9

Battery Storage and Standalone System Design

A standalone system supplies electric power independent of an electrical distribution network. Such systems can be generally classified into two categories: those with or without significant storage, as shown in Figure 9.1.

Systems without bulk energy storage can be direct-coupled, power-conditioned or hybrid, the configurations of which are shown in Figure 9.2. The diagrams provide a basic representation, but practical systems are more complex than shown.

Direct-coupled systems are the simplest PV applications, designed to match the PV output to the load, as shown in Figure 9.2a. They are commonly used for ventilation fans and water pumps for irrigation, and so on. In most systems, control circuits are implemented to switch on and off the connection depending on the voltage the PV output, which is an indicator of the available solar power. Such systems are incapable of accurate MPPT due to their lack of power conditioning.

All direct-coupled systems can be modified to incorporate a power-conditioning unit to enhance control. Such a system is shown in Figure 9.2b, with a power conditioner included between the PV generator and the load. Power conditioning is very effective for a PV system without significant energy storage. The MPPT function can be used to maximize the PV output regardless of environmental variations. The power interface can also be controlled to meet specific load requirements, such as a constant voltage supply.

A hybrid system usually uses a conventional engine-based generator in parallel with the PV power source. Both share the same distribution channel to the common load, as shown in Figure 9.2c. The DC/AC converter produces AC power from the PV source and supplies the load through the distribution network. The PV power contribution can reduce the power generation required from the generator, resulting in a fuel saving. The PV system is usually controlled through MPPT to yield the highest solar energy harvest.

Even though the diagram in Figure 9.2c shows only one motor generator, the system can be composed of multiple generation units in parallel connection. For the best fuel-saving performance, communication is generally required to coordinate the PV output with the engine-based generators. Coordination is important when the PV power penetration becomes significant, say more than 25%. When multiple motor generators are available in a standalone system, the system can be optimized to improve efficiency. For example, running two generators each at 50% of capacity is generally more fuel efficient than operating four, each at 25% of capacity. Using real-time measurements of the load condition and PV generation, the centralized coordinator can schedule the overall generation facilities in an economical way, so as to give the best performance in terms of system efficiency and fuel saving.

Photovoltaic Power System: Modeling, Design, and Control, First Edition. Weidong Xiao.

Companion Website: www.wiley.com/go/xiao/pvpower

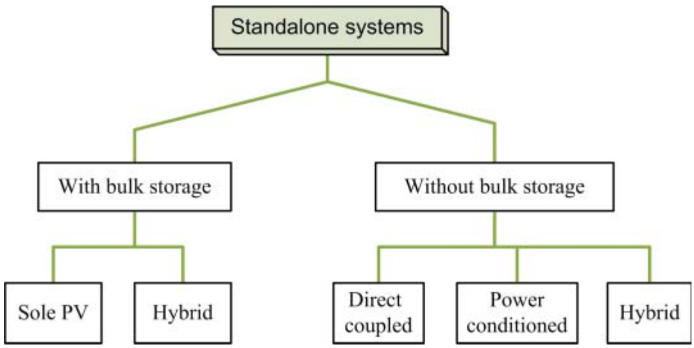

Figure 9.1 General classification of standalone PV systems.

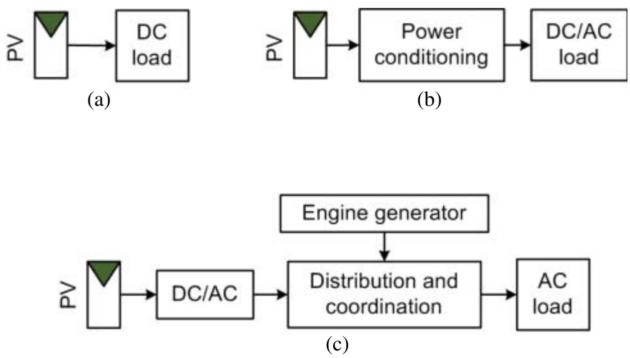

Figure 9.2 Standalone systems without bulk energy storage: (a) direct-coupled; (b) with power conditioning; (c) hybrid solution.

