PHOTOVOLTAIC NANOGRID: PARALLEL OPERATING INVERTERS AND ENERGY MANAGEMENT FLOW

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# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CF</td>
<td>Cost Function</td>
</tr>
<tr>
<td>CHB</td>
<td>Cascaded H-Bridge</td>
</tr>
<tr>
<td>DDP</td>
<td>Deterministic Dynamic Programming</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resource</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DP</td>
<td>Dynamic Programming</td>
</tr>
<tr>
<td>DOC</td>
<td>Depth Of Charge</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency</td>
</tr>
<tr>
<td>LF</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>MSWI</td>
<td>Modified Sine Wave Inverter</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nicke Metal Hydride</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
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</tr>
<tr>
<td>PDP</td>
<td>Piecewise Dynamic Programming</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>RB</td>
<td>Rule Based</td>
</tr>
<tr>
<td>SOC</td>
<td>State Of Charge</td>
</tr>
<tr>
<td>SOH</td>
<td>State Of Health</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptable Power Supply</td>
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Dedicated to My Family
Abstract

This thesis first presents the design of a lightweight, compact and high reliability modified sine wave inverter. The inverter is integrated with foldable photovoltaic (PV) panel, maximum power point tracking (MPPT) charger and rechargeable battery to construct a portable PV nanogrid that can supply both DC and AC loads, for campers, hikers and especially soldiers on the move.

The designed modified sine wave inverters are able to operate in parallel to achieve higher power rating and higher system reliability. However, existing current sharing methods used to parallel either pure sine wave inverters or DC-DC converters cannot be applied directly to modified sine wave inverters because of possible circulating currents. This dissertation proposes methods to safely parallel the modified sine wave inverters without adding filtering inductors or capacitors. The methods merge approaches used to parallel pure sine wave inverters with methods sometimes used to parallel DC-DC converters. The developed approaches are then extended to parallel cascaded H-bridge multilevel inverters.

For a even higher power movable nanogrid, such as those that may include a solar tents, battery storage and a diesel generator, it is not feasible to parallel too many designed inverters for energy management. For such system, the research proposes optimal power management approaches to reduce operating costs by managing the power flows in a PV-diesel generator hybrid nanogrid with batteries. The proposed algorithms utilize dynamic programming (DP) technique to optimize the power flows in the system to meet the load demand, achieve maximum utilization of the
solar energy available, minimize fuel consumption and increase battery life cycle, simultaneously. The optimization algorithm also deals with the uncertainty of the PV power.
Chapter 1

Introduction

1.1 Motivation and Background

Economic pressures, technology achievements and environmental incentives are changing the face of electricity generation. Centralized generating facilities are giving way to smaller, more distributed generation [1]. This kind of distributed generation (DG) encompasses a wide range of prime mover technologies, such as internal combustion engines, gas turbines, microturbines, photovoltaic, fuel cells and wind power. A better way to realize the emerging potential of DG is to take a systems approach, which views generation and associated loads as a subsystem or a microgrid [2]. Microgrids can be defined as systems that have at least one DG of distributed energy resource (DER) and associated loads, with the ability to form intentional islands in electrical distribution systems. The DGs can operate
in parallel to the grid or can operate in ‘island’ mode (stand-alone), providing uninterruptable power supply (UPS) services. The microgrid disconnects from the utility during large events (i.e. faults, voltage collapses), but may also intentionally disconnect when the quality of power from the grid falls below certain standards. Microgrids are a future power system configuration providing clear economic and environmental benefits compared to expanding our legacy modern power systems. They can also offer improved service reliability and a reduced dependency on the local utility \[3–5\].

Extensive research, development and demonstration efforts on microgrids have provided operating concepts in laboratories and in pilot installations. However, the microgrids, until now, are usually grid-tie and developed at the power level in the tens to hundreds of kilowatts for local distributed energy. For the low power level in the several kilowatts, such as a residential electrical system, the microgrid concept can also be applied, and it may be termed a nanogrid \[6–9\]. The nanogrid keeps many of the same benefits of a microgrid, such as power quality and reliability, alleviating peak load pressure seen by grid, avoiding peak energy costs and reducing fossil fuel use/carbon emissions.

Fig. 1.1 illustrates the block diagram of an ideal nanogrid system. Power from the local renewable resources is converted by power electronics to supply the local DC and AC loads, and it also has the interface to accept/feed power from/to other DC or AC grids. Because the renewable energy sources may be intermittent, batteries
can be utilized as energy buffers. Wired or wireless communication are accompa-
nied with each energy flow to transmit data to the power management controller of the system, which is in charge of the whole system. The inputs of the controller could be necessary information, such as past load patterns, renewable energy generation data or cost of the energy of other grids. The outputs of the controller are the commands to manage the power flow in the system. The objective of the power flow management is to solve certain optimization problems, for example, to realize load prioritization, optimizing the use of sustainable energy and peak load shaving.

In this research, we consider to further reduce the nanogrid power level to 100W suitable for the individual soldier or recreational hiker, and we will focus on the renewable energy source to be portable, flexible solar panels, which are lightweight and easy to carry. Their application has already been widely utilized in the US Army, as shown in Fig. 1.2.

![Block diagram of an ideal nanogrid system.](image-url)
Chapter 1. Introduction

(a) Foldable PV panels
(b) Solar tent

Figure 1.2: PV applications for army.

The grand vision of this research is to revolutionize the human-on-the-move energy systems by creating a plug and play portable energy systems composed by multiple nanogrids, as shown in Fig. 1.3. Each nanogrid is at a low power level of 100W - 5kW and its structure is applicable for individual portable PV panels, solar tents and even Humvee batteries. From a low power level (several hundred Watts) individual nanogrid point of view, several individuals can connect existing handheld nanogrids together to share power, so as to achieve AC power output at higher power to run various equipment. This leads to higher peak current capabilities, better utilization of foldable PV panels, and gives partially charged batteries more flexibility to run equipment for longer missions (e.g. > 72hrs). From a high power level (several kilo Watts) point of view, the small individual nanogrid will be able to create power in its own island, but it will also be able to connect to larger power nanogrids that contain Humvee batteries or solar tents. Similarly, they can all be connected to diesel generators or any other compatible nanogrid, and the whole energy system can be further connected to a high power utility grid.
or other microgrids. The vision is to have plug-and-play interconnected nanogrids that have bidirectional power flow and are able to operate peer-to-peer, meaning that AC and DC power outputs of all the nanogrids are perfectly synchronized, independent of the power level of each one.

![Diagram of a future military microgrid](image)

**Figure 1.3:** Grand vision of plug-and-play and peer-to-peer future military microgrid constructed by multiple nanogrids.

Each nanogrid has its own energy management controller, and all the nanogrids can communicate with each other through communication bus to coordinate the power flow in the microgrid, as shown in Fig. 1.3. By doing so, optimal operation of the system can be achieved. For example, the controller can prioritize loads and send energy to the most important loads when there is inadequate power; the diesel generator consumption can be regulated to reduce the fuel usage, and the state of charge (SOC) of batteries can maintained in the proper range.
1.2 Problem Statement

This thesis research will develop lightweight energy management electronics, interconnectivity protocols between low energy systems, control software, and optimization in power management, all for the purpose to operate small power level nanogrids.

Specifically, the strategic goals or objectives of this research are three-fold:

1.2.1 Small Size, High Reliability and Low Cost Handheld PV Nanogrid

Portable (handheld) PV nanogrid for individuals should have small size, high reliability and low cost. As a result, there exist tradeoffs between the real system shown in Fig. 1.4 and the ideal nanogrid shown in Fig. 1.1. The first goal of this thesis is to propose the design of a modified sine wave inverter. The designed inverter can be integrated to a handheld PV nanogrid consisting of a foldable PV panels, an MPPT charger, and smart batteries that can supply power to either DC or AC loads. The potential difficulties lie in the compact design of modified sine wave inverters and its integration into the MPPT charger to generate AC and DC power simultaneously [10]. Also the research needs to develop a dedicated controller to optimize energy management and power system protection. At last, the designed inverter should have the ability to be connected in parallel or in series
for the further research. Chapter 2 describes in more detail the research outcomes on the portable handheld nanogrids.

![Block diagram of the simplest PV nanogrid system](image)

**Figure 1.4**: Block diagram of the simplest PV nanogrid system that can supply both DC and AC loads, the arrows are the directions of the energy flow.

### 1.2.2 Parallel Operation of Inverters

After the individual handheld nanogrid is designed, the next stage of the research will be to combine them in parallel to increase power levels. Inverter parallel operation can expand the capacity and enhance the redundancy, expandability and reliability of inverter interfaced power system. As a result, the second goal of this research is to develop methods to parallel the modified sine wave inverters. However, parallel connections of inverters is more complex than paralleling DC sources, because the magnitude, phase and frequency of output voltage and current of each inverter should all be taken into account to minimize circulating current flowing among the parallel inverters, to achieve equal load sharing and to deliver high
quality power. Several control strategies have been previously proposed in literature to parallel inverters. They can be classified into two main groups according to the use of control wire interconnections. The first group is based on active load sharing techniques, such as centralized [11], master-slave (MS) [12–16], circular chain control (3C) [17], and average load sharing (ALS) [18–20]. These control schemes can achieve both good output-voltage regulation and equal current sharing, but they need a critical intercommunication line among modules, which could reduce the system reliability and expandability. The second group is based on the frequency and droop method, which makes tight adjustments over the output voltage frequency and amplitude of the inverter, as a power dependent function, to compensate for the active and reactive power unbalances [21–25]. This kind of control scheme only needs local measured information and does not rely on intercommunication signals between the inverters. Therefore it can achieve higher reliability and flexibility.

For this research, a difficulty lies in the impedance mismatch among the inverter that introduces circulating current. Also, there may be power balance issues that will cause some inverter modules to be thermally overstressed or even damaged. On the other hand, unlike in traditional microgrids, the working condition is more complicated in the proposed nanogrid because the modified sine wave inverters are used instead of the pure sine wave inverters. The parallel operating modified sine wave inverter scenario has not been investigated in previous literature, and
therefore, this research must introduce control methods specifically for the paralleling of modified sine wave inverters. The second objective of this research will be to propose approaches to maintain good current sharing. Chapter 3 presents the research results pertaining to paralleling the modified sine wave inverters.

1.2.3 Power Flow Management in the Nanogrid

Parallel operation of handheld PV nanogrids can achieve several hundred Watts, but it is unrealistic to assume dozens of users will get together to create power levels in several kilowatts. For power level of several kilowatts, solar tents may be used as shown in the right part of Fig. 1.3. For this kind of nanogrid, research must be focused on the power flow management.

In remote areas, diesel generators are regularly used as a power source for supplying electrical energy but the transport and storage of the fuel becomes difficult and dangerous if the area is battlefield. The integration of solar tents in the power system can reduce a large amount of fuel consumption by diesel generators. However, the solar energy generated by solar tents is intermittent, so that a battery is normally introduced as the energy storage to alleviate power fluctuation. Thus, the solar tent nanogrid can be considered as a hybrid power system, and the third part of this thesis research will study how to make best use of the PV energy with the lowest costs, especially the fuel consumption of the external diesel generator. Design and operation of such nanogrid needs the consideration of two aspects,
optimal sizing of the solar tent, energy storage and diesel generator [26–28] and optimal energy management [29–33]. However, most of the proposed methods in the literature are for high power level and grid-tie applications, and they cannot be used directly for the smaller power systems studied in this research. So, the last objective of this research is to propose new power management controller suitable for the PV nanogrid at the power level in the range 100W-5kW. Chapter 4 further explains the proposed research in the power flow management.

1.3 Dissertation Organization

To solve the problems listed above and to achieve the PV nanogrid system introduced, this dissertation aims to re-investigate the modified sine wave inverter applications in the nanogrid at the power level of several hundred watts. The research also proposes new methods to parallel multiple modified sine wave inverters and extends the approach to parallel multilevel inverters. For the nanogrid system at the power level of several kilowatts, this dissertation proposes a new optimal energy flow management algorithm. Therefore, we can achieve multiple desired optimization goals at the same time. Specifically, the dissertation is organized as follows.

The design, prototyping and testing of a low cost, low power (~100W), and small energy management system is presented in Chapter 2. Chapter 3 discusses the new method to achieve parallel working of modified sine wave inverters and its extension
to parallel multilevel inverters. Chapter 4 focuses on the design of optimal energy flow management algorithm for a PV-diesel generator hybrid nanogrid system with batteries. In Chapter 5, a summary of the thesis research results is presented and future research works are addressed.

A brief summary of each chapter is listed below.

**Chapter 2:** Modified Sine Wave Inverter in a Portable Nanogrid. In this chapter, the benefits and drawbacks of a modified sine wave inverter versus pure sine wave inverter are compared. Then design of a modified sine wave inverter for the portable nanogrid system is demonstrated. After that, a portable nanogrid system integration is explained. Finally, experimental results of the modified sine wave inverter for the portable nanogrid system are presented.

**Chapter 3:** Parallel Operation of Modified Sine Wave Inverters. After the individual modified sine wave inverter is designed, the next step is to achieve parallel operation of multiple designed inverters to achieve higher power level, better system redundancy and improved flexibility. In this chapter, the problem statement for the parallel operation of modified sine wave inverters is first introduced. A literature review of past research is also presented. Then, a new method to parallel modified sine wave inverters is proposed. It utilizes dead
time control to eliminate the circulating current and adopts piecewise master-slave current sharing to equalize output power of each inverter. Experimental results of parallel working of modified sine wave inverters is shown to verify the proposed method. The proposed method for the parallel operation of modified sine wave inverters is then extended to the parallel operation of multilevel inverters. Experimental results for parallel five-level inverters validates the new approaches.

Chapter 4: Optimal Power Flow Management in a Photovoltaic Nanogrid with Batteries. Besides the parallel operation of the inverters in the designed nanogrid, another important aspect for this research is to achieve the optimal energy flow in the nanogrid. Chapter 4 first presents the system configuration and modeling of a PV nanogrid. After the system modeling, optimization problem formulation is derived. The objective of the optimization is to achieve low fuel consumption, low battery lifetime loss and maximum utilization of the available solar energy simultaneously. To realize this objective, three algorithms are proposed. The first algorithm is a rule based algorithm. It may not achieve optimal energy flow but it will not violate system operation constraints, so it will be used as a reference. The second algorithm is using dynamic programming (DP), and it can achieve global system optimization, as long as load profile and PV
power are known. To deal with uncertainty of PV power, a modified DP algorithm is proposed. Simulation and experimental results are demonstrated to verify the effectiveness of the proposed algorithms.

Chapter 5: Conclusion and Future Research. In this chapter, the conclusions of the thesis are presented, and future work is discussed in detail.

1.4 Contributions

This dissertation demonstrates several major research contributions and technical advancements over the previous solutions.

Contribution 1: Individual modified sine wave inverters are designed. The designed inverter utilizes a high frequency transformer to reduce size and cost, employs parallel converter architecture to increase reliability and exploits a digital signal processor (DSP) to achieve full system protection and other needed functions. The designed inverter can be easily utilized with a PV panel, MPPT charger and battery in order to construct a portable nanogrid system which can supply both DC and AC loads simultaneously.

Contribution 2: Parallel operation of modified sine wave inverters is realized in the low power portable nanogrid system. For the first time, a method
to parallel the modified sine wave inverters without adding filtering inductors or capacitors is developed. The method merges approaches used to parallel pure sine wave inverters with approaches sometimes used to parallel DC-DC converters. Switch signals must be carefully synchronized; robust DC-DC converters serve as inputs of the H-bridge, while piecewise master-slave DC-DC converter strategies are used to equalize current distributions among the inverters.

**Contribution 3 :** *Optimal energy flow algorithms are developed in the PV tent nanogrid system.* An algorithm for the PV nanogrid has been derived to optimize the power flow using DP. With the battery storage integrated as the energy buffer, the algorithm can achieve maximum possible utilization of the solar energy, lowest fuel consumption, and lowest battery health loss simultaneously. Compared with the rule based algorithm, the advantages of the designed algorithm are verified by the simulation and experimental results.
Chapter 2

Modified Sine Wave Inverter in a Small Energy Management System

For individual applications, a 150W digital controlled modified sine wave inverter has been designed, tested and successfully integrated with the Maximum Power Point Tracking (MPPT) charger, PV panel and battery to construct a portable nanogrid system. The research contributions presented in this chapter for the achievement of the individual nanogrid system include:

- Advantages and disadvantages of modified sine wave inverter versus pure sine wave inverter have been investigated. It is found that although pure sine wave inverters are applicable for all AC loads, modified sine wave inverters
are cheaper, lighter, often more compact and can still supply power to most types of AC loads. Specifically, modified sine wave inverters are suitable for the type of problems studied in this research pertaining to soldiers on-the-move.

- A low cost, small size and reliable modified sine wave inverter is designed and experimentally built. Its structure and features are explained. The designed inverter utilizes a high frequency transformer to reduce size and cost, employs parallel converter architecture to increase reliability, and exploits a digital signal processor (DSP) to achieve full system protection and other needed functions.

- The designed modified sine wave inverter can be easily integrated with PV panel, MPPT charger and battery to construct a portable nanogrid system, which can supply both DC and AC loads simultaneously. The system has the architecture as shown in Fig. 1.4 and the energy flow can be controlled by the cooperation of the MPPT charger and inverter.

- Experimental test results are presented to verify the performance of the inverter designed, and the portable nanogrid system constructed. The inverter has compact design, and it can output reliable AC power in modified sine waveform. The designed handheld nanogrid can supply DC and AC loads at the same time with the foldable PV panels as the input source.
2.1 Benefits of modified sine wave inverter versus pure sine wave inverter

Extensive research, development, and demonstration efforts have focused on pure sine wave inverters. This attention is due to their accurate sinusoidal waveform and minimum total harmonic distortion (THD), which is compatible with utility grid standards. However, the disadvantage of the pure sine wave inverter is that typically it is expensive and bulky due to the big and heavy transformer and output filter. The cost for a pure sine inverter is high, and often a great number of loads do not need such a stringent THD that the pure sine wave inverter provides. Another category of inverters, modified sine wave inverters, have seen widespread commercial application, particularly in the low power level. As shown in Fig. 2.1, a modified sine wave inverter output voltage is a modified square wave with some dead spots between its positive and negative half-cycles. Specifically, the 3-level voltage of a modified sine wave inverter is $V_{dc}$, 0, $-V_{dc}$, and duty cycle and magnitude of the waveform are controlled to regulate output voltage to $120V_{RMS}$. The 3-level voltage waveform is connected directly to the load without using any output inductor. Compared with the pure sine wave inverter, the modified sine wave inverter is cheaper, lighter, and often more compact. A most commonly found application of a modified sine wave inverter is the 12V input cigarette lighter inverter for automobiles, as shown in Fig. 2.2. The hikers, campers and especially soldiers on the move have to carry many kinds of electronic devices and the burden
is heavy. As a result, a compact and light-weight individual modified sine wave inverter to supply stand-alone AC power is beneficial.

![Diagram of Pure Sine Wave and Modified Sine Wave](image1)

**Figure 2.1:** Comparison of pure sine wave, modified sine wave and multilevel waveforms.

![Image of Modified Sine Wave Inverter](image2)

**Figure 2.2:** A typical commercial car-use modified sine wave inverter and its output voltage waveform.

### 2.2 Design of the modified sine wave inverter for the portable nanogrid system

It is easier to produce the 3-level modified sine wave than the pure sine wave. Based on the switching frequency and transformer frequency adopted, modified sine wave
inverters can be classified as low frequency (LF) or high frequency (HF). A LF modified sine wave inverter first converts the DC source into a low voltage AC waveform and then uses a low frequency transformer (100 or 120 Hz) to step up the low magnitude AC voltage to the 120V\textsubscript{AC}, as shown in Fig. 2.3(a) and Fig. 2.3(b). The topology of the LF modified sine wave inverter is simple but the size and weight are large due to the large LF transformer. On the other hand, as shown in Fig. 2.3(c), a HF modified sine wave inverter typically contains two stages. The first stage is a step-up DC-DC converter with HF switches, HF transformer, and rectifier that boosts the DC source to a high DC voltage (\(V_{\text{DC}}\)). The second stage is an H-bridge topology circuit that converts the \(V_{\text{DC}}\) to 120V\textsubscript{AC}. As illustrated in Fig. 2.4, an H-bridge in a modified sine wave inverter that has three-level output voltage. The input of the H-bridge is a controllable voltage \(V_{\text{dc}}\) from a step-up DC-DC converter. The output voltage of the H-bridge \(V_L\) can be \(+V_{\text{dc}}, 0, -V_{\text{dc}}\), depending on the status of the four MOSFETs in the H-bridge. Fig. 2.4 also demonstrates the typical drive signal scenario of H-bridge switches and stages:

**Stage 1:** \(S_1\) and \(S_4\) are ON, \(S_2\) and \(S_3\) are OFF, \(V_L = +V_{\text{dc}}\);

**Stage 2:** \(S_3\) and \(S_4\) are ON, \(S_1\) and \(S_2\) are OFF, \(V_L = 0\);

**Stage 3:** \(S_2\) and \(S_3\) are ON, \(S_1\) and \(S_4\) are OFF, \(V_L = -V_{\text{dc}}\);

Compared with LF modified sine wave inverters, HF modified sine wave inverters with the same power rating are lighter, smaller and more compact due to the use of an HF transformer. As a result, in this research all modified sine wave inverters
Chapter 2. *MSWI in a Small Energy Management System*

(a) push-pull topology with shorting winding  
(b) H-bridge with LF transformer

![Diagram](image)

**Figure 2.3:** Modified sine wave inverter topology candidates.

![Diagram](image)

**Figure 2.4:** Drive signals of H-bridge switches and output voltage of the modified sine wave inverter.
are HF with two stage architecture. As shown in Fig. 2.5, the input of the inverter is 24V DC voltage (with 20-33V range) from PV/battery management system, and the output is 120V AC, 60Hz modified sine wave. The inverter contains two stages: step up dc-dc conversion stage generates high DC voltage (142V) and H-bridge stage (DC-AC) produces 120V 60Hz modified sine output. A DSP will monitor and regulate both stages. It can also fulfill many functions such as over voltage/current/power protection and communication with other DSP-based devices and modules.

