Chapter 2
Literature Survey

2.1 Introduction

A fundamental characteristic of a PV system is that power is produced only when sunlight is available. For systems in which the PV is the only generation source, storage is typically needed since an exact match between available sunlight and the load is limited to a few types of systems – for example, powering a cooling fan. In hybrid or grid-connected systems, where batteries energy storage (BESs) are not inherently required, they may be beneficially included for load matching or power conditioning. By far the most common type of storage is chemical storage, in the form of a battery energy storage (BES), although in some cases other forms of storage can be used [24]. For example, for small, short-term storage, a flywheel or capacitor can be used for storage, or for specific, single-purpose PV systems, such as water pumping or refrigeration, storage can be in the form of water or ice.

In any PV system that includes BESs, the BESs become a central component of the overall system which significantly affects the cost, maintenance requirements, reliability, and design of the PV system. Because of the large impact of BESs in a stand-alone PV system, understanding the properties of BESs is critical in understanding the operation of PV systems. The important BES parameters that affect the PV system operation and performance are the BES maintenance requirements, lifetime of the BES, available power, and efficiency. An ideal BES would be able to be charged and discharged indefinitely under arbitrary charging/discharging regimes and would have high efficiency, high energy density, low self-discharge, and below cost. These are controlled not only by the initial choice of the BES but also by how it is used in the system, particularly how it is charged and discharged and its temperature. However, in practice, no BES can achieve the above set of requirements, even if the normally dominant requirement for low cost is not considered. This chapter provides an overview of BES operation and uses for PV systems. The aim

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of this chapter is to present the reader with enough information to understand how important it is to specify an appropriate type of BES and with sufficient capacity, for satisfactory use in a PV system.

2.2 Why Use a Battery Energy Storage in PV Systems?

The energy output from the solar PV systems is generally stored in BES deepening upon the requirements of the system. Mostly BESs are used in the stand-alone PV system, and in the case of grid-connected system, BESs are used as a back-up system [25]. The primary functions of the BES in a PV system are:

- It acts as a buffer store to eliminate the mismatch between power available from the PV array and power demand from the load. The power that a PV module or array produces at any time varies according to the amount of light falling on it (and is zero at nighttime). Most electrical loads need a constant amount of power to be delivered. The BES provides power when the PV array produces nothing at night or less than the electrical load requires during the daytime. It also absorbs excess power from the PV array when it is producing more power than the load requires [26].
- The BES provides a reserve of energy (system autonomy) that can be used during a few days of very cloudy weather or, in an emergency, if some part of the PV system fails.
- The BES prevents large, possibly damaging, voltage fluctuations. A PV array can deliver power at any point between a short circuit and an open circuit, depending on the characteristics of the load it is connected to.
- Supply surge currents: to supply surge or high peak operating currents to electrical loads or appliances [14].

2.3 BES Types and Classifications

Even BESs from the same manufacturers differ in their performance and its characteristics. Different manufacturers have variations in the details of their BES construction, but some common construction features can be described for almost all BESs. BESs are generally mass produced; it consists of several sequential and parallel processes to construct a complete BES unit. Different types of BESs are manufactured today, each with specific design for particular applications. Each BES type or design has its individual strengths and weaknesses. In solar PV system predominantly, lead-acid BESs are used due to their wide availability in many sizes, low cost, and well-determined performance characteristics. For low-temperature applications, nickel-cadmium cells are used, but their high initial cost limits their use in most PV systems. The selection of the suitable BES depends upon the application and the designer. In general, BESs can be divided into two major categories, primary and secondary BESs [21].

2.3.1 Primary BES

Primary BESs are non-rechargeable, but they can store and deliver electrical energy. Typical carbon-zinc and lithium BESs commonly used primary BESs. Primary BESs are not used in PV systems because they cannot be recharged.

2.3.2 Secondary BES

Secondary BESs are rechargeable, and they can store and deliver electrical energy. Common lead-acid BESs used in automobiles and PV systems are secondary BESs. The BESs can be selected based on their design and performance characteristics. The PV designer should consider the advantages and disadvantages of the BESs based on its characteristics and with respect to the requirements of an application. Some of the important parameters to be considered for the selection of BES are lifetime, deep-cycle performance, tolerance to high temperatures and overcharge, maintenance, and many others [27]. Examples of rechargeable BES systems are:

- Lead-acid
- Nickel-cadmium (Ni-Cd)
- Nickel-iron
- Nickel-metal hydride (Ni-MH)
- Rechargeable lithium of various types, especially lithium-ion

This book's main focus is on the use of lead-acid BESs in stand-alone PV systems.