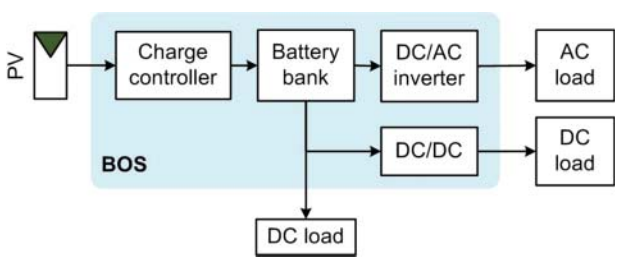

Figure 9.3 Standalone PV system with bulk energy storage.

A steady power supply is demanded by loads in the majority of standalone systems. As discussed in Section 1.9, bulk energy storage – mainly rechargeable batteries – is generally required to mitigate the intermittency of solar energy. Systems with bulk energy storage, can be divided into two groups: standalone PV and hybrid. These are shown in Figures 9.3 and 9.4, respectively. It should be noted that the diagrams are general representations, since practical systems may be more complex. Furthermore, overcurrent protection (OCP) is mandatory for any system with battery storage, even though no protection circuits are shown in the diagrams.

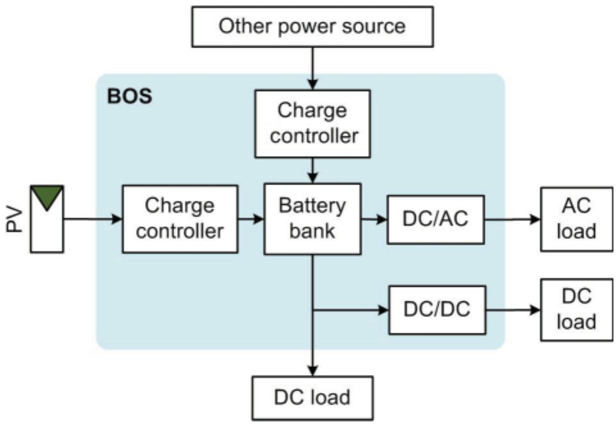

Figure 9.4 Hybrid system including PV and bulk energy storage.

As shown in Figure 9.3, the battery charging cycles should be properly maintained by the charge controller with integration of MPPT to give the highest solar energy harvest. Any extra PV power bypasses the battery buffer and supplies the loads directly. The battery bank forms an unregulated DC bus since the voltage varies by up to ±20% from the nominal voltage according to the state of charge. The unregulated bus can directly supply DC loads if they are insensitive to voltage variation. A DC/DC converter should be implemented to regulate the output voltage and supply the dedicated load if constant DC voltages at different levels are required. When AC loads are present, DC/AC conversion should be used to convert from the unregulated DC bus to AC.

A hybrid system involves use of additional power sources alongside the PV generator, as shown Figure 9.4. Additional power can come from wind turbines, fuel cells, or conventional engine-based generators. Such a system can balance the battery charge and the power from PV or other power sources since multiple charge controllers are included. The coordination can be achieved using a centralized controller or a distributed sharing algorithm implemented in each charge controller. PV power generation is expected to use MPPT to give the highest clean energy contribution. There is also an option for fuel-based power sources to bypass the battery and supply the load directly, although this configuration is not shown in Figure 9.4. A direct connection can minimize power losses in the conversion stages.

9.1 Batteries

A rechargeable battery is defined as an energy storage device that converts chemical energy into electrical energy and vice versa. People are tending to use more and more rechargeable batteries instead of the disposable counterparts due to cost savings and environmental concerns. Due to the bulk energy storage requirement in standalone PV systems, it is important to understand the different battery technologies and to select one accordingly. Battery cells are the basic electrochemical units that form a battery module and pack, as shown in Figure 9.5. A large battery power system is usually constructed from battery banks. When the battery system becomes more and more

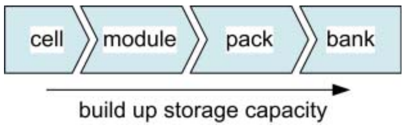

Figure 9.5 Formation of battery power systems from cell to bank.

complicated and powerful, special attention should always given to incorporate protection devices for safety purposes. For portable devices such as cell phones a single battery cell can be used.