![Diagram of inverter](image)

**Figure 2.5:** Designed modified sine wave inverter for the portable nanogrid system.

To achieve a small size, high performance and high reliability portable nanogrid system, the following aspects are specially considered and implemented in the design of the inverter, and they can be classified into two categories: hardware design and software design.
2.2.1 Hardware Design

As shown in Fig. 2.5, in one inverter there are two step up DC-DC converters with push-pull topology in parallel as the first stage to boost the input low DC voltage (20V–33V) to a high DC voltage (142V). The advantages of this architecture include:

- With two converters working in parallel, each converter only handles half of the output power. The heat generated by the power loss can be more evenly distributed. As a result, the reliability of the inverter is improved.

- The drive signals of two converters are phase shifted with 180 degree, so the parallel output voltage ripple is reduced.

- At light load condition it is possible to use only one converter to work, while terminating the operation of the other one, so as to increase the efficiency.

To accomplish the small size of the inverter, transformer windings are etched in the PCB, as shown in Fig. 2.6(a), so that the low profile transformer core can be used and the total height of the boards is reduced.

As operating temperature increases, the reliability of an electronic devices decreases. As shown in Fig. 2.6(b) heat sink is utilized as a heat removal method to ensure the proper operation of the inverter in high temperature environments such as desert. The two DC-DC boards are glued directly to the heat sink to achieve
lower thermal resistance. As a result, higher allowable ambient temperature can be achieved.

![Hardware design considerations.](image)

**Figure 2.6:** Hardware design considerations.

### 2.2.2 Software Design

The inverter designed has two blocks in cascade: a step-up DC-DC converter and an H-bridge. The H-bridge only performs the modified sine wave modulation and has no feedback loop. The digital feedback control is focused on the voltage of the push-pull DC-DC converter that serves as the input for each H-bridge. The output voltage compensator $G_{VC}(z)$, as plotted in Fig. 2.7(a) is designed as a digital PI compensator with a transfer function given by

$$G_{VC}(z) = \frac{U(z)}{E(z)} = K_p + \frac{K_i}{1 - z^{-1}}$$

(2.1)

where $U(z)$ is the $Z$ transform of $u(n)$, which is output of the PI compensator, $E(z)$ is the $Z$ transform of $e(n)$, which is the error sequence of the output.
voltage and the reference. $K_p$, and $K_i$, are proportional gain and integral gain respectively.

From the step-up DC-DC converter point of view, when the H-bridge is in Stages 1 and 3 (refer to Fig. 2.4), the DC-DC converter is connected to the inverter output load. When the H-bridge is in Stage 2, the DC-DC converter is in no load mode because it is isolated from the AC load due to the OFF state of the switch $S_1$. 

**Figure 2.7:** (a) Block diagram of the digital control for the step-up DC-DC converter; (b) PI controller with on/off control.
and $S_2$, and therefore there is no power exchange. Hence, the DC-DC converter is always in transient procedure from no load to the connected AC load and then to no load again and so on. As shown in Fig. 2.7, based on this characteristic, an on/off control for the step-up DC-DC converter is proposed as follows:

- During Stage 1 and 3, the voltage feedback loop with the PI compensator will tune the output voltage to be $V_{ref}$;

- During Stage 2, because the step-up DC-DC converter will not feed power to the AC load, the PWM signals of the switches in the DC-DC converter are turned off, the output voltage is held by the output capacitors of the converter.

Therefore, the input signal of the digital PWM (DPWM) module $c(n)$ is given by

$$c(n) = S \cdot u(n)$$

(2.2)

where $u(n)$ is the output of the PI compensator, $S = S(n)$ is a control parameter and its value is 1 during Stage 1 and 3, and is 0 during Stage 2. If $c(n)$ equals 0, the DPWM will not generate PWM signals.

### 2.3 Portable Nanogrid System Integration

Fig. 2.8 - Fig. 2.10 demonstrate the architecture, block diagram and pictures of the designed portable nanogrid system. It contains three main components: MPPT
Chapter 2. MSWI in a Small Energy Management System

Figure 2.8: Architecture of the designed portable nanogrid system.

Figure 2.9: Block diagram of the designed portable nanogrid system.

Figure 2.10: Pictures of the real portable nanogrid system modules with notes.
charger, battery and inverter. The input source of the MPPT charger could be a 60W solar panel with MPP voltage at 8-40V or a DC power supply with 8-40Vdc. The battery is the energy buffer for the system, and its chemistry could be dumb, smart NiMH or Li-ion. The inverter is described in the previous sections to be a modified sine wave inverter with small size, light weight and high performance. For the simplicity and reliability of the whole system the DC bus voltage is directly from the battery so it is unregulated but stable enough for most of the DC loads. The energy flow of the system can be written as

\[
P_{PV}(t) = P_{BAT}(t) + P_{DC, L}(t) + P_{AC, L}(t)
\]  

(2.3)

where \(P_{PV}(t)\) is the power from the solar panel, \(P_{BAT}(t)\) is the power exchange of the battery, \(P_{DC, L}(t)\) is the consumed DC load power and \(P_{AC, L}(t)\) is the consumed AC load power. Please note that the battery power can be positive (charging) and negative (discharging) in different scenarios.

Because the inverter output is a 60Hz modified sine wave, the input current of the inverter is in the form of 120Hz pulses. This energy oscillation will be reflected to the input of the MPPT charger so it is difficult to find MPPT with a heavy AC load. This is one of the most challenging problems in the designed nanogrid system and the solution is explained in detail in [36].
2.4 Test results of the modified sine wave inverter for the portable nanogrid system

![Picture of the portable nanogrid system](image)

**Figure 2.11:** (a) Output AC voltage measurement with the voltage meter; (b) Output modified sine waveforms; (c) Step-up DC-DC converter primary side switch drive signals.

Fig. 2.11 shows the picture of the portable nanogrid system with the important
waveforms. The output voltage of the inverter is 120Vrms which is verified by a voltage meter, as shown in Fig. 2.11(a). Fig. 2.11(b) illustrates the 60Hz output modified sine wave and Fig. 2.11(c) shows the 150kHz drive signals of the push-pull switches.

The stable inverter output voltage is the basis to perform parallel operation of the designed inverters, as will be shown in Chapter 3. To achieve better DC voltage dynamic performance, on/off control described in Section 2.2.2 is implemented in the DC-DC converter. Fig. 2.12(a) shows the waveforms when on/off control described in Section 2.2.2 is NOT implemented in the first stage DC-DC converter of the designed MSWI. For all the inverter stages ($V_{DC}$, 0, $-V_{DC}$), the same gains in the output voltage PI controller are used. Because in Stage 2 the DC-DC converter does not feed power to the load but the output capacitors of the step-up DC-DC converter will continue to be charged with the input DC source. The output voltage of the DC-DC converter increases in Stage 2 to a high level. When Stage 1 or 3 begins, the DC output voltage drops because of the connected AC load. It is more difficult to parallel the outputs of the inverters with the high fluctuation of the DC voltage.

Fig. 2.12(b) shows the waveforms when on/off control described in Section 2.2.2 is implemented in the first stage DC-DC converter of the designed MSWI. From Ch3 (purple) waveform in Fig. 2.12(b), we can find the output voltage is smooth and does not have noise. This is because when inverter output voltage is 0V, the gains of the output voltage PI controller are set to be 0, which means no
Figure 2.12: Dynamic response of the step-up DC-DC converter output voltage versus inverter output voltage, $R_L = 144 \, \Omega$ (100W), $4\,\text{ms/div}$. (a) without on/off control; (b) with on/off control.
PWM signals will be generated and the output voltage of the first stage DC-DC converter is held by its output capacitor. During the stages when inverter output voltage is $V_{DC}$ or $-V_{DC}$, the output voltage controller has the same parameter values as in Fig. 2.12(a). The voltage undershoot is only 2V and the duration of this undershoot is 2.4ms. Compared with Fig. 2.12(a), the voltage variation due to the H-bridge on and off is greatly reduced by the proposed on/off control.

2.5 Conclusion

In this chapter, the architecture and design of a portable nanogrid is presented. The nanogrid is developed for the camper, hiker, and soldiers on the move. As a result, it should be lightweight, small size and compact. In order to achieve these features, modified sine wave inverter (MSWI), instead of pure sine wave inverter, is adopted in the proposed nanogrid. Advantages and disadvantages of MSWI and pure sine wave inverter are discussed and compared. The design procedure of the MSWI is demonstrated. Inboard winding technique is used to make the board low profile, paralleling of the first stage DC-DC converter and heat sink are utilized to achieve high reliability. The designed MSWI can be connected with a foldable PV panel, a smart battery and an MPPT charger to construct the portable nanogrid. This small power system can harvest solar energy to charge the battery, and supply power to both DC and AC load. Specifically, the gain scheduling technique is explained for the MSWI controller to realize lower dynamic response.
oscillation. This feature is important for the parallel operation of the designed MSWIs that will be presented in the next chapter.
Chapter 3

Parallel Operation of Modified Sine Wave Inverters

In this chapter a method to operate modified sine wave inverters in parallel is proposed. The results obtained with this research demonstrate that it is economically feasible to produce standard modular modified sine wave inverters. Fig. 3.1 illustrates the proposed energy system, and this is suitable for hikers, campers, and soldiers on the move.

Specifically, this chapter presents the following research contributions of the parallel operation of modified sine wave inverters:

- For the first time, a method to parallel modified sine wave inverters without
adding filtering inductors or capacitors is developed. The method merges approaches used to parallel pure sine wave inverters with approaches sometimes used to parallel DC-DC converters. Switch signals must be carefully synchronized; robust DC-DC converters serve as inputs of the H-bridge, while piecewise master-slave DC-DC converter strategies are used to equalize current distributions among the inverters.

• The methods to parallel modified sine wave inverters are extended to successfully parallel cascaded H-bridge (CHB) multilevel inverters, without adding external inductors. The drive signals must be synchronized with dead time
control to guarantee safe operation, and current sharing compensator is utilized to equalize inverter output currents.

- Experimental results are provided to show the effectiveness of the proposed low cost methods for paralleling both modified sine wave inverters as well as multilevel inverters.

### 3.1 Problem Description

Parallel operation of power converters can achieve better reliability, maintainability and thermal management of the whole system. To parallel pure sine wave inverters, various control strategies have been proposed and adopted. However, to date, there has been no effort to parallel modified sine wave inverters. This lack of consideration ignores the widespread usage of the low cost inverters in the huge, low power (<200W) inverter commercial market. There is both a need and a benefit to allowing a user to create higher power from multiple low cost inverters whose sources can be batteries or low power solar panels.

The parallel operation of multiple nanogrid systems for higher AC power needs the parallel operation of modified sine wave inverters. To achieve this goal the system architecture to parallel $N$ modified sine wave inverters is proposed with the topology shown in Fig. 3.2. Inverter #1, Inverter #2, and so on to Inverter #N are modified sine wave inverters with DC input $V_{dc1}$, $V_{dc2}$...$V_{dcN}$ respectively.
Parallel Operation of MSWIs

$L_{w1}$, $R_{w1}$ to $L_{wN}$, $R_{wN}$ are wire impedances of $N$ inverters. $Z_L$ is the impedance of an AC load. The output of each inverter can be $V_{dci}$, 0 and $V_{dci}$ ($i=1,2\ldots n$), depending on the state of the pair of switches $S_{i1}$ - $S_{i3}$ and $S_{i2}$ - $S_{i4}$ ($i=1,2\ldots n$), as shown in Fig. 2.4.

**Figure 3.2:** Simplified equivalent circuit of $N$ modified sine wave inverters working in parallel.
Chapter 3. Parallel Operation of MSWIs

3.2 Literature review

3.2.1 Circulating current in inverter parallel operation

Parallel operation of inverters can achieve high reliability and redundancy, and it is a required feature of the AC microgrids proposed in previous literature. It is an advantage to achieve the $N + X$ redundancy in microgrids, where $N$ interfacing inverters supply the load, and $X$ additional inverters stay in reserve. They are also highly flexible to increase the capacity of the system when more power is needed.

The proper parallel operation of the $N$ modules that configure the microgrid is crucial. Generally speaking, a parallel inverter system must achieve the following features:

- The same output-voltage amplitude, frequency and phase;
- Equal current sharing between the parallel units;
- Flexibility to increase the number of units;
- Plug and play operation, also known as hot-swap capability at any time.

Fig. 3.3 shows an example of a microgrid with two parallel inverter systems. Each DG system has an energy source and a storage system, a grid-interfacing voltage source inverter (VSI) and output LC filters. In the grid-tie operation mode, the microgrid is connected to the grid at the point of common coupling (PCC) through
Chapter 3. Parallel Operation of MSWIs

Figure 3.3: Two parallel inverter system in microgrid.

a static transfer switch (STS), and each DG unit generates proper active and reactive power. In islanding operation mode, the DG units should be able to share the total power demanded by the local loads, adjusting its output voltage references as a function of the dispatched power.

Figure 3.4: Illustration of circulating current in a two inverter parallel operation system

Ideally there will be no circulating current among parallel inverters when their
output voltages have the same frequency, phase and amplitude. However, in reality there could be a difference between the instantaneous output voltages due to the modulation parameters difference of inverters. Hence, a circulating current may be present among the parallel inverters. The circulating current \(i_c\) is particularly dangerous at no-load or light-load conditions, since one or several modules can absorb active power operating in rectifier mode, as shown Fig. 3.4. This current increases the dc input voltage level, which can result in damage to the dc input capacitors or in a shutdown due to overload. Therefore it is important to restrain the circulating current of the parallel inverter system by control techniques that will be reviewed in the next section.

### 3.2.2 Existing control strategies for inverter parallel operation

Several control strategies to parallel pure sine wave inverters have been proposed and adopted to achieve even current distribution and eliminate the possible circulating current. They can be classified into two main groups according to the use of control wire interconnections. The first group is based on active load sharing techniques, such as centralized [11], master-slave (MS) [12–16], circular chain control (3C) [17], and average load sharing (ALS) [18–20]. These control schemes can achieve both good output-voltage regulation and equal current sharing, but they need critical intercommunication line among modules, which could reduce
the system reliability and expandability. The second group is based on the frequency and droop method \([21–25]\), which makes tight adjustments over the output voltage frequency and amplitude of the inverter, as a power dependent function, to compensate for the active and reactive power unbalances. This kind of control scheme only needs locally measured information of an inverter, does not rely on intercommunication signals between the inverters, therefore it can achieve higher reliability and flexibility.

### 3.2.2.1 Active load sharing

The first category of inverter paralleling control methods is active load sharing. This technique needs intercommunication links to interchange critical parameter values such as voltage and current. This kind of scheme includes concentrated, master-slave (MS), circular chain control (3C), and average load sharing (ALS). Active load-sharing techniques require the output voltage reference phase signal, which can be achieved by a dedicated line or by using a Phase Lock Loop (PLL) circuit to synchronize all parallel inverters. In a typical parallel inverter application, the reference voltage is either synchronized with the external bypass utility line or, when there is no such a utility line present, with an internal oscillator signal.

1. **Concentrated Control** \([11]\)
The control scheme of concentrated control or centralized control is shown in Fig. 3.5. The current reference $i_j^*$ of each module is calculated as:

$$i_j^* = \frac{i_L}{N} \quad \text{for} \quad j = 1 \ldots N$$

(3.1)

where $i_L$ is the total load current and $N$ is the number of modules.

The current error $\Delta i_j$ is obtained by subtracting the current reference value with the current of each module, and then it is processed through controller $G_i(s)$ in the current control loop. $\Delta i_j$ is decoupled to active current $\Delta i_{pj}$, and reactive current $\Delta i_{qj}$, and then $\Delta i_{pj}$ and $\Delta i_{qj}$ are utilized to regulate the phase and amplitude of the output voltage reference of each inverter.

Using this approach, it is necessary to acquire the total load current $i_L$, so it is more difficult to be used in a large distributed system.

**Figure 3.5:** Block diagram of a centralized controller for paralleled inverter system.
2. Master-slave control (MS) [12–16]

As shown in Fig. 3.6, in master-slave control technique, the master module regulates the load voltage. The current references from the remaining modules (all slaves) will follow the master current $i_M$ as:

$$i_s^* = i_M \text{ for } s = 2 \ldots N$$

As a result, essentially in the MS scheme, the master can be considered as a voltage source inverter (VSI), whereas the slaves work as current source inverters (CSI). If the master unit fails, one of the slave units should take over the function of the master to avoid total failure of the system. Here are the most adopted candidates of how to choose the master:

- Rotary: the master is arbitrarily chosen.
• High-crest current: the master can be fixed by the module that brings the maximum rms or crest current.

• The inverter with the highest power becomes the master.

3. Circular chain control (3C) [17]

In this control strategy, shown in Fig. 3.7(a), the inverters are in circular chain connection. The current reference of the inner current loop control of each inverter tracks the inductor current of its previous module, forming a current control ring to achieve an equal current distribution. The current reference of each inverter can be expressed as [17]

\[
i_1^* = i_N
\]

\[
i_k^* = i_{k-1} \quad \text{for} \quad k = 2 \ldots N
\]  

Fig. 3.7(b) illustrates the example of a inverter system with 3C strategy implemented. To increase system reliability by detecting and isolating damaged inverter modules, there are two bidirectional communication loops. In the figure the solid line and dotted line denote a transmitting path and a receiving path, respectively. If a signal is not received by the successive module, which means something is wrong with the previous module, the protection switch will be closed to ensure a continuity of load power distribution among healthy modules. For instance, if the control signal loop of inverter 1 is broken, the current distribution signal cannot be received by inverter 2 and then
inverter 2 will send a protection signal to inverter 1 through the receiving path to close switches $T_{41}$ and $R_{21}$. In this scheme, any module can become the master than control the load voltage.

![Diagram of multi-module inverter system controlled with 3C strategy](image1)

![Bidirectional communication loop for detecting and isolating damaged inverter modules](image2)

**Figure 3.7:** (a) Block diagram of the multi-module inverter system controlled with 3C strategy. (b) A bidirectional communication loop used for detecting and isolating damaged inverter modules [17].

4. **Average load sharing (ALS)** [18–20]

   In average load sharing control schemes, as shown in Fig. 3.8, there are two buses, one is the voltage reference bus to synchronize all output voltages of paralleling inverters in phase; the other is the current sharing bus to enable each inverter to contribute equal power to the load.

   Each inverter provides a measurement of its own output current $i_j$ and the sum of these currents is averaged by means of a common current bus and this averaged current is the reference for each individual module. The current reference for $N$ inverter modules can be expressed as
The error between $i_{s*}$ and $i_j$ in each individual inverter tends to be zero after being processed by a high gain current controller $H_j$ and then added onto the voltage reference of each inverter. All output currents of inverters will be the same. Thus, equal current sharing is achieved.

This control scheme is highly reliable due to the real democratic conception, in which no Master-Slave (MS) philosophy is present. The approach is highly modular and expandable, making it interesting for industrial inverter parallel systems. In general, this scheme is the most robust and useful of the aforementioned controllers. The limitation of this method lies in the bandwidth of the voltage loop, there is always a trade-off between stability

$$i_{s*} = \frac{1}{N} \sum_{j=1}^{N} i_j$$  (3.4)
and current dynamics/current sharing performance. Instead of using current information, active and reactive power can be used as another derived ALS method.

### 3.2.2.2 Droop control

The second category of inverter paralleling control scheme is droop control method [21–25]. It only requires local measurements, and it does not rely on critical communication links, so that it can achieve higher reliability and flexibility in the physical location of the modules.

The droop method is derived from the theories in large-scale power systems, where drooping the frequency of the ac generator connected to the utility can increase its active power. In parallel connected inverter system, adjusting the frequency and amplitude of the inverter output voltage reference can tune the active and reactive power respectively of each inverter. In Fig. 3.9, \( Z e^{j\theta} = R + jX \) is the line impedance, \( P \) and \( Q \) are the active and reactive power flowing into point A respectively; \( U_1 \) and \( U_2 \) are amplitude of inverter voltage and grid voltage; \( \delta \) is power angle.