2.4 Battery Energy Storage Characteristics

The use of BESs in PV systems differs from the use of BESs in other common BES applications. For PV systems, the key technical considerations are that the BES experiences a long lifetime under nearly full discharge conditions. Common rechargeable BES applications do not experience both deep cycling and being left at low states of charge for extended periods of time. For example, in BESs for starting cars or other engines, the BES experiences a large, short current drain but is at full charge for most of its life. Similarly, BESs in uninterruptible power supplies are kept at full charge for most of their life. For BESs in consumer electronics, the weight or size is often the most important consideration [28]. This section provides an overview of the critical BES characteristics or specifications, including BES voltage, capacity, charging/discharging regimes, efficiency, etc.

2.4.1 Battery Energy Storage Charging

In a stand-alone PV system, the ways in which a BES is charged are generally much different from the charging methods BES manufacturers use to rate BES performance. The BES charging in PV systems consists of three modes of BES charging: normal or bulk charge, finishing or float charge, and equalizing charge [29].

- *Bulk or Normal Charge*: It is the initial portion of a charging cycle performed at any charge rate, and it occurs between 80% and 90% SOC. This will not allow the cell voltage to exceed the gassing voltage.
- *Float or Finishing Charge*: It is usually conducted at low to medium charge rates. When the BES is fully charged, most of the active material in the BES has been converted to its original form, generally voltage/current regulation that is required to limit the overcharge supplied to the BES.
- *Equalizing Charge*: It consists of a current-limited charge to higher voltage limits than set for the finishing or float charge. It is done periodically to maintain consistency among individual cells. An equalizing charge is typically maintained until the cell voltages, and specific gravities remain consistent for a few hours.

2.4.2 Battery Energy Storage Discharging

- *Depth of Discharge (DOD):* The DOD of BES is defined as the percentage of capacity that has been withdrawn from a BES compared to the total fully charged capacity. The two common qualifiers for DOD in PV systems are the allowable or maximum DOD and the average daily DOD.
- *Allowable DOD*: The maximum percentage of full-rated capacity that can be withdrawn from a BES is known as its allowable DOD. In stand-alone PV systems, the low voltage load disconnect set point of the BES charge controller dictates the allowable DOD limit at a given discharge rate. Depending on the type of BES used in a PV system, the design allowable DOD may be as high as 80% for deep-cycle, motive power BESs, to as low as 15–25%. The allowable DOD is related to the autonomy, in terms of the capacity required to operate the system loads for a given number of days without energy from the PV array.
- *Average Daily DOD*: This is the percentage of the full-rated capacity that is withdrawn from a BES with the average daily load profile. If the load varies seasonally, the average daily DOD will be greater in the winter months due to the longer nightly load operation period. For PV systems with a constant daily load, the average daily DOD is generally greater in the winter due to lower BES temperature and lower rated capacity. Depending on the rated capacity and the average daily load energy, the average daily DOD may vary between only a few percent in systems designed with a lot of autonomy or as high as 50% for marginally sized BES systems. The average daily DOD is inversely related to auton-

omy; meaning that systems designed for longer autonomy periods (more capacity) have a lower average daily DOD.

