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A review of the integration of Energy Storage Systems (ESS) for utility grid support

***Abstract**. Energy storage systems (ESS) have recently become an indispensable solution to many operational issues related to the integration of distributed generation (DG) technologies in electricity grids. Most of the applications are in the form of power quality mitigation and management of the energies between DG and electricity grids. This paper presents a review of the present status of worldwide applications and recent research on ESS. Of particular interest is the deployment of battery energy storage system (BESS) technologies for utility grid support and the approaches used in power system simulation studies. BESS steady state and dynamic modelling methods are also discussed.*

***Streszczenie.** W artykule zaprezentowano przegląd stanu wiedzy na temat zastosowań i badań układów magazynowania energii ESS. Szczególną uwagę zwrócono na układy z ogniwami w zastosowaniu jako element zintegrowanej sieci. (**Zintegrowane systemy magazynowania energii – przegląd stanu wiedzy**)*

Keywords: power systems, distributed generation, energy storage, renewable energy.
Słowa kluczowe: systemy energetyczne, magazynowanie energii, energia odnawialna.

Introduction

The worldwide projection of renewable energy (RE) shares is expected to be in the range of 15% to 25% by 2020 [1]. In Malaysia, the government has recently announced a target RE penetration of 2080 MW over the same timeframe [2]. Increasing grid integration from multiple DGs, particularly from wind and solar sources, introduces several technical issues in grid operation, which sometimes requires the deployment of energy storage system (ESS) technologies. Furthermore, ESS fulfils the need for better management of the energies extracted from renewable energy sources.

The role of ESS in power systems has been reviewed by several researchers who have investigated state-of-the-art storage technologies suitable for energy and power applications [3-6]. Comparisons of different storage characteristics, including emerging storage technologies, have also been presented. Some examples of large scale multi-megawatt systems currently installed worldwide have been described by [7, 8], while others have discussed the potential of storage devices when coupled with flexible AC transmission system (FACTS) devices [9-11]. In the literature, the varieties of storage methods available for use in power systems, including traditional and emerging storage technologies, such as pumped hydroelectric storage systems (PHS), compressed air energy storage (CAES), flywheel energy storage, semiconducting magnetic energy storage (SMES), ultracapacitors and battery energy storage systems (BESS), have also been described.

Most of these storage methods, particularly BESS, require a power electronic interface consisting of solid state switching devices to control the flow of energies. In the context of power system simulation studies, it may be challenging to model power systems that utilise such high frequency switching devices, particularly for approaches that use dynamic modelling. A number of equivalent circuit models for battery energy storage are available [12-15]; however, their suitability depends on the application and desired goal. Some studies use simple models focused on improving the control systems used [16], while others employ more accurate dynamic battery models [17, 18] for technical evaluation of the impact of integrating BESS into electricity grid with renewable energy sources. Aside from technical evaluations, some studies have shown an interest in economic evaluations [19, 20]. In this context, there is a growing need to develop consistent and comprehensive analysis tools to examine the technical and economic feasibility of integrating ESS into electricity grids. This paper presents a review of the application and integration of ESS into electricity grids and highlights practical installations worldwide. The research and development strategies for the BESS are detailed. Finally, the challenges for BESS studies are further discussed, and the approaches used in power system simulation studies for the mitigation of intermittent renewable energy sources are described.

Review on ESS world-wide Installations

ESSs are used for various power utility applications all over the world. A summary of installations for different application purposes is given in Table I, whereas detailed descriptions are given in the following sections according to their three major functional categories:

A. Large scale storage for energy applications
B. Fast discharge storage for power applications
C. Battery energy storage systems (BESS)

A. Large scale storage for energy applications

This storage category is characterised by capacities that normally exceed megawatt levels with discharge capabilities of up to hours or days. PHS and CAES are examples of this category. These types of storage methods have been used for load levelling and peak shaving applications for decades. The first applications of PHS were in Italy and Switzerland around the 1890s, while the first application of CAES was in the Huntorf plant in Bremen, Germany, which has been commercially operated since 1978 [21]. Typical PHS and CAES have efficiencies of around 65%-85% and 40%-50%, respectively, and maximum outputs that exceed several thousands of megawatts and a few hundreds of megawatts, respectively.