It should be noted that all batteries exhibit self-discharge, the rate depending on the battery type and temperature. Furthermore, all batteries have a limited cycle life, their lifetime depending on the battery type, the conditions of charge and discharge, the temperature, and other conditions of use.

9.1.1 Battery Types

Common rechargeable batteries are based on lead, nickel, lithium, or sodium. It is important to understand the cell nominal voltage and characteristics and to select the correct type for the given application.

Lead-based batteries

Lead-based battery technology is mature and therefore low-cost and reliable. This is the main reason that lead-based batteries are still widely used for vehicles and back-up energy storage. They are often referred to as "lead-acid" batteries, because dilute sulfuric acid and lead are used for the electrolyte and plate, respectively. Table 9.1 summarizes the common terms and basic characteristics of lead-acid batteries. Two main categories can be considered: flooded and sealed. Because of their advantages of safety and low maintenance requirement, more and more applications are using sealed modules instead of the old flooded type. Sealed modules also include the VRLA, AGM, and gel types, which are described in the table.

The battery module, typically rated at either 12 V or 6 V, is built from lead-acid cells with a nominal voltage of 2 V. Lead-acid batteries can also be classified in another way:

Table 9.1 Common lead-acid battery types.

Type	Description
Flooded	Old lead-acid technology with liquid electrolyte inside the cell. Regular maintenance is required by adding distilled water.
Sealed	Also called "maintenance-free" battery since the cell is sealed without water. Generally considered safer than flooded batteries.
Valve-regulated lead-acid (VRLA)	The battery module includes a valve for release of hydrogen and oxygen gasses during charging.
Absorbent glass mat (AGM)	The electrolyte is suspended in a special glass mat. High efficiency.
Gel	Contains a silica type gel to suspend the electrolyte. Does not tend to sulfate or degrade as easily as wet cells.

as starting or deep-cycle batteries. A starting battery is to used provide instant power, such as in a starter motor. Such a battery is also termed as the "cranking" type. For standalone PV systems, deep-cycle batteries are commonly used. These are built to provide continuous electric power, with high capacities and long cycle lives. The commercial term "solar batteries" often refers to deep-cycle batteries. Even though lead-acid batteries are still widely used in renewable energy systems, the following drawbacks lead to the use of other battery technologies:

- low energy capacity density per unit volume
- low energy capacity density per unit weight
- slow charge speed
- limited cycle life.

Nickel-based batteries

The common types of nickel-based batteries are summarized in Table 9.2. Nickel–metal-hydride (NiMH) batteries were introduced in 1992 and are commonly used in low-cost consumer products (Powers 2000). The battery is composed of nickel hydroxide and a hydrogen-absorbing alloy. Most rechargeable NiMH batteries follow the the American National Standards Institute (ANSI) standard, and are sized as A, AA, or AAA. A standard AA size cell typically has a capacity of 1800–2500 mAh. The cylindrical forms are available to replace primary batteries, which are not rechargeable. The hydrogen-absorbing alloy is capable of absorbing and releasing hydrogen at a higher density level than the cadmium compound used in nickel–cadmium (NiCd) batteries. One important application of NiMH technology is in the hybrid vehicle, the Toyota Prius. According to a report from the National Renewable Energy Laboratory of the USA (Kelly et al. 2002), the battery system is designed to have a nominal voltage of 273.6 V and a capacity of 6.5 Ah. The system includes 38 battery modules, each formed by six cells in series.

NiCd batteries used to be considered one of the most reliable battery technologies, and have been produced since 1980 (Powers 2000). They have been widely used in the space and aviation industries. For example, they have been used in the main and auxiliary power units in the Boeing 777 airliner. The Boeing 777 has one of the best safety records in aviation history, supporting claims for the reliability performance of NiCd batteries. The battery pack used has a nominal voltage of 24 V and a capacity of 16 Ah. It is formed from 20 NiCd cells and weights 48.5 kg.

The battery shares the same structure as its NiMH counterpart. NiCd batteries use nickel oxide as the cathode, a cadmium compound as the anode and potassium

Table 9.2 Common nickel-based batteries.