- *State of Charge (SOC):* This is defined as the amount of energy as a percentage of the energy stored in a fully charged BES. Discharging a BES results in a decrease in SOC, while charging results in an increase in SOC.
- *Autonomy:* Generally, autonomy refers to the time a fully charged BES can supply energy to the system loads when there is no energy supplied by the PV array. Longer autonomy periods generally result in a lower average daily DOD and lower the probability that the allowable (maximum) DOD or minimum load voltage is reached.
- *Self-Discharge Rate*: In open-circuit mode without any charge or discharge current, a BES undergoes a reduction in SOC, due to internal mechanisms and losses within the BES. Different BES types have different self-discharge rates, the most significant factor being the active materials and grid alloying elements used in the design.
- *Battery Lifetime:* Battery lifetime is dependent upon a number of design and operational factors, including the components and materials of BES construction, temperature, frequency, DODs, and average SOC and charging methods.
- *Temperature Effects:* For an electrochemical cell such as a BES, temperature has important effects on performance. As the temperature increases by 10° C, the rate of an electrochemical reaction doubles, resulting in statements from BES manufacturers that BES life decreases by a factor of two for every 10° C increase in average operating temperature. Higher operating temperatures accelerate corrosion of the positive plate grids, resulting in greater gassing and electrolyte loss. Lower operating temperatures generally increase BES life. However, the capacity is reduced significantly at lower temperatures, particularly for lead-acid BESs. When severe temperature variations from room temperatures exist, BESs are located in an insulated or other temperature-regulated enclosure to minimize BES.
- *Effects of Discharge Rates:* The higher the discharge rate or current, the lower the capacity that can be withdrawn from a BES to a specific allowable DOD or cutoff voltage. Higher discharge rates also result in the voltage under load to be lower than with lower discharge rates, sometimes affecting the selection of the low voltage load disconnect set point. At the same BES voltage, the lower the discharge rates, the lower the BES SOC compared to higher discharge rates.
- *Corrosion*: The electrochemical activity resulting from the immersion of two dissimilar metals in an electrolyte or the direct contact of two dissimilar metals causing one material to undergo oxidation or lose electrons and causing the other material to undergo reduction or gain electrons. Corrosion of the grids supporting the active material in a BES is an ongoing process and may ultimately dictate the BES's useful lifetime. BES terminals may also experience corrosion due to the action of electrolyte gassing from the BES and generally require periodic cleaning and tightening in flooded lead-acid types [14, 30].

Table 2.1 Compare the properties for some types of BESs [31]

Specifications	Lead-acid	Ni-Cd	Ni-MH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/Kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance (mΩ)	<100 12 V peak	100–200 6 V peak	200–300 6 V peak	150–300 7.2 V	25–75 per cell	25–50 per cell
Cycle life (80% discharge)	200–300	1000	300–500	500–1000	500–1000	1000–2000
Fast-charge time	8–16 h	1 h typical	2–4 h	2–4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Low. Can't tolerate trickle charge		
Self-discharge/month	5%	20%	30%	<10%		
Cell voltage	2 V	1.2 V	1.2 V	3.6 V	3.8 V	3.3 V
Charge Cutoff Voltage (V/cell)	2.4	Full charge detection by voltage signature		4.2	4.2	3.6
Discharge cutoff voltage (V/cell)	1.75	1	1	2.5–3	2.5–3	2.8
Peak load current Best result	5A 0.2A	20A 1A	5A 0.5A	>3A <1A	>30A <10A	>30A <10A
Charge temperature	−20 to 50 °C	0 to 45 °C		0 to 45 °C		
Discharge temperature	−20 to 50 °C	−20 to 65 °C		−20 to 60 °C		
Maintenance requirement	3–6 months	30–60 days	60–90 days	Not required		
In use since	Late 1800s	1950	1990	1991	1996	1999

2.4.3 Compare the Characteristics of Some Types of BESs

There are a large number of BES parameters. Depending on which application the BES is used for, some parameters are more important than others. The following is a list of parameters that may be specified by a manufacturer for a given type of BES which is listed in Table 2.1. For example, in a typical BES for a general car, the energy density is not relevant – a BES is a small fraction of the total BES weight, and consequently, this parameter would typically not be listed for a conventional car BES. However, in electric vehicle applications, the BES weight is a significant fraction of the overall weight of the vehicle, and so the energy densities will be given [26].

2.5 Lead-Acid Battery Energy Storage

Lead-acid BESs are the most commonly used type of BES in PV systems. Although lead-acid BESs have a low energy density, only moderate efficiency, and high maintenance requirements, they also have a long lifetime and low costs compared to other BES types. One of the singular advantages of lead-acid BESs is that they are the most commonly used form of BES for most rechargeable BES applications (e.g., in starting car engines) and therefore have a well-established, mature technology base [32].

A lead-acid BES or cell in the charged state has positive plates with lead dioxide (PbO_2) as an active material, negative plates with high surface area (spongy) lead as an active material, and an electrolyte of the sulfuric acid solution in water (about 400–480 g/mL, density 1.241.28 kg/L). On discharge, the lead dioxide of the positive plate and the spongy lead of the negative plate are both converted to lead sulfate in Fig. 2.1. Lead-acid BESs store energy by the reversible chemical reaction shown below [33].