Because the principle drawbacks for these methods are geographical restrictions and high initial costs, especially for PHS systems, several attempts for improving the technology have been made. The Yanbaru seawater PHS in Japan is an example plant that operates by pumping seawater up into the reservoir [22]. Another example for the improvement of the CAES system is the implementation of fabricated storage tanks [3], and there are also efforts to use high pressure underground piping to increase efficiency to 70% [4].

Over the last 60 years of operation, PHS capacity all over the world has expanded to more than 90 GW, which is nearly 3% of the global generation capacity [21]. Most of the installations are found in the USA, in which 2.5% of the national stored electricity passes through energy storage systems, the majority of which are PHS systems [23]. Similarly, CAES systems are also widely accepted in the USA as opposed to in other countries, such as Japan, some European countries and others, where its application is limited due to economic feasibility and geographical restrictions. In general, these storage methods serve various functions, including energy management, peak shaving, spinning reserve, VAR support and frequency control.

B. Fast discharge storage for power applications

This group of storage has very fast discharge capability with high power discharge on the order of seconds or less. Flywheel, SMES and ultracapacitors are examples that fall into this category. These devices have very high efficiency, which are in the range of 90% and above, and lifetimes of 20 to 40 years. Due to high power discharge capability, these types of storage devices are presently not suitable for load levelling and peak shaving purposes like other high-energy storage technologies. However, they are superior for various power quality purposes. Traditional UPS systems utilised these storage devices as a backup supply for sensitive loads, such as FACTS devices with energy storage used for mitigation of voltage sags and swells, flicker and harmonics [11, 24, 25].

Flywheels have been used in power systems for more than a century. Current generation flywheels have storage capacities of 100 kW, and 15 minute flywheels developed by the Beacon Power Corporation allow gauging in parallel to provide storage output at the multi megawatt level [26]. Aside from power quality applications and frequency and voltage regulation, recent developments in flywheels have shown a growing interest in their application for mitigating fluctuations of renewable energy sources [27, 28]

SMES was first introduced around 1969 and has since been used for many applications, including load levelling, spinning reserve, transient and dynamic stability, power quality and increasing transmission line capacity [29, 30]. Despite a number of useful applications reported in the literature, real-life large-scale installations of SMES are still considered costly, and most of the literature describes computer and laboratory simulations. In the USA, the first SMES used for power grid applications was implemented in 1981 for power quality and grid stability on the 500kV Pacific Intertie that interconnects California and the Northwest [31]. Similar to flywheel technology, SMES is used to enhance the performance of grids connected to wind farms, particularly in stabilising fluctuations of the wind turbine output [32, 33].

Ultracapacitors (or supercapacitors) are a highly viable technology that has received attention by utilities and vehicle applications. In power system applications, they have been studied for power quality purposes, such as ride through improvement in electric motor drives during voltage sags and in custom power devices [30]. Due to its high cost, it is rarely used as single units but instead in hybrid systems where it is combined with high energy storage devices, such as lead acid batteries [34].

C. Battery Energy Storage Systems (BESS)

Battery energy storage systems (BESS) refer to secondary chemical battery technologies. They have been used in many areas for power utilities, which have evolved from flooded lead acid to valve-regulated lead acid (VRLA), nickel cadmium (NiCd), nickel metal hydride (NiMH) and lithium-ion (Li-ion). Newer designs, which are at different stages of development, include sodium sulphur (NaS) and sodium nickel chloride (ZEBRA). Electrochemical flow cell systems or flow batteries, such as vanadium redox (VRB) and zincbromine (ZnBr), are also promising technologies because their rated power and storage capacity are scalable depending on the reactor size and electrolyte tanks [34]. However, flow batteries are currently still a new technology and considered a costly investment.

