ENERGY MANAGEMENT AND MULTI-LAYER
CONTROL FOR NETWORKED MICROGRIDS

By

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I would like to thank my wife and daughters for the continuous support and understanding during this study. I also would like to express my sincere gratitude to my parents for supporting me spiritually throughout completing this dissertation and my life in general.
A networked microgrid system is a group of neighboring microgrids that has ability to interchange power among the connected microgrids in order to increase the reliability and resiliency. A microgrid within a networked microgrid system can operate in different possible configurations including: islanded microgrid, an asynchronously grid-connected microgrid, a synchronously grid-connected microgrid, and networked microgrids. These possible configurations for networked microgrids, non-dispatchability of renewable energy, and different ownership of microgrids offer challenges in controlling voltage, frequency and in energy management for all possible operating scenarios. This leads to a control design problem which is nonlinear and multi input-multi output (MIMO).

The novel control architecture developed in this dissertation to address these
challenges has multiple layers, which can switch between different operating modes to work in all possible scenarios. The outer layer is designed to be slower than the inner layer. The local controllers as part of the inner layer are designed based on the large-signal model to enable microgrid to operate in a wide range of operating points. A well designed PI controllers and feed-forward measured system responses will compensate for the nonlinearity. The dq-based control that works in constant trajectory and can decouple control variables to create a single input-single output (SISO) system is used for voltage source converter (VSC) control. Local controllers coordinate with upper layers to regulate voltage magnitude and frequency, as well as output power of the DG(s).

These layered control structures also integrate with a microgrid level energy management system or microgrid central controller (MGCC) for power and energy balance in microgrid in islanded, synchronous/asynchronous grid-connected, or net-worked microgrid modes. The MGCC can operate in two different operating modes: economic and resilient operation. In case of missing reference signal, the decentralized energy management will switch to local control mode and will activate droop control. Simulation results indicate the superiority of designed control algorithms compared to existing ones using a number of test case studies.
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Dedication

To Hera, my dear wife and best friend, for her patience and support during this work

To Haniyah & Fathinah, my beloved daughters, for the happiness they brought into our lives

And

To my mother and late father, for their love and hope on me
CHAPTER 1. INTRODUCTION

1.1 Introduction

This chapter provides introduction to microgrid, challenges in control of networked microgrid and dissertation objectives to address those challenges. The interest in microgrids has significantly increased over the last decade given its potential benefits to provide reliable, environmentally friendly, and sustainable electricity especially from renewable energy sources (RES) and under extreme weather conditions [1]. Before the microgrid concept was introduced, a number of research works have been published related to integration of distributed generation (DG). It was quickly realized that installing individual DG in power systems may create problems as many as it solves. Hence, microgrid concept was proposed to overcome some of those problems [2,3].

Many aspects of microgrid ranging from architecture to controls have been researched and implemented in laboratory test-beds and in field. Given low inertia and intermittent renewable energy output within microgrid, frequency and voltage control becomes a very challenging task, especially in isolated microgrids. Number of
Microgrids are expected to increase at an exponential rate owned privately or by electric utility. Given that a grid-connected microgrid can consume power and can also feed power back to the grid, energy management that works in both scenarios becomes a challenging task. With the evolution of networked microgrids, designing control and energy management algorithms becomes more complex. Challenges in developing microgrid energy management and controls which work in all possible configurations of networked microgrids as well as solution approaches to address these challenges are addressed in this dissertation.

In order to develop the energy management and control, system characteristics and model must be known in advance and with sufficient details. A system with high penetration of non-dispatchable renewable distributed generators (DGs) has different characteristics from a system that mainly contains dispatchable DGs. Different characteristics lead to specific requirements in the control design, such as a wide range of operating points and maximum power mode for renewable DGs.

