed. $Cp(\lambda, \beta)$ is the power co-efficient between the tip-speed ratio λ and the pitch angle β. ρ is the density of air and A denotes the wind turbine swept area.

$$Pw(v) = \begin{cases} 0, & v \le vci \quad \text{or} \quad v \ge vco \\ 0.5\rho ACp(\lambda,\beta)v^3, & vci \le v \le vr \\ P\text{rated} \quad \text{wt}, & vr \le v \le vco \end{cases} \tag{1}$$

b. Solar power modeling: Let Ypv be the rating of the solar panel in kilowatt. Solar power generated P_{pv} in a panel is dependent on the solar irradiation Gc and temperature Tc is incident on the panel. α is the temperature coefficient and fpv is the derating factor of the solar panel. Then, $GSTC$ and $TSTC$ are the irradiation and temperature values at standard test conditions.

$$P_{pv} = Y_{pv} f_{pv} \frac{G_c}{G_{STC}} \left[1 + \alpha\left(T_c - T_{STC}\right)\right] \tag{2}$$

The simulation is run based on real-time data recorded from a wind test station in southern Tamil Nadu, India. The wind speed profile and the irradiation and temperature are shown in **Figures 6** and **7**, respectively. Data measurements were conducted for a period of ten days and simulations carried out.

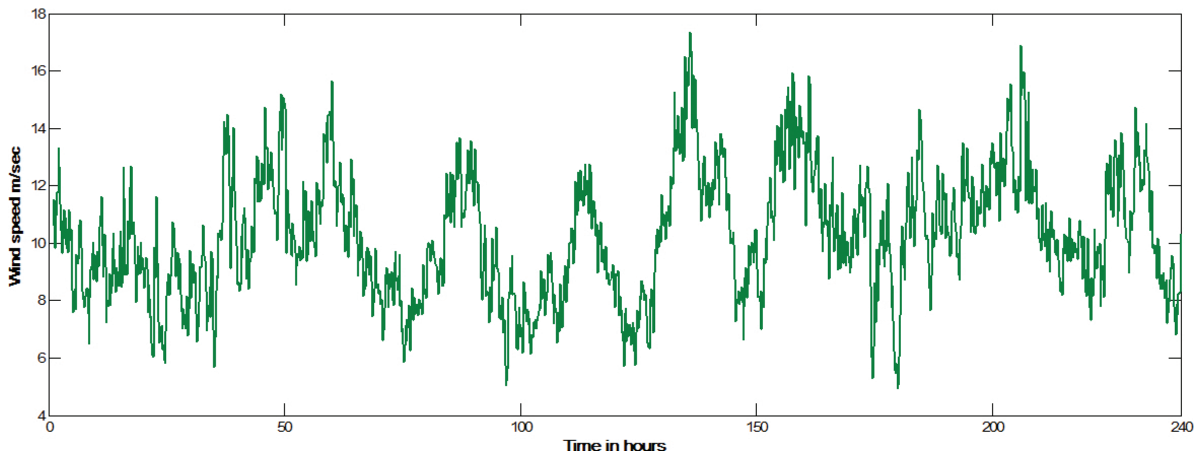

Figure 6. Wind speed in meter per second.

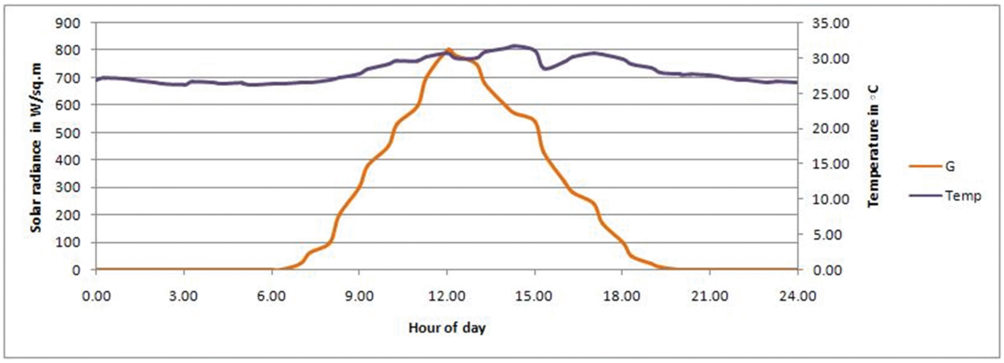

Figure 7. Solar irradiation and temperature.

The sum power thus generated by the wind and the solar system calculated using equations (2) and (2) is considered to be P_{gen} and is found to be highly intermittent and varying. It becomes a very difficult task for the system operator to schedule this power to the grid. Such high invariabilities also pose to destabilize the grid and tend to affect the quality of the delivered power. Hence, the power generated needs to be dispatched based on a scheduling strategy which eliminates the intermittencies and meets the demand. Also, it is to be noted that maximum wind generation occurs at times like late nights when the load on the grid is at minimum and hence this power cannot be dispatched. Any sudden surges created by wind power cannot be accommodated immediately and the hybrid renewable energy system (HRES) must adhere to feed in power limits of the grid. So, the scheduling strategy takes into account a certain amount of peak shaving and ramp rate-limiting features to address these issues. The power generated (denoted by P_{gen}) and the power to be dispatched (denoted by *Dem*) is simulated and plotted in **Figure 8**. There is a need to manage the energy generated to meet the dispatch curve. Let us explore some energy management strategies to improve this power scenario and understand the need and role of energy storage in the form of case studies developed for a wind-PV HRES using Matlab. Each case study clearly presents the management strategy implemented to operate the storage system optimally.