- Lead-acid overall reaction [32]:

$$\begin{array}{ccc} \text{Charged} & & \text{Discharged} \\ PbO_2 + Pb + 2H_2SO_4 & \Leftrightarrow & 2PbSO_4 + 2H_2O \end{array} \tag{2.1}$$

- Lead-acid positive terminal reaction:

$$\begin{array}{ccc} \text{Charged} & & \text{Discharged} \\ PbO_2 + 3H^+ + HSO_4^- + 2e^- & \Leftrightarrow & PbSO_4 + 2H_2O \end{array} \tag{2.2}$$

- Lead-acid negative terminal reaction:

$$\begin{array}{ccc} \text{Charged} & & \text{Discharged} \\ Pb + HSO_4^- & \Leftrightarrow & PbSO_4 + H^+ + 2e^- \end{array} \tag{2.3}$$

Note that the electrolyte (sulfuric acid) takes part in this basic charge and discharge reactions, being consumed during discharge and regenerated during charge. This means that the acid concentration (or density) will change between charge and discharge. It also means that an adequate supply of acid is needed at both plates when the BES is discharging in order to obtain the full capacity.

The lead-acid BES system has a nominal voltage of 2.0 V/cell as shown in Fig. 2.2. The typical end voltage for discharge in PV systems is 1.8 V/cell, and the typical end voltage for charging in PV systems varies between 2.3 and 2.5 V/cell, depending on the BES, controller, and system type. The relation of open circuit voltage to SOC is variable but somewhat proportional. However, if charging or discharging is interrupted to measure the open circuit voltage, it can take a long time (many hours) for the BES voltage to stabilize enough to give a meaningful value.

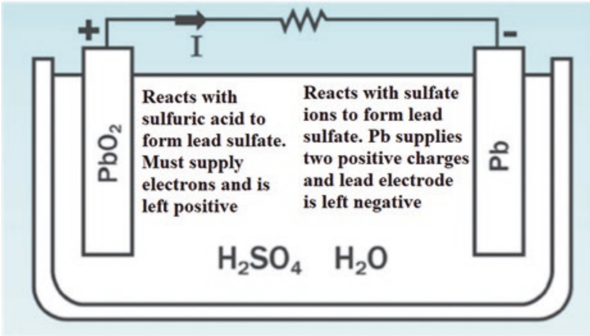

Fig. 2.1 Chemical reaction when a battery is being discharged [33]

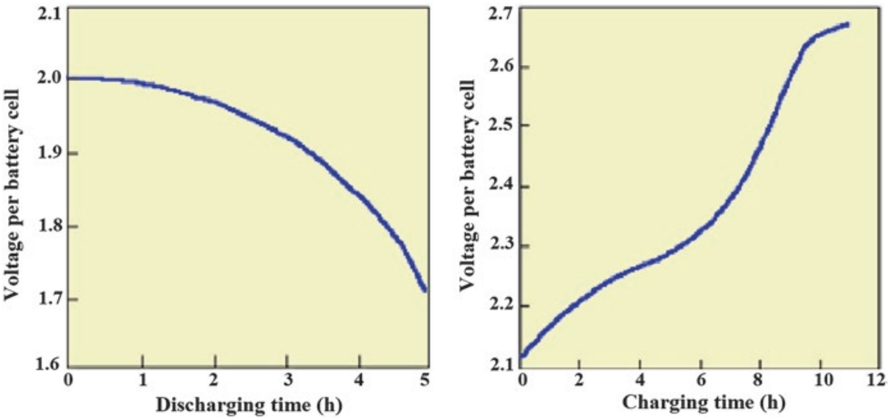

Fig. 2.2 Charge and discharge characteristic of lead-acid BES voltage per cell [31]

2.6 Calculating Battery Size for a PV System

We now list the full process of correctly calculating the capacity required for a particular battery type in a specific PV system [34].

2.6.1 Select the Appropriate Voltage

This is defined by the load (and PV array) nominal voltage unless some DC/DC converter is present in the system. This sets the number of cells or blocks that must be connected in series.

2.6.2 Define Maximum Depths of Discharge

These must be defined for each battery type according to the mode of operation [26].

- The maximum DOD for autonomy reserve is normally set at 80% for a lead-acid battery.
- The maximum daily DOD may either be set arbitrarily (e.g., a figure of 20–30% is common).
- For seasonal storage (if used), a maximum DOD needs to be set.
- For open batteries in most PV systems, a charge rate faster than the 10-hour rate is not recommended.
- For sealed batteries, another consideration is the highest overcharge current that can be sustained with efficient gas recombination, and this is temperature-dependent.