Traditionally, the inverter output impedance is considered to be inductive due to the high inductive component of the line impedance and the large inductor filter. In this situation, \( X \gg R \), which means that \( R \) may be neglected. If also the power
angle $\delta$ is small, then $\sin \delta \approx \delta$ and $\cos \delta \approx 1$. the following well-known expressions can be derived.

\[
\delta \approx \frac{XP}{U_1U_2} \tag{3.5}
\]

\[
U_1 - U_2 \approx \frac{XQ}{U_1} \tag{3.6}
\]

For $X \gg R$, (3.5) demonstrates that the power angle depends predominantly on $P$, whereas (3.6) shows that voltage difference depends predominantly on $Q$. As a result, regulating $P$ can control the phase angle, which is dynamically controlled by the frequency, whereas adjusting $Q$ can tune the inverter voltage amplitude. By controlling $P$ and $Q$ independently, frequency and amplitude of the grid voltage are determined. This is the principal of the well-known frequency and voltage droop control through active and reactive power respectively.
\[ f - f_0 = -k_p(P - P_0) \]  
(3.7)

\[ U_1 - U_0 = -k_q(Q - Q_0) \]  
(3.8)

\[ U_0 \]

\[ f_0 \]

\[ k_p \]

\[ f \]

\[ k_q \]

\[ Q_0 \]

\[ Q \]

\[ U_1 \]

\[ P_0 \]

\[ P \]

**Figure 3.10:** Droop control characteristics: (a) frequency vs. active power. (b) voltage vs. reactive power.

\( f_0 \) and \( U_0 \) are rated frequency and grid voltage respectively, and \( k_p \) and \( k_q \) are the droop frequency and amplitude coefficients. \( P_0 \) and \( Q_0 \) are the set points for active and reactive power of the inverter. This conventional droop control scheme, adopting \( P - f \) and \( Q - U \) relationships described in (3.7) and (3.8), is shown in Fig. 3.10. The block diagram of the conventional droop control scheme is shown in Fig. 3.11. If the droop coefficients (\( k_p \) and \( k_q \)) are increased, good power sharing can be realized at the cost of degrading the voltage regulation.
3.2.3 The reasons that existing converter parallel operation techniques cannot be directly used in this research

The equivalent circuits of two paralleled DC-DC converters and pure sine wave DC-AC inverters are shown in Fig. 3.12. For DC-DC converter paralleling, each converter can be considered a DC voltage source in series with a resistor, by using the Thevenin theorem [37–43]. For pure sine wave inverter paralleling, each inverter can be regarded as an AC voltage source in series with impedance [44–51]. Unlike DC-DC converter paralleling techniques, which only control the magnitude...
of DC voltage level, pure sine wave inverter paralleling techniques will also tune the phase of AC power sources to achieve equal active power distribution among paralleled inverters.

The modified sine wave inverters in the system, however, cannot be simply considered a DC or AC source. Therefore, existing current sharing methods to parallel pure sine wave inverters or DC-DC converters cannot be applied directly to modified sine wave inverters. Unlike DC-DC converters, which have constant DC voltage outputs, the output voltages of modified sine wave inverters are piecewise constant with different levels. On the other hand, unlike pure sine wave inverters that can adjust phase angle, phase shift is not allowed among modified sine wave inverters in parallel because of the huge circulating current that is introduced (will
be explained in the next section). As a result, a new method must be created to share the load current \( (I_L) \) equally among the \( N \) modified sine wave inverters \( (I_1, I_2, \ldots I_n) \) while keeping peak current levels in the H-bridge switches to be in safe operating ranges.

### 3.3 Proposed method to parallel modified sine wave inverters

Ideally the \( N \) paralleled inverters can work with equal current sharing if the following criteria are exactly satisfied:

(a) Drive signals of four MOSFETs in \( N \) H-bridges \( (S_{11} - S_{14} \text{ to } S_{n1} - S_{n4}) \) are perfectly synchronized by communication;

(b) \( V_{dc1} = V_{dc2} = \ldots = V_{dcn} \);

(c) On resistances of MOSFETs in \( N \) H-bridges and line impedances \( (L_1, R_1 \text{ to } L_n, R_n) \) of \( N \) inverters are exactly the same.

Of course, the ideal conditions listed above are never realized in working conditions, particularly without additional control and synchronization. In fact, paralleling modified sine wave inverters without specialized current sharing techniques will damage the inverters, as shown below.
3.3.1 Dead time control method to eliminate circulating current

For criteria (a), timing error of synchronization for drive signals will cause a phase shift of output modified sine waves, and produce very large circulating current between the inverters at the transient edges between each of the two stages. As shown in Fig. 3.13(a), it is possible that Inverter #1 is in Stage 1 while Inverter #2 has already moved to Stage 2 due to a drive signal synchronization timing error. The equivalent circuit shows that Vdc1 will be shorted through the path $L_{w1}$,
The wire impedances of $L_{w1}$, $R_{w1}$ and $L_{w2}$, $R_{w2}$ are very low for modified sine wave inverters, indicating this circulating current has very high peak value. As such, this circulating current will damage the switches in the H-bridges and the inverters will fail. Adding any high value external inductor at the inverter output can alleviate this kind of circulating current, but this adjustment will greatly impair the advantage of modified sine wave inverters in that they have no heavy and bulky output LC filters. Instead, a dead time control for drive signals is proposed that can totally cut off the circulating current path, as shown in Fig. 3.14, as long as the following criteria are satisfied:

$$ T_{2a} = T_{2c} > T_{error} \quad (3.9) $$

where $T_{2a}$ is the time between the falling edge of $S_1$ and rising edge of $S_3$, $T_{2c}$ is the falling edge of $S_4$ and rising edge of $S_2$, and $T_{error}$ is the timing error between the two H-bridge drive signals.

Table 3.1 shows the drive signals of the four switches in H-bridge during different Stages. And Fig. 3.15 demonstrates the detailed working condition when two modified sine wave inverters in parallel have phase shift with dead time control.
Figure 3.14: (a) Drive signals for optimized dead time control. (b) Stage 2 enlarged.

Table 3.1: Drive signals with dead time control

<table>
<thead>
<tr>
<th>Stage</th>
<th>Drive Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_1$</td>
</tr>
<tr>
<td>1</td>
<td>ON</td>
</tr>
<tr>
<td>2a</td>
<td>OFF</td>
</tr>
<tr>
<td>2b</td>
<td>OFF</td>
</tr>
<tr>
<td>2c</td>
<td>OFF</td>
</tr>
<tr>
<td>3</td>
<td>OFF</td>
</tr>
</tbody>
</table>

3.3.2 Piecewise master-slave current sharing to equalize output current

To compensate for the current imbalance caused by unequal line impedances and other parameter differences, a master-slave strategy is implemented to equalize current distributions among the $N$ inverters. During Stage 2, the $N$ H-bridges
Figure 3.15: Parallel working of two modified sine wave inverters with timing error of drive signals in two H-bridges, Inverter #1 is lag to Inverter #2. (a) #1 in Stage 1, #2 in Stage 1; (b) #1 in Stage 1, #2 in Stage 2a; (c) #1 in Stage 2a, #2 in Stage 2a; (d) #1 in Stage 2a, #2 in Stage 2b; (e) #1 in Stage 2b, #2 in Stage 2b; (f) #1 in Stage 2b, #2 in Stage 2c; (g) #1 in Stage 2c, #2 in Stage 2c; (h) #1 in Stage 2c, #2 in Stage 3; (i) #1 in Stage 3, #2 in Stage 3.
do not feed active power to the load; during Stage 1 and Stage 3, the paralleled inverter system can be considered a system constructed with paralleled DC-DC converters. Hence, we call this piecewise master-slave current sharing.

The equivalent block diagram in Stage 1 and Stage 3 with master-slave current sharing strategy is shown in Fig. 3.16. Master inverter current during Stages 1 and 3 is sampled and held on a constant time interval. Then this current value is transferred to the N-1 slave inverter as the current reference. During the same time interval, slave inverter current is also sampled and held. A digital current compensator $G_{\text{IC}}(z)$ in each slave module will inject its output signal to modify the reference voltage of $V_{\text{ref}2} \ldots V_{\text{ref}n}$ based on the difference between the averaged master and slave inverter current. The increased or decreased voltage loop error signal will adjust the duty cycle and consequently force the output current of the DC-DC converter to increase or decrease.

In the proposed system, the digital current compensator $G_{\text{IC}}(z)$ also serves as a PI controller, and the design procedure follows the methods discussed in [37–43]. The new challenges to adopting the master-slave strategy are, 1) the current sharing control loop is preferred to have a fast speed of response that can achieve the equal current sharing in at least half cycle (120Hz); 2) the current sharing control should have the ability to cross zero voltage region (Stage 2), meaning if a load step occurs at the end of the Stage 1 or Stage 3, the current sharing control loop can stop at the beginning of Stage 2 and resume at the end of the Stage 2. For a 100kHz switching frequency DC-DC converter, its internal voltage control loop
could be nearly 10kHz, while the current sharing control loop can be kept as nearly 1kHz, which is ten times slower than the voltage loop. This speed of response is much faster than most of that achieved in the methods of paralleling pure sine wave inverters. The second challenge can be conquered by the on/off control of the step-up DC-DC converter together with the piecewise current sharing control. The on/off control of the step-up DC-DC converter will store all necessary voltage control loop information at the beginning of the zero voltage region (Stage 2) and restore them at the end of the Stage 2. And the piecewise current sharing control will only execute in Stage 1 and Stage 3, and then will cease in Stage 2. By doing so the current sharing control loop can be considered as a consecutive procedure.
like implemented in paralleling DC-DC converters.

3.4 Experimental verification for parallel working of modified sine wave inverters

An experimental setup for a paralleled modified sine wave inverter system is built to verify the proposed method, as shown in Fig. 3.17 and Fig. 3.18. The outputs of two identical 100W modified sine wave inverters are connected in parallel to serve different resistance loads. Each inverter contains two modules in cascade: the first module is a step-up DC-DC converter that boosts 20-33Vdc to 142Vdc; the second module is an H-bridge which converts the 142V DC voltage to 120V$_{RMS}$ 60Hz modified sine wave output. CAN bus communication is utilized to synchronize drive signals of the MOSFETs of two inverter H-bridges and transfer and receive the voltage and current information of each inverter. Due to the number of bits transferred to synchronize, the interrupt response time in DSP software and the hardware delays, the timing error of drive signals synchronization can reach 100$\mu$s. To guarantee there is no circulating current between the two inverters, the dead time $T_{2a}$ and $T_{2c}$ are set up to be 400$\mu$s. By implementing this dead time in the drive signals of the H-bridges, the outputs of the two inverters can be connected directly in parallel without adding any additional inductors.
3.4.1 Parallel operation of two modified sine wave inverters without the current sharing loop

The first experiment is to verify the effectiveness of the proposed dead time control.

For this experiment, the CAN bus is utilized to synchronize drive signals of the two inverters, but no other information is exchanged. Fig. 3.19 shows the waveforms
Figure 3.19: Output currents of two paralleled modified sine wave inverters WITHOUT current sharing loop.
of two modified sine wave inverters working in parallel with $R_L = 144$ Ω, (100W) and 72 Ω (200W), without the current sharing loop. Under these conditions, with the implementation of the dead time control proposed, the two inverters can be paralleled directly without any circulating current. However, because there is no current sharing applied, the load current is naturally distributed between the two inverters but with different current values. As described in Chapter 2, for the MSWI designed, the duty cycle of inverter output voltage is 35.2% and peak value is 143V. As a result, for resistive load, the duty cycle of load current is also 35.2% and peak value is $143V/R_L$, where $R_L$ is the load resistor. The inverter currents under the two conditions are summarized in Table 3.2. This current difference results from two reasons:

(i) There exists the output voltage ($V_{dc1}$ and $V_{dc2}$) difference of the two step-up DC-DC converters. Each inverter has the DC voltage ($V_{dc}$) output feedback loop. As shown in Fig. 3.16, the DC voltage of each inverter is sensed by the analog to digital conversion (ADC) of a DSP through a resistor divider. Then the sensed voltage is compared with voltage reference, the error signal is applied to a digital PI controller to generate the PWM signal to tune the output DC voltage. As a result, the error of analog to digital conversion (ADC) of the DSP, the tolerance of resistor divider in the DC voltage feedback circuit, and the tolerance of the PWM generator will all affect the output voltage variation. Therefore, $V_{dc1}$ and $V_{dc2}$ cannot be exactly the same value.
Table 3.2: Summary of experimental results, two inverter parallel operation without current sharing

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Peak Load Current (A)</th>
<th>Peak current Inverter #1 (A)</th>
<th>Peak current Inverter #2 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_L=144\Omega, (100W)$</td>
<td>0.993</td>
<td>0.25</td>
<td>0.743</td>
</tr>
<tr>
<td>$R_L=72\Omega, (200W)$</td>
<td>1.986</td>
<td>0.786</td>
<td>1.2</td>
</tr>
</tbody>
</table>

(ii) There exists difference between the inverter output impedances. Although the outputs of the two inverters are directly connected, line impedance difference still exists due to the different ON resistances of the MOSFETs in two H-bridges and other parasitic parameters.

As shown in Fig. 3.19 and Table 3.2, the output current difference between the two inverters decreases with the increasing AC resistive load. When $R_L=144\Omega, (100W)$, the output current of Inverter #1 is nearly 25% of the total load current, while Inverter #2 is nearly 75%. When $R_L=72\Omega, (200W)$, the output current of Inverter #1 is nearly 40% of the total load current, while Inverter #2 is nearly 60%. Since the current sharing is more important in heavy load condition, under the test conditions performed, the natural current sharing is acceptable in steady state due to the droop characteristic of the two inverters even in the absence of a current sharing loop. However, due to the different combinations of inverter output voltages and impedances, the natural distribution of load current among the paralleled inverters cannot be controlled, so we need to implement load sharing method to guarantee the current distribution in an acceptable range.
Table 3.3: Summary of experimental results, two inverter parallel operation with current sharing

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Peak Load Current (A)</th>
<th>Peak current Inverter #1 (A)</th>
<th>Peak current Inverter #2 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_L = 144 \Omega, (100W)$</td>
<td>0.993</td>
<td>0.497</td>
<td>0.497</td>
</tr>
<tr>
<td>$R_L = 72 \Omega, (200W)$</td>
<td>1.986</td>
<td>0.993</td>
<td>0.993</td>
</tr>
</tbody>
</table>

3.4.2 Parallel operation of two modified sine wave inverters with the current sharing loop

Fig. 3.20 shows the waveforms of two modified sine wave inverters working in parallel with $R_L = 144 \Omega$ (100W) and 72 $\Omega$ (200W) with the current sharing loop. From the figure, the inverter output currents are overlapped with each other, meaning they have the same amplitude. The output current values are summarized in Table 3.3. With the current sharing loop applied, the load current is evenly distributed between the two inverters, verifying the effectiveness of the current sharing loop in steady state.

3.4.3 Dynamic response of parallel operation of two modified sine wave inverters

For this experiment, a load step from $1096 \Omega$ (13W) to $96 \Omega$ (150W) is applied to the output of two paralleled inverters by using resistor box. Dynamic response of the two conditions, two paralleled inverters without current sharing and with current sharing, is compared as follows.
Figure 3.20: Output currents of two paralleled modified sine wave inverters WITH current sharing loop. Ch1 and Ch2 are overlapped because the Inverter #1 and Inverter #2 currents are nearly equal.
Figure 3.21: Dynamic response of the output currents of two paralleled modified sine wave inverters with load step from $R_L = 1096 \Omega$ (13W) to $R_L = 96 \Omega$ (150W).
Fig. 3.21(a) shows the dynamic response of the two inverter output currents when AC load $R_L$ is changing from 1096Ω (13W) to 96Ω (150W) without current sharing loop. At light load (1096Ω, 13W), Inverter #2 output current has noticeable higher amplitude than Inverter #1. After the load step, Inverter #2 will take over all the load current (nearly 1.5A) while the output current of Inverter #1 is very low (nearly 0). This means although the current distribution of the two inverters in steady state without the current-sharing loop is acceptable, unbalanced output currents will occur in the transient period, this unbalance current could be as high as $I_L$. This kind of unbalance should be eliminated by the current sharing method, otherwise the inverter with high output current may enter protection mode and the whole system will become unstable due to this current unbalance.

Fig. 3.21(b) shows the dynamic response of the two inverter output currents when AC load $R_L$ is changing from 1096 Ω (13W) to 96 Ω (150W) with current sharing loop. Even at light load (1096Ω, 13W), Inverter #1 output current is overlapped with Inverter #2, meaning a good steady state current sharing is achieved during this light load. After the load step, noticeable output current unbalance occurs, with output current of Inverter #1 is higher than output current of Inverter #2. But the unbalanced output currents will maintain only for a half cycle in this transient. After that, the two output currents will overlap with each other, meaning a new even current distribution status is achieved and each inverter will provide $1/2I_L$.

From the experimental results presented, both the effectiveness of the dead time
control and piecewise master-slave current sharing proposed have been verified. With the proposed dead time control, the two MSWIs can be paralleled directly without any inductors in between. The load current distribution in two inverters is acceptable but with difference. However, this uncontrolled current distribution in the inverter parallel operation is unreliable in transient, the unbalanced current during low load to high load transient may trigger the current protection of one inverter and the stable operation of the whole system will be affected. With the implementation of the proposed piecewise master-slave current sharing, in steady state the load current is evenly distributed in the two inverters, and in transient this even load current distribution can be achieved again only after less than half cycle.

3.5 Direct parallel operation of multilevel inverters

In the proposed parallel operation of modified sine wave inverters, as shown in Fig. 3.1, the essential feature is to harvest solar energy from multiple PV panels to feed power for AC loads or utility grid. This is similar to harvest solar energy from PV strings, which contains multiple PV panels in series and parallel. For such PV strings, the typical inverter system diagrams are shown in Fig. 3.22. In Fig. 3.22(a), multiple PV strings are connected in parallel and then feed DC power to a centralized inverter. The advantage of this scenario is the simple system
architecture because there is only one power electronics converter. But in each PV string the PV panels are connected in series, if one PV module has failure function or lower performance, the efficiency of the whole system will be decreased. Partial shading, module degradation, dust, debris and bird drippings can all cause the module power mismatch in the system. To solve this problem, system diagrams shown in Fig. 3.22(b) and Fig. 3.22(c) can be utilized. Fig. 3.22(b) adopts string inverter to reduce the risk of string failure, while Fig. 3.22(b) utilize microinverter for each module to limit the failure to only one module. Literature and reports have reported significant power gain increase by using string inverter and microinverter, compared with centralized inverter.

Figure 3.22: Inverter topologies for PV strings: (a) Centralized. (b) String. (c) Microinverter.
In recent years, extensive research, development and demonstration efforts have focused on multilevel inverters due to the lower power ratings of the power devices used and their lower cost [52–55]. There are three basic multilevel topologies: neutral point clamped (NPC), flying capacitor, and cascaded H-bridge (CHB). Among all the multilevel inverter topologies, CHB multilevel inverters have seen wide use in applications of solar energy system, because the connected sources for the first two multilevel topologies cannot be independent, while the source can be independent in the case of CHB. As shown in Fig. 3.23, a CHB inverter contains N H-bridges in cascade, the input voltage of each H-bridge is Vdc and the output voltage of each H-bridge can be $V_{dc}$, 0, $-V_{dc}$. The output voltage of the inverter can be $2n + 1$ levels as $N \cdot V_{dc}$, $(N - 1) \cdot V_{dc}$, $\ldots$, $2 \cdot V_{dc}$, $V_{dc}$, 0, $-V_{dc}$, $-2 \cdot V_{dc}$, $\ldots$, $-(N - 1) \cdot V_{dc}$, $-N \cdot V_{dc}$, depending on the state of the 4 switches in the N cascaded H-bridges. In literature, another solution for the scenario shown in Fig. 3.22 is demonstrated in Fig. 3.24. Each microinverter in Fig. 3.22(c) is replaced with a capacitor in parallel with a H-bridge, and then the N H-bridges are connected in series to construct a CHB inverter. With proper control of each H-bridge, the independent control of each dc-link voltage can be realized, and the tracking of the maximum power point for each string of PV panels can be achieved. Additionally, low ripple sinusoidal-current waveforms are generated with almost unity power factor. Compared with the microinverter solution shown in Fig. 3.22, this method can save the stage of step-up DC-DC, so as to increase the total efficiency. However, the control algorithm for the CHB inverter shown in Fig. 3.24
is complicated and not easy to implement.

![Diagram of CHB multilevel inverter with N H-bridges]

**Figure 3.23:** Topology of a CHB multilevel inverter with $N$ H-bridges.

The relationship between modified sine wave inverter and CHB multilevel inverter is that a modified sine wave inverter includes 3 levels: $V_{dc}$, $0$, $-V_{dc}$, while a multilevel inverter possesses $2N + 1$ levels: $N \cdot V_{dc}$, $(N - 1) \cdot V_{dc}$, $\ldots$, $2 \cdot V_{dc}$, $V_{dc}$, $0$, $-V_{dc}$, $-2 \cdot V_{dc}$, $\ldots$, $-(N - 1) \cdot V_{dc}$, $-N \cdot V_{dc}$, where $N$ is the number of the DC sources needed. As a result, modified sine wave inverters can be considered a special type of multilevel inverter when $N = 1$, and a CHB multilevel inverter needs $N$ H-bridges to produce $2N + 1$ level output voltage. In this research the $N$ H-bridges can be realized by $N$ designed modified sine wave inverters and the architecture is illustrated in Fig. 3.25. Advantages of the shown architecture are:
Figure 3.24: Topology of a grid-tied CHB multilevel inverter for $N$ string PV panels.

i) each modified sine wave inverter is an independent module; and 2) the input of each module ($V_{gi}$) can be supplied from an independent charger or battery output, as described in Chapter 2, or from the same DC source if necessary because of the high frequency (HF) transformer isolation. The batteries in the system enable the CHB inverter constructed not only work in day but also in night. But it should be pointed out that because each MSWI in the CHB inverter is designed for 120V\textsubscript{RMS}, it is not recommended to connect too many MSWIs in series. Otherwise each MSWI cannot work in its highest efficiency region. But it is still an effective way to create a low THD CHB inverter.
Figure 3.25: (a) System diagram of CHB inverter constructed by multiple MSWIs. (b) equivalent diagram of n-Module CHB inverter system, each module can be the nanogrid system designed.
After the construction of CHB inverter shown in Fig. 3.25, the next step is to parallel the multilevel inverters in order to supply higher power AC loads. The new nanogrid system structure is shown in Fig. 3.26. Traditionally, the parallel operation of CHB multilevel inverters adopts the methods of paralleling pure sine wave inverters, which have been proposed and discussed in [56, 57]. However, for these conventional methods the multilevel inverters can only be paralleled after the output inductor, which is typically bulky and heavy. More importantly, because the output current sharing regulation of each inverter responds to cycle-by-cycle changes, it operates at a slow speed. If CHB multilevel inverters can operate directly in parallel prior to the filter inductor, the following merits can be achieved:

- The basic architecture of the nanogrid presented can be flexibly configured in series and parallel to construct the parallel operation multilevel inverters, as shown in Fig. 3.27.
- For a stand-alone load that does not require low total harmonic distortion (THD), CHB inverters can be paralleled and connected to the load directly, in order to save the costly and bulky inductors.
- For grid-tie applications or for the load that does need low THD, just one output filter is needed.
- Higher bandwidth current sharing regulation for high performance applications can be achieved in less than one cycle.
Chapter 3. Parallel Operation of MSWIs

3.6 Proposed Method to Parallel Multilevel Inverters

Ideally the $m$ paralleled CHB multilevel inverters in Fig. 3.28 can work with equal current sharing if the following criteria are exactly satisfied:

(a) The drive signals of the switches in the $n$ H-bridges of $m$ inverters ($S_{11,1}$-$S_{14,1}$ to $S_{11,m}$-$S_{14,m}$, $S_{21,1}$-$S_{24,1}$ to $S_{21,m}$-$S_{24,m}$, ... $S_{n1,1}$-$S_{n4,1}$ to $S_{n1,m}$-$S_{n4,m}$) are perfectly synchronized;

(b) The corresponding output voltages of the H-bridges are the same:

$$V_{1,1} = V_{2,1} = ... = V_{m,1}, \quad V_{1,2} = V_{2,2} = ... = V_{m,2}, ..., \quad V_{1,n} = V_{2,n} = ... = V_{m,n};$$

(c) No parameter variations among the modules.