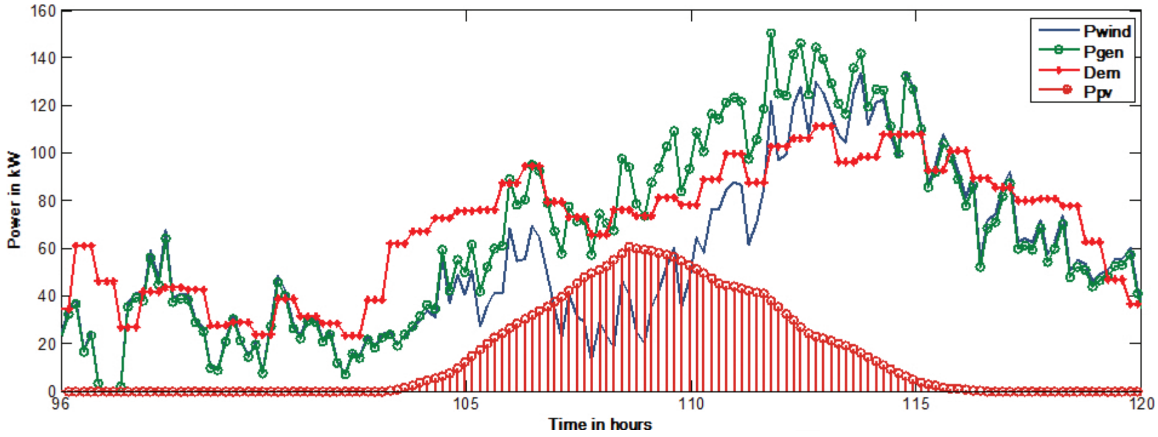

Figure 8. Power graph showing generated and scheduled power.

6.1. Case 1: Without storage

In this scenario the power generated by the HRES has to be delivered as it is generated. So at times when $P_{gen} > Dem$ the demand is met and the excess generation is stalled leading to spilling losses. At times when $P_{gen} < Dem$, the generated power is entirely fed to meet the demand and the excess demand has to be shed thus leading to shedding losses. Additionally, the shed power has to be met by some other form of conventional energy like a backup diesel generator. The power curve showing power mismatch between the P_{gen} and *Dem* is plotted as shown in **Figure 9**.

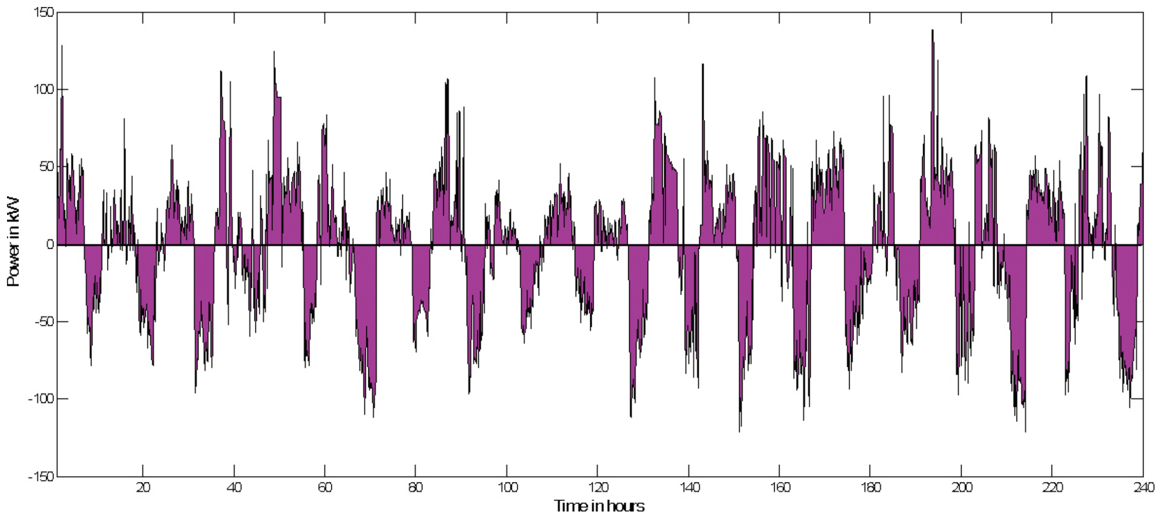

Figure 9. Power mismatch curve.

Evaluation of simulation results show that the total energy delivered by the HRES for the simulated duration of 10 days is 18.64 MWh, with a total of 4.5 and 4.8 MWh of energy lost due to spilling and shedding, respectively. This led to an overall estimated loss of power supply probability (LPSP) of 26.14% [34].