In general, batteries can be used for both power and energy applications with discharge durations from minutes up to a few hours. Therefore, the choice of battery storage for particular purpose involves consideration of both the energy and power related cost. Reference [35] described the projected future cost of BESS based on a collection of publications, and those suitable for power and energy applications are illustrated in Fig. 1.

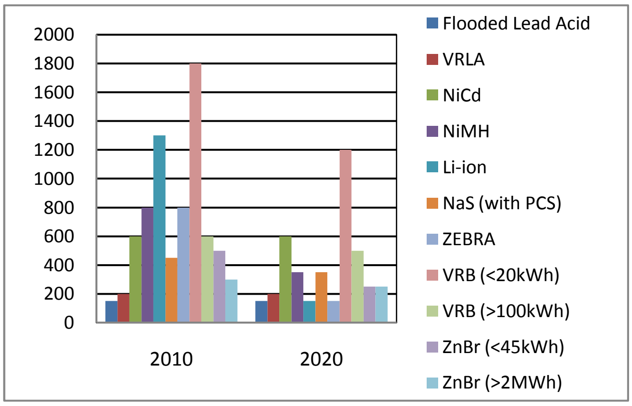


Fig.1. Present and future cost ($/kWh) of chemical batteries for utility applications

Of the different battery technologies available, lead acid batteries are the most popular due to their cost, technological maturity and availability. Although the price for flooded lead acid batteries is lower, they are inferior in terms of chemistry and require additional maintenance costs, such as topping off with distilled water. VRLA is currently the most popular choice for this type of battery, as they are maintenance free and have a lifespan of 1000-2000 cycles at 75% depth of discharge and have an efficiency of approximately 70%-80% [34]. New implementations of VRLA batteries use special carbon formulations in the negative electrode, which minimises or eliminates many common failure mechanisms, such as premature capacity and water loss [35]. VRLA batteries have been used in many commercial and large-scale energy management applications. There are also a considerable number of megawatt-sized lead acid UPS systems currently being used in financial institutions, server farms, airports and so forth in the USA. Because the lifespan of lead acid batteries is relatively short, they need to be replaced periodically, which is the limiting factor for isolated power systems.

Compared to lead acid batteries, NiCd, NiMH and Li-ion batteries have higher energy densities, greater efficiency and require less maintenance. A large scale 27 MW (14.6 MWh) storage bank of NiCd batteries was installed in Fairbanks, Alaska for backup generation in the event of problems with the intertie [7]. Currently, the investment required for large-scale NiMH and Li-ion battery systems is still considered costly. However, they are a highly viable option for replacing NiCd batteries due to their excellent capacity and efficiency and because they do not contain any hazardous materials. NiMH and Lithium (Li-ion and LiFePO4) batteries are currently the battery of choice for the EV industry, and their prices are expected to gradually decrease in the future.

NaS batteries are widely used in Japan as a result of the collaboration between the Tokyo Electric Power

Company(TEPCO) and NGK Insulators Ltd. [36]. They are primarily suitable for large scale, non-mobile applications, such as grid energy storage [7]. However, as the operating temperature of the NaS battery modules are in the range of 300°C - 360°C, they have to be heated externally to achieve optimal operation [34], which further increases their installation and maintenance cost. A NaS cell is characterised by a long lifespan, energy efficiencies up to 75 % and specific energies 3 to 4 times that of a lead acid battery. The self-discharge is very low and have life cycles of up to 4500 cycles [37]. These characteristics are suitable for many applications, including stabilising intermittent renewable energy and substation applications, such as load levelling, peak shaving and emergency power supply.

The installation and maintenance costs associated with flow batteries are still a concern of utilities companies. However, small-scale systems are already commercially available, and larger demonstration projects were started several years ago. From the feasibility studies of the demonstration projects by [38], flow batteries seem to be an attractive storage device for future large scale applications, such as peak power support at wind farms and distribution level balancing. Of the different types of chemical flow batteries, vanadium redox (VRB), polysulphide bromide (PSB) and zinc bromine (ZnBr) are the most common and are being actively developed and commercially installed for small-scale applications.

