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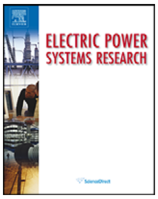

Battery energy storage technology for power systems—An overview

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ABSTRACT

The penetration of renewable sources (particularly wind power) in to the power system network has been increasing in the recent years. As a result of this, there have been serious concerns over reliable and satisfactory operation of the power systems. One of the solutions being proposed to improve the reliability and performance of these systems is to integrate energy storage devices into the power system network. Further, in the present deregulated markets these storage devices could also be used to increase the profit margins of wind farm owners and even provide arbitrage. This paper discusses the present status of battery energy storage technology and methods of assessing their economic viability and impact on power system operation. Further, a discussion on the role of battery storage systems of electric hybrid vehicles in power system storage technologies had been made. Finally, the paper suggests a likely future outlook for the battery technologies and the electric hybrid vehicles in the context of power system applications.

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1. Introduction

The need for storage devices and their utilization in power systems has long been debated. An overview of the different storage technologies, their applications and limitations are discussed in [1–5]. The earlier reviews on storage technology [1,2] focus exclusively on lead-acid battery technology. In [1] the economic models, their controls, ratings and applications found in US power systems are discussed and in [2] the possible future applications are suggested. In [3] the use of battery energy technology to improve the power quality (mainly voltage depressions and power interruptions) and reliability of the power system are discussed. Some of the reviews carried out recently in [4,5] discuss about the various storage technologies and suggest that so far the battery technology is the most widely used storage device for power system applications. In [4] the authors state the support provided by the DOE

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(US) and other organizations to demonstrate the application of various storage technologies (predominantly battery technologies) at different power utility companies in North America. Further it is stated that the energy storage technology will be the key to the future development of renewable energy. In [6] some of the commercial successes in electric power storage technologies have been discussed and it also discusses some of the emerging applications in power storage like wind farm power stabilization, etc. The report [7] provides a catalogue of the various current technologies (steam, hydro, wind, etc., and storage being one of them). Their future outlooks, evaluations of security of supply and environmental impacts, climate change evaluations, and technical and economic analysis, in the context of energy planning activities.

In spite of the large number of investigations carried out to apply different storage technologies to power systems, very few of them have been implemented in practice. Some of the main reasons for this limited practical application are:

(1) The conventional power system had large amounts of generating sources whose generation could be easily varied to match the load demand. Also most of these systems operate in a interconnected manner and the power from generators in other areas can be used to balance the load demand. In such a situation it is very difficult to justify the economic gains obtained in using storage technologies.
(2) Lack of practical experience and lack of availability of tools which could be used for: (i) operational cost optimization and (ii) assess the benefits of storage technology (considering the market models) during planning.

Now, the scenario is changing and there are large number of generating sources (mostly non-conventional) whose power output cannot be controlled. The power from these generators varies according to the availability of the resources (for example in case of wind turbine, it depends on the availability of wind). Additionally, many of these generating sources would be operating as distributed generators. In this case, during the non-availability of the power system grid, it may be beneficial to operate these uncontrollable sources in an island mode. Also the storage technologies could play a vital role in improving the overall stability and reliability of power system (islolated/grid connected/systems with large share of renewable sources) and could defer the costs need to improve the transmission and distribution capacity to meet ever growing power demand. The storage technologies could also play an important role in the deregulated markets like providing arbitrage, increasing the value of renewable power in some of these markets, etc.

There are many types of storage technologies available at present. Although examining all these technologies is necessary, this paper concentrates only on battery storage technologies and gives an overview of the following:

(1) Different types of battery energy storage technologies (batteries as well as their controls) available at present.
(2) State some of the battery energy storage technologies implemented/planning to be implemented in an actual power system.
(3) Identify the likely future power system applications and analysis tools needed to be developed to examine the economic as well as technological benefits of various battery energy storage technology.
(4) Discuss the use of electric drive vehicle (EDV) power to improve the reliability of electric utilities.

The various ways in which battery and EDV technologies can help in improving the reliable operation of the future power systems is explained by considering the Danish electricity grid. The Danish electricity grid has a special characteristic of high wind power and distributed generation penetration. This type of electricity grid is being envisioned as the future electricity networks in many other countries. Although about 20% of the total electricity demand was met by wind power alone in 2007 in Denmark, there are ambitious targets set by the politicians to increase the wind power penetration to 50%. In this context, the different technologies which would assist 50% wind power penetration in Denmark (by 2025) are being examined and one such technology is the battery technology, which is presented in this paper.

2. Battery energy storage technology

The battery energy storage system (BESS) comprises mainly of batteries, control and power conditioning system (C-PCS) and rest of plant. The rest of the plant is designed to provide good protection for batteries and C-PCS. The battery and C-PCS technologies are the major BESS components and each of these technologies is rapidly developing. So the present state-of-art of each of them have been discussed separately.

2.1. Batteries

The batteries are made of stacked cells where-in chemical energy is converted to electrical energy and vice versa. The desired battery voltage as well as current levels are obtained by electrically connecting the cells in series and parallel. The batteries are rated in terms of their energy and power capacities. For most of the battery types, the power and energy capacities are not independent and are fixed during the battery design. Some of the other important features of a battery are efficiency, life span (stated in terms of number of cycles), operating temperature, depth of discharge (batteries are generally not discharged completely and depth of discharge refers to the extent to which they are discharged), self-discharge (some batteries cannot retain their electrical capacity when stored in a shelf and self-discharge represents the rate of discharge) and energy density.

