Increased Energy Delivery for Parallel Battery Packs with No Regulated Bus

A Dissertation Submitted to
The Department of Electrical and Computer Engineering

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Doctor of Philosophy

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Abstract

In this dissertation, a new approach to paralleling different battery types is presented. A method for controlling charging/discharging of different battery packs by using low-cost bi-directional switches instead of DC-DC converters is proposed. The proposed system architecture, algorithms, and control techniques allow batteries with different chemistry, voltage, and SOC to be properly charged and discharged in parallel without causing safety problems. The physical design and cost for the energy management system is substantially reduced.

Additionally, specific types of failures in the maximum power point tracking (MPPT) in a photovoltaic (PV) system when tracking only the load current of a DC-DC converter are analyzed. The periodic nonlinear load current will lead MPPT realized by the conventional perturb and observe (P&O) algorithm to be problematic. A modified MPPT algorithm is proposed and it still only requires typically measured signals, yet is suitable for both linear and periodic nonlinear loads.

Moreover, for a modular DC-DC converter using several converters in parallel, the input power from PV panels is processed and distributed at the module level. Methods for properly implementing distributed MPPT are studied. A new approach to efficient MPPT under partial shading conditions is presented. The power stage architecture achieves fast input current change rate by combining a current-adjustable converter with a few converters operating at a constant current.
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Chapter 1

Motivation, background, and dissertation organization

A Battery Management System (BMS) is an electronic solution to monitor the state of charge (SOC) and state of health (SOH) of batteries, manage the charging/discharging process, and optimize the power flow control in a power system. This type of battery management is necessary for a variety of applications, including portable, industrial, and vehicle use. Consumer products like laptops, PDAs, cell phones, and electric razors all require a BMS, as do non-consumer goods such as portable X-ray equipment. In industry, BMS are used for meters, alarms, security systems, uninterruptible power supplies (UPS), oil drilling, oceanography, spacecraft/satellites, military equipments, electric vehicles (EVs), and hybrid electric vehicle (HEV). A comparison of BMS in several important applications is listed in Table 1.1.

A BMS consists of rechargeable batteries, a battery charge management unit, a protection circuit, fuel gauges, and voltage/current/temperature sensing circuits. It should
be able to provide the following functions: battery protection, charging/discharging control, SOC prediction, SOH prediction, cell balancing, history of all battery-related parameters, authentication and identification, and communications.

In the following subsections, an overview of BMS is presented, first by introducing the historical development of electric razors and then by presenting more recent, advanced microgrid architectures. Then the open research questions that motivated this dissertation are presented, followed by a summary of the dissertation organization.

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<tr>
<th>BMS Design Difficulty</th>
<th>Easy</th>
<th>Moderate</th>
<th>Moderate</th>
<th>Hard</th>
</tr>
</thead>
</table>
1.1 Electric Razor Battery Management Systems

Before the invention of the electric razor, the most popular tools for shaving were straight razors and disposable safety razors. The first electric razor was invented in 1928 by Jacob Schick, a retired U.S. Army Lieutenant Colonel. On November 6th, 1928, a patent for the first handheld electric shaver was granted to Jacob Schick [1]. In 1929, the first commercial model was introduced to the market. The design of the first electric razor was too cumbersome to be marketable because it required a grapefruit-sized external motor that turned a shaft connected to a cutting head, and it had to be operated with two hands [2]. On May 13th, 1930, a patent for a handheld electric shaver with a miniature motor inside was granted to Jacob Schick [3]. He began selling his first one-handed electric razor on March 18th, 1931 for $25 [4] (about $416 in 2014 US dollars) in New York. About 3,000 electric razors were sold in the first year [2], and sales increased until 2 million were in users’ hands by 1937 [4].

The original concept of Jacob Schick’s electric razor was to use an AC-to-DC converter to drive the small DC motor inside the razor. A user needed to plug the shaver into a wall AC outlet for operation. In the 1950s and 1960s, battery-powered electric razors were invented that improved portability as well as reduce the risk of an electric shock [5-10]. A rechargeable battery was sealed inside the shaver. The battery provided the power to drive the DC motor and eliminated the need for AC power. Some of the battery-powered electric razors included a built-in AC-DC rectifier as a charger and a
switch between the battery and the motor, as illustrated in Figure 1.1, so that the following three operation modes are available:

1) *Shaving without plugging onto an AC outlet*: The battery is discharged when shaving. The switch between the battery and the motor is closed.

2) *Shaving with plugging onto an AC outlet*: The battery is charged when shaving. The switch between the battery and the motor is closed.

3) *Charging with plugging onto an AC outlet*: The battery is charged. The switch between the battery and the motor is open.

This type of energy architecture represents one of the first widespread commercial applications of a BMS.

Figure 1.1 Built-in AC-DC rectifier in a battery-powered electric razor and a switch between the battery and the motor to control the operation mode. (a) Schematic in [6] (b) Schematic in [10].

As will be introduced in the following sections, the BMS technologies previously driven by the consumer electric razor had been applied to many industrial applications. In
this dissertation, similar concepts of the BMS technologies for the original by small handheld electric razors are extended to support large-scale military and camping power conversion operations in remote areas, particularly where a reliable utility grid is not available and multiple batteries as well as renewable energy sources have to be used.

1.2 Microgrid

A microgrid is a localized electrical system consisting of distributed energy sources (diesel generators, solar panels, wind turbines, fuel cells, or a combination of different sources) and energy storage such as batteries. It has the ability to supply multiple loads (DC and/or AC). When supplying AC loads, a microgrid can be either connected to the utility grid (on-grid / grid-tied) or disconnected to the utility grid (off-grid / electrically islanded). Microgrids have the power to efficiently and flexibly meet the growing energy demand of rural communities, whether they serve the energy demand of a few houses or large military installations.

A grid-tied microgrid provides the following benefits:

- **Highly reliable energy**: A microgrid can serve as a backup power supply in the event of an outage. Unlike a backup generator, there is usually no delay after an outage occurs and before the energy sources and energy backup are connected, significantly improving the energy reliability.

- **Improved diesel generator efficiency**: Batteries in a microgrid can absorb sudden changes in loads and energy sources. This allows a diesel generator to always operate at full load with optimized efficiency, saving fuel costs.
• *Maximized economic value*: When renewable resources such as solar and wind energy are used, the “free” renewable energy can be sold to the utility grid operators to reduce the electricity bill. Electricity delivered and sold to the utility grid can be used to help balance production and load of the power systems.

An islanded microgrid is suitable for areas where a utility grid is not available, such as remote areas in developing countries and military outposts. The power demand in these “off-grid” areas are met by diesel generators or renewable electricity generating equipment, such as solar panels and/or wind turbines. A portable microgrid for remote personal use is one kind of islanded microgrid with small-scale power capability. This portable microgrid is introduced in the following section.

### 1.3 Remote power sources and personal portable microgrid

With the revolutionary advancements and convenience of portable electric and electronic products, demand for portable electric power continues to grow. Today’s consumers demand instantaneous power on newer and more powerful smart phones, tablets, cameras, GPS, and even home appliances as they are out and about or enjoying outdoor activities. In these outdoor environments wall outlets are often not available; consequentially most portable electronic devices are powered by batteries. However, although battery technology has improved over the past decades, battery capacity still remains well behind the power demands of modern consumer electronics. This lack in
progress creates a significant problem: consumers have to either spend more time charging their batteries or procure more batteries as backup energy for their electronic devices.

In urban areas charging batteries is convenient. The widespread accessibility of wall outlets in homes and buildings make it easy to recharge electronic devices whenever necessary. For people who live, work, or travel in remote areas, however, it is more difficult to charge batteries. Their distance from traditional charging sources and limited energy sources or lack of utility grid can cause even more difficulty. For power applications in remote areas, battery capacity (Ampere-Hour) is usually the key factor that determines the run time of a battery that powers all the electric/electronic devices and household appliances. In order to increase the run time of a battery that powers electronic devices and appliances, there are two commonly used approaches. One option is to run a portable diesel generator to power all the devices and to charge the batteries when their state of charge (SOC) is low. These generators provide an added level of insurance by backing up power and are relatively easy of transport and install. Yet, diesel generators also have significant/distinct disadvantages. In addition to power, diesel generators also produce air and noise pollution. The air pollutant contains various chemical gases and heavy particulates that can be harmful for human health. Furthermore, generators cannot operate continuously; they require maintenance and fuel delivery to keep functioning and producing power. Finally, generators are not efficient; their fuel consumption increases during light loads. Because of these problems, running diesel generators in remote areas might not be preferred or even practical. An alternative option is to purchase or use extra rechargeable batteries and replace a battery that has been drained with a new one or one
with a full state of charge. The drained battery can then be recharged to full through a separate charging process if an extra power source (e.g. solar panels) is available. The following two examples illustrate the use of multiple batteries and solar panels as remote power sources.

1.3.1 Campers/Hikers at camping sites

Figure 1.2 shows a camper’s inventory of DC loads and a histogram to graphically represent the energy consumption per day (Ah/day) in his camper trailer [11]. There are five DC loads, including a refrigerator (consuming 19.968 Ah/day) for food storage, a water pump (consuming 3.75 Ah/day) for taking a shower, a sine wave inverter (consuming 9.8 Ah/day) for AC appliance, a LED camping light (consuming 5 Ah/day), and a USB phone charger (consuming 7.5 Ah/day). The total energy consumption per day is 46.018 Ah. The camper also carries a deep-cycle battery with a capacity of 105 Ah. Because discharging this kind of deep-cycle battery more than 50% will shorten its lifetime, the normal target maximum usage is limited at a Depth of Discharge (DoD) equal to 50%. Therefore, the total run time of the battery is only 1.14 days (105 / 2 / 46.018 = 1.14) without the help of solar panels. If the camper’s energy usage increases much more, having solar panels and two batteries in parallel should be considered. Having two batteries in parallel also has another benefit: if the run time of one battery is $T$, then the run time of two parallel batteries could be noticeably longer than $2T$ [12]. However, this parallel configuration for increasing total battery capacity requires the batteries to be the same type and have the same SOC and capacity or else risk safety issues. While this advice about parallel configuration is widely accepted, it may be
difficult to follow in actuality if several campers bring their own batteries; each camper’s batteries might be of different battery chemistry and may have different SOC, capacities, and ages. These constraints might make parallel configuration of batteries unfeasible for charging electronic/electric devices at campsites.

Figure 1.2 A camper’s inventory of DC loads in his camper trailer [11].
1.3.2 Soldiers in the field

Figure 1.3 shows a soldier carrying a heavy, potentially unwieldy pack, which could weigh up to 170 lbs, for a 72-hour mission [13]. In a remote area without access to wall outlets or generators, the most common solution for obtaining power is to carry batteries, such as BA5590 Lithium/Sulfur-Dioxide batteries (non-rechargeable) [14], BB390 NiMH batteries (rechargeable) [15], and BB2590 Lithium-ion batteries (rechargeable) [16].

Table 1.2 lists the physical characteristics of BA5590, BB390, and BB2590 batteries. As listed in Table 1.2, batteries are heavy (≥ 2.25 lb / 1.02 kg). Carrying more batteries—to increase the available power—might not be practical or convenient because of the added physical burden to the soldier who is already carrying heavy equipment.
Figure 1.3 A soldier carries heavy and unwieldy loads for a 72-hour mission [13].

Table 1.2 Physical Characteristics of BA5590, BB390, and BB2590 Batteries

<table>
<thead>
<tr>
<th>Battery</th>
<th>Chemistry</th>
<th>Rechargeable?</th>
<th>Weight</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA5590</td>
<td>Lithium/Sulfur-Dioxide</td>
<td>No</td>
<td>2.25 lb / 1.02 kg</td>
<td>15.0 Ah</td>
</tr>
<tr>
<td>BB390</td>
<td>NiMH</td>
<td>Yes</td>
<td>3.90 lb / 1.76 kg</td>
<td>9.8 Ah</td>
</tr>
<tr>
<td>BB2590</td>
<td>Lithium-ion</td>
<td>Yes</td>
<td>3.10 lb / 1.40 kg</td>
<td>13.6 Ah</td>
</tr>
</tbody>
</table>

Solar power is often used to alleviate this problem. The substitution of a small, lightweight, and foldable solar panel [9] reduces the weight of a soldier’s pack as well as
the number of batteries a soldier must carry. In addition, these panels can be used as a remote power source to charge rechargeable batteries. A highly efficient and compact solar charger is required to convert solar power.

Frequently on the move, soldiers in the field need the batteries to be the main DC power sources to power many different types of equipment, including radios, robots, portable electronics, tactical voice encryption devices, autonomous underwater vehicles (AUVs), unmanned underwater vehicles (UUVs), remote battlefield sensor systems (REMBASS), position locator and reporting systems (PLRS), and thermal imaging night sight systems [15, 17-21]. In a command center, soldiers also need AC power to power AC loads (e.g. coffee makers, lighting, fans, electric coolers, TVs, computers, etc). In order to have both DC and AC outputs, an individual portable microgrid consisting of a DC-DC converter/charger and a DC-AC inverter is required, as shown in Figure 1.4(a). In this microgrid system, the DC-AC inverter is connected in parallel with the battery.

Due to their manifold power needs, soldiers require a microgrid that allows them to use multiple batteries in parallel to increase the overall remote power capacity. This type of microgrid can be used as a solar battery charging station or a mobile power source in order to meet the energy demands for loads heavier than those one battery can support, as the system diagram shows in Figure 1.4(b). This power system uncovers new obstacles for soldiers and researchers alike. Because soldiers might be equipped with different types of batteries—with differing chemistry, SOC, or voltage—charging multiple batteries in a parallel configuration might be dangerous because large voltage imbalance among different batteries will cause large circulating current and over-charging/discharging. Even when the chemistry, brand, and model of rechargeable
batteries are the same, the age and remaining SOC or capacity of those batteries may differ from soldier to soldier based on each soldier’s individual battery usage.

![Diagram of portable microgrid](image)

Figure 1.4 (a) System diagram of an individual portable microgrid. (b) System diagram of a portable microgrid using multiple batteries in parallel to increase overall remote power capacity.

1.4 Different batteries in parallel and research problems

As seen in the examples or the camper and the soldier, using different batteries in parallel may be necessary to meet power/energy needs in remote areas. In fact, this
problem occurs not only to campers and hikers at camp sites and soldiers in the field, but also at remote solar battery charging stations in rural areas [22] or remote solar/wind powered telecommunication stations [23]. The technical difficulties resulting from using different batteries in parallel leads to a number of new research problems:

- Is it possible to charge or discharge battery with different chemistries, SOC, or voltage in parallel?
- What is the optimized system architecture to minimize power loss during charging/discharging?
- What is the best way to control the energy flow between solar panels, different parallel batteries, and loads?
- Are maximum-power-point-tracking (MPPT) algorithms developed for a single charger to obtain the maximum power from solar panels still effective when applied to parallel batteries?
- Can multiple individual battery chargers be used in parallel to achieve a portable and small-scale microgrid?
- For charging, how are MPPT algorithms implemented in this portable microgrid system so that they do not interfere with each other?

1.5 Dissertation organization

The following research is motivated by the research problems listed above and strives to provide practical solutions to address them. The presented solutions are applicable, but not limited, to campers, hikers, and soldiers moving through isolated areas. This
dissertation yields new insights on how to properly increase energy delivery to/from different batteries operating in parallel in the most efficient manner, how we can minimize the impact of periodic nonlinear loads on MPPT, and how we can distribute MPPT to multiple converters when multiple solar panels are available. Specifically, this dissertation is organized as follows:

- In Chapter 2, general technical challenges derived from using different battery packs in parallel and the main goals of this research are presented.

- In Chapter 3, a new system architecture, aiming to eliminate the need for DC/DC converters to interface with each battery pack and the load, is proposed. Algorithms for properly charging/discharging different battery packs in parallel are presented and tested. A prototype experimental system with four different battery packs is built to verify and demonstrate the benefits of the energy management algorithms. Because of substantially fewer parts, the physical design and cost for the energy management system architecture is substantially reduced. This has benefits in the portable/handheld electronics market.

- In Chapter 4, the MPPT techniques realized by maximizing the output current or voltage of the DC-DC converter are reviewed. When the load of the DC-DC converter is a resistive load, such as a resistor or a battery, maximizing the output current of the DC-DC converter is widely chosen to realize MPPT. Without a DC-AC inverter connected in parallel with the battery, this MPPT technique usually works well. However, if a DC-AC inverter is connected in parallel with the battery, this technique might fail in some situations. The analysis and the solution of this problem are presented in Chapter 6.
Chapter 1

- In Chapter 5, it is found that a DC-AC inverter connected in parallel with the battery will cause MPPT techniques reviewed in Chapter 4 to fail. This is because a DC-AC inverter is as a nonlinear periodic load, especially when its load current changes fast. This chapter presents simulation and experimental results to explain the essence of the problem and provides a solution using a modified MPPT method. The solution is verified in theory, simulation, and experiments.

- In Chapter 6 and Chapter 7, prototypes of an individual portable microgrid and a small-power microgrid that allows connection up to four batteries in parallel are presented. They are designed and built based on the results presented in preceding chapters. Their functions, features, converter topology, parallel/series mode selection, power flow control, and MPPT are introduced. Additionally, MPPT methods for evenly and unevenly distributing power to modular DC-DC converters in parallel are discussed.

- In Chapter 8, conclusions and future research are presented.

1.6 Contributions

The major scientific research contributions and scientific advancements over the state-of-art techniques are summarized as follows.

- A new approach to paralleling different battery types is presented: By adopting the system architecture, algorithms, and control techniques presented in this dissertation, batteries with different chemistry, voltage, and state of charge can be properly charged
and discharged in parallel without causing safety problems. The presented methodology is simple and cost effective.

- **Specific types of failures in the Maximum power point tracking (MPPT) when tracking only the load current are eliminated**: By adopting the improved MPPT algorithm proposed in this dissertation, the MPPT efficiency will not degrade even when periodic nonlinear loads presented at the output of the DC-DC converter.

- **New MPPT algorithms that are faster than state of the art and can successfully operate in partial shading are derived**: This control strategy is realized by changing the number of parallel connected DC-DC converters and adjusting their input current limit. By taking advantage of fast input current change, the proposed control scheme performs optimized MPPT under partial shading conditions (the solar panel exhibits multiple maximum power points). The complexity of control hardware/software is reduced, since no current sharing is required for paralleled converters.
Chapter 2

Introduction

This chapter presents the general technical challenges generated from using different battery packs in parallel and the main goals of this research. First, applications of using series and parallel battery packs are reviewed. The scope of this research will focus on parallel operation of different battery packs. The demand and problems of connecting different battery packs in parallel are introduced afterwards. Methods in previous research for solving these problems using additional devices/converters between each battery pack and a load are also reviewed. The additional devices/converters between each battery pack and a load result in energy loss from battery packs when discharging current to a load and increase design complexity of chargers when charging current into battery packs. The goal of this research is to present a new method without using additional devices/converters between each battery pack and the unregulated bus to

1) Manage charging/discharging different battery packs in parallel;

2) Maximize charging efficiency and available energy delivered from different battery packs in parallel;
3) Alleviate the problems resulting from connecting different battery packs in parallel, such as circulating current

This chapter is organized as follows:

- In Section 2.1, the applications of using series and parallel battery packs are reviewed.
- In Section 2.2, the potential demand of connecting different battery packs in parallel is presented. The reason why connecting different battery packs in parallel might be inevitable in some circumstances is explained.
- In Section 2.3, potential applications of operating different battery packs in parallel are presented.
- In Section 2.4, problems resulting from connecting different batteries in parallel without adding additional devices/converters between each battery pack and a load are reviewed.
- In Section 2.5, prior art solutions in previous research using additional devices/converters between each battery pack and the DC distribution bus are presented.

2.1 Series and parallel battery packs

Battery cells are connected in series to increase the voltage while keeping the same capacity rating (ampere-hour). Battery cells are connected in parallel to increase the capacity rating while keeping the same voltage. In real-world applications, a group of battery cells are connected in series to form a battery pack (or string) to provide required large voltages, then a group of these battery packs (or strings) are connected in parallel to
form a battery bank to provide required capacities. This is common practice in many rechargeable battery backup applications, including laptops [24], portable energy storages for soldiers in battle fields [15, 16] and hikers camping in mountains [25], uninterruptible power supplies (UPS) [14, 26], telecommunication stations [27-29], electric/hybrid-electric vehicles (EV/HEV) [30, 31], and solar battery charging stations in rural area [32, 33]. Therefore, there is a huge demand for rechargeable batteries, battery chargers, and battery management systems (BMS). These markets are still growing and driven by innovations in consumer electronics, telecommunications, automotives, and industrial technologies. Figure 2.1 shows some of these applications.

Figure 2.1(a) shows the inside of a six-cell laptop battery pack. The six cells are connected in a 3s2p (3 series 2 parallel) configuration: three cells are connected in series in a string to provide the system voltage level; two strings are connected in parallel to provide the required storage capacity. Due to the limited space in the pack, increasing the total capacity is achieved by choosing battery materials having higher power density. Figure 2.1(b) shows that a smart phone is being charged by a military Lithium-ion battery pack through a battery-to-USB charger. The battery pack contains 24 commercial Lithium-ion cells connected in a 4s6p (4 series 6 parallel) configuration. It was developed and deployed by US Army to provide soldiers light-weight and high-power portable remote power sources. Figure 2.1(c) shows the battery bank inside an electrical vehicle. The electric vehicles use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion. The electric motors are driven by a large battery bank that could consist of more than 7000 cells connected in series/parallel configuration. Figure 2.1(d) shows a solar battery charging station (SBCS) and its battery
bank in rural area. The idea of SBCS is to let the people bring their batteries to the charging station to recharge them. Then these batteries were brought back to provide power to the housing appliances such as fluorescent lamps, TVs, radio players, and inverters. If a SBCS is combined with an additional battery backup (several battery packs in parallel), the housing appliances and radio telephone for public service can be installed in the SBCS to provide extra functions. Figure 2.1(e) shows the large battery bank designed as a secondary power source for telecommunication stations. The DC power provide by the battery bank may be converted to AC for uninterruptible power supply (UPS) applications during utility outages. The service time of the battery bank for UPS applications might be minutes, hours, or days, depending on the amount of battery packs connected in parallel and the load conditions.

Figure 2.1 (a) A six-cell battery bank used in a laptop. (b) A smart phone is being charged by a military battery bank for soldiers in remote area. (c) An electric vehicle powered by a large battery bank. (d) A solar battery charging station in rural area and its battery bank. (e) A large battery bank designed for uninterruptible power supply (UPS) applications as a backup energy source in telecommunication stations.
Chapter 2

2.2 Demand of connecting different battery packs in parallel

When connecting battery packs in parallel to increase the ampere-hour capacity, using the same battery packs (same voltage, capacity, chemistry, age, etc) is usually strongly recommended by the battery manufacturers. The intention of this suggestion is to avoid any potential safety problem resulting from the imbalance among parallel battery packs. In some circumstances, however, connecting different battery packs in parallel might be inevitable. For example, in a battery bank, an aged battery pack might need to be replaced by a new one, or a new battery pack might be added into the battery bank to increase the total power capacity of the system. This generates a new research challenge that has not been studied before: what is the best way to manage a battery bank consisting different battery packs in parallel? Specifically, the following questions are considered for a battery bank consisting of different battery packs in parallel:

- What are the potential problems resulting from the imbalanced parallel battery packs?
- What are the practical solutions for addressing the above problems?
- What are the best strategy or optimized strategies for charging and discharging this battery bank for all kinds of applications?
- Is it possible to predict or determine the runtime and operating power limit of this battery bank?
- In a microgrid system using solar panels as the power source, a battery bank might be required for backup or auxiliary power to fulfill the current demand from the AC load. This load current is time-varying and may lead to the maximum power point tracker
(MPPT) of the solar panels to fail. What is the reason for this failure and is it possible to derive a practical method to make the MPPT reliable?

2.3 Parallel operation of different battery packs and its challenges

The use of the multiple parallel battery packs adds system capacity and redundancy [34-39]. This approach has been adopted extensively in uninterruptible power supply (UPS), telecommunication (Telecom) stations, electric/hybrid-electric vehicles (EV/HEV), and solar battery charging stations in rural area.

The IEEE standard 1184-2006 [40] for UPS systems states that “Ideally, the (parallel) strings should be as similar as possible. At a minimum, float voltage requirements must be compatible.” Therefore, before connecting a new string of series connected cells, the string has to be recharged by a separate charging process until its voltage reaches the existing strings’ voltage [41], as shown in Figure 2.2.
Before connecting a new string of series connected cells, the string has to be recharged by a separate charging process until its voltage reaches the existing strings’ voltage. Research on operating “different” batteries in parallel strings has previously been proposed [34-38, 41, 42]. Experiments on parallel operation of valve-regulated lead-acid (VRLA) batteries validated that operating VRLA batteries with different capacities and/or different SOCs is feasible [35, 42]. After that, with the success of nickel and lithium based batteries, researchers started thinking of mixing VRLA and other types of batteries with higher capacity and fewer safety risks in parallel. The system behaviors of mixing VRLA with nickel cadmium batteries [41] and mixing VRLA with lithium-ion batteries [36, 37] were studied, and it was concluded that mixing VRLA with nickel cadmium or lithium-ion batteries strings is feasible and beneficial in some Telecom and stationary applications without the need of increasing operating and maintenance costs if each string has similar recommended float voltage.

The reason that in parallel operation each battery pack’s resting voltage has to be similar to the recommended float voltage is to avoid so-called “circulating current”
flowing among strings at different SOCs or voltages. Connecting a new battery pack at very low SOC or voltage to the existing strings at very high SOC or voltage could be hazardous, especially when the existing battery packs are under float charging because the new string receives the charge current not only from the existing strings but also from the rectifier/charger [41]. Hence, it is recommended that the string has to be recharged by a separate charging process until its voltage reaches the existing strings’ voltage.

However, when resting voltages differ noticeably in each battery pack, the lowest float charge voltage must be used so as to not overcharge some batteries (safety). Therefore, in the case of aged batteries, different chemistries, etc., it is not possible to charge each parallel string to full SOC. This would cause circulating current, even when all batteries are disconnected to the DC bus [38, 41]. A purpose of this research is to alleviate this issue.

Unlike the battery packs in UPS and Telecom stations, in which the battery packs stay at fully charged state most of the time as long as the AC grid power is available, the charged state of the battery packs in other applications without AC grid power might be arbitrary. Therefore, when users want to increase the system capacity by adding more battery packs in parallel, following the recommendation that the new added battery packs must have the same voltage as the existing battery packs’ voltage might be impractical or hard to achieve. Some of these demands presently exist, while others might not exist at present but can be forecasted to be required in the near future. Examples in real-world applications of increasing system capacity by adding more battery packs in parallel are given as below:
• *Electric Vehicle (EV) / Hybrid Electric Vehicle (HEV)*: The driver might want to increase the travel range anytime, no matter what level of charge state of the existing battery bank is. Another battery pack in parallel might be added as a range extender. The added battery pack may be used in combination with the first battery pack to supply operational power to the electric vehicle [43]. It is likely the new added battery pack’s charge state is different from the existing battery bank’s charge state.

• *Telecommunication Stations*: To increase the capacity, new battery packs might be added in parallel without disconnecting the existing battery bank so that the Telecom service is not interrupted. For stations with limited space, an alternative way for capacity expansion is to replace part of the low-capacity battery packs in the existing battery bank with high-capacity battery packs [36, 37, 44]. Moreover, for solar/wind powered telecom stations in remote areas, it is likely that the new added battery pack’s charge state is different from the existing battery bank’s charge state, especially when the weather is not good enough to maintain the existing battery bank at fully charged state.

• *Solar Battery Charging Station (SBCS) in rural area*: SBCS with an additional battery backup in rural area provides public services of battery charging, as well as the housing appliances and radio telephone [32]. Adding more battery packs in parallel with the existing battery backup can provide longer service time or more public service.

• *Soldier/Hiker Portable Microgrid*: In the battlefield or in the mountains, soldiers and hikers may want to use the multiple battery packs in parallel in order to increase overall capacity.
2.4 Problems resulting from using different batteries in parallel

In the examples listed in Section 2.3, using different battery packs in parallel might lead to the following three challenges:

- **Circulating current** – The generation of huge circulating current generated by voltage mismatch among battery packs might cause fire hazard or energy loss [41].

- **Over-charging** – It is not possible to charge each pack to a fully charged state at the same time when resting voltages differ noticeably in each battery pack, if the packs are directly connected in parallel. The risk of over-charging and/or overheating batteries increases because the pack with lower SOC and/or resting voltage will drain more current when float charging is applied on all different batteries at the same time [45].

- **Over-discharging** – The risk of over-discharging, overheating, and capacity loss increases because the battery pack with higher SOC and/or resting voltage will source more current to the load, especially when SOCs and/or resting voltages differ noticeably in each battery pack [12, 46, 47].

2.4.1 Circulating current

Figure 2.3(a) shows two different battery packs connected in parallel. $V_{T,1}(t)$ and $V_{T,2}(t)$ are the terminal voltages of Batteries #1 and #2. $R_{int,1}$ and $R_{int,2}$ are the internal resistances and assumed to be time-invariant. $R_w$ is the cable resistance and also assumed to be time-invariant. Assume $V_{T,1}(t) > V_{T,2}(t)$ initially before two battery packs are connected in
parallel. After they are connected in parallel, a circulating current is generated by voltage mismatch and can be described as follows:

\[ I_{1\rightarrow2}(t) = \frac{V_{T,1}(t) - V_{T,2}(t)}{R_{\text{int},1} + R_{\text{int},2} + R_w} \] (2-1)

The circulating current \( I_{1\rightarrow2}(t) \) would be very high if the terminal voltages \( V_{T,1}(t) \) and \( V_{T,2}(t) \) differ noticeably, because \( R_{\text{int},1} \), \( R_{\text{int},2} \), and \( R_w \) are usually very small. \( V_{T,1}(t) \) and \( V_{T,2}(t) \) will be self-balanced eventually after a certain amount of time \( T \) such that no circulating current is generated. During the period \( T \), the energy loss on battery packs’ internal resistance and cable resistance is

\[
E_{\text{loss}} = (R_{\text{int},1} + R_{\text{int},2} + R_w) \int_{0}^{T} [I_{1\rightarrow2}(t)]^2 \, dt = \frac{\int_{0}^{T} [V_{T,1}(t) - V_{T,2}(t)]^2 \, dt}{R_{\text{int},1} + R_{\text{int},2} + R_w} \] (2-2)

Figure 2.3(b) shows the current \( I_1(t) \), \( I_2(t) \), \( \text{SOC}_1(t) \), and \( \text{SOC}_2(t) \) of two different lithium-ion battery packs connected in parallel. The initial voltages \( V_{T,1}(0) \) and \( V_{T,2}(0) \) are 16.3V (SOC\(_1\)(0) = 99%) and 14.85 V (SOC\(_2\)(0) = 21%), respectively. \( R_{\text{int},1} \), \( R_{\text{int},2} \), and \( R_w \) are 0.2Ω, 0.2Ω, and 0.1Ω, respectively. The period \( T \) is 5.78 hours. The accumulated energy loss during the period \( T \) is about 2.76Wh. Because the capacity of a fully charged battery (100% SOC) is 200Wh, the total capacity of the two battery packs is 240Wh. This means during the period \( T \), 1.15% (2.76Wh/240Wh) of the available energy is wasted due to the circulating current in standby mode.
2.4.2 Problems of charging

For lead-acid and lithium-based batteries, a two-stage charge method is usually adopted: 1) Constant-Current (CC) mode - charge the battery with the same charging current until a threshold voltage is reached; 2) Constant-Voltage (CV) mode – the charging current is limited to keep the voltage of the battery constant. At the end of CV mode, charging process is terminated when the current has dropped to a low threshold current.

Assume initially a lithium-based (or lead-acid) battery bank consisting of several battery packs in parallel is charged and the charger operates in CC or CV mode. The output voltage of the charger keeps at $V_H$ when a user intends to add a new lithium-based (or lead-acid) battery pack at very low SOC or voltage $V_L$ to the existing battery bank.

The new battery pack may or may not receive huge charge current from the charger:
• If the output power of the charger is too small, its output voltage will be between $V_H$ and $V_L$ because the existing battery bank and the new battery pack are self-balanced. The output power of the charger might be too small such that the new battery pack is charged mainly by the existing battery bank, leading to a circulating current and the energy loss as described in Section 2.4.1. An example is illustrated in Figure 2.4. This situation might happen when a renewable energy such as solar is adopted as the input power source.

• If the output power of the charger is large enough to keep output voltage at $V_H$, the charge current into the new battery pack might be too high, according to equation (2-1). The charging current into the new battery might exceed the limit that the battery pack can safely handle. This situation might happen in a UPS or telecommunication station when the utility grid is adopted as the input power source.

To avoid the circulating current or excessive charge current when charging the new battery pack, the user has to disconnect the existing battery bank and recharge the new battery pack until the existing battery bank and the new battery pack have the same SOC or voltage. Therefore, it is not possible to charge each pack to fully charged state at the same time when resting voltages differ noticeably in each battery pack.
If the output power of the charger is too small to charge both batteries, the new battery pack with $V_{T,2} = 15.2\,\text{V}$ is charged mainly by the existing battery bank with $V_{T,1} = 16.5\,\text{V}$, leading to a circulating current and the energy loss. The switch between Battery #2 and the DC bus is closed at $t = 100\,\text{s}$. Positive current means charging and negative current means discharging.

### 2.4.3 Problems of discharging

It is possible that the battery bank switches from charging mode to discharging mode when the load current increases, before all battery packs are balanced and fully charged. This might occur when an old battery pack is replaced by a new one or an additional battery pack is inserted to increase the power capability. The battery pack with higher SOC and lower internal resistance will source more current to the load, as shown in Figure 2.5. This generates the following problems:

- **Over-discharge** – In the worst case, a battery pack with relatively higher SOC than other battery packs might source all of the current to the load. This might lead to over-discharge of a single battery.
• **Capacity loss** – The Peukert's law [12] defines the relationship between the battery capacity and discharging current: \( C_p = I^k \times T \), where \( C_p \) denotes the maximum battery capacity at one ampere discharge rate, \( I \) the discharge current, \( T \) the maximum discharge time, and \( k \) the Peukert's coefficient. When the discharge rate increases, the battery's available capacity decreases, which also reduces the runtime of the battery. The typical value \( k \) is larger than one and its ranges are 1~1.05 [48], 1~1.2 [49], and 1~1.6 [50] for lithium-ion, NiMH, and lead-acid battery, respectively.