Research and development of BESS

There are continuous efforts in the research and development of ESS, particularly in battery-type chemistry. Some studies focus on the improvement of material and manufacturing methods in order to increase power and energy capacity. Other studies are related to the battery management system and applications, such as the development of power conditioning systems and control. In general, the challenges in BESS research and development can be broadly divided into:

A. Development of advance battery technologies
B. Development of control and power conditioning systems
C. Development of comprehensive systems analysis and modelling tools

A. Development of advance battery technologies

The research strategy for developing advanced batteries is currently focused on increasing the power and energy density, extending lifetime and life cycle, decreasing charge-discharge cycle times, ensuring safe operation and reducing cost [35]. BESS, such as lead-acid, nickel and lithium batteries, may employ advanced chemistry and improved electrode materials. For example, the positive electrode of VRLA batteries is exposed to corrosion, which shortens the lifetime of the batteries. Therefore, various materials have been evaluated for improving their resistance to corrosion [39]. Aside from corrosion of the electrode plate, battery research has also focused on electrolytes, safety vent, sealed parts, container cover and others. Proactive maintenance of batteries may be required to ensure that the installed battery banks achieve their expected lifetime. Such a strategy includes the development of battery management algorithms to monitor battery operations to ensure proper maintenance of the batteries [40, 41].

Other research efforts have been focused on developing next generation novel storage technologies, such as by combining the characteristics of Li-ion batteries with flow batteries that make use of liquid electrolyte tanks in flow batteries [42]. The flexibility of BESS also increases when two or more storage technologies are combined to form a hybrid system that is controlled by flexible power conditioning systems, which enables instantaneous power supplies and stores energy over longer durations. However, the topology of hybrid BESS is complex and requires support from advanced electronics [34].

B. Development of control and power conditioning systems

Control algorithms and power conditioning systems serve as auxiliary supports for the energy storage unit that forms the BESS. Control algorithms are employed to achieve longer lifetime, maximum output and optimal efficiency from energy storage devices. For example, battery energy storage involves chemical reactions where charging and discharging processes must follow the manufacturer's recommendations. Improper charge and discharge strategies result in degradation of battery components and quality, which may shorten their lifetime and reduce their capacity.

Power conditioning systems work as a battery converter, as most storage devices output DC waveforms. The converter allows bi-directional power flow to control the charge and discharge of the batteries. In other words, the energy storage devices not only generate but also accept power from the grid during the charging process [43]. The power converter functions depend on the storage technology used and specific applications. The topology may include a connection between two different voltage level buses, which utilises conventional DC-DC buck/boost converters or isolated DC-DC converters. Alternatively, a connection can be made between DC and AC voltage buses, which uses conventional AC-DC converters [34]. For large scale energy storage used in transmission support, these power converter topologies may be combined to set up a power conditioning system consisting of DC-DC converters to connect the battery strings in parallel and inverter to connect the battery to the electricity grid [34]. For each of these cases, the development of a power conditioning system is not straightforward, as new energy storage devices require more complex systems and safety precautions as compared to the traditional well-established storage batteries, such as lead acid and NiCd.

C. Development of comprehensive systems analysis and modelling tools

A comprehensive system analysis of BESS is required to evaluate its economic and operational benefits and system reliability. The key component for a comprehensive analysis tool relies on software-based modelling and simulation techniques. The impact of integrating storage technologies into the electricity grid can be studied with various mathematical models depending on application needs, such as either steady state or dynamic models. For the case of BESS, a number of models can be used, and the selection of a suitable model depends on the required simulation accuracy and parameters. The battery equivalent circuit model may be integrated into a renewable energy system model and simulated together to evaluate its impact and optimise the battery in terms of cost and efficiency [44]. This method is widely accepted due to the availability of simulation software programs, such as PSCAD/EMTDC, MATLAB, PSS/E and others, which offer users the flexibility to evaluate these simulations. Further details on the BESS steady state and dynamic modelling approaches are discussed in the following section.