Figure 3.26: Parallel operation diagram of multiple modified sine wave inverters working in series to construct a multilevel inverter and then in parallel.
Figure 3.27: (a) Schematic of two 5-level CHB inverters in parallel; (b) Output phase voltage waveforms of each H-bridge and the 5-level inverter.
Of course the ideal conditions listed above are never perfectly realized in real working conditions, particularly without additional control and synchronization. In fact, paralleling the CHB multilevel inverters without specialized current sharing techniques will damage the inverters, as shown below. For simplicity and to easily illustrate the working principle, from now on, only two 5 level (2 H-bridges) inverters in parallel will be considered, as shown in Fig. 3.27(a). The voltage waveforms of each H-bridge and inverter are illustrated in Fig. 3.27(b), assuming that all the input DC sources \( V_{dci,j} \), \( i = 1,2, j = 1,2 \) for the H-bridges have the same voltage level \( V_{DC} \). Refer to Fig. 3.25, because \( V_{dci,j} \) is controlled by the first stage of MSWI, it is easy to achieve accurate DC voltage level of \( V_{DC} \).

Similar to what is presented in Section 3.3, a timing error of the synchronization for drive signals will cause a phase shift of output multilevel waveforms. For example, as shown in Fig. 3.29, two 5 level CHB inverters, Inverter #1 and #2, are operating in parallel directly. Inverter #1 has two H-bridges, H-bridge #1-1 and #1-2, in series, while Inverter #2 has two H-bridges, H-bridge #2-1 and #2-2 in series. It is possible that the falling edge of H-bridge #2-1 of Inverter #2 voltage \( V_{2,1} \) is in advance of H-bridge #1-1 of Inverter #1 voltage \( V_{1,1} \) at the time \( \left( \frac{1}{2} - \omega_1 \right) T \). Referring to Fig. 2.4, this means that H-bridge #1-1 of Inverter #1 is in Stage 1 while H-bridge #2-1 of Inverter #2 has already moved to Stage 2 due to a drive signal synchronization timing error. In this condition, \( V_{dc1,1} \) is shorted and a circulating current with high peak value will be produced. As such, this circulating current will damage the switches in H-bridges and the
inverters will fail. Adding any high value external inductor at the inverter output can alleviate this kind of circulating current but the inductor is normally heavy and bulky, so this adjustment will not only add cost but also impair the dynamic performance of the inverters.

With the method developed in Section 3.3, the possible circulating current in the paralleled multilevel inverters can be eliminated, as illustrated in Fig. 3.30. As long as the dead time is longer that the synchronous timing error, the off switch will cut off the circulating current path so that there will be no circulating current even if there exists a small synchronization error.

**Figure 3.28:** Schematic diagram of m CHB multilevel inverters working in parallel.
Figure 3.29: Circulating current due to the timing error of drive signals, Inverter #1 is in Stage 1 and Inverter #2 is in Stage 2.

Figure 3.30: Circulating current elimination with the proposed dead time control.
To compensate for the current unbalance resulting from the unequal line impedances and the resolution of analog to digital conversion (ADC) of the digital signal processor (DSP), master-slave strategy is utilized to achieve equal current distributions between the two inverters. Inverter #1 is the master and Inverter #2 is the slave. However, unlike conventional master-slave strategies, the method implemented here has different control diagram according to different inverter working phases, as shown shown in Fig. 3.31.

(i) During the angular time intervals 
\[ [0, \omega_1 T], [(1/2 - \omega_1)T, (1/2 + \omega_1)T] \] and \[ [(1 - \omega_1)T, T], \] the output voltages of the two inverters are 0. From the first stage DC-DC converters perspective, they are in no load condition. Hence the two inverters do not feed active power to the load. The master-slave strategy will not be implemented during these angular time intervals. In other words, the current sharing compensator (CSC) of the slave inverter will turn off during these angular time intervals.

(ii) During the angular time intervals 
\[ [\omega_1 T, \omega_2 T], [(1/2 - \omega_2)T, (1/2 - \omega_1)T], [(1/2 + \omega_1)T, (1/2 + \omega_2)T] \] and \[ [(1 - \omega_2)T, (1 - \omega_2)T], \] the output voltages of Inverter #1 and Inverter #2 are \( V_{1,1} \) and \( V_{2,1} \) respectively, both the nominal voltage levels are \( V_{DC} \). The equivalent circuit during these angular time intervals is shown in Fig. 3.31(b) as two DC-DC converters working in parallel with the load. Fig. 3.31(b) also illustrates the master-slave current sharing strategy during these angular time intervals. Master inverter current is
transferred to the slave inverter as the current reference and a digital CSC will inject its output signal to modify the reference voltage of $V_{2,1}$ based on the difference between the master and slave inverter currents. The increased or decreased voltage loop error signal will force the duty cycle and consequently force the output current of the DC-DC converter #2-1 to increase or decrease.

(iii) During the angular time intervals $[\omega_2 T, (1/2 - \omega_2)T]$ and $[(1/2 + \omega_2)T, (1 - \omega_2)T]$, the nominal output voltages of the two inverters are $2V_{DC}$. As shown in Fig. 3.31(c), the equivalent circuit for each inverter is two DC-DC converters with the outputs in series during these angular time intervals. Fig. 3.31(c) also plots the master-slave current sharing strategy during these angular time intervals. Compared with the strategy implemented in (ii), the digital CSC will inject its output signal to modify not only the reference voltage of $V_{2,1}$, but also that of $V_{2,2}$, based on the difference between the master and slave inverter currents. Hence, the output voltages of $V_{2,1}$ and $V_{2,2}$ can be tuned and consequently the output currents of the DC-DC converter #2-1 and #2-2 will be forced to increase or decrease.

The current sharing control is not consecutive but has the ability to cross different angular time intervals. Hence, we call this piecewise master-slave current sharing. The current sharing control loop can be kept 10 times slower than the DC-DC converter internal control loop, which normally has crossover frequency in the
tens of kHz. As a result, the bandwidth for the proposed current sharing control can be nearly several kHz, which is much faster than paralleling conventional pure sine wave inverters. And the equal current distribution can be achieved in one cycle after the current disturbance occurs.

3.7 Experimental Verification of the Proposed Method to Parallel Multilevel Inverters

Two experimental setups for a paralleled 5 level CHB inverter system are built to verify the proposed method as shown in Fig. 3.32. The outputs of two identical 100W, 5 level CHB inverters are connected in parallel to serve a resistance load. Each inverter contains two H-bridges in series to produce a 5 level AC voltage waveform, and the input voltage of each H-bridge is from an independent DC-DC converter. The difference of the two setups is, in Fig. 3.32(a) the resistor is connected to the outputs of two inverters directly, while in Fig. 3.32(b) there is LC filter in between the load resistor and the two inverter outputs. CAN bus communication is utilized to synchronize drive signals of the switches of two inverter H-bridges and to transfer and receive the voltage and current information of each inverter. Due to the number of bits transferred for drive signal synchronization, the interrupt response time in the software and the hardware delays the timing error between the drive signals of two inverters can reach 100µs. To eliminate the circulating current between the two inverters, the dead time is set as 250µs.
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Figure 3.31: (a) Illustration of different time intervals. (b) Equivalent master-slave current sharing diagram during the angular time intervals \([\omega_1 T, \omega_2 T]\), \([(1/2 - \omega_2)T, (1/2 - \omega_1)T]\), \([(1/2 + \omega_1)T, (1/2 + \omega_2)T]\); (c) Equivalent master-slave current sharing diagram during the angular time intervals \([\omega_2 T, (1/2 - \omega_2)T]\) and \([(1/2 + \omega_2)T, (1 - \omega_2)T]\)
By implementing this dead time in the drive signals of the H-bridges, the outputs of the two inverters can be connected directly in parallel without adding any additional inductors.

Figure 3.32: Experimental setup diagram of two 5-level inverter in parallel
3.7.1 Parallel Working of Two 5 Level CHB Inverters without LC Filter (Fig. 3.32(a))

Fig. 3.33 shows the waveforms of two 5 level CHB inverters working in parallel in transient from $R_L=176\,\Omega$ (82W) to $76\,\Omega$ (190W) with and without current sharing loop. Under these conditions, because the resistor load is connected directly to the 5 level voltage outputs of the two inverters, so the output currents of the two inverters also have 5 levels.

As shown in Fig. 3.33(a), without current sharing loop, the load current is naturally distributed between the two inverters, but the output peak to peak (pk-pk) current of Inverter #1 (1.4A) is higher than that of Inverter #2 (0.5A) before the load step when $R_L=176\,\Omega$. This difference is decreased after the load step when $R_L=76\,\Omega$. Under this condition, the output pk-pk current of Inverter #1 is 2.4A while the output pk-pk current of Inverter #2 is 1.7A. Since the current sharing is more important in heavy load condition, the natural current sharing is good in steady state due to the similar droop characteristic of the two identical inverters even in the absence of a current sharing loop. The dynamic response is also acceptable under this transient condition.

As shown in Fig. 3.33(b), with the current sharing loop, before the load step when $R_L=176\,\Omega$, both the output pk-pk currents of Inverter #1 and Inverter #2 are 0.9A. While after the load step when $R_L=76\,\Omega$ both the output pk-pk currents of Inverter #1 and Inverter #2 are 2.05A. The load current is evenly distributed between the
two inverters both before and after the load step, verifying the effectiveness of the current sharing loop in steady state. With the current sharing loop, the dynamic response is better than that without the current sharing loop. This conclusion can be seen viewing the transient responses in Fig. 3.33(a) and Fig. 3.33(b). As shown in Fig. 3.33(a), without current sharing loop the load step from $R_L=176\Omega$ to $76\Omega$ will cause more than half cycle (10ms) for the two inverters to reach the steady state again. In contrast, with current sharing loop the two inverters will achieve balanced output currents in 2ms with the same load step, as shown in Fig. 3.33(b).

Fig. 3.34 shows the waveforms of two 5 level CHB inverters without output filter working in parallel in transient from $\Omega=1076\Omega$, (13W) to $76\Omega$ (190W) with and without current sharing loop, the load step under this condition is much bigger than the test condition in Fig. 3.33. As shown in Fig. 3.34(a), without current sharing loop the load step from $R_L=1076\Omega$ to $76\Omega$ will cause three cycles (50ms) for the two inverters to reach the steady state again. Also the dynamic response without current sharing loop has severe distortion. The output current of Inverter #1 will take over all the load current at the beginning of the load step. And the output pk-pk current of Inverter #1 can reach 4.1A while the output current of Inverter #2 is nearly zero. In contrast, as shown in Fig. 3.34(b), the dynamic response with current sharing loop is stable during the whole transient procedure, and the unbalanced currents will maintain less than half cycle (9ms), verifying the fast dynamic response of the current sharing loop in transient.
Figure 3.33: Dynamic response of the output currents of two 5 level CHB inverters with load step from $R_L = 176 \, \Omega$ (82W) to $R_L = 76 \, \Omega$ (190W).
Figure 3.34: Dynamic response of the output currents of two 5 level CHB inverters with load step from $R_L = 1076 \, \Omega$ (82W) to $R_L = 76 \, \Omega$ (190W).
3.7.2 Parallel Working of Two 5 Level CHB Inverters with LC Filter (Fig. 3.32(b))

If the load requires low THD, the two 5 level inverters can still be directly paralleled before one inductor (95mH) and one capacitor (10µF), shown in Fig. 3.32(b), which can filter the multilevel voltage and current waveforms to be sinusoidal. Under this condition, even current distribution can still be achieved with the proposed master-slave current sharing strategy.

Fig. 3.34(a) shows the waveforms of two 5 level CHB inverters working in parallel with $R_L=96\Omega$ (150W) without the current sharing loop. Under this condition, Inverter #1 output RMS current is 0.357A while Inverter #2 output RMS current is 0.574A from the measurement of the oscilloscope. And the Inverter #1 output peak to peak (pk-pk) current is 2.4A while Inverter #2 output pk-pk current is 1A. The two output currents are unbalanced with significant difference when the LC filter is added.

Fig. 3.34(b) shows the waveforms of two 5 level CHB inverters working in parallel with $R_L=96\Omega$ (150W) with the current sharing loop. Under this condition, Inverter #1 output RMS current is 0.419A while Inverter #2 output RMS current is 0.396A from the measurement of the oscilloscope. And both the output pk-pk currents of Inverter #1 and Inverter #2 are 1.7A. The two output currents have close RMS values, verifying the effectiveness of the current sharing loop in steady state even with LC filters.
Inverter #1
Output Current, 1A/div

Inverter Output Voltage, 200V/div

Inverter #2
Output Current, 1A/div

Figure 3.35: Output currents of two 5 level CHB inverters in steady state with $R_L = 96 \, \Omega$
3.8 Conclusion

In this section, a method has been derived to parallel $N$ modified sine wave inverters without external inductor filters connected to any of the inverter outputs. Dead time control is implemented to eliminate the circulating current caused by the phase shift between the inverters. A new piecewise master-slave control method is adopted to compensate for current unbalance and to achieve better load sharing performance. Experimental results have been reported to validate the proposed approach. The parallel working of modified sine wave inverters can be implemented at low cost, and there is opportunity for a massive commercial market. It is demonstrated that current sharing can be achieved at speeds typical of when paralleling DC-DC converters (e.g., bandwidths $\sim$ 1kHz for current sharing), which is much faster than paralleling conventional pure sine wave inverters (either PWM or VSI) in which the current sharing loop cross frequency is typically less than $\sim$ 10Hz. The methods developed can be further applied to the parallel working of CHB multilevel inverters, representing the completion of the parallel operation of multiple modified sine wave inverters.
Chapter 4

Optimal Power Flow

Management in a Photovoltaic Nanogrid with Batteries

4.1 Introduction

Traditionally, for the remote area where utility grid cannot reach, diesel generator (genset) is a useful energy source to supply power [58]. Due to the low efficiency of the genset at light load, dump loads are often connected to maintain genset output power at high efficiency operation (Fig. 4.1(a)) [59]. However, a dump load is nothing more than a resistor (heating element) that is used for dumping electricity when it is not needed. It could be a water heater or air heater or some
other resistive load. The power consumed by the dump load is wasted when heat is not wanted. To solve this problem, energy storage systems can be adopted to realize the dump load function (Fig. 4.1(b)) [60]. It can absorb power when load power is low and feed power when demand is high. This can, therefore, reduce fuel consumption of the genset. To further save the fuel consumption, renewable energy can also be added to the system (Fig. 4.1(c)) [61–64]. The intermittent characteristic of renewable energy can be buffered by the energy storage, and more saving of fuel consumption can be achieved. The demonstrated system architecture in Chapter 2 can be utilized for a higher power nanogrid system (3kW ∼ 5kW) that is suitable for small rural-based households, schools, clinics, enterprises and even military bases, where the main utility grid cannot be reached. However, for such medium sized nanogrid systems, it is not feasible to parallel too many small power inverters. Therefore, a nanogrid that contains large solar panels or a solar tent, MPPT charger, energy storage batteries, bidirectional inverter and diesel generator (genset) can be constructed. For such power system architecture, research focuses on the power flow management of the whole system to minimize the fuel consumption and reduce the total operation cost [65–71].

In this chapter, three algorithms are proposed for the solar tent nanogrid with batteries and diesel generator (genset) to optimize the power flow for the energy system. The algorithms developed attempt to satisfy the load demand, achieve full
utilization of the solar energy generated, lower fuel consumption and improve battery health/life-cycle simultaneously. Specifically, the contributions of this Chapter include:

- Section 4.2 gives the system configuration and modeling of the solar nanogrid. This section introduces the new problem statement: Is it possible to realize the optimal power flow in the PV nanogrid under design constraints that include tolerance of varying irradiance, minimizing fuel costs, and maximizing battery life cycle expectancy?

- Section 4.3 introduces three algorithms to control the power flow in the PV nanogrid. The first one is the Rule Based (RB) algorithm, which is easy to
implement but may not achieve optimal power flow management in the proposed nanogrid. The second algorithm utilizes Dynamic Programming (DP) technique that can schedule the power flow more reasonably for the evaluation period based on the irradiance and load profile, so as to reduce the operating cost. To deal with the uncertainty of PV power, designed RB and DP algorithms are combined together to derive a piecewise DP algorithm. This algorithm can achieve the advantage of the low complexity of RB algorithm, while at the same time remain the global optimization of DP algorithm most of the time.

- Simulation and experimental results are provided in Section 4.4 to demonstrate the effectiveness of the proposed algorithms.

## 4.2 System Modeling

![Diagram of PV nanogrid system](image)

**Figure 4.2:** Power direction and sign convention in the PV nanogrid system.

Fig. 4.2 presents the scheme of the PV nanogrid system with power flow directions. The two main buses, a 24V\(_{\text{DC}}\) bus and a 120V\(_{\text{AC}}\) bus, are connected through a
bidirectional DC-AC inverter. An MPPT charger (DC-DC converter) transfers the energy from the solar tent to the DC bus, and the battery storage is also connected to the DC side. Local AC loads and diesel generator (genset) are connected to the AC bus. If needed, more DC and AC devices can be connected to extend the functionality of the PV nanogrid. The sign convention in Fig. 4.2 is used as the reference throughout the rest of the chapter. According to the specified sign convention, the power balance in the system can be described as

\[ P_{DC}(t) + P_{PV}(t) = P_{BAT}(t) + P_{L}(t) \]  \hspace{1cm} (4.1)

where \( P_{DC} \) is the power generated by genset, \( P_{PV} \) is the output power of MPPT charger, \( P_{BAT} \) is the power to the battery storage, and \( P_{L} \) is the power to the AC loads, at time \( t \). With supervisory energy management, all possible power flow scenarios are listed in Appendix A can be realized. Each scenario will consume different diesel or battery lifetime. To achieve the optimal power flow management, each term in (4.1) is analyzed in detail in this chapter. For simplicity only, the power electronics in the nanogrid presented in Fig. 4.2 is assumed to have unity power efficiency, which means there is no power loss in the MPPT charger or bidirectional inverter.
4.2.1 Solar power \( (P_{PV}) \)

In the nanogrid, solar energy should be utilized as a higher priority than genset, so as to reduce fuel consumption. The power flow management supervisor should have the information of the past, current and future (predicted) available PV power to perform power flow scheduling. To calculate the available solar power, first solar irradiance \( I_{rr} \) should be calculated, measured or forecasted. Total irradiance \( I_{rr} \) incident on a solar array is the sum of three different irradiance items [72]

\[
I_{rr} = I_{rr,b} + I_{rr,d} + I_{rr,r}
\]  

(4.2)

where \( I_{rr,b} \) is beam irradiance, \( I_{rr,d} \) is diffuse irradiance and \( I_{rr,r} \) is reflected irradiance. The three irradiance items can be calculated respectively as

\[
I_{rr,b} = I_b \cdot R_b 
\]  

(4.3)

\[
I_{rr,d} = I_d \cdot A_i \cdot R_b + I_d \cdot (1 - A_i) \cdot (1 + \cos \beta)/2 \cdot [1 + \sin(\beta/2)^3] 
\]  

(4.4)

\[
I_{rr,r} = I \cdot \rho_g \cdot (1 - \cos \beta)/2 
\]  

(4.5)

\( I_b \) in (4.3) stands for beam radiation that equals to Direct Normal Irradiance (DNI) \( \cdot \cos(\theta_Z) \), \( I_d \) in (4.4) is Diffuse Horizontal Irradiance (DHI), and \( I \) in (4.5) represents hourly Global Horizontal Irradiance (GHI). DNI, DHI and GHI for some
specific places can be found through the website database such as [73]. Other symbols in (4.3) - (4.5) are listed in Table 4.1.

As long as the parameters in (4.3) - (4.5) are known, irradiance of a PV panel $I_{rr}$ can be calculated, and then the DC power of a PV panel generated can be computed as [74]

$$P_{PV\_Panel} = I_{rr} \cdot \tau_{PV} \cdot S \cdot \eta_C$$

(4.6)

where

$$\eta_C = \eta_{ref} [1 - \beta_{ref}(T_c - T_{ref}) + \gamma_{ref} \log I_{rr}]$$

(4.7)

and definitions of each parameter in (4.6) and (4.7) are listed in Table 4.2.