• **Degraded lifetime** – High discharge current will lead to high temperature of the battery. One of the drawbacks resulting from high temperature is that batteries age much faster at high temperature. Another drawback is that high temperature might activate the protection circuit inside the battery and the battery will be disconnected. Therefore, only part of the energy stored in the battery can be used unless the battery is cooled down, which also consumes extra energy and cost. Figure 2.6 shows an example that a battery is discharged by 12A constant current at different ambient temperature [51]. Before thermal protection activates, only 27% of available capacity can be used under the ambient temperature 45°C.
Figure 2.5 The battery pack with higher SOC and lower internal resistance will source more current to the load. In this example, the 12A load current is not evenly shared by two batteries. The two switches are closed at $t = 45$s. Positive current means charging and negative current means discharging.

Figure 2.6 High temperature might activate the protection circuit inside the battery and the battery will be disconnected [51].
2.5 Existing solutions

According to [52], a battery management system (BMS) with battery charge/discharge regulator between the battery and the distribution bus is called “regulated system” while connection through a switch/diode between the battery and the distribution bus is called “unregulated system.”

The most common approach to solve the problems described in Section 2.4 in a “regulated system” is to insert bidirectional DC/DC converters at the output stage of each battery to provide stable output voltage on the DC distribution bus [30, 31], as the “regulated bus” shown in Figure 2.7. It is easy to boost up the voltage with individual converter to a regulated bus with desired voltage, even if the battery packs are different. Charging/discharging current of each battery pack can be easily controlled by each DC/DC converter. Besides, there will no circulating current among different battery packs. However, this approach will increase the number of power electronic parts and the cost as well as the complexity of the system.

In contrast to a “regulated system,” an “unregulated system” has no bidirectional DC/DC converters at the output stage of each battery to provide stable output voltage on the DC distribution bus. Instead, in “unregulated systems,” only resistors or diodes are inserted between each battery and the distribution bus. Figure 2.8(a) illustrates that external resistors are inserted to compensate the deviation of internal resistance of each battery to equalize the output voltage of each output stage [53]. The benefit of this approach is that the circulating current among different battery packs can be reduced by the resistors. This approach is easy to apply but has the disadvantage of extra power
consumption on the resistors when charging/discharging. Another way is to replace the external resistors by diodes [54], as shown in Figure 2.8(b). The benefit of this approach is that there will be no circulating current among different battery packs due to diodes’ reverse blocking. Of course, even though a low-voltage-drop Schottky diode is used, the diodes still causes extra power consumption when discharging. Further, the main disadvantage of this approach is that battery packs are only allowed to discharge.

Figure 2.7 The “regulated system”: Bidirectional DC/DC converters are inserted between each battery and the distributed bus to provide stable output voltage.

Figure 2.8 The “unregulated system”: (a) Resistors are inserted between each battery and the distributed bus [53]. (b) Diodes are inserted between each battery and the distributed bus [54]. The voltage on the unregulated bus is not constant in both cases.
Chapter 2

For both approaches shown in Figure 2.8, the voltage on the distribution bus is not constant and depends on the states of each battery pack, so the distribution bus in the unregulated system is also called “unregulated bus.” The goal of this research is to present a new approach without using additional devices/converters between each battery pack and the unregulated bus to maximize energy delivery to/from different battery packs in parallel, and mitigate the problems described in Section 2.4. The proposed new approach is described in chapter 3 and will provide the benefit of reduced cost and complexity of the energy management system.

2.6 Conclusion

In this chapter, we present the applications and the problems of operating different battery packs in parallel. In some circumstances, connecting different battery packs in parallel might be inevitable. There are prior art solutions that use additional devices/converters between each battery pack and the distribution bus to solve the problems. However, these solutions either induce power loss or increase the cost/complexity of the system. In next chapter, a new approach without using additional devices/converters between each battery pack and the unregulated bus is introduced. This new approach, including the system architecture and charging/discharging algorithms, will be able to eliminate the need for resistors, diodes, or DC-DC converters to interface with each battery pack and the load, reduce the cost and complexity of the energy management system, and alleviate the problems of circulating current, over-charging, and over-discharging when different battery packs are operating in parallel.
Chapter 3

Proposed new system architecture and algorithms

Using different batteries in parallel without buffer DC/DC converters will cause safety and reliability problems of batteries that include circulating currents, over-charging, over-discharging, high temperature, and degraded battery lifetime. This chapter introduces a new system architecture that permits parallel operation of battery packs without the need for DC-DC converters to interface between each battery pack and the load. This new system architecture will be able to:

1) Eliminate the need for DC-DC converters to interface with each battery pack and the load;

2) Reduce the cost and complexity of the energy management system.

This chapter also introduces new charging/discharging algorithms that will be able to (but not limited to):
1) Charge different battery packs to their full SOC, and minimize the cost or total charging time if renewable energy sources are used;

2) Discharge different battery packs and dynamically determine the sequence and the number of discharging battery packs according to the amount of load current;

3) Allow battery packs with different chemistries to be used in the system.

The proposed idea has been successfully verified by simulating, building, and testing a prototype charge station consisting of four battery packs, a charger, bi-directional switches, and a supervisory host controller. Algorithms for charging and discharging different battery packs in parallel in the most efficient and safest way were implemented in the software and verified. The concept of using parallel battery packs with different chemistries has also been verified. Because of substantially fewer parts and no need of DC-DC converter interfacing each battery and the DC bus, the physical design and cost for the energy management system architecture is substantially reduced.

This chapter is organized as follows:

- In Section 3.1, a new system architecture, aiming to eliminate the need for DC/DC converters to interface between each battery pack and the load, is presented. The new concepts of the energy management operation are also presented.

- In Section 3.2, the major functions and control flow of the host controller in the proposed new system architecture are introduced.

- In Section 3.3, the definition of various load conditions is introduced first, followed by the algorithms for properly and safely discharging batteries in parallel. Batteries
with different chemistries can be used in parallel as long as their operating voltage ranges are close.

- In Section 3.4, experimental results of the proposed algorithms implemented in the new system architecture are presented.

### 3.1 System architecture without DC-DC converters

Figure 3.1 shows the proposed new system architecture of this research for managing parallel battery packs with no regulated bus. The battery packs in Figure 3.1 are referred to as “batteries”, although they normally are battery packs with multiple battery cells. The illustrated features of the proposed system architecture include:

- **N batteries, each connected through its own bi-directional switch to a DC bus.** The DC bus is, therefore, semi-regulated, since it is clamped to a battery voltage value that will have variation. For example, in the prototype system, four Lithium ion batteries with nominal 14.4 V and 13.6 Ah capacity (4 cells of 3.6 V nominal in series), are utilized. In fact, the batteries will have voltage variation from 14 ~ 16.5 V depending on the state of charge.

- **A Supervisory Host to determine when to open and close each switch to the DC bus.** The microcontroller monitors the bus voltage, the open circuit voltage of each battery, and the charging/discharging current of each battery. If the batteries are SMBus compliant, then it may also monitor each battery’s SOC.
Chapter 3

- **Power Management Control Software operating on the microcontroller.** A contribution of this research is that it proposes a new manner to operate the power management flow that enables increased energy delivery to the load. This is explained in Section 3.3.

- **A Charger connected to the DC bus.** In this system’s architecture, the power to the load may be delivered either from the batteries, the charger, or both.

![System Architecture Diagram](image)

Figure 3.1 The system architecture proposed for managing parallel battery packs with no regulated bus.

The prior-art methods of using batteries in parallel described in previous chapter are illustrated in Figure 3.2 [55] and Figure 3.3 [40, 41]. Compared to the architectures shown in Figure 3.2 and Figure 3.3, the proposed new system architecture demonstrates the following novel features: First, both the architectures shown in Figure 3.1 and Figure 3.2 allow the use of different types and different chemistries of batteries in parallel.
However, when some of the batteries in Figure 3.2 are drained, they must be replaced by new ones, or they should be removed from the system for a separate charging process. By adding a charger at the input stage, as shown in Figure 3.1, the batteries can be directly charged by an input energy source to replenish their charge state. Second, Figure 3.3 illustrates the architecture of a UPS, whose input energy source is a utility grid converted by a rectifier. This architecture does not allow users to insert a battery with different SOC or terminal voltage in parallel: The existing batteries are under float-charge state, and the new inserted battery with low state of charge will be over-charged by both the rectifier and the existing batteries. In contrast to Figure 3.3, in the proposed architecture shown in Figure 3.1 switches are used between each battery and the DC bus. The switches provide users the flexibility to connect or disconnect batteries to the DC bus in accordance with the load conditions monitored by the supervisory host. Therefore, different batteries are allowed to be inserted anytime without the concern of overcharging.

![Figure 3.2 The concept of parallel-connected battery power module [55]. It allows the use of different batteries in parallel. However, when some of the batteries are drained, they must be replaced by new ones, or be pulled out of the system for a separate charging process.](image)
Figure 3.3 The architecture of UPS does not allow users to insert a battery with different SOC or terminal voltage in parallel [40, 41]: The existing batteries are under float-charge state, and the new inserted battery with low state of charge will be over-charged by both the rectifier and the existing batteries.

The fundamental new concepts of the energy management operation in Figure 3.1 are listed as follows:

- **With no load or light load, only one battery is connected to the DC bus.** The benefit of connecting only one battery at low or no load is that it is now possible to have the \( N-1 \) batteries in the system be of different SOCs, different internal resistances, from different manufacturers, etc. There will be no circulating current between the batteries from voltage mismatch when the switch to the battery is open. This is the major benefit of [3], but we have removed the N-DC/DC converters.

- **At heavy or medium load, all or some of the switches are quickly closed to connect other batteries to the bus.** When load increases, there is a drop in the bus voltage due to the internal resistance of the single battery that is nominally connected. When the bus voltage drops below another battery’s open circuit voltage and the difference
exceeds a threshold value, the supervisory host connects that battery to the DC Bus. Alternatively, each individual battery pack could monitor its own open circuit voltage and the bus voltage and make distributed decisions.

- Each battery may be charged to its full SOC individually, even if it creates a voltage mismatch between the batteries. By charging batteries one at a time, full SOC is achievable and therefore, extending the amount of energy that can be provided to the load. This is not true if all the batteries are connected in parallel when they are being charged due to the impedance and voltage mismatches between them.

- Discharging currents from the batteries may be partially controlled. At heavy load, all the batteries will be connected to the bus and there is no control of how the current flows. Higher voltage batteries (resting voltage) will likely provide more current than the batteries with lower voltage (and likely lower SOC). However, for medium and light loads, the host has the capability to control averaged discharging currents from the batteries using Intermittent Discharging strategy [55-57].

### 3.2 Host controller

According to Figure 3.1, the system can operate in the following three modes: 1) charging mode, 2) discharging mode, and 3) mixed mode, a combination of 1) and 2). (The results of this dissertation about energy management in modes 1 and 2 have been published in [58] and [59], respectively.) An optimized charging strategy and an optimized discharging algorithm are integrated into a single host controller to make the system be able to work in any situation.
1) **Charging mode without any load**: In this mode, the system operates like a battery charging station. For example, the system with PV panels as input power source is called solar battery charging stations (SBCS), which is considered one of the options for rural off-grid electrification. For people living in remote areas whose income is too low, SBCS is the most viable option [32, 33]. When people bring their battery packs to SBCS for recharging, it is very likely that their battery packs’ remaining capacity and SOC are different. There are various charging strategies in terms of minimizing the cost or total charging time for SBCS. An optimized low-cost charging strategy for increasing solar energy exploitation to minimize total charging time is also explained in [58], derived from this dissertation research.

2) **Discharging mode without any input power from the charger**: In this mode, the system operates like a backup power station. Because different battery packs are allowed to be used in this system, the load might not be evenly shared by each individual battery packs. In the worst case, the battery pack with the highest SOC will source all needed current to the load, and this battery pack might have a risk of over discharging. Therefore, methods for preventing any battery pack from over discharging and for properly sharing a heavy load by as many battery packs as possible are necessary. This will be described in Section 3.3.

3) **Mixed mode with any input power from the charger and any load**: In this mode, the input power might be higher or lower than the load demand. When the input power is higher than the load demand, part of the input power is used to charge the battery packs. When the input power is lower than the load demand, part of the load demand is supplied
by discharging battery packs. So the operating mode of the system might constantly switch between charging mode and discharging mode.

To make the system suitable for any situation, especially when a renewable energy source is used, a host controller dedicated to the mixed mode is designed and built. Optimized charging strategies and discharging algorithms are integrated into the host controller. As will be explained in the next section, during the transition from no load to heavy load, the algorithms for optimized discharging must take into account the optimized charging strategy in order not to violate one of the settings in the charging strategy. Figure 3.4 gives an overview of the control flow programmed in the host controller. The program can be summarized as below:

- **Acquiring:** For $N$ batteries, each is given an address $k$ ($1 \leq k \leq N$). The host controller constantly acquires battery information from the $k$-th battery, including SOC, resting voltage, charging/discharging current, etc.

- **Grouping and segregating:** In the optimized charging strategy, once the SOC or resting voltage of specific batteries is higher than a threshold ($\text{SOC}_{\text{th,High}}$ or $\text{V}_{\text{th,High}}$), this battery will be segregated from the group qualified for charging until all batteries’ SOCs or resting voltages are higher than the threshold. For discharging, any specific battery with SOC or resting voltage lower than a threshold ($\text{SOC}_{\text{th,Low}}$ or $\text{V}_{\text{th,Low}}$) will be segregated from the group qualified for discharging to prevent from over discharging and triggering under-voltage protection.

- **Sorting:** Sort the batteries in the group qualified for charging using SOC and resting voltage in descending sequence, as shown in Figure 3.5. In the prototype system, three types of batteries are allowed to be recharged: smart Lithium-ion with System
Management Bus (SMBus), dumb Lithium-ion without SMBus, and dumb NiMH. Smart Lithium-ion batteries have the highest recharge priority because they provide real-time parameter readings directly through SMBus, including SOC, temperature, cycle count, remaining capacity, estimated runtime to empty, battery status, etc, increasing ease of battery management. Dumb Lithium-ion batteries have the second highest recharge priority. NiMH batteries have the lowest recharge priority because they have higher self-discharge rate than Lithium-ion and require different charging algorithm. The sorting result gives the priority of charging sequence of each battery when input power is higher than the load demand.

- **Opening/Closing switches** $S_1$–$S_N$: Determine which switches must be opened or closed according to the acquired battery information, the grouping/segregating/sorting result, and the load conditions.

The communication among the host controller, the charger, and each battery relies on RS485 and SMBus protocols. The details of RS485 and SMBus implementation are given in the Appendix.
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Figure 3.4 Overview of the control flow programmed in the host controller

Figure 3.5 The definition of the qualified battery types and charging priority.
3.3 Discharging different batteries in parallel

3.3.1 Definition of different load conditions

The definitions of no load, light load, medium load, and heavy load are illustrated in Figure 3.6.

- **No load**: The load demand is zero. The system charges only one battery if the power from the input source is greater than zero.

- **Light load**: The load demand is light such that it takes power from only one battery and/or from the input source.

- **Medium load**: The load demand is medium such that it takes power from at least two but not all batteries and from the input source.

- **Heavy load**: The load demand is heavy such that it takes power from the input source and from all batteries.

The number of the batteries connected to the DC bus varies in accordance with the degree of the load demand. The Supervisory Host decides the number and the sequence of batteries needed to be connect to the DC bus.
For example, if SOCs of all batteries are known and \( \text{SOC}_1 \geq \text{SOC}_2 \geq \text{SOC}_3 \geq \ldots \geq \text{SOC}_N \), the strategy may be to connect Battery #1 with \( \text{SOC}_1 \) to the DC bus at no load, connecting Battery #2 with \( \text{SOC}_2 \) if the load increases a small amount, and connecting the third, fourth, and fifth batteries if the load increases substantially. If SOCs are unknown, the sequence can be determined by their open circuit voltage \( V_{\text{oc},k} \) (1 \( \leq k \leq N \)). For example, when \( V_{\text{oc},1} \geq V_{\text{oc},2} \geq V_{\text{oc},3} \geq \ldots \geq V_{\text{oc},N} \), the strategy becomes connecting Battery #1 with \( V_{\text{oc},1} \) to the DC bus at no load, connecting Battery #2 with \( V_{\text{oc},2} \) if the load increases a little bit, and connecting the third, fourth, and fifth batteries as the load increases.

### 3.3.2 Connecting batteries for increasing load

In Figure 3.6 (a) and (b), there is only one battery, Battery #3, with highest SOC or resting voltage connected to the DC bus at no load or light load. Except the switch \( S_3 \), all the switches are kept at open state. The idea of keeping \( N-1 \) switches open at no load or
light load is new because it provides the flexibility of removing or inserting several of \(N-1\) different batteries without the concern of circulating current and overcharging current from the charger. This flexibility cannot be achieved using the system architecture shown in Figure 3.3. It can be achieved using the system architecture shown in Figure 3.2. However, this requires a charger and \(N\) bi-directional DC-DC converters.

According to Figure 3.6 (c) and (d), switches \(S_i\) are required to be connected to the DC bus when the load abruptly increases. Therefore, a new mechanism of determining the number and the sequence of selected batteries required to be connected to the DC bus is developed: By sensing the instantaneous bus voltage and comparing it with the \(N-1\) batteries’ resting voltage, the number of batteries to be connected is determined. Only the batteries with resting voltage higher than the instantaneous bus voltage are connected to the DC bus. This idea is important because it minimizes the risk of over-discharging batteries. It also eliminates the possibility of circulating current among the “strong” batteries and “weak” batteries. The algorithm of connecting more batteries when the load increases are introduced as follows.

3.3.2.1 Algorithm

When the load increases, there will be a transient voltage drop on the DC bus, as shown in Figure 3.7. It is possible to compare \(V_{BUS}\) with the open-circuit voltage of the batteries not connected to the DC bus. When \(V_{BUS}\) drops below the resting voltage of a battery, it becomes a candidate to be connected to the DC bus.
By measuring the transient voltage drop on the DC bus, the number of the batteries needed to be connected to the DC bus can be determined.

Figure 3.8 (a) shows the algorithm to decide when to close the switches $S_1 \sim S_N$. The visualization of the algorithm is also shown in Figure 3.8 (b) and (c). The nomenclature used in the algorithm shown in Figure 3.8 is listed in Table 3.1.

At initial time, assume that the battery with the highest voltage is the only battery connected to the DC bus. When the load increases, there is a quick drop in the DC bus voltage due to the increasing discharging current and the internal resistance of the single battery that is connected to the DC bus. The voltage drop $\Delta V_{BUS}$ is defined by $V_{BUS}(t_a) - V_{BUS}(t_b)$, as shown in Figure 3.8 (b), where $V_{BUS}(t_a)$ denotes the instantaneous voltage value of $V_{BUS}$ before the voltage drop occurs and $V_{BUS}(t_b)$ denotes the instantaneous voltage value of $V_{BUS}$ right after the voltage drop occurs. In Figure 3.8 (c), the voltage gap $\Delta V_{GAP,k}$ is defined by $V_{oc,k} - V_{BUS}(t_b)$, where $V_{oc,k}$ denotes the open-circuit voltage of Battery #k not connected to the DC bus before the voltage drop occurs.
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Figure 3.8 (a) The algorithm to close the switches $S_1 \sim S_N$ between the batteries and DC bus. (b) Condition 1: Check if $\Delta V_{BUS}$ is larger than $\alpha$. (c) Condition 2: Check if $\Delta V_{GAP,k}$ is larger than $\beta$.

Table 3.1 Nomenclature used in the algorithm in Figure 3.8

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{BUS}(t_a)$</td>
<td>The historical voltage on the DC bus</td>
</tr>
<tr>
<td>$V_{BUS}(t_b)$</td>
<td>The voltage on the DC bus, updated every 180μs</td>
</tr>
<tr>
<td>$V_{oc,k}$</td>
<td>The open-circuit voltage of Battery #k</td>
</tr>
<tr>
<td>$\Delta V_{BUS}$</td>
<td>$V_{BUS}(t_a) - V_{BUS}(t_b)$</td>
</tr>
<tr>
<td>$\Delta V_{GAP,k}$</td>
<td>$V_{oc,k} - V_{BUS}(t_b)$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>The minimum required voltage drop $\Delta V_{BUS}$ on the DC bus</td>
</tr>
<tr>
<td>$\beta$</td>
<td>The minimum required voltage gap $\Delta V_{GAP,k}$</td>
</tr>
</tbody>
</table>

A first threshold, $\alpha$, representing the minimum required voltage drop $\Delta V_{BUS}$ on the DC bus is defined in Figure 3.8 (b), while a second threshold, $\beta$, representing the minimum required voltage gap $\Delta V_{GAP,k}$ is defined in Figure 3.8 (c). The algorithm always examines the following two conditions:
\[ \Delta V_{BUS} \equiv V_{BUS}(t_a) - V_{BUS}(t_b) > \alpha ? \quad (3-1) \]
\[ \Delta V_{GAP,k} \equiv V_{oc,k} - V_{BUS}(t_b) > \beta ? \quad (3-2) \]

First, (3-1) is examined. If \( \Delta V_{BUS} > \alpha \) is satisfied, which means a voltage drop on the DC bus is confirmed, then (3-2) is examined for Battery \( #k \) not connected to the DC bus. If \( \Delta V_{GAP,k} > \beta \) is satisfied, which means that \( V_{oc,k} \) higher than the DC bus is confirmed, then the switch \( S_k \) is closed such that Battery \( #k \) is able to share the load current. For medium load, the switches of the batteries with a lower voltage of SOC may not be closed. For heavy load, the switches of all batteries will be closed.

The way of determining \( \alpha \) and \( \beta \) thresholds is given in the Appendix. The purposes of setting the thresholds \( \alpha, \beta \), and the importance of (3-1) are listed as below:

- **Determine the number and the response time of connecting necessary batteries:** The purpose of (3-2) is to ensure that the batteries with resting voltage \( V_{oc,k} \) higher than \( V_{BUS} \) and not connected to the DC bus can be connected as quickly as possible after the load increases. The threshold \( \beta \) determines the number and the response time of connecting necessary batteries.

- **Distinguish two circumstances of increasing load and no load:** Examining (3-1) judges whether \( \Delta V_{GAP,k} \) in (3-2) results from real voltage drop on the DC bus when the load increases or from the difference between \( V_{BUS} \) and \( V_{oc,k} \) of the batteries not connected to the DC bus when there is no load. The threshold \( \alpha \) is used to distinguish the two circumstances of increasing load and no load (i.e. no voltage drop on the DC bus).
• *Eliminate possible circulating current induced by SOC/resting-voltage sorting when there is no load:* Applying discharging algorithm with (3-2) and without (3-1) would cause circulating current among batteries when there is no load. With the help of (3-1), this problem is avoided. Assume only smart and dumb Lithium-ion batteries are used in the system, the undesired circulating current could occur due to SOC/resting-voltage sorting in the following situations if only (3-2) is examined, as illustrated in Figure 3.9:

- **Situation 1 in Figure 3.9 (a):** All batteries are “smart” with SMBus, “fresh” with a small number of cycle counts, from the same manufacturer, with the same capacity, and one of the batteries has SOC ≥ 90%. According to Figure 3.5, a smart Lithium-ion battery with SOC ≥ 90% will have lower charging priority so it should be disconnected from the DC bus when there is no load. However, if the resting voltage of the smart battery with SOC ≥ 90% is higher than the DC bus voltage $V_{BUS}$, which equals to the resting voltage of another battery with SOC < 90% and with the highest charging priority, and the voltage different is greater than $\beta$ in (3-2), the smart battery with SOC ≥ 90% will be reconnected to the DC bus and source current to the battery with SOC < 90% and with the highest charging priority.

- **Situation 2 in Figure 3.9 (b):** All batteries are “smart” with SMBus and their SOCs are lower than 90%. But NOT all of them are “fresh” with a small number of cycle counts, from the same manufacturer, and have the same capacity. In this situation, a battery’s SOC is not proportional to its resting voltage. When there is no load, the battery connected to the DC bus, which has the highest SOC and the highest
charging priority, does not necessarily have the highest resting voltage. This means $V_{BUS}$ is not necessarily greater than the resting voltages of other batteries which have lower SOC and are disconnected from the DC bus. If one of those batteries disconnected from the DC bus has higher resting voltage than $V_{BUS}$, and the voltage different is greater than $\beta$ in (3-2), it will be reconnected to the DC bus and source current to the battery with the highest charging priority.

- Situation 3 in Figure 3.9 (c): Both “smart” and “dumb” batteries are mixed and all smart batteries have not been charged to full SOC. According to Figure 3.5, a dumb Lithium-ion battery will have lower charging priority, so it should be disconnected from the DC bus when there is no load. There will be only one smart battery that has the highest charging priority connected to the DC bus, so the DC bus voltage $V_{BUS}$ will equal to the resting voltage $V_{oc,smart}$ of the smart battery connected to the DC bus. If the resting voltage $V_{oc,dumb}$ of any dumb battery is higher than $V_{BUS}$, the dumb battery would be reconnected to the DC bus and source current to the smart battery. The unwanted circulating current between a smart battery and a dumb battery occurs when the condition (3-2) is satisfied ($V_{oc,dumb} - V_{BUS} > \beta$).

- However, if the resting voltage of one of the dumb batteries is higher than the DC bus voltage $V_{BUS}$, which equals to the resting voltage of the smart battery with the highest charging priority, and the voltage different is greater than $\beta$ in (3-2), the dumb battery will be reconnected to the DC bus and source current to the smart battery with the highest charging priority. (will be removed because the information presented here is the same as the situation 3 in Figure 3.9 (c))
Situation 4 in Figure 3.9 (d): At least one Lithium-ion battery has been charged to full and is not allowed to be charged anymore, so it is disconnected from the DC bus when there is no load. It could be a smart battery with SOC = 100% (its resting voltage could be close to 16.5 V) or a dumb battery with resting voltage equal to 16.5 V. Similar to Situation 3, the resting voltage of the fully-charged battery is certainly higher than the DC bus voltage $V_{BUS}$, which equals to the resting voltage of the battery with the highest charging priority. The voltage different is greater than $\beta$ in (3-2), the fully-charged battery will be reconnected to the DC bus and source current to the battery with the highest charging priority.

The circulating current problem in all of the above situations can be generalized as follows:

“When any of the Lithium-ion battery that is disconnected from the DC bus due to its lower charging priority has higher resting voltage $V_{oc}$ than the DC bus voltage $V_{BUS}$, and the voltage different is greater than $\beta$ in (3-2), it will be reconnected to the DC bus and source current to the battery with the highest charging priority if only (3-2) is examined.”

Therefore, (3-1) must be examined in addition to (3-2) to avoid the circulating current problem induced by SOC/resting-voltage sorting when there is no load.
The undesired circulating current could occur due to SOC/resting-voltage sorting if only the condition (3) is examined. The battery with priority 2 will source current to the battery with priority 1. (a) Situation 1. (b) Situation 2. (c) Situation 3. (d) Situation 4.

3.3.2.2 Self-Balance

As defined in Figure 3.6 (b), when the load is light, the battery connected to the DC bus may slowly drain. It is possible that the load increases so slowly that (3-2) is satisfied for other batteries (not connected to the DC bus) with lower SOCs or resting voltages, but (3-1) is not valid because there is no abrupt voltage drop on the DC bus. In this case, the other batteries will not be connected until the SOC or resting voltage of the sole battery connected to the DC bus is lower than other batteries. Then the charging sequence is reprioritized by the sorting function built in the host controller. A new priority will be given by the sorting function and only one of the batteries with the highest SOC or resting voltage will be connected to the DC bus to support the light load. Accordingly, another benefit might be obtained: if the load is always light and/or increases slowly, it will automatically bring all batteries into voltage balance ultimately. The benefits
brought by balanced battery packs are two-fold: 1) All battery packs are able be charged at the same time when input power is high enough. 2) All battery packs are able be discharged at the same time to provide maximized load current or power. An example of self-balance when the load is light will be illustrated in Section 3.4.6.

3.3.2.3 Allowed battery voltage and mixing batteries with different chemistries

In the prototype system, four Lithium-ion batteries with a nominal voltage 14.4 V and a nominal capacity 13.6 Ah (four cells of 3.6 V nominal in series), are utilized. In fact, the batteries will have resting voltage variation from ~14.0 V (SOC = 0 %) to ~16.5 V (SOC = 100 %) depending on their SOCs [51, 60]. Although the types of batteries are the same in our prototype system, other batteries with different type of chemistry such as NiMH can be used, as long as the nominal voltage is within the range between 14 V and 16.5 V. For example, NiMH batteries with nominal voltage 14.3 V (eleven cells of 1.3 V nominal in series) can be mixed with Lithium-ion batteries in parallel. The ability of mixing Lithium-ion and NiMH batteries in parallel will be illustrated in Section 3.4.7.

3.3.3 Disconnecting batteries after they have been connected

While the number of required batteries needed to be connected to the DC bus is determined by the algorithm described in Section 3.3.2 when the load abruptly increases, the system also needs a mechanism to disconnect these batteries from the DC bus in order to avoid circulating current among them. A new approach on how to disconnect batteries is as follows: 1) Based on the information obtained from the sorting result of these batteries (using SOC or resting voltage in descending sequence), examine if the battery with the highest SOC or resting voltage is discharging. 2) If the battery with the highest
SOC or resting voltage is discharging, examine whether any of the other batteries connected to the DC bus are being charged. If so, disconnect the charging battery so that it no longer drains current from another battery. The details of this new approach on how to disconnect batteries after they have been connected are presented below.

At heavy load, multiple batteries are connected to the DC bus. As load current transitions to lighter load, the DC bus voltage increases. Eventually the bus voltage may rise above the resting voltage of a specific battery. When this occurs, there will be circulating current to that battery, which means that one battery (or more batteries) is charging while other batteries are discharging. When this occurs, it is important to disconnect the batteries being charged from the DC bus.

Suppose there are \( N \) batteries in the system. At no load or light load, \( V_{oc,k} (1 \leq k \leq N) \) is known and the sequence from the highest to the lowest is: \( V_{oc,1} \geq V_{oc,2} \geq \ldots \geq V_{oc,k} \geq \ldots \geq V_{oc,N} \). The charge/discharge current \( I_{D,k} \) of each battery is defined as below:

\[
I_{D,k} > 0: \text{Discharging}
\]

\[
I_{D,k} < 0: \text{Charging.}
\]

\[
I_{D,k} = 0: \text{No charge/discharge current or the switch } S_k \text{ is open}
\]

Suppose there are \( m \) (\( 1 \leq m \leq N \)) batteries connected to the DC bus due to the increasing load. Before the load current decreases, \( I_{D,k} (1 \leq k \leq m) \) is positive (discharging) for the \( m \) batteries connected to the DC bus. When the load current starts decreasing, the switch \( S_k \) should be opened once negative \( I_{D,k} \) is detected. Figure 3.10 illustrates the algorithm for opening the switch \( S_k \) when load current decreases.

First, the parameter \( m \) (the number of the batteries connected to the DC bus) is always monitored. The current \( I_{D,k} \) is inspected only when \( m > 1 \), which means there are at least
two batteries connected to the DC bus. If \( m > 1 \), the current \( I_{D,1} \) is inspected first to see if \( I_{D,1} \) is positive. The positive \( I_{D,1} \) indicates Battery #1 with the highest \( V_{oc,1} \) is discharging to either the reduced load or to other batteries with lower \( V_{oc,k} \). When \( I_{D,1} > 0 \) is fulfilled, the currents \( I_{D,m}, I_{D,(m-1)}, I_{D,(m-2)}, \ldots, I_{D,3}, I_{D,2} \) are inspected sequentially to see if they are negative (being charged) or zero (no charge/discharge current). The switch \( S_k \) is opened when \( I_{D,k} \) is negative or zero. Finally, some of the batteries with lower \( V_{oc,k} \) are disconnected from the DC bus due to the decreasing load. No circulating current among the batteries is guaranteed.

Figure 3.10 The algorithm to turn off the switch \( S_k \) when load current decreases.
3.4 Experimental Results and Discussion

3.4.1 Experimental setup

Figure 3.11 shows the implementation of a laboratory prototype. The supervisory host is formed by dsPIC33FJ256GP710A DSP. The host communicates with the charger and controls the switches $S_k$ via RS485 network. The internal resistance of the battery from manufacturer-A and manufacturer-B are approximately 0.1185 $\Omega$ and 0.1579 $\Omega$, respectively. The internal resistance of each battery is extracted based on a commonly-used electrical battery model described in [61]. The electrical battery model and the experiments performed to extract the internal resistance are given in the Appendix. Knowing the internal resistance and the maximum discharge current limits of each battery helps to estimate the maximum energy each battery is able to deliver to the load. And the maximum energy the system is able to deliver to the load can be calculated accordingly. In the following experiments, an assumption is made that the internal resistance values of the batteries from the same manufacturer are the same.

Two kinds of experiments were conducted to verify the proposed algorithms for 1) increasing step load and 2) increasing step load followed by decreasing step load. The test conditions and experimental setup are tabulated in Table 3.2 and Table 3.3. Increasing load experiments are performed in the Experiments-1~3. Increasing step load followed by decreasing step load experiment is performed in Experiment-4. In Experiment-1, $\alpha = \beta = 0.3$ V. In Experiment-2~4, $\alpha = \beta = 1$ V. A DC-AC inverter is used.
as the single load in Experiment-1 and a DC electronic load is used as the single load in Experiment-2~4. The purpose of these experiments is to verify the algorithms proposed in Section 3.3.2 and Section 3.3.3 for an increasing load and a decreasing load, respectively.

![Image of laboratory prototype](image)

Figure 3.11 The implementation of a laboratory prototype built for testing.