A droop-based primary frequency control, combined with a secondary frequency/voltage restoration control, for power sharing among parallel inverter-based distributed generators (DGs) in a microgrid have been discussed in [4,5]. The droop is based on the maximum power capacity of each DG. However, a renewable-based DG does not have a constant maximum power capacity as it depends on the atmospheric conditions. Hence, the primary droop-based control as well as the secondary
frequency/voltage restoration is not suitable for non dispatchable DGs. The renewable energy sources that depends on the atmospheric conditions, such as solar and wind energy, cannot be scheduled to generate power/energy whenever it is needed. There are multiple solutions to control frequency and voltage with non dispatchable DGs. First solution is withholding some of the power capacity and use it for frequency and voltage control leading to not producing the maximum power. Second solution is utilizing dispatchable sources only to compensate for non dispatchability of renewable DG. Third solution will be based on utilizing energy storage devices, which will be the most efficient given decreasing price of energy storage devices. With the energy storage devices, the energy management and control should be designed to harvest maximum available power through a maximum power point tracking (MPPT) algorithm and to store the extra energy to the energy storage element(s), such as battery, available in the microgrid. The energy management and control should also schedule dispatchable DG(s) and regulates power transfer between grid and microgrid based on state of charge (SOC) of the battery. In case of no storage device availability, a remote storage device can be utilized or resources available from dispatchable generations and grid need to be utilized to regulate the frequency and voltage as renewable energy output changes.

The energy management and control must work in normal conditions when communication network is available and microgrid central controller (MGCC) can send
reference signal to its lower level controllers. However, the energy management and control must also work in case of emergency when there is a failure in communication network.

The number of microgrids is expected to increase in future. A utility company can own these microgrids with full access to control the power transfer between the utility grid and the microgrid as well as output from each DGs. A community or private company can also own a microgrid. In this case, power transfer between the utility grid and the microgrid is based on an agreement between both parties and cannot be regulated with full control. The connection of these different microgrids to the grid is shown in Fig. 1.1. With increasing number of microgrids, it will be difficult to operate the distribution system at distribution management system (DMS) level as microgrid power consumption will vary between maximum load and maximum generation leading to high uncertainty. DC tie line can be used to control the power exchange with the microgrids. Two or more microgrids can form a networked microgrid system that allow them to interchange power within microgrids. The microgrid involved in this networked microgrid system can operate in different possible configurations including: islanded microgrid, an asynchronously grid-connected microgrid, a synchronously grid-connected microgrid, and networked microgrids. These possible configurations and specific characteristics of renewable energy offer challenges in designing control and management algorithms for voltage, frequency and power in all
possible operating scenarios.

1.2 Research Problem Description

A microgrid can operate in islanded or grid connected modes, as well as autonomously switch between these two modes. In an islanded mode, the microgrid is responsible to regulate its own voltage magnitude and frequency. This responsibility is usually given to one power source, while other source(s) regulate power generation. If the microgrid is connected to the grid without any tie-line converter, the responsibility to regulate voltage and frequency is taken over by the grid, while the sources
inside the microgrids are responsible to regulate power generation. If the microgrid is connected to the grid through a tie-line converter, the responsibility of the sources inside the microgrid is the same as in the islanded mode because the tie-line converter can be assumed as an isolation between the grid and microgrid. Since the sources inside a microgrid can be converter-based sources and/or inertia-based sources, control mechanism need to be designed which works with these two types of sources. In addition, energy storage element(s) may also exist in a microgrid. The detail controller roles are shown in Fig. 1.2.

Fig. 1.2 shows the responsibility of each converter/source and also the control goal of each converter/source. For example, the goal of the photovoltaic (PV) converter is to produce maximum available power from the PV arrays. This goal is an individual goal of the PV converter that has to be linked to the system level goal of the microgrid which, for examples, is power balancing inside the microgrid. Since an energy storage is also involved, energy management must also be considered other than power management. Hence, the challenge is to design an energy management and control system that integrate different local controllers to reach a common goal.

Two or more microgrids may form a networked microgrid system and interchange power within microgrids. The power and control architecture of a networked microgrid system is shown in Fig. 1.3. Each microgrid in this networked microgrid system has the same topology as the microgrid in Fig. 1.2 so that the control roles re-
Fig. 1.2: Controller roles of: (a) microgrid without a tie-line converter, and (b) microgrid with a tie-line converter.