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6.2. Case 2: With a single battery bank

In this scenario, consider a VRB with the system to improve the power delivery and reduction of losses. Flow batteries have been proving to be an excellent solution for integration of renewable systems due to their ability to store huge capacities for longer time and deliver over 10,000 charge/discharge cycles. A detailed sizing study was conducted to evaluate the optimum size of the battery using Bat optimization algorithm. The methodology can be referred in [34]. The optimum size thus found for this case is 1250 Ah operating at 120 V. The specifications of the VRB battery are tabulated in Table 1. VRB battery is a modular structure, with each module has a rating of 625 Ah 48 V (30 kWh). Hence the VRB battery has two parallel banks, each having three modules in series. Thus, the total number of battery modules is 6. The VRB battery is modelled based on SOC given by

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) + P_b(t) \times \frac{\Delta t}{E_{bess}} \tag{3}$$

*Ebess*is the energy capacity of the battery in kilowatt hour and *Pb*(*t*)is the power to be charged/discharged by the battery in time durationΔt. A simple energy management strategy is developed to avoid any over/under charging of the battery. It is shown in **Figure 10**. The power delivered (P_{dis}) curve plotted against Dispatch (*Dem*) and the power mismatch ($Dem\text{-}P_{dis}$) curves are shown in **Figure 11**. **Figure 12** shows the SOC of the VRB battery.

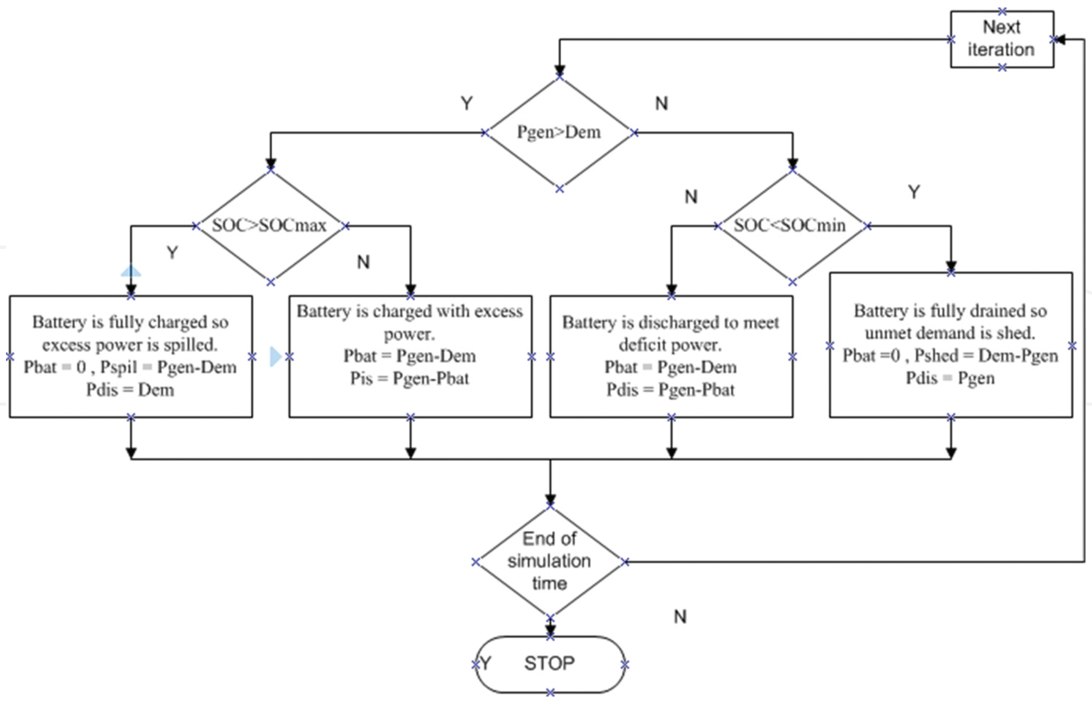

Figure 10. Energy management of VRB battery.

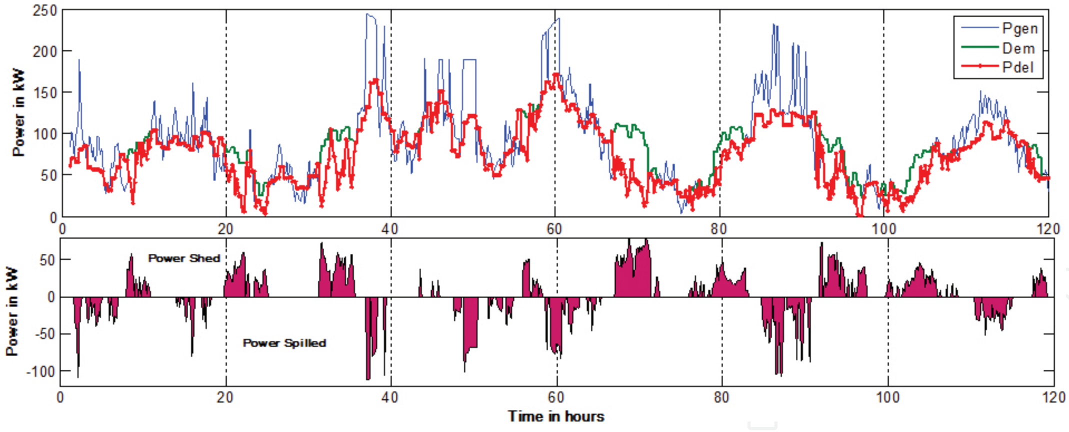

Figure 11. Power delivered curve (*Dem vs* P_{dis}) and power mismatch curve.