Type	Description
Nickel–metal-hydride (NiMH)	The cell is rated at 1.2 V. The battery is composed of a positive plate containing nickel hydroxide as the positive electrode and a hydrogen-absorbing alloy as the negative electrode.
Nickel–cadmium (NiCd)	The cell voltage is rated at 1.2 V. The battery uses a nickel oxide and cadmium compound.

hydroxide solution as the electrolyte. They also use the ANSI standard AA and AAA sizes, but are no longer as widely available as their NiMH counterparts. They exhibit low voltage drop over the discharge period, but the energy density is no longer competitive with the latest battery technologies. Standard AA cells generally have capacities of 600–800 mAh, which is significantly lower than NiMH cells. Nickel-based batteries show a memory effect that tends to “remember” the previous operation cycle, so a relatively deeper charge/discharge cycle is required than for batteries without a memory effect. The self-discharge rate of nickel-based batteries is significantly higher than the latest lithium-based technologies.

Lithium-based batteries

Lithium-based technologies have drawn significant attention and grown exponentially due to their significant advantages, such as high energy density per unit volume and per unit weight. The typical cell voltage rating is 3.6 V, which is generally higher than other types. The self-discharge rate is lower than that of NiMH batteries and there is no memory effect. Furthermore, high efficiencies can be demonstrated in fast charge and discharge. In a lithium-ion cell, the positive electrode is usually activated by cobalt acid lithium, while the negative electrode is activated by highly crystallized specialty carbon. The lithium cobalt oxide material is ionized and the ions move to the negative electrode. During discharge, the ions move to the positive electrode and turn into the original compound.

The advantages of lithium-ion batteries mean they are widely used for transportation fleets and portable electronic devices. Table 9.3 outlines two examples of lithium-ion batteries that have attracted much media coverage in recent years. Further information about these technologies and the latest updates can be sourced from the relevant websites at www.boeing.com and www.chevrolet.com.

The Boeing 787 airliner uses lithium-ion batteries to replace their NiCd counterparts. This gives a significant improvement in terms of power capacity and high power over the Boeing 777. However, in the first year of service, the aircraft suffered a number of fire incidents resulting from the lithium-ion battery packs. As a result of the Boeing 787 incidents, in 2013, Airbus reverted to NiCd batteries for the newly developed A350 XWB.

The Chevrolet Volt is a plug-in hybrid vehicle and is an example of a lithium-ion battery application for ground transportation. The battery pack is rated at 16.5 kWh at a nominal voltage of 355.2 V. The capacity of the battery pack is not as high as other

Table 9.3 Typical applications of lithium-ion batteries.

Applications	Battery pack specification
Boeing 787	Each battery unit is configured with 8 lithium-ion cells Nominal voltage of 32 V, 28.6 kg weight More powerful but lower weight and smaller size than NiCd counterpart
Chevy Volt	Battery pack weighs 197 kg, formed from 288 lithium-ion cells Nominal voltage 355.2 V and 16.5 kWh capacity Narrow cycle of charge and discharge (60% of total capacity) is used for day-to-day operation

electric vehicles because the vehicle is also equipped with an internal combustion engine which can drive an electric generator and provide charge if required. The system is designed for a light charge and discharge cycle in order to prolong the battery life cycle. It has generally received positive reviews thanks to the selection of an appropriate battery technology and the design of the battery management system.

Lithium-based technologies are the latest battery technology, with more and more applications emerging, including utility-scale storage. Safety precautions should be always taken; the high energy density is advantageous, but is potentially hazardous. Misuse and lack of protective measures may cause battery explosion or ignition.

One special technology is the sodium–sulfur (NaS) battery, which has several important advantages: high energy density, long cycle life, low-cost materials, and high efficiency. The Japanese company, NGK Insulator Inc, is the major manufacturer for this technology (Beaudin et al. 2010). According to the company's website at https://www.ngk.co.jp, an NaS battery cell uses sulfur as the positive electrode and sodium as the negative electrode. Beta alumina ceramic is used between the electrodes. During discharge, sodium ions are released from the negative electrode and are transferred through the solid electrolyte into the sulfur at the positive electrode. The battery charging is the reverse of the discharge process, with sodium forming in the negative electrode. High operating temperatures are required for molten sodium, which limits use to stationary applications. The nominal voltage of an NaS cell is 2 V. The technology is considered suitable as an energy buffer for mitigating power intermittency in renewable electricity resources, such as solar and wind. The high operating temperature is also a concern because of the fire hazard involved.