Currently, significant development is going on in the battery technology. Different types of batteries are being developed of which some are available commercially while some are still in the experimental stage. The batteries used in power system applications so far are deep cycle batteries [8](similar to the ones used in Electric vehicles) with energy capacity ranging from 17 to 40 MWh and having efficiencies of about 70–80%. Of the various battery technologies [8], some seem to be more suitable (have been used) for power system applications and these have been discussed briefly below:

(1) Lead acid: each cell of a lead-acid battery comprises a positive electrode of lead dioxide and a negative electrode of sponge lead, separated by a micro-porous material and immersed in an aqueous sulfuric acid electrolyte (contained in a plastic case).
[(b)]
(a) Flooded type: in the flooded type battery an aqueous sulphuric acid solution is used. During discharge, the lead dioxide on the positive electrode is reduced to lead oxide, which reacts with sulfuric acid to form lead sulfate; and the sponge lead on the negative electrode is oxidized to lead ions, that reacts with sulfuric acid to form lead sulfate. In this manner electricity is generated and during charging this reaction is reversed.

(b) Valve regulated (VRLA) type: the VRLA uses the same basic electrochemical technology as flooded lead-acid batteries, except that these batteries are closed with a pressure regulating valve, so that they are sealed. In addition, the acid electrolyte is immobilized.

(2) Sodium sulphur (NaS): a NaS battery consists of molten sulfur at the positive electrode and molten sodium at the negative electrode separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. During discharge, positive sodium ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2 V. The battery is kept at about 300 °C to allow this process.

(3) Lithium ion (Li ion): the cathode in these batteries is a lithiated metal oxide and the anode is made of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts dissolved in organic carbonates. When the battery is being charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where the combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge.

(4) Metal air: the anodes in these batteries are commonly available metals with high energy density like aluminum or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good hydroxide($OH-$) ion conductor such as potassium hydroxide (KOH). The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH.

(5) Flow batteries: this type of battery consists of two electrolyte reservoirs from which the electrolytes are circulated (by pumps) through an electrochemical cell comprising a cathode, an anode and a membrane separator. The chemical energy is converted to electricity in the electrochemical cell, when the two electrolytes flow through. Both the electrolytes are stored separately in large storage tanks outside the electrochemical cell. The size of the tanks and the amount of electrolytes determines the energy density of these batteries. However, the power density in flow-batteries depends on the rates of the electrode reactions occurring at the anode and cathode. Flow batteries are often called redox flow batteries, based on the redox (reduction–oxidation) reaction between the two electrolytes in the system.

Some of the main characteristics of flow batteries are: high power, long duration, power rating and the energy rating are decoupled, electrolytes can be replaced easily, fast response and can go from charge to discharge modes in about 1 ms (because most redox reactions reaction time is very short), low efficiencies (due to the energy needed to circulate the electrolyte and losses due to chemical reactions). The system does not have any self-discharge, as the electrolytes cannot react when they are stored separately.

(a) Regenerative fuel cell (polysulphide bromide PSB or Regenesys): PSB is a regenerative fuel cell technology that provides a reversible electrochemical reaction between two salt solution electrolytes (sodium bromide and sodium polysulphide). PSB electrolytes are brought close together in the battery cells where they are separated by a polymer membrane that only allows positive sodium ions to go through, producing about 1.5 V.

(b) Vanadium redox (VRB): in each cell of a VRB, the vanadium redox couples [9] are stored in mild sulfuric acid solutions (electrolytes). During the charge/discharge cycles, H^+ ions are exchanged between the two electrolyte tanks through the hydrogen-ion permeable polymer membrane, to produce a voltage of 1.4–1.6 V.

(c) Zinc bromin (ZnBr): in each cell of a ZnBr battery, two different electrolytes flow past carbon–plastic composite electrodes in two compartments separated by a micro-porous poly olefin membrane. During discharge, Zn and Br combine into zinc bromide, generating 1.8 V across each cell. During charge, metallic zinc will be deposited (plated) as a thin film on one side of the carbon–plastic composite electrode.

Amongst all these batteries, the lead-acid battery is the oldest and most mature technology, which has been used for a majority power system applications. The Li-ion, NaS and NiCd batteries seem to represent the leading technologies. in high-power-density battery applications. Of these, Li-ion possesses the greatest potential for future development and optimization. In addition to small size and low weight the Li-ion batteries offer the highest energy density and storage efficiency close to 100%, which makes them ideally suited for portable devices. However, some of the major drawbacks Li-ion technology are its high cost (due to manufacturing complexity arising from the special circuitry to protect the battery) and the detrimental effect that deep discharging has on its lifetime.

Although NiCd and lead-acid can supply excellent pulsed power, they are large, contain toxic heavy metals and suffers from severe self-discharge. The NaS battery, although being much smaller and lighter than NiCd, operates at 300 °C and requires constant heat input to maintain the molten states of the electrolytes. The metal–air batteries have low cost and high energy densities (ideal for many primary battery applications) but are very difficult to be recharged.

The flow batteries are also promising for applications which require long duration storages due to its non-self-discharge capability. A major drawback of the flow battery system is the increased capital and running costs associated with the operation of a chemical plant involving pump systems, flow control with external storage. The main challenges associated with the future development of flow-battery technology are concerned with providing increased power density.