### Table 3.2 The test conditions for verifying the proposed algorithms

<table>
<thead>
<tr>
<th>Load</th>
<th>Increasing Load</th>
<th>Increasing Load + Decreasing Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>Light → Medium</td>
<td>Light → Heavy</td>
</tr>
<tr>
<td>(α, β)</td>
<td>(0.3 V, 0.3 V)</td>
<td>(1 V, 1 V)</td>
</tr>
<tr>
<td>I_L</td>
<td>2 A → 7.5 A</td>
<td>2.2 A → 20 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Figure 3.13</td>
<td>Figure 3.16</td>
</tr>
<tr>
<td></td>
<td>Figure 3.14</td>
<td>Figure 3.16</td>
</tr>
<tr>
<td></td>
<td>Figure 3.15</td>
<td>Figure 3.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3 The experimental setup for verifying the proposed algorithms

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Battery #1</th>
<th>Battery #2</th>
<th>Battery #3</th>
<th>Battery #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Manufacturer</td>
<td>A₁</td>
<td>A₁</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>$V_{oc}$ (V)</td>
<td>15.98</td>
<td>15.11</td>
<td>16.40</td>
</tr>
<tr>
<td></td>
<td>SOC (%)</td>
<td>81</td>
<td>34</td>
<td>100</td>
</tr>
<tr>
<td>2, 3, 4</td>
<td>Manufacturer</td>
<td>A₂</td>
<td>A₂</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>$V_{oc}$ (V)</td>
<td>15.43</td>
<td>15.13</td>
<td>16.00</td>
</tr>
<tr>
<td></td>
<td>SOC (%)</td>
<td>54</td>
<td>42</td>
<td>89</td>
</tr>
</tbody>
</table>

The bidirectional switch $S_N$ between Battery #N and the DC bus consists of two back-to-back pMOSFET, as shown in Figure 3.12. The switch is opened if its gate voltage $V_{GATE,N}$ is $\sim 2.5$ V and is closed if $V_{GATE,N}$ is $\sim 15$ V.

![Switch Circuit](image)

Figure 3.12 The circuit of the switch $S_N$ between Battery #N and the DC bus.
3.4.2 Increasing load: light to medium with $\alpha = \beta = 0.3$ V (Experiment-1)

The goal of this experiment is to verify the effectiveness of the algorithm illustrated in Figure 3.8 as well as conditions (3-1) and (3-2) when the load current increases from light load (2 A) to medium load (7.5 A). According to Figure 3.6 (b) and Table 4-3, only Battery #3 with the highest $V_{oc}$ (16.4 V) and SOC (100 %) is connected to the DC bus when the load current is 2 A (light). According to Figure 3.6 (c), when the load current increases to 7.5 A (medium), at least one more battery will be connected to the DC bus to share the load. The following experimental result shows that Battery #1 with the second highest $V_{oc}$ (15.98 V) and SOC (81 %) is properly connected to the DC bus after the load current increases to 7.5 A (medium). The system response to the change of the load current, including the DC bus voltage $V_{BUS}$, the gate voltage $V_{GATE,1}$ of the switch $S_1$, and a toggle signal $V_{\text{toggle}}$ used to indicate the switch $S_1$ is opened or closed, is shown below.

Figure 3.13 and Figure 3.14 show the system response when the load current $I_L$ is increased from light (2A) load to medium (7.5A) load. In Figure 3.13 and Figure 3.14, Channel-1 is the waveform of load current, $I_L$, drained by a DC-AC inverter with a resistive load; Channel-2 the bus voltage $V_{BUS}$, including a DC offset voltage of 14 V; Channel-3 the gate voltage $V_{GATE,1}$ of the switch $S_1$ (PMOSFETs); and Channel-4 the toggle signal $V_{\text{toggle}}$ which toggles from 0 V to 5 V or from 5 V to 0 V after the following two events are detected: first, both (3-1) and (3-2) are satisfied ($\Delta V_{BUS} > \alpha$ and $\Delta V_{GAP,1} > \beta$) and second, the switch $S_1$ is closed. The bus voltage $V_{BUS}$ is 16.1 V before the load
increases from 2 A to 7.5 A. Figure 3.15 shows the system operation before and after the load increases.

Originally, only Battery #3, with highest open-circuit voltage, is connected to the DC bus, as shown in Figure 3.15. Increasing the load caused $V_{BUS}$ to drop. In Figure 3.13, at $t = t_1$, the voltage drop $\Delta V_{BUS}$ has reached 0.3 V. In Figure 3.14, at $t = t_2$, both “$\Delta V_{BUS} > 0.3$ V” and “$\Delta V_{GAP,3} > 0.3$ V” are detected at the same time so that the switch $S_1$ is closed to connect Battery #1 to the DC bus at $t = t_3$. Therefore, the gate voltage $V_{GATE,1}$ of the switch $S_1$ starts dropping from 15.1 V (OFF-state) at $t = t_3$. At $t = t_4$, although the PMOSFETs are not fully turned on ($V_{GATE,1} >> 2.5$ V), $V_{BUS}$ starts rising because Battery #1 is connected to the DC bus. Figure 3.15 shows that at the steady-state the PMOSFETs are fully turned on and two batteries are used to fulfill the 7.5 A load demand.

The reason why Battery #2 and Battery #4 are not connected to the DC bus in Figure 3.15 is that the increasing load is not heavy enough to make $\Delta V_{GAP,2} > 0.3$ V and $\Delta V_{GAP,4} > 0.3$ V. If the increasing load is much higher than 7.5 A so that $V_{BUS}$ is lower than $V_{oc,2}$ (15.11 V) and $V_{oc,4}$ (15.28 V), they will all be connected to the DC bus. This experimental behavior is as predicted by the proposed discharge algorithm: Battery #k is connected to the DC bus only when (1) the minimum required voltage drop $\Delta V_{Drop}$ on the DC bus is detected, and (2) the minimum required voltage difference $\Delta V_{GAP, k}$ between DC bus voltage and open-circuit voltage of Battery #k is detected. In this experiment, only Battery #1 fulfills both criteria so it is connected to the DC bus as predicted.
Figure 3.13 Load current (Channel-1: 5 A/division), DC bus voltage $V_{BUS}$ (Channel-2: 1 V/division with a 14 V DC offset), the gate voltage $V_{GATE,1}$ of the PMOSFETs switch $S_1$ (Channel-3: 5 V/division), and the toggle signal $V_{toggle}$ (Channel-4: 5 V/division) when load current increases from 2 A to 7.5 A.

Figure 3.14 Zoom-in of Figure 3.13.
3.4.3 Increasing load: light to medium with $\alpha = \beta = 1 \text{ V}$ (Experiment-2)

The goal of this experiment is to verify the effectiveness of the algorithm illustrated in Figure 3.8 as well as conditions (3-1) and (3-2) when the load current increases from light load (2.2 A) to medium load (20 A). According to Figure 3.6 (b) and Table 4-3, only Battery #3 with the highest $V_{oc}$ (16 V) and SOC (89 %) is connected to the DC bus when the load current is 2.2 A (light). According to Figure 3.6 (c), when the load current increases to 20 A (medium), at least one more battery will be connected to the DC bus to share the load. The following experimental result shows that Battery #4 with the second highest $V_{oc}$ (15.77 V) and SOC (77 %) and Battery #1 with the third highest $V_{oc}$ (15.43 V) and SOC (54 %) are properly connected to the DC bus after the load current increases to 20 A (medium). The system response to the change of the load current, including the discharging current of Battery #3, Battery #4, and Battery #1, is shown below.
Figure 3.16 shows the system response when the load current is increased from 2.2 A to 20 A. Both (3-1) and (3-2) are satisfied ($\Delta V_{BUS} > \alpha$ and $\Delta V_{GAP,k} > \beta$) for Battery #1 and Battery #4 after the load current increases so the switches $S_1$ and $S_4$ are closed. Originally, only Battery #3, with highest open-circuit voltage, is connected to the DC bus, as shown in Figure 3.16. Before $t = 0$, the inverter draws 2.2 A from Battery #3. At $t = 0$, a constant-current load of 18 A is applied to the DC electronic load. The increasing load current $I_L$ caused $V_{BUS}$ to drop. The discharging current $I_{D,3}$ from Battery #3 jumps to 8.5 A immediately and the switches $S_1$ and $S_4$ are closed because “$\Delta V_{BUS} > 1$ V” and “$\Delta V_{GAP,k} > 1$ V ($k = 1, 4$)” are satisfied for Batteries #1 and #4. The discharging current $I_{D,3}$ falls to 4.5 A because part of the load current begins to be shared by Batteries #1 and #4. At $t = 0.6$ ms, the discharging currents $I_{D,1}$, $I_{D,3}$, and $I_{D,4}$ keep increasing as $I_L$ increases. At $t = 80$ ms, as $I_L$ reaches about 20 A, the discharging currents $I_{D,1}$, $I_{D,3}$, and $I_{D,4}$ start stabilizing at 5.8 A, 7.6 A, and 6.6 A, respectively.

The three batteries have successfully connected to share the load as designed and predicted by the proposed battery management algorithm, although the higher voltage batteries will tend to supply more current to the load.
3.4.4 Increasing load: light to heavy with $\alpha = \beta = 1V$

(Experiment-3)

The goal of this experiment is to verify the effectiveness of the algorithm illustrated in Figure 3.8 as well as conditions (3-1) and (3-2) when the load current increases from light load (1.9 A) to heavy load (29 A). According to Figure 3.6 (b) and Table 4-3, only Battery #3 with the highest $V_{oc}$ (16 V) and SOC (89 %) is connected to the DC bus when the load current is 1.9 A (light). According to Figure 3.6 (d), when the load current increases to 29 A (heavy), all batteries will be connected to the DC bus to share the load.

The following experimental result shows that Battery #4 with the second highest $V_{oc}$ (15.77 V) and SOC (77 %), Battery #1 with the third highest $V_{oc}$ (15.43 V) and SOC (54
percent), and Battery #2 with the lowest $V_{oc}$ (15.13 V) and SOC (42 %) are all properly connected to the DC bus after the load current increases to 29 A (heavy). The system response to the change of the load current, including the discharging current of all batteries, the DC bus voltage $V_{BUS}$, and the gate voltages $V_{GATE,1}$, $V_{GATE,2}$, and $V_{GATE,4}$ of the switches $S_1$, $S_2$, and $S_4$, is shown below.

Figure 3.17 shows the system response when the load current is increased from light (1.9 A) to heavy (29 A). Both (3-1) and (3-2) are satisfied ($\Delta V_{BUS} > \alpha$ and $\Delta V_{GAP,k} > \beta$) for Battery #1, Battery #2, and Battery #4 after the load current increases so the switches $S_1$, $S_2$, and $S_4$ are closed. Originally, only Battery #3, with the highest open-circuit voltage, is connected to the DC bus, as shown in Figure 3.17. Before $t = 0$, the inverter draws 1.9 A from Battery #3. At $t = 0$, a constant-current load of 27 A is applied to the DC electronic load. The increasing load current $I_L$ caused $V_{BUS}$ to drop. The load current $I_{D,3}$ from Battery #3 bounces to 10.8 A immediately and the switches $S_1$, $S_2$, and $S_4$ are closed because “$\Delta V_{BUS} > 1$ V” and “$\Delta V_{GAP,k} > 1$ V ($k = 1, 2, 4$)” are satisfied. The discharging current $I_{D,3}$ falls to 6.7 A because part of the load current begins to be shared by Batteries #1 and #4. At $t = 0.6$ ms, the discharging currents $I_{D,1}$, $I_{D,3}$, and $I_{D,4}$ keep increasing as $I_L$ increases. Before $t = 28$ ms, the discharging currents $I_{D,1}$, $I_{D,3}$, and $I_{D,4}$ start stabilizing at 8.3 A, 9.5 A, and 9.1 A, respectively. At $t = 28$ ms, the switch $S_2$ is closed because “$\Delta V_{BUS} > 1$ V” and “$\Delta V_{GAP,2} > 1$ V” are satisfied. The discharging currents $I_{D,1}$, $I_{D,3}$, and $I_{D,4}$ fall to 6.0 A, 7.9 A, and 7.6 A, respectively, because part of the load current begins to be shared by Battery #2. At $t = 100$ ms, as $I_L$ reaches about 29 A, the discharging currents $I_{D,1}$, $I_{D,2}$, $I_{D,3}$, and $I_{D,4}$ start stabilizing at 7.2 A, 5.7 A, 8.0 A, and 7.6 A respectively.
Figure 3.17 Load current of each battery when the load current was increased from 1.9A (light load) to 29A (heavy load).

Figure 3.18 shows measured $V_{BUS}$ and gate voltages $V_{GATE,1}$, $V_{GATE,2}$, and $V_{GATE,4}$ of the switches $S_1$, $S_2$, and $S_4$ when the load current increases from light (1.9A) load to heavy (29A) load. Before $t = 0$, the inverter draws 1.9 A from Battery #3 and $V_{BUS}$ is close to 15.5 V. The gate voltages of the switches $S_1$, $S_2$, and $S_4$ are about 15 V, which indicates $S_1$, $S_2$, and $S_4$ are open. At $t = 0$, a constant-current load of 27 A is applied to the DC electronic load. The increasing load current $I_L$ caused $V_{BUS}$ to drop. At $t = 0.9$ ms, $V_{GATE,4}$ of the switch $S_4$ drops to about 2V, which indicates $S_4$ becomes closed because “$\Delta V_{BUS} > 1$ V” and “$\Delta V_{GAP,4} > 1$ V” are satisfied. $V_{BUS}$ jumps back up to 15 V because part of the load current begins to be shared by Battery #4. However, the bus voltage continues to drop since $I_L$ keeps increasing. At $t = 3.8$ ms, $V_{GATE,1}$ and $V_{GATE,2}$ drop to about 2 V, which
indicates $S_1$ and $S_2$ are closed because the criteria for Batteries #1 and #2 in Figure 3.9 are fulfilled. $V_{BUS}$ bounces to 14.8 V because part of the load current begins to be shared by Batteries #1 and #2. Finally, all batteries are connected to the DC bus.

Figure 3.18 The measured $V_{BUS}$ and gate voltages $V_{GATE_1}$, $V_{GATE_2}$, and $V_{GATE_4}$ of the switches $S_1$, $S_2$, and $S_4$ when the load current was increased from 1.9 A (light load) to 29 A (heavy load).

The experimental results illustrated in Sections 4.4.1~4.4.4 verify that the proposed discharging algorithm introduced in Section 3.3.2.1 works well and allows different state-of-charged battery packs to seamlessly operate together in various load conditions. The load can be effectively distributed to a few qualified battery packs when it increases from light load to medium load or heavy load. Therefore, the risk of over-discharging or over-heating of a single battery pack can be minimized. Both the system safety and reliability are improved.
3.4.5 Decreasing load: heavy to no load with $\alpha = \beta = 1$ V

(Experiment-4)

Figure 3.19 shows the system response when load current first increased from no load (0 A) to heavy load (33 A) and then decreased from heavy to no load. In the beginning of the period (a), both (3-1) and (3-2) are satisfied ($\Delta V_{BUS} > \alpha$ and $\Delta V_{GAP,k} > \beta$) for Battery #1, Battery #2, and Battery #4 after the load current increases, so the switches $S_1$, $S_2$, and $S_4$ are closed. In the end of the period (b), the algorithm illustrated in Figure 3.10 is performed after the load decreases to zero so the switches $S_1$, $S_2$, and $S_4$ are opened.

At $t = 0$, a constant-current load of 33 A with 1-second duration is applied. The switches $S_1$, $S_2$, and $S_4$ are closed because “$\Delta V_{BUS} > 1$ V” and “$\Delta V_{GAP,k} > 1$ V ($k = 1, 2, 4$)” are satisfied. At the final stage of period (a), the discharging currents $I_{D,1}$, $I_{D,2}$, $I_{D,3}$, and $I_{D,4}$ stabilize at 7.4 A, 6.5 A, 9.9 A, and 8.7 A respectively. All four batteries have been successfully connected to the load. At $t = 1.05$ s, the 33 A load is removed. At the initial stage of period (b), Batteries #3 and #4 start charging to Batteries #1 and #2 because of the voltage mismatch. Then the algorithm in Figure 3.10 is implemented to prevent the circulating current. At $t = 1.6$ s, the switch $S_1$ is opened because $I_{D,3} > 0$ and $I_{D,1} < 0$. At $t = 1.7$ s, the switch $S_2$ is open because $I_{D,3} > 0$ and $I_{D,2} < 0$. Since Batteries #1 and #2 have been disconnected from the DC bus, Battery #3 starts charging Battery #4 because of the voltage mismatch. At $t = 1.8$ s, the switch $S_4$ is opened because $I_3 > 0$ and $I_4 < 0$. At the final stage of period (b), only Battery #3 is connected to the DC bus for no load condition.
Figure 3.19 The system response when the load first increased from no load (0 A) to heavy load (33 A) and then decreased from heavy to no load. A constant-current load of 33 A with 1-second duration is applied to the DC electronic load.

Figure 3.20 shows the measured $V_{BUS}$ and gate voltages $V_{GATE,1}$, $V_{GATE,2}$, and $V_{GATE,4}$ of the switches $S_1$, $S_2$, and $S_4$, when the load current is increased from 0 A to 33 A and then decreased from 33 A to 0 A. It shows batteries are connected successfully when the load goes up and disconnected when load goes down. Before $t = 0$, only Battery #3 is connected to the DC bus for no load and $V_{BUS}$ is close to 16 V. The gate voltages of the switches $S_1$, $S_2$, and $S_4$ are about 15 V, which indicates $S_1$, $S_2$, and $S_4$ are open. At $t = 0$, a constant-current load of 33 A with 1-second duration is applied to the DC electronic load. Then voltages of the switches $S_1$, $S_2$, and $S_4$ drops to about 2.5 V, which indicates $S_1$, $S_2$, and $S_4$ are closed. $V_{BUS}$ falls to and stays at 14.3 V during period (a) until $t = 1.05$ s, at
which the constant-current load of 33 A is removed. In the beginning of period (b), $V_{BUS}$ bounces to 15.5 V because the load is removed and all batteries are connected in parallel. Then the algorithm in Figure 3.10 begins to prevent the circulating current. The switches $S_1$, $S_2$, and $S_4$ are opened at $t = 1.15$ s, $1.25$ s, and $1.35$ s, respectively. Finally, $V_{BUS}$ is close to 16 V because only Battery #3 is connected to the DC bus for no load condition. Therefore, the algorithm correctly disconnects unwanted batteries, yet keeps the single desired battery connected to the DC bus.

![Diagram](image)

Figure 3.20 The measured $V_{BUS}$ and gate voltages $V_{GATE,1}$, $V_{GATE,2}$, and $V_{GATE,4}$ of the switches $S_1$, $S_2$, and $S_4$ when the load first increased from no load (0 A) to heavy load (33 A) and then decreased from heavy to no load. It shows that batteries are connected successfully when the load goes up and disconnected when load goes down. A constant-current load of 33 A with 1-second duration is applied to the DC electronic load.
3.4.6 Self-balance

A battery bank with voltage-balanced battery packs provides two benefits: 1) All battery packs with the same chemistry can be charged at the same time. 2) All battery packs with the same chemistry can be discharged at the same time to provide maximum load current or instantaneous power capability. When self-voltage-balance is achieved, the energy flow control becomes simple. The following example shown in Figure 3.21 (a) illustrates how constant sorting contributes to self-voltage-balance when the load is light, as describe in Section 3.3.2.2 previously. The initial condition of the batteries are:

Battery #1: SOC$_1$ = 54%, $V_{oc,1} = 15.43$ V; Battery #2: SOC$_2$ = 40%, $V_{oc,2} = 15$ V;
Battery #3: SOC$_3$ = 89%, $V_{oc,3} = 16.03$ V; Battery #4: SOC$_4$ = 77%, $V_{oc,4} = 15.75$ V.

The initial priority is determined by sorting SOC: #3 > #4 > #1 > #2. The load is a 3 A constant current.

At the first stage shown in Figure 3.21 (a), only Battery #3 is connected to the DC bus. The load slowly drains Battery #3 and reduces SOC$_3$. The second stage, shown in Figure 3.21 (b), begins when SOC$_3$ becomes lower than SOC$_4$. Battery #4 is connected to the DC bus and Battery #3 is disconnected. So the load slowly drains Battery #4 and reduces SOC$_4$. When SOC$_4$ becomes lower than SOC$_3$, Battery #3 is connected to the DC bus again and Battery #4 is disconnected. Consequently, Battery #3 and Battery #4 will be connected to the DC bus alternately until the third stage begins. The third stage, shown in Figure 3.21 (c), begins when SOC$_3$ and SOC$_4$ start to be lowered than SOC$_1$. Battery #1 is connected to the DC bus while Battery #3 and Battery #4 are disconnected. So the load slowly drains Battery #1 and reduces SOC$_1$. When SOC$_1$ becomes lower lowered than
SOC$_3$ or SOC$_4$, Battery #3 or Battery #4 is connected to the DC bus again, and Battery #1 is disconnected. Consequently, Battery #1, Battery #3, Battery #4 will be connected to the DC bus alternately until the final stage begins. In the final stage shown in Figure 3.21 (d), all batteries are connected to the DC bus alternately and self-balance is achieved.

The algorithm can be built into the supervisory host or within individual batteries to ensure the system response to the change of increasing load is fast enough. Then the battery, which has already been connected to the DC bus, does not over discharge or trigger the low-voltage disconnector within the battery.

### 3.4.7 Mixing batteries with different chemistries

Although the types of batteries used in previous experiments are all Lithium-ion, other batteries with different type of chemistry such as NiMH can be used, as long as the nominal voltage is within the range of the Lithium-ion variation, i.e. between 14 V and 16.5 V in our prototype system. This range is determined based on the fact that each Lithium-ion battery used in previous experiments uses two parallel strings of four AA size cells of 3.5−4.2 V in series. (The Lithium-ion battery used in previous experiments has two “legs” and each leg has two parallel strings.)

To demonstrate the ability of mixing Lithium-ion and NiMH batteries in parallel described in Section 3.3.2.3, one BB 390 NiMH battery is chosen to replace one of the Lithium-ion batteries in the prototype system. The different battery chemistries are only allowed to be connected in parallel when discharging. The algorithms do not permit simultaneous charging of the different battery chemistries in parallel because they require different charging strategies.
Chapter 3

Figure 3.21 The constant sorting function built in the host controller contributes to self-balance when the load is light. (a) $V_{BUS}$ and $I_L$ of each battery versus time. The first stage: only Battery #3 is connected to the DC bus. (b) The second stage: only Batteries #3 and #4 are connected to the DC bus (c) The third stage: only Batteries #1, #3, and #4 are connected to the DC bus. (d) The final stage: All batteries are connected to the DC bus. The initial conditions of the batteries -- Battery #1: SOC$_1$ = 54%, $V_{oc,1}$ = 15.43 V. Battery #2: SOC$_2$ = 40 %, $V_{oc,2}$ = 15 V. Battery #3: SOC$_3$ = 89 %, $V_{oc,3}$ = 16.03 V. Battery #4: SOC$_4$ = 77 %, $V_{oc,4}$ = 15.75 V. Initial priority: #3 > #4 > #1 > #2.
To verify the system’s ability of mixing batteries with different chemistries and discharging in parallel, a NiMH battery pack is tested with Lithium-ion battery packs. Figure 3.22 (a) shows a NiMH battery pack having two parallel strings of eleven AA-size cells of 1.2-1.5 V in series with overall voltage range 13.2-16.5 V. It is tested with one Lithium-ion battery, as shown in Figure 3.22 (b). The experimental setup and the initial conditions are illustrated in Figure 3.23. An increasing-load experiment is performed to examine if the NiMH battery is able to share a heavy load with the Lithium-ion battery using the discharging algorithm introduced in Section 3.3.2.1.

Figure 3.22 (a) An extra NiMH cell is added in each string of the BB 390 NiMH battery (The BB 390 NiMH battery also has two “legs” and each leg has two parallel strings.) (b) The modified BB 390 NiMH battery is put into the prototype system with one Lithium-ion battery and an increasing-load experiment is performed to examine if the BB 390 NiMH battery is able to share the load with the Lithium-ion battery.
The SOC and testing voltage of the Lithium-ion battery are 80% and 15.73 V. The resting voltage of the NiMH battery is 15.22 V. The sorting function of the host controller determines the priority of the Lithium-ion battery is higher than the NiMH battery, so in the beginning only the Lithium-ion battery is connected to the DC bus when the load is light (2 A). Figure 3.24 shows DC bus voltage $V_{BUS}$, load current, and discharge current of the NiMH battery in a system with two batteries: one is Lithium-ion and the other is NiMH battery. In the beginning the discharge current of the NiMH battery is zero because the NiMH battery is disconnected from the DC bus. When the load current increases from 2 A to 10 A, $V_{BUS}$ decreases from 15.22 V to 14.20 V. The algorithm described in Section 3.3.2.1 and Figure 3.8 makes the NiMH battery be connected to the DC bus in 2ms so the load is shared by both batteries. The NiMH battery begins sourcing 3.6 A to the load and $V_{BUS}$ increases from 14.20 V to 14.62 V.
This experiment verifies that (i) the proposed discharge algorithm works well even if the battery chemistries are different, and (ii) load sharing in a mixed-mode system with parallel packs of Lithium-ion and NiMH batteries is feasible. This is an important benefit of the proposed algorithms. NiMH can be a cheaper solution for capacity expansion of existing Lithium-ion battery bank in applications such as EVs and telecommunication stations. On the other hand, Lithium-ion batteries have higher energy density. It may even be desirable to add Lithium-ion capacity to older battery banks with NiMH storage.

Figure 3.24 DC bus voltage $V_{BUS}$ (Channel-3: 1 V/division with a 14 V DC offset), load current $I_L$ (Channel-2: 2 A/division), and discharge current (Channel-1: 2 A/division) of the NiMH battery. When the load current increases from 2 A to 10 A, the NiMH battery is connected to the DC bus in 2ms so the load is shared by both batteries.
3.5 Conclusion

In this chapter, we propose a battery management system that nominally connects a single battery (or string of series cells) at a time until the load requires higher current. As load current increases, more batteries are quickly connected to the DC bus to provide energy to the loads. As load current decreases, some batteries are quickly disconnected from the DC bus to avoid the circulating current. With this controlled architecture, it is possible to charge each battery to its full SOC, account for voltage mismatches, and utilize intermittent discharging strategies. The proposed algorithms have been verified by a laboratory prototype. Although the prototype is originally designed for the portable auxiliary power system in remote applications, the concept can be applied to remote stationary application such as battery charging station.

A main contribution of this research is to demonstrate how to properly connect different battery packs in parallel, even when their resting open-circuit voltages, SOCs, and chemistries differ.

Specifically, the contributions of the research in this chapter include:

- *A new method for controlling charging/discharging of different battery packs by using low-cost bi-directional switches instead of DC/DC converters is proposed.* Because of substantially fewer parts, the physical design and cost for the energy management system architecture is substantially reduced. This has benefits in the portable/handheld electronics market.

- *Each different battery pack can be individually charged to its full SOC,* even though the battery packs are often connected directly in parallel.
• **Special discharging algorithms are proposed to control the sequence and the number of battery packs used to share the load according to the load transient condition.** At heavy load, a higher number of battery packs are connected in parallel. At light load, only one battery pack is connected. The decision of switching in/out more battery packs is executed by a supervisory host made up of a microcontroller unit (MCU) or a digital signal processor (DSP).

• **The circulating current among the batteries due to voltage mismatch and SOC/resting-voltage sorting is avoided.** The discharging algorithms have been verified by a prototype system in which four battery packs in parallel with different voltages within predefined range are utilized.

• **The proposed discharging algorithm works well even if the battery chemistries are different.** Load sharing in a mixed-mode system with parallel packs of Lithium-ion and NiMH batteries is feasible and has been verified.
Chapter 4

MPPT by means of tracking output parameters of a DC-DC converter

Maximum power point tracking (MPPT) is a technique to obtain maximum power from photovoltaic (PV) panels in any given irradiance conditions. The MPPT controller is usually realized in a DC-DC converter between PV panels and loads. Conventionally, the duty ratio $d_C$ of the DC-DC converter is regulated such that a global maximum power point (MPP) of PV panels, $P_{MPP}$, can be found at a specific PV voltage $V_{MPP}$ and PV current $I_{MPP}$, as shown in Figure 4.1. Adjusting the duty ratio, $d_C$, will alter the input voltage of the DC-DC converter, which is equal to the operating voltage of the PV panel. Therefore, changing the duty ratio of the DC-DC converter will alter the operating point of the PV panel. The goal is to operate the PV panel at its maximum producing operating point.
In many PV systems, batteries are used as a load or an energy backup. In their first approximation, batteries can be considered as an ideal voltage source. Therefore, the output voltage $V_{out}$ of the DC-DC converter can be considered as a constant when batteries are used as a load or an energy backup. Assuming the efficiency of the DC-DC converter is $\eta$, the relationship between the input power and the output power of the DC-DC converter can be derived as below:

$$P_{out} = V_{out} I_{out} = \eta P_{in} \quad (4-1)$$

Since $V_{out}$ of the DC-DC converter can be considered as a constant, $I_{out}$ of the DC-DC converter is proportional to $P_{in}$ if $\eta$ is also a constant. Therefore, maximizing the output current $I_{out}$ of the DC-DC converter can maximize the input power $P_{in} (= P_{MPP})$ [62-78].

In reality, $\eta$ is not always a constant. So the PV panels might operate close the MPP when $I_{out}$ is maximized.
In addition to $I_{out}$ of the DC-DC converter, $V_{out}$ of the DC-DC converter can also be used as the control variable for finding the MPP if the load is a current source [77, 79-81]. For a current-source load, $I_{out}$ in (4-1) is a constant. $V_{out}$ of the DC-DC converter is proportional to $P_{in}$ if $\eta$ is also a constant. Therefore, maximizing the output voltage $V_{out}$ of the DC-DC converter can maximize the input power $P_{in} (= P_{MPP})$. Once again, in reality, $\eta$ is not always a constant. So the PV panels might operate close the MPP when $V_{out}$ is maximized.

The motivation to track only one parameter ($I_{out}$ or $V_{out}$ of the DC-DC converter) when performing MPPT are twofold: 1) the efficiency of the DC-DC converter is not constant, so maximizing input power does not necessarily maximize the output power; 2) it requires fewer sensors and no multiplier (in the software or hardware). This has benefits in small and portable MPPTs, such as the ones described in this dissertation. In this chapter, MPPT techniques by tracking output parameters of the DC-DC converters are briefly reviewed. This chapter is organized as follows:

- In Section 4.1, analog control techniques for tracking output current of the DC-DC converter with a battery as a load are reviewed.
- In Section 4.2, digital control techniques for tracking output current of the DC-DC converter with a battery as a load are reviewed.
- In Section 4.3, digital control techniques for tracking either output current or voltage of the DC-DC converter without a battery as a load are reviewed.
- In Section 4.4, the selection on tracking output current or voltage of the DC-DC converter is discussed.
4.1 Tracking output current (with a battery): Analog control

4.1.1 Analog feedback control techniques in early days

The analog feedback control techniques for MPPT have been studied [62-64, 70] and deployed in remote area power supply (RAPS) [70], a solar-powered race vehicle [63], and satellite power systems [62] in early days (in 90’s). In these applications, a battery is used as an energy back-up. MPPT by tracking only the output current $I_{\text{out}}$ of the DC-DC converter has been proved to be effective.

The methods in [62-64, 70] for maximizing the output current $I_{\text{out}}$ of the DC-DC converter is realized by “positive feedback,” as the option 2 shown in Figure 4.1. The output current $I_{\text{out}}$ is fed into a MPPT controller and the output of the MPPT controller is fed into the input of the pulsed width modulator (PWM). The PWM unit generates a control signal to control the duty ratio of the switches in the DC-DC converter. Instead of using simple feedback control with feedback gain and a commercial PWM generator [62, 70], the MPPT controller and PWM in [63] are realized by complex analog circuits, including a differentiator, a comparator, a clocked flip-flop, and an integrator that is used to realize PWM. Figure 4.2 shows the function blocks of the clocked auto-oscillation MPPT control system in [63].
Figure 4.2 The MPPT controller and PWM are realized by complex analog circuits, including a differentiator, a comparator, a clocked flip-flop, and an integrator [63].

4.1.2 CMOS analog integrated circuit (IC)

Different MPP trackers implemented in an analog integrated circuit (IC) have been studied in [65-68, 82-84] for ultra-low-power (~ mW) solar energy harvester and low-power (under 40W) solar battery chargers. The on-chip analog solutions allow high switching frequencies to reduce the size and the cost of the passive components such as input/output capacitors and inductors. MPPT by tracking output current of the DC-DC converter provides reduced complexity of analog circuit because no multiplier is necessary [65-68, 84].

In [65], an analog MPP tracker without multipliers, differentiators, and integrators is proposed and simulated. The hill-climbing MPPT algorithm is realized by adjusting the output reference current $I_{ref}$, which is controlled by charging or discharging a capacitor at the output of a 4-state charge-pump circuit, as shown in Figure 4.3. In [66], an analog MPP tracker is designed for an indoor solar energy harvester. While its power
consumption is only 3.5 μW, the maximum conversion efficiency when PV panels operate at the MPP, $P_{out}/P_{MPP}$, is only 70%. The poor efficiency is due to large power loss of on-chip switching devices, planer type MOSFETs. In [68], a load current based analog MPPT controller is simulated. The main building blocks of the analog MPPT controller are a differentiator, a comparator, a SR flip-flop, an integrator, and a PWM generation circuit. The concept of this analog MPPT controller is similar to the one used in a solar race car [63].

Figure 4.3 The output reference current $I_{ref}$ is controlled by charging or discharging a capacitor at the output of a 4-state charge-pump circuit [65].

In [67, 84], the analog MPPT controller is integrated with the PV panels installed on the roof of an electric vehicle. The MPPT block consists of an operational transconductance amplifier (OTA), and analog block, and a control block, as shown in Figure 4.4. The OTA is an amplifier whose differential input voltage produces an output current. The output current $I_{out}$ of the DC-DC converter is measured by sensing the voltage across the shunt resistor $R_{SH}$. The voltage across the shunt resistor $R_{SH}$ becomes the differential input voltage of the OTA. Therefore, maximizing the output current of the OTA maximizes the output current of the DC-DC converter.
Figure 4.4 The output current $I_{out}$ of the DC-DC converter is measured by sensing the voltage across the shunt resistor $R_{sh}$ between the nodes SH+ and SH−. So maximizing the output current of the OTA maximizes the output current of the DC-DC converter [67, 84].

4.1.3 Advantages and disadvantages of analog MPPT

Although the MPPT techniques in [62-68, 70, 84] demonstrate that the output current $I_{out}$ of the DC-DC converter can be used as the control parameter when a battery is used as a load, inherent limitations of these methods still exist: In [64], knowing the characteristics of the PV panels for curve fitting is required before designing the system parameters. Besides, none of the approaches in [62-68, 70, 84] is able to address the problem of finding the true MPP in the partial shading condition, which usually causes multiple local MPPs. While it is reported that reducing the number of PV cells in each string of a PV panel can alleviate partial shading effect [84], the minimum number of PV cells in each string still has to be large enough to supply the analog control circuit.