2.6.3 Calculate the Battery Capacity

The battery type recommended for using in solar PV system is deep-cycle battery. Deep-cycle battery is specifically designed to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years. The battery should be large enough to store sufficient energy to operate the appliances at night and cloudy days. To find out the size of the battery, calculate as follows [35]:

(a) Calculate total Watt-hours per day used by loads.
(b) Divide the total Watt-hours per day used by 0.85 for battery loss.
(c) Divide the answer obtained in item (b) by 0.8 for DOD.
(d) Divide the answer obtained in item (c) by the nominal battery voltage.
(e) Multiply the answer obtained in item (d) with days of autonomy (the number of days that you need the system to operate when there is no power produced by PV panels) to get the required Ampere-hour capacity of deep-cycle battery.

$$\text{Battery Capacity}(\text{Ah}) = \frac{\text{Total Wh per day used by loads}}{0.85 \times 0.8 \times \text{normal battery voltage}} \times \text{day of autonomy} \tag{2.4}$$

2.7 The Supercapacitor Energy Storage System in PV System

Supercapacitors (SCs) are based on electrochemical cells that contain two conductor electrodes, an electrolyte and a porous membrane that permits the transit of ions between the two electrodes. Thus, the presented layout is similar to the electrochemical cells of batteries. The main difference between SC (or ultracapacitors or double-layer capacitors) and batteries lies in the fact that no chemical reactions occur in the cells but the energy is stored electrostatically in the cell [36].

In SCs, the electrodes and the electrolyte are electrically charged (the cathode is positively charged, the anode is negatively charged, and the electrolyte contains both positive and negative ions) as shown in Fig. 2.3. At each of the electrode surfaces, there is an area that interfaces with the electrolyte, and it is in each of these areas where the phenomenon of the "electrical double layer" occurs. By applying a voltage between the electrodes, both the electrodes and the electrolyte become polarized. This means that the positive charge of the cathode is transferred to the area interfacing with the electrolyte, forming a layer of positive ions. In turn, the negative ions of the electrolyte are transferred to the same electrolyte/cathode interface, forming a negative charge balancing layer of ions. These two layers build up an "electrical double layer." The mechanism behind the operating principle of such a double layer can be explained using the Helmholtz model [37].

The model establishes that the two layers are separated by a layer of solvent molecules of the electrolyte, called the inner Helmholtz plane. This layer of solvent molecules actually separates the positive and negative charges of the electrode and electrolyte, thus acting as a dielectric. Ultimately, there is a potential difference between the two layers of positive and negative ions derived from the electric field within them, and the double layer can be taken to resemble a capacitor (the described double layer concept can be observed in Fig. 2.3; see also Fig. 2.4).

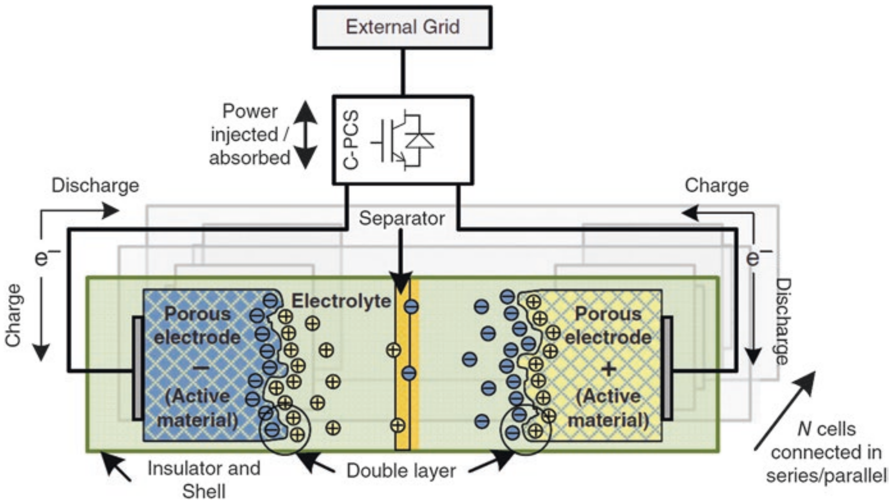

Fig. 2.3 The illustrative topology of a SC, depicting the electrical double layers at each electrode/electrolyte interface [40]