Then the available solar power of a solar tent and the available maximum power can be generated by the MPPT charger are computed as

$$P_{PV\_tent} = D \cdot N \cdot P_{PV\_Panel}$$

(4.8)
Table 4.2: Symbols in (4.6) - (4.9)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{PV}$</td>
<td>transmittance of PV module</td>
</tr>
<tr>
<td>$S$</td>
<td>area of solar cells on one panel</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>calculated cell efficiency</td>
</tr>
<tr>
<td>$\eta_{ref}$</td>
<td>cell efficiency at $T_{ref}$ and 1000 W/m$^2$ irradiance</td>
</tr>
<tr>
<td>$\beta_{ref}$</td>
<td>temperature coefficient of the material</td>
</tr>
<tr>
<td>$T_c$</td>
<td>cell temperature</td>
</tr>
<tr>
<td>$T_{ref}$</td>
<td>reference temperature (25°C)</td>
</tr>
<tr>
<td>$\gamma_{ref}$</td>
<td>solar radiation coefficient of the material</td>
</tr>
<tr>
<td>$D$</td>
<td>derating factor for losses</td>
</tr>
<tr>
<td>$N$</td>
<td>number of PV panels in the tent</td>
</tr>
<tr>
<td>$\eta_{mppt}$</td>
<td>conversion efficiency of the MPPT charger</td>
</tr>
</tbody>
</table>

and

$$P_{PV, aval} = \eta_{mppt} \cdot P_{PV, tent}$$ \hspace{1cm} (4.9)

where $0 \leq \eta_{mppt} \leq 1$ is conversion efficiency of the MPPT charger. In this research, we neglect this efficiency, so $\eta_{mppt} = 1$.

Other symbols in (4.6) - (4.9) are explained in Table 4.2.

It should be noted that $P_{PV, aval}$ is the maximum possible PV power that can be utilized from the solar tent to charge the battery through DC bus or supply the AC load through the inverter. The real output power of the MPPT charger is $P_{PV}$. Although $P_{PV}$ equals to $P_{PV, aval}$ most of the time, if the battery has been fully charged and the load power is lower than $P_{PV, aval}$, it is possible that $P_{PV}$ is lower than $P_{PV, aval}$, which means not all available PV energy is exploited.
Chapter 4. Optimal Power Flow Management

(a) DEUTZ 30kW

(b) DEUTZ 95kW

(c) Cummins and Kohler different power levels

Figure 4.3: Fuel consumption curves for several commercial Gensets
4.2.2 Genset Power ($P_{DG}$)

Fuel consumption of genset ($F_{DG}$) is not always a linear function of genset power ($P_{DG}$). Fig. 4.3 illustrates several commercial gensets fuel consumption information. From the figures we can find that after the load power is higher than 50% of the genset power rating, the fuel consumption is relatively constant for kWh, which means fuel consumption can be considered proportional to the load power. When the load power is lower than 50% power rating, the relationship between fuel consumption and load power may become nonlinear. In this region, look-up table or curve-fitting can be used.

For all the algorithms developed in this research, there is a constraint that the genset is only operating when its output power is higher than 50% maximum power rating. As discussed, in this region, the genset output power can be considered as proportional to fuel consumption. As a result, genset output power is used to evaluate fuel consumption instead of utilizing liters of fuel consumed.

4.2.3 Battery power ($P_{BAT}$)

$P_{BAT}$ can be either positive (charging) or negative (discharging) according to the different power directions. It is the product of battery voltage and current:

$$P_{BAT}(t) = V_{BAT}(t)I_{BAT}(t)$$  \hspace{1cm} (4.10)
Battery voltage is also a function of battery current, and they are all related to the battery state of charge (SOC) and state of health (SOH). In order to achieve accurate power flow management of nanogrid proposed, battery SOC and SOH need to be investigated in detail as follows.

4.2.3.1 Battery state of charge (SOC) model

In this thesis, lead acid battery will be used as the energy storage in the nanogrid. In literature, there has been comprehensive study of battery electrical models with most of them having similar equivalent circuits [75–84]. In this research battery models presented in [76, 77] are adopted because they are developed for lead acid batteries and well accepted in literature. The equivalent circuit of the model, as shown in Fig. 4.5(a), is able to describe the battery voltage dynamic response to a current step shown in Fig. 4.4. With a current step \( I \) to 0, where \( I \) is the current entering battery before \( t_0 \), the battery voltage can be calculated as

\[
v(t) = E + \sum_{i=0}^{n} R_i I \quad t \leq t_0
\]

\[
v(t) = E + R_1 I e^{-t/\tau_1} + \cdots + R_n I e^{-t/\tau_n} \quad t > t_0
\]

(4.11)

where \( n \) is the order number to approximate real voltage response to a current step for a given accuracy. \( R_i \quad (i = 1, \ldots, n) \) is the resistor for each \( RC \) sub circuit in series. And \( \tau_i = C_i R_i \quad (i = 1, \ldots, n) \).
Figure 4.4: Battery voltage response to a current step from $I$ to 0.

Figure 4.5: Lead-acid battery equivalent circuits
The basic lead acid battery electrical and thermal characteristics can be described as

\[
\frac{dQ_e}{dt} = -I_m
\]

\[
\frac{d\theta}{dt} = \frac{1}{C_\theta} \left( P_s - \frac{\theta - \theta_a}{R_\theta} \right) \quad (4.12)
\]

where \(Q_e\) is the extracted charge from the battery, \(I_m\) is the charge current shown in Fig. 4.5, \(\theta\) is the averaged electrolyte temperature, \(C_\theta\) is the battery thermal capacitance, \(P_s\) is source thermal power, i.e., the heat that is generated internally in the battery, \(\theta_a\) is the ambient temperature and \(R_\theta\) is thermal resistance between the battery and its environment.

Battery capacity in unit of Ah can be described as

\[
C(I, \theta) = \frac{K_cC_0 \left( 1 + \frac{\theta}{-\theta_f} \right)^\varepsilon}{1 + (K_c - 1)(I/I^*)^\delta} \quad (4.13)
\]

where \(K_c, C_0, \varepsilon, I^*\) and \(\delta\) are constant for a particular battery. \(\theta_f\) is the electrolyte freezing temperature that depends mainly on the electrolyte specific gravity. Its value can be assumed as equal to \(-35^\circ C\) or \(-40^\circ C\) \[76, 77\].

From (4.13) we can find that the battery capacity is the function of battery temperature and current. The term \((1 + \theta/ - \theta_f)^\varepsilon\) illustrates the dependence of the capacity on the temperature \(\theta\), while the other parts of (4.13) describe the relationship of the capacity to the battery current. If \(\theta\) is \(0^\circ C\) and current \(I\) equals the reference current \(I^*\), we obtain \(C_0 = C(I^*, 0)\).
\[ SOC = 1 - \frac{Q_e}{C(0, \theta)} = 1 - \frac{Q_e}{K_e C(I^*)} \]  
\[ DOC = 1 - \frac{Q_e}{C(I_{avg}, \theta)} \]  
where \( Q_e(t) = \int_0^t -I_m(\tau)d\tau \), and when \( t = 0 \), the battery is fully charged. \( I_{avg} \) is the average current equal to the current flowing through \( R_1 \).

The battery model represented by \( n \)th order circuit shown in Fig. 4.5(a) can be simplified to first order model shown in Fig. 4.5(b), which contains only one \( RC \) branch. And the equations related to this model are

\[ E_m = E_{m0} - K_E(273 + \theta)(1 - SOC) \]
\[ R_0 = R_{00}(1 - A_0(1 - SOC)) \]
\[ R_1 = -R_{10}\ln(DOC) \]
\[ R_2 = R_{20} \frac{\exp A_{21}(1 - SOC)}{1 + \exp(A_{22}I_m/I^*)} \]  
where the parameters \( E_{m0}, K_E, R_{00}, R_{10}, R_{20}, A_0, A_{21}, A_{22} \) and \( I^* \) are constant for a given battery.

The branch between nodes \( P \) and \( N \) of Fig. 4.5(b) can be expressed as

\[ I_p = V_{PN}G_{p0}\exp(V_{PN}/V_{p0} + A_p(1 - \theta/\theta_f)) \]  
and we have
Fig. 4.5(a) and Fig. 4.5(b) are for accurate description of the dynamic performance of the battery. In the topic discussed in this chapter, the dynamic response of the battery can be neglected, and only battery steady state is taken into the optimization procedure. In order to further reduce the complexity of the battery model for the optimal power flow management, Fig. 4.5(c) is utilized. In this model the capacitor voltage dynamics and the parasitic branch current ($I_P$) are eliminated. Another assumption for this model is that the battery temperature $\theta$ is a constant, which means $\theta(\tau) = \theta(t)$. Therefore, the battery model is simplified to

$$\frac{dSOC}{d\tau} = \frac{I_{BAT}(\tau)}{C(0, \theta(t))}$$

(4.18)

and

$$V_{BAT} = E_m + R_{eq} \cdot I_{BAT}$$

(4.19)

where $R_{eq} = R_0 + R_1 + R_2$ and $E_m = E_{m0} - K_{E\theta}(1 - SOC)$.

### 4.2.3.2 Battery state of health (SOH) model

The lifetime loss of a lead acid battery is a complicated procedure which is influenced multiple physical and chemical processes, that should include corrosion of electrode, acid stratification that accelerates battery aging, gassing current,
sulfation and sulfate crystal growth at both positive and negative electrode, and
degradation of active material. Compared with battery SOC models, although sev-
eral battery SOH models are proposed in literature [85–95], accurate SOH models
are still under development. A widely accepted method by many simulation and
optimization tools is equivalent number of charge-discharge cycles until the bat-
tery cannot supply satisfactory electric capacity. It defines the end of the battery
lifetime when a specified number of full charge-discharge cycles are reached. The
number of nominal battery cycles, $Z_N$, can be calculated as

$$Z_N = \frac{1}{C_N} \int_0^T |I_{dch}(\tau)|d\tau$$

(4.20)

where

$$I_{dch} = \begin{cases} I_{BAT}, & \text{if } I_{BAT} > 0 \\ 0, & \text{otherwise} \end{cases}$$

(4.21)

and $C_N$ is the nominal capacity of the battery.

From (4.21) we can find that battery lifetime will not change when $I_{BAT}$ is positive
(charging) but battery lifetime loss is proportional to $I_{BAT}$ when $I_{BAT}$ is negative
(discharging), this means only battery discharge will influence battery lifetime,
as shown in Fig. 4.6. All batteries have limited usage cycles, when a specified
number of full charge-discharge cycles are reached, the battery lifetime ends. Here
one cycle is defined as a fully charged battery is discharged to the cut off voltage,
for lead-acid battery the cut off voltage is 1V per cell. The IEC standard defines
the number of cycles \( Z_{IEC} \), when \( Z_N = 0 \), battery state of health (SOH) is 1; when \( Z_N = Z_{IEC} \), the capacity of the battery will drop below the given threshold (80% in IEC standard), and SOH reaches 0.

A more accurate weighted Ah-throughput approach is proposed in [85, 87]. At different conditions, discharge current has different weights \( f_i(t) \), the weight cycling number \( Z_W \) can be written as

\[
Z_W = \frac{1}{C_N} \int_0^T \prod_i f_i(\tau) |I_{dch}(\tau)| d\tau \quad (4.22)
\]

where \( \prod_i f_i(\tau) \) is the product of the coefficients that represent physical and chemical processes including impact of state of charge (SOC), sulfate-crystal structure, acid stratification. Actually battery aging is a combination of both cycling and corrosion. Without corrosion, the effective of weighted number of cycles would be

---

**Figure 4.6**: Illustration of battery lifetime loss.
higher, approximately $1.6 \cdot Z_{IEC}$ [85]. So when $Z_W = 1.6Z_{IEC}$, the battery SOH reaches 0, and the capacity loss $C_{deg}$ by cycling is calculated as

$$C_{deg}(t) = C_{deg, limit} \cdot \exp \left[ -C_z \cdot \left( 1 - \frac{Z_W(t)}{1.6 \cdot Z_{IEC}} \right) \right] \quad (4.23)$$

where $C_{deg, limit}$ is the degradation limit (reached when the full battery capacity is 80% of the nominal capacity by only cycling), and $C_z$ is a constant that equals to 5 [85].

In this research, only the impact of the battery SOC coefficient $f_{SOC}(t)$ is taken into the account in (4.22) and it can be rewritten as

$$Z_W = \frac{1}{C_N} \int_0^T f_{SOC}(\tau) |I_{dch}(\tau)| d\tau \quad (4.24)$$

or in the discrete form as

$$Z_W(t + \Delta t) = Z_W(t) + \frac{f_{SOC}(t) \cdot |I_{dch}(t)| \cdot \Delta t}{C_N} \quad (4.25)$$

$f_{SOC}(t)$ is calculated as

$$f_{SOC}(t) = 1 + (c_{SOC,0} + c_{SOC, min}(1 - SOC_{min}(t)_{10})) \cdot f(I, n) \Delta t_{SOC}(t) \quad (4.26)$$
The three factors that affect $f_{SOC}$ are explained as follows.

(i) In the first item of (4.26) \( (c_{SOC,0} + c_{SOC,min}(1 - SOC_{min}(t)|_{t_0})) \), $c_{SOC,0}$ and $c_{SOC,min}$ are constant slope for SoC factor and impact of the minimum SoC on the SoC factor respectively. They are constant and represent the increase in $f_{SOC}(t)$ with time at SoC = 0 and the influence of $SOC_{min}$. $SOC_{min}(t)|_{t_0}$ is the minimum SoC since the last fully charged state, as shown in Fig. 4.7, where fully charged state is when SoC is higher than $SOC_{limit}$. When fully charged, $SOC_{min}(t)|_{t_0}$ is 1 and the first item equals to $c_{SOC,0}$. When battery is fully discharged, $SOC_{min}(t)|_{t_0}$ is 0 and the first item equals to $c_{SOC,0} + c_{SOC,min}$. As a result, the lower the battery SOC, the higher the weight $f_{SOC}(t)$. This phenomenon coincide with [93, 94], where it is suggested that batteries are best operated at high SOCs to optimize the lifetime.

![Figure 4.7: Illustration of $SOC_{min}(t)|_{t_0}$](image-url)
(ii) \( f(I, n) \) is the current factor, and it can be expressed as \( \sqrt{I_{\text{ref}}/I} \), where \( I_{\text{ref}} \) is the reference current (typically 0.1C), and \( I \) is defined as the discharge current at the start of fully charged state, as illustrated in Fig. 4.8.

\[ SOC_{\text{max}} \quad SOC_{\text{min}} \]

\[ t_0 \quad t_d \quad t_0 \quad t_d \]

\[ I_{\text{discharge}} \]

**(Figure 4.8):** Illustration of \( f(I, n) \).

(iii) \( \Delta t_{SOC}(t) = t - t_0 \) is the time from last fully charged state, as shown in Fig. 4.9. The longer the battery is not fully charged, the higher \( f_{SOC}(t) \).

\[ SOC_{\text{max}} \quad SOC_{\text{min}} \]

\[ t_0 \quad t_0 \]

\[ M_{SOC}(t) \]

**(Figure 4.9):** Illustration of \( \Delta t_{SOC}(t) \).
From (4.26) we can know that the same discharge current will produce different battery lifetime loss. The longer discharge time, the discharge current tends to erode more battery SOH; discharge at lower SoC tends to shorten more battery lifetime; for higher discharge current rates at the start of fully charged state, the lifetime increases, whereas lower currents decrease the cycle lifetime.

### 4.2.4 AC load \((P_L)\)

Nanogrid load pattern is dependent on day type, such as weekday or weekend, season, weather, economics, and special events. Accurate load profile is indispensable for the optimal energy control of the nanogrid. Since the optimal power flow management needs to schedule power flow in advance, load forecasting is imperative. Regarding the time span that load forecasting is concerned, load forecasting can be classified into four types: very short-term (a few minutes to an hour) [96–99], short-term (one hour to one week) [100, 101] medium-term (one week to one year) [102, 103] and long-term (more than one year) [104–106]. For each type, different load forecasting techniques will be utilized, including the linear regression, time series [96, 107–109], artificial intelligence [110, 111], machine learning [101, 106], neutral network and wavelet methods [99, 101].

Load forecasting is beyond the scope of this research. In this thesis, load profile is assumed a priori knowledge, which means power flow management knows the accurate load power at each time before it makes decisions.
4.3 Problem Formulation

Fig. 4.10 illustrates the function of the energy management flow controller of the PV nanogrid. With the given input parameters, the power flow of the PV nanogrid can be scheduled and controlled to achieve the following objectives:

- Lowest fuel consumption of the genset;
- Lowest battery life cycle loss;
- Maximum utilization of the solar energy available.

As a result, the ideal condition is:

- During the given evaluation period, no genset energy ($E_{DG}$) consumed;
- During the given evaluation period, battery SOC does not change, so that the battery SOH is not consumed;

\[ \text{Figure 4.10: Function of the power flow management controller.} \]
During the given evaluation period, all solar energy is utilized.

As a result, the objective function of the optimization can be formulated as

$$\text{Min}(CF) = \text{Min}\{\int_0^T (w_1 F_{DG}(P_{DG}) + w_2 \text{SOH}(P_{BAT}(t)) + w_3 [P_{PV,\text{aval}}(t) - P_{PV}(t)])dt\}$$

(4.27)

where $CF$ is the abbreviation of Cost Function. It contains three items as follows.

(i) The first item is the fuel consumption of the genset $F_{DG}$ at the power level $P_{DG}$.

(ii) The second item is the battery state of health (SOH). It represents the lifetime loss of the battery $Z_N$ or $Z_W$, as described in the Section Battery state of health (SOH) model.

(iii) The third item is the difference between the available PV power $P_{PV,\text{aval}}$ and the utilized PV power $P_{PV}$. So the third term in (4.27) represents how much solar energy is wasted.

Actually the third item is related to the first and second item. In this research we have a constraint that the battery SOC should return to its initial state at the end of the optimization period, which means the battery is only an energy buffer. Any solar energy wasted will be compensated by genset energy, so that the cost of fuel consumption increases.
\[ P_{PV,\text{eval}}(t) - P_{PV}(t) = F_{DG}^* \] 

(4.28)

As a result, the cost function can be simplified to

\[ \text{Min}(CF) = \text{Min}\left\{ \int_0^T (w_1 F_{DG}(P_{DG}) + w_2 SOH(P_{BAT}(t))dt) \right\} \]

(4.29)

where \( w_1 \) and \( w_2 \) are weight coefficients. In this application, \( w_1 > w_2 \) because the fuel consumption is the most important item to be minimized than to save the life cycle of the battery.

At the same time, to achieve the goal above, the operating of the whole system cannot violate the constraints as listed below:

- The battery storage should not be charged (discharged) beyond the maximum (minimum) SOC, which can be described as

\[ SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}} \]

(4.30)

- The battery SOC at the end of the optimization period should be the same as the initial SOC:

\[ SOC_{\text{end}} = SOC_{\text{start}} \]

(4.31)
• The charge (discharge) power for the battery storage should not exceed the maximum (minimum) power:

\[ P_{\text{BAT}}^{\text{min}} \leq P_{\text{BAT}}(t) \leq P_{\text{BAT}}^{\text{max}} \]  (4.32)

please note that the power of the battery is bidirectional, as a result, \( P_{\text{BAT}}^{\text{max}} \) (positive) and \( P_{\text{BAT}}^{\text{min}} \) (negative) in (4.32) is maximum charge and discharge power respectively.

• The diesel generator has upper and lower power limitation:

\[ P_{\text{DG}}^{\text{min}} \leq P_{\text{DG}}(t) \leq P_{\text{DG}}^{\text{max}} \]  (4.33)

• When the diesel generator is turned on (off), it should remain on (off) for a minimum set time:

\[ T_{\text{DG,ON}} \geq T_{\text{DG,ON}}^{\text{min}} \]  (4.34)

\[ T_{\text{DG,OFF}} \geq T_{\text{DG,OFF}}^{\text{min}} \]  (4.35)

In practice, the continuous function of \( CF \) can be transferred to discrete form for analysis. As a result, the problem is formulated as a system evolution divided in an \( N \) stage decision process:

\[ N = (T - t_0)/\Delta t \]  (4.36)
where \( T \) and \( t_0 \) are the beginning and end time of the optimization period respectively; \( \Delta t \) is the time interval between two stages. At each stage \( k \in \{1\ldots N\} \), the state of the system is described by a set of quantity called state variables, and the objective function can be converted to

\[
\text{Min}(CF) = \text{Min}\left\{ \sum_{k=1}^{N} (w_1 F_{DG}[P_{DG}(k)] + w_2 \text{SOH}(P_{BAT}(k))) \right\}
\]

subject to (4.30) - (4.35)

As a result, an algorithm must be created so as to meet the load demand at any time while minimize the cost function described above. At the same time all the constraints (4.30) - (4.35) must be satisfied in the PV nanogrid.

4.4 Proposed Power Flow Management Algorithms

Related optimization efforts can be found in hybrid electric vehicle (HEV) energy flow management [112–119], which has a comparative power level as the nanogrid presented in this thesis. Energy management for HEV could be classified to two categories. The first type can be called rule based method. It employs heuristic knowledge and implement control techniques such as fuzzy logic and deterministic approaches, such as state machine and power follower. The second type is optimization based method. It can be divided into global optimization and real-time optimization. global optimization utilizes mathematical tools, such as
linear programming, dynamic programming and game theory. Real-time optimization employs control theory such as robust control and model predictive control (MPC). However, the system architecture in a typical HEV is different from the nanogrid presented. There is no renewable energy source, such as PV panels in HEV, and HEV energy management only needs to deal with the uncertainty of the load power; and for HEV there exists regeneration power from the load to the energy storage system, which is not the case in the nanogrid.