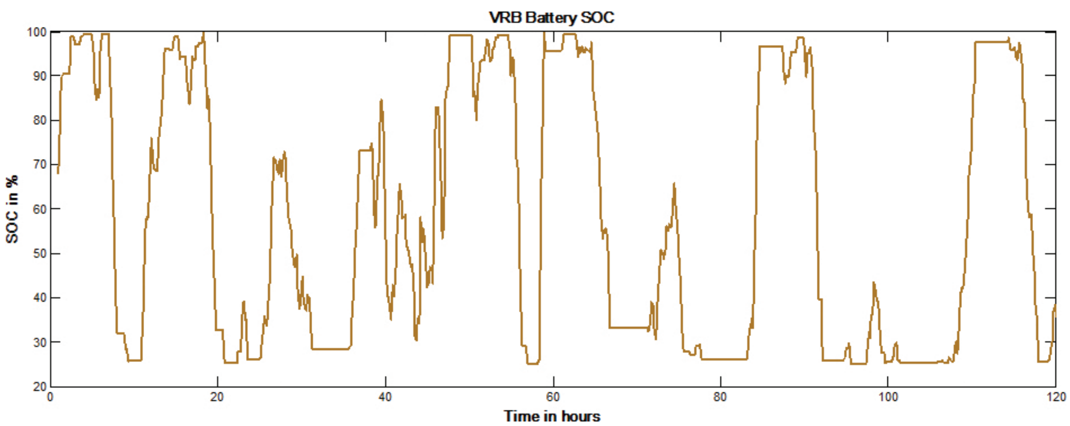

Figure 12. SOC of VRB battery.

The total energy delivered by the HRES is now increased to 23.2 MWh, and the shedding and spilling losses are reduced to 2.6 MWh and 2.2 MWh, respectively, resulting in a profit of 1020.4 $ in the simulation period for 10 days. Assuming VRB battery energy cost of about 600 $/kWh, the payback period is evaluated as about 6 years. The LPSP is also reduced to 11.25%.

6.3. Case 3: With hybrid battery energy storage

In this scenario, let us consider a VRB and a lithium-ion battery system to be integrated in parallel with the system to improve the power delivery and reduction of losses. Lithium-ion batteries are characteristics of high power capacities which can be utilized to balance the intermittencies experienced in this case. The lithium-ion battery is operated for high power requirements and VRB for storing energy for longer duration. Hence, Li battery is of higher power capacity and VRB is sized to be with higher energy capacity. Power limits for Li and VRB batteries is set to be 60 and 30 kW, respectively. The specifications of the Li-ion battery are shown in Table 1. The VRB battery has an energy capacity of 625 Ah (75 kWh) and is formed by connecting three 625 Ah 48 V modules in series. The Li-ion battery capacity is 250 Ah (30

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kWh). A simple energy management strategy is developed to avoid any over/under charging of both the batteries as shown in **Figure 13**. As shown, the VRB battery is checked for power limits and operated. Li-ion battery is operated only when the power requirement is beyond the limit of VRB battery or when the VRB battery is completely full/dry. The power delivered (P_{dis}) curve plotted against Dispatch (*Dem*) and the power mismatch (*Dem*–P_{dis}) curves are shown in **Figure 14**. **Figure 15** shows the SOC of the VRB and Li-ion batteries. It is to be noted that the Li-ion battery undergoes more charging/discharging cycles due to its smaller capacity and greater depth of discharge.

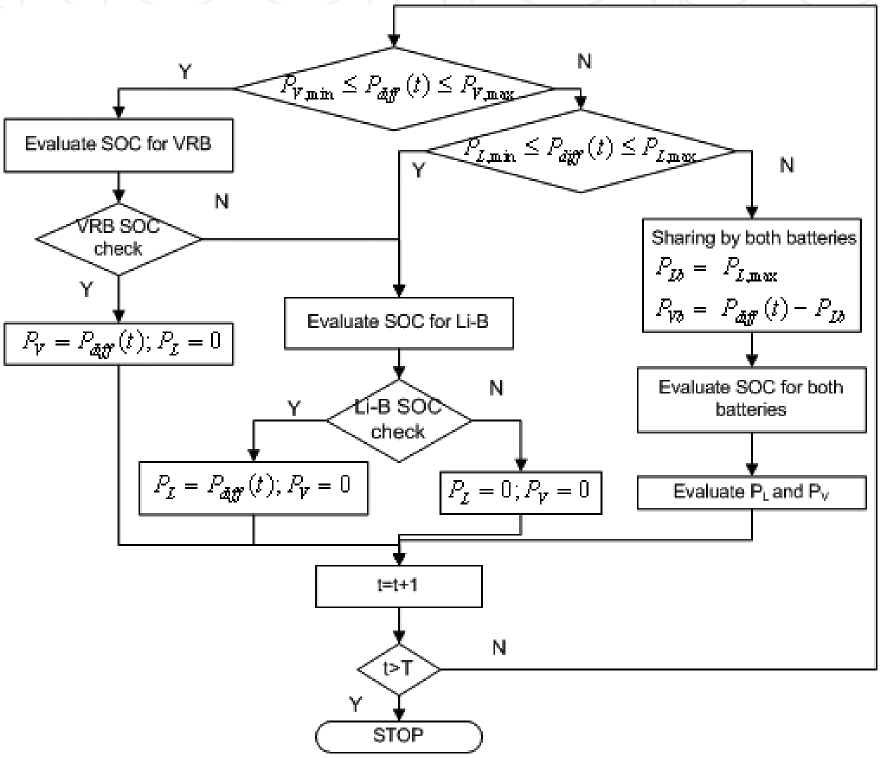

Figure 13. Energy management of hybrid BESS.