BESS modelling and simulation studies

Lead acid batteries, such as VRLA cells, are currently the most optimal devices from a cost and performance standpoint [4]. They are widely deployed for commercial use and continuously studied as a means of mitigating many of the issues related to power systems.

Table I. A summary of real-world utilisation of different type of energy storage devices for different applications

Storage category	Name	Operational dates	Capacity	Remarks
Energy application	Bath Country PHS station, USA	1985 –present	2772MW	• Currently the largest in North America
	Ludington PHS power plant, USA	1973 – present	1872MW	• Load levelling and peak shaving • Serves 1.4 million residential customers
	Dnister PHS power plant, Ukraine	2009 – present	2268MW	• Currently the largest in Europe
	Guangdong PHS power plant, China	2000 – present	2400MW	• Currently the largest in China
	Okutataragi PHS power station, Japan	1974 – present	1932MW	• Currently the largest in Japan
	Huntorf CAES power plant, Germany	Since 1978	290MW	• 290MW full output for 4 hours. • 12 hours off peak power used to fully charge
	McIntosh CAES plant, Alabama USA	Since 1991	110MW	• 110MW full output power for 26 hours • Fuel consumption is 25% better than Huntorf
Power application	20MW flywheel plant, Stephentown, New York, USA	Expected spring 2011	20MW	• High speed flywheel by Beacon Power used for PQ applications, such as grid frequency and voltage regulation • Fulfils 10% of NY frequency regulation needs
	200 kW flywheel in Dogo Island, Japan	Since 2003	100kW	• Used for stabilisation of wind power output
	1MW/s SMES system, Wisconsin, USA	Unknown	1MW/s	• Six units in operation • Inject power into a collapse-prone transmission loop
BESS	Metlakatla Power and Light (MP&L), Alaska, USA	1997 – present	1MW, 1.4MWh	• VRLA batteries • Applications include voltage regulation and displacing diesel generation
	Golden Valley Electric Association (GVEA), Fairbanks, Alaska, USA	2003 – present	27MW, 14.6MWh	• NiCd batteries • Applications include VAR support, spinning reserve and power system stabilisation
	AEP DES system at Chemical Station, N. Charleston, WV, USA	2006 – present	1.0MW, 7.2MWh	• NaS batteries for substation upgrade deferral
	Long Island, NY BusTerminal Energy Storage, USA	2008 – present	1.2MW, 6.5MWh	• NaS batteries for load shifting application
	Sumitomo Densetsu office Osaka, Japan	2000 – present	3MW, 800kWh	• VRB flow batteries for peak shaving application
	Pacificorp Castle Valley, Utah,USA	2004 – present	250kW, 2MWh	• VRB flow batteries used for distribution line upgrade deferral and voltage support

Studies by [17] utilised a third order dynamic lead acid battery model to accurately differentiate the effectiveness of the proposed control schemes for dispatching wind and solar energy. A STATCOM was used to interface the battery banks and electricity grid to control the power flow, which ensured dispatchable output of renewable energy. Another study by [18] employed a simplified dynamic battery model to study the application of battery storage for solving power quality issues arising from the use of proton exchange membrane fuel cells based standalone DG. In this study, the batteries were connected to the DC bus of a power conditioning system of renewable energy sources through a DC-DC converter. The converter served many functions, including stabilising the DC bus output and controlling the charging and discharging of the BESS. In a microgrid system, BESS is an indispensable component for supporting different modes of operation, such as islanding, grid-connected or standalone modes. BESSs also serve as surge modules to form a standard microsource interface for microgrids, which enables plug and play functionality of a microsource that utilises DC energy sources, such as photovoltaic (PV) cells, fuel cells and others [16, 45]. Some studies have used BESS as an energy source for FACTS devices to mitigate power quality issues, such as voltage sags and flicker [24, 25]. In general, the role of power electronic interfaces for BESS is an important aspect that realises smooth integration and operation of DG with RE sources. Normally, BESS system controls are based on the state of charge (*SOC*) of battery chemistry, therefore, an accurate implementation of battery models is vital. *SOC* is an important aspect in battery modelling and is defined as the battery available capacity, which is given by equation:

$$SOC(t) = \frac{Ah_{nom} + \int_0^t I(t)dt}{Ah_{nom}} \times 100 \quad (1)$$

where: Ah_{nom} – nominal cell capacity, I – battery current.