This research is focused on global energy optimization of the nanogrid. The most commonly used techniques include The Linear Programming (LP)/Mixed-Integer Linear Programming (MILP) [120–123], Model Predictive Control (MPC) [92, 124], Quadratic Programming (QP) [114], Dynamic Programming (DP) [32, 33, 71]. LP is employed when the optimization can be formulated into linear form. When some optimization constraints are binary, MILP technique has to be used. However, LP and MILP need the system to be deterministic, they are unsuitable for optimization with forecast parameters. MPC is a model-based optimization method. It has the ability to evaluate all time input parameters in an analytic model to achieve optimization of the objective function. For nonlinear problems, MPC method may need large computational cost. Quadratic Programming (QP) optimization can reduce the computational cost and give good results to formulate the problem in a relaxing form. But it needs the objective function to be convex or concave. Finally, Dynamic Programming (DP) technique is useful to obtain an optimal sequence of decisions (shortest path) must be acquired to achieve global
optimization. The optimal results can be achieved by splitting the sequential decision problem into smaller steps, and for each step or several steps to find local optimization results.

In this thesis, DP has been selected to perform optimal energy flow management. Before the DP algorithm is proposed, a non-optimal rule based algorithm has been developed. Although it can not achieve global optimization of the energy flow in the nanogrid, it can guarantee appropriate operation of the system with respect to the constraints shown in the previous section. It will be used as a reference for the performance evaluation of the optimization algorithms.

4.4.1 Rule based energy management algorithm

RB is an effective method to perform energy management in the nanogrid. It cannot achieve optimal power flow management, but it will not violate the constraints discussed in the previous section. RB can be used as a comparison to evaluate the performance of the optimal power flow management algorithm developed later.

Rule based algorithm is a suitable choice for PV nanogrid energy management that complies with the following rules:

- If PV and battery storage energy is enough, the load power is supplied by the PV energy and battery storage, and the genset is turned off to save fuel consumption. This rule can be described as:
If $P_{PV}(k) + [SOC(k) - SOC_{min}] / \Delta t > P_L(k)$,
then $P_{DG}(k) = 0$.

- If the battery storage SOC reaches SOC_{min}, then the genset is turned on to supply the load power and charge the battery storage simultaneously. Under this condition, the power to charge the battery is setup as low as possible to save fuel consumption of the genset. This rule can be described as:

If $P_{PV}(k) + [SOC(k) - SOC_{min}] / \Delta t < P_L(k)$,
then $P_{DG}(k) = P_L(k) - P_{PV}(k) - [SOC(k) - SOC_{min}] / \Delta t$.

If $P_{DG}(k) < P_{DG,min}$,
then $P_{DG}(k) = P_{DG,min}$ and $SOC(k + 1) = [P_{DG}(k) - P_L(k) + P_{PV}(k)] \Delta t + SOC(k)$.

The flow chart of rule base algorithm is demonstrated in Fig. 4.11. The advantage of the rule based algorithm is that it only needs the solar irradiance and load profile information for the next $\Delta t$. This information is easy to acquire by the averaging of several previous $\Delta t$ irradiance and load profile information. The disadvantage of the rule based algorithm is that it is only focused on the lowest fuel consumption of genset but does not take other factors, such as battery SOH loss into consideration. Because RB algorithm does not forecast how much PV power will be available at the start of one day, it is possible that the battery SOC remains at a low level so as to accommodate maximum possible PV power. This is not good for battery SOH from the analysis in the previous section. But this
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\[ P_{PV} = 0 \]

**Initialization**

\[ k = 1 \]

**Algorithm**

\[ k > N ? \]

**END**

**Back**

\[ PPV(k) > 0 ? \]

\[ k = k + 1 \]

\[ PPV = 0 \]

\[ Algorithm \]

**Back**

\[ k > N ? \]

**END**

**Figure 4.11**: Rule based algorithm flow chart
algorithm can make best use of the solar energy, so that the fuel consumption can be remained to a low level. Fuel consumption saving of the genset is often the highest priority in the proposed nanogrid. The power scheduling results achieved by the rule based algorithm can be used as the comparison reference for the more advanced optimal control algorithm.

4.4.2 Dynamic programming algorithm with perfect state information

Among several commonly used techniques for optimization, in this thesis we adopt Dynamic Programming (DP) to perform optimal power flow management for the designed PV nanogrid system. Definitions and fundamental principles of DP may be found in [125]. DP is suitable to attain a certain global optimization goal with specified constraints for sequential or multistage decision problems. It is a decision-making process which is affected by predecessors and successors of each stage. Specifically for this research, the optimal power flow management problem will be converted to a multistage decision model. SOC of the battery storage at each stage is chosen to be the main parameter to be investigated, as shown in Fig. 4.12. The reason to choose battery SOC is that this parameter is the most suitable one to perform DP. The given time period is divided into $N$ stages where $N$ follows (4.36). The number of states ($M$) in each stage is discretized with a
step size $\Delta SO\bar{C}$ from $SOC_{\min}$ to $SOC_{\max}$:

$$M = \frac{SOC_{\max} - SOC_{\min}}{\Delta SO\bar{C}}$$  \hfill (4.38)

So the states of the optimization process can be described as an $M \times N$ matrix. Please note that $SOC_0$ corresponds to the initial SOC, which is not included in the matrix. A transition between two states over one time step corresponds to a SOC variation. $SOC_{arc}(i, j, k) (i = 1 \ldots M, j = 1 \ldots M, k = 1 \ldots N)$ means the transition from $SOC(i, k - 1)$ to $SOC(j, k)$. For each $SOC_{arc}$, first $P_{BAT}$ can be calculated as

$$P_{BAT}(i, j, k) = f(SOC_{arc}(i, j, k), \Delta t)$$  \hfill (4.39)

As shown in Fig. 4.12, battery SOC in each stage $k = 1 \ldots N$ is ordered from $SOC_{\max}, SOC_2, \ldots, SOC_i(j), \ldots, SOC_{\min}(SOC_M)$. Therefore, $SOC_{arc}(i, j, k)$, which is the transition from $SOC(i, k - 1)$ to $SOC(j, k)$, indicating being charged when $i < j$, and being discharged when $i > j$. $f(SOC_{arc}(i, j, k), \Delta t)$ is the function to describe power variation of $SOC_{arc}(i, j, k)$ during $\Delta t$, it can be derived from what has been discussed in Section 4.2.3.1.

Because $P_{PV, ava}(k)$ and $P_L(k)$ are known parameters for each stage, $P_{DG}(i, j, k)$ can be calculated as

$$P_{DG}(i, j, k) = P_L(k) - P_{PV}(i, j, k) + P_{BAT}(i, j, k)$$  \hfill (4.40)
so that the cost function can be evaluated for each transition as

\[
Cost(i, j, k) = w_1 F_{DG}(P_{DG}(i, j, k)) + w_2 SOH(P_{BAT}(i, j, k))
\] (4.41)

The optimization problem is formulated as the battery SOC and genset power sequence evolution in the multi-stage decision making process. Each evolution is corresponding to a CF value. The goal is to solve the shortest path problem, which is to find the optimal sequence of SOC transition from the initial time to the final time that achieves the final state from the initial state with the lowest CF value. The shortest path finding flow chart is shown in Fig. 4.13, where \(sp(j, k)\) represents the shortest path from \(SOC(j, k)\) to the initial SOC \((SOC_{ini})\). This algorithm is derived from Bellman algorithm [125], and as shown in Fig. 4.13. There are two ways to achieve the goal, referred to as forward and backward DP. Their algorithms are presented in pseudo-code as follows.

**Algorithm 1** Pseudo code of forward Dynamic Programming Algorithm

1: procedure LOWEST COST PATH FINDING FORWARD
2: \(x_0 \leftarrow SOC_{start}\)
3: for all \(x_1 \in X_1\) do
4: \(CF_1(x_1) = cost(x_0, x_1)\)
5: end for
6: for \(k = \{2, 3, \ldots, N\}\) do
7: for all \(x_k \in X_k\) do
8: \(CF_k(x_k) = \min_{x_{k-1} \in X_{k-1}} \left[ cost(x_{k-1}, x_k) + CF_{k-1}(x_{k-1}) \right] \)
9: end for
10: end for
11: end procedure
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Stage 0

Stage 1

*** Stage N-1

Stage N

(a) Forward DP approach

Stage 1

Stage 2

*** Stage N-1

Stage N

(b) Backward DP approach

Stage k-1

Stage k

(c) cost function between two consecutive stages

Figure 4.12: DP for multi-stage shortest path problem.
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Algorithm 2 Pseudo code of backward Dynamic Programming Algorithm

1: procedure LOWEST COST PATH FINDING BACKWARD
2: \( x_N \leftarrow \text{SOC}_{stop} \)
3: for all \( x_{N-1} \in X_{N-1} \) do
4: \( CF_{N-1}(x_{N-1}) = \text{cost}(x_{N-1}, x_{N-1}) \)
5: end for
6: for \( k = \{2, 3, \ldots, N\} \) do
7: for all \( x_{N-k} \in X_{N-k} \) do
8: \( CF_{N-k}(x_{N-k}) = \min_{x_{N-k+1} \in X_{N-k+1}} \left[ \text{cost}(x_{N-k+1}, x_{N-k}) + CF_{N-k+1}(x_{N-k+1}) \right] \)
9: end for
10: end for
11: end procedure

For this research, initial SOC and final SOC are specified, so the DP algorithm can either start from initial SOC, which is forward DP, or start from final SOC, which is backward DP. From the simulation results we can find that they are both effective for DP with deterministic state information.

4.4.3 Algorithm with imperfect state information (forecast PV power)

Theoretically, the DP algorithm proposed can achieve global optimization, meaning it has a better performance than RB algorithm. However, the DP algorithm needs accurate information of PV power in advance to achieve the global optimization results, so that it is a deterministic DP (DDP) algorithm. In reality, there always exists error between the forecast PV power and real (measured) PV power. With the delicately designed PV forecasting methods, the error between forecast and measured PV power over one year or one month can be very small.
But for a specific given day, it is possible that there is significant difference between forecast and measured PV power. Fig. 4.14 illustrates the four typical combinations of forecasted PV power, measured PV power and load power scenarios. In the figures, the forecast and measured PV power is the scaled down data from [134], which uses a machine-learning approach for regional PV power forecasting of up to 2 days ahead with hourly resolution. The scheduling of genset power is generated by using DP with forecast PV power one day ahead, and this scheduling is implemented with real PV power during the day. However, because of the error in the forecast and real PV power, it is possible that the battery will
reach its minimum or maximum SOC, and battery SOC may not return to the given level at the end of the evaluation period.

Consider Fig. 4.15(a), for example. By using DP with the forecast PV power, the scheduling of the genset power pattern shown in Fig. 4.15(b) is acquired. If the real PV power is exactly the same as forecast PV power, this genset output power schedule can achieve minimum fuel consumption and lowest battery SOH loss at the same time, and the expected battery SOC evolution during the day, shown as the blue curve in Fig. 4.15(c), will not hit upper (90%) or lower (10%)
limit. However, because there is error between forecast and real PV power, if the genset output power scheduling in Fig. 4.15(b) is applied with real PV power scenario, the real battery SOC evolution in the day is shown as the green curve in Fig. 4.15(c). For this instance, between 8pm - 4pm, genset is turned off because the forecast PV power and battery stored energy is high enough to sustain the load power. Unfortunately, the real PV power is lower than the forecast PV power, so that the battery stored energy is consumed faster than anticipated. As shown in Fig. 4.15(c), real battery SOC will be lower than 10% at 3pm because of the lower real PV power than forecast.

To deal with the uncertainty of PV power, while at the same time achieve closer to optimal energy flow management with DP, a hybrid of DP and RB algorithm, called hybrid DP plus RB is proposed as follows.

(i) For one day ahead, energy flow scheduling by using DP with the forecast PV power data will be calculated. The energy flow management will implement the acquired genset power scheduling at the beginning of the day. If the forecast PV power is accurate enough, this scheduling can achieve optimal results.

(ii) From sunrise to sunset, energy flow scheduling by using DP with the forecast PV power is implemented. At the same time, system status, especially battery SOC is monitored, and next hour PV power is utilized to forecast if battery SOC will vary beyond the limit or not, like in RB algorithm. If
Figure 4.15: (a) forecast PV power, real PV power and load power in Fig. 4.28(a) Day 2. (b) Scheduling of the genset power by using DP with the forecast PV power. (c) Battery SOC variation comparison, forecast (blue), and real (green).
battery SOC will be lower or higher than the limit, RB algorithm will kick in to prevent the system to violate constraints.

(iii) After the sunset, because there is non-uncertainty in the PV forecast, DP can be performed again from sunset time to the next sunrise. The battery SOC at the sunset time is the initial SOC and 50% is used as the find SOC to acquire new scheduling of the genset power. Optimal power flow can be achieved during this time period.

Continuing to use Fig. 4.15(a) as the example. As shown in Fig. 4.16, the original scheduling will be utilized until 2pm, when battery SOC tends to be lower than 10%. At 2pm, RB kicks in to turn on the genset to charge the battery and supply the AC load until 6pm, when there is no solar energy anymore. After 6pm, DP will be performed again to achieve the optimal power flow from 6pm to 24pm, and to return the battery SOC back to 50% at the end of the day.

Simulation results shown in the next section can verify the effectiveness of this method, and also a discussion is given for explanation of the method in different scenarios of the forecast and real PV power.
4.5 Simulation and Experimental Results

4.5.1 Simulation Results

4.5.1.1 Forward DP vs. Backward DP

In this research, both forward DP and backward DP algorithms are designed and evaluated. The MATLAB code for the two algorithms are given in Appendix A. Fig. 4.17 illustrates the comparison of the two programs. They are applied to achieve the optimal energy flow during one day, given the same PV and load power patterns. From the results we can find that the SOC and genset power curves are almost the same with the two different approaches, except small difference at two early morning hours. This difference can compensate each other so that it will not affect the total cost. Many other PV power and load scenarios have been
evaluated and the difference between the two approaches is, also, minimal. So the
forward DP and backward DP can be considered as both effective if deterministic
information is given.

4.5.1.2 Rule Based vs. Deterministic DP

Simulations are constructed in MATLAB to verify the effectiveness of the proposed
algorithms with the irradiance data of April 2013 at Las Vegas [73], NV. The
output power of the PV tent is calculated as described in Section 4.2. Due to
the lack of the load information in this area, residential load data of April 2013
from New Hampshire Electric Cooperative [135] is used instead. At the end of the evaluation period the battery SOC is expected to be the same as the initial SOC (50%, although this percentage can be selected by the designer).

Fig. 4.18 shows the simulation results of the rule based algorithm on April 21, 2013. With this energy management strategy the available solar energy can be fully utilized most of the day except 15:00-16:00, when the solar power available...
is higher than the PV power used because the battery SOC has already reached $SOC_{max}$, so that no more available solar energy can be stored. $P_{DG}$ during the day is always within the $P_{DG_{min}}$ and $P_{DG_{max}}$. And at the end of the day battery SOC returns to 50% as the same as the beginning SOC of the day.

**Figure 4.19:** Simulation results of the DP algorithm for one day.

Fig. 4.19 demonstrates the simulation results of the DP algorithm on the same day. With the appropriate scheduling of the system energy flow, the available solar
energy can be fully utilized all day. The fuel consumption, which is proportional to the genset energy consumed, is lower with the DP algorithm than with rule based algorithm, as shown in Table 4.3. More significantly, the battery SOH loss with the DP algorithm is lower than with the rule based algorithm.

The proposed algorithms can accept any evaluation period, not restricted to one day. Fig. 4.20 shows the simulation results of the rule based algorithm on April 21-23, 2013. With RB algorithm, the available solar energy can be fully utilized most of the day, but not always. When the battery SOC has already reached $SOC_{\text{max}}$, no more available solar energy can be stored. If the PV power is higher than load power, available PV power is not fully utilized. $P_{DG}$ during the day is always within the $P_{DG,\text{min}}$ and $P_{DG,\text{max}}$. And at the end of the period, battery SOC returns to 50% as the same as the beginning SOC of the period.

Fig. 4.21 demonstrates the simulation results of the DP algorithm on the same period. With the appropriate scheduling of the system energy flow, the available solar energy can be fully utilized during all three days, and the fuel consumption, which is proportional to the genset energy consumed, is lower with the DP algorithm than with rule based algorithm, as shown in Table 4.4. Because the RB algorithm is only focused on fuel consumption and does not consider battery SOH loss optimization, DP can achieve noticeable lower battery SOH loss than the rule based algorithm.

It should be noted that in order to achieve minimum fuel consumption, the rule
based algorithm tends to turn on and off the genset more frequently than the DP
algorithm, as shown in Fig. 4.20 and Fig. 4.21. This is because in the rule based
algorithm, battery SOH is not considered, and the rule based algorithm can only
take the information of the next hour into account. The genset is controlled by RB
algorithm to only work at the minimum power level to save the fuel consumption.
The genset is turned on to supply power, both to the battery and the load and
turned off during next hour to use the battery to supply the load.

Fig. 4.22 shows the simulation comparisons of RB and DP for the same 30 days.
The real PV and load power curves for the 30 days are shown in Fig. 4.22(a). In
some days the peak PV power is higher than the load power, whereas in some
other days the peak PV power is lower than the load power. For the 30 days, both
RB and DP algorithms have the same fuel consumption (748.73kWh). However,
from battery SOH loss perspective, as shown in Table 4.5 and Fig. 4.23, for each
day DP has a lower battery lifetime loss and for the total 30 days DP has 13.95%
less battery lifetime loss than RB.

Another disadvantage of RB algorithm is, because PV power information is not
available, battery SOC is kept at a low level to accommodate possible PV energy
in the future. As discussed in Section 4.2.3.2, for the same discharge current,
operating at low SOC tends to decrease battery lifetime loss more. As shown in
Fig. 4.22(b), for all 30 days DP has a higher battery SOC level than RB, this
means from battery SOH loss perspective, the potential benefit of DP is higher
than 13.95% as shown in Table 4.5.
In summary, when PV power is known, the proposed DP algorithm can perform a better scheduling of power flow management in the nanogrid, so as to achieve lower fuel consumption and significant decreased battery SOH loss than RB algorithm.

**Figure 4.20:** Simulation results of the rule based algorithm for three day.
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Figure 4.21: Simulation results of the DP algorithm for three day.

Table 4.3: DAILY COSTS USING DIFFERENT ALGORITHMS

<table>
<thead>
<tr>
<th>Day</th>
<th>Genset Energy Consumed (kWh)</th>
<th>Battery SOH Loss(SOC %)</th>
<th>Rule Based</th>
<th>DP</th>
<th>Rule Based</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 20</td>
<td>11.7808</td>
<td>11.7808</td>
<td>149</td>
<td>124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr. 21</td>
<td>10.5782</td>
<td>10.3487</td>
<td>149</td>
<td>146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr. 22</td>
<td>11.4683</td>
<td>11.0228</td>
<td>154</td>
<td>148</td>
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<td></td>
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<tr>
<td>Savings</td>
<td></td>
<td></td>
<td><strong>2%</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>7.73%</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.4: 3 Day Costs Using Different Algorithms

<table>
<thead>
<tr>
<th>Day</th>
<th>Rule Based Genset Energy Consumed (kWh)</th>
<th>Rule Based Battery SOH Loss (SOC %)</th>
<th>DP Genset Energy Consumed (kWh)</th>
<th>DP Battery SOH Loss (SOC %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 20-22</td>
<td>33.9683</td>
<td>438</td>
<td>33.1523</td>
<td>402</td>
</tr>
<tr>
<td>Savings</td>
<td>2.4%</td>
<td>8.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) 30 days real PV (blue *) and load (red ×) power

(b) Battery SOC variation with RB (blue *) and DP (green ◦)

**Figure 4.22:** Simulation results for 30 days, RB and DP comparison.
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**Figure 4.23:** Comparison of SOH loss in Fig. 4.22.

**Table 4.5:** 30 days (shown in Fig. 4.22) battery SOH total loss

<table>
<thead>
<tr>
<th>SOH Loss (Cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
</tr>
<tr>
<td>DP</td>
</tr>
<tr>
<td>Saving</td>
</tr>
</tbody>
</table>

**Table 4.6:** Description of 4 typical $P_{PV}$ and $P_L$

<table>
<thead>
<tr>
<th>Case #</th>
<th>Related Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fig. 4.24(a)</td>
<td>$P_{PV\text{--measured}} &gt; P_{PV\text{--forecast}} &gt; P_L$ most of the day</td>
</tr>
<tr>
<td>2</td>
<td>Fig. 4.24(b)</td>
<td>$P_{PV\text{--forecast}} &gt; P_{PV\text{--measured}} &gt; P_L$ most of the day</td>
</tr>
<tr>
<td>3</td>
<td>Fig. 4.24(c)</td>
<td>$P_L &gt; P_{PV\text{--measured}} &gt; P_{PV\text{--forecast}}$</td>
</tr>
<tr>
<td>4</td>
<td>Fig. 4.24(d)</td>
<td>$P_L &gt; P_{PV\text{--forecast}} &gt; P_{PV\text{--measured}}$</td>
</tr>
</tbody>
</table>
4.5.1.3 Algorithm to Deal with PV Power Uncertainty

Fig. 4.24 shows the forecast PV power, measured PV power and load power curves for four typical cases, and each case is described in Table 4.6.

For each case, three algorithms are performed and compared. The first algorithm is RB, which will use forecast PV power data to schedule the genset flow, but will be applied to the measured PV power and load power. The second algorithm applies proposed hybrid DP plus RB in Section 4.4.3, which utilizes forecast PV
power and load power to schedule the genset power one day ahead. The calculated genset power schedule is applied during the day before sunset time, while battery SOC and other system conditions are still monitored. If battery SOC becomes higher than 90% or lower than 10%, RB will be implemented until sunset. Otherwise, the results acquired by using DP with forecast PV power will be utilized.