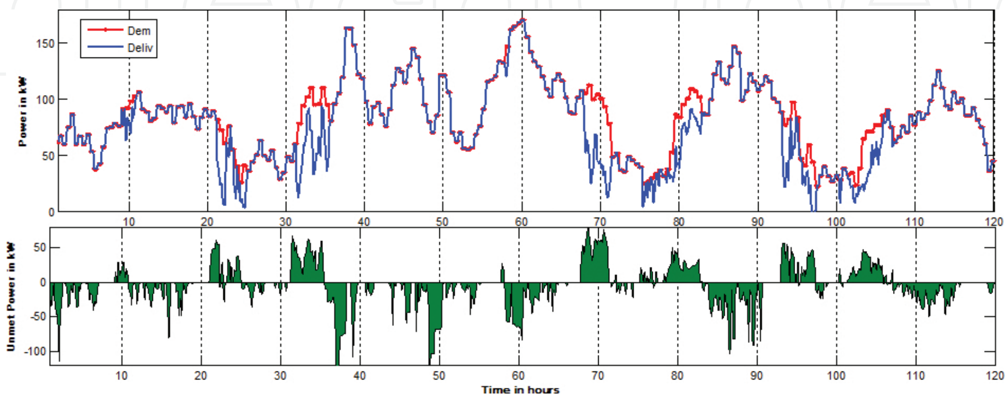

Figure 14. Power delivered curve (*Dem vs* P_{dis}) and power mismatch curve.

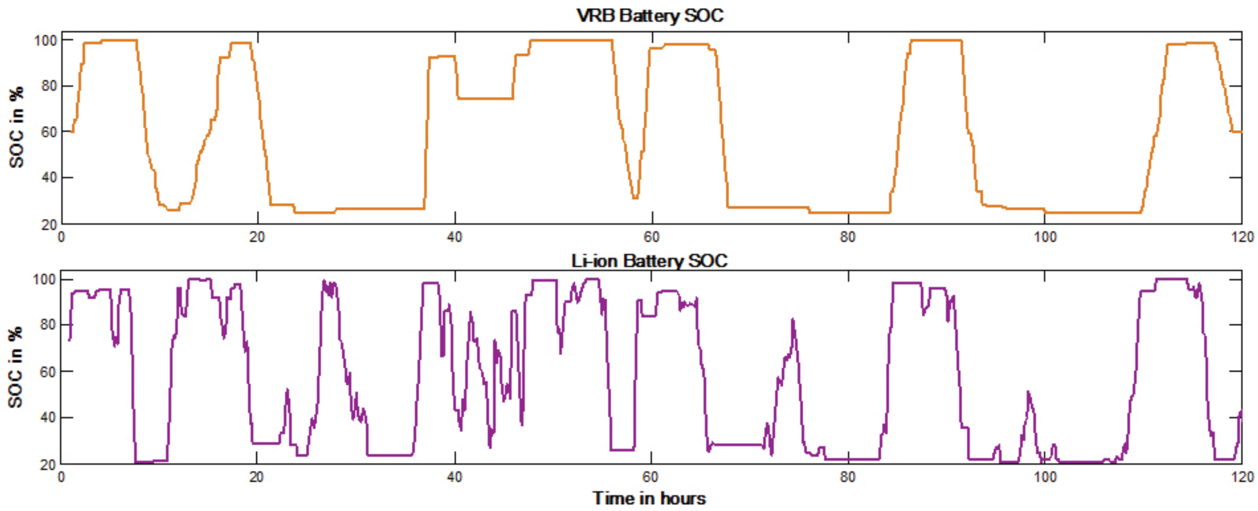

Figure 15. SOC of VRB and Li-ion battery.

The total energy delivered by the HRES is now increased to 23.2 MWh, and the shedding and spilling losses are reduced to 1.9 and 1.7 MWh, respectively, resulting in a profit of 19,697$ in the simulation period for 10 days. Assuming the VRB battery energy cost of about 600 $/kWh and the Li-ion battery energy cost of about 500 $/kWh, the payback period is evaluated as about 4 years. The LPSP is also reduced to 8.28%.

6.4. Case 4: With dual VRB battery energy storage

: In this scenario, let us consider a dual VRB to be integrated in parallel with the system to improve the power delivery and reduction of losses. VRB battery modules of capacity which is the same as the ones used in Case 2 is taken but instead of operating them as a single 150 kWh system, they are now operated as two separate VRB battery banks. Each bank has three 625 Ah 48 V batteries in series. Thus let VRB1 and VRB2 be two separate VRB batteries, each of size 90 kWh. Cost of investment for battery remains the same, as the number of battery modules used is the same. But more power electronic components are used as both batteries need individual control. They are operated in master–slave relationship to enable complete charge/discharge cycles to improve lifetime and performance of the VRB. First VRB1 is set as master battery which undertakes all charging and VRB2 is the slave battery which only takes care of discharging cycles. Once either battery reaches its peak limits (fully charged or discharged), the roles of batteries are interchanged. In cases when the power requirement exceed the power limit of any one battery then both batteries also operate in parallel to deliver the required power mismatch. A simple energy management strategy is developed as shown in **Figure 16** to avoid any over/under charging of both the batteries implemented using fuzzy logic for optimal power sharing between the dual batteries. The power delivered (P_{dis}) curve plotted against dispatch (*Dem*) and the power mismatch ($Dem–P_{dis}$) curves are shown in **Figure 17**. **Figure 18** shows the SOC of the two VRB batteries, respectively.