Table 1 summarizes the battery technology used/likely to be used in power system applications and also indicates some of the features of these technologies. The details like efficiency, cost, energy density, operating life cycle have been obtained from [10–12]. The operating life cycle of a battery depends to a large extent on the depth of discharge and the operating temperature. Generally, discharging the battery completely (100% depth of discharge) or operating at temperatures higher than the ambient temperature affects the battery life adversely. The extent to which the battery life is reduced due to deep discharges and high temperatures depends on the type of battery. For example, for every 10– 15 ° F increase in temperature above 70 ° C the life of the lead-acid (VRLA) batteries is reduced by half. The life span given in Table 1 corresponds to ambient operating temperature and specified depth of discharge. This table also gives the largest battery unit installed/planning to be installed in the power system network—its location and rating.

Apart from the applications given in table, there are many other power systems where-in the battery technologies have been used. For example, some of the earliest commercial use of battery storage device were at Bewag, Germany (17 MW/14 MWh battery for frequency regulation) and at Southern California Edison Chino substation (10 MW/40 MWh for load leveling,rapid spinning reserve and instantaneous frequency control [13,14]). The earliest transportable battery (lead-acid), located at the Phoenix distribution system [15] is a multi-mode battery. The battery switches between

Table 1
Battery technologies—characteristics and commercial units used in electric utilities [10–12].

Battery type	Largest capacity (commercial unit)	Location & application	Comments
Lead acid (flooded type)	10 MW/40 MWh	California-Chino Load Leveling	η = 72–78%, cost [d]50–150, life span 1000–2000 cycles at 70% depth of discharge, operating temperature −5 to 40° C [a], 25 Wh/kg, self-discharge 2–5%/month, frequent maintenance to replace water lost in operation, heavy
Lead acid (valve regulated)	300 kW/580 KWh	Turn key system [b] Load Leveling	η = 72–78%, cost [d]50–150, life span 200–300 cycles at 80% depth of discharge, operating temperature −5 to 40° C [a], 30–50 Wh/kg, self-discharge 2–5%/month, less robust, negligible maintenance, more mobile, safe (compared to flooded type)
Nickel Cadmium (NiCd)	27 MW/6.75 MWh [c]	GVEA Alaska Control power supply Var compensation	η = 72–78%, cost [d]200–600, life span 3000 cycles at 100% depth of discharge, operating temperature −40 to 50 °C, 45–80 Wh/kg, self-discharge 5–20%/month, high discharge rate, negligible maintenance, NiCd cells are poisonous and heavy
Sodium Sulphur (NaS)	9.6 MW/64 MWh	Tokyo Japan Load Leveling	η = 89% (at 325 °C), life span 2500 cycles at 100% depth of discharge, operating temperature 325 °C, 100 Wh/kg, no self-discharge, due to high operating temperature it has to be heated in stand-by mode and this reduces its overall η, have pulse power capability of over 6 times their rating for 30 s
Lithium ion			η ≈100%, cost [d]700–1000, life span 3000 cycle at 80% depth of discharge, operating temperature −30 to 60 °C, 90–190 Wh/kg, self-discharge 1%/month, high cost due to special packaging and internal over charge protection
Vanadium redox (VRB)	1.5 MW/1.5 MWh	Japan Voltage sag Peak load shaving	η = 85%, cost [d]360–1000, Life span 10,000 cycles at 75% depth of discharge, operating temperature 0–40 °C, 30–50 Wh/kg, negligible self-discharge
Zinc Bromine	1 MW/4 MWh	Kyushu EPC	η = 75%, cost [d]360–1000, operating temperature 0–40 °C, 70 Wh/kg, negligible self-discharge, low power, bulky, hazardous components
Metal air			η = 50%, cost [d]50–200, Life span few 100 cycles, operating temperature −20 to 50 °C, 450–650 Wh/kg, negligible self-discharge, recharging is very difficult and inefficient, compact
Regenerative fuel cell (PSB)	15 MW/120 MWh (under development)	Innogy's Little Barford station UK	η = 75%, cost [d]360–1000, operating temperature 0–40 °C, negligible self-discharge

[a] Operating at higher temperature will reduce the life and operating at lower temperature will reduce the efficiency.
[b] At Milwauke, Wisconsin.
[c] Provides 10 MVar even when the battery is not discharging.
[d] Capital cost in Euro/kWh.

power quality (2 MW up to 15 s) and power management (200 kW for 45 min) mode.

2.2. Controls and power conditioning system (C-PCS)

The C-PCS form a vital part of the BESS. It interfaces the batteries to the loads (utility/end user) and regulates the battery charge/discharge, charging rate, etc. The C-PCS cost is significant and it can be greater than 25% of the overall energy storage system. However, this technology is maturing rapidly due to the recent developments in the power conditioning systems of the renewable and distributed energy sources. At present research is being carried out to reduce the overall cost, improve reliability, and develop more efficient and better packaging of power conditioning system.

Generally, the BESS C-PCS are designed to use the BESS to achieve many functions [16,17]. Such multi-function BESS have been designed in an attempt to make the BESS technology more economical and cost effective. In order to develop multi-functional BEES several investigators have suggested many control philosophies. Some of the studies design controls BESS to directly improve the power system reliability and operation and the others are indirect applications (normally in the form of adding new features/providing greater capabilities to custom power devices, SVC, STATCOM, etc.). Here the controls designed for direct and indirect BESS applications have been discussed separately.