9.1.2 Battery Terminology

A battery module is formed from series-connected cells sealed into one unit. Battery modules are mechanically and electrically assembled to form a battery pack. In large-scale systems, battery packs are grouped together to form a battery bank. A battery management system is generally required to regulate the battery system operation and protect it from damage if the capacity becomes significant; multiple cells in complex configurations can exhibit mismatches, which can be unsafe. The important terms relating to battery voltage are described in the following:

- *Nominal voltage*: can refer to the cell, module, or pack levels, and is the voltage reference for system rating and design. When batteries are used in practical systems, the terminal voltage is generally different from the nominal voltage. The terminal voltage depends on the instant load condition, state of charge, and temperature.
- *Cut-off voltage*: the least allowable voltage to discharge the battery. For rechargeable batteries, any discharge operation may result in damage when the terminal voltage is lower than the cut-off limit.
- *Open-circuit voltage*: measured when no charge or discharge is taking place. It is commonly considered as an indicator of battery capacity. Compared to the nominal voltage, a high value indicates high remaining SOC. However, the absolute value also depends on the temperature.
- *Float voltage*: voltage level for the battery charger to maintain a trickle charge when the battery has been fully charged. The voltage level is generally defined to maintain the battery capacity against discharge and avoid overcharging the battery.

The terms for energy and capacity are as follows:

- *Nominal battery capacity* is generally defined as the total amp-hours available. If a battery capacity is 1 Ah, without considering power loss, it indicates that the nominal capacity can be fully discharged in 1 h if the discharge current is 1 A. On the other hand, in theory, the battery can be fully charged from empty when a current of 1 A is applied for 1 h.
- *C-rate* is the rate at which a battery is charged or discharged relative to its rated capacity. If a battery capacity is 1 Ah, a 1C discharge rate means that the discharge current is 1 A. A C/4 charge rate indicates the charge current is 0.25 A. In theory, the time to fully charge from empty is 4 h when C/4 is applied.
- *State of charge (SOC)*: is an expression of the present battery capacity as a percentage of the rated capacity.
- *Depth of discharge (DOD)* refers to the percentage of battery capacity that has been discharged over the rated capacity.
- *Nominal energy* is an important term to define the energy capacity of batteries. It can be derived from the nominal voltage (V) and capacity (Ah). The measurement unit is Wh or kWh. Its value is important to size standalone PV systems with consideration of the load profile.
- *E-rate* is the rate at which a battery is charged or discharged relative to its nominal energy.

Other important terms are:

- *Charge cycle* is defined as the process of charging a rechargeable battery to a high capacity and discharging to a low capacity. In a PV power system, it is usually counted day by day since the charge happens during daytime and discharge is at nighttime.
- *Deep cycle* for a rechargeable battery is when it is charged to more than 80% of the SOC and then discharged to less than 20% of the SOC. Since the cycle life depends on the DOD, frequent deep-cycle operation generally causes fast aging and a short life span.
- *Recommended charge current* is the ideal current at which the battery is initially charged (to roughly 70% of SOC) under a constant charging scheme before transitioning to constant voltage charging. Temperature should be always considered when determining the recommended charge current.
- *Recommended charge voltage* is the voltage at which the battery is allowed to be charged up to the full capacity. The cycle charge includes both the regulation of current and voltage. Temperature is generally required to precisely determine the recommended charge voltage.
- *Cycle life* is the number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. The evaluation and estimation of cycle life should be based on specific charge and discharge conditions, such as the charge rate, discharge rate, DOD, temperature, and humidity. It is generally considered that the higher the DOD per cycle, the lower the cycle life.

9.1.3 Charging Methods

Charging is a process to restore a discharged battery to the required capacity. It is important to use a proper charging method and maintain proper charge cycles for long battery lifetime. Battery charging methods are in three categories:

- cycle charging
- compensating charging
- float charging.