The current is negative during cell discharge and positive when the cell is being charged. In simulations, the integration of this battery current equation is rather difficult at the start and end of the charging and discharging processes because in these regions, the current curve is highly nonlinear (exponential function) due to variations in cell temperature. Therefore, it is critical for the user to consider factors such as internal resistance, discharge type, discharge mode and rate of charge or discharge in their modelling order to accurately estimate the variation in the *SOC* [14].

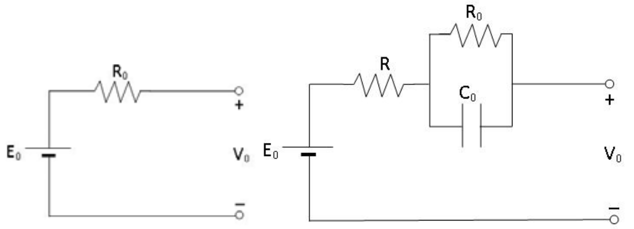
Depending on the simulation requirements, such as when the battery dynamics are less important, a simple and easy to implement battery model can be used. Figure 2 gives simple and Thevenin models of a battery cell. The simple battery model, as shown in Fig. 2(a), consists of an open circuit voltage (EMF denoted by E_0) in series with its internal resistance (R_0), while the Thevenin model (Fig. 2(b)) considers overvoltage elements, which are represented by R_0 and C_0 in parallel [14]. The terminal voltages (V_0) of simple and Thevenin battery models are described as:

(2) $$V_0 = R_0 I$$

(3) $$V_0 = E_0 - I(R + R_0) + IR_0 e^{-t/R_0C_0}$$

where: V_0 – battery terminal voltage, I – battery current, R, R_0, C_0 – internal battery constants

In practice, the simple model may be used by assuming that there is unlimited energy from E_0, while the Thevenin model assumes certain elements to be constant, which is only accurate if the dynamic behaviour of the system is not taken into account.



(a) (b)

Fig.2. Simple equivalent circuit battery models: (a) simple battery model, (b) Thevenin battery model

Several generic models also have been devised based on simple models to account for the nonlinear behaviour of the battery elements, which more accurately estimate the *SOC*. The normalised form of the equations with respect to the battery capacity allows the user to implement the model for any type and size of lead-acid batteries. Generic models from [46] and [47], given in Fig. 3 and Fig. 4, are examples of widely used models in power system and electric vehicle research. These models are used because their implementation is relatively straightforward because no hardware testing is required to obtain empirical parameters. The parameters of the model can simply be extracted from the manufacturer discharge curves, which are available from the battery datasheet.

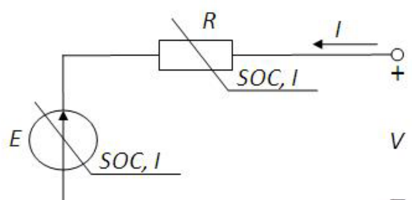


Fig. 3. Lead acid battery model by Copetti et al [46]

The discharge and charge voltage equations for the generic battery model shown in Fig. 3 are represented by equations (4) and (5), respectively,

(4) $$V_d = \left[2.085 - 0.12(1 - SOC)\right] - \frac{I}{C_{10}}\left(\frac{4}{1 + I^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02\right)(1 - 0.007\Delta T)$$

(5) $$V_c = \left[2 + 0.16SOC\right] + \frac{I}{C_{10}}\left(\frac{6}{1 + I^{0.86}} + \frac{0.48}{(1 - SOC)^{1.2}} + 0.036\right)(1 - 0.025\Delta T)$$

where: V_d – discharge voltage, V_c – charge voltage, I – battery current, *SOC* – battery state of charge, C_{10} – capacity model, ΔT – temperature difference.