Fig. 1.3: Networked microgrid Architecture: (a) power network architecture, and (b) control network architecture.
main the same. The control architecture shows three main components of the control and their functions are as follows:

- **Networked microgrid central controller (NMGCC)** is the highest level control in a networked microgrid system and responsible to coordinate the microgrid central controllers (MGCCs) in order to regulate power transfer among the microgrids as well as between the grid and microgrids. NMGCC can be located at distribution control center as part of Distribution Management System or can be located at one of the Microgrid center control center.

- **Microgrid central controller (MGCC)** is responsible to regulate power-balancing inside an individual microgrid and to send microgrid’s important data to NMGCC in a networked microgrid system and to send set points to local controllers. If the microgrid is not in a networked microgrid system, MGCC is the highest level control and assume similar responsibility as NMGCC in a networked microgrid system.

- **Local controllers** responsible to reach its own control goal as described in Fig. 1.2 while coordinating with MGCC to reach the system level control goal.

Considering that a microgrid may switch from one operation mode to another, the responsible controller may also switch or a controller may change its responsibility. For example, an MGCC is just passing an information between NMGCC and
local controllers in a networked microgrid system, but will become the main responsible controller if that microgrid is not part of a networked microgrid system. The information flow between one control level to another requires a communication network. If there is a communication network failure, the local controllers must rely on local measurements only and take over the responsibility of the higher level control to make sure that most of the system level goals are reached. In order to make the transition smooth, the energy management and controller must be designed well to reconfigure itself to meet the control requirements of microgrid.

A nonlinear system such as microgrid needs a nonlinear control or a linear control that works for the linearized model of the nonlinear system. Due to the complexity of the nonlinear control, a linearization process to design a linear controller for a nonlinear system is preferred. However, the linear control needs to anticipate for the existence of nonlinear characteristics of the system by an additional means such as feedforward of the measured system responses.

Since a microgrid is a hybrid system consisting of several converters/sources, the system may be considered a multi input-multi output (MIMO) system which adds complexity to the controller design. This complexity can be minimized if a suitable control can be used to decouple the control variables such that each control variable can be controlled independently. Hence, the microgrid can be considered as a combination of several single input-single output (SISO) system that is easy to
Based on the above problem description, the following research questions need to be answered:

- How to design control mechanism to meet voltage and frequency criteria as well as improve dynamic responses with variable sources in microgrids?

- How to design linear controllers for a nonlinear system with wide range operating points?

- How to design control mechanism for a hybrid system consisting of resources with different characteristics and control goals, while ensuring that system level goals can be achieved?

- How to design reconfigurable control mechanism to adapt with islanded, grid connected (synchronous and asynchronous) and networked microgrid operating conditions and also with missing reference control signal due to communication network failure?

- How to enable economic or resilient operation into microgrid energy management system?
1.3 Research Objectives

The purpose of this research is to design an energy management and multi-layer control for networked microgrids for frequency and voltage control as well as power balancing in two different operational modes: a) Resilient operation b) economic operation. The designed energy management and control must be able to self-reconfigure itself to adopt with islanded, synchronous and asynchronous grid connected as well as networked microgrid operation. The energy management and control must also be able to self-reconfigure following a communication network failure. Additionally, the energy management and control mechanism should be able to work with different possible ownership of microgrids and also work with non-dispatchable DG.

The specific objectives of this dissertation are:

- Develop mathematical algorithms for voltage and frequency control as well as power management in single microgrid with non-dispatchable DGs,

- Utilize the solution of a single microgrid problem for a networked microgrid system which works with different ownership of microgrids,

- Develop control architecture that allows transition from centralized to decentralized control given loss of reference control signals with communication failure,
• Develop reconfigurable control architecture that adopts with islanded, syn-
chronous and asynchronous grid connected as well as networked microgrid op-
eration,

• Develop a multiple-mode microgrid energy management architecture for eco-
nomic or resilient operation that works with multi-layer centralized control.