The standard cycle charge usually starts with a constant current, and then a constant voltage. Cycle charging is designed to charge the battery from a low percentage of SOC to a higher level or full charge. It starts with a constant-current charge cycle and allows the voltage to rise, as illustrated in Figure 9.6. It is commonly referred to as the bulk stage, since most capacity is recovered during this cycle. The maximum charging current is usually set to prevent any significant temperature rises, would result in fast aging and early degradation. The C-rate is commonly used as a measure of the charging current. When the voltage reaches the upper level, the charging cycle becomes a constant-voltage operation. This is also referred to as the "absorption stage". The battery capacity will be recovered to the full level at this stage when the charge current reaches a significantly low level, as shown in Figure 9.6.

Compensating charging is also called trickle charging, and is applied to maintain the battery capacity against self-discharge. Float charging is used where the battery is in parallel connection with the load. In PV power systems, solar power is used to supply the load during the day, while any surplus power is used to charge the battery. A strict charging cycle for constant current is difficult to maintain in the float charging process due to the variation of load conditions. Both trickle and float charging are considered constant-voltage charging methods since the battery voltage must be maintained at a constant level.

Table 9.4 shows the typical ratings to charge lead-acid batteries. It should be noted that the ratings are for a constant temperature of 25°C and are presented only for reference purposes. Accurate ratings should follow the manufacturer's recommendations, along with consideration of environmental conditions. The setting can be calculated according to the nominal voltage and battery capacity. For a battery module rated as 12 V/100 Ah, to perform cycle charging, the recommended charge current is 40 A and the voltage is 14.4 V.

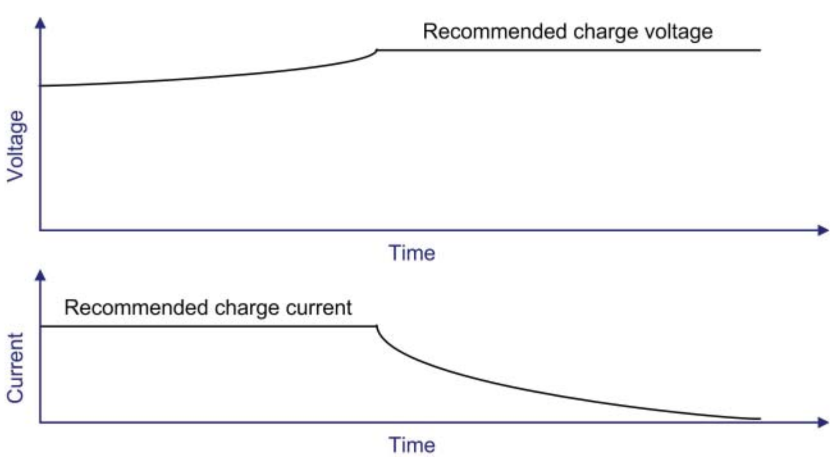

Figure 9.6 Cycle charge with constant current and constant voltage: top, charging voltage; bottom, charging current.

Table 9.4 Typical settings for charging lead-acid batteries.

Charging method	Recommendation
Constant current for cycle charge	Recommended current is 0.4C or lower. The lower the rating, the longer the charging time.
Constant voltage for cycle charge	Recommended voltage is 120% of the nominal voltage.
Trickle charging	Recommended voltage is 115% of the nominal voltage.
Float charging	Recommended voltage is 115% of the nominal voltage.

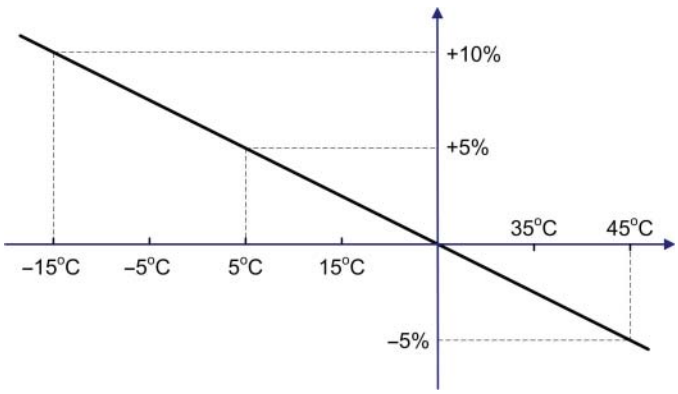

Figure 9.7 Charging voltage with temperature compensation.