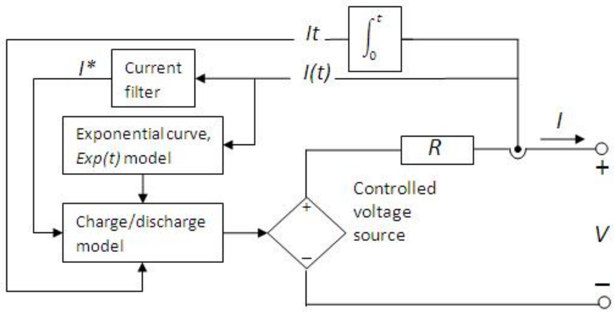


Fig. 4. Generic battery model for lead-acid, NiCd, NiMH and Li-ion batteries [47]

The first term of equations (4) and (5) represents the voltage variation and the second term is the variation of the internal resistance as a function of SOC and electrolyte temperature (T). The model equations were rewritten based on the functions of a 10 hour of rated capacity (capacity model, C_{10}) extracted from the manufacturer data sheet [46]. The calculation of the *SOC* is obtained based on equation (1), where the integration of current entering and leaving the battery terminals is performed at every simulation time step (Δt).

For the generic model shown in Fig. 4, the corresponding discharge and charge equations for the case of lead-acid cells are given by the following set of equations [47],

(6) $$V_d = E_0 - R \cdot I - K\frac{Q}{Q - It}\left(It + I^*\right) + Exp(t)$$

(7) $$V_c = E_0 - R \cdot I - K\frac{Q}{It - 0.1Q}I^* - K\frac{Q}{Q - It}It + Exp(t)$$

where: V_d – discharge voltage, V_c – charge voltage, I – battery current, E_0 – internal EMF, R – internal resistance, K – polarisation constant (V/Ah) or polarisation resistance (Ω), Q – battery capacity (Ah), It – actual battery charge, I^* - filtered current

Clearly from these equations, the polarisation effects are taken into account where the polarisation resistance and voltage terms included in the equations are denoted by the third term of equation (6) and the third and fourth terms of the equation (7), respectively. *Exp(t)* is a hysteresis phenomenon between the charge and discharge states regardless of the SOC of the battery, which occurs within the exponential area of the charge and discharge curves. The approximation of *Exp(t)* is given by the equation:

(8) $$Exp(t) = B\left|I(t)\right|\left(-Exp(t) + A \cdot u(t)\right)$$

where: B – exponential zone time constant (Ah^{-1}), A – exponential zone amplitude (V), $u(t)$ – charge/discharge mode.

Using similar procedure of extracting model parameters, the model for charge discharge terminal voltage for other type of batteries such as NiCd, NiMH and Li-ion are also available [47].

If greater simulation accuracy is required, the user should consider a higher order dynamic battery model that is more realistic. Some available models were developed based on laboratory testing and manipulation of manufacturer data in order to understand battery behaviours at various operating conditions. Therefore, it is quite challenging to implement dynamic battery models, as *SOC* estimation is rather complex as a result of the many nonlinear elements in batteries. Figure 5 and Fig. 6 show second and third order battery models proposed by [15] and [13].

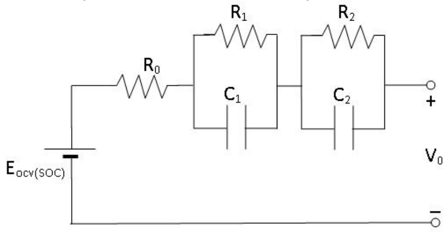


Fig. 5. Second order Randell model

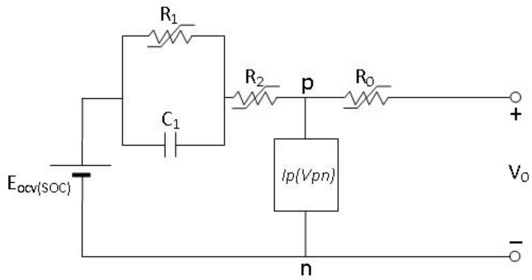


Fig. 6. Third order battery model

Where: $E_{ocv(SOC)}$ – battery EMF, R_0, R_1, R_2, C_1, C_2 – internal dynamic battery elements, $I_p(V_{pn})$ – current dynamics for cell's self discharge