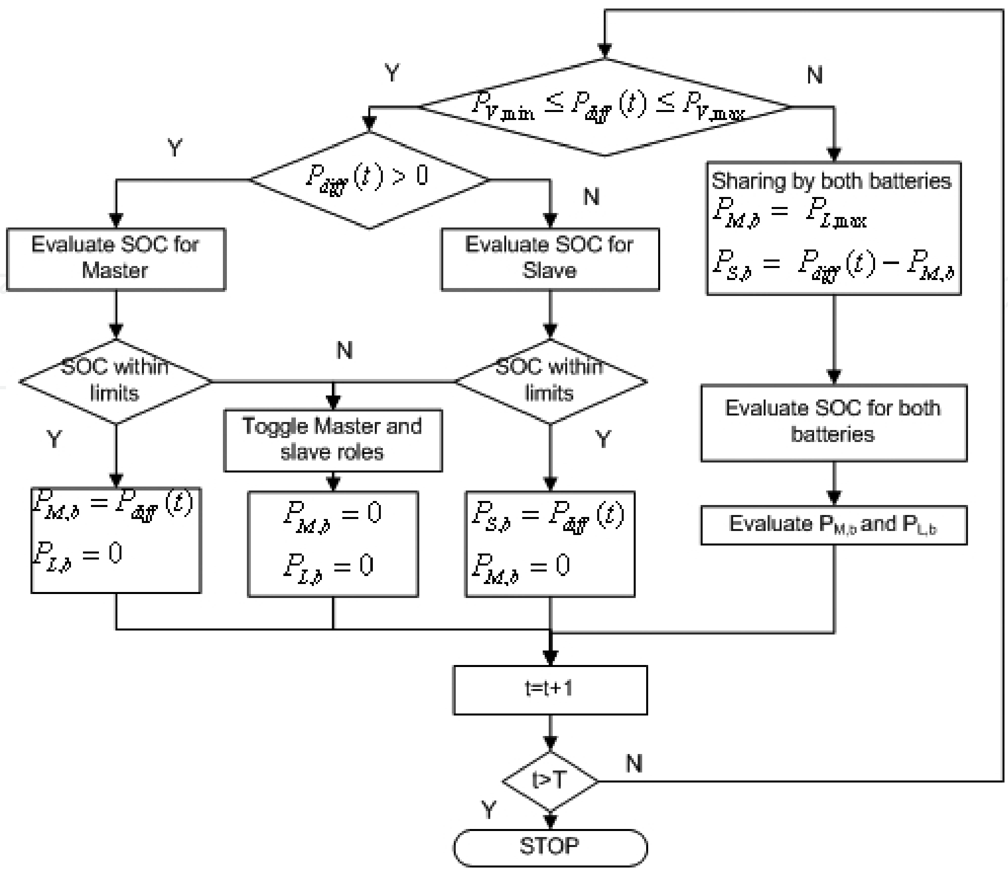

Figure 16. Energy management of dual VRB battery.

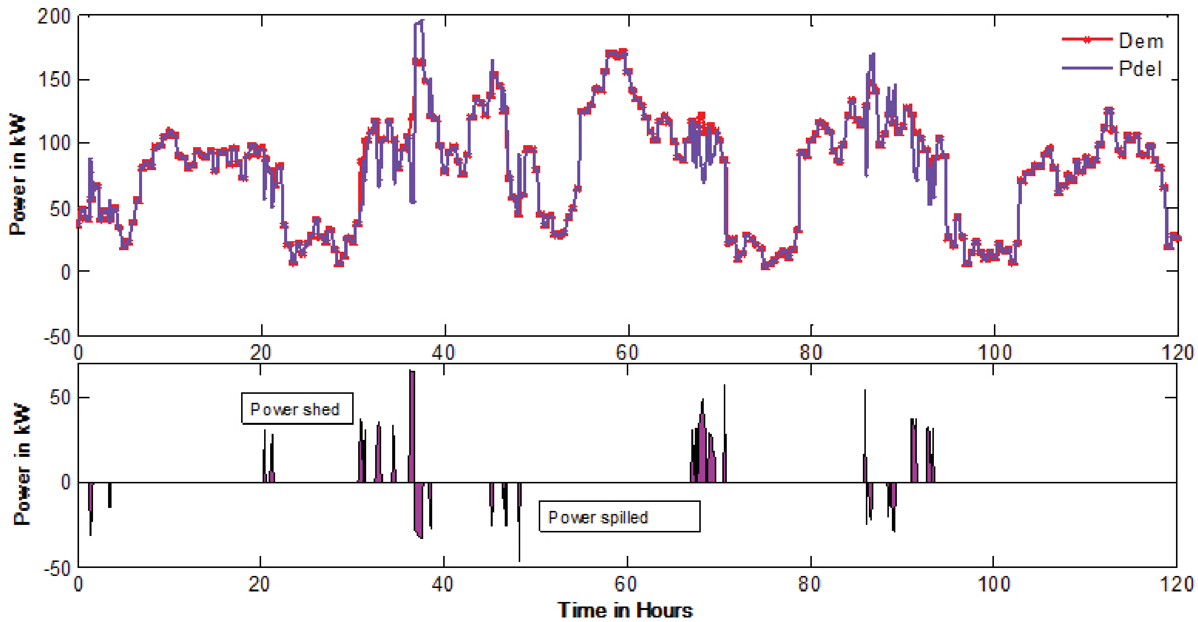

Figure 17. Power delivered curve (*Dem vs* P_{dis}) and power mismatch (*Dem*–P_{dis}).