2.2.1. BESS controls designed for improving power system reliability and power quality (direct power system application)

The enormous development in designing the BESS controls can be attributed to a large extent to the rapid growth in power electronic devices. The BESS controls designed for direct power system applications either consider interconnected system [16,18–22] or isolated systems [23] or hybrid systems [24,25]. Recently, a few investigations have also been carried out to examine the operation [26] and controls [27] of micro grids with BESS. Table 2 summarizes the power system applications for which the BESS controls have been designed. Table presented here indicates the diverse applications for which the BESS controls have been designed but it is not exhaustive. From Table 2 it may be seen that theoretically BESS controls can be designed to achieve different objectives and to be used in different types of systems. However, most of these investigations (except [23]) neither attempt to quantify the benefits of the BESS controls (taking into account the C-PCS costs) nor attempt to make any suggestions about the optimal size/capacity of BESS for the present day market based systems. Although most of these investigators state that increasing BESS capacity improves its capabilities and there by power system performance, no suggestion has been made regarding choosing the optimal size/capacity of BESS. In [23] a heuristic method has been used to choose the BESS capacity but no attempt has been made to quantify the monetary benefits.

Table 2
Direct BESS applications in power system.

	System/locationof BESS	Suggested application/study carried out
1	Near consumers [19]	Suggested for curtailing daily peak demand so as to-improve security (survive disturbances during peak loads), reduce the need for spinning reserve, eliminate the need for demand forecasting and peaking generators
2	Israeli isolated system [23]	Simulation studies to study the impact of a 30-MW BESS on frequency regulation of the system. Suggests other applications like reducing: (i) frequency fluctuation and (ii) spinning reserve
3	Wind-Diesel [25] stand-alone system	Controlling active and reactive power of redox flow batteries using neural networks. Simulation studies carried out to examine the effect of load and wind disturbances
4	Fixed speed wind farm [22]	Smoothing wind farm power output, improving transient stability and providing reactive power support are illustrated through simulations
5	Interconnected power system [21]	Eliminate uncertainty in forecasting the annual peak demand. Other applications, i.e., load leveling, emergency supply, damping of inter area oscillations are demonstrated experimentally (lab setup) using 100 Ah, 110 V lead-acid batteries
6	Interconnected system [18]	Peak load shaving, compensate load unbalance, harmonic and reactive powers (maintain nearly UPF and operate as UPS. A 5-kVA prototype BESS used to demonstrate these in a laboratory
7	Demand side applications [16]	Can be operated in grid connected (active filter, power conditioner, voltage stabilizer) or stand-alone (UPS) mode. Demonstrates these features experimentally (lab) on a 5-kVA battery and through simulation
8	Laboratory Set up [20]	Load leveling, active filtering and operation as UPS-these features of the designed BESS controls are demonstrated experimentally (lab set-up) on a 100-Ah, 110-V lead-acid battery bank

2.2.2. BESS controls designed for improving custom power device capabilities (indirect power system applications)

Most of the indirect applications use BESS to improve the performance and enhance the capabilities of flexible AC transmission system (FACTS) devices. The application of BESS with static compensator (STATCOM) has been explored in [28–30], while in [31] the use of BESS for storage power flow controller (SPFC) has been suggested. On the other hand, in [17] the control of dynamic voltage regulator (DVR) with BESS (for voltage dip mitigation) has been discussed. The design and coordination of FACTS and BESS controls (on a laboratory scale) has been well established and this may be seen from Table 3. Also these studies also demonstrate the benefits of integrating BESS with FACTS device experimentally. In spite of all these advantages, very few BESS-FACTS devices are commercially available. Some of the main reasons for this limited applications are: (i) integrating BESS to FACTS device makes it bulkier and costly. Hence, at present, BESS-FACTS device have very limited commercial applications and are restricted either to systems where-in the benefits out weighs the cost or to systems already having FACTS devices (BESS is integrated to increase the capability of the existing FACTS device).

3. Use of electric drive vehicles (EDV) batteries for power systems

The possibility of using EDV as BESS in power system has been recognized in [2,32] as early as the last decade. Of late a few investigations have been carried out [33] to examine the role of renewable energy/storage technologies for the EDV. Even though it is well known that the BESS used for EDV could also be used for power system applications, only recently in [34,35], the practicality has been examined. In [34], an attempt has been made to assess the economic benefits of using different vehicle types (fuel cell, battery and plug-in hybrid electric vehicle) for providing base load, peak power, spinning reserve and frequency regulation services to the power system has been carried out. While in their companion paper [35], the authors examine the systems and processes needed to tap energy in vehicles and implement vehicle-to-grid power. Further, this study also examines the applicability of vehicle-to-grid power for serving as a back-up for the renewable sources, i.e., wind and solar.

Although the investigation carried out in [34,35] are encouraging, they appear to be only preliminary indicating and discussing

Table 3
Indirect BESS applications in power systems.