Fig. 2.4 Supercapacitor modules from Maxwell Technologies, Appendix A

Therefore, the magnitude of the electrical potential (in Volts) between the two layers of positive and negative ions at each electrode/electrolyte interface, in conjunction with the resultant capacitance (in Farads), determines the energy stored in the SC. Thus [38],

$$E_{SC}\left(\text{joules}\right) = \frac{1}{2} C V^2 \tag{2.5}$$

The voltage generated in the cell is dependent on the strength of the electric field between the layers building up each of the “electrical double layers” described above. This electric field is, in turn, proportional to the amounts of positive and negative ions located at the electrode/electrolyte interface. So to avoid the transfer of ions between the two layers of positive and negative ions, thus decreasing the voltage within the double layers, the breakdown voltage of the dielectric should be maximized. As noted before, this dielectric is provided by solvent molecules of the electrolyte. In this way, the selection of the electrolyte is key to ensuring the maximum energy capacity. Usually, both aqueous and organic electrolytes are commonly found, the latter being the most common type. With aqueous electrolytes, a cell voltage of around 1 V can be obtained, while it can be increased up to 2.5 V by using organic types.

As stated in Eq. (2.6), the second factor affecting the energy capacity of SCs is the capacitance of the cell. The capacitance (in Farads) of a capacitor is given by the quotient between the stored charge (in Coulombs) per unit of voltage (in Volts), so

$$C = Q / V \tag{2.6}$$

In addition, the capacitance can be expressed as a function of the permeability of the dielectric, its thickness, and the area holding each of the layers of the electrical double layer. Then,

$$C = \varepsilon \varepsilon_0 \frac{A}{d} \tag{2.7}$$

where ε is the dielectric constant, ε_0 is the permittivity of a vacuum, A is the effective area of the surface of the electrode, and d is the dielectric thickness.

In order to maximize the capacitance, different metal-oxide electrodes, electronically conducting polymer electrodes, and activated carbon electrodes are used in industry. These materials are porous, so they can maximize the effective area of the electrode in which ions can be allocated. The most common types are the ones based on activated carbon since they can lead to SCs with a high energy density and capacitances around 5000 F [36], that is, capacities up to 1000 times per unit volume more than those of conventional electrolytic capacitors.

About the distribution of capacitance between the two electrical double layers in the cell, we can distinguish between symmetrical and unsymmetrical SCs. Symmetrical ones are those with the same effective area in both electrodes. Since the cell can be considered to resemble two capacitors in series (given by the two double layers at each electrolyte/electrode interface), the total capacitance can be formulated as

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} \tag{2.8}$$

where C_1 and C_2 are the equivalent capacitances in each electrical double layer. As mentioned, the electrolyte and electrode materials have a fundamental influence on the energy and power capacity of the SC and also on its dynamic behavior. To be precise and with reference to the SC dynamics, one defining parameter is the

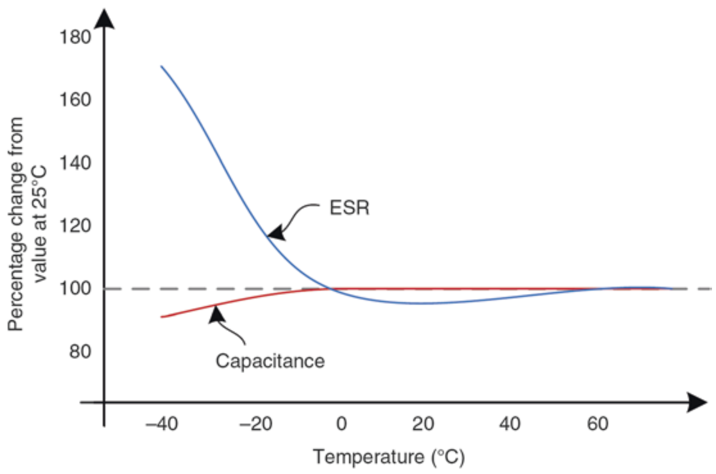

Fig. 2.5 The capacitance and the ESR as temperature-dependent characteristics. Appendix A

so-called charge/discharge time constant, τ. This is given by the product of the equivalent series resistance (ESR) of the SC and its capacitance. Thus,

$$\tau = R_{\mathrm{ESR}} C \tag{2.9}$$

The time constant is the time needed to discharge 63.2% of full capacity with a current limited only by the internal resistance – or the ESR as it is commonly known – of the SC. The ESR weights the losses in the SC while charging and discharging, that is, those associated with the movement of ions within the electrolyte and across the separator. The ESR is normally in the range of milliohms and is a temperature-dependent parameter, as presented in Fig. 2.5.