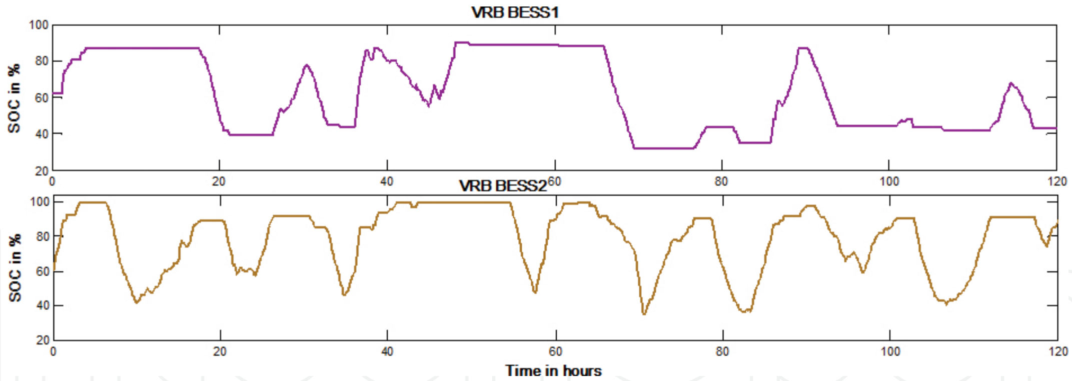

Figure 18. Dual VRB battery SOC.

The total energy delivered by the HRES is now increased to 23.3 MWh, and the shedding and spilling losses are reduced to 0.212 and 0.0925 MWh, respectively, resulting in a profit of 28,133$ in the simulation period for 10 days. Assuming the VRB battery energy cost of about 600 $/kWh, the payback period is evaluated as about 4 years. The LPSP is now reduced to 1.21%. Thus, the energy management of the energy storage has a great impact on the performance of the power system.

7. Conclusion

Energy storages are becoming indispensible for operation of DGs integrating renewable power sources. Advancement in technology now ensures power storage and delivery from few seconds to days/months. Optimized selection, sizing and siting of ESS will be critical for design engineers. Effective implementation and usage of ESS in the distributed grid requires intelligent and flexible energy management strategies capable of handling the dynamics of distributed systems. Most energy management systems focus on grid power balance and SOC of ESS. Recent research works focus on implementing energy management to minimize operating costs, manage uncertainties and reduce emissions. Application of optimization tools and techniques has enabled the development of flexible and effective energy management strategies. An effective dispatch and management strategy also needs to ensure efficient storage operation so as to enable its full life cycle usage. The challenge is to prioritize these objectives and evaluate a strategy most optimum for the considered application which can assure reliable power delivery without affecting system stability.

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References

[1] REN21 – Renewable Energy Policy Network for the 21st Century. The First Decade: 2004–2014 – 10 years of renewable energy progress. 2015.

[2] International Energy Agency. Distributed generation in liberalised electricity markets, 2002. 2002.

[3] Robert H. Lasseter. Microgrids and distributed generation. Intelligent Automation and Soft Computing. 2010;16(2): 225–234. DOI: 10.1080/10798587.2010.10643078.

[4] Purchala K., Belmans R., Exarchakos L., Hawkes A.D. Distributed generation and the grid integration issues. EUSUSTEL. https://www.eusustel.be/public/documents_publ/WP/WP3/WP%203.4.1%20Distributed%20generation%20and%20grid%20integration%20issues.pdf. Date accessed: 10/04/2016

[5] Lopes J.A.P., Moreira C.L., Madureira A.G. Defining control strategies for microgrids islanded operation. IEEE Transactions on Power Systems. 2006;21(2): 916–924.

[6] DOE. DOE Global Energy Storage Database [Internet]. [Updated: 26 October, 2015]. Available from: http://www.energystorageexchange.org/projects/data_visualization [Accessed: 4 February, 2016].

[7] Fathima A.H., Palanisamy K. Battery energy storage applications in wind integrated systems – A review. In: International Conference on Smart Electric Grid (ISEG), India; 19–20 September 2014. IEEE Xplore Digital Library. p. 1–8. DOI: 10.1109/ISEG.2014.7005604.

[8] Gharavi H., Ardehali M.M., Ghanbari-Tichi S. Imperial competitive algorithm optimization of fuzzy multi-objective design of a hybrid green power system with considerations for economics, reliability, and environmental emissions. Renewable Energy 2015;78:427–437. DOI: 10.1016/j.renene.2015.01.029.

[9] Nykamp S., Bosman M.G.C., Molderink A., Hurink J.L, Smit G.J.M. Value of storage in distribution grids — Competition or cooperation of stakeholders? IEEE Transactions on Smart Grid. 2013;4(3):1361–1370. DOI: 10.1109/TSG.2013.2254730.

[10] Ipsakis D., Voutetakis S., Seferlis P., Stergiopoulos F., Elmasides C. Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage. International Journal of Hydrogen Energy 2009;34:7081–7095.