	Battery type model	System & rating	Suggested application	Comments
1	–	DVR/BESS [17]	Voltage dip mitigation on a distribution system	Simulation (PSCDA/EMTDC) results presented for a 1 and 2 phase voltage sag
2	VLRA gel variable DC voltage source	STATCOM/BESS	Voltage control, oscillation 3 kVA [28] capacity control damping, transmission	Simulation (PSCAD) results compared with the experimental results to demonstrate the controller performance
3	–	SPFC UPFC/BESS Controllable [31] shunt current	Load leveling for energy management, power factor correction, harmonic filter, spinning reserve	Experimental (lab setup) and simulation results presented to illustrate harmonic control and grid current compensation
4	Constant DC voltage source	STATCOM/BESS 2 MVA [30]	Improving stability and power quality of fixed speed wind turbine	Simulation (PSCDA/EMTDC) results presented for a 2-MW wind turbine and extrapolated for a wind farm
5	VLRA gel constant DC voltage source	STATCOM/BESS [29]	Stability of a single gen. system with STACOM/BESS subjected to 3 phase fault of different durations	Compares in terms of modularity, switching losses and transient stability impact of different BESS/STATCOM topologies experimentally (lab set-up) and through simulation (PSCAD)

the likely future directions for vehicle-to-grid power. However, detailed investigations need to be carried out to develop methods to quantify the benefits of vehicle-to-grid power from the point of view of power systems as well as electric vehicles. Further, a framework needs to be developed which could be used to effectively and economically tap the electric vehicle power to the grid system.

4. BESS models for economic and power system stability studies

In order to study and quantify the impact of BESS on the power system operation and economics several investigations have been carried out. The investigations concerned with economic/optimal sizing, model the BESS from the cost point of view (BESS-economic models) and those concerned with assessing the operational benefits model the BESS the response to power system disturbances at appropriate time scales (BESS-operational model). Since the BESS models used for these two types of studies are completely different, they have been discussed separately.

4.1. BESS models used for economic analysis

Some studies have been carried out to assess the economic benefits of BESS (optimal sizing, etc.) for utility side [36–39] and for demand side [40,41] applications.

(1) Utility side applications: in [36] the method used to determine BESS installation site and capacity of BESS for load leveling application in a distribution system in Korea has been described. The BEES installation site and capacity is found by calculating the improvement in load factor at each main transformer in the distribution substation. On the other hand in [37] an island system has been considered and a comparative study of the dynamic operating cost benefits of BESS for three different utility applications, i.e., automatic generation control, load leveling and spinning reserve have been calculated using the production costing program (DYNASTORE). As an alternative to the DYNASTORE program,in [38] the authors develop an algorithm for economic dispatch and for finding BESS capacity. This method combines the multi-pass dynamic programming with a time shift technique. In [39] a methodology for monetary value analysis of the BESS for load leveling, control power and peak shaving has been suggested. For these applications the economics of different BESS viz., conventional-lead acid and NiCd as well as VRB batteries have been compared.

(2) Demand side applications: in [40] advanced multi-pass dynamic programming has been modified to determine the optimal BESS size and optimal contract capacities for time-of-use (TOU) rate customers at Taiwan Power Company. The focus in [41] has been on cost analysis of a hybrid PV-BESS (isolated system) for demand side applications in southern Taiwan ROC. The economic value of the PV-BESS system is analyzed by considering the load, utility, battery and PV data as well as the specific cost, escalation factor of each of these equipments. However, as stated by the authors, no attempt has been made to include the critical factors like power quality, protection, reliability and security of the isolated system while analyzing the cost benefits.

All these studies consider vertically integrated utilities and do not incorporate the market models to assess the benefits of BESS in the present day deregulated market. The recent investigations carried out by VRB power systems, Canada [9], focus exclusively on integrating VRB BESS to wind power systems [42–45] and some of these studies assess the benefits of VRB BESS in the context of deregulated markets. In [42,43] the benefits of integrating BESS to the Ireland system has been examined considering the different market models and it attempts to provide a economic benefit assessment method, which could perhaps be extended to other system studies. However, as stated in [43] the assessment method is conservative because it considers the monetary gains obtained by using BESS to reduce market imbalances in the Ireland-wind farm system but does not take into account the other benefits like capability of providing ancillary services, etc. Hence, in order to obtain more realistic assessment of BESS benefits, it is necessary to incorporate the multi-functionality of BESS and the appropriate market models. At present, there seems to be no clarity about modeling the multi-functional feature of the BESS (particularly, when a single BESS is used to operate at different time scales, i.e., short duration like power quality and long duration like power management) for a more realistic economic assessment.

4.2. BESS models for power system studies

The operational models of BESS can be further classified based on the power system study time scale. the investigations carried out so far mainly focus on examining the effect of BESS on (i) reliability and (ii) stability of the power system:

(1) BESS-power system reliability analysis: in [46] the focus has been on finding a method to assess the reliability of generating systems operating in parallel with energy storage facilities. For this purpose the well being technique (which incorporates deterministic technique into a probabilistic evaluation) has been suggested in an attempt to provide better insight to power system planners.