After sunset, because the load power profile is assumed a known parameter, DP can be performed from the battery SOC at sunset time to the end of the day, so that local optimization during night time can be achieved and battery SOC can return to 50% at midnight, when there is no PV power available and 50% SOC level is easy to achieve by scheduling the genset power. The third algorithm tested is the deterministic DP that replaces the forecast PV power with the actual measured PV power data, so that there is no longer any forecast error. The results achieved from this algorithm can be considered as the ideal evolution of SOC and genset output power during the evaluation period.

The simulation results of fuel consumption and battery lifetime loss are listed in Table 4.7. From the table, we can find that, from battery SOH loss perspective, the proposed hybrid DP plus RB is always better than RB. However, from fuel consumption perspective, in Case 1 hybrid DP plus RB (16.15kWh) is slightly higher than RB (15.98kWh), the reason is explained as follows.

For Case 1 in Fig. 4.24, Fig. 4.25 shows the scheduling of the genset power with forecast PV power. For forecast PV power profile, the capacity of the battery can absorb all the PV energy for future use, so that no PV energy will be wasted.
However, the real PV power is higher than the forecast PV power, and under Case 1 condition, the capacity of the battery cannot absorb all the PV energy during the day, some PV energy will be wasted and the genset power must be used to compensate it. The real evolution of the battery SOC is shown as the red curve in Fig. 4.26 by using hybrid DP plus RB. If at the beginning of the day RB is utilized, because RB always keeps battery SOC as low as possible, most of the PV energy available can be absorbed. If at the beginning of the day the real PV power is known, deterministic DP can acquire the information that surplus PV energy cannot be fully utilized due to the battery capacity. It can then keep the battery SOC as low as possible. But DP with forecast PV power does not have accurate PV power information, so that it might not leave enough battery capacity for the real PV power. Therefore, when more PV power is produced than expected, the battery SOC may reach its limit and extra PV power must be wasted. This is a situation that should be avoided.

Figure 4.25: DP results with forecast PV power for Fig. 4.24(a), the genset power (red), battery power (blue) and battery SOC variation (green).

This can be verified in the battery SOC variations shown in Fig. 4.27. At the
Figure 4.26: Illustration of the proposed hybrid DP plus RB for the condition in Fig. 4.24(a), please note that green curve (scheduling with the real PV power) is only for reference, in reality battery SOC can not become higher than 100%, so that the PV power that charge the battery SOC to be higher than 100% is wasted.

beginning of the evaluation day shown in Fig. 4.24(a), Deterministic DP has the lowest battery SOC, while DP with forecast PV power has the highest battery SOC. The lower the battery SOC is, the more PV energy that can be stored and utilized, so that less fuel is consumed by the genset.

Figure 4.27: For Case 1, comparison of the battery SOC at the beginning of the evaluation day.

Fig. 4.28 shows the simulation result comparisons of RB (Section 4.4.1) with real
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Table 4.7: Comparison of Results with Different Algorithms for the Four Typical Cases

<table>
<thead>
<tr>
<th>Case #</th>
<th>Genset Energy Consumed (kWh)</th>
<th>Battery SOH Loss (SOC %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>RB</strong></td>
<td><strong>Hybrid DP</strong></td>
</tr>
<tr>
<td>1</td>
<td>15.98</td>
<td>16.15</td>
</tr>
<tr>
<td>2</td>
<td>17.82</td>
<td>17.82</td>
</tr>
<tr>
<td>3</td>
<td>31.37</td>
<td>31.37</td>
</tr>
<tr>
<td>4</td>
<td>28.81</td>
<td>28.81</td>
</tr>
</tbody>
</table>

PV power, DP (Section 4.4.2) with real PV power, and hybrid DP and RB (Section 4.4.3) with forecast and real PV power for the same 30 days shown in Fig. 4.22. The forecast PV, real (measured) PV and load power curves for the 30 days are shown in Fig. 4.28(a). The forecast PV power are acquired by using the methods presented in [134]. In some days, the forecast PV power has low error with real PV power, whereas in some other days the forecast PV power has significant error with the real PV power. For each day, the three algorithms are performed to schedule the genset output power, and the battery SOC changes based on the scheduling are shown in Fig. 4.28(b).

In Table 4.8, the third column DP(Ideal) means using DP with real PV power, so that the results can be considered as ideal. As shown in Table 4.8 and Fig. 4.29, for the 30 days both RB and DP algorithms have the same fuel consumption (748.73kWh), while hybrid DP and RB has a slight higher (0.11%) fuel consumption (749.57kWh). From battery lifetime perspective, hybrid DP and RB can save 7% battery SOH loss than RB. However, because hybrid DP and RB algorithm utilize forecast PV power, which has error, it has nearly 7% more battery lifetime
loss than DP with real PV power, which can achieve minimum battery lifetime loss and minimum fuel consumption at the same time.

Figure 4.28: Simulation results for 30 days, RB, hybrid DP and RB, and DP comparison.
### Table 4.8: 30 days fuel consumption (FC) and battery SOH total loss comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>FC(kWh)</th>
<th>Saving</th>
<th>SOH Loss (Cycles)</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>748.73</td>
<td>0</td>
<td>36.445</td>
<td>0</td>
</tr>
<tr>
<td>Hybrid DP+RB (DP with the forecast PV power + RB)</td>
<td>749.57</td>
<td>-0.11%</td>
<td>33.936</td>
<td>6.89%</td>
</tr>
<tr>
<td>DP with the real PV power</td>
<td>748.73</td>
<td>0</td>
<td>31.363</td>
<td>13.95%</td>
</tr>
</tbody>
</table>

#### 4.5.1.4 Discussion

In Table 4.9, the forecast PV energy and the real PV energy in each of the 30 days are listed. They are calculated as the integral of the forecast PV power and the real PV power in one day respectively. The difference between these two energies can be used to evaluate how close the two power curves are. In the simulation the battery capacity is 4.8kWh, and the energy error is divided by the battery capacity to get a percentage value. The value is more intuitive to evaluate how
Table 4.9: Comparison of forecast PV energy and measured (real) PV energy in Fig. 4.28(a).

<table>
<thead>
<tr>
<th>Day</th>
<th>Forecast PV energy (kWh)</th>
<th>Real PV energy (kWh)</th>
<th>Energy error (kWh)</th>
<th>Energy error percentage (%)*</th>
<th>Hybrid DP condition (described in Table 4.10)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>16.14</td>
<td>15.42</td>
<td>0.72</td>
<td>15.03</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>9.01</td>
<td>6.82</td>
<td>2.20</td>
<td>45.76</td>
<td>II</td>
</tr>
<tr>
<td>3</td>
<td>5.99</td>
<td>2.08</td>
<td>3.91</td>
<td>81.41</td>
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</tr>
<tr>
<td>4</td>
<td>3.24</td>
<td>1.32</td>
<td>1.92</td>
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</tr>
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<td>5</td>
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<td>3.15</td>
<td>65.55</td>
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<tr>
<td>6</td>
<td>12.83</td>
<td>4.41</td>
<td>8.42</td>
<td>175.41</td>
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</tr>
<tr>
<td>7</td>
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<td>3.92</td>
<td>1.23</td>
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<tr>
<td>8</td>
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<td>0.53</td>
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</tr>
<tr>
<td>9</td>
<td>9.72</td>
<td>11.78</td>
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</tr>
<tr>
<td>10</td>
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<td>-18.05</td>
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</tr>
<tr>
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<td>0.44</td>
<td>9.25</td>
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</tr>
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<td>0.86</td>
<td>17.99</td>
<td>I</td>
</tr>
<tr>
<td>29</td>
<td>4.63</td>
<td>0.49</td>
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<td>86.12</td>
<td>II</td>
</tr>
<tr>
<td>30</td>
<td>12.21</td>
<td>11.81</td>
<td>0.40</td>
<td>8.32</td>
<td>I</td>
</tr>
</tbody>
</table>

*Note: Energy error percentage is calculated as error energy divided by the battery capacity, which is 4.8kWh.
### Table 4.10: Three hybrid DP conditions discussed in Section 4.5.1.4.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
<th>Total Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>In hybrid DP + RB, RB will not turn on due to too low or too high battery SOC</td>
<td>14</td>
</tr>
<tr>
<td>II</td>
<td>In hybrid DP + RB, RB will turn on due to too low battery SOC</td>
<td>13</td>
</tr>
<tr>
<td>III</td>
<td>In hybrid DP + RB, RB will turn on due to too high battery SOC</td>
<td>3</td>
</tr>
</tbody>
</table>

easily the error between the forecast and the real PV energy can be compensated by the battery energy storage. For the implementation of the hybrid DP plus RB, there are three conditions used to determine when RB turns on, as listed in Table 4.10. They are explained in detail as follows.

If the forecast PV power is close to the real PV power, the scheduling of the genset power by using DP with day ahead forecast PV power is applicable to the real condition with acceptable battery variation. This means in the proposed hybrid DP plus RB algorithm, RB will not turn on due to too low or too high battery SOC. And the battery SOC can return to 50% at the end of the day by tuning the genset power at night, when there is no uncertainty of the PV power.

Consider Day1 in Fig. 4.28(a) as an example. The forecast PV power, real PV power and load power are enlarged in Fig. 4.30(a). The forecast PV power curve is nearly overlapped with the real PV power curve. As shown in Fig. 4.30(b), the scheduling of the genset power by using DP with forecast PV power can be applied to the real PV power in the whole day, without reaching battery upper or lower
limits. At the end of the day, battery SOC is 35\% instead of 50\%. This difference can be compensated by using DP at night time (18pm - 24pm).

In the evaluated 30 days shown in Fig. 4.28(a), there are 14 days classified with the condition that the forecast PV power is ”close” to the real PV power, and RB will not be triggered. They are listed in the rightest column of Table 4.9.

![Power Profile](a)

![Battery SOC](b)

**Figure 4.30:** (a) forecast PV power, real PV power and load power in Fig. 4.28(a) Day 1. (b) Battery SOC variation comparison, forecast (blue), real (green) and real after tuning (red).

The second condition is when forecast PV power is higher than real PV power, and the deficit PV power (the forecast PV power minus the real PV power) will cause battery SOC to reach its lower limit, so that RB turns on. Under this condition,
the battery SOC is at a level lower than expected, but fuel consumption will not increase because the battery SOC does not reach its higher limit, so that no PV energy is wasted. This has been presented in Section 4.4.3 example and the figures are redrawn in Fig. 4.31.

In the evaluated 30 days shown in Fig. 4.28(a), there are 13 days that can be classified to this condition that the forecast PV power is lower than the real PV power, and this causes RB to be triggered when battery SOC reaches its lower limit (10%). They are listed in the rightest column of Table 4.9.

The third condition is when the total forecast PV energy in the day is lower than the real PV energy in that day, AND real PV power peak is higher than the load power. The surplus PV power must be stored in the battery, but DP with forecast PV power does not anticipate this condition. As a result, the surplus PV energy may push the battery SOC to be higher than the upper limit, which means some PV energy will be wasted and the genset energy must eventually be used to compensate the wasted energy. This condition is discussed in previous section for Fig. 4.24(a). Day 9 in Fig. 4.28(a) is also in this condition. Because the surplus PV energy is not taken into account, DP with the forecast PV power cannot schedule enough battery SOC margin, so that battery SOC will reach 90% and some PV energy is wasted, as shown in Fig. 4.32.

In the evaluated 30 days shown in Fig. 4.28(a), there are 3 days that can be classified to this condition that the forecast PV power is higher than the real PV
Chapter 4. *Optimal Power Flow Management*

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Figure 4.31: (a) forecast PV power, real PV power and load power in Fig. 4.28(a) Day 2. (b) Scheduling of the genset power by using DP with the forecast PV power. (c) Battery SOC variation comparison, forecast (blue), real (green) and real after tuning (red).
power, and this causes RB to be triggered when battery SOC reaches its higher limit (90%). They are listed in the rightest column of Table 4.9.

\[
\begin{array}{|c|c|}
\hline
\text{PV Power} & \text{Wasted} \\
\hline
\end{array}
\]

Figure 4.32: (a) forecast PV power, real PV power and load power in Fig. 4.28(a) Day 9. (b) Battery SOC variation comparison, forecast (blue), real (green) and real after tuning (red). Please note that green curve (scheduling with the real PV power) is only for reference, in reality battery SOC can not become higher than 100%, so that the PV power that charge the battery SOC to be higher than 100% is wasted.

As discussed in previous sections, the highest priority of the designed energy management algorithms is to save fuel consumption. For the third condition, in future research a possible solution can be implemented is stochastic dynamic programming, which can deal with the uncertainty of the state information and treat the
uncertainty as a probability distribution. However, the probability distribution can only be acquired through the analysis of history forecast and real PV power data. The error between the forecast and real PV power varies based on weather. For example, sunny days and cloudy days may have different models for their error between the forecast and real PV power. As a result, pattern recognition method might be introduced. This topic is beyond the scope of this thesis, and it may be investigated in future research.

4.5.2 Experimental Results with RB and Deterministic DP Algorithms

The experimental test bench of a nanogrid system has been established. The main building blocks are described in Table 4.11, and the photograph is shown in Fig. 4.33. In the tests to compare rule based and DP algorithms, the test time is 3730 seconds, the load is setup to be at a constant level (380W) and the PV power is a square wave from 950 s to 2150 s with the high power level at 730W and low power level at 0. The utility grid is used to replace the genset in the system.

4.5.2.1 RB vs. DP

Fig. 4.34 shows the experimental results of the rule based algorithm, in which the battery and PV energy is utilized at a higher priority. In this experiment, voltage thresholds are used to represent the SOC thresholds. If the battery voltage is lower
than a given value (22V in this experiment), the grid power will be transferred to supply the AC load. At the beginning of the test period, the battery voltage is 23V, and at the end of the test period, the battery voltage is expected to be at the given final level (23.4V). The energy change in the battery is presented in the form of integration of the battery current over the time, which can be considered as the SOC change in the battery.

Fig. 4.35 demonstrates the experimental results of the ideal DP algorithm with the same load and PV profiles in the same time period. At the beginning of the test period the battery voltage is 23V while at the end of the test period the battery voltage is 23.4V. As shown in Table 4.12, the performance of two algorithms are evaluated by AC power consumption and battery SOH loss. From AC power consumption perspective, RB (202.07Wh) is lower than DP (215.56Wh). But note that due to the error of battery voltage vs. SOC, the final SOC of RB is 1.71Ah lower than its initial SOC. This energy must be compensated to perform the comparison between RB and DP, because DP has its final SOC the same as initial SOC. As a result, from total energy consumption perspective, RB consumed 242.29Wh whereas DP consumed 215.56Wh, RB consumed 11% more energy than DP. From battery SOH loss perspective, DP has 58.8% less the accumulated discharged energy from the battery than RB. Further DP has battery SOC that is at a higher overall level than RB. From the analysis of battery SOH model in Section 4.2.3.2, this pattern can extend battery lifetime. The experiments help validate the effectiveness of the optimization algorithms derived in this thesis.
Figure 4.33: (a) Block diagram of a 1.5kW PV nanogrid system as the test bench; (b) Test bench overview for a 1.5kW PV nanogrid system.
Table 4.11: Test bench items of the 1.5kW nanogrid system

<table>
<thead>
<tr>
<th>Main Building Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Inverter/Charger unit</td>
</tr>
<tr>
<td>2. Distribution box</td>
</tr>
<tr>
<td>3. Battery (behind the oscilloscope)</td>
</tr>
<tr>
<td>4. DC power supply</td>
</tr>
<tr>
<td>5. DC load</td>
</tr>
<tr>
<td>6. AC load (halogen lamps)</td>
</tr>
<tr>
<td>7. System control panel</td>
</tr>
<tr>
<td>8. PC with software for monitoring and configuring the system</td>
</tr>
<tr>
<td>9. MPPT charger (not shown in the picture)</td>
</tr>
<tr>
<td>10. PV simulator (not shown in the picture)</td>
</tr>
</tbody>
</table>

Figure 4.34: Experimental results of the rule based algorithm.
Figure 4.35: Experimental results of the DP algorithm.

Table 4.12: Experimental results using RB and DP, when the PV power assumed known

<table>
<thead>
<tr>
<th>Time</th>
<th>AC Energy Consumed (Wh)</th>
<th>Battery SOH Loss(Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rule Based</td>
<td>DP</td>
</tr>
<tr>
<td>3730s</td>
<td>202.07</td>
<td>215.56</td>
</tr>
<tr>
<td>Initial SOC</td>
<td>0 Ah</td>
<td>0 Ah</td>
</tr>
<tr>
<td>Final SOC</td>
<td>-1.71 Ah</td>
<td>0 Ah</td>
</tr>
<tr>
<td>Compensation Energy</td>
<td>40.22 Wh</td>
<td>0 Wh</td>
</tr>
<tr>
<td>Total Needed Energy</td>
<td>242.29 Wh</td>
<td>215.56 Wh</td>
</tr>
<tr>
<td>Savings</td>
<td>11%</td>
<td>58.8%</td>
</tr>
</tbody>
</table>
4.5.2.2 DP with PV Power uncertainty

Fig. 4.36 shows three PV power curves and one load power curve. The green curve is the forecast PV power. If the real PV power is exactly the same as the forecast PV power, the power management in the nanogrid schedules the genset power as shown in Fig. 4.37. Before the PV power becomes high, the genset is ON to supply the AC load, but not charge the battery, so that the battery SOC keeps constant. After the PV power becomes high, the genset is OFF. Because the PV power is higher than the load power, it can charge the battery and supply the AC load at the same time. When the PV power becomes low, the battery will supply the AC load for a while until the battery SOC returns to its initial level. Then the genset will be turned ON again to supply the AC load but not charge the battery.
However, the real PV power is not exactly the same as the forecast PV power. As shown in Fig. 4.36, it could be lower (red curve) or higher (cyan curve) than the forecast PV power (green curve). The experiments of the two conditions are performed and the results by using DP with uncertainty are explained as follows.

Fig. 4.38 shows the experimental results by using hybrid DP (DP + RB) with the real PV power that is lower than the forecasted PV power. Before the PV power becomes high, the genset is ON to supply the AC load, but it is not charging the battery, so that battery SOC keeps as a constant. This procedure is the same as shown in Fig. 4.37. However, when the real PV power becomes high, it is lower than the forecast PV power, and it is not enough to supply the AC load. Battery energy has to be consumed to feed the AC load together with the real PV power. As a result, battery SOC begins to drop. After the real PV power becomes low, the battery continues to supply the AC load, until it reaches the lower limit 22V when RB will be implemented. The genset will be ON to charge the battery and supply the AC load at the same time. After the battery SOC returns to its initial level, battery charge is turned off and the genset only supplies the AC load.

In comparison, Fig. 4.39 shows the experimental results by using RB with the real PV power that has the same PV profile as shown in Fig. 4.38. In this experiment, voltage thresholds are used to represent the SOC thresholds. If the battery voltage is lower than a given value (22V in this experiment), the grid power will be transferred to supply the AC load. At then end of the test period, battery SOC, represented as the integral of battery current, returns to its original level.
Table 4.13: Experimental results using RB and hybrid DP, when the forecast PV power is lower than the real PV power shown in Fig. 4.36

<table>
<thead>
<tr>
<th>Time</th>
<th>AC Energy Consumed (Wh)</th>
<th>Battery SOH Loss (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rule Based</td>
<td>Hybrid DP</td>
</tr>
<tr>
<td>2420s</td>
<td>169.38</td>
<td>156.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.14: Experimental results using RB and hybrid DP, when the forecast PV power is higher than the real PV power shown in Fig. 4.36

<table>
<thead>
<tr>
<th>Time</th>
<th>AC Energy Consumed (Wh)</th>
<th>Battery SOH Loss (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rule Based</td>
<td>Hybrid DP</td>
</tr>
<tr>
<td>2420s</td>
<td>97.43</td>
<td>82.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 4.13, compared with the RB results, hybrid DP can save the energy from utility by 7.32% and SOH loss is 44.98% less.

Fig. 4.40 shows the experimental results by using hybrid DP (DP + RB) with the real PV power that is higher than the forecast PV power. Before the PV power becomes high, the procedure is the same as shown in Fig. 4.37 and Fig. 4.38. However, when the real PV power becomes high, it is higher than the forecast PV power. The surplus PV power charges the battery and the battery SOC rises more quickly than in Fig. 4.37. Fortunately, the battery is not fully charged, so that the surplus PV power can totally be stored in the battery. After the real PV power becomes low, the battery continues to supply the AC load. In this case the battery power is high enough to supply the AC load at the end of the evaluation period.
In comparison, Fig. 4.41 shows the experimental results by using RB with the real PV power that has the same PV profile as shown in Fig. 4.40. In this experiment, voltage thresholds are used to represent the SOC thresholds. If the battery voltage is lower than a given value (22V in this experiment), the grid power will be transferred to supply the AC load. At then end of the test period, battery SOC, represented as the integral of battery current, returns to its original level. As shown in Table 4.14, compared with the RB results, hybrid DP can save the energy from utility by 15.42% and SOH loss is 26.95% less.

The experimental results shown in Fig. 4.36 to Fig. 4.40 have verified the effectiveness of the proposed hybrid DP plus RB algorithm, which can deal with the PV power uncertainty. The comparison of the battery SOC evolution in the three aforementioned cases is shown in Fig. 4.42. The expected battery SOC evolution is shown as the blue curve, by using DP with the forecast PV power. However, in reality the real PV power can be lower and higher than the forecast PV power. By using hybrid DP, the battery SOC evolutions are the green curve and the red curve in Fig. 4.42. If the real PV energy is lower the forecast PV energy, battery SOC will decrease and it might trigger RB when it reaches lower limit. If the real PV energy is higher than the forecast PV energy, battery SOC will increase and it might trigger RB when it reaches higher limit. The performance achieved by the hybrid DP is higher than the RB, as shown in Table 4.13 and Table 4.14.