Besides, although MPPT by tracking output current of the DC-DC converter provides reduced complexity of high-speed analog circuit because no multiplier is necessary, when compared to the digital solutions including microcontroller and digital signal processor (DSP), the overall design and implementation complexity of analog MPPT are still high.
4.2 Tracking output current (with a battery): Digital control

4.2.1 Advantages and disadvantages of digital MPPT

Compared to analog MPPT methods introduced in Section 4.1, MPPT controllers realized by a microcontroller or a DSP provide the following features that analog MPPT methods cannot provide:

- Various MPPT algorithms, including perturb-and-observe (P&O) [69, 75, 85, 86], incremental conductance [87], fractional open-circuit voltage [88], fractional short-circuit current [88], fuzzy logic [89, 90], and neural network [91], can be easily implemented in the control software without using any discrete differentiator or integrator.

- The true MPP can be found by sophisticated algorithms when partial shading on PV panels occurs.

- The on-chip resources such as internal program/data memory, analog-to-digital converters (ADC), digital-to-analog converters (DAC), PWM generators, and other peripherals greatly reduce the number of discrete components in traditional discrete analog circuit. So the cost and size of the entire system is reduced.

- The parameters such as voltage, current, and temperature can be filtered using a digital filter implemented in the control software without using a physical RC filter.

- Because the data processing is programmable, considerable flexibility is available in arithmetic computations and improving system performance with incremental
programming adjustments.

The accuracy of the parameter measurements depend on the resolution of ADC. Because of the digital signal processing, the quantization errors of ADC is unavoidable. The quantization errors can be minimized by increasing ADC resolution. However, they always remain within ±1/2 least significant bit (LSB). Besides, the PWM resolution of a digital MPPT controller is limited by it switching frequency. High switching frequency induces low PWM resolution, thus limiting the minimum step of regulating the duty ratio of the DC-DC converter. So the operating point might oscillate around the MPP when P&O or incremental conductance MPPT algorithms is used.

4.2.2 MPPT realized by a microcontroller or a digital signal processor (DSP)

MPPT by tracking the output current of the DC-DC converter using a microcontroller or a DSP has been proposed in [71-75] for battery chargers. In [71], the MPP is found by increasing output current reference $I_{\text{ref}}$ of the DC-DC converter from zero until the real output current $I_{\text{out}}$ of the DC-DC converter does not increase along with $I_{\text{ref}}$. The DC-DC converter operates at a fixed operating point unless a certain amount of change on PV voltage of battery voltage is detected. One of the disadvantage of using the algorithm in [71] is that a local maxima might be found first in partial shading environment and the system will stop looking for the real MPP. Another disadvantage is that fast changing irradiance on PV panels or fast changing voltage on loads will always make the system restart the searching process, lowering the overall conversion efficiency.
Modification of the conventional P&O algorithm is presented in [72-75]. In [74], implementing P&O algorithm with a bypass switch is proposed to maximize the power delivered to a battery when voltages of PV panels and the battery are closely matched. In [72, 75], implementing P&O algorithm with adjustable duty ratio step and adjustable perturbation frequency is proposed. Optimization and tradeoffs between the controller’s speed and MPPT efficiency are discussed.

4.3 Tracking output parameters without batteries

4.3.1 Load: DC/AC inverter feeding a grid

The P&O MPPT control realized by maximizing the output current of the DC-DC converter without a battery as a energy backup is proposed in [78]. Figure 4.5 shows the system block diagram of the grid connected PV system. The PV panels and the DC-DC converter operate as a current source to the H-bridge. Without a battery connected at the output of the DC-DC converter as a buffer, large noise occurs when the output current of the DC-DC converter is measured. So noise filtering for $I_{out}$ based on averaging is necessary in the control software. Besides, over current protection is also necessary to ensure the output current of the DC-DC converter does not exceed the rating of the DC-DC converter.
The P&O MPPT control realized by maximizing the output voltage of the DC-DC converter without a battery as a energy backup is proposed in [80]. The system block diagram is similar to the one shown in Figure 4.5. The P&O algorithm is performed in four regions according to the open-circuit voltage $V_{oc}$ of the PV panel: $0V \sim 0.25 \ V_{oc}$, $0.25 \ V_{oc} \sim 0.5 \ V_{oc}$, $0.5 \ V_{oc} \sim 0.75 \ V_{oc}$, and $0.75 \ V_{oc} \sim V_{oc}$. The result of performing P&O algorithm in four regions is the same as a global search, so the true MPP can be found even though partial shading occurs.

Maximizing the output current [78] or voltage [80] of the DC-DC converter requires fast output parameter measurements in the DC-DC converter and the MPPT algorithm with respect to the input current change of the H-bridge. Besides, noise filtering for $I_{out}$ or $V_{out}$ is necessary, meaning $I_{out}$ or $V_{out}$ must be sampled many times in very short time duration. These requirements might cause challenges for some low-cost microcontrollers and DSPs if the input current the H-bridge also changes fast.
4.3.2 Load: a resistor

The modified P&O MPPT control realized by maximizing the output voltage of the DC-DC converter without a battery as an energy backup is proposed in [79]. An output voltage reference $V_{ref}$ is set to adjust the output voltage $V_{out}$ of the DC-DC converter. Due to the lack of a battery as a buffer, noise filtering for $V_{out}$ based on averaging is also necessary in the control software. The average $V_{out}$ of the DC-DC converter is computed from 100 samples and compared to $V_{ref}$. The proposed MPPT algorithm in [79] is evaluated by to partial shading conditions: 1) cell-level shading and 2) string-level shading. The partial shading condition can be inferred by using additional sensors to sense each individual string voltage. The string voltage across the bypass diode will become negative if partial shading occurs on the string. With the help of the string voltage information, a 2-step MPPT algorithm combining conventional P&O and a global search is used to find the real MPP.

4.4 Tracking output current or voltage of the DC-DC converter?

According to the review presented in Sections 5.1–5.3, MPPT by tracking output current of the DC-DC converter is chosen in most literature [62-78], especially when there is a battery as a load or an energy backup [62-77]. The reason is that with a battery as a load, the output voltage of the DC-DC converter is almost constant. When there is no battery, MPPT can be realized by either maximizing the output current or the output voltage of the DC-DC converter [77-81].
Although using a battery as a load provides nearly constant output voltage of the DC-DC converter, care should be taken when there is another load connected in parallel with the battery. A heavy load might cause the battery to start discharging, making a voltage drop at the output of the DC-DC converter. If the load changes fast, the output voltage of the DC-DC converter will also change fast. In this case, the battery can no longer be considered as a constant-voltage source. So MPPT by tracking the output current of the DC-DC converter might encounter difficulties. This leads to the research that will be presented in Chapter 5.

Compared to tracking the output voltage of the DC-DC converter, tracking the output current provides the benefit that the outputs of multiple DC-DC converters can be connected in parallel. When tracking the output voltage of the DC-DC converter is chosen, the converter behaves like a voltage source. The outputs of several DC-DC converters cannot be connected in parallel because voltage sources cannot be connected in parallel. In contrast, tracking the output current of the DC-DC converter makes the converter be seen as a constant current source, and the outputs of several DC-DC converters can be connected in parallel to charge batteries or power loads. So increasing the output power rating of the DC-DC converter in a PV system can be implemented by simply connecting several converters in parallel. In Chapter 6, MPPT by tracking output current of four DC-DC converters in parallel will be presented.

### 4.5 Conclusion

In this chapter, MPPT techniques realized by maximizing the output current or voltage of the DC-DC converter are reviewed. It is shown that for most PV systems with batteries
as energy storage, tracking the output current of the DC-DC converter is widely adopted, whether implemented in analog or digital controllers. Tracking the output current provides the advantages of fewer sensors, simplified circuits, and ease of building a modular DC-DC converter using several converters in parallel to charge batteries or power loads.

A fast-changing load connected in parallel with batteries might cause problems when tracking only the output current of the DC-DC converter. Besides, for a modular DC-DC converter using several converters in parallel, the input power from PV panels is processed and distributed at the module level. Methods about how to properly implement distributed MPPT (DMPPT) need to be studied. The MPPT approaches for dealing with fast-changing loads and DMPPT will be presented in Chapter 5 and Chapter 6.
Chapter 5

A Maximum Power Point Tracking Method for PV Systems Supplying a Periodic Nonlinear Load

For most linear loads, finding the maximum power point (MPP) by using the traditional perturb-and-observe algorithm to track the maximum output current of the DC-DC converter in a PV system is a proven technique. However, when the load is nonlinear and exhibits negative impedance, traditional methods might no longer be applicable. This chapter presents a method to overcome this challenge. The proposed maximum power point tracking (MPPT) algorithm still only requires typically measured signals, yet is suitable for both linear and periodic nonlinear loads.

This chapter is organized as follows:

- In Section 5.1, traditional perturb-and-observe (P&O) algorithm is reviewed and the methods of finding MPP by tracking only one output parameter of the DC-DC converter, either the output voltage or the output current, are summarized.
• In Section 5.2, the effect of the periodic nonlinear load current ($I_{load}$) on tracking the output current ($I_{out}$) of the DC-DC converter is explained analytically and verified by both simulations and experiments. The $I_{out}$ oscillation resulting from the periodic nonlinear $I_{load}$ will cause the conventional P&O algorithm to fail, often converging to a less than optimal $I_{out}$ of the DC-DC converter.

• In Section 5.3, a modified P&O algorithm with extended perturbation period is proposed. A guideline for tracking $I_{out}$ of the DC-DC converter correctly, even when there is periodic nonlinear $I_{load}$, is given.

• In Section 5.4, the experimental results of the proposed MPPT algorithm are given. The experiments are carried out on a prototype micro-grid consisting of a buck-boost DC-DC converter, a DC electronic load, and a 12V (nominal voltage) battery. When the amplitude of periodic nonlinear $I_{load}$ is lower than $I_{out}$, the real MPP can easily be found. When the amplitude of periodic nonlinear periodic nonlinear $I_{load}$ is higher than $I_{out}$, it is difficult to find the real MPP. In the latter case, the modified P&O procedure with extended perturbation period is incorporated to successfully converge to the real MPP.

### 5.1 Review of perturb-and-observe (P&O) algorithm

Extensive research on maximum power point tracking (MPPT) techniques has been conducted to insure the photovoltaic (PV) arrays always provide the maximum power to the load [88]. Different MPPT algorithms can be implemented in the MPPT controller,
including perturb-and-observe (P&O) [69, 75, 85, 86], incremental conductance [87], fractional open-circuit voltage [88], fractional short-circuit current [88], fuzzy logic [89, 90], and neural network [91]. These techniques are usually implemented by using a power converter (DC-DC or DC-AC) to interface the PV array with the load. The input reference voltage $V_{ref}$ (or the duty cycle $d_C$ of the converter) of the power converter is then regulated by the rules defined in the MPPT algorithm. In actuality, the PV output power is not necessarily equal to the load power, and it is the energy at the load that is desired to be maximized. Specifically, the power converter between the panel and the load may exhibit nonlinear characteristics. Therefore, tracking the output power $P_{out}$ of the power converter is the true target of interest, as shown in Figure 5.1 (a) [77]. For most load types with non-negative impedance characteristics, such as a battery and a resistor, maximizing output voltage $V_{out}$ or output current $I_{out}$ of the power converter has proved equivalent to maximizing $P_{out}$ [76, 77], as shown in Figure 5.1 (b). By controlling only one of the output parameters $V_{out}$ or $I_{out}$, the hardware or software designed for MPPT can be simplified. Table 5.1 summarizes the literature review of adopting the concept of tracking $V_{out}$ or $I_{out}$. 
For most load types with non-negative impedance characteristics, such as a battery and a resistor, maximizing output voltage $V_{out}$ or current $I_{out}$ of the power converter has proved equivalent to maximizing $P_{out}$ \[76, 77\].

**Figure 5.1** For most load types with non-negative impedance characteristics, such as a battery and a resistor, maximizing output voltage $V_{out}$ or current $I_{out}$ of the power converter has proved equivalent to maximizing $P_{out}$ \[76, 77\].

**Table 5.1 The literature review of adopting the concept of tracking $V_{out}$ or $I_{out}$**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Analog/Digital</th>
<th>Track $V_{out}$ or $I_{out}$</th>
<th>Load</th>
<th>Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>[62-66, 68-70, 92]</td>
<td>Analog</td>
<td>$I_{out}$</td>
<td>Battery</td>
<td>Battery</td>
</tr>
<tr>
<td>[71-77, 81]</td>
<td>Digital</td>
<td>$I_{out}$</td>
<td>Battery, resistor, or a combination of both</td>
<td>Battery</td>
</tr>
<tr>
<td>[93]</td>
<td>Digital</td>
<td>$I_{out}$</td>
<td>DC/AC inverter feeding the grid</td>
<td>None</td>
</tr>
<tr>
<td>[79]</td>
<td>Digital</td>
<td>$V_{out}$</td>
<td>Boost converter feeding a resistor</td>
<td>None</td>
</tr>
<tr>
<td>[80]</td>
<td>Digital</td>
<td>$V_{out}$</td>
<td>Current source</td>
<td>None</td>
</tr>
</tbody>
</table>
In general, MPPT algorithms are often realized by either the positive-feedback (PF) method for analog circuits [62-66, 68-70, 92] or the P&O method for digital solutions, such as digital-signal-processor (DSP) and microcontroller unit (MCU) [71-75, 77, 79-81, 93, 94]. The principle of the P&O algorithm to track $I_{out}$ (or $V_{out}$) is explained as follows.

In P&O algorithm, the operating point of the PV panel is perturbed by increasing or decreasing duty ratio $d_C$ or $V_{ref}$ in control loop. This perturbation causes a small increase or decrease of $I_{out}$ (or $V_{out}$). The measured $I_{out}$ (or $V_{out}$) after the perturbation is compared with the $I_{out}$ (or $V_{out}$) measured before the perturbation. If the $I_{out}$ after the perturbation is higher than the $I_{out}$ before the perturbation, the algorithm continues perturbing $I_{out}$ (or $V_{out}$) in the same direction. Otherwise the algorithm perturbs $d_C$ or $V_{ref}$ in the reverse direction as in the previous perturbation.

The perturbation on $I_{out}$ (or $V_{out}$) is realized by directly or indirectly controlling the duty cycle $d_C$ of the DC-DC converter, as shown in Figure 5.2. For direct duty cycle control in Figure 5.2 (a), $d_C$ is the control parameter of the MPPT controller. For indirect duty cycle control in Figure 5.2 (b), the PV voltage $V_{in}$, controlled by a voltage reference $V_{refs}$, is the control parameter of the MPPT controller. The difference between $V_{in}$ and $V_{ref}$ is fed into the P, PI, or PID controller to adjust the duty cycle $d_C$ of the DC-DC converter so that $V_{in}$ equals $V_{ref}$. The voltage reference $V_{ref}$ is controlled by the MPPT controller so the indirect duty cycle control is also called reference voltage control. In this chapter, only the reference voltage control adopted to track $I_{out}$ in the P&O algorithm is discussed.
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The typical flow chart of the reference-voltage-control P&O algorithm is illustrated in Figure 5.3.

![Flow Chart](image)

**Figure 5.2** Block diagrams of (a) direct duty cycle control and (b) indirect duty cycle control (also called reference voltage control).

When the load is a battery, tracking $I_{out}$ is sometimes preferred because the output voltage of the power converter is clamped by the battery becoming a nearly constant-voltage source [62-66, 68, 70-74, 81, 92], making it more difficult to detect increasing or decreasing voltage. Methods of tracking $I_{out}$ and $V_{out}$ without a battery as the load have been reported in [79, 80, 93].
For micro-grid and grid-tie applications with battery backup, a complete PV system is made up of one or more PV arrays, a DC-DC converter, and a DC-AC inverter, as shown in Figure 5.4. Using batteries as energy storage enhances the reliability of the whole PV system. This chapter studies the feasibility of tracking MPP by tracking $I_{out}$ of the DC-DC converter in Figure 5.4, especially when the load current, $I_{load}$, is nonlinear and periodic,
such as modified-sine-wave inverters and pure-sine-wave inverters. When the amplitude of the periodic nonlinear $I_{load}$ is greater than $I_{out}$, the loads at the output of the DC-DC converter will exhibit large negative impedance, making the theorem proposed in [76, 77] inapplicable. This can often, therefore, confuse the MPPT controller.

5.2 Challenges of finding MPP when the load is nonlinear

5.2.1 The impact of $I_{load}$ on $I_{out}$

In this section, we consider the case of a solar PV system with battery backup, as shown in Figure 5.4. Power to the load can be supplied by the battery, PV, or both simultaneously. In Figure 5.4, if $I_{load} = 0$, then $I_{out}$ equals the charging current $I_B$. Let $V_B$
and \( R_B \) denote the open-circuit voltage and internal resistance of the battery, respectively. The output voltage \( V_{out} \) when \( I_{load} = 0 \) can be expressed in the following two forms:

\[
V_{out} = V_B + I_B \times R_B
\]  
\[
P_{out} = V_{out} \times I_{out}
\]

Because \( I_{out} \) equals the charging current \( I_B \) when \( I_{load} = 0 \), the relationship between \( I_{out} \) and \( P_{out} \) when \( I_{load} = 0 \) can be directly derived from (5-1) and (5-2):

\[
R_B \times I_{out}^2 + V_B \times I_{out} - P_{out} = 0
\]  
\[
I_{out} = \frac{-V_B + \sqrt{V_B^2 + 4R_B P_{out}}}{2R_B}
\]

Assuming \( V_B \) and \( R_B \) are constant, maximizing \( P_{out} \) is equivalent to maximizing \( I_{out} \). This claim still holds true if the battery is replaced by any nonlinear load, as long as the load has non-negative impedance (\( dI_{out} / dV_{out} \geq 0 \)), [77].

When \( I_{load} \neq 0 \), \( I_{out} \) can be derived from Kirchhoff’s Current Law (KCL):

\[
I_{out} = I_{load} + I_B
\]

The output voltage \( V_{out} \) when \( I_{load} \neq 0 \) can be expressed as follows:

\[
V_{out} = V_B + (I_{out} - I_{load}) \times R_B
\]

The relationship between \( I_{out} \) and \( P_{out} \) when \( I_{load} \neq 0 \) can be directly derived from (5-2) and (5-5):

\[
R_B \times I_{out}^2 + (V_B - I_{load} \times R_B) \times I_{out} - P_{out} = 0
\]
\[ I_{out} = \frac{-(V_B - I_{load}R_B) + \sqrt{(V_B - I_{load}R_B)^2 + 4R_B P_{out}}}{2R_B} \]  

(5-8)

From (5-7), it can be seen that \( I_{out} \) depends on both \( P_{out} \) and \( I_{load} \). Therefore, tracking the maximum \( I_{out} \) does not necessarily guarantee \( P_{out} \) is maximized. The derivative of \( I_{out} \) in (5-7) with respect to \( I_{load} \) is derived to understand the effect of \( I_{load} \) on \( I_{out} \):

\[ \frac{dI_{out}}{dI_{load}} = \frac{1}{2} \left[ 1 - \frac{(V_B - I_{load}R_B)}{\sqrt{(V_B - I_{load}R_B)^2 + 4R_B P_{out}}} \right] \]  

(5-9)

Figure 5.5 shows \( I_{out} \) and \( V_{out} \) with respect to \( I_{load} \) when \( P_{out} \) is fixed at different levels by assuming the PV arrays operate at MPP and the DC-DC converter is lossless. Figure 5.6 shows the derivative of \( I_{out} \) with respect to \( I_{load} \) at different \( P_{out} \) level.

Figure 5.5 Simulated \( I_{out} \) and \( V_{out} \) of the DC-DC converter with respect to \( I_{load} \).
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Figure 5.6 The derivative of $I_{out}$ with respect to $I_{load}$ at different $P_{out}$ levels. Assume PV arrays operate at MPP and the DC-DC converter is lossless.

According to (5-7), (5-8), Figure 5.5 and Figure 5.6,

- Increasing $I_{load}$ ($P_{out}$) while keeping $P_{out}$ ($I_{load}$) constant will make $I_{out}$ increase and $V_{out}$ decrease.

- When $P_{out}$ is low, the changes in $I_{load}$ have less impact on $I_{out}$.

- When $R_B$ is close to zero, $dI_{out}/dI_{load}$ approaches to zero, meaning the changes in $I_{load}$ have no impact on $I_{out}$. This can be achieved by paralleling more batteries.
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For example, typical load currents for portable PV-battery applications are shown in Figure 5.7 and Figure 5.8: pure-sine-wave inverter in Figure 5.7 and modified-sine-wave inverter in Figure 5.8. The period of $I_{load}$ is denoted as $T_L$ in both cases and the duty cycle of $I_{load}$ in Figure 5.8 is denoted as $d_L$. The typical $I_{out}$, which oscillates, is shown for both cases. The $I_{out}$ oscillation implies that the MPPT algorithm can fail if

(i) the changes in $I_{out}$ resulting from the P&O method ($\Delta I_{out}|_{P&O}$) are lower than that resulting from the change of load current ($\Delta I_{out}|_{NonlinearLoad}$);

(ii) $\Delta I_{out}|_{P&O}$ and $\Delta I_{out}|_{NonlinearLoad}$ have opposite signs;

(iii) the period of the P&O method is not chosen properly.

For example, assume the P&O starts at point A or C in Figure 5.1 (b). Tracking $I_{out}$ will lead to reverse direction or oscillation around point A or C, if the conditions (i)-(iii) are satisfied.

Figure 5.7 The effect of periodic nonlinear $I_{load}$ (pure-sine-wave inverter) on $I_{out}$. 
5.2.2 Simulations and experiments of $I_{\text{load}}$ effect

Simulations shown in Figure 5.9 are performed in order to understand the causes of failure in the MPPT convergence. Figure 5.10 and Figure 5.11 show the simulation results with and without periodic nonlinear $I_{\text{load}}$. The open-circuit voltage ($V_{\text{OC}}$), short-circuit current ($I_{\text{SC}}$), and MPP ($V_{\text{MPP}}$, $I_{\text{MPP}}$, $P_{\text{MPP}}$) of the solar panel assumed are $V_{\text{OC}} = 21.67\text{V}$, $I_{\text{SC}} = 5.46\text{A}$, and ($V_{\text{MPP}} = 18.05\text{V}$, $I_{\text{MPP}} = 5.13\text{A}$, $P_{\text{MPP}} = 92.6\text{W}$). A synchronous buck converter model is used in the simulation. Figure 5.10 shows the parameters of the solar panel and the duty cycle $d_C$ of the converter with respect to time when $I_{\text{load}} = 0$. The MPPT is carried out by tracking $I_{\text{out}}$. After $t = 0.011\text{s}$, the MPP is found at $I_{\text{out}} = 9.12\text{A}$ and $d_C = 0.5869$. This result means the operating point A in Figure 5.1(b) eventually moves to the point B. Figure 5.11 shows the parameters of the solar panel and the duty cycle $d_C$ of the converter with respect to time when $I_{\text{load}}$ is periodic and nonlinear. The MPPT is carried out by tracking $I_{\text{out}}$, which is the sum of the output current $I_o$ when $I_{\text{load}} = 0$ and the increment of the output current $\Delta I$ resulting from periodic nonlinear $I_{\text{load}}$. In Figure 5.11, $\Delta I$ is a square wave function with amplitude 0.05 times $I_o$, period 15 ms, and
duty cycle of its PWM is 50%. The correct duty cycle of the power converter $d_C$ (0.5869) cannot be found and it starts oscillating at $t = 0.001s$. In the end, the MPP is found incorrectly at $I_{out} = 1.12A$ and $d_C = 0.0557$ instead of the correct answer of $I_{out}$ and $d_C$. This means the operating point A in Figure 5.1(b) does not move to the point B and gets stuck nearby the point A itself.

Figure 5.9 Matlab/Simulink simulation performed in order to understand the causes of failure in the MPPT convergence.
Figure 5.10 Simulation results to understand the causes of failure in the MPPT convergence: Without the periodic nonlinear $I_{load}$, the real MPP is found at $I_{out} = 9.12A$. 
Figure 5.11 Simulation results to understand the causes of failure in the MPPT convergence: With the periodic nonlinear load, the MPP is found at $I_{\text{out}} = 1.12\text{A}$; the real MPP cannot be found because the correct duty cycle $d_C (0.5869)$ is not reached.
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It is simple to demonstrate how typical P&O algorithms are unable to converge to the proper MPP when $I_{load}$ changes. Consider Figure 5.4 with a 14.1V NiMH battery ($R_B = 0.15\Omega$) with a modified-sine-wave inverter as in Figure 5.8 with $I_{max} = 10A$. $P_{in}$ is provided by a small solar panel. The reference $I_{ref}$ set in the converter for controlling $I_{out}$ is intentionally set at a constant value, 3.4A. This constant-current setting is used to simulate the condition that the system operates at an arbitrary point on the curve in Figure 5.1 (b). The pulse current $I_{load}$ is generated by a DC electronic load with period $T_L = 15ms$ and the duty cycle $d_L$ of $I_{load}$ is 66.67%. Before $I_{load}$ is applied, $I_{out}$ is 3.33A, as shown in Figure 5.12. After $I_{load}$ is applied, $I_{out}$ becomes nonlinear and $I_{out}$ peak current at the rising and falling edges of $I_{load}$ is observed, as shown in Figure 5.13. In P&O algorithm, the input reference voltage $V_{ref}$ (or duty ratio $d_C$) is increased or decreased by $V_{ref}$ (or $d_C$), and then the $I_{out}$ may be observed. However, with nonlinear loads, the increase/decrease in $I_{out}$ could be due to the perturbation on $V_{ref}$ (or duty ratio $d_C$ of the DC-DC converter) or due to the load change. Therefore, the MPPT cannot tell exactly whether the power change is due to the load current or the perturbation on $V_{ref}$ (or duty ratio $d_C$ of the DC-DC converter). The MPPT may perturb $V_{ref}$ (or $d_C$) in the wrong direction causing the operating point to move away from the MPP.
Figure 5.12 Experimental measurements of $I_{out}$ and $V_{out}$ of the DC-DC converter with respect to time: Before periodic nonlinear $I_{load}$ is applied. Channel-1: Input voltage of the DC-DC converter (10V/div); Channel-2: Output current of the DC-DC converter (5A/div); Channel-3: Output voltage of the DC-DC converter (10V/div); Channel-4: Output power of the DC-DC converter (100W/div).
Figure 5.13 Experimental measurements of $I_{\text{out}}$ and $V_{\text{out}}$ of the DC-DC converter with respect to time: After periodic nonlinear $I_{\text{load}}$ is applied, $I_{\text{load}}$ with amplitude $I_{\text{max}} = 10\, \text{A}$, period $T_L = 15\, \text{ms}$, and duty cycle $d_L = 66.67\%$ is generated from a DC electronic load. Channel-1: Input voltage of the DC-DC converter (10V/div); Channel-2: Output current of the DC-DC converter (5A/div); Channel-3: Output voltage of the DC-DC converter (10V/div); Channel-4: Output power of the DC-DC converter (100W/div).
5.3 Method to minimize load switching effect on tracking maximum output current of the charger

Figure 5.8 and Figure 5.13 reveal that the behaviors of the $I_{out}$ waveform during each period $T_L$ have similar characteristics. These waveforms imply that the average output current $<I_{out}>$ in each $T_L$ should be the same. Therefore, by tracking $<I_{out}>$ during the period $T_L$ instead of tracking the single-point $I_{out}$, the effect of the load change on $I_{out}$ can be minimized. The increment/decrement $\Delta V_{ref}$ (or $\Delta d_C$) of the input reference voltage $V_{ref}$ (or duty ratio $d_C$) is ensured to be due to the perturbation, not the load change.

Specifically, the output current, $I_{out}$, used in the traditional P&O algorithm shown in Figure 5.3 has to be replaced by the average current $I_{avg} = <I_{out}>$, which is defined in (4), where $t_0$ is the arbitrary start time of the MPPT. The number $n$ is an integer and $m$ is the total sampling number during the period $nT_L$. The format of the number $m$ can be chosen as a power of two so that $I_{avg}$ can be derived from binary shift-right operation of $I_{sum}$ in the firmware programmed in the MCU. Or, to simplify, replace the $I_{out}$ used in the traditional P&O algorithm with the $I_{sum}$, which avoids the binary shift-right operation.

The flow chart of the modified P&O algorithm using (5-4) is illustrated in Figure 5.14.

$$
<I_{out}> = I_{avg} = \frac{\int_{t_0}^{t_0+nT_L} I_{out}(\lambda)d\lambda}{nT_L} = \frac{\sum_{k=0}^{m-1} I_{out}[t_0+k]}{m} \equiv \frac{I_{sum}}{m} \quad \text{(5-10)}
$$
The integer \( n \) in (5-4) should be large enough to minimize the load current effect but also has to be small enough to make tracking time in an acceptable range (less than a few seconds). Besides, the periodic nonlinear load with a specific switching frequency generates voltage variation at the battery’s terminal with the same frequency. For most of resistive loads, the frequency is 50 or 60 Hz, which means the load switching period \( T_L \) is a constant. It is easy to design a MPPT controller using (5-4) for a periodic nonlinear load with constant \( T_L \). However, if inductive loads are connected to the output of the DC-AC inverter, the frequency of the inductive loads might not be constant. So \( T_L \) is no longer constant. Therefore, methods of load frequency/period detection could be implemented into the MPPT controller to automatically calculate the necessary period \( T_{P&O} \) of each

Figure 5.14 The flow chart of the modified P&O algorithm using average output current \(< I_{out}>\).
perturb-and-observe procedure based on the load frequency. This approach assures that MPPT efficiency is always maximized even though $T_L$ is changing. The load frequency/period detection can be achieved by either time-domain or frequency-domain approach:

- **Time-domain approach:**
  a. Sample the battery’s terminal voltage in time domain. (Both DC and AC components are included.)
  b. Compute the average the voltage data (DC component is remained.)
  c. Subtract the average voltage from all the data. At this stage the data only contains the AC component.
  d. Calculate the time difference between zero crossing points of the voltage data containing only the AC component. $T_L$ equals to two times the time difference.

- **Frequency-domain approach:**
  a. Sample the battery’s terminal voltage in time domain. (Both DC and AC components are included.)
  b. Apply Fast Fourier transform (FFT) and then zero the voltage value associated with zero frequency (DC component).
  c. Apply inverse FFT to recover the voltage data without DC. At this stage the data only contains the AC component.
  d. Calculate the time difference between zero crossing points of the voltage data containing only the AC component. $T_L$ equals to two times the time difference.
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The period $T_{P&O}$ of each P&O procedure in the modified P&O algorithm should be long enough that $T_{P&O}$ equals $nT_L$. The necessary tracking time from point A to point B in Figure 5.1 (b) is proportional to $T_{P&O}(= nT_L)$ and the reciprocal of the increment $\Delta d_C$. A large number for the $T_{P&O}(= nT_L)$ or a small number for the $\Delta d_C$ will lead to very long tracking time. For example, the period $T_L$ of $I_{load}$ shown in Figure 5.7 and Figure 5.8 is 15ms. The minimum $T_{P&O}$ is 15ms when $n = 1$. If $\Delta d_C = 0.0001$, as the increment value used in Figure 5.10 and Figure 5.11, the total tracking time from $d_C = 0$ to $d_C = 0.5869$ will be 88s, which is too long. If $\Delta d_C$ used in Figure 5.10 and Figure 5.11 is enlarged a hundred times, the total tracking time will be reduced to 0.88s, which is acceptable.

In this section, a modified P&O algorithm with extended perturbation period $T_{P&O}$ is proposed. Instead of tracking $I_{out}$, the modified P&O algorithm tracks $I_{sum}$, which ultimately leads to the real MPP. Compared to the conventional P&O algorithm tracking only the output current $I_{out}$ of the converter, the proposed MPPT procedure maintains the simplicity of tracking only the output current while avoiding the effect of the load change when the load current is periodic and nonlinear.

5.4 Experimental Results

The experimental setup, as shown in Figure 5.15, is built with a buck-boost DC-DC converter and a DC electronic load to simulate the modified-sine-wave inverter load that produces load current, as shown in Figure 5.8. The input voltage range of the converter is 8-40V. The open-circuit voltage and the short-circuit current of the PV panel used in this
experiment are 38.6V and 1.14A, respectively. Several halogen lamps are used to simulate the indoor sunlight source. NiMH battery is used with resting voltage \( V_B \) and the internal resistance \( R_B \) of 14.1V and 0.15Ω, respectively.

Figure 5.16 shows the output current and input voltage of the converter with respect to the duty cycle \( d_C \) of the buck converter when the converter operates in buck mode, measured by manually setting a fix duty ratio ranging from 18% to 56% with 2% step. For \( V_{out} = 14.1V \), the MPP is obtained when the duty ratio of the buck converter is 42% and the corresponding input voltage of the converter is 34.51V. On the other hand, \( V_{out} = 13V \) is achieved by applying a 6.67A constant-current load to the battery. The MPP is obtained when the duty ratio \( d_C \) of the buck converter is 42% and the corresponding input voltage of the converter is 32.44V.

![Diagram of experimental setup for testing the proposed P&O MPPT algorithm with constant current load and periodic nonlinear load.]

Figure 5.15 The experiential setup for testing the proposed P&O MPPT algorithm with constant current load and periodic nonlinear load.
Figure 5.16 The output current and input voltage of the converter with respect to the duty ratio when the converter operates in buck mode, measured by setting a fix duty ratio from 18% to 56% with 2% step.

Figure 5.17 shows the input voltage $V_{in}$, the input reference voltage $V_{ref}$, the duty cycle $d_C$ of the converter, and the output current $I_{out}$ of the converter when MPPT is carried out by the P&O algorithm during a time interval of 147s. The period $T_{P&O}$ between two perturbations on $V_{in}$ is 15ms, during which $I_{out}$ is sampled 64 times and $I_{sum}$ is calculated according to (5-4), which is repeated in (5-11), with $m = 64$, $T_L = 15ms$, and $n = 1$. 

![Diagram showing output current and input voltage vs. duty ratio](image-url)
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\[
\langle I_{out} \rangle = I_{avg} = \frac{\int_{t_0}^{t_0+nT_L} I_{out}(\lambda) d\lambda}{nT_L} = \frac{\sum_{k=0}^{m-1} I_{out}[t_0 + k]}{m} = \frac{I_{sum}}{m}
\]

(5-11)

\[
\frac{15ms}{t_0=0} = \frac{\int_{0}^{15ms} I_{out}(\lambda) d\lambda}{15ms} = \frac{\sum_{k=0}^{63} I_{out}[k]}{64} = \frac{I_{sum}}{64}
\]

- Period 1 (0 s ~ 56 s): \(I_{load}\) is zero. \(I_{out}\) is constant and equals to the charging current of the battery.