[11] Dash V., Bajpai P. Power management control strategy for a stand-alone solar photovoltaic-fuel cell–battery hybrid system. Sustainable Energy Technologies and Assessments 2015;9:68–80. DOI: 10.1016/j.seta.2014.10.001.

[12] Goebel C., Callaway D.S., Jacobsen H. The impact of state of charge management when providing regulation power with energy storage. IEEE Transactions on Power Systems. 2014;29(3):1433–1434.

[13] Reihani E., Sepasi S., Roose L.R., Matsuura M. Energy management at the distribution grid using a battery energy storage system (BESS). Electrical Power and Energy Systems. 2016;77:337–344.

[14] Tewari S., Mohan N. Value of NAS energy storage toward integrating wind: Results from the wind to battery project. IEEE Transactions on Power Systems. 2013;28(1):532–541.

[15] Díaz-González F., Sumper A., Gomis-Bellmunt O., Bianchi F.D. Energy management of flywheel-based energy storage device for wind power smoothing. Applied Energy 2013;110:207–19.

[16] Chandra S., Gayme D.F., Chakrabortty A. Coordinating wind farms and battery management systems for inter-area oscillation damping: A frequency-domain approach. IEEE Transactions on Power Systems. 2014;29(3):1454-1462.

[17] Zhou K., Ferreira J.A., de Haan S.W.H. Optimal energy management strategy and system sizing method for stand-alone photovoltaic-hydrogen systems. International Journal of Hydrogen Energy 2008;33:477–489.

[18] García P., Torreglosa J.P., Fernández L.M., Jurado F. Optimal energy management system for standalone wind turbine/photovoltaic/hydrogen/battery hybrid system with supervisory control based on fuzzy logic. International Journal of Hydrogen Energy 2013;38:14146–14158.

[19] García P., Torreglosa J.P., Fernández L.M., Jurado F, Langella R., Testa A. Energy management system based on techno-economic optimization for microgrids. Electric Power Systems Research 2016;131:49–59.

[20] Cheng Y., Chuang M., Liu Y., Wang S., Yang Z. A particle swarm optimization based power dispatch algorithm with roulette wheel re-distribution mechanism for equality constraint. Renewable Energy 2016;88:58-72.

[21] Wang C., Liu Y., Li X., Guo L., Qiao L., Lu H. Energy management system for stand-alone diesel-wind-biomass microgrid with energy storage system. Energy 2016;97:90-104.

[22] Mohammadi S., Mozafari B., Solimani S., Niknam T. An adaptive modified firefly optimisation algorithm based on Hong's point estimate method to optimal operation management in a microgrid with consideration of uncertainties. Energy 2013;51:339-348.

[23] Mohammadi S., Soleymani S., Mozafari B. Scenario-based stochastic operation management of microgrid including wind, photovoltaic, micro-turbine, fuel cell and energy storage devices. International Journal of Electrical Power and Energy Systems. 2014;54:525–535.

[24] Mohammadi S., Mozafari B., Solimani S., Niknam T. Stochastic scenario based model and investigating size of ESS for PEM-fuel cell unit commitment for microgrid consid-

ering profitable strategies. IET Generation, Transmission and Distribution 2014;8(7): 1228–1243. DOI:10.1049/iet-gtd.2013.0026.

[25] Chaouachi A., Kamel R.M., Andoulsi R., Nagasaka K. Multiobjective intelligent energy management for a microgrid. IEEE Transactions on Industrial Electronics. 2013;60(4): 1688–1699.

[26] Chen Y., Wu Y., Song C., Chen Y. Design and implementation of energy management system with fuzzy control for DC microgrid systems. IEEE Transactions on Power Electronics. 2013;28(4):1563-1570.

[27] Feroldi D., Rullo P., Zumoffen D. Energy management strategy based on receding horizon for a power hybrid system. Renewable Energy 2015;75:550-559.

[28] Palma-Behnke R., Benavides C., Lanas F., Severino B., Reyes L., Llanos J., DorisSáez A. Microgrid energy management system based on the rolling horizon strategy. IEEE Transactions on Smart Grid. 2013;4(2):996-1006.

[29] Shu Z., Jirutitijaroen P. Optimal operation strategy of energy storage system for grid-connected wind power plants. IEEE Transactions on Sustainable Energy. 2014;5(1): 190-199.

[30] Gabash A., Li P. Active-reactive optimal power flow in distribution networks with embedded generation and battery storage. IEEE Transactions on Power Systems. 2012;27(4):2026-2035.

[31] Fu Q., Montoya L.F., Solanki A., Nasiri A., Bhavaraju V., Abdallah T., Yu D.C. Microgrid generation capacity design with renewables and energy storage addressing power quality and surety. IEEE Transactions on Smart Grid. 2012;3(4):2019-2027.

[32] Silva-Monroy C.A., Member IEEE, Watson J. Integrating energy storage devices into market management systems. Proceedings of the IEEE. 2014;102(7):1084-1093.

[33] Abdeltawab H.H., Mohamed Y.A.R.I. Market-oriented energy management of a hybrid wind-battery energy storage system via model predictive control with constraint optimizer. IEEE Transactions on Industrial Electronics. 2015;62(11):6658-6670.

[34] Fathima A.H., Palanisamy K. Optimized sizing, selection, and economic analysis of battery energy storage for grid-connected wind-PV hybrid system. Modelling and Simulation in Engineering 2015. vol.2015, 16 pages Article ID 713530. DOI: 10.1155/2015/713530.