It should be pointed out that for the condition shown in Fig. 4.40, if the real PV power is even higher than the PV power shown in Fig. 4.40, it is possible that
the battery will reach its full SOC, so that some PV power will be wasted and 
the wasted PV power must be compensated by the genset power, and the fuel 
consumption is increased.

4.6 Conclusion

In this chapter, the optimal energy flow in the nanogrid is presented. First, the 
energy system model is derived including PV panel, battery SOC, battery SOH, 
diesel generator (genset), load profile and power electronics. Second, the problem 
description is presented. For the nanogrid proposed, the optimal energy flow has 
maximum utilization of the solar energy, lowest fuel consumption and lowest bat-
tery health loss, while at the same time not to violate certain constraints. Third, 
energy flow algorithms are derived. The proposed rule based (RB) algorithm may 
not achieve optimal energy flow, but it will not violate the constraints. A sec-
ond proposed algorithm is deterministic dynamic programming (DP). As long as 
the information of PV and load profiles are accurate, the algorithm can achieve 
optimal energy flow in the nanogrid. To deal with the uncertainty of PV power, 
hybrid DP plus RB is proposed. If the forecast PV power is accurate enough, 
scheduling by using DP with the forecast PV power is applied. If battery SOC 
hits upper or lower limits during the operation time when using DP with forecast 
PV power, the system will switch to RB, so as to prevent violation of constraints.
Figure 4.37: Experimental results of the DP algorithm with forecast PV power.
Figure 4.38: Experimental results of the hybrid DP algorithm with real PV power lower than forecast PV power.
Figure 4.39: Experimental results of the RB algorithm with real PV power lower than forecast PV power.
Figure 4.40: Experimental results of the hybrid DP algorithm with real PV power higher than forecast PV power.
Figure 4.41: Experimental results of the hybrid RB algorithm with real PV power higher than forecast PV power.
Compared with the RB algorithm, the advantages of the deterministic DP algorithm are verified by the simulation and experimental results. Also, the simulation results for the hybrid DP plus RB algorithm that can deal with the uncertainty of PV power is demonstrated for most typical PV and load conditions, help verify the effectiveness of the proposed method.

Figure 4.42: Comparison of the battery SOC evolutions in the three conditions shown in Fig. 4.36.
Chapter 5

Conclusions and Future Work

The research presented in this dissertation designed standalone nanogrid system for individuals by building modified sine wave inverters. The inverters were able to work both in parallel and in series. If the inverters are configured to work in parallel, even power distribution of the paralleled inverters can be achieved by applying piecewise master-slave current sharing technique, and there is no circulating current by implementing dead time control. If the inverters are configured to work in series, they can produce multilevel AC outputs, that can reduce the THD. The constructed multilevel inverters can also work in parallel with the methods proposed. From the system level perspective, the optimal energy flow in the nanogrid has been investigated and new energy control algorithms have been proposed. The main contributions of the research are summarized below, and recommendations for future work are presented.
5.1 Conclusions

The achieved results and major research contributions of this dissertation are summarized as follows:

- In Chapter 2, the architecture of a portable nanogrid is presented. Specifically, a lightweight, compact and high reliability modified sine wave inverter is designed in the nanogrid. Together with the foldable PV panel, MPPT charger and smart battery, the developed nanogrid can effectively harvest solar energy to supply both AC and DC loads.

  - Modified sine wave inverters (MSWI) are introduced in detail in this chapter, and they are compared with pure sine wave inverters. Their advantages and limitations are compared and discussed. The reasons MSWI are used in this research are explained.

  - The architecture of the developed portable nanogrid is illustrated. The designed nanogrid is suitable for individuals like campers, hikers and especially soldiers on the move. It can harvest solar energy from the foldable PV panel to supply both DC and AC loads simultaneously. The battery utilized in the system can buffer the energy transfer and act as the main energy source when solar energy is not available.
- Specifically, in order to achieve suitable dynamic response of the first stage DC-DC converter in the inverter designed, gain scheduling technique is utilized. At different phase of AC output voltage, different gain magnitude in the feedback controller is adopted to avoid large undershoot and overshoot of the output voltage, especially, during transient times of different AC load output power levels.

- In Chapter 3, a method is proposed to parallel the designed modified sine wave inverters directly, so as to achieve higher AC power and equitable power sharing.

- With the designed modified sine wave inverter, the next step is to make multiple such inverters to work in parallel to achieve higher AC power, while at the same time to maintain a even power sharing among them. A brief literature review of the parallel operation of DC-DC converters and DC-AC inverters is presented in this chapter. However, unlike parallel operation of pure sine wave inverters, the paralleled MSWIs do not have inductors in-between them, so that the possible circulating current cannot be attenuated; unlike parallel operation of DC-DC converters, the polarity of MSWIs is not constant, and the voltage level is not consecutive. As a result, none of the methods proposed in literature can be implemented directly for the parallel working of MSWIs.
In Chapter 3, a new method to parallel MSWIs is proposed. Without the proper control of the possible circulating current, the current could become very high and damage the inverters. The first contribution of the proposed method is to use dead time control to fully eliminate the circulating current when multiple MSWIs are paralleled. By adding a proper dead time in between the synchronized phase transient, the short circuit of the DC source can be avoided. The second contribution of the proposed method is to use piecewise master-slave current sharing approach to equalize the load current distribution in each paralleled MSWI. The current sharing control loop will only perform its function during the inverter output voltage equals to $V_{dc}$ or $-V_{dc}$. Therefore, from the inverter first stage DC-DC conversion perspective, the current sharing is consecutive. The effectiveness of the proposed method is verified by the experiments using CAN bus as the communication in the multiple designed MSWIs.

The designed MSWI is able to work both in parallel as well as in series in order to construct a multilevel inverter. The architecture of the multilevel inverter is similar to cascaded H-bridge inverter in literature, but the DC voltage can be controlled individually by each DC-DC converter connected. The developed method to parallel MSWI is modified to parallel multilevel inverters. Experimental results are shown the parallel operation of the constructed multilevel inverters, so that the flexibility
of the nanogrid designed is verified.

- In Chapter 4, optimal energy flow management for solar tent nanogrid is discussed at the system level. Optimization algorithms are proposed to achieve the minimal fuel consumption, maximum solar energy utilization, and battery lifetime saving.

  - The architecture presented in Chapter 2 can be utilized not only for portable nanogrid but also for even higher power nanogrid with a solar tent (instead of foldable PV panel). To design the optimal energy control algorithms, the model of each component in the nanogrid is discussed, with special focus on the PV power, lead acid battery SOC/SOH, diesel generator and load condition.

  - The optimal energy flow to schedule the power flow at each time interval during the given time period. The goal is to achieve low fuel consumption, maximum PV power utilization and minimum battery lifetime loss with specified constraints. First, a non-optimal rule-based algorithm has been proposed based on heuristic knowledge. This algorithm can guarantee system operation not to violate the constraints, but it will not take the whole PV power and load pattern into account. It does not achieve global optimization. Second, a dynamic programming algorithm is developed. With deterministic information, the developed algorithm can calculate the cost of the power flow for each time period
evaluated and then achieve the global optimization. Simulation and experimental results are shown to verify the effectiveness of the proposed DP algorithm.

- The proposed DP algorithm achieves global optimization energy flow with the day-ahead PV power information. However, in reality, there always existing error between the forecasted PV power and real PV power. A new optimization method is proposed that combines the DP and Rule-based algorithms to mitigate the affordable uncertainty of the PV power. The genset power scheduling by using DP with the one day ahead forecast PV power will be utilized first. If the real PV power has high error, RB will be implemented to prevent the system operation violating the constraints. Simulation and experimental results have illustrated the effectiveness of the proposed approach.

5.2 Future Work

In this dissertation, both circuit level and system level approaches for the nanogrids have been developed to increase the flexibility, expandability and reliability of the systems. The designed MSWIs can operate in parallel and in series without possible circulating current and with proper power sharing. Optimization control has been applied to achieve lower fuel consumption and longer battery lifetime.

To continue this research, possible future work may include:
• Parallel operation of MSWIs and multilevel inverters.

– Although the MSWI can save the space and weight of output LC filter and simplify control complexity, its output has high THD. As shown in Fig. 5.1, there are two main ways to create a quasi pure sine wave so as to reduce the harmonics and THD. The first method is to use SPWM technique, which controls the drive signals of the H-bridge to generate different duty cycles of pulses to eliminate low frequency harmonics. The second method is to use multilevel voltage to approach pure sine wave. If the switching frequency and control loop bandwidth can be much higher than the design presented, the size and weight of the first stage DC-DC converter output filter and the output LC filter can be greatly reduced.

Future research can investigate how to achieve very high frequency in the first stage DC-DC converter, yet keep the second stage H-bridge to be low frequency. The output voltage of DC-DC converter can be controlled to produce approximate pure sine wave, or any waveform wanted. The possible benefits include small size, high dynamic response and simple control strategy for second stage H-bridge.

– As shown in Fig. 5.2, in this research there is no control of the input power of the designed inverter, which contains undesirable double harmonic, $2f$, components where $f$ is the inverter output frequency. The
double harmonics in the power have possible negative influence on the battery health and MPPT performance of the PV charger.

Extra circuits should be studied that might mitigate this double line frequency harmonic. As shown in Fig. 5.3, possible decoupling techniques include passive decoupling capacitor with battery, decoupling circuit in parallel with battery, and decoupling circuit in series with battery. Future research can investigate which technique is the best for the inverter proposed, and how to design the decoupling circuit.

– Presently, the synchronization of the drive signals and power information exchange are realized by CAN bus, which is robust and high frequency. However, it is possible that the CAN bus becomes physically broken, has poor connection or becomes interrupted. Under this condition, the proposed piecewise master-slave current sharing method
Chapter 5. Conclusions and Future Work

Figure 5.2: Input current of the modified sine wave inverter designed.

Figure 5.3: Possible power decoupling architectures: (a) passive decoupling capacitor with battery; (b) decoupling circuit in parallel with battery; (c) decoupling circuit in series with battery.
cannot be implemented. To solve this problem, power line communication (PLC) method might be a good candidate to eliminate extra communication wires. PLC transfers signals through the power line, which always exists for the parallel operation of multiple inverters. Another possible candidate is to utilize wireless communication, which has the similar advantage over the current CAN bus solution. How to achieve stringent synchronization through these communication methods needs further investigation. Future research can study the robustness of PLC and wireless communication between inverters and how to shield possible noise to improve the reliability of the system. Also, when the master inverter in the proposed piecewise master-slave current sharing method fails, future research should investigate how to seamlessly change the master through communication.

- In this research, several designed MSWIs can work in series to construct a multilevel inverter. For each H-bridge in the multilevel inverter, the output duty cycle is different, while the voltage level is the same, which means it will feed different power to the load. In a CHB multilevel inverter with $N$ H-bridges, each H-bridge input DC source has different output power. The larger duty cycle of the H-bridge, the higher output power of the connected DC source. For example, with the duty cycles shown in Fig. 5.4, $P_{dc1} > P_{dc2} > \cdots > P_{dcN}$. Future research should
investigate the selection of the duty cycle and its relation to the condition of the input battery. The lower voltage battery could have smaller duty cycle, while the higher voltage battery could have wider duty cycle, so as to balance the different battery energy capacity. The benefits include longer running of the AC load, healthier batteries, and higher overall system efficiency because of the reasonable power distribution in different voltage/SOC batteries.

\[
\sum_{i=1}^{N} V_{i} = \sum_{i=1}^{N} P_{dc,i}
\]

**Figure 5.4:** In a CHB multilevel inverter with \( N \) H-bridges, each H-bridge input DC source has different output power.

- The aforementioned future work for parallel MSWIs can also be extended to the parallel operation of multilevel inverters. If each MSWI can have very high switching frequency and control loop bandwidth,
the multilevel inverter can have even lower harmonics and THD with multiple H-bridges in series. The technical challenges for paralleling the multiple H-bridge inverters is an open area for research.

- **Nanogrid energy flow optimization.**

  - In this thesis, the load pattern in the nanogrid is a known parameter to design the optimal energy flow algorithms. In real applications, only predicted load conditions can be acquired. Future research should consider the uncertainty of the load in the nanogrid energy flow algorithm development. A possible approach may utilize the of mathematical tool of stochastic dynamic programming [136–140], which can find the solution of shortest path problem based on the possibility estimation of state change. As shown in Fig. 5.5(b), for deterministic DP, if the system is in stage $k$ and a given decision $(P_{DG},k)$ is applied to $SOC(i,k-1)$, the state that the system at the next stage $k$ can be determined to be $SOC(j,k)$ because the load and PV power are known parameters at stage $k$. However, as shown in Fig. 5.5(c), if the load power is unknown, with a specific decision, the transitions from state $SOC(i,k-1)$ at stage $k-1$ to stage $k$ cannot be determined but can be described by a probability distribution $p(i,j,k)$, based on the estimated probability of the uncertain load power. Then stochastic dynamic programming can be utilized to find the shortest path of the battery SOC evolution. Future
research can investigate how to utilize stochastic dynamic programming to deal with uncertainty.

For other components in the nanogrid, better models could be also derived in future research to improve the final results. For example, efficiency curves for MPPT charger and inverter in the system can be used to refine the real power in the system.

![Diagram](image)

**Figure 5.5:** (a) DP for multi-stage shortest path problem.; (b) deterministic DP stage transition; (c) stochastic stage transition.

- As shown in Fig. 5.6, in practice several nanogrid system presented in this thesis may work in parallel. Each nanogrid may have similar PV
power pattern but different load power scenarios. The proposed optimal control algorithms could in the future be modified for a larger paralleled system. Also, in such system, there may exist dump load, DC load and remote AC load, and any new optimal energy management system should have the ability to schedule power generation and consumption for all the components in the system.

In Fig. 5.7, the individual or paralleled nanogrid is also able to connected with utility grid. The cost function in the proposed DP algorithm should be modified accordingly. Fig. 5.6 shows an example of electricity price variation with different hours during one day and different months. The cost function discussed in Chapter 4 can be modified to minimize

\[
\int_0^T (w_1 D_{Grid}(P_{Grid}(t)) + w_2 SOH(P_{BAT}(t)) + w_3 [P_{PV, aval}(t) - P_{PV}(t)]) dt
\]

(5.1)

\(w_1\) and \(w_2\) are weight coefficients. It contains three items, the second item is the battery state of health (SOH), and the third item is the difference between the available PV power \(P_{PV, aval}\) and the utilized PV power \(P_{PV}\). They are the same as in Chapter 4. Instead of evaluation of the fuel consumption, the first item \(D_{Grid}\) is the electric bill price from utility company at the power level \(P_{Grid}(t)\), and \(P_{Grid}(t)\) is time variant based on different hours during one day and different months. Future
Figure 5.6: Multiple proposed nanogrid in parallel with genset or utility grid.
research can investigate optimal power management of the nanogrid with utility electricity price variation. This may have the ability to minimize monetary costs, which is an important aspect in the utility and consumer markets.

Figure 5.7: A typical electricity price plan in different months and hours: (a) winter months; (b) summer months; (c) summer peak months. In the figures, TOU means Time of Use.[141]
Appendix A

All States in the Solar Tent Nanogrid System

Figure A.1: Solar tent nanogrid system.
The complete states of the proposed solar tent nanogrid system (Fig. A.1) are listed as follows. Please note that the DC load and the remote AC load are beyond the scope of this research, so they are neglected in the states.

<table>
<thead>
<tr>
<th>#</th>
<th>State Diagram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>Standby mode, all devices are off</td>
</tr>
<tr>
<td>1</td>
<td><img src="image" alt="State 1 Diagram" /></td>
<td>Battery is charged by the MPPT charger, inverter is in standby mode.</td>
</tr>
<tr>
<td>2</td>
<td><img src="image" alt="State 2 Diagram" /></td>
<td>Battery is charged by the MPPT charger, AC load is supplied by the genset and the inverter is in pass through mode. The system is divided to two independent subsytems (DC and AC).</td>
</tr>
<tr>
<td>3</td>
<td><img src="image" alt="State 3 Diagram" /></td>
<td>MPPT charger is turned off, no energy exchange in battery. The energy is directly from genset to the AC load, the inverter is in pass through mode.</td>
</tr>
</tbody>
</table>
The AC load is supplied by the battery. The inverter is in inverting mode, which means inverter is producing AC power from DC bus.

The AC load is supplied by the PV energy. No energy exchange in the battery. The inverter is in inverting mode.

The AC load is supplied by both the PV energy and the battery. The battery is discharging. The inverter is in inverting mode.

The AC load is supplied by the PV energy. The battery is charged by the surplus PV energy. The inverter is in inverting mode.
<table>
<thead>
<tr>
<th>Page</th>
<th>Diagram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td><img src="image1.png" alt="Diagram 1" /></td>
<td>The AC load is supplied by both the battery and genset. The inverter is in grid-support mode, which means inverter is producing AC power from DC bus to supply AC load together with the genset.</td>
</tr>
<tr>
<td>9</td>
<td><img src="image2.png" alt="Diagram 2" /></td>
<td>The AC load is supplied by the PV energy and genset. No energy exchange in the battery. The inverter is in grid-support mode.</td>
</tr>
<tr>
<td>10</td>
<td><img src="image3.png" alt="Diagram 3" /></td>
<td>The AC load is supplied by the PV energy, the battery and the genset. The battery is discharging. The inverter is in grid-support mode.</td>
</tr>
<tr>
<td>11</td>
<td><img src="image4.png" alt="Diagram 4" /></td>
<td>The AC load is supplied by the PV energy and genset. The battery is charged by the surplus PV energy. The inverter is in grid-support mode.</td>
</tr>
</tbody>
</table>
Table A.1: Complete States of the Solar Tent Nanogrid System

To summarize, the system states can be classified to the following modes:

- **Stop mode** (*State 0*): all devices are OFF.
• **MPPT mode** (*State 1*): inverter is not working, only MPPT charger is producing power from solar tent to charge the battery.

• **Pass through mode** (*State 1 and 2*): AC load is powered directly by the genset, no AC power from the inverter.

• **Inverting mode** (*State 4-7*): AC load is powered by the inverter, genset is OFF.

• **Grid support mode** (*State 8-11*): AC load is powered by the inverter and the genset together.

• **Charging mode** (*State 12-13*): Inverter is producing both AC and DC power.

• **Sell mode** (*State 14-17*): If genset is replaced by utility grid, in this mode inverter is "selling" DC power to the grid. However, in the nanogrid with genset, the AC power generated by the inverter is not feeding to the genset but consumed by the remote AC loads.
Appendix B

MATLAB Code for Forward and Backward Dynamic Programming

Here is the MATLAB code for forward and backward dynamic programming algorithms designed for the optimal energy control of the nanogrid described in Chapter 4. They can be used for any shortest path problems with $N$ stages, a start point, an end point and corresponding cost for each two consecutive states.

```matlab
%% shortest path (sp) algorithm: forward
% sp(i,k,k) means the shortest path route from the start point to
% SOC(i,k), i belongs to 1...M (SOC percentages), k belongs to
% 1...N (stages). each route contains k notes. For example,
% sp(SOC_stop_num,N,:) is the route from the start point to
% specified point (SOC_stop_num) at 24pm, which contains N points.
```

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Appendix B. MATLAB Code for Forward and Backward DP

sp_fwd = zeros(M,N,N);

% shortest path length from the start point to SOC(i,k);
sp_len_fwd = zeros(M,N);

% forward algorithm
for k = 1:N
    for j = 1:M
        if k == 1
            sp_fwd(j,k,k) = SOC_start_num;
            sp_len fwd(j,k) = cost arc(SOC_start_num,j,k);
        else
            sp_len_fwd(j,k) = sp_len_fwd(1,k-1) + cost arc(1,j,k);
            sp_fwd(j,k,k) = 1;
            sp_fwd(j,k,1:(k-1)) = sp_fwd(1,k-1,1:(k-1));
        for i = 2:M
            sp_len_new = sp_len_fwd(i,k-1) + cost arc(i,j,k);
            if(sp_len_new < sp_len_fwd(j,k))
                sp_len_fwd(j,k) = sp_len_new;
                sp_fwd(j,k,k) = i;
                sp_fwd(j,k,1:(k-1)) = sp_fwd(i,k-1,1:(k-1));
            end
        end
    end
end

% shortest path (sp) algorithm: backward

Appendix B. MATLAB Code for Forward and Backward DP

% backward algorithm
% sp_bkwd(i,k,k) means the shortest path route from the stop point to
% SOC(i,k), each route contains N-k+1 notes. For example,
% sp_bkwd(SOC_start_num,1,:) is the route from the stop point to
% specified point (SOC_start_num) at 0am, which contains N points.
sp_bkwd = zeros(M,N,N);
sp_len_bkwd = zeros(M,N);
% sp_temp = zeros(M,N,N); % use as the oposite direction of sp_bkwd
for k = 1:N
    for i = 1:M
        if k == 1
            sp_bkwd(i,N-k+1,N-k+1) = SOC_stop_num;
            sp_len_bkwd(i,N-k+1) = cost_arc(i,SOC_stop_num,N-k+1);
        else
            sp_len_bkwd(i,N-k+1) = sp_len_bkwd(i,N-k+2) + ...
                                cost_arc(i,1,N-k+1);
            sp_bkwd(i,N-k+1,N-k+1) = 1;
            sp_bkwd(i,N-k+1,(N-k+2):N) = sp_bkwd(1,N-k+2,(N-k+2):N);
        for j = 2:M
            sp_len_new = sp_len_bkwd(j,N-k+2) + ...
                        cost_arc(i,j,N-k+1);
            if(sp_len_new < sp_len_bkwd(i,N-k+1))
                sp_len_bkwd(i,N-k+1) = sp_len_new;
                sp_bkwd(i,N-k+1,N-k+1) = j;
                sp_bkwd(i,N-k+1,(N-k+2):N) = ...
                sp_bkwd(j,N-k+2,(N-k+2):N);
end
end
end
end
end
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