- Period 2 (56 s ~ 93 s): \(I_{load}\) is positive and with amplitude \(I_{max} = 10A\), period \(T_L = 15ms\), and duty cycle \(d_L = 66.67\%\). The duty cycle \(d_L = 66.67\%\) implies the average load current is \(\langle I_{load}\rangle = 6.67A\). \(I_{out}\) oscillates because of the oscillating load current \(I_{load}\).

- Period 3 (93 s ~ 147 s): \(I_{load}\) is zero. \(I_{out}\) is constant and equals to the charging current of the battery. \(I_{out}\) is constant and equals to the charging current of the battery.

According to Figure 5.16, \(V_{in}\) at the MPP should be close to 34.51V when the average load current \(\langle I_{load}\rangle = 0\) and close to 32.44V when \(\langle I_{load}\rangle = 6.67A\) is applied. When \(\langle I_{load}\rangle = 0\), \(V_{in}\) oscillates around 34.51V. However, when there is a periodic load current with \(\langle I_{load}\rangle = 6.67A\), \(V_{in}\) does not oscillate around 32.44V and the minimum \(V_{in}\) is 26.22V, which is far away from the MPP. This indicates that \(n = 1\) is too small for MPP convergence and should, therefore, be increased.
Figure 5.17 The input voltage $V_{in}$, the input reference voltage $V_{ref}$, the duty cycle $d_C$ of the converter, and the output current $I_{out}$ of the converter when MPPT is carried out by the P&O algorithm. The time interval is 147s. $I_{load}$ is zero during 0–56s and 93–147s, and a periodic load current with $<I_{load}> = 6.67\, \text{A}$ with period $T_L = 15\, \text{ms}$ and duty cycle $d_L = 66.67\%$ is applied during 56–93s. Case 1: $T_{P&O} = 15\, \text{ms}$, $m = 64$, $T_L = 15\, \text{ms}$, and $n = 1$. 
Figure 5.18 shows $V_{in}$, $V_{ref}$, $d_C$, and $I_{out}$ of the converter when the period $T_{P&O}$ between two perturbations is extended to 120ms, during which $I_{out}$ is sampled 64 times and the corresponding $I_{sum}$ is calculated according to (4), which is repeated in (6), with $m = 512$, $T_L = 15ms$, and $n = 8$.

$$
\langle I_{out} \rangle = I_{avg} = \frac{t_o + \pi T_L}{nT_L} = \frac{\sum_{k=0}^{m-1} I_{out}[t_0 + k]}{m} = \frac{I_{sum}}{m}
$$

(6)

- **Period 1** (0 s ~ 56 s): $I_{load}$ is zero. $I_{out}$ is constant and equals to the charging current of the battery.
- **Period 2** (56 s ~ 93 s): $I_{load}$ is positive and with amplitude $I_{max} = 10A$, period $T_L = 15ms$, and duty cycle $d_L = 66.67\%$. The duty cycle $d_L = 66.67\%$ implies the average load current is $<I_{load}> = 6.67A$. $I_{out}$ oscillates because of the oscillating load current $I_{load}$.
- **Period 3** (93 s ~ 147 s): $I_{load}$ is zero. $I_{out}$ is constant and equals to the charging current of the battery. $I_{out}$ is constant and equals to the charging current of the battery.

During the period when $<I_{load}> = 0$, $V_{in}$ oscillates around 34.8V, which is close to 34.51V indicated in Figure 5.16. When a periodic load current with $<I_{load}> = 6.67A$ is applied, $V_{in}$ oscillates around 32.99V, which is close to 32.44V indicated in Figure 5.16. So the oscillation around the MPP is improved qualitatively when the periodic $I_{load}$ is applied.
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The input voltage \( V_{\text{in}} \), the input reference voltage \( V_{\text{ref}} \), the duty cycle \( d_C \) of the converter, and the output current \( I_{\text{out}} \) of the converter when MPPT is carried out by the P&O algorithm. The time interval is 147s. \( I_{\text{load}} \) is zero during 0–56s and 93–147s, and a periodic load current with \(<I_{\text{load}}> = 6.67\text{A}\) with period \( T_L = 15\text{ms} \) and duty cycle \( d_L = 66.67\% \) is applied during 56–93s. Case 2: \( T_{\text{P\&O}} = 120\text{ms}, m = 512, T_L = 15\text{ms}, \) and \( n = 8 \).

The improvement on MPPT efficiency during the period 2 in Figure 5.17 and Figure 5.18 can be expressed qualitatively using root-mean-square deviation (RMSD) as below:
Chapter 5

\[
RMSD(V_{in}) = \sqrt{\frac{\sum_{p=1}^{q}[V_{in}(p) - V_{MPP}]^2}{q}} \tag{5-12}
\]

where \( V_{MPP} \) is 32.44V, \( q \) denotes the number of total samples of \( V_{in} \), and \( V_{in}(p) \) denotes the \( p \)th sample of input voltage \( V_{in} \). The RMSD is used to measure how close the \( V_{MPP} \) is to those \( V_{in} \) data points. According to (5-12), the RMSD (\( V_{in} \)) during Period 2 (56 s ~ 93 s) in Figure 5.17 is 2.8785 V while the RMSD (\( V_{in} \)) during the same period in Figure 5.18 is 1.1181 V. The much smaller RMSD in Figure 5.18 indicates that extending \( T_{P&O} \) from 15 ms to 120 ms significantly improve the MPPT efficiency.

To improve the \( V_{in} \) oscillation further, the perturbation period \( T_{P&O} \) can be extended longer than 120ms. However, it will also increase the settling time at the beginning of the P&O procedure. The zero-start settling time at the beginning of the P&O procedure shown in Figure 5.18 is 3s.

5.5 Conclusions

This chapter discloses challenges of MPPT when sensing only the output current and nonlinear periodic nonlinear loads. The periodic nonlinear load current will cause the output current \( I_{out} \) to oscillate and makes finding MPP by tracking only the \( I_{out} \) via the conventional P&O algorithm problematic. This chapter presents simulation and experimental results to explain the essence of the problem and support the validity of a modified MPPT method. The analysis becomes important when the load has negative impedance.
Chapter 6

Prototype for portable microgrid

In this chapter, a low-power (150W) portable microgrid and a medium-power (600W) portable microgrid are presented. They are designed using the research results presented in preceding chapters, built jointly with PowerFilm Inc., and tested by U.S. Army Natick Soldier Systems Center. Both systems provide a convenience of powering 12/24 V DC and 120 V AC loads simultaneously while charging one or multiple batteries using foldable solar panels or high-power energy source. The unique functions and features fulfill the demands of modern soldiers in battle fields or remote areas.

Details of the individual charger in the low-power portable microgrid are presented in this chapter first. Then the medium-power portable microgrid is presented. Four individual chargers are operated in parallel so the input power is distributed, improving the system’s redundancy. The medium-power system is designed for soldiers who want a plug-and-play battery power system that allows different state-of-charge batteries to seamlessly operate together. One of its unique features is that the system can operate even though the batteries connected in parallel are different.
Chapter 6

Methods of the maximum power point tracking (MPPT) realized in both systems are also presented. A new MPPT approach dedicated to the situation that uniform input power sharing among parallel DC-DC converters is not required is also presented in this chapter.

This chapter is organized as follows:

- In Section 6.1, a commercial-grade prototype of a low-power (150W) portable microgrid is presented. This portable microgrid consists of a single buck-boost DC-DC converter and a single DC-AC inverter. Functions, features, operation of the buck-boost DC-DC converter, and realization of MPPT are introduced.

- In Section 6.2, a prototype of a medium-power (600W) portable microgrid is presented, including its functions, features, and operation. This portable microgrid is designed and built according to the system architecture presented in Chapter 3. It consists of four buck-boost DC-DC converter modules in parallel. The concept of distributed MPPT (DMPPT) for uniform and non-uniform input power sharing is also introduced.

- In Section 6.3, a new approach to efficiently track the desired maximum power point for photovoltaic systems under partial shading conditions is presented. This approach is suitable for DMPPT when uniform input power sharing among parallel converters is not required. By taking advantage of fast current change, the control scheme effectively combines perturb-and-observe (P&O) tracking and periodic global maximum power point (MPP) searching, and fulfills fast tracking as well as maintaining ease of implementation even though partial shading on solar panels occurs.
6.1 Single charger in a low-power (150 W) portable microgrid

The product of the low-power portable microgrid is an individual “universal” power source for a soldier to carry in his backpack. This microgrid utilizes the military BB390 NiMH or BB2590 lithium-ion battery for energy storage. It provides a soldier two DC outputs and one AC output even while charging a battery: 12/24 V DC output, and 120 V AC output. When 120 V AC output is chosen, the system also provides 24 V DC output.

This portable microgrid consists of a single DC-DC converter/charger and a single DC-AC micro-inverter. The charger inside the portable microgrid features a buck-boost configuration with purely digital controller for maximum power point tracking (MPPT), battery charging/discharging regulation, and energy flow control. The details about the single charger inside this portable microgrid are presented as follows.

6.1.1 Functions and features

Figure 6.1 shows the low-power portable microgrid consisting of a single DC-DC converter/charger and a single DC-AC micro-inverter. The charger in this microgrid provides the following characteristics the same as the ones in previous work [95]:

- MPPT keeps solar panel at optimal power producing point at all times – for fastest charging.
• Either BB2590 (lithium-ion) or BB390 (NiMH) battery with two independent legs is accepted as an energy storage. Either a dumb (without SMBus) or a smart BB2590 (with SMBus) is accepted.

• A solar panel, DC power supply, or Humvee battery can be used as an input energy source to charge a battery.

• Input DC voltage range of the charger: 8-40 V.

• PWM switching frequency: 200 kHz.

The charger also provides the following new-added features and different characteristics from previous work [95]:

• MPPT keeps solar panel at optimal power producing point at all times even if the load is periodically changing.

• An input energy source can be used to power the inverter while charging a battery (power pass-through).

• When the load is heavy, both the input energy source and the battery provide power to the load.

• Parallel/Series mode is selectable. The two independent battery legs of BB2590 or BB390 are automatically connected in parallel or series by detecting the type of the cable connected to the output of the charger.

• When a DC-AC micro-inverter (input voltage range 22-33 V) is connected to the output of the charger, the two independent battery legs of BB2590 or BB390 are automatically connected in series mode.
• The charger implements the SMBus protocol for communication between the microcontroller and a smart BB2590 lithium-ion battery with SMBus-compatible battery fuel gauge.

• Output DC voltage range of the charger: 10-16.5 V in parallel mode; 20-33 V in series mode.

• Maximum output current of the charger: 3.6 A in parallel mode; 1.8 A in series mode.

• Maximum output power of the charger: 59.4 W (3.6A @ 16.5 V or 1.8A @ 33 V).

• Output current resolution: ± 50 mA.

• Output voltage resolution: ± 35.75 mV.

• Input voltage resolution: ± 45.45 mV.

• Sampling rate: 180 μs.

• A/D conversion resolution: 10 bits.

Figure 6.1 A 150W portable microgrid served as an individual “universal” power source for a soldier to carry in his backpack.
6.1.2 Parallel/Series mode selection

The charger provides a soldier two DC output source options even while charging a battery: 12 V or 24 V DC output, which is determined by connecting two battery legs in parallel or series. When an inverter is connected to the output of the charger, the operating mode automatically switches to series mode because the input voltage range of the inverter is 22-33 V. Switching between parallel and series modes is achieved by sensing if there is a “parallel/series” connector or an inverter connected to the output of the charger.

There are four switches used in the charger to realize parallel/series operating mode, as shown in Figure 6.2. $S_1$ and $S_2$ are bi-directional switches consisting of two back-to-back PMOSFETs. $S_3$ and $S_4$ are switches consisting of only one NMOSFET. When parallel mode is selected, the switches $S_1$, $S_2$, and $S_4$ are closed and $S_3$ is open. So the two battery legs are connected in parallel. When series mode is selected, the switches $S_2$ and $S_3$ are closed while $S_1$ and $S_4$ are open. So the two battery legs are connected in series.

The parallel/series mode selection is realized by detecting the existence of a “parallel” connector, a “series” connector, or a DC-AC micro-inverter. Figure 6.3 illustrates the control circuit for parallel/series mode detection. The charger uses one digital output (PORTA.4) and two digital inputs (PORTC.5 and PORTB.4) of a microcontroller to determine parallel or series operating mode. The digital output PORTA.4 always generates a 10 Hz square wave signal with duty ratio 50% and is connected to pin 2 of J5 through a 10 kΩ resistor. The digital input PORTC.5 is also connected to pin 2 of J5.
through a 10 kΩ resistor. The digital input PORTB.4 is connected to pin 1 of J5 through a 10 kΩ resistor. There exists four possible configurations:

- **Case 1**: There is neither a “parallel/series” connector nor an inverter connected to the output of the charger. The two battery legs are connected in parallel and provides a 12V (nominal) output when 1) The logic state sensed by the digital input PORTC.5 is the same as that generated from the digital output PORTA.4; 2) The logic state sensed by the digital input PORTB.4 is logic 1 because pin 1 of J5 is connected to 5 V through a 75 kΩ resistor.

- **Case 2**: A “parallel” connector is connected to the output of the charger and pin 2 of J5 is connected to pin 4 of J5. The two battery legs are connected in parallel and provides a 12V (nominal) output when 1) The logic state sensed by the digital input PORTC.5 is logic 0 because pin 2 and pin 4 of J5 are connected; 2) The logic state sensed by the digital input PORTB.4 is logic 1 because pin 1 of J5 is connected to 5 V through a 75 kΩ resistor.

- **Case 3**: A “series” connector is connected to the output of the charger and pin 2 of J5 is connected to pin 3 of J5. The two battery legs are connected in series and provides a 24V (nominal) output when 1) The logic state sensed by the digital input PORTC.5 logic 1 because pin 2 and pin 3 of J5 are connected; 2) The logic state sensed by the digital input PORTB.4 is logic 1 because pin 1 of J5 is connected to 5 V through a 75 kΩ resistor.

- **Case 4**: A DC-AC inverter is connected to the output of the charger and pin 1 of J5 is connected to pin 4 of J5. The two battery legs are connected in series and provide a 24V (nominal) output when 1) The logic state sensed by the digital input PORTC.5 is
the same as that generated from the digital output PORTA.4; 2) The logic state sensed by the digital input PORTB.4 is logic 0 because pin 1 and pin 4 of J5 are connected.

Figure 6.2 The switches for parallel/series mode selection.

Figure 6.3 The principle of parallel/series mode detection.
6.1.3 Power flow control

Figure 6.4 shows a system including a DC input energy source, a charger, a battery (with two legs), and a DC load when the system operating in parallel mode. $I_1$ and $I_2$ denote charging currents of leg-1 and leg-2 when the switches $S_1$ and $S_2$ are closed. $I_L$ denotes the load current. Depending on the load condition, three power flow states are defined as below: no load, light load, and heavy load.

- **State 1 (No load):** In this mode, $I_L = 0$ because there is no load. The input energy is used to charge the battery. So $I_1 > 0$ and $I_2 > 0$.

- **State 2 (Light load):** In this mode, $I_L > 0$ but is not heavy. The input energy is used to power the load while charging the battery (power pass-through). So $I_1 > 0$ and $I_2 > 0$.

- **State 3 (Heavy load):** In this mode, $I_L > 0$ and is heavy. The input energy is not large enough to power the load. The battery has to discharge to share the load demand. So $I_1 < 0$ and $I_2 < 0$. 
The charger always measures $I_1$, $I_2$, and $I_L$ to monitor the power flow state and open the switches $S_1$ and/or $S_2$ to prevent from over-charging or over-discharging when necessary. It also computes the output current $I_{out}$ of the charger, which equals to the sum of $I_1$, $I_2$, and $I_L$. When the charger is able to provide output current higher than 3.6 A, the output current will be limited at constant 3.6 A to ensure the output power of the charger does not exceed its power rating (~60 W).

### 6.1.4 Topology

The buck-boost converter is modified from previous work [95]. The reason why buck-boost topology is chosen is that both input and output of the charger have large voltage
variation: input between 8 V and 40 V; output between 10 V and 16.5V in parallel mode and between 20 V and 33V in parallel mode.

The buck-boost converter contains four switches, two capacitors, and an inductor, as the schematic shown in Figure 6.5. When $V_{in}$ is greater than $V_{out}$, the switch $Q_8$ is open. The switches $Q_5$ and $D_3$ operate as in a standard asynchronous buck converter. When $V_{in}$ is less than $V_{out}$, the switch $Q_5$ is closed. The switches and $Q_8$ and $D_2$ operate as in a boost converter. The output of the converter is split into three branches: one connected to the load (through a current sense resistor $U_1$) and the other two connected to the two battery legs (through a bi-directional switch $Q_1/Q_2$ or $Q_6/Q_7$ and a current sense resistor $U_2$ or $U_3$).

![Figure 6.5 Schematic of the buck-boost converter.](image)

The charger consists of two separate PCBs connected through two inner connectors: 1) Control board: components for sensing, PWM/LED/switch control, and communication are integrated on the control board. 2) Power board: components for power conversion and high-current sensing are integrated on the power board. The control board and the power board are separated in order to improve heat dissipation. Figure 6.6 shows the top view and bottom view of the control board and the power board.
Figure 6.6 (a) Top view of the control board. (b) Top view of the power board. (c) Bottom view of the control board and the power board. The two boards are connected through two inner connectors.
6.1.5 The state machine operation

A state machine with multiple sequential logic states is programmed in the charger to control ON/OFF states of the switches $S_1$ and $S_2$ shown in Figure 6.2 and the charging process. The state machine is a low-level routine that is executed every 5 s. Different state machines are designed for BB2590 lithium-ion battery and BB390 NiMH battery. When operating in parallel mode, the state machine is similar to the one designed in previous work [95]. When operating in series mode, the state machine degenerates to a simplified form with less sequential logic states. The details of the state machine and new elements added are summarized as below.

6.1.5.1 BB390 NiMH battery in parallel mode

The state machine for BB390 NiMH battery in parallel mode is shown in Figure 6.7 (a). There are seven sequential logic states in the state machine and are described as below in a specific sequence:

- **State 0:** The system first confirms the two battery legs are in parallel configuration and the battery type is NiMH. If a primary battery is connected or there is no battery connected to the charger, the state machine will always stay in this state and the DC-DC converter will not be turned on. Input voltage under 6.67 V also makes the state machine stay in this state. In this initial state, the DC-DC converter is always turned off. The switch $S_1$ is open and $S_2$ is closed.

- **State 6:** If there is a voltage mismatch between two battery legs’ voltages $V_{B1}$ and $V_{B2}$, and $V_{B1} > V_{B2}$, the state machine will leave state 0 and enter state 6 to start charging
only the battery leg-2. In this state, the DC-DC converter is turned on. The switch $S_1$ is open and $S_2$ is closed.

- **State 5**: If there is a voltage mismatch between two battery legs’ voltages $V_{B1}$ and $V_{B2}$, and $V_{B1} < V_{B2}$, the state machine will leave state 0 and enter state 5 to start charging only the battery leg-1. In this state, the DC-DC converter is turned on. The switch $S_1$ is closed and $S_2$ is open.

- **State 3**: If there is no voltage mismatch between two battery legs’ voltages $V_{B1}$ and $V_{B2}$, the state machine will leave states 5 or 6 and enter state 3 to start charging both battery legs. In this state, the DC-DC converter is turned on. The switches $S_1$ and $S_2$ are closed.

- **State 2**: If the temperature derivative $dT_2/dt$ of battery leg-2 rises above the threshold, the state machine will leave state 3 and enter state 2 to start charging only the battery leg-2. In this state, the DC-DC converter is turned on. The switch $S_1$ is open and $S_2$ is closed.

- **State 1**: If the temperature derivative $dT_1/dt$ of battery leg-1 rises above the threshold, the state machine will leave state 3 and enter state 1 to start charging only the battery leg-1. In this state, the DC-DC converter is always turned on. The switch $S_1$ is closed and $S_2$ is open.

- **State 4**: If the temperature difference derivative $d(T_1-T_2)/dt$ or $d(T_2-T_1)/dt$ rises above the threshold, the state machine will leave states 1 or 2 and enter state 4 to charge both battery legs with a fixed low current. In this state, the DC-DC converter is turned on. The switches $S_1$ and $S_2$ are closed.
6.1.5.2 BB2590 lithium-ion battery in parallel mode

The state machine for BB2590 lithium-ion battery in parallel mode is shown in Figure 6.7 (b). There are five sequential logic states in the state machine and are described as below in a specific sequence:

- **State 0**: The system first confirms the two battery legs are in parallel configuration and the battery type is lithium-ion. If a primary battery is connected or there is no battery connected to the charger, the state machine will always stay in this state and the DC-DC converter will not be turned on. Input voltage under 6.67 V also makes the state machine stay in this state. In this initial state, the DC-DC converter is always turned off. The switch $S_1$ is open and $S_2$ is closed.

- **State 6**: If there is a voltage mismatch between two battery legs’ voltages $V_{B_1}$ and $V_{B_2}$, and $V_{B_1} > V_{B_2}$, the state machine will leave state 0 and enter state 6 to start charging only the battery leg-2. In this state, the DC-DC converter is turned on. The switch $S_1$ is open and $S_2$ is closed.

- **State 5**: If there is a voltage mismatch between two battery legs’ voltages $V_{B_1}$ and $V_{B_2}$, and $V_{B_1} < V_{B_2}$, the state machine will leave state 0 and enter state 5 to start charging only the battery leg-1. In this state, the DC-DC converter is turned on. The switch $S_1$ is closed and $S_2$ is open.

- **State 3**: If there is no voltage mismatch between two battery legs’ voltages $V_{B_1}$ and $V_{B_2}$, the state machine will leave states 5 or 6 and enter state 3 to start charging both battery legs. The charger uses a constant current (CC) to charge the battery until $V_{B_1}$ and $V_{B_2}$ reach 16.5V. When battery voltage reaches 16.5V, the charger reduces the output


reference current $I_{\text{ref}}$ to keep the battery voltage under 16.5V. In this state, the DC-DC converter is turned on. The switches $S_1$ and $S_2$ are closed.

- **State 4:** If the reference current $I_{\text{ref}}$ is under a threshold current of each battery leg, the battery is considered as fully charged. The state machine will leave state 3 and enter state 4 to stop charging both battery legs. In this state, the DC-DC converter is turned off. The switches $S_1$ and $S_2$ are closed.

![Figure 6.7](image-url) (a) The state machine for BB390 NiMH battery in parallel mode. (b) The state machine for BB2590 lithium-ion battery in parallel mode.

### 6.1.5.3 BB390 NiMH battery in series mode

The state machine for BB390 NiMH battery in series mode is shown in Figure 6.8 (a). Because the switch $S_1$ is always open in series mode, the state machine degenerates from the one shown in Figure 6.7 (a) to having just four states. They are described as below in a specific sequence:
• \textit{State 0}: The same as the state 0 described in Section 6.1.5.1.

• \textit{State 6}: If the battery type is NiMH and battery status is okay, the state machine will leave state 0 and enter state 6 to start charging both battery legs in series mode. In this state, the DC-DC converter is turned on. The switch $S_1$ is open and $S_2$ is closed.

• \textit{State 2}: If the temperature derivative $dT_1/dt$ of battery leg-1 or $dT_2/dt$ of battery leg-2 rises above the threshold, the state machine will leave state 6 and enter state 2. A 10-minute timer is used to determine if the high $dT_1/dt$ or $dT_2/dt$ maintains for longer than 10 minutes. If the high $dT_1/dt$ or $dT_2/dt$ cannot maintain for 10 minutes, the state machine will go back to state 6. In state 2, the DC-DC converter is turned on. The switch $S_1$ is open and $S_2$ is closed.

• \textit{State 4}: If the high $dT_1/dt$ or $dT_2/dt$ maintains for longer than 10 minutes in state 2, the state machine will leave state 2 and enter state 4 to charge both battery legs in series mode with a fixed low current. In this state, the DC-DC converter is turned on. The switch $S_1$ is open and $S_2$ is closed.

\subsection*{6.1.5.4 BB2590 lithium-ion battery in series mode}

The state machine for BB2590 lithium-ion battery in \textit{series} mode is shown in Figure 6.8 (b). Because the switch $S_1$ is always open in series mode, the state machine degenerates from the one shown in Figure 6.7 (b) to having just three states. They are described as below in a specific sequence:

• \textit{State 0}: The same as the state 0 described in Section 6.1.5.2.
• **State 6:** If the battery type is lithium-ion and battery status is okay, the state machine will leave state 0 and enter state 6 to start charging both battery legs in series mode. The charger uses a constant current (CC) to charge the battery until one of \( V_{B1} \) and \( V_{B2} \) reaches 16.5V. When one of the battery voltages reaches 16.5V, the charger reduces the output reference current \( I_{ref} \) to keep that battery voltage under 16.5V. In this state, the DC-DC converter is turned on. The switch \( S_1 \) is open and \( S_2 \) is closed.

• **State 4:** If the reference current \( I_{ref} \) is under a threshold current, the battery is considered as fully charged. The state machine will leave state 6 and enter state 4 to stop charging the battery legs. In this state, the DC-DC converter is turned off. The switch \( S_1 \) is open and \( S_2 \) is closed.

![Diagram](image)

Figure 6.8 (a) The state machine for BB390 NiMH battery in series mode. (b) The state machine for BB2590 lithium-ion battery in series mode. The state machine degenerates from the one shown in Figure 6.7.
6.1.5.5 Load detection

According to the power flow shown in Figure 6.4, a battery can be charged when there is no load or a light load. So a battery can be fully charged and the state machine enters state 4 when there is no load or a light load. When the load becomes so heavy that it requires more current than the output current the charger can deliver, the battery starts discharging. For BB390 NiMH battery, when the load is connected and increases to make battery voltage lower than the threshold $V_{\text{th,NiMH}}$, the state machine will leave state 4 and enter state 0 to restart the system, as shown in Figure 6.7 (a) and Figure 6.8 (a). For BB2590 lithium-ion battery, when the load is connected and increases to make battery voltage lower than the threshold $V_{\text{th,Li-ion}}$, the state machine will leave state 4 and enter state 0 to restart the system, as shown in Figure 6.7 (b) and Figure 6.8 (b).

6.1.6 Maximum power point tracking

The charger proposed in previous work [95] presents a PV system with battery backup but no load is connected. Hence tracking maximum output power can be achieved by tracking the maximum charging current. The charger discussed in this chapter is applicable to more generalized case in which a resistive load is connected in parallel with the battery. The maximum output power is achieved by maximizing the output current of the charger, which equals to the sum of charging current and load current.

When a DC-AC inverter (modified-sine-wave inverter or pure-sine-wave inverter) is connected to the output of the charger, it generates a periodic nonlinear load to the
charger and the battery. The traditional methods for maximum power point tracking (MPPT) might fail due to the periodic nonlinear load [96]. Two MPPT approaches for maximizing output current have been implemented in the charger to deal with a periodic nonlinear load: 1) modified perturb-and-observe (P&O); 2) globally scanning with output current filtering. The former approach has been presented in [96] and Chapter 6. The latter is discussed as below.

The implementation of MPPT for maximizing output current is achieved by periodically globally scanning the entire range of the input voltage $V_{in}$ of the dc-dc converter (the output voltage of the PV panel) and recording the output current $I_{out}$ of the converter based on the input reference voltage $V_{ref}$. The regulation on $I_{out}$ is realized by indirectly controlling the duty cycle $d_C$ of the DC-DC converter, as shown in Figure 6.9. The input voltage $V_{in}$ of the DC-DC converter, controlled by a reference voltage $V_{ref}$, is the control parameter of the MPPT controller. The difference between $V_{in}$ and $V_{ref}$ is fed into the P, PI, or PID controller to adjust the duty cycle $d_C$ of the DC-DC converter so that $V_{in}$ equals $V_{ref}$. The output current $I_{out}$ is sampled and filtered. The filtered $I_{out}$ is stored in the MPPT controller. The voltage $V_{MPP}$ at the maximum output current point $I_{MPP}$ is found after each scan and the charger will keep $V_{in} = V_{ref}$ until the next scan is launched.
Figure 6.9 The duty cycle $d_C$ of the DC-DC converter is indirectly controlled by adjusting input reference voltage $V_{ref}$. The output current $I_{out}$ is sampled $N$ times and filtered.

Adopting the scanning method gives two major advantages in practice. First, it is easy to implement in the microcontroller. Second, in case of partial shading on the PV panel, which probably leads to multiple local MPPs, it is a reliable way to find the global MPP. The major disadvantage, however, is the inevitable power loss due to the interrupt for scanning during normal operation of DC-DC converter. This problem can be mitigated by shorting the scanning time by either reducing the sampling time or reducing the number of sampling data while keeping the acceptable data resolution.

The global MPPT scan begins at $V_{ref} = 40$ V and ends at $V_{ref} = 8$ V in a descending manner while the voltage step $\Delta V_{ref}$ during the scan is 0.227 V. The charger performs MPPT scan every 2 minutes and each scan takes less than 2 seconds.
6.2 Parallel chargers in a medium-power (600W) portable microgrid

The product of low-power (600 W) portable microgrid is a system enabling the soldiers to use multiple different batteries in parallel to increase overall capacity. This microgrid utilizes up to four military smart/dumb BB2590 lithium-ion batteries for energy storage. It provides the soldier two DC output source and one AC output options even while charging batteries: 12 / 24 V DC and 120 V AC outputs.

This portable microgrid consists of four DC-DC converters/chargers, a 12V-to-24V DC-DC converter, and a DC-AC pure-sine-wave inverter. The chargers inside this portable microgrid have the same configuration and functions as the individual charger presented in Section 6.1. Besides, two communication protocols are built in the charger’s software: 1) SMBus communication is built so each charger can directly communicate with a smart BB2590 lithium-ion battery; 2) RS485 communication is built so each charger can be directly communicate with the host controller. The details about the medium-power portable microgrid are presented as follows.

6.2.1 Functions and features

Figure 6.10 shows the system diagram of the medium-power portable microgrid consisting of four DC-DC converters/chargers, a 12V-to-24V DC-DC converter, and a DC-AC pure-sine-wave inverter. The system is built based on the architecture and algorithms presented in Chapter 3. Figure 6.11 illustrates the major functions and features:
• Only smart and dumb BB2590 lithium-ion batteries are accepted (but charging prioritization is given to smart batteries). BB390 NiMH batteries are accepted only when a specific connector without additional identifier pins is used.
• Batteries can be removed or put in at anytime. But at least one battery has to be in the system for proper system operating.
• The two battery legs in each battery always operate in parallel mode.
• The system charges one battery at a time using all input power sources.
• Charging priority is determined by battery type, remaining state of charge (SOC), and resting voltage.
• Up to four solar panels or any high-power energy source (e.g. DC power supply or Humvee battery) with voltage range 8-40 V can be used as an input energy source to charge batteries.
• Four chargers perform MPPT scan synchronously and independently operate each individual solar panel at its optimum power operating point.
• The 12 V DC and 120 V AC outputs provide up to 600W power to a load.
• AC and DC loads can be simultaneously utilized even when charging batteries.
• Power to the loads can be supplied from batteries, solar panels/high-power source, or combination of both (automatic passing through power from solar panels if loads are light).
• *Smart load sharing among batteries:* At least one battery is used to provide the output power when light load is detected. More batteries will share the heavy duty if a heavy load is detected.
• **Prevent circulating current among batteries:** The host controller automatically monitors and terminates circulating current among batteries after heavy-to-light load transition is detected.

• **Display battery and charger status on the LCD:** The LCD periodically shows charging priority, SOC, voltage, and state of charging/discharging/standby of each battery.

• **Display battery type using LEDs:** The on-board red and green LEDs indicates the battery type, presence of the input power source, and if the battery is fully charged or not.

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Figure 6.10 System diagram of the 600W portable microgrid. It enables the soldiers to use multiple different batteries in parallel to increase overall capacity.
6.2.2 Operation

6.2.2.1 Initialization

If there is at least one BB2590 rechargeable lithium-ion battery identified by the charger, no matter it is smart (with SMBus) or dumb (without SMBus), the system is powered up. Each charger begins collecting battery data including voltage, current, temperature, etc. If the battery is SMBus compatible, more information such as SOC is available through SMBus. The host controller collects all batteries’ data from all chargers through RS485 network. It decides the priority of charging based on the batteries’ data.
At this moment only the first priority battery will be connected to the 12 V DC bus during a normal operating procedure, while the switches between the 12 V DC bus and the other batteries are open for disconnecting batteries with lower charging priority. The reason why only one battery is connected to the 12 V DC bus is to avoid circulating current among different batteries.

The host enables all the chargers to charge the first priority battery. (The other batteries in the system are not being charged.) In the beginning, each charger tries to convert the input power into a regulated voltage to charge the battery. If the input power is large enough, each charger will find its operating condition and start charging process. If the input power is too low to allow all four chargers to find their own operating conditions at the same time, the chargers will stop searching the operating condition and wait for a synchronous MPPT command from the host controller. The host constantly sends a synchronous MPPT command to all the chargers so that they can perform MPPT scanning simultaneously. Then the optimum operating condition for all chargers will be assigned by the host and the charging will begin.

6.2.2.2 Battery type identification and message shown on the LCD

The LCD shows the charging priority, battery types, SOC, voltage, and battery status of all batteries periodically. The definition of the battery types, priority of charging, and complete examples of message on the LCD screen are listed in Table 6.1.

When an Ultralife connector (Model UCA0039) with two identifier pins is used, as shown in Figure 6.12(a), the system can identify Smart, LiIon, NiMH, and Prim. batteries. When a Brentronics connector (Model BTA-70762-1) without two identifier pins is used,
as shown in Figure 6.12 (b), the system cannot identify NiMH battery because NiMH and Primary will be treated as the same type. Thus, the user will not see “NiMH*Voltage” on the LCD even if a NiMH battery is connected.