1.4 Research Gap and Solution Approach

Based on the literature review, the following research gaps have been identified:

1. No work has been done considering different possible microgrid ownership,

2. No work has been done to design reconfigurable control to adopt with loss of
reference signal while utilizing maximum power from renewable power source(s),

3. Limited work has been done considering networked microgrids,

4. None of the existing control mechanism can adopt with all possible following
operational scenarios: islanded, synchronous grid connected, asynchronous grid
connected, networked microgrids,

5. No work has been done considering economic and resilient operation algorithms
with multi-layer control of microgrid.
The following research tasks are proposed to the dissertation objectives and to fill the above research gaps:

- Task 1: Modeling distributed energy sources (DERs) and integration into microgrid(s), including the maximum power point tracking (MPPT) algorithm as indispensable part of a photovoltaic (PV) system,

- Task 2: Developing voltage and frequency control architecture, as well as modeling and simulation of local control for DERs and tie-line converter, that uses feedforward measured system responses for linear PI control to compensate for nonlinear characteristics of the system and allow the controllers to work in a wide range of operating points by using large-signal model to anticipate for variability of renewable sources and big changes of the load. The dq control is used for voltage source converter (VSC) to have a constant control trajectory and to simplify a MIMO system to SISO system,

- Task 3: Designing and simulating an energy management and multi-layer control for power balancing and transition between centralized and decentralized control,

- Task 4: Designing control for a networked microgrid system,

- Task 5: Developing energy management algorithms for economic or resilient operation,
• Task 6: Testing and validation of developed algorithm through several test case studies.

1.5 Dissertation Organization

This dissertation is organized in 8 chapters, as follows:

• Chapter 1 introduces the microgrid, describes challenges in microgrid control and energy management and provides the objectives of this dissertation.

• Chapter 2 provides a review of existing research work for microgrid control, including the control algorithms for small-scale renewable based distributed generator (DG) and distributed storage (DS).

• Chapter 3 discusses about system and component modeling. This chapter provides details of the microgrid modeling as well as all the components. The microgrid model will address the microgrid in different operating modes, from single islanded microgrid to networked microgrids.

• Chapter 4 addresses the voltage magnitude and frequency control. The voltage magnitude and frequency is the lowest level control in the multi-layer control proposed in this dissertation. This level of control consists of two loops: current-mode control and voltage-mode control. The discussion in this chapter
addresses the voltage magnitude and frequency of a single DG as well as the entire microgrid.

• Chapter 5 discusses about control for power interchange. The power interchange control is for regulating power balancing inside the microgrid. This control is based on current-mode control that can be extended by using a relationship between active power and the direct component of the current as well as reactive power and the quadrature component of the current. This power control if combined with a DC voltage control can be used to control a back-to-back voltage source converter (VSC) that can be used as a tie-line converter.

• Chapter 6 addresses frequency-response-based decentralized control. The frequency-response-based control is a droop-based control that is applied for power balancing inside a microgrid in case of communication network failure. The commonly used droop control for power sharing between parallel DGs is used in different way to slightly decrease or increase the frequency. This off nominal frequency can be sensed by the local controller of dispatchable DG(s) and MPPT so that suitable control action can be taken to minimize the power mismatch.

• Chapter 7 provides energy management for MGCC based on operational modes. This energy management is aimed to coordinate lower level controls that have
different objective in order to achieve global objectives to improve resiliency and economic operation of microgrid. This energy management is also able to auto delegate its functionality to lower level control by switching to decentralized control in case of no communication network failure.

- Chapter 8 summarizes contributions of this dissertation with a conclusion and future works.
1.6 References


CHAPTER 2. STATE OF THE ART IN MICROGRID CONTROL

2.1 Introduction

This chapter provides literature review of existing microgrid control techniques for regulating voltage, frequency and energy management. This chapter provides an overview of microgrids and microgrid controls including local, centralized, and decentralized controls. Energy storage applications in microgrids are discussed followed by challenges in microgrid controls. Literature review and research needs are also provided. Finally, summary of this chapter will be provided.