Apart from the ESR and the capacitance, the third characteristic parameter for the SC is the leakage resistance, which weights the self-discharge of the cell. This resistance is much higher than the ESR. All three parameters – the capacitance, the ESR, and the leakage resistance – can be found in manufacturers' datasheets, and from them, averaged models for SCs can be built.

SCs are characterized by offering high ramp power rates, high cyclability, high round-trip efficiency (of up to 80%), and a high specific power, in W/kg, and power density, in W/m^3 (10 times more than for conventional batteries). The latter characteristic defines SCs as well suited for applications that impose major volumetric restrictions. On the other hand, major drawbacks of the technology are related to its high self-discharge rates (of up to 20% of the rated capacity in only 12 h) and its limited applicability to situations where high power and energy are needed. In fact, the development of SCs is mostly focused in fields such as automotive and portable devices. Finally, it is worth noting that as a short timescale, SCs are unsuitable in that they are expensive in comparison with other competitors such as flywheels. Their cost is estimated at 10 times the cost per kWh of flywheels.

SCs are, in general, young technologies. The first prototypes were developed in 1957 by H.I. Becker (General Electric). However, the first related studies were carried out in the nineteenth century by Helmholtz, who discussed the electrical behavior of a metal surface while immersed in an electrolyte. Currently, intense research activity is underway to scale up SC size and to improve their performance, so that they will be suitable for both stationary and nonstationary applications – such as in the fields of electromobility and PV system.

2.8 Literature Survey of Previous Works

This section provides literature survey of previous works and methods about a stand-alone PV system with the battery-supercapacitor hybrid energy storage system (HESS). The block diagram of the system is shown in Fig. 2.6. There are many researches on the modeling of PV array, MPPT, and half-bridge bidirectional DC/DC converter, and energy storage systems have been studied.

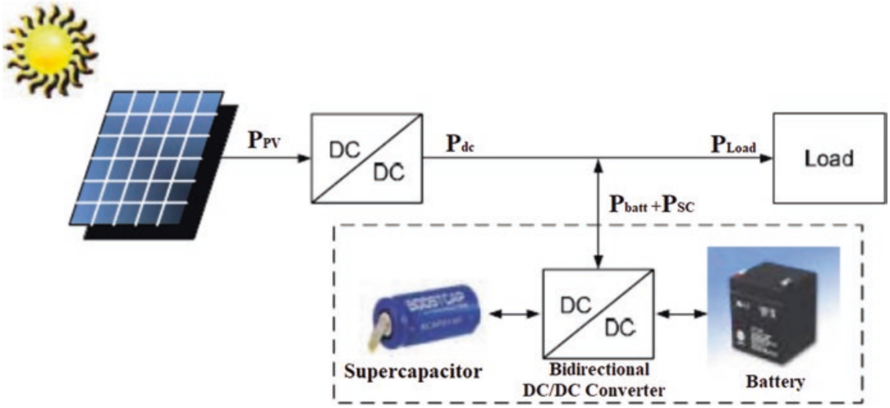

Fig. 2.6 Block diagram of stand-alone PV system with BS-HESS

2.8.1 Review of Related Researches About PV Modeling

K. Ishaque, Z. Salam, and H. Taheri [39] presented an improved modeling approach for the two-diode model of PV module based on four parameters. The proposed model is tested on six PV modules of different types (multi-crystalline, monocrystalline, and thin film) from various manufacturers.

J. Maherchandani, Ch. Agarwal, and M. Sahi [40] presented an efficient and accurate single-diode model for the estimation of the solar cell parameters using the hybrid genetic algorithm and Nelder-Mead simplex search method from the given voltage-current data.

Z. Ahmad and S. Singh [41] presented a method to extract the internal parameters such as ideality factor, series, and shunt resistance of any solar PV cell using block diagram modeling of PV cell/module using Matlab/Simulink model.

S. Lineykin, M. Averbukh, and A. Kuperman [42] implemented the single-diode equivalent circuit to modeling amorphous silicon PV modules. This approach combined numerical solution of two transcendental and two regular algebraic equation systems with single parameter fitting procedure.

B. Chitti Babu and Suresh Gurjar [43] presented modeling approach of PV modules using an ideal two-diode model. This model was simplified by omitting series and shunt resistances, only four unknown parameters from the datasheet were required to analyze the proposed model.