Table 6.1 The definition of battery types, charging priority, and message on LCD

<table>
<thead>
<tr>
<th>Priority</th>
<th>Battery Types</th>
<th>Step 3-1</th>
<th>Step 3-2</th>
<th>Step 3-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Smart, Avg. SOC &lt; 90% and higher SOC</td>
<td>#X StateOfCharge A 81% B 85%</td>
<td>#X Smart*Voltage A15.44V B15.80V</td>
<td>#X A:StandbyMode B:Charging</td>
</tr>
<tr>
<td>2</td>
<td>Smart, Avg. SOC &lt; 90% and lower SOC</td>
<td>#X StateOfCharge A 60% B 59%</td>
<td>#X Smart*Voltage A15.00V B14.90V</td>
<td>#X A:StandbyMode B:StandbyMode</td>
</tr>
<tr>
<td>3</td>
<td>Smart and Avg. SOC &gt;= 90%</td>
<td>#X StateOfCharge A 100% B 98%</td>
<td>#X Smart*Voltage A16.35V B16.31V</td>
<td>#X A:FullyCharge B:Charging</td>
</tr>
<tr>
<td>4</td>
<td>Li-ion and higher voltage</td>
<td>#X LiIon*Voltage A16.01V B15.98V</td>
<td>#X A:Discharging B:Discharging</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Li-ion and lower voltage</td>
<td>#X LiIon*Voltage A14.88V B14.90V</td>
<td>#X A:StandbyMode B:StandbyMode</td>
<td></td>
</tr>
<tr>
<td>Forbidden</td>
<td>NiMH*</td>
<td>#X Prim.*Voltage A13.40V B13.22V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forbidden</td>
<td>Primary</td>
<td>#X Prim.*Voltage A14.00V B14.12V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forbidden</td>
<td>No RS485 Connection</td>
<td>No Signal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forbidden</td>
<td>No Battery Connected to the Charger</td>
<td>No Battery</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: “#x” means the number of the battery. The range is 1~4.
Note 2: “StandbyMode” means charging current < 0.2 A or discharging charging current < 0.2 A.
Note 3: “Charging” means charging current >= 0.2 A.
Note 4: “Discharging” means discharging current >= 0.2 A.
Note 5: “FullyCharge” means the SOC of the “Smart” battery is 100% or the voltage of “LiIon” battery is close to 16.5V.
Note 6: “A” means the leg-1(between pins 1 and 4) of the battery; “B” means the leg-2(between pins 2 and 5) of the battery.
Note 7: “No Signal” means the host is not able to communicate with the charger. Make sure the wires for RS485 communication are connected properly.
Note 8: The system can not identify NiMH battery because NiMH and Primary are treated as the same type. Thus, the user will see “Prim.*Voltage” on the LCD even if a NiMH battery is connected.
Figure 6.12 (a) Ultralife connector (Model UCA0039) with two identifier pins. (b) Brentronics connector (Model BTA-70762-1) without two identifier pins.

6.2.2.3 Priority of charging

Only “Smart” and “dumb” lithium-ion batteries are allowed to be used in the system. In case of plugging NiMH or primary batteries to the chargers by accident, the host controller will automatically force the charger to open the switches between the battery and the 12 V DC bus to prevent from charging.

The “Smart” battery with average SOC less than 90% has the highest priority. If there are at least two “Smart” batteries with average SOC less than 90%, the one with higher average SOC will be charged first. For example, a “Smart” battery with 81% and 85% SOC has higher priority than the one with 60% and 59% SOC. The reasons why charging one battery with higher SOC at a time are that the soldier wants the battery charged as quickly as possible and that the soldier is happy with a battery at 90% SOC. So the soldier will just take it at 90% and not wait for it to charge all the way to 100%.
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If the average SOC values of the “Smart” batteries have been equal to or larger than 90%, they will be charged together. That is, the switches between the DC bus and those “Smart” batteries will be closed to allow charging these batteries simultaneously.

If there is a dumb lithium-ion battery, the host controller will decide not to charge it until all the smart lithium-ion batteries have been fully charged (average SOC = 100%). In the case that there are at least two dumb lithium-ion batteries and the smart lithium-ion batteries have already been fully charged, the dumb lithium-ion battery with higher average voltage will be charged first.

6.2.2.4 Power flow control

The power flow control for no-load, light-load, and heavy-load conditions are demonstrated in Figure 6.13. If there is no load or the load is very light, only the first priority battery will be charged, e.g. Battery #3 shown in Figure 6.13 (a) and (b).

If the load increases but is not heavy, the first priority battery will begin discharging and possibly with the help of the other battery which has similar SOC or terminal voltage. As shown in Figure 6.13 (c), Battery #3 begins discharging and Battery #1 also contributes to providing power to the load.

If the load is too heavy or during inverter startup, all four batteries will contribute to providing power to the load, as shown in Figure 6.13 (d). This load sharing feature is realized using the discharging algorithm presented in Chapter 3. The charger #1, #2, and #4 detects the voltage drop. Therefore, the switches of #1, #2, and #4 are closed so all batteries are connected to supply a heavy load.
Figure 6.13 The power flow control for (a) no-load, (b) light-load with Battery #3 being charged, (c) light-load with Battery #3 being discharged, and (d) heavy-load. The messages shown on the LCD screen are listed for indicating the power flow.

When the load becomes from heavy to light, however, the circulating current problem among these batteries could happen if there is a large voltage mismatch among these
batteries, as the example shown in Figure 6.14(a). After the load becomes light, Battery 
#2 and Battery #3 begin discharging due to their higher voltage, and Battery #1 and 
Battery #4 begin charging due to their lower voltage. This duration of the circulating 
current can be minimized by the anti circulating current algorithm presented in Chapter 3. 
The host controller opens the switches of #1, #2, and #4 (not necessarily at the same time) 
between the 12 V DC bus and the batteries to stop the circulating current, as shown in 
Figure 6.14 (b).

Figure 6.14 (a) The power flow when the circulating current happens. (b) The discharging or charging 
current of #1, #2, and #4 is detected so the host controller decides to open the switches of #1, #2, and #4 to 
stop the circulating current.

6.2.3 Maximum power point tracking

According the system diagram shown in Figure 6.10, there are two independent input 
power sources: one is solar input using four separate low-power (~60 W) solar panels,
and the other is high-power (> 240 W) input using a Humvee heavy-duty battery or DC power supply. It is also possible to connect a high-power solar panel (~ 190 W) to the high-power input. Whether using four separate solar panels or a high-power solar panel as an input source, it requires MPPT to maximize energy conversion efficiency. Since the power conversion is distributed to four parallel chargers in the proposed microgrid system, the concept of so-called “distributed maximum power point tracking (DMPPT)” technique [97-102] is adopted in the system.

The difference between the DMPPT method used in our system and the one proposed in [101, 102] is that in our proposed system the MPPT controller is distributed into each charger. The approach in [101, 102] is composed of $N$ parallel connected converters with an external MPPT controller. The external MPPT controller directly controls the duty ratio of each converter. So these converters can be synchronized to perform MPPT by the same control signal from the external MPPT controller. In our proposed system, each converter has its own MPPT controller and the host is not really in charge of MPPT control. The host controller indirectly controls each converter by sending a “synchronous MPPT command” through the RS485 communication network. This special command can be accepted by all the chargers at the same time and each charger will perform its MPPT after receiving the synchronous command.

Depending on the choice of using four separate solar panels or a high-power solar panel as an input source, the realization of DMPPT can be classified into three categories:

- Chargers’ inputs are not connected in parallel, as shown in Figure 6.15 (a).
- Chargers’ inputs are connected in parallel, and uniform input power sharing is required, as shown in Figure 6.15 (b).
Chargers’ inputs are connected in parallel, and uniform input power sharing is not required, as shown in Figure 6.15 (c).

Figure 6.15 Three categories of DMPPT used in the 600W microgrid: (a) Chargers’ inputs are not connected in parallel. (b) Chargers’ inputs are connected in parallel, and uniform input power sharing is required. (c) Chargers’ inputs are connected in parallel, and uniform input power sharing is not required. The configuration in (a) is applicable when four low-power solar panels are used, whether they are the same or not. The configurations in (b) and (c) are only applicable when four solar panels are the same or single high-power solar panel is used.

6.2.3.1 Chargers’ inputs are not connected in parallel

The configuration shown in Figure 6.15 (a) is applicable when four low-power solar panels are used, whether they are the same or not. In this case, each charger performs its MPPT on each PV panel thus the total input power can be maximized. The MPPT algorithm can be either modified P&O presented in presented in [96] and Chapter 6 or a global scan presented in Section 6.1.6.
When solar panels with different characteristics are used, chargers’ inputs should not be connected in parallel because connecting different solar panels in parallel will lower the maximum sum of power each solar panel can provide.

6.2.3.2 Chargers’ inputs are connected in parallel, uniform input power sharing is required

The configuration shown in Figure 6.15 (b) is applicable when four solar panels are the same or single high-power solar panel is used. The total input power is evenly shared by four chargers. All of the chargers might not work at full load, but their duty ratios (direct MPPT control) or input reference voltages (indirect MPPT control) are the same and can be assigned by the host controller.

In the proposed microgrid, the host periodically sends a synchronous MPPT command to all the chargers so that they can perform MPPT scan simultaneously. Each charger performs its MPPT scan after receiving the synchronous command and finds its own MPP; that is, the best input reference voltage $V_{\text{ref}}$. Each charger sends its own $V_{\text{ref}}$ value to the host controller through RS485 network. The host will then assign the input reference voltage $V_{\text{ref, host}}$ to each charger. After receiving $V_{\text{ref, host}}$ as its operating condition, each charger begins converting the input power to charge the first priority battery and/or power the load.

6.2.3.3 Chargers’ inputs are connected in parallel, uniform input power sharing is not required

This configuration is only applicable when four solar panels are the same or single high-power solar panel is used. The total input power is not evenly distributed. Some of
the chargers work at full load (60 W) and some do not. As shown in Figure 6.15 (c), for a high-power solar panel which can provide 190 W input power, three chargers work at full load (60 W) and one charger just deliver 10 W.

The DMPPT without uniform input power sharing can be achieved by turning on $N$ chargers sequentially and let some chargers work at full load and one charger work at adjustable load. A proof-of-concept experiment to demonstrate this approach is introduced as follows. More sophisticated DMPPT method using fast input current change and its details will be presented in Section 6.4.

Figure 6.16 shows the experimental setup for demonstrating the concept of turning on three chargers sequentially and let two chargers work at full load and one charger work at adjustable load. The chargers’ inputs are connected in parallel and uniform input power sharing is not required. The duty ratio of each charger is not directly controlled by the host controller. But the output reference current $I_{ref}$ of each charger can be controlled by the host controller through RS485 network. A PV simulator with 161 W is used to simulate a 190 W high-power solar panel. The outputs of the chargers are connected to a lithium-ion battery and a 5 A constant-current load.
Figure 6.16 The experimental setup for demonstrating the concept of turning on $N$ chargers sequentially and let some chargers work at full load and one charger work at adjustable load.

Figure 6.17 shows two control modes of a single charger. One of the two control modes will be chosen after the charge is powered up. The output reference current $I_{\text{ref}}$ of the charger is first set to a maximum value $I_{\text{ref,max}}$, which is the reference for the charger working at full load. Then the charger starts adjusting all possible duty ratios of the DC-DC converter to see if the output current $I_{\text{out}}$ of the charger equals to at a specific duty ratio $d_c$. If $d_c$ can be found, the charger enters “output current control mode (OCCM).” In OCCM mode, $I_{\text{out}} = I_{\text{ref,max}}$ and the variable “OCCM_Flag” in the software is set to 1. If $d_c$ cannot be found, the charger enters “input voltage control mode (IVCM).” In IVCM mode, $I_{\text{out}} = 0$, the variable “OCCM_Flag” in the software is set to 0, and the charger is turned off and wait for the host controller’s command.
Once the system is powered up, the host controller executes sequential commands listed in Figure 6.18 to realize DMPPT without uniform input power sharing. The procedure is summarized as below:

- **Steps 0–2**: Determine the number of chargers working at full load. The initial output reference current $I_{ref}$ of each charger is set to a maximum value $I_{ref,\text{max}}$, which is the reference for the charger working at full load (~60 W). Since the maximum input power is 161 W, only two chargers can work at full load.

- **Steps 4–7**: Determine the output reference current $I_{ref} = I_{adj} = I_{out,\text{max}}$ of the charger working at adjustable load. $I_{ref}$ of the charger working at adjustable load is controlled by the host controller.
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- **Steps 8~10**: The host controller assigns $I_{ref} = I_{adj} = I_{out,max}$ to the charger working at adjustable load. At the end of the searching process, two chargers work at full load with $I_{ref} = I_{ref,max}$ and one charger works at adjustable load with $I_{ref} = I_{adj}$.

![Diagram](image)

Figure 6.18 The sequential commands the host controller executes to realize DMPPT without uniform power sharing.

Figure 6.19 shows the measured PV voltage $V_{PV}$, PV current $I_{PV}$, and PV power $P_{PV}$ with respect to time. After the step 4 (S4), chargers #1 and #2 work at full load so $P_{PV}$ reaches 131.62 W. Figure 6.20 shows a snapshot of the operating point obtained from the PV simulator.

During the step 7, the host controller controls charger #3 to look for the optimized output reference current $I_{adj}$. The output reference current $I_{adj}$ increases from 0 with a step of 0.12 A until charger #3 finds the optimized output reference current $I_{adj}$. So $P_{PV}$ increases from 131.62 W to 159.95 W. Figure 6.21 shows a snapshot of the operating point during the searching process obtained from the PV simulator.
At the end of step 10, chargers #1 and #2 work at full load with $I_{\text{ref}} = I_{\text{ref, max}} = 3.6$ A and charger #3 works at adjustable load with $I_{\text{ref}} = I_{\text{adj}} = 1.68$ A. So the measured $P_{PV}$ is 160.45 W. Figure 6.22 shows a snapshot of final operating point obtained from the PV simulator.

Figure 6.19 The PV voltage $V_{PV}$, PV current $I_{PV}$, and PV power $P_{PV}$ with respect to time.
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Figure 6.20 The operating point after executing the step 4. Chargers #1 and #2 work at full load.

Figure 6.21 The operating point during the step 7. Chargers #1 and #2 work at full load. Charger #3 is looking for optimized output reference current $I_{adj}$. 
Figure 6.22 The operating point after executing the step 10. Chargers #1 and #2 work at full load with $I_{ref} = I_{ref, max} = 3.6$ A. Charger #3 is looking for optimized output reference $I_{adj}$ with $I_{ref} = I_{adj} = 1.68$ A.

### 6.3 Conclusion

In this chapter, the low-power (150 W) portable microgrid and the medium-power (600 W) portable microgrid are presented. First, the characteristics of the individual charger in the low-power portable microgrid are introduced, including its functions, features, converter topology, parallel/series mode selection, power flow control, and MPPT. The individual charger forms the core of the medium-power portable microgrid; that is, the DC-DC converter in the medium-power portable microgrid is composed of four individual chargers operating in parallel and controlled by the host controller. The
operation of the medium-power portable microgrid is presented. Besides, MPPT
approaches for two systems are also discussed.

Specifically, the contributions of the research in this chapter include:

- A military grade 150 W portable microgrid consisting of one charger and one DC-AC
  inverter has been designed, developed, built, and field tested.

- A 600 W portable microgrid consisting of four chargers, one DC-AC inverter, and one
  DC-DC converter, has been designed, developed, built, and tested experimentally.
Chapter 7

MPPT by fast input current change

7.1 Introduction

To maximize energy conversion efficiency, it is always important to have the photovoltaic (PV) modules operating at a unique optimized point. This has led to many maximum power point tracking (MPPT) approaches during the last decade [88, 103]. Among them, the scheme of “perturb and observe (P&O)” [69, 75, 85] is often used in commercial products due to its ease of use. However, in practical implementations, PV arrays can exhibit multiple peak power points due to partial shading or mismatch of PV panels. This prevents the basic P&O control from finding the real maximum power point (MPP).

To address the above-mentioned issue, recent research proposes some improved MPPT control methods [75, 104-108]. The solutions are classified into two categories: centralized MPPT and distributed MPPT. In comparison, distributed MPPT [104] usually achieves higher efficiency at a penalty of increased cost, since individual power
optimizers are used for every PV module. Centralized MPPT might be more suitable to achieve design trade-offs between efficiency and cost. Its major examples include two-stage method [105], adaptive reconfigurable structure [106], global MPP tracking algorithm [107], variable scan step [75, 108], and etc. The two-stage method [105] searches the vicinity of the global MPP at the first stage, followed by gradual approaching of the optimized point. The drawback is that the real MPP may not be tracked in some conditions. Alternatively, adaptive reconfigurable structure is suggested to optimize the efficiency with dynamic connection at various shading conditions [106]. But its implementation is expensive, and demands large number of switches and sensors. Furthermore, dividing rectangles (DIRECT) algorithm [107] is presented to fulfill fast tracking as well as maintaining ease of implementation. However, the scan speed is still not as fast as P&O algorithms, and the increased control complexity adds extra risk for the system. In addition to that, [75, 108] utilize variable step size to further improve the tracking speed. Of course, the maximum step size is still limited by the control loop to avoid instability or oscillation.

This section proposes a new approach to efficiently track the expected MPP under partial shading conditions. The power stage architecture achieves fast input current change rate by combining a current-adjustable converter with a few converters operating at a constant current. By taking advantage of fast current change, the controller effectively combines P&O tracking and periodic global MPP searching. Specifically, the following advantages are obtained:

- **Complexity of control circuit/program and board layout is reduced, since no current sharing is required for paralleled converters.** The controller changes input
current by directly connecting/disconnecting \( N-1 \) out of a total of \( N \) converters and adjusts current for 1 out of a total of \( N \) converters.

- **Fast input current change is achievable for the PV system by instantaneous hardware adjustment.** This can be fulfilled by changing the number of connected converters.

- **By taking advantage of fast input current change, the proposed control scheme performs optimized MPPT under partial shading conditions (the PV exhibits multiple MPPs).** Fast tracking and ease of implementation are fulfilled by simultaneous implementation of P&O tracking and periodic global MPP searching.

### 7.2 Operation principles

As has been introduced in Section 7.1, the proposed PV system utilizes \( N \) converters and a centralized controller to perform optimized MPPT. Specifically, the **power stage architecture eliminates the limitation of input current change rate**, and thus, by taking advantage of fast current change, **the new control scheme tracks global MPP without sacrificing dynamic response**. The technical details are described as below.

#### 7.2.1 Power stage architecture and related features

Generally, conventional multi-phase converters [109] have the following limitations: (1) Current sharing is demanded. Therefore, the converters need to communicate and minimize parasitic parameter difference in order to evenly distribute the current. This
leads to increased complexity for control and board layout, and potentially affects reliability and cost. (2) Because input current of a PV system usually has large variation, paralleling many converters may cause unnecessary waste. Even if the controller can turn on/off several converters according to load variation, phase shedding control [110, 111] can often cause extra limitations during transient conditions. (3) Moreover, even with fast control loop, the current change rate is still limited to avoid instability or oscillation.

Figure 7.1 (a) describes the concept of the proposed power stage architecture to address the above concerns. The proposed power stage architecture has $N$ converters in parallel. It is assumed that all the converters have the same maximum power rating, and the PV output power is always below the total power rating of $N$ converters. To adaptively set the number of paralleled converters, 1 out of a total of $N$ converters has adjustable current $i_A$ (shown in the figure as “DC/DC #N”), and the other $N-1$ converters operate at full load condition with a constant input current $I_C$. The number of connected converters with a constant current $I_C$ is controlled by the switches $S_k$ for $k = 1, 2, ..., N-1$. The total input current of the system $I_{IN}$ equals to $m \times I_C + i_A$ where $m$ is the number of closed switches $S_k$.

According to the requirement of MPPT control, the controller calculates the expected input current $I_{IN}$ and dynamically determines the number of connected converters for energy delivery. The current-adjustable converter and the remaining converters function with different purposes. For example, by instantaneously connecting or disconnecting converters with constant current $I_C$, fast input current change rate is achieved without the influence of control loop. Also, capability to gradually adjust the input current is needed for P&O control. This can be fulfilled by the converter (DC/DC #N) with adjustable current $i_A$. 

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Figure 7.1 The concept of the proposed power stage architecture and MPPT control method: (a) System diagram of the proposed power stage architecture. (b) MPP searching time using the proposed MPPT control method can be reduced by a factor of $n/N_1$, where $n = 1, 2, 3, \ldots, N_1$. 

Traditional Full-Range Voltage Scanning

Proposed Fast MPPT Control Method: Periodic Multi-Range Scan
The processes of the traditional full-range voltage scan and proposed periodic multi-region scan are illustrated in Figure 7.1 (b), where $T_1$ is the required time to complete a full-range scan in period (I) that is defined as a global voltage scan between the PV’s open-circuit voltage $V_{oc}$ and zero for all possible operating points to determine the MPP.

For a PV system with only one converter, the traditional full-range voltage scan guarantees that MPP can be found, but it cannot guarantee that the operating point always locates at the MPP if the PV’s power-voltage characteristic changes in the period (II). Yet, on the contrary, the proposed fast MPPT control method checks part of all the operation points every short period of time $T/N_1$ within a time period of $T$, providing the following benefits over the traditional full-range voltage scan:

- If global MPP is found in the period (III), the time to find this MPP using the proposed periodic multi-range scan can be smaller than $T_1$ (reduced by a factor of $n/N_1$, where $n = 1, 2, 3, \ldots, N_1$).
- If basic P&O tracking has already found the global MPP, the PV system can stay in the optimized operating point even if periodic multi-range scan is still going on.
- Since the proposed MPPT control method is not only faster than traditional full-range voltage scan but also able to quickly find out the global MPP from multiple MPPs, harnessing maximum possible energy from the PV system is guaranteed.

The global scan can be achieved by controlling the number of connected converters with full power or current along with the adjustment of the converter #N. The whole operating range is checked by a periodic scan of many small regions.
Chapter 7

This chapter mainly focuses on a simplified system with a single PV array, but the idea can also be extended to a large system, such as a solar battery charging station (SBCS). That is, individual users may have their own small PV panels for charging their own batteries as well as use multiple different batteries in parallel to provide public services [32]. Previous work on optimized charging/discharging strategies has been published in [58, 59] as far as maximizing solar energy exploitation and the run time of batteries are concerned. When multiple PV panels are connected to the charging station, those resources can be combined into a large PV system, whose MPPT performance can be optimized by the proposed distributed power stage architecture.

7.2.2 Specific implementation of P&O tracking + periodic global MPP searching to optimize MPPT control

Ideally, conventional full-range voltage scan schemes can precisely find the desired operating point for a PV array. This is based on the assumption that the irradiance condition stays the same or has very slow change. However, when the irradiance varies quickly with time, it is hard for the power optimizer to follow the change, since full-range voltage scan exhibits slow response and can only be fulfilled periodically. On the other hand, directly dealing with MPPT control with basic P&O control (which has relatively faster response) is not a proper solution due to the factor of partial shading. In this case, the power optimizer may trap at a local power peak, which is due to the confusion caused by multiple MPPs.
To deal with the challenge of global maximum power point tracking, the research in this chapter proposes a new control scheme/concept to combine P&O tracking and periodic global MPP searching. It should be noted that effective combination of P&O tracking and periodic global MPP searching requires fast input current change, which is a unique aspect of the proposed power stage architecture shown in Figure 7.1. This is because the PV system needs instantaneous large step current change in order to minimize low frequency transition time (from small input current to large input current), and thus, expedites the procedure of global MPP searching. Figure 7.2 shows a design example, which includes complementary operation of two operation modes.
Figure 7.2 Illustration of the proposed control scheme/concept: (a) Mode 1 (b) Case I in Mode 2 (c) Case II in Mode 2.
Specifically, continuous operation of Mode 1 ensures instantaneous response to irradiance change. In case the system temporarily traps at a local MPP, Mode 2 functions periodically to find a new region with higher power peak. To avoid slow response and unnecessary power loss, the time length of Mode 2 is relatively negligible in comparison with the time length of Mode 1.
Mode 1: The condition of this mode is shown in Figure 7.2(a). Assume the operating point is near a local MPP and $N-1$ out of a total of $N$ converters transfer energy from PV to the battery with a constant input current, which is defined as the maximum input current of an individual converter. The remaining converter, shown as “DC/DC #N” in Figure 7.1 (a), gradually adjusts the input current with a step of $\Delta I_N$ for P&O. When the curve of “power vs. current” changes (from curve 1 to curve 2) due to irradiance variation, the operation point immediately switches from “MPP 1” to “A” before current change. Then, followed by P&O control from converter #N, the PV system gradually tracks the local MPP.

Mode 2: The detailed transition procedure between Mode 1 and Mode 2 is illustrated in Figure 7.3. Converter #N−1 is disconnected after receiving the control signal. It is usually recommended to have converter #N−1 used for other purposes in the system. Thus, a large input current change with a step of $\Delta I_{max}$, which is defined as the maximum input current of an individual converter, is injected to check another region. (Different large step sizes are attempted by connecting/disconnecting more converters.) Then, the controller checks a few points in the new region. If the new region exhibits lower output power from PV as shown in Figure 7.2(b), the controller quickly switches back to the original MPP by connecting converter #N−1. Different from existing techniques, the system does not need to gradually adjust the current back to the original region. On the other hand, if the PV exhibits higher power as shown in Figure 7.2(c), the system stays in the new region to continue the procedure of Mode 1.
7.3 Experimental results

To verify the principle of the proposed power stage architecture along with the new control scheme, a prototype of the power stage with multiple parallel converters switching at 200 kHz is built, as shown in Figure 7.4. The prototype includes: (1) Ametek Photovoltaic Simulator (Model ETS80 with 80V/10.5A) is used to generate power according to the feature of a foldable PowerFilm® PV array; (2) three buck-boost converters (with controllers of PIC18F6527) are paralleled for power conversion. Converters #1 and #2 operate with fix input current, and converter #3 operates with adjustable input current; (3) Ultralife UBI-2590 lithium-ion battery (15V/13.6AH) in parallel with 5A DC load is used as the output; (4) A DSP (dsPIC33FJ256GP710A) is used as host controller, and communicates with charger through RS-485 network.

Figure 7.4 The prototype of the power stage with three parallel converters controlled by the host controller. A photovoltaic simulator is used as the power source. A lithium-ion battery and a 5 A DC load are connected to the output.
7.3.1 Searching global/local MPP using traditional scan

Figure 7.5 shows a typical current-voltage and power-voltage characteristics of a PV system with partial shading. There are two local MPPs located at the points A ($V_{pv} = 35$ V) and B ($V_{pv} = 17$ V). Conventional full-range voltage scan can precisely find the desired global operating point A. It can be achieved by gradually adjusting $V_{pv}$ with a fixed voltage step $\Delta V$ within a fixed amount of time $\Delta t$. The total scan time equals to $(V_{oc} / \Delta V) \times \Delta t$, where $V_{oc}$ is the open-circuit voltage of the PV system. In the case that $V_{oc} = 40$ V, $\Delta V = 0.5$ V, and $\Delta t = 15$ ms, it takes 1.2 s to find the global MPP.

Suppose that the system initially operates at point A (or B). In order to verify if the point A (or B) is the global MPP, the system needs to check the power level of point B (or A). In this case the system needs to change the operating points and compare their power levels. Without changing $\Delta V$ and $\Delta t$, the system needs 540 ms to transit between the points A and B. This slow tracking time can be improved by the proposed power stage and control method to efficiently track the desired global MPP under partial shading conditions.
7.3.2 Searching global/local MPP with proposed power stage architecture and control scheme

According to Figure 7.1 (a), multiple converters with full power/current can be connected or disconnected for the scan check. Since the prototype has three converters, in the following experiments, converter #2 is connected or disconnected to provide fast input current change. And the input current of converter #3 is adjusted for a small-range scan.

Three experiments are demonstrated below: First, an experiment of case I in Mode 2 demonstrates the situation that the true MPP has been found and the system performs a
small-range scan by disconnecting converter #2 and adjusting converter #3. Then the operating point jumps back to the true MPP. Second, an experiment of case II in Mode 2 demonstrates the situation that a local MPP (not true MPP) has been found and the system performs a small-range scan by connecting converter #2 and adjusting converter #3. Then the operation stays in the new region and finds the true MPP. Finally, an experiment of the combination of previous two situations is demonstrated.

**Experiment 1: Case I in Mode 2**

The current-voltage and power-voltage characteristics of a PV system with partial shading are shown in Figure 7.6(a). There are three local MPPs: $V_{pv} = 19$ V, 26 V, and 36 V. Initially the system operates in Mode 1 and at the global MPP (the point A) where $V_{pv} = 26$ V and $I_{pv} = 5.1$ A. Converters #1, #2, and #3 are all connected. Converters #1 and #2 transfer energy from the PV to the battery with a constant input current while converters #3 transfers energy from the PV to the battery with an adjustable input current for searching global MPP.

The system changes to Mode 2 periodically to check if there is another operating point providing higher power peak than the power at point A. When the system transits from Mode 1 to Mode 2, converter #2 is disconnected after receiving the control signal from the host controller. By disconnecting converter #2, the system operating point could shift to any point on the right side of point A due to instantaneous largely decreased input current. Location of the new operating point in Mode 2 is determined by regulating the input current of converter #3. Then, the controller performs a small-range voltage scan,
which indirectly adjusts the input current of converter #3, to check if there is a new operating point providing higher power peak than the power peak at point A.

An example of the transition procedure between Mode 1 and Mode 2 is illustrated in Figure 7.6(b). The system first transits from the operating point A ($V_{pv} = 26$ V, $I_{pv} = 5.1$ A) to the operating point B ($V_{pv} = 38$ V, $I_{pv} = 1.6$ A) in Mode 2 by disconnecting converter #2 and regulating input current of converter #3. Then the controller performs a small-range scan between point B and point C ($V_{pv} = 34.5$ V, $I_{pv} = 2.4$ A). The controller decides to jump back to the operating point A by reconnecting converter #2 and operates in Mode 1 because all of the operating points between point B and point C cannot provide higher power peak than the power peak at the point A. After staying at the point A in Mode 1 for 100 ms, the system transits to Mode 2 from the operating point A to the operating point C by disconnecting converter #2 and regulating input current of converter #3. Then the controller performs a small-range scan between the points C and D ($V_{pv} = 31$ V, $I_{pv} = 2.5$ A). The controller decides to jump back to the operating point A and operates in Mode 1 because all of the operating points between the points C and D cannot provide higher power peak than the power peak at point A.
Figure 7.6 (a) The current-voltage and power-voltage characteristics of a PV system and critical operating points. (b) The waveforms of the PV voltage $V_{pv}$ (Channel-1: 10 V/div), the PV current $I_{pv}$ (Channel-2: 2 A/div), and the PV power $P_{pv}$ (Channel-Math: 100 W/div). The system operates at the point A initially and periodically checks a few points in the new region.

**Experiment 2: Case II in Mode 2**

The current-voltage and power-voltage characteristics of a PV system with partial shading are the same as the ones shown Figure 7.7(a). However, the initial operating
point is not at the global MPP. As shown in Figure 7.7(a), initially the system operates in Mode 1 and at the local MPP (point A) where $V_{pv} = 36$ V and $I_{pv} = 2.4$ A. *Converter #2 is disconnected.* Converter #1 transfers energy from the PV to the battery with a constant input current while converter #3 transfers energy from the PV to the battery with an adjustable input current. The system temporarily traps at the point A because of P&O MPPT.

The system changes to Mode 2 periodically to check if there is another operating point providing higher power peak than the power at point A. When the system transits from Mode 1 to Mode 2, converter #2 is reconnected after receiving the control signal from the host controller. By *reconnecting converter #2,* the system operating point could shift to any point on the left side of point A due to instantaneous largely increased input current. Location of the new operating point in Mode 2 is determined by regulating the input current of converter #3. Then, the controller performs a small-range voltage scan, which indirectly adjusts the input current of converter #3, to check if there is a new operating point providing higher power peak than the power peak at point A.

An example of the transition procedure between Mode 1 and Mode 2 is illustrated in Figure 7.7(b). The system first transits from the operating point A ($V_{pv} = 36$ V, $I_{pv} = 2.4$ A) to the operating point B ($V_{pv} = 28$ V, $I_{pv} = 3.6$ A) in Mode 2 by reconnecting converter #2 and regulating input current of converter #3. Because the operating point B provides more power than operating point A, the controller decides to stay at the point B, operates in Mode 1, and keeps performing P&O MPPT between the points B and D ($V_{pv} = 24$ V, $I_{pv} = 5.3$ A) until it finds the local MPP (which is also the global MPP in this case), point C ($V_{pv} = 26$ V, $I_{pv} = 5.1$ A), in the new region.
Figure 7.7 (a) The current-voltage and power-voltage characteristics of a PV system and critical operating points. (b) The waveforms of the PV voltage $V_{pv}$ (Channel-1: 10 V/div), the PV current $I_{pv}$ (Channel-2: 2 A/div), and the PV power $P_{pv}$ (Channel-Math: 50 W/div). The system operates at the point A initially and periodically checks a few points in the new region.

**Experiment 3: Combination of Cases I& II for Mode 2**

The current-voltage and power-voltage characteristics of a PV system with partial shading are shown in Figure 7.8(a). There are two local MPPs: $V_{pv} = 17$ V and 34 V.
Initially the system operates in Mode 1 and at the local MPP (the point A) where $V_{pv} = 17 \text{ V}$ and $I_{pv} = 6.4 \text{ A}$. *Converters #1, #2, and #3 are all connected.* Converters #1 and #2 transfer energy from the PV to the battery with a constant input current while converters #3 transfers energy from the PV to the battery with an adjustable input current. The system temporarily traps at point A because of P&O MPPT.

An example of the transition procedure between Mode 1 and Mode 2 is illustrated in Figure 7.8(b). The system first transits from the operating point A ($V_{pv} = 17 \text{ V}, I_{pv} = 6.8 \text{ A}$) to the operating point B ($V_{pv} = 26 \text{ V}, I_{pv} = 4 \text{ A}$) in Mode 2 by disconnecting converter #2 and regulating input current of converter #3. Then the controller performs a small-range scan between the points B and C ($V_{pv} = 23 \text{ V}, I_{pv} = 4 \text{ A}$). The controller decides to jump back to the operating point A and operates in Mode 1 because all of the operating points between the points B and C cannot provide higher power peak than the power peak at the point A. After staying at the point A in Mode 1 for 100 ms, the system transits to Mode 2 from the operating point A to the operating point C and a small-range scan is performed between the points C and D ($V_{pv} = 20 \text{ V}, I_{pv} = 4 \text{ A}$). The controller decides to jump back to the operating point A and operates in Mode 1 because all of the operating points between the points C and D cannot provide higher power peak than the power peak at point A. After staying at the point A in Mode 1 for 100 ms, the system transits to Mode 2 from the operating point A to the operating point E ($V_{pv} = 38 \text{ V}, I_{pv} = 2 \text{ A}$) by disconnecting converter #2 and regulating input current of converter #3. Then the controller performs a small-range scan starting from the point E toward the point G ($V_{pv} = 34 \text{ V}, I_{pv} = 3.9 \text{ A}$). Once the operating point reaches the point H ($V_{pv} = 36 \text{ V}, I_{pv} = 3.4 \text{ A}$), the controller knows that the operating point H provides higher power than the point A.
So the controller decides to stay within the region between points H and G, operates in Mode 1, and keeps performing P&O MPPT between the points H and F ($V_{pv} = 32$ V, $I_{pv} = 4$ A) until it finds the local MPP (which is also the global MPP in this case), point G, in the new region.