2.2 Introduction to Microgrid

A microgrid is an interconnection of distributed energy sources, such as microturbines, wind turbines, fuel cells and PVs integrated with storage devices, such as batteries, flywheels and power capacitors on low voltage distribution systems [1]. A basic microgrid architecture is shown in Fig. 2.1. This architecture is commonly
known as the Consortium for Electric Reliability Technology Solutions (CERTS) architecture [2,3].

This microgrid consists of a group of radial feeders, which could be part of a distribution system or a buildings electrical system. There are three sensitive-load feeders (Feeders A-C) and one non-sensitive-load feeder (Feeder D). The sensitive load feeders contain sensitive loads that must always be supplied. On the contrary, the non-sensitive load feeder is the feeder that may be shut down if there is a disturbance or power quality problems on the utility; the non-sensitive load feeder will be left to ride through the disturbance or power quality problems [2,3].
When there is a problem with the utility supply, Feeders A-C can island from the grid using the static switch that can separate in less than a cycle to isolate the sensitive loads from the power grid to minimize disturbance to the sensitive loads. In an islanded operation, a microgrid will work autonomously, therefore must have enough local generation to meet the demands of the sensitive loads [2,3]. Furthermore, a disturbance requiring a feeder operates individually may also occur. If this latter case is considered in the microgrid design, each sensitive-load feeder must have enough local generation to supply its own loads while the non-sensitive-load feeder will rely on the utility supply.

Post-disturbance, the microgrid will reconnect to the utility and work normally as a grid-connected system. In this grid-connected, excess local power generation, if any, will supply the non-sensitive loads or charge the energy storage devices for later uses. The excess power generated by the microgrid may also be sold to the utility; in this case, the microgrid will participate in the market operation or provide ancillary services [1, 4, 5].

The disconnection or reconnection processes must be specified by the point of common coupling (PCC), a single point of connection to the utility located on the primary side of the transformer. At this point the microgrid must meet the established interface requirements, such as defined in IEEE standard 1547 series [6–12]. Furthermore, the successful disconnection or reconnection processes depend upon
microgrid controls. The controllers must insure that the processes occur seamlessly and the operating points after the processes are satisfied [2,3]. More detail information about the microgrid controls will be explained in the next section.

The last main part of the CERTS architecture is the energy manager which is responsible to manage system operation through power dispatching and voltage setting to each microsource controller. Some possible criteria for the microgrid to fulfill this responsibility are as follows [2]:

1. insure that the necessary electrical loads and heat are fulfilled by the microsources;

2. insure that the microgrid satisfies operational contracts with the utility;

3. minimize emissions and/or system losses; and

4. maximize the operational efficiency of the microsources.

Since the first time introduced in 2001 in [13], the microgrid concept has been researched and implemented significantly in several countries, such as U.S., E.U., Japan, and Canada [14]. Research on microgrid has reached not only software simulation level, but also laboratory test-bed and field model levels. The following are examples of test-beds for testing different components, control strategies, and storage technologies of microgrids [4,15]:
• a specially designed single phase system of the NTUA with agent control software,

• a general test site for distributed energy resources (DER), called DeMoTec at ISET,

• a flywheel test rig at the University of Manchester.

The increased interest on microgrids is triggered by the potential benefits of the microgrid that may provide reliable, secure, efficient, green, and sustainable electricity from RES [16]. A microgrid can improve reliability and security of power distribution system, especially for sensitive loads, because microsources will ensure that the sensitive loads will receive enough power in any operating condition. Different from function of a single distributed generator (DG) attached to a conventional distribution network, microsources will act as main power generation instead of standby power generation.

Power system efficiency may increase up to 90% if combined heat and power (CHP) is applied in the microgrid to utilize heat for local uses [17]. In addition, the efficiency increase can also result from loss reduction in transmission lines related to local power generation for local uses. Moreover, the local uses of local power generation will reduce energy or power density of transmission lines so that transmission line congestion can be reduced and investments on transmission line upgrade can be
Environmental friendliness can be achieved due to the current trend to increase the RES participations in microgrids; this participation increase will significantly reduce green house gas (GHG) emissions [20–24]. Furthermore, RES can also ensure energy sustainability due to the nature of their availability; RES can gradually substitute fossil fuels that have limited sources. Ideally, energy can be harvested at no cost, besides installation, operational, and maintenance costs, from RES. However, renewable energy is naturally intermittent so that an energy storage system is required to optimize energy utilization [16,25–30].