The second order battery model, as shown in Fig. 5, considers an internal EMF that varies with *SOC* and the output impedance of a series resistance in a cascade with two *RC* branches, which represent cell dynamics. The mixed algorithm introduced by this model combines both the well-known coulomb-counting method and model-based method for *SOC* estimation, which claims to be highly accurate over a *SOC* range of 20%-80% [15]. In practice, this model gives good performance in compensating for the slow start-up transient of a particular prime mover for a microgrid test system [45].

Compared to the second order model, the third order model offers greater consistency but increased complexity and computation time. The model consists of an internal EMF, which varies as a function of *SOC* and electrolyte temperature, and dynamic internal impedances (denoted by *R0, R1, R2* and *C1*), as depicted in Fig. 6. The parasitic branch, *Ip(Vpn)*, models water electrolysis that occurs at the end of the charging process of the lead acid battery. Further details on the description of specific parameters for this model is given in [13], and its corresponding implementation issues, such as identification of empirical parameters and explanation for use in specific practical applications, are detailed in [48]. This model is widely accepted for many applications, as it is widely applicable and accurately simulates realistic operating characteristics. Specific applications of BESSs that utilise this model include simulations of long-term behaviour in systems to study long-term power dispatching for renewable energy based DG [17].

All of the aforementioned models have their limitations. The use of simple or generic model is easy to implement but sometimes results in less accurate simulation results. On the other hand, the use of more accurate dynamic higher order models is not always a good choice because of their increased computational complexity simulation time. Appropriate models should be chosen based on the application and degree simulation accuracy required. For example, the effect of self-discharge of a particular battery is negligible if continuous battery operation is taken into account. However, for standby power system applications, it is important to consider the self-discharge effect because the battery operates according to particular events that sometimes rarely occur.

Conclusion

Energy storage systems (ESS) allow for the smooth integration of clean energy generation sources, such as wind and solar energy. Increasing interest in ESS, particularly in battery technologies, has led to increased research and deployment of BESS, which will contribute to their future viability. Among the BESS technologies available, lead acid batteries are currently the most widely used battery due to their cost, technological maturity and availability. The motivation for continuous development of battery technologies includes many factors, such as application flexibilities and decreasing investment costs resulting from parallel advancement of the technologies for use in power system and electric vehicle applications.

In this paper, a review of real-world utilisation of various storage technologies is discussed, and most of the installation examples provided are still under operation. State-of-the-art research and development of BESS are generally focused on increasing their power, energy capacity and applications. The approaches used in power system simulation studies are also described with a specific focus on chemical battery modelling by means of electrical equivalent circuit models. Steady state and dynamic models of lead-acid batteries are reviewed based on their distinct characteristics and applications. Overall, it can be concluded that the on-going challenges, particularly for power system researchers in the research and development of energy storage technologies, are in the following forms:

- Development of improved software and hardware models for studies in energy storage applications. One possible approach is to utilise software and hardware design, simulation and testing
- Research on high-efficient power conditioning system for ESS to further improve their efficiency so as to meet their expected lifetime. This approach requires power electronic design for the converter interface of BESS and system control.
- Analysis based on power system simulation studies for proper coordination of ESS with renewable energy sources. This can be studied using commercially available software, such as PSCAD/EMTDC, Matlab simulink, PSS/E and others. Design of control methods for particular operation modes is essential.
- Studies on the optimal type, location and size of ESS, which is a major concern for utility companies. This may require statistical data analysis, and many heuristic methods are available.

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