By applying the proposed power stage architecture and periodic multi-range scan approach in the built prototype, a fast MPPT without trapping at local MPP under partial shading conditions and spending long tracking time is obtained. The experimental results verify the principle and the performance of concept illustrated in Figure 7.1.

### 7.4 Conclusion

In this chapter, a new approach to efficiently track the desired maximum power point for photovoltaic systems under partial shading conditions is proposed. The distributed power stage architecture consisting of a few constant-current converters and a current-adjustable converter provides the benefit of fast input current change. By taking advantage of fast input current change, a fast MPP search combining P&O and periodic multi-range scan is achieved by a simple and instantaneous hardware adjustment. A prototype consisting of three converters has been built and tested to verify the effectiveness of the new approach.
Figure 7.8 (a) The current-voltage and power-voltage characteristics of a PV system and critical operating points. (b) The waveforms of the PV voltage $V_{pv}$ (Channel-1: 10 V/div), the PV current $I_{pv}$ (Channel-2: 2 A/div), and the PV power $P_{pv}$ (Channel-Math: 50 W/div). The system operates at the point A initially and periodically checks a few points (between B and D, between E and F) in the new region.
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Conclusion and Future Research

This dissertation develops methods that maximize energy delivery of microgrid systems and thus uses these methods to fulfill the demand of remote power sources. The developed methods are suitable for, but not limited to, the following remote power occasions: campers at camping sites, soldiers on the battlefield, solar battery charging stations, solar/wind powered telecommunication stations, and electric vehicles. In this final chapter, we will review the research contributions of this dissertation and propose recommendations for future research.

8.1 Contributions

The main research contributions of this dissertation are listed as follows:

- The major technical difficulties of parallel operation of different battery packs are identified (Chapter 2): Applications require connecting different batteries in parallel are reviewed. Technical difficulties of operating different battery packs in parallel are identified. The conventional solution to these technical difficulties is to use
additional devices/converters between each battery and the load to assure that batteries with different voltages are never directly connected in parallel. Otherwise, circulating current among the batteries may occur and result in over-charging and over-discharging. This dissertation proposed a method without using additional devices/converters between each battery and the load, to avoid the circulating current. The approach maximizes charging efficiency and available discharging ability delivered from different battery packs in parallel.

- **A new battery management system for managing different batteries in parallel is proposed** (Chapter 3): A new method for controlling charging/discharging of different battery packs by using low-cost bi-directional switches instead of DC/DC converters is proposed. Because of substantially fewer parts, the physical design and cost for the energy management system architecture is substantially reduced. This has benefits in the portable/handheld electronics market. Each different battery pack can be individually charged to its full SOC, even though the battery packs are often connected directly in parallel. Special discharging algorithms are proposed to control the sequence and the number of battery packs used to share the load according to the load transient condition. At heavy load, a higher number of battery packs are connected in parallel. At light load, only one battery pack is connected. The decision of switching in/out more battery packs is executed by a supervisory host made up of a microcontroller unit (MCU) or a digital signal processor (DSP). Meanwhile, the circulating current among the batteries due to voltage mismatch is avoided by only switching in multiple battery packs as the load becomes heavy. The algorithms have
been verified by a prototype system in which four battery packs in parallel with
different voltages within predefined range are utilized.

- **Classical MPPT algorithms by tracking output current of the DC-DC converter**
  are reviewed (Chapter 4): Various MPPT algorithms by tracking the output
parameters of the DC-DC converter are reviewed, especially the algorithm in which
tracking the output current is adopted. Tracking the output current is of interest for the
types of remote power PV systems studied in this research because there are often
batteries connected to the output of the DC-DC converter. Maximizing the output
current of the DC-DC converter is equivalent to maximizing the input power (the
output power from a PV panel) of the DC-DC converter if the batteries are considered
as a constant voltage sources. The chapter also explained the difficulties that may
occur if the batteries’ terminal voltages change fast: The conventional MPPT
algorithm by tracking the output current of the DC-DC converter might be fooled and
the system may not operate near its maximum power point.

- **A new MPPT technique suitable for a periodic nonlinear load is developed**
  (Chapter 5): The performance of MPPT with respect to different kinds of loads has
been studied, simulated, and experimentally documented. The impacts of periodic
nonlinear load currents, especially with high transient AC components, on MPPT
efficiency have been verified by simulations and experiments. A proposed modified
P&O MPPT approach is developed that can successfully operate at the MPP. The
approach keeps the simplicity of tracking only the output current of the DC-DC
converter even though the load is nonlinear and exhibits negative impedance, as long
as it changes periodically.
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- **Military grade portable microgrids are designed and built** (Chapter 6): A low-power microgrid consisting of one charger, one battery, and one inverter is designed and built. The modified P&O MPPT algorithm presented in Chapter 4 and the global scan with output current filtering presented in Chapter 5 are implemented in the charger. Both techniques are used to address the problem that the conventional MPPT by tracking output current of the DC-DC converter might fail when a DC-AC inverter is connected in parallel with a battery. Then, the charger developed in the low-power microgrid is used to design and build a medium-power microgrid, which consists of four chargers, four batteries (could be the same or different), one commercial DC-DC converter, and one commercial DC-AC inverter. This microgrid is designed and built according to the architecture and charging/discharging algorithms presented in Chapter 3. It provides users in remote area the benefit that different batteries can be used in parallel to increase remote power capacity, while also addressing the issues of parallel operation of different batteries identified in Chapter 2.

- **A new distributed MPPT technique by fast input current change is developed and implemented** (Chapter 7): The conventional distributed MPPT techniques are realized by evenly distributing solar power to multiple DC-DC converters connected in parallel. In this chapter, a distributed MPPT technique realized by unevenly distributing solar power to multiple DC-DC converters in parallel is proposed and verified by proof-of-concept experiments. The idea is to quickly turn on several DC-DC converters working to immediately operate at full load. A separate DC-DC converter supplements power tracking by operating at adjustable load. The controller effectively combines P&O tracking and periodic global MPP searching to track real MPP, even under
partial shading conditions. Since uniform power sharing among all the parallel converters is not a requirement, the complexity of control software/hardware is simplified.

8.2 Recommendation for future research

Future work recommended to build upon the findings in this dissertation is proposed as follows:

- **Create a MPPT controller for a periodic nonlinear load with arbitrary frequency**

  A more advanced MPPT controller could be designed specifically for a periodic nonlinear load with arbitrary frequency. During the development of the MPPT controller presented in Chapter 5, the frequency of the periodic nonlinear load is known because we assume the load is a DC-AC inverter so the frequency of the voltage variation at the battery’s terminal is 50 or 60 Hz. This assumption is valid only when resistive loads, such as lamps and incandescent bulbs, are connected to the output of the DC-AC inverter. However, if inductive loads are connected to the output of the DC-AC inverter, the frequency of the inductive loads might not be constant. So the frequency of the voltage variation at the battery’s terminal (input of the DC-AC inverter) is no longer fixed at 50 or 60 Hz.

  Typical application of an inductive load is an AC electric motor driven by a variable-frequency drive (VFD) [112, 113]. A VFD is an adjustable-speed drive that controls the speed and torque of an AC motor by adjusting the input voltage and
frequency of the AC motor. The speed (revolutions per minute, RPM) of an AC induction motor can be expressed as follows [113]:

$$\text{RPM} = \frac{120 \times f}{P}$$

where $f$ denotes the applied frequency in Hertz and $P$ the number of magnetic poles. For example, a motor with a 900 RPM base speed could be a 4-pole motor operated at 30 Hz. The benefit of varying motor speed by means of VFD is to minimize power loss especially in pump applications, where the load’s power could varies with the cube of the speed.

Therefore, for inductive loads with variable frequency, methods of load frequency detection should be studied and implemented into the MPPT controller. The MPPT controller could automatically calculate the necessary period of each perturb-and-observe procedure based on the load frequency to assure MPPT efficiency is always maximized.

- **Battery modeling**

  With an accurate battery model, the SOC of a battery can be estimated from measured charging/discharging current and terminal voltage. Furthermore, the maximum available charging/discharging power and the runtime could be predicted based on the accurate SOC estimation. The ability of accurately estimating SOC information is crucial for applications in which users desire to predict the maximum cruising range according to remaining available power and runtime of a battery bank, such as electric vehicles (EVs) and autonomous underwater vehicles (AUVs). An accurate SOC estimation can help drivers plan an optimal energy-efficient route and
speed. It also minimizes the risk of running out of power before arriving at the destination or a charging station.

The most common way to estimate a battery’s SOC is Coulomb-counting. This is done by measuring the charging/discharging current and integrating it in time. Although this method is easy to implement and is commonly used, however, it is very sensitive to current measurement error and the accuracy degrades along with long-term drift. So the SOC requires to be calibrated when the SOC reaches zero or 100% when a charger detects that the battery is fully drained or charged. The smart Lithium-ion batteries used in this research have so-called “fuel-gauge,” which is a Coulomb counter, to estimate SOC. The charger designed in this research simply gets SOC information by communicating with the fuel-gauge inside a smart battery through System Management Bus (SMBus).

Another way to estimate a battery’s SOC is to use a circuit model with a constant voltage source and capacitor/resistor pairs to represent a battery, as shown in Figure 8.1. The open-circuit voltage $V_{oc,k}$ of the voltage source is a non-linear function of $SOC_k$, where $k$ is the $k$-th battery is the system. State estimation methods for nonlinear system can be used jointly with the battery model shown in Figure 8.1, thus providing the following benefits: (i) SOC estimation is perform in real time. (ii) Long-term SOC drift due to accumulated measurement error is avoided.
The relationship between $\text{SOC}_k$ and $V_{oc,k}$ in Figure 8.1 can be extracted from the data of $V_{oc}$-versus-SOC charging/discharging experiments. The data is usually used to perform curve-fitting and $V_{oc,k}$ can be expressed in polynomials with single variable $\text{SOC}_k$ [61]:

$$V_{oc,k}(\text{SOC}_k) = \sum_{p=0}^{q} a_p \cdot \text{SOC}_k^p = a_0 + a_1 \cdot \text{SOC}_k + a_2 \cdot \text{SOC}_k^2 + a_3 \cdot \text{SOC}_k^3 \cdots$$

(8-1)

The $\text{SOC}_k$ of Battery #\(k\) is the ratio of remaining capacity to the nominal total capacity, which can be expressed as below:

$$\text{SOC}_k(t) = \text{SOC}_k(0) - \int_{0}^{t} \frac{I_{DK}(t)}{C_{\text{nom},k}} d\tau$$

(8-2)

where $C_{\text{nom},k}$ denotes the nominal total capacity of Battery #\(k\).

A complete discrete-time state space model including $\text{SOC}_k$ as one of the states can be derived as below:

---

Figure 8.1 (a) A commonly-used electrical model for a single battery [61]. (b) Voltage response when a step load current is applied to a single battery.
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\[
\begin{bmatrix}
V_{TS,k}[m+1] \\
V_{TL,k}[m+1] \\
SOC_k[m+1]
\end{bmatrix}_{n_k[m+1]} =
\begin{bmatrix}
T \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
R_{TS,k} & 0 & 0 \\
0 & R_{TS,k} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{TS,k}[m] \\
V_{TL,k}[m] \\
SOC_k[m]
\end{bmatrix}_{n_k[m]} +
\begin{bmatrix}
-1 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
R_{TS,k} \cdot e^{-R_{TS,k} \cdot T} \\
R_{TL,k} \cdot e^{-R_{TL,k} \cdot T} \\
- \frac{T}{C_{nom,k}}
\end{bmatrix}
\begin{bmatrix}
I_{D,k}[m] \\
I_{B,k}[m]
\end{bmatrix}_{n_k[m]}
\]

(8-3)

Since \( V_{oc,k}(SOC_k) \) is nonlinear, the system in (3) can be modeled as the following general nonlinear system:

\[
x_k[m+1] = f_k(x_k[m], u_k[m]) + w_k[m]
\]

\[
y_k[m] = g_k(x_k[m], u_k[m]) + v_k[m]
\]

(8-4)

where \( w_k[m] \) represents “process noise” which cannot be measured and \( v_k[m] \) represents “measurement noise” resulting from the sensors.

In the new proposed battery management system, different batteries are allowed to be connected in parallel. When discharging in parallel, each battery with different \( SOC_k \) will have different discharging current \( I_{D,k} \). For a system with \( N \) batteries (\( 1 \leq k \leq N \)) connected to the DC bus, the state space model of the system can be expressed as follows:

\[
X[m+1] = F[m] + W[m]
\]

\[
Y[m] = G[m] + V[m]
\]

(8-5)

where \( X = [x_1, x_2, \ldots, x_k, \ldots, x_N]^T \), \( Y = [y_1, y_2, \ldots, y_k, \ldots, y_N]^T \), \( F = [f_1, f_2, \ldots, f_k, \ldots, f_N]^T \), \( G = [g_1, g_2, \ldots, g_k, \ldots, g_N]^T \), \( W = [w_1, w_2, \ldots, w_k, \ldots, w_N]^T \), and \( V = [v_1, v_2, \ldots, v_k, \ldots, v_N]^T \).

Note that the vector \( Y \) includes terminal voltages of all batteries connected to the DC bus. Because there is no resistor or diode between each battery and the DC bus, the components in the vector \( Y \) should be all equal to the voltage of the DC bus.
Many state estimation methods have been proposed for nonlinear systems, including Extended Kalman filters (EKF) [86, 114], unscented Kalman filters (UKF)[115, 116], and NPR Kalman filters [117]. EKF uses a linearization process to approximate a nonlinear system by taking the first-order Taylor-series expansion. UKF uses unscented transformation technique to linearize a nonlinear system. UKF is accurate to the third order for Gaussian inputs for all nonlinearities and at least to the second order for non-Gaussian inputs. Both EKF and UKF need to differentiate the model and have been used for single-battery modeling. *The process of finding a derivative of the model might not be efficient for some low-cost microcontrollers and DSPs because it requires more data memory and might consume more processing time. An estimation method without the need of differentiating the model could be more efficient for low-cost microcontrollers and DSPs.*

The NPR Kalman filters is a *derivative-free* state estimation method. To the best of the author’s knowledge, no one has applied this method on battery modeling. Therefore, future research may intend to apply this method to estimate the SOC and terminal voltage and predict the maximum available charging/discharging power and the runtime. The literature review, experiments, and verification of NPR Kalman filters on battery modeling are the remaining tasks needed to be finished in the future.

### 8.3 Conclusion

In this dissertation, we have presented the methods of maximizing energy delivery for different battery packs in parallel without regulated bus. The major contribution of this
dissertation is to prove that different battery packs can be used in parallel by adopting the approaches developed in this dissertation, even if there is no DC-DC converter, diode, or resister between each battery pack and the load. Although we have developed, designed, and built battery management systems managing the energy flow among input power sources, different battery packs, and loads for military use, the ideas can be also applied to remote power applications such as campers/hikers at camping sites, telecommunication stations, solar battery charging stations, and electric vehicles for extending the service time of different battery packs in parallel.

The first part of this dissertation proposes a new system architecture and new algorithms to address the technical difficulties of using different battery in parallel. For charging, each different battery pack can be individually charged to its full SOC. For discharging, algorithms are proposed to control the sequence and the number of battery packs used to share the load according to the load transient condition. The concepts of the proposed algorithms are verified and the benefits of this energy management system are demonstrated. Because of substantially fewer parts and no need of DC-DC converter interfacing each battery and the DC bus, the physical design and cost for the energy management system architecture is substantially reduced.

The second and the third part of this dissertation propose methods of maximizing the conversion efficiency between input power sources and loads when solar panels are used as the input power sources in our proposed system architecture. There are two new maximum power point tracking (MPPT) methodologies proposed and verified in this dissertation: (i) For a system with battery as energy storage and a periodic nonlinear load, a modified perturb-and-observe algorithm by tracking only the output current of the DC-
DC converter is proposed to address the problem of poor MPPT efficiency induced by the periodic nonlinear load. (ii) For a system with multiple DC-DC converters connected in parallel, a new distributed MPPT control strategy by fast input current change is proposed. The fast input current change is achieved by quickly turning on/off chargers and does not require uniform power sharing among all the parallel converters. It provides the benefit of fast maximum power point search even though there is partial shading.

Finally, recommendation of future research is proposed: (i) the modified perturb-and-observe algorithm by tracking only the output current of the DC-DC converter could be improved such that it is suitable for periodic nonlinear loads with arbitrary frequency. (ii) Derivative-free state estimation methods (NPR Kalman filters) can be used to estimate SOC of a battery and it could be easy and efficient to implement the state estimation methods in low-cost microcontrollers and DSPs.
Bibliography


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Bibliography


Bibliography


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Bibliography


Appendix

A. Internal Resistance Measurement

Figure A.1 shows the implementation of a laboratory prototype built for testing. The supervisory host is formed by dsPIC33FJ256GP710A DSP. The host communicates with the charger and controls the switches $S_k$ via RS485 network.

The battery bank consists of four lithium-ion batteries from two different manufacturers, each with nominal voltage 14.4V and nominal capacity 13.6Ah. The maximum continuous discharge current $I_{D,k,MAX}$ of the batteries from manufacturer-A and manufacturer-B are 20A [60] and 12A [51], respectively. To verify whether the internal...
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Resistance $R_{S,k}$ of the batteries used in the prototype is independent of the instantaneous battery voltage $V_{T,k}$, an intermittent discharging experiment were performed to extract $R_{S,k}$ of each type of the batteries for the SOC range 0-100%. The duty ratio and the intermittent discharging current are 25% (40s ON, 120s OFF). The batteries are discharged from full (16.5V, SOC = 100%) to empty (10V, SOC = 0%). The instantaneous battery voltage $V_{T,k}$ was recorded so that $R_{S,k}$ can be extracted from the instantaneous voltage drop $V_{\text{Drop},k}$. Figure A.2 shows $V_{T,k}$-versus-time and $R_{S,k}$-versus-time graphs of one battery from manufacturer-A. The magnitude of the intermittent discharging current is 12A. The extracted $R_{S,k}$ is approximately a constant until $V_{T,k}$ approaches 10V. The extracted $R_{S,k}$ of the batteries from manufacturer-B also exhibits the same trend. This implies the $R_{S,k}$ of the batteries used in the prototype is independent of $V_{T,k}$.

Figure A.2 The instantaneous battery voltage $V_{T,k}$ of one battery from manufacturer-A when an intermittent discharge of 12A was applied. The computed internal resistance $R_{S,k}$ is approximately a constant until $V_{T,k}$ approaches 10V.
To examine the relation between $R_{S,k}$ and $I_{D,k}$, different magnitudes of step load currents were applied to the batteries. This can be done without considering $V_{T,k}$. Figure A.3 shows the battery voltage $V_{T,k}$ with respect to time when different $I_{D,k}$ ($1A \leq I_{D,k} \leq I_{D,k,MAX}$) was applied to the batteries from both manufacturers. The corresponding $V_{Drop,k}$ versus $I_{D,k}$ was computed based on the data in Figure A.3, as shown in Figure A.4. $V_{Drop,k}$ is observed to be linearly dependent to $I_{D,k}$ for the batteries from both manufacturers, so linear regression was conducted to extract $R_{S,k}$. The $R_{S,k}$ of the battery from manufacturer-A and manufacturer-B are approximately 0.1185 Ω and 0.1579 Ω, respectively. In the following experiments, an assumption is made that $R_{S,k}$ values of the batteries from the same manufacturer are the same.

Figure A.3 The battery voltage $V_{T,k}$ with respect to time when different discharge current $I_{D,k}$ was applied to a single battery. (a) Manufacturer-A: $1A \leq I_{D,k} \leq 20A$. (b) Manufacturer-B: $1A \leq I_{D,k} \leq 12A$. 

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Figure A.4 The computed $V_{\text{Drop},k}$ with respect to different $I_{D,k}$. The results show that $V_{\text{Drop},k}$ is linearly dependent on $I_{D,k}$ for the batteries from both manufacturers. Then $R_{S,k}$ is extracted from linear regression.
(a) Manufacturer-A: $R_{S,k} \sim 0.1185 \, \Omega$. (b) Manufacturer-B: $R_{S,k} \sim 0.1579 \, \Omega$.

B. How to Determine $\alpha$ and $\beta$ Thresholds

In Chapter 3, we have introduced the thresholds $\alpha$ and $\beta$:

A first threshold $\alpha$ representing the minimum required voltage drop $\Delta V_{\text{BUS}}$ on the DC bus is defined in Figure A.5(a), while a second threshold $\beta$ representing the minimum required voltage gap $\Delta V_{\text{GAP},k}$ is defined in Figure A.5(b). The algorithm always examines the following two conditions:

$$\Delta V_{\text{BUS}} \equiv V_{\text{BUS}}(t_a) - V_{\text{BUS}}(t_b) > \alpha ? \quad (1)$$

$$\Delta V_{\text{GAP},k} \equiv V_{\text{oc},k} - V_{\text{BUS}}(t_b) > \beta ? \quad (2)$$

Eq. (1) is examined first. If $\Delta V_{\text{BUS}} > \alpha$ is satisfied, which means a voltage drop on the DC bus is confirmed, then Eq. (2) is examined for Battery #k not connected to the DC bus. If $\Delta V_{\text{GAP},k} > \beta$ is satisfied, which means that $V_{\text{oc},k}$ higher than the DC bus is confirmed, then the switch $S_k$ is closed such that Battery #k is able to share the load current. For medium load, the switches of
the batteries with a lower voltage of SOC may not be closed. For heavy load, the switches of all batteries will be closed.

When the load increases, there is a quick drop in the DC bus voltage due to the increasing discharging current $I$ and its voltage drop across the internal resistance $R_s$ of the single battery that is connected to the DC bus. Thus,

$$\Delta V_{BUS} \equiv V_{BUS}(t_a) - V_{BUS}(t_b) = I_D \times R_S$$  \hspace{1cm} (3)$$

The internal resistance $R_s$ can be derived from the instantaneous voltage drop $\Delta V$. The $R_s$ of one of the lithium-ion battery used in the experiments is about 0.1579$\Omega$ for the specific lithium-ion batteries used in our proposed system. Besides, according to [51], the maximum allowed discharging current $I$ for single lithium battery is 12A. This means the maximum $\alpha$ is 1.89V. Therefore, the range of $\alpha$ is roughly chosen as

$$\alpha < \alpha_{\text{MAX}} = \Delta V_{BUS,\text{MAX}} = I_{D,\text{MAX}} \times R_S = 1.89V$$  \hspace{1cm} (4)$$

Figure A.5. (a) Condition 1: Check if $\Delta V_{BUS}$ is larger than $\alpha$. (b) Condition 2: Check if $\Delta V_{GAP_k}$ is larger than $\beta$. 

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For example, if $\alpha = 1V$, criteria (1) is satisfied when the increased load current exceeds about 6.33A (52.78% C-rate).

On the other hand, $\beta$ can be a fixed value for all batteries or a dynamic function of $V_{BATTERY}$. In either case, $\beta$ should be less than 0.5V per cell for Li-ion batteries (about 3.03-3.57% nominal voltage) or the battery that had been connected to the DC bus might be over discharged. Three examples are given as below:

- $\beta = 1V$ for all batteries:

  Consider two batteries in the system. The first one is 16V and connected to the DC bus. The second one is 15V and disconnected from the DC bus. Because $\beta = 1V$, $V_{BUS}$ has to be as low as 14V so that criteria (2) is satisfied. However, the voltage drop $\Delta V_{BUS}$ (2V) on the DC bus will cause the first battery to discharge more than 12A, which exceeds the maximum allowed discharging limit for single lithium battery.

- $\beta = 0.3V$ for all batteries:

  Consider two batteries in the system. The first one is 16V and connected to the DC bus. The second one is 15V and disconnected from the DC bus. Because $\beta = 0.3V$, $V_{BUS}$ has to be as low as 14.7V so that criteria (2) is satisfied. The voltage drop $\alpha$ (1.3V) on the DC bus will cause the first battery to discharge about 8.23A, which does not exceed the maximum allowed discharging limit for single Li-ion battery.

- $\beta = 0.2 \times (V_{BATTERY} – 14V)$ for all batteries:

  Consider four batteries in the system.

  $$V_{BATTERY}(1) = 14.5V$$
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\[ V_{\text{BATTERY}}(2) = 16.4\text{V} \]
\[ V_{\text{BATTERY}}(3) = 16.0\text{V} \]
\[ V_{\text{BATTERY}}(4) = 15.0\text{V} \]

Because \( V_{\text{BATTERY}}(2) \) is the highest, initially only Battery #2 is connected to the DC bus. \( \beta \) values of Batteries #1, #3, and #4 are

\[ \beta \text{ of Battery } #1 = 0.2 \times [V_{\text{BATTERY}}(1) - 14\text{V}] = 0.1\text{V} \]
\[ \beta \text{ of Battery } #3 = 0.2 \times [V_{\text{BATTERY}}(3) - 14\text{V}] = 0.4\text{V} \]
\[ \beta \text{ of Battery } #4 = 0.2 \times [V_{\text{BATTERY}}(4) - 14\text{V}] = 0.2\text{V} \]

\( V_{\text{BUS}} \) has to be as low as 14.4V, 15.6V, and 14.8V for Batteries #1, #3, and #4 respectively so that criteria (2) is satisfied. The lower the open circuit voltage \( V_{\text{BATTERY}} \), the smaller the threshold \( \beta \). Besides, as \( V_{\text{BATTERY}} \) is 14V, \( \beta = 0 \), which means as long as \( V_{\text{BUS}} \) is as low as 14V, the battery with \( V_{\text{BATTERY}} = 14\text{V} \) is connected. If the rule of “\( \beta = 0.3\text{V for all batteries} \)” in the second example is chosen, \( V_{\text{BUS}} \) has to be as low as 13.7V so that the battery with \( V_{\text{BATTERY}} = 14\text{V} \) is connected. This may increase the risk of over-discharge of other batteries which have been connected to the DC bus.

The above examples show that the purpose of choosing lower \( \beta \) for Battery \#k is to reduce the risk of over-discharging the batteries which have been connected to the DC bus. Whether each battery is assigned with the same or different \( \beta \), the recommended maximum \( \beta \) is 0.5V for the Li-ion batteries used in the experiments.

The minimum \( \alpha \) and \( \beta \) must be a small positive but non-zero number. The quantity of the minimum \( \alpha \) and \( \beta \) is determined by the resolution of the analog-to-digital converter (ADC) and the ADC error due to non-ideal factors such as quantization error and noise.
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Besides, the ADC error is magnified by the gain of the voltage divider, which is used to scale the battery voltage value to conform to the ADC’s available dynamic range [118]. In general, the minimum $\alpha$ and $\beta$ can be determined by the following equation:

$$\alpha_{MIN} = \beta_{MIN,k} \geq n \times \frac{V_{REF+} - V_{REF-}}{2^n - 1} \times G_{vd} \equiv n \times Q \times G_{vd}$$  \hspace{1cm} (5)

where $Q$ denotes the least significant bit (LSB) voltage, $n$ denotes the amount of LSB voltage due to non-idealities, $V_{REF+}$ and $V_{REF-}$ denote the maximum and minimum analog input values specified for the ADC, $R$ denotes the resolution of ADC, and $G_{vd}$ denotes the gain of the voltage divider. For example, in the prototype system a 10-bit ($R = 10$) ADC is used with $n = 3$, $V_{REF+} = 5V$, $V_{REF-} = 0V$, and $G_{vd} = 7.821$. So $\alpha_{MIN}$ and $\beta_{MIN,k}$ for each battery are 0.115V. The chosen $\alpha$ and $\beta$ should be always higher than the lower limit, or there is a chance that without increasing load the battery not connected to the DC bus might be connected accidentally when $\Delta V_{BUS}$ is not positive and $V_{BUS}$ is not lower than the resting voltage $V_{oc,k}$ of Battery $#k$.

C. SMBus Implementation

The software for SMBUS communication has been developed in both C and Assembly version. The C source code was developed by Stephanie Quinn and the Assembly source code was translated from C source code and developed by Chung-Ti Hsu. Parts of both source codes are listed in next pages.
#if defined(__dsPIC33F__)  
/* #include "p33Fxxxx.h" */  
#include "p33FJ128MC804.h"  //h file for the device   
#endif  
#endif  
//Include file for toggle debug

// Configuration Register Settings  
// Internal FRC Oscillator  
_FOSCSEL(FNOSC_FRC);  // FRC Oscillator  
_FOSC(FCKSM_CSECMD & OSCIOFNC_OFF & POSCMD_NONE);  
  // Clock Switching is enabled and Fail Safe Clock Monitor is disabled  
  // OSC2 Pin Function: OSC2 is Clock Output  
  // Primary Oscillator Mode: Disabled  

_FWDT(FWDTEN_OFF);  // Watchdog Timer Enabled/disabled by user software

volatile int rw;  
volatile int da;  

unsigned char RAMBuffer[256];  //RAM area which will work as EEPROM for Master I2C device  
void tglPinInit();  
void i2c1_init();  //Program for initializing I2C1 Module  
void I2C1MASTER();  //Program for initializing I2C1 Module

//Begin the Main Function

int main(void)  
{  
  //unsigned int i;  
  // Configure Oscillator to operate the device at 40Mhz  
  // Fosc= Fin*M/(N1*N2), Fcy=Fosc/2  
  // Fosc= 7.37*43/(2*2)=80Mhz for 7.37 input clock  
  PLLFBDS=41;  // M=43  
  CLKDIVbits.PLLPOST=0;  // N1=2  
  CLKDIVbits.PLLPRE=0;  // N2=2  
  OSCTUN=0;  // Tune FRC oscillator, if FRC is used  
  // Disable Watch Dog Timer  
  RCONbits.SWDTEN=0;  
}  

// Clock switch to incorporate PLL
__builtin_write_OSCCONH(0x01);        // Initiate Clock Switch to
    // FRC with PLL (NOSC=0b001)
__builtin_write_OSCCONL(0x01);        // Start clock switching
while (OSCCONbits.COSC != 0b001);    // Wait for Clock switch to occur

// Wait for PLL to lock
while(OSCCONbits LOCK!=1);
// Now PLL is ready
/* for(i = 0;i<256;i++)
 { 
    RAMBuffer[i] = i;       //Initialize RAMBuffer with some value
    //in case MasterI2C device wants to read
    //before it writes to it.
 } */

i2c1_init();     // Program code for I2C1 module

while(1)
{
    I2C1MASTER();     // Program code for I2C1 module
}
}
/**********************************************************************
* Name  : i2c_MC804.c
* Author: Stephanie Quinn
***********************************************************************/

#if defined(__dsPIC33F__)
#include "p33Fxxxx.h"
#else defined(__PIC24H__)  
#include "p24Hxxxx.h"
#endif

void tglPin();  //external pin 7 will toggle HIGH

unsigned char DevAddWrite;
unsigned char DevAddRead;
unsigned char CommandCode[30];  //create arrays for storing command codes and data
unsigned char DataLSB[30];      //used for dummy read
unsigned char DataMSB[30];      //used for dummy read
unsigned char PEC[30];          //used for dummy read
unsigned int j;                 //used with the arrays
unsigned int k;                 //used with the arrays
unsigned int LoopComplete;      //indicates when 28 Command Codes and data have been completed
unsigned int state;
unsigned int i;
unsigned int countstate0;
unsigned int countstate1;
unsigned int countstate2;
unsigned int countstate3;
unsigned int countstate4;
unsigned int countstate5;
unsigned int countstate6;
unsigned int countstate7;
unsigned int countstate8;
unsigned int countstate9;
unsigned int countstate10;
unsigned int countstate11;
unsigned int countstate12;
unsigned int countstate13;
unsigned int countstateBusReset;
unsigned int countInt0;
unsigned int countInt1;
unsigned int countInt2;
unsigned int countInt3;
unsigned int countInt4;
unsigned int countInt5;
unsigned int countInt6;
unsigned int countInt7;
unsigned int countInt8;
unsigned int countInt9;
unsigned int countInt10;
unsigned int countInt11;
unsigned int countInt12;
unsigned int countInt13;
unsigned int countIntBusReset;

void i2c1_init(void)
{
    for(j=0; j<=28; j++)
    {
        CommandCode[j]=j;  //initialize arrays
        DataLSB[j]=j;      //used for dummy read
        DataMSB[j]=j;      //used for dummy read
        PEC[j]=j;          //used for dummy read
    }

    k=0;  //initialize k for arrays

    LoopComplete=0;  //initialize

    /*******************************************************************************
     I2C Settings for dsPIC33 in Master Mode
     *******************************************************************************/

    /* Settings for I2C1CON =1001 0001 0100 0000
       *                      |||| |||| |||| |||SEN=0 Start condition not in progress (when
operating as I2C Master)*
    *                      |||| |||| |||| |||RSEN=0 Repeated Start condition not in
progress (when operating as I2C Master)
    *                      |||| |||| |||| |PEN=0 Stop condition not in progress (when
operating as I2C Master)
    *                      |||| |||| |||| RCEN=0 Receive sequence not in progress (when
operating as I2C Master)
    *                      |||| |||| |||ACKEN=0 Acknowledge sequence not in progress
(when operating as I2C Master)
    *                      |||| |||| ||ACKDT=0 Send ACK during Acknowledge (when
operating as I2C Master)
    *                      |||| |||| |STREN=1 Enable software or receive clock stretching
    *                      |||| |||| GCEN=0 General call address disabled
    *                      |||| |||| SMEN=1 Enable I/O pin thresholds compliant with SMBus
specs
    *                      |||| ||DISSLW=0 Slew rate control enabled
    *                      |||| |A10M=0 I2C1ADD is a 7-bit slave address
    *                      |||| IPMIEN=0 Intelligent Peripheral Management Interface mode
disabled
    *                      |||SCLREL=1 release SCL clock
    *                      ||I2CSID=0 continue operation in Idle mode
    *                      |Bit 14=0 not implemented
    *                      I2CEN=0 disables I2C1 module */

    //I2C1BRG = 0x0030;  //baud rate register--value from i2cEmem.c, didn't work */
    //I2C1BRG = 0x001F9;  //for I2C clock of 78 kHz, I2C1BRG is 9 bits maximum */
    //I2C1BRG = 0x001FF;  //for I2C clock of 77.1 kHz, I2C1BRG is 9 bits maximum */
    //I2C1BRG = 0x00188;  //for I2C clock of 100 kHz, I2C1BRG is 9 bits maximum */
    I2C1BRG = 0x01FF;  //for I2C clock, I2C1BRG is 9 bits maximum
/* I2C1ADD = 0x0008; //this is the SMBus Host address 0001 000, dspIC33 is pretending to be the host */
/* I2C1ADD = 0x0009; //this is the device address for charger 0001 001 */
I2C1ADD = 0x0000; //this is the dummy device address
I2C1MSK = 0x0000; // no address masking

I2C1CON = 0x9140; //enable I2C1 module, enable SMBus-compliant I/O pins, enable clock stretching

DevAddWrite = 0x0016; //Smart battery address 0001 011 plus 0
DevAddRead = 0x0017; //Smart battery address 0001 011 plus 1

/* CommandCode = 0x0000; //Command Code initialized */

IEC1bits.MI2C1IE = 1; //enable Master Events Interrupt Request
IFS1bits.MI2C1IF = 0; //Initialize I2C1 Master Events Interrupt Flag Status Bit

state=1; //initialize state
i=0; //initialize i
countstate0=0; //initialize countstate

countstate1=0;
countstate2=0;
countstate3=0;
countstate4=0;
countstate5=0;
countstate6=0;
countstate7=0;
countstate8=0;
countstate9=0;
countstate10=0;
countstate11=0;
countstate12=0;
countstate13=0;
countstateBusReset=0;
countInt0=0;
countInt1=0;
countInt2=0;
countInt3=0;
countInt4=0;
countInt5=0;
countInt6=0;
countInt7=0;
countInt8=0;
countInt9=0;
countInt10=0;
countInt11=0;
countInt12=0;
countInt13=0;
countIntBusReset=0;
I2C Master Interrupt Service Routine

The following events cause an MI2C Interrupt:
--Successful completion of START, RESTART, or STOP Condition
--Transmission of ACK/NACK by Master
--Data byte transmitted or received
--Bus Collision

This function checks to see which event in the I2CMaster function
caused the interrupt, sets the next step in the I2CMaster function,
and clears the I2C Master Interrupt flag.