(2) BESS-power system stability analysis: in [23] an attempt has been made to quantify the technical benefits of using a BESS in an isolated power system for providing frequency regulation. For this purpose, the frequency variance of an isolated Israel system with and without BESS has been calculated for a measured load disturbance. In [47–49] dynamic models of BESS have been suggested with a view of using them for power system studies. In [47] a dynamic model of BESS (expressed as a transfer function block) for large scale power system studies has been suggested. This model is developed by combining the known converter model (equivalent circuit model) with the available battery model (which represents the characteristics and internal losses). In [48] the modeling and data requirements for BESS for power system stability studies have been discussed. These BESS models have been implemented in the PowerTech labs Transient Stability, Small Signal Stability and Voltage Security Assessment Tools (in the context of series and shunt controlled VSC FACTS devices). One of the recent investigations [49] presents an electrical model of NaS battery taking into account factors like energy, power, voltage, internal resistance, service life, depth of discharge and temperature. This electrical model (VI behavior) has been validated experimentally at different power output discharge level.

Although, different types of battery models have been used, most of them (except [49]) do not refer to any particular battery type and even do not model the effects of depth of discharge, battery operating temperature, service life, etc. However, it is known that these factors do affect the electrical performance of the battery (the extent to which it affects depends on the type of battery) and hence will have some impact on the power system stability. However, it still remains to be examined to what extent these factors affect the stability results and to what extent they could be incorporated in the stability models with little/no difficulty.

5. BESS-future outlook

The future for BESS looks to be promising and the likely BESS applications in power systems can broadly be classified based on the time scales into following types:

(1) Instantaneous applications (0 to few seconds): mainly rapid spinning reserve, primary frequency control, ride though capability, power quality: These applications require batteries with high power densities and BESS which can immediately deliver short bursts of large power.
(2) Short term applications (few seconds to minutes): secondary and tertiary frequency regulation-ancillary services, smoothing of power output from wind farms, Demand side applications-active and reactive power control, harmonic compensation, black start capability: These applications require modest power and energy densities batteries and the BESS must be able to store energy for a longer duration of time.
(3) Mid term (minutes to few hours <5 h): utility side applications-mainly market imbalance, arbitrage, load balancing, peak load shaving (2 and 4 h duration), improving reliability of: (i)systems with large amount of renewable energy, (ii) isolated systems and (iii) micro-grids, support for transport and automobile feeding, deferment of new generation and transmission construction in cases where up-gradation is needed due to the increase in peak demand: These applications require high energy density batteries.
(4) Long term/multi-MWh applications (days): avoid new generation and transmission construction cost: These applications require very high energy density batteries and at present such technologies are not cost effective.

Of the various applications mentioned above, the first three, namely instantaneous, short term and mid term applications seem to be commercially feasible at present. Currently the BESS seems to be cost effective when designed for storage less than 5 h. While the multi-MWh applications are attractive, the batteries storing modest amount of power and delivering for seconds/minutes seem to be commercially successful. The immediate success of BESS in rapid and short term applications is because of their capability to react instantly to system disturbances, which a conventional synchronous generator cannot do. The mid term BESS applications could become more commercially viable if the utilities could use the battery banks of EDV to better manage and control the power system. It has been stated in [50] that by 2025 the EDV would become economically viable and attractive. Further, the BESS of these vehicles would have ratings comparable to the domestic consumer demands. Hence, utilization of these batteries would save capital costs for electric utilities. Due to these reasons the use of EDV BESS appears to find applications in power systems. However to make this technology feasible a framework needs to be developed, which is beneficial for both the utility and the EDV BESS consumer.

5.1. BESS and EDV as storage devices in emerging electric grids

The BESS and EDV will have a large influence on the economic operation and planning of emerging electric grids. This is explained in detail by considering the Danish electricity grid as an example for the emerging electricity grid.

The electricity grid in Denmark is divided into two parts namely Western (DK West) and Eastern Denmark (DK East) and at present there is no physical interconnection between these two parts. The DK West operates in synchronism with the UCTE grid and the DK East with the Nordic grid. The 2007 DK West electricity grid can be considered as an example of the emerging electricity grid due to the following main reasons:

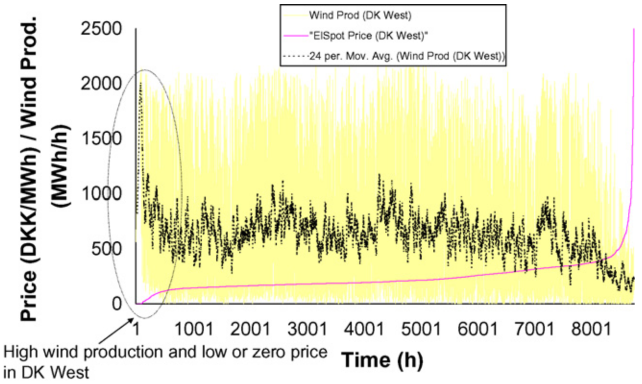

Fig. 1. 2007 wind production and ElSpot market price in DK West.

(1) During the year 2007 on an average about 24% of the total electricity demand in DK West was met by wind power alone.
(2) During this year about 45% of the total electricity demand in DK West was supplied by distributed resources of which 21% is from combined heat and power plants (CHP).
(3) In 2007, there were many hours when the wind production alone exceeded the total electricity demand in DK West.

For an electricity grid with these characteristics, the BESS or EDV could have a significant influence on the following:

(1) Electricity market prices and wind power production: the recorded electricity market prices (ElSpot price in DK West) and the wind power production in DK West are shown in Fig. 1. From this it can be seen that in 2007 in DK West the ElSpot price is either zero or very low during high wind power production. A consequence of this is that the pay back for wind power producers decreases. The Nordpool has proposed to introduced negative market prices and in such a case it is quiet likely that the economics is not favorable to operate the wind turbines during high production periods. This problem becomes even more critical when the wind power production is increased to meet 50% of the total consumption (2025 target set for Denmark). In such a situation the battery technology can add value and allow economically feasible methods of achieving the 2025 targets set for wind power production. Specifically, the batteries could store the energy during high wind and low price periods and deliver when necessary.