Ideally, the battery should be stored or operated in a environment in which the ambient temperature is conditioned. High temperatures accelerate aging, while low temperatures constrain capacity. Temperature compensation should be considered for the charging voltage when the battery temperature varies significantly and can be sensed. The objective is to either prevent fast aging if the battery temperature too high or to guarantee sufficient charging when the temperature is lower than required. The general rule is to increase the charging voltage if the temperature is lower than 25°C and decrease it when temperature is higher than 25°C. For lead-acid batteries, it is recommended to have a compensation slope to adjust the charging voltage according to the temperature. Figure 9.7 shows a reference chart for temperature compensation with a slope of −0.25% per degree. For example, if the nominal charge voltage is 14.4 V for a 12-V battery module, the charging voltage should be adjusted to 15.8 V if the temperature is 15°C below zero. When the temperature becomes 45°C, the charging voltage is set to 13.7 V according to the compensation curve. It should be noted that different battery manufacturers might recommend different values for temperature compensation.

The settings in Table 9.4 are considered a general reference. Battery temperature is considered as the main factor that affects aging and damage. The charging rating can be more accurately defined and automatically adjusted if the battery temperature can be monitored as it charges. Without temperature sensing, the battery charging cycle is usually defined in a conservative way in order to avoid any unexpected temperature rises that would cause fast aging and damage. Rapid charging can be performed when the battery temperature is either monitored or regulated. The charging current and voltage can be adaptively adjusted in real time in response to temperature variations.

For example, the charging current for rapid charging can be regulated up to 1C for NiMH batteries when the ambient temperature is higher than 0°C but lower than 40°C, according to the recommendation of Panasonic. The rapid charging should be turned off if one of the following conditions is detected, at which point trickle charging is activated:

- the NiMH cell voltage reaches the extreme level of 1.8 V
- the cell voltage starts to drop by up to 10 mV
- the cell temperature increases too fast; up to 2°C/min
- the cell temperature reaches the upper limit of 40°C
- the rapid charge time is recorded up to 90 min.

Panasonic recommends a two-stage cycle charging for its lithium-ion batteries. It starts with a constant-current charging cycle and the voltage is allowed to rise. When it reaches the upper voltage limit, the charging cycle becomes a constant-voltage operation, which maintains the battery voltage at a constant level. The battery capacity is considered to be fully recovered at this stage. The typical settings for lithium-ion batteries are summarized in Table 9.5. The charge should be stopped if the charge current decreases to 0.1C. It is considered a malfunction if the charging time is longer than 720 min and the current is still higher than 0.1C. Charging should be stopped and an error should be signaled by the charge controller.

If the initial battery voltage is only 80% of the nominal voltage, the battery is usually considered as deep discharged. To avoid any damage caused by rapid charging, a slow charging process should be used, in which the charge current is set to 0.1C or less. It should be noted that the recommended ratings for various charge methods is only a general reference; the manufacturer's recommendation should be always followed because of the variety of different battery technologies.

9.1.4 Battery Mismatches and Balancing Methods

Similar to the construction of PV modules and strings, battery modules and packs are formed from multiple cells in series connection, so as to reach the required voltage level. Ideally, all battery cells in one battery pack are identical and share the same SOC and electrical characteristics. However, mismatches happen along each string since battery cells can be different, for various reasons, such as manufacturing defects, temperature gradients, and uneven aging. Between 1% and 10% of mismatches are due to manufacturing defects (Rehman et al. 2014).

During charging and within one string, a stronger cell gains SOC faster than a weaker one. During discharging, the SOC of the weaker cell decreases faster than the

Table 9.5 Typical settings for charging lithium-ion batteries.

Charging method	Recommendation
Constant current for cycle charge	Recommended current is up to 0.7C. The lower the rating, the longer the charging time.
Constant voltage for cycle charge	Recommended voltage is 117% of the nominal voltage.
Charge temperature	Between 10°C and 45°C.