2.8.2 Review of Related Researches About MPPT of PV System

MPPT is a power electronic device with computer that is connected between PV power source and load to extract maximum power from a PV module and satisfy the highest efficiency. Until now numerous of MPPT techniques have been developed to increase the efficiency of the PV system and satisfy the optimal MPPT. These techniques vary in various aspects such as tracking speed, oscillations around MPP, cost, and hardware required for implementation. Most famous MPPT controllers available are fractional open circuit voltage, fractional short circuit current [44], hill climbing [45, 46], P&O [48, 49], InCond [50, 51], incremental resistance [50], ripple correlation control [51], fuzzy logic [52], artificial neural networks [53], particle swarm optimization [54], and sliding mode [55].

P. Francisco and M. Ordonez [56] presented the zero-oscillation, adaptive-step P&O MPPT strategy for solar PV panels. This combined strategy reduced steady-state losses and improved transient behavior during slope changes irradiance while maintaining a similar implementation complexity.

M. Killi and S. Samanta [57] suggested the positive sign of current change to avoid the problem, but this solution is only for increasing of irradiance and lacking information about rapid decreasing of weather.

2.8.3 Review of Related Researches About Half-Bridge Bidirectional DC/DC Converter

To appropriately interface the batteries and the SCs in the HESS (such as in hybrid electric vehicle), a bidirectional DC/DC converter is required to control the power flow in two directions. R M. Schupbach and J.C. Balda [58] presented analysis, design, and comparative study of several bidirectional non-isolated DC-DC converter topologies.

F. A. Himmelstoss and M. E. Ecker [59] who introduced a bidirectional DC/DC half-bridge converter presented analyses with a view to obtaining maximum voltage and current ratings for the elements, rms values for the semiconductor devices, and a rough approximation of the losses.

J. Cao and A. Emadi [60] presented compared to the conventional HESS design, which uses a larger DC/DC converter to interface between the ultracapacitor and the battery/dc link to satisfy the real-time peak power demands and design a much smaller DC/DC converter working as a controlled energy pump to maintain the voltage of the ultracapacitor at a value higher than the battery voltage for the most city driving conditions.

2.8.4 *Review of Related Researches About a Stand-Alone PV System with HESS*

In this paragraph review of previous research on the PV stand-alone systems is related with a BS-HESS. W. Jing, C. H. Lai, M. L. Dennis Wong, and W. S. H. Wong [61] illustrate in islanded microgrid system the battery tenders to be the most vulnerable element in terms of durability. Poorly managed battery charge/discharge process is one of the main life-limiting factors. To improve the battery life, a novel energy storage system topology and a power allocation strategy are proposed.

I. Shchur and Y. Biletskyi [62] discussed the stand-alone PV system; under variable of daily and weather solar irradiation, special devices are used for energy storage. In order to remove stress from batteries during sudden load change, it is advisable to use HESS by adding a *SC* module to battery.

J. Cao and A. Emadi [60] presented in their paper a battery/ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles. Compared to the conventional HESS design, which uses a larger DC/DC converter to interface between the ultracapacitor and the battery/dc link to satisfy the real-time peak power demands, the proposed design uses a much smaller DC/DC converter working as a controlled energy pump to maintain the voltage of the ultracapacitor at a value higher than the battery voltage for the most city driving conditions.

Lee Wai Chong, Yee Wan Wong, Rajprasad Kumar Rajkumar, and Dino Isa [63] presented comparison between the stand-alone PV system with BS-HESS and the conventional stand-alone PV system with battery-only storage system for a rural household. Stand-alone PV system with passive BS-HESS and semi-active BS-HESS is presented in this study.

2.9 Summary

This chapter presented and reviewed the importance of energy storage systems in PV system. The energy from PV systems is generally stored in BES deepening upon the requirements of the system. The main functions of the BES in a PV system are used to store energy to eliminate the mismatch between PV power and power load demand. Most electrical loads need a constant amount of power to be delivered. The BES provides power when the PV array produces nothing at night or less than the electrical load requires during the daytime. The BES provides a reserve of energy that can be used during a few days of very cloudy weather or in an emergency. The BES prevents large, possibly damaging, voltage fluctuations. The types of BES used with PV systems were also clarified, and a comparison was made between these types in terms of charging and discharging characteristics. This chapter also explained the details of the most common type of batteries used in PV systems, the lead-acid battery. The operation of lead-acid battery, internal structure, and common types has been explained. In addition, this chapter presents a review of SC in terms of working theory, internal components, and general properties.