    Apart from increasing wind power "value", the integration of battery technology can also help in reducing the difference between the ElSpot area (DK West) market price and the system price during congestion, etc. Fig. 2 shows the variation of electricity prices in DK West and the System price (ideally system price and DK West prices must be the same but during grid bottlenecks or congestion, etc., it is different). From this figure it may be seen that the DK West price deviates to a very large extent from the system price and it is during these hours that the DK West electricity prices are extremely high/zero. If a battery storage device is available then even during congestion the electricity market price can be regulated within a narrow band by appropriately charging/discharging it.

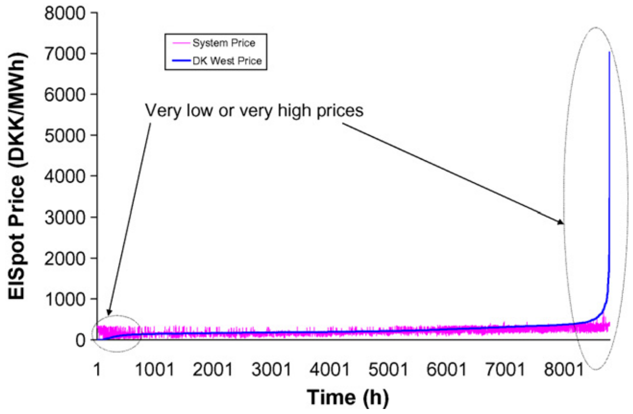

Fig. 2. 2007 ElSpot market price in DK West and the system price.

(2) Balancing power price and wind power variation: the spot market is a day ahead market and the production-load forecasts are used for bidding. However, in reality there are forecast errors which result in difference between the bided and actual values of generation and demand. Hence, in Denmark to maintain generation-load balance, there is another balancing market which closes 1 h before the hour of operation and is called ElBas. Generally, the power price at the balancing market is higher than the ElSpot market prices. For example, in 2007 the Danish TSO (Energinet.dk) paid a premium price to reduce the generation during high wind power production and is shown in Fig. 3. From this figure it may be seen that during some hours the TSO paid more than 1000 DKK/MWh even though the average ElSpot price was around 320 DKK/MWh. Further, during low wind production a very high price (above 2000 DKK/MWh) was paid to increase generation to balance the consumption.

If battery storage devices are used then these large price variations can be reduced. The battery can store excess power during high wind production (marked region in Fig. 3) and deliver it when required. Further, the batteries could also reduce the costs a wind power producer bears due to improper forecasts. The battery storage can provide the regulating/balancing power for wind turbines. The EDV batteries can also be used to provide the “balancing power” for the wind power plants.

(3) Power quality improvement: the battery storage devices can be used for improving the power quality of a distribution system. Also by judiciously placing the battery in the distribution network the voltage and the distribution system loss can be regulated.

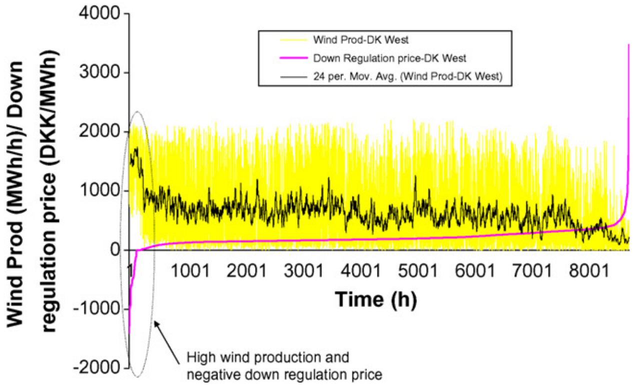

Fig. 3. Regulating and wind power variation in DK West (2007).

(4) Black start capability: the batteries will have a high economic value if they will be used for black start during grid outages. However, quantifying their exact economic gain provided by batteries when used for black start is still an open problem.

(5) Deferral of transmission and distribution costs: the Transmission System Operator (TSO) in Denmark is planning to reinforce the Danish transmission system to allow 50% wind power penetration in future. However, the planning studies carried out by Energinet.dk [51] indicate that to integrate 50% wind power in the Danish electricity grid would require increased cross-border transmission capacity. This could not only be expensive but is also time consuming due to the involvement of the various countries. In such a context a battery storage device cannot only prove to be economical but also will make Danish electricity grid self-sustainable.

(6) Island mode operation: a part of the eastern Danish electricity grid (Bornholm electricity grid) is connected to the Nordic interconnected grid through a single underground sea cable. This cable has been damaged by ship anchors for three times in the last 5 years. When the cable is damaged it takes a long time to make the cable operational and during this period the Bornholm electricity grid operates in an island mode. The wind power penetration in Bornholm is quiet significant (32.4% of the total electricity demand on this island was met by wind power during 2007) and when operated in island mode they cause large power fluctuations. Hence, to operate the system reliably in island mode most of the wind turbines are shut down. The battery storage technology can be seen as an option to smooth the power fluctuation and there by help in reliably operating such a system in island mode.