/*=============================================================================*/
void __attribute__((interrupt, no_auto_psv)) _MI2C1Interrupt(void)
{
  
  if(I2C1STATbits.BCL==1)
  {
    countInt0=countInt0+1;
    state=1;
    //If yes, then go to Start Condition
  }

  else if((I2C1STATbits.S==1)&&(state==1))
  {
    countInt1=countInt1+1;
    state=2;
    //If Yes, then Transmit Device Address byte
  }

  else if((I2C1STATbits.TBF==0)&&(state==2))
  {
    countInt2=countInt2+1;
    if(I2C1STATbits.ACKSTAT==1)
    {
      state=0;
      //Smart battery didn't Acknowledge
      //You must begin again at the Start Condition
    }
    else if(I2C1STATbits.ACKSTAT==0)
    {
      state=3;
      //Smart battery Acknowledges receipt of byte
      //So, the next step is to transmit the Command Code
    }
  }

  else if((I2C1STATbits.TBF==0)&&(state==3))
  {
    countInt3=countInt3+1;
    if(I2C1STATbits.ACKSTAT==1)
    {
      state=0;
      //Smart battery didn't Acknowledge
      //You must begin again at the Start Condition
    }
    else if(I2C1STATbits.ACKSTAT==0)
    {
      state=4;
      //Smart battery Acknowledges receipt of byte
      //The next step is to send the Restart Condition
    }
  }

  else if ((I2C1CONbits.RSEN==0)&&(state==4))
  {
    countInt4=countInt4+1;
    state=5;
    //The next step is to transmit the
else if((I2C1STATbits.TBF==0)&&(state==5)) //Was the Transmit Device Address plus 1 completed?
{
    countInt5=countInt5+1;
    if(I2C1STATbits.ACKSTAT==1) //Smart battery didn't Acknowledge
        state=0; //You must begin again at the Start Condition
    else if(I2C1STATbits.ACKSTAT==0) //Smart battery Acknowledges receipt of byte
        state=6; //The next step is to receive the Data LSB from the battery
}
else if((I2C1STATbits.RBF==1)&&(state==6)) //Was the Data LSB received from the battery?
{
    countInt6=countInt6+1;
    DataLSB[k]=I2C1RCV; //Move Data LSB out of the I2C1RCV register
    state=7; //The next step is to send the Acknowledge to the battery
}
else if((I2C1CONbits.ACKEN==0)&&(state==7)) //Was the Master's Acknowledge completed?
{
    countInt7=countInt7+1;
    state=8; //The next step is to receive the Data MSB from the battery
}
else if((I2C1STATbits.RBF==1)&&(state==8)) //Was the Data MSB received from the battery?
{
    countInt8=countInt8+1;
    DataMSB[k]=I2C1RCV; //Move Data MSB out of the I2C1RCV register
    state=9; //The next step is to send the Acknowledge to the battery
}
else if((I2C1CONbits.ACKEN==0)&&(state==9)) //Was the Master's Acknowledge completed?
{
    countInt9=countInt9+1;
    state=10; //The next step is to send the Stop Condition
}
else if((I2C1STATbits.RBF==1)&&(state==10)) //Was the PEC received from the battery?
{
    countInt10=countInt10+1;
    PEC[k]=I2C1RCV; //Move PEC out of the I2C1RCV register
    state=11; //The next step is to send the Acknowledge to the battery
}
else if((I2C1CONbits.ACKEN==0)&&(state==11)) //Was the Master's Acknowledge completed?
{
    countInt11=countInt11+1;
    state=12; //The next step is to send the Stop Condition
}
else if((I2C1CONbits.PEN==0)&&(state==12)) //Was the Stop Condition (indicating end of message) completed?
{
    countInt12=countInt12+1;
    state=1; //If yes, then try to begin Start Condition
    k=k+1; //increment arrays
}

else if((I2C1CONbits.PEN==0)&&(state==0)) //Was the Stop Condition (to reset the bus) completed?
{
    countIntBusReset=countIntBusReset+1;
    state=1; //If yes, then try to begin Start Condition
}
else
{
    countInt13=countInt13+1;
    state=0; //default state
}

I2C1STATbits.BCL=0;  //Clear Bus Collision detect bit
IFS1bits.MI2C1IF = 0;  //Clear the IFS1 Interrupt Flag;

/*=============================================================================*/
I2C Slave Interrupt Service Routine
=============================================================================*/
void __attribute__((interrupt, no_auto_psv)) _SI2C1Interrupt(void)
{
    IFS1bits.SI2C1IF = 0;  //Clear the DMA0 Interrupt Flag
}

/*=============================================================================*/
I2C Master SMBus Host Communication with Smart Battery
This function steps through the protocol for sending a message to the Smart Battery.
=============================================================================*/
/*void I2CMASTER(unsigned char DevAddWrite, unsigned char CommandCode, unsigned char
DevAddRead, unsigned int State,
unsigned char PEC) */
void I2C1MASTER()
while(k<=28) //loop through 29 Command Codes 0x0000 through 0x0001c
{
  if(countstateBusReset==1000)
    break; // this step added so that host can break out of loop if battery isn't acknowledging
  if(state==0) //If the host has to stop communication in the middle of the packet
  {
    //for some reason, it should always send the stop bit to reset everyone
    //on the bus
    countstateBusReset=countstateBusReset+1;
  }
  I2C1CONbits.ACKEN=0; //I2C1CON<4:0> must be 0 before attempting to set PEN bit
  I2C1CONbits.RCEN=0;
  I2C1CONbits.PEN=0;
  I2C1CONbits.RSEN=0;
  I2C1CONbits.SEN=0;
  I2C1CONbits.PEN=1; //Generate Stop Condition
  while(I2C1CONbits.PEN) //Wait for Stop Condition
  {
    /* if(I2C1STATbits.IWCOL==1) //Did a Write Collision occur?
    {
      I2C1STATbits.IWCOL=0; //Clear the Write Collision bit
      state=0; //Resend the message
    }
    else
      state=1; //START CONDITION is next
    */
  }
  if(state==1) //START CONDITION/
  {
    countstate1=countstate1+1; //count the number of times the program hits state 1
    for(i=0;i<=5000;i++) //need a minimum delay of TBUF=4.7usec between Stop and Start Condition per SMBus spec
    {
      i=i+1;
    }
    if((I2C1STATbits.P==1)&&(I2C1STATbits.S==0)) //Is the bus idle?
    {
      I2C1CONbits.SEN=1; //If Yes, then generate Start Condition
    }
  }
  while(I2C1CONbits.SEN) //Wait for completion of Start Condition
/* if(I2C1STATbits.IWCOL==1)   //Did a Write Collision occur?
   {
      I2C1STATbits.IWCOL=0;   //Clear the Write Collision bit
      state=0;   //Resend the message
   }
   */
}

else if(state==2)   //TRANSMIT DEVICE ADDRESS
{
   countstate2=countstate2+1;
   if (I2C1STATbits.TBF==0)   //check to see if I2C1TRN register is empty
   {
      I2C1TRN=DevAddWrite;   //Send Device Address plus 0
      while(I2C1STATbits.TRSTAT)   //Wait while Master Transmission (8 bits and ACK)
         is in progress
         {
         }
   }
   while(I2C1STATbits.TBF)   //Wait for data transmission (8 bits)
   {
      /* if(I2C1STATbits.IWCOL==1)   //Did a Write Collision occur?
         {
            I2C1STATbits.IWCOL=0;   //Clear the Write Collision bit
            state=0;   //Resend the message
         }
         */
      }
   }
   }
   if(state==3)   //TRANSMIT COMMAND CODE
{
   countstate3=countstate3+1;
   if (I2C1STATbits.TBF==0)   //check to see if I2C1TRN register is empty
   {
      I2C1TRN=CommandCode[k];   //Send Command Code
      while(I2C1STATbits.TRSTAT)   //Wait while Master Transmission (8 bits and ACK) is
         in progress
         {
         }
   }
   while(I2C1STATbits.TBF)   //Wait for data transmission (8 bits)
   {
      /* if(I2C1STATbits.IWCOL==1)   //Did a Write Collision occur?
         {
            I2C1STATbits.IWCOL=0;   //Clear the Write Collision bit
            state=0;   //Resend the message
         }
         */
      }
   }
}
else if (state==4) //RESTART CONDITION
    { countstate4=countstate4+1;
      I2C1CONbits.RSEN=1;
      while(I2C1CONbits.RSEN) //wait for completion of Restart Condition
          {
          }
    }

else if (state==5) //TRANSMIT DEVICE ADDRESS FOR READ
    { countstate5=countstate5+1;
      if (I2C1STATbits.TBF==0) //check to see if I2C1TRN register is empty
          {
            I2C1TRN=DevAddRead;   //Send Device Address plus 1
            while(I2C1STATbits.TRSTAT) //Wait while Master Transmission (8 bits and ACK) is in progress
                {
                }
          }
    }
while(I2C1STATbits.TBF) //Wait for data transmission (8 bits)
    { if(I2C1STATbits.IWCOL==1)  //Did a Write Collision occur?
        {
          I2C1STATbits.IWCOL=0; //Clear the Write Collision bit
          state=0;   //Resend the message
        }
    }

else if (state==6) //RECEIVE DATA LSB
    { countstate6=countstate6+1;
      I2C1CONbits.ACKEN=0;   //I2C1CON<4:0> must be 0 before attempting to set RCEN bit
      I2C1CONbits.RCEN=0;
      I2C1CONbits.PEN=0;
      I2C1CONbits.RSEN=0;
      I2C1CONbits.SEN=0;
      I2C1CONbits.RCEN=1;  //Enable Master to receive Data LSB from battery
      while(I2C1CONbits.RCEN) //Wait for Data LSB to be received
            {
            if (I2C1STATbits.I2COV==1) //Did a Receive Overflow occur?
                {
                I2C1STATbits.I2COV=0; //Clear Receive Overflow bit
                state=0;    //Resend the message
                }
            }
    }
else if(state==7)  //ACKNOWLEDGE DATA LSB
{
    countstate7=countstate7+1;
    I2C1CONbits.ACKEN=0; //I2C1CON<4:0> must be 0 before attempting to set ACKEN bit
    I2C1CONbits.RCEN=0;
    I2C1CONbits.PEN=0;
    I2C1CONbits.RSEN=0;
    I2C1CONbits.SEN=0;
    I2C1CONbits.ACKDT=0;  //Master sets Acknowledge to 0 to indicate receipt of Data LSB
    I2C1CONbits.ACKEN=1; //Master sends Acknowledge bit to battery
    while(I2C1CONbits.ACKEN) //Wait for ACK to complete
    {
        /* if(I2C1STATbits.IWCOL==1) //Did a Write Collision occur? 
        { 
            I2C1STATbits.IWCOL=0;  //Clear the Write Collision bit 
            state=0;  //Resend the message 
        } */
    }
} else if(state==8)  //RECEIVE DATA MSB
{
    countstate8=countstate8+1;
    I2C1CONbits.ACKEN=0; //I2C1CON<4:0> must be 0 before attempting to set RCEN bit
    I2C1CONbits.RCEN=0;
    I2C1CONbits.PEN=0;
    I2C1CONbits.RSEN=0;
    I2C1CONbits.SEN=0;
    I2C1CONbits.RCEN=1;  //Enable Master to receive Data MSB from battery
    while(I2C1CONbits.RCEN) //Wait for Data MSB to be received
    {
        if (I2C1STATbits.I2COV==1) //Did a Receive Overflow occur?
        {
            I2C1STATbits.I2COV=0;  //Clear Receive Overflow bit 
            state=0;  //Resend the message 
        }
    }
} else if(state==9)  //ACKNOWLEDGE DATA MSB
{  
    countstate9=countstate9+1;
    I2C1CONbits.ACKEN=0; //I2C1CON<4:0> must be 0 before attempting to set ACKEN
I2C1CONbits.RCEN=0;
I2C1CONbits.PEN=0;
I2C1CONbits.RSEN=0;
I2C1CONbits.SEN=0;

I2C1CONbits.ACKDT=0;  //Master sets Acknowledge to 0 to indicate receipt of Data MSB

I2C1CONbits.ACKEN=1;  //Master sends Acknowledge bit to battery
while(I2C1CONbits.ACKEN)  //Wait for ACK to complete
{
    /* if(I2C1STATbits.IWCOL==1)  //Did a Write Collision occur?
    {
        I2C1STATbits.IWCOL=0;  //Clear the Write Collision bit
        state=0;  //Resend the message
    }
    */
}

else if(state==10)  //RECEIVE DATA PEC, Packet Error Checking byte
{
    countstate10=countstate10+1;
    I2C1CONbits.ACKEN=0;  //I2C1CON<4:0> must be 0 before attempting to set RCEN bit
    I2C1CONbits.RCEN=0;
    I2C1CONbits.PEN=0;
    I2C1CONbits.RSEN=0;
    I2C1CONbits.SEN=0;
    I2C1CONbits.RCEN=1;  //Enable Master to receive PEC from battery
    while(I2C1CONbits.RCEN)  //Wait for PEC to be received
    {
        if (I2C1STATbits.I2COV==1)  //Did a Receive Overflow occur?
        {
            I2C1STATbits.I2COV=0;  //Clear Receive Overflow bit
            state=0;  //Resend the message
        }
    }
}

else if(state==11)  //ACKNOWLEDGE DATA PEC
{
    countstat11=countstat11+1;
    I2C1CONbits.ACKEN=0;  //I2C1CON<4:0> must be 0 before attempting to set ACKEN bit
    I2C1CONbits.RCEN=0;
    I2C1CONbits.PEN=0;
    I2C1CONbits.RSEN=0;
    I2C1CONbits.SEN=0;
    I2C1CONbits.ACKDT=1;  //Master sets Acknowledge to 1 so slave won't send more
//and so slave will not hold data line low waiting for clocks from Master

I2C1CONbits.ACKEN=1;  //Master sends Acknowledge bit to battery
while(I2C1CONbits.ACKEN)  //Wait for ACK to complete
{

/* if(I2C1STATbits.IWCOL==1)  //Did a Write Collision occur? */
{
    I2C1STATbits.IWCOL=0;  //Clear the Write Collision bit
    state=0;  //Resend the message
}
/* */

else if (state==12)  //STOP CONDITION
{
    countstate12=countstate12+1;
    I2C1CONbits.ACKEN=0;  //I2C1CON<4:0> must be 0 before attempting to set PEN bit
    I2C1CONbits.RCEN=0;
    I2C1CONbits.PEN=0;
    I2C1CONbits.RSEN=0;
    I2C1CONbits.SEN=0;
    I2C1CONbits.PEN=1;  //Generate Stop Condition
    while(I2C1CONbits.PEN)  //Wait for Stop Condition
    {
/* if(I2C1STATbits.IWCOL==1)  //Did a Write Collision occur? */
{
    I2C1STATbits.IWCOL=0;  //Clear the Write Collision bit
    state=0;  //Resend the message
}
/* */

} else
{
    countstate13=countstate1+1;
    state=0;  //default state
}
}

else
{

}

LoopComplete=k;  // k=28 indicates that all Command Codes have been read in
SMBusSoc

movlw DisableHighLowISR
movwf PIE1 ; From B'01000010' to B'00000000'

movff BSR, BSR_TEMP2
banksel I2C_Channel
movlw BatteryType_Primary ; check if BatteryType is primary or nothing
cpfslt BatteryType
goto SMBusSocEnd_LJ03

; Initialize
clrf jj
clrf I2C_Channel
; clrf CommandCode
; clrf kk
clrf I2CFail1_Counter
clrf I2CFail2_Counter
clrf BatteryType
movlw BatteryType_Li_woSMBus
movwf BatteryType ; assume BatteryType = BatteryType_Li_woSMBus

Init
movlw 0x0D
movwf CommandCode
movwf kk

Begin
movlw I2CFail1_Counter_Max
cpfslt I2CFail1_Counter
goto SMBusSocEnd
movlw I2CFail2_Counter_Max
cpfslt I2CFail2_Counter
goto SMBusSocEnd

CollisionCheck ; Did a bus collision occur?
movlw 0x01

Check_BCL1IF
btfss PIR2, BCL1IF ; Check BCL1IF
bra Check_BCL2IF
bcf PIR2, BCL1IF ; Clear Bus Collision Flag

Check_BCL2IF
btfss PIR3, BCL2IF ; Check BCL2IF
bra State0
bcf PIR3, BCL2IF ; Clear Bus Collision Flag
movwf state ; A bus collision occurred, goto start condition
bra Begin

; *** Begin I2C Data Transfer Sequences ***

State0
movlw 0x00
cpfs eq state
bra State1
; Send and Check the STOP condition and wait for it to complete.
call Clear_SSPxCON2
btfsc I2C_Channel, 0
bra State0_I2C2
bra State0_I2C1
State0_I2C1
bsf SSP1CON2, PEN ; Send STOP condition
call WaitMSSP1 ; Wait for I2C operation to complete
incf state
bra State1
State0_I2C2
bsf SSP2CON2, PEN ; Send STOP condition
call WaitMSSP2 ; Wait for I2C operation to complete
incf state
bra State1
I2CWrite
; Send START condition and wait for it to complete
State1
movlw 0x01
cpseq state
bra State2
Waiting ; Minimum delay of TBUF = 4.7u sec between
incf jj ; Stop and Start Conditions per SMBus spec.
nop ; Each loop is about 0.9u sec
nop
nop
nop
movlw 0xFF ; 0.9u sec * 255 = 230u sec
cpseq jj
bra Waiting ; Total delay is 230u sec
; It seems like the minimum value. (Not 4.7u sec)
clfj jj
call Clear_SSPxCON2
btfsc I2C_Channel, 0
bra State1_I2C2
bra State1_I2C1
State1_I2C1
bsf SSP1CON2, SEN ; Generate START Condition
call WaitMSSP1 ; Wait for I2C operation to complete
incf state
bra State2
State1_I2C2
bsf SSP2CON2, SEN ; Generate START Condition
call WaitMSSP2 ; Wait for I2C operation to complete
incf state
bra State2
; Send and Check ADDRESS BYTE, wait for it to complete
State2
movlw 0x02
cpseq state
bra State3
call Clear_SSPxCON2
btfsc I2C_Channel, 0
bra State2_I2C2
bra State2_I2C1
bra State2_I2C2

tfsc SSP1STAT, BF ; Check if SSP1BUF is empty
bra State2
movlw B'00010110' ; Load Write Address Byte
call Send_I2C_Byte ; Send Byte
call WaitMSSP1 ; Wait for I2C operation to complete
tfsc SSP1CON2, ACKSTAT ; Check ACK Status bit to see if I2C
bra I2CFail1
incf state
bra State3

State2_I2C2

tfsc SSP2STAT, BF ; Check if SSP1BUF is empty
bra State2
movlw B'00010110' ; Load Write Address Byte
call Send_I2C_Byte ; Send Byte
call WaitMSSP2 ; Wait for I2C operation to complete
tfsc SSP2CON2, ACKSTAT ; Check ACK Status bit to see if I2C
bra I2CFail2
incf state
bra State3

; Send and Check COMMAND BYTE, wait for it to complete
State3

movlw 0x03
cpfseq state
bra State4
call Clear_SSPxCON2
tfsc I2C_Channel, 0
bra State3_I2C2
bra State3_I2C1

State3_I2C1

tfsc SSP1STAT, BF ; Check if SSP1BUF is empty
bra State3
movff CommandCode, WREG
call Send_I2C_Byte ; Send Byte
call WaitMSSP1 ; Wait for I2C operation to complete
tfsc SSP1CON2, ACKSTAT ; Check ACK Status bit to see if I2C
bra I2CFail1
incf state
bra State4

State3_I2C2

tfsc SSP2STAT, BF ; Check if SSP1BUF is empty
bra State3
movff CommandCode, WREG
call Send_I2C_Byte ; Send Byte
call WaitMSSP2 ; Wait for I2C operation to complete
tfsc SSP2CON2, ACKSTAT ; Check ACK Status bit to see if I2C
bra I2CFail2
incf state
bra State4

I2CRead

; Send RESTART condition and wait for it to complete
State4
movlw 0x04
    cpfseq state
    bra State5
    call Clear_SSPxCON2
    btfs I2C_Channel, 0
    bra State4_I2C2
    bra State4_I2C1

State4_I2C1
    bsf SSP1CON2, RSEN ; Generate RESTART Condition
    call WaitMSSP1 ; Wait for I2C operation to complete
    incf state
    bra State5

State4_I2C2
    bsf SSP2CON2, RSEN ; Generate RESTART Condition
    call WaitMSSP2 ; Wait for I2C operation to complete
    incf state
    bra State5

; Send and Check ADDRESS BYTE, wait for it to complete
State5
    movlw 0x05
    cpfseq state
    bra State6
    btfs I2C_Channel, 0
    bra State5_I2C2
    bra State5_I2C1

State5_I2C1
    btfs SSP1STAT, BF ; Check if SSP1BUF is empty
    bra State5
    movlw B'00010111' ; Load Read Address Byte
    call Send_I2C_Byte ; Send Byte
    call WaitMSSP1 ; Wait for I2C operation to complete
    btfs SSP1CON2, ACKSTAT ; Check ACK Status bit to see if I2C
    bra CollisionCheck
    incf state
    bra State6

State5_I2C2
    btfs SSP2STAT, BF ; Check if SSP1BUF is empty
    bra State5
    movlw B'00010111' ; Load Read Address Byte
    call Send_I2C_Byte ; Send Byte
    call WaitMSSP2 ; Wait for I2C operation to complete
    btfs SSP2CON2, ACKSTAT ; Check ACK Status bit to see if I2C
    bra CollisionCheck
    incf state
    bra State6

; Switch MSSP module to I2C Receive mode
State6
    movlw 0x06
    cpfseq state
    bra State7
    btfs I2C_Channel, 0
    bra State6_I2C2
    bra State6_I2C1
State6_I2C1
216       State6_I2C1
217   btfsb SSP1STAT, BF ; Check if SSP1BUF is empty
218       bra State6
219   call Clear_SSPxCON2
220       bsf SSP1CON2, RCEN ; Enable Receive Mode (I2C)
221 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
222 ; The receive mode is disabled at end automatically by the MSSP module.
223   call WaitMSSP1 ; Wait for I2C operation to complete
224   lfsr FSR0, DataLSB_Leg1
225   movff kk, WREG
226   movff SSP1BUF, PLUSW0 ; Move Data LSB out of SSP1BUF, save it to *(DataLSB_Leg1 + kk)
227       incf state
228       bra State7
229 ; Send ACK bit for Acknowledge Sequence
230   movlw 0x07
231   cpseq state
232       bra State8
233   call Clear_SSPxCON2
234   btfsb I2C_Channel, 0
235       bra State7_I2C2
236       bra State7_I2C1
237       State7_I2C1
238   bcf SSP1CON2, ACKDT ; ACK DATA to send is 0, which is ACK.
239       bsf SSP1CON2, ACKEN ; Send ACK DATA now.
240 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
241 ; The receive mode is disabled at end automatically by the MSSP module.
242   call WaitMSSP1 ; Wait for I2C operation to complete
243       incf state
244       bra State8
245       State7_I2C2
246   bcf SSP2CON2, ACKDT ; ACK DATA to send is 0, which is ACK.
247       bsf SSP2CON2, ACKEN ; Send ACK DATA now.
248 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
249 ; The receive mode is disabled at end automatically by the MSSP module.
250   call WaitMSSP2 ; Wait for I2C operation to complete
251       incf state
252       bra State8
253 ; Switch MSSP module to I2C Receive mode
254   movlw 0x08
255   cpseq state
256       bra State9
257 ; Switch MSSP module to I2C Receive mode
258   movlw 0x08
259   cpseq state
260       bra State9
261 ; Switch MSSP module to I2C Receive mode
262   movlw 0x08
263   cpseq state
264       bra State9
265 ; Switch MSSP module to I2C Receive mode
266   movlw 0x08
267   cpseq state
268       bra State9
btfscl I2C_Channel, 0
bra State8_I2C2
bra State8_I2C1
State8_I2C1
 btfscl SSP1STAT, BF ; Check if SSP1BUF is empty
bra State8
 call Clear_SSPxCON2
bsf SSP1CON2, RCEN ; Enable Receive Mode (I2C)
 bra State8
 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
call WaitMSSP1 ; Wait for I2C operation to complete
1fsr FSR0, DataMSB_Leg1
movff kk, WREG
movff SSP1BUF, PLUSW0 ; Move Data MSB out of SSP1BUF, save it to *(DataMSB_Leg1 + kk)
incf state
bra State9
State8_I2C2
 btfscl SSP2STAT, BF ; Check if SSP1BUF is empty
bra State8
 call Clear_SSPxCON2
bsf SSP2CON2, RCEN ; Enable Receive Mode (I2C)
 bra State8
 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
call WaitMSSP2 ; Wait for I2C operation to complete
1fsr FSR0, DataMSB_Leg2
movff kk, WREG
movff SSP2BUF, PLUSW0 ; Move Data MSB out of SSP1BUF, save it to *(DataMSB_Leg1 + kk)
incf state
bra State9
 ; Send ACK bit for Acknowledge Sequence
State9
 movlw 0x09
 cpfseq state
bra State10
 call Clear_SSPxCON2
btfscl I2C_Channel, 0
bra State9_I2C2
 bra State9_I2C1
 bcf SSP1CON2, ACKDT ; ACK DATA to send is 0, which is ACK.
bsf SSP1CON2, ACKEN ; Send ACK DATA now.
 bra State9_I2C2
 bcf SSP2CON2, ACKDT ; ACK DATA to send is 0, which is ACK.
bsf SSP2CON2, ACKEN ; Send ACK DATA now.
 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
call WaitMSSP1 ; Wait for I2C operation to complete
incf state
bra State10
 ; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
call WaitMSSP2 ; Wait for I2C operation to complete
incf state
bra State10

; Switch MSSP module to I2C Receive mode
State10
movlw 0x0A
cpseq state
bra State11
btfs I2C_Channel, 0
bra State10_I2C2
bra State10_I2C1

State10_I2C1
btfs SSP1STAT, BF ; Check if SSP1BUF is empty
bra State10
call Clear_SSPxCON2
bsf SSP1CON2, RCEN ; Enable Receive Mode (I2C)

; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
; The receive mode is disabled at end automatically by the MSSP module.
call WaitMSSP1 ; Wait for I2C operation to complete
lfsr FSR0, PEC_Leg1
movff kk, WREG
movff SSP1BUF, PLUSW0 ; Move PEC_Leg1 out of SSP1BUF, save it to *(PEC_Leg1 + kk)
incf state
bra State11

State10_I2C2
btfs SSP2STAT, BF ; Check if SSP1BUF is empty
bra State10
call Clear_SSPxCON2
bsf SSP2CON2, RCEN ; Enable Receive Mode (I2C)

; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
; The receive mode is disabled at end automatically by the MSSP module.
call WaitMSSP2 ; Wait for I2C operation to complete
lfsr FSR0, PEC_Leg2
movff kk, WREG
movff SSP2BUF, PLUSW0 ; Move PEC_Leg1 out of SSP1BUF, save it to *(PEC_Leg1 + kk)
incf state
bra State11

; Send ACK bit for Acknowledge Sequence
State11
movlw 0x0B
cpseq state
bra State12

call Clear_SSPxCON2
btfs I2C_Channel, 0
bra State11_I2C2
bra State11_I2C1

State11_I2C1
bsf SSP1CON2, ACKDT ; ACK DATA to send is 1, which is NACK.
bsf SSP1CON2, ACKEN ; Send ACK DATA now.

; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
; The receive mode is disabled at end automatically by the MSSP module.
call WaitMSSP1 ; Wait for I2C operation to complete
incf state
bra State12

State11_I2C2

bsf SSP2CON2, ACKDT ; ACK DATA to send is 1, which is NACK.
bsf SSP2CON2, ACKEN ; Send ACK DATA now.

; Get the DATA BYTE and wait for it to complete. Data is in SSP1BUF when done.
; The receive mode is disabled at end automatically by the MSSP module.
call WaitMSSP2 ; Wait for I2C operation to complete
incf state
bra State12

; Send and Check the STOP condition and wait for it to complete.

State12

movlw 0x0C
cpfseq state
clrf state
call Clear_SSPxCON2
btfsc I2C_Channel, 0
bra State12_I2C2
bra State12_I2C1

State12_I2C1

bsf SSP1CON2, PEN ; Send STOP condition
call WaitMSSP1 ; Wait for I2C operation to complete
bra State12_End

State12_I2C2

bsf SSP2CON2, PEN ; Send STOP condition
call WaitMSSP2 ; Wait for I2C operation to complete
bra State12_End

State12_End

clrf state
incf state
incf kk
incf CommandCode
call Clear_SSPxCON2

movlw 0x1D ; D'30'
movlw 0x0E ; D'14'
cpfsigt kk
bra Statel
bra Ending

; *** SUBROUTINES & ERROR HANDLERS ***

I2CFail1

incf I2CFail1_Counter
bsf SSP1CON2, PEN ; Send STOP condition
call WaitMSSP1 ; Wait for I2C operation to complete
bcf PIR2, BCL1IF
movlw 0x01
movwf state
bra Begin

I2CFail2

incf I2CFail2_Counter
bsf    SSP2CON2, PEN ; Send STOP condition
call   WaitMSSP2 ; Wait for I2C operation to complete
bcf    PIR3, BCL2IF
movlw  0x01
movwf  state
bra    Begin

; This routine sends the W register to SSPBUF, thus transmitting a byte.
; Then, the SSP1IF flag is checked to ensure the byte has been sent successfully.
; When that has completed, the routine exits, and executes normal code.
Send_I2C_Byte
movwf  SSP1BUF ; Get value to send from W, put in SSP1BUF
movwf  SSP2BUF ; Get value to send from W, put in SSP1BUF
return

; This routine waits for the last I2C operation to complete.
; It does this by polling the SSP1IF flag in PIR1.
WaitMSSP1
btfss  PIR1, SSP1IF ; Check if done with I2C operation
bra    WaitMSSP1 ; I2C module is not ready yet
bcf    PIR1, SSP1IF ; I2C module is ready, clear flag.
return
WaitMSSP2
btfss  PIR3, SSP2IF ; Check if done with I2C operation
bra    WaitMSSP2 ; I2C module is not ready yet
bcf    PIR3, SSP2IF ; I2C module is ready, clear flag.
return

Clear_SSPxCON2
movlw  B'11100000'
andwf  SSP1CON2 ; clear [4:0]: ACKEN, RCEN, PEN, RSEN, SEN
andwf  SSP2CON2 ; clear [4:0]: ACKEN, RCEN, PEN, RSEN, SEN
return

Ending
movlw  0x00
movlw  0x00
clrfr  PIR2
clrfr  jj
movlw  0x0D
movwf  kk
movwf  CommandCode
clrfr  state
btfsc  I2C_Channel, 0
bra    SMBusSocEnd
btg    I2C_Channel, 0
goto   Init
SMBusSocEnd
movlw  I2CFail1.Counter_Max ;if I2CFail1.Counter /= 3
cpfsLt I2CFail1.Counter
goto   SMBusSocEnd_LJ01 ;set BatteryType_Li_woSMBus
movlw  I2CFail2.Counter_Max ;if I2CFail2.Counter /= 3
cpfsLt I2CFail2.Counter
goto   SMBusSocEnd_LJ01 ;set BatteryType_Li_wiSMBus
goto   SMBusSocEnd_LJ02 ;set BatteryType_Li_wiSMBus
SMBusSocEnd_LJ01

movlw BatteryType_li_wiSMBus
movwf BatteryType

movlw RelativeSOCWrong
movwf DataLSB_Leg1+

movwf DataLSB_Leg2+

goto SMBusSocEnd_LJ03

SMBusSocEnd_LJ02

movlw BatteryType_li_wiSMBus
movwf BatteryType

goto SMBusSocEnd_LJ03

SMBusSocEnd_LJ03

incf I2C_Counter
addlw 0x00 ; Clear carry bit

clr PIR1

clr PIR2

clr PIR3

movff BSR_TEMP2, BSR

movlw EnableHighLowISR

movwf PIE1 ;From B'00000000' to B'01000010'

;Enable ADC interrupt (low level)

;Enable TMR2 to PR2 match interrupt (high level)

return

504

505

506