(7) Ancillary service: a detailed investigation presented in [52] indicates that EDVs are ideally suited for providing ancillary services for the Danish electricity grid. The results presented in [52] show that the EDVs can economically provide some ancillary services to the Danish electricity grid. This statement to a certain extent can be justified by examining the power and energy capacities of the EDV batteries. The EDV batteries have limited/low energy capabilities (most of it used for driving) and can deliver high power for very short duration of time. These characteristics of EDV batteries make it ideally suited for ancillary services which also require high power for short duration of time (low energy).

There is a political drive to increase wind power production to meet 50% of the total electricity demand by about 2025. It is also suggested that around 2025 about 40% of the primary units which are in operation today will be replaced by wind power plants. The Danish TSO (Energinet.dk) carried out a planning study for such an envisioned future electricity grid. One of the major conclusion of this study is that about 0.7 TWh of total generated energy can neither be transmitted across to the neighboring countries (assuming the present day interconnection capacities) nor can be consumed internally within Denmark (projected 2025 electricity consumptions). The BESS and EDVs would play a major role in the reliable operation of such an electricity grid. In fact, the government in Denmark is promoting the commercialization of EDVs to meet the EU goals and to reduce the CO_2 emissions. Further, some demonstration projects are being planned to demonstrate the use of EDVs for rendering grid services.

5.2. BESS technology

Amongst the various battery technologies available at present, the Flow batteries could find applications in systems which require high power as well as long duration and those applications in which the battery is not cycled frequently. While the lead-acid batteries would continue to find applications in which require high-power-densities, the other advanced battery technologies like NaS and NiCd could also be used for these applications. The NiCd batteries designed primarily for mid term applications (modest amount of power for long duration of time) could also be used for instantaneous applications (providing large amount of power for short duration of time). The Li-ion batteries seems to be ideally suited for portable devices and applications requiring high energy density and high over all efficiency of BESS.

The future BESS controls and power conditioning system may be designed to emulate the operation of a synchronous generator in the power system. Further, these controls could have better flexibility and could allow the BESS to operate in both grid connected and isolated mode (automatic switching between the two modes). Also the responses of the BESS obtained in these two modes can be made much superior than the conventional synchronous generator. This is because the inertia, governor droop and damping for a BESS can be set (dynamically) according to the power system requirements.

Regarding analyzing the effect of BESS on power system operation and cost, models and methods need to be developed which can incorporate the multi-functional features of the BESS and can represent its operation ranging from seconds to hours. The economic assessment methods need to be more realistic (replacing the present conservative methods) and incorporate the market models appropriately. The BESS models used for power system operational studies need to be validated with the actual BESS response (for each type) and then generalized. It would be desirable to easily integrate the BESS models with the standard power system analysis programs.

6. Concluding remarks

The battery storage technology will play a major role in the reliable and economic operation of smart electric grids with significant amounts of renewable power. In the context of Denmark, it would play an important role in helping achieve the ambitious target of 50% of the total electricity demand to be met by wind power alone by 2025. In future for other electricity grids too, the battery and EDV technologies could be an integrated to the electricity grid economically. These devices (battery and EDV) would not only assist in operating the future electricity grids reliably but could also assist in economically integrating renewable generating sources.

As far as the battery technology is concerned, in future there will be significant development in reducing the battery cost and improving their reliability. The EDV batteries would be largely lithium ion or nickel metal hydride and there are ongoing efforts to improve the reliability and costs of these new battery technologies. It is envisioned that the EDVs would be extensively used as battery storage device for providing ancillary services to the electricity grids.

The future of large scale batteries extensively designed for using in electricity grid is also quiet promising. The large scale batteries are being integrated in the development of some wind farms (particularly wind farms connected to weak grids or connected to stand alone or island grid). However, the new battery technology like vanadium redox flow batteries will be extensively used instead of the conventional lead-acid batteries.

Apart from the development of battery technology, it is necessary to develop analysis tools to examine the technical and economic feasibility of integrating battery/EDVs in electric networks. So far most of the economic analysis were based on simple spreadsheet calculations. However, now advanced tools need to be developed to assess the economics of using battery technology in electricity grids. The tools developed in future to assess the economic benefits of using batteries in electric grid must consider the electricity market in place (including planned market changes), accuracy of wind/solar power forecast tools and the possibility of using batteries for multiple applications. Assessing the economic feasibility of EDVs for rendering grid services would be even more complex as the gains will heavily depend on the EDV driving pattern, state of charge, EDV charging/discharging, architecture and regulatory framework allowing EDV interaction with the electricity grid. The technical assessment would require development of reliable battery models for power system studies to be carried out at different time scales (ranging from seconds to hours). In the context of EDVs, innovative techniques need to be developed to model large number of distributed small capacity batteries for power system studies (stability, load flow, power quality, etc.).

In the context of Denmark, the battery and EDV technology will play a major role in achieving reliably and economically the ambitious wind power penetration target (50% of electricity demand to be met by wind power) set for 2025. The battery storage device (large scale) would also to a certain extent defer the transmission and distribution costs. Also, the EDV and large scale battery storage would add market value to wind power and make the wind power economics less dependent on the reliability of wind forecasts. The EDV in particular seems to be ideally suitable for economically providing some ancillary services. Several studies are underway [52] to investigate and develop new architectures for integrating storage technology (EDV in particular) in the future Danish electricity networks.

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