2.3 Microgrid Control

Microgrid controllers have responsibilities to ensure that [2]:

- microsources work properly at predefined operating point or slightly different from the predefined operating point but still satisfy the operating limits;

- active and reactive powers are transferred according to necessity of the microgrids and/or the distribution system;

- disconnection and reconnection processes are conducted seamlessly;

- market participation is optimized by optimizing production of local mi-
crosources and power exchanges with the utility;

- heat utilization for local installation is optimized;

- sensitive loads, such as medical equipment and computer servers are supplied uninterruptedly;

- in case of general failure, the microgrid is able to operate through black-start; and

- energy storage systems can support the microgrid and increase the system reliability and efficiency.

Based on the above responsibilities and the controller coordination, the microgrid controls can be classified as local controls, centralized controls, and decentralized controls. More detailed information about these controllers will be explained in this section.

2.3.1 Local Control

Local controls are the basic category of microgrid controls. The main usage of local controllers is to control microsources. This type of controllers is aimed to control operating points of the microsources and their power electronic interfaces without communication systems, resulting in simple circuitry and low cost. The
measured data for local controllers are local voltages and currents [2,3]. In most microgrid applications, local controllers will coexist with other type of controllers, while in fully islanded microgrids, as described in [31–33], the local controllers are the only required controllers. The local controllers must also ensure the plug-and-play function of microsources; one or several microsources must be able to seamlessly connect to or disconnect from the distribution network when and where they are needed [34,35].

Most microsources require power-electronic interfaces to convert their output to suit power system specifications. The general model for a microsource is shown in Fig. 2.2. It contains three basic elements: prime mover, dc-link interface, and voltage source converter (VSCI). The VSC controls both the magnitude and phase of its output voltage, \( \vec{V} \) in order to control real and reactive powers. The voltage regulation is crucial for a microgrid with integration of large number of microsources in order to overcome oscillation caused by high penetration of microsources. The voltage regulation is also used to insure that there are no large circulating reactive current between sources [2,3].

Besides the voltage regulation, microsources must also regulate active and reactive powers. The most common methods to regulate these powers are droop-based active and reactive power controls. These droop controls are scale-down and modified versions of droop-based controls in conventional grid. The droop based controls
Fig. 2.2: General model of a microsource connected to a microgrid

consist of voltage-reactive power and frequency-active power droop controls \([36,37]\).

The description of voltage-reactive power droop control can be seen in Fig. 2.3. As the reactive current generated by the microsource becomes more capacitive, the operating voltage will increase. Therefore the local voltage set-point is reduced to keep the voltage at or near its initial set-point. On the other hand, the local voltage set-point is increased if the reactive current becomes more capacitive. The limit of reactive current increase and decrease is defined by \(Q_{\text{max}}\), which is a function of volt-ampere (VA) rating of the converter and the power generated by the prime mover \([2,3]\).

In a grid-connected operation, microgrid loads receive power both from the grid and from local microsources, depending on the customers situation. If the grid power is lost because of voltage drops, faults, blackouts, etc., the microgrid can transfer smoothly to islanded operation. In addition, the microgrid is usually equipped with a capability to intentionally operate in islanded mode of operation \([38]\). With
this capability, the microgrid can be islanded intentionally for specific reasons even though there is no disturbance or power quality problem in the utility side. After the separation of the microgrid from the main grid, the voltage phase angles at each microsource in the microgrid change, resulting in an apparent reduction or increase in local frequency depending upon the power mismatches. The local frequency will decrease if the microgrid receives power from the utility in grid-connected operation but will increase if the microgrid send power to the utility in grid-connected operation [39]. The dependency of frequency on power allows each microsource to provide its proportional share of load without immediate new power dispatch from the Energy Manager.

An example of droop for two microsources is shown in Fig. 2.4. In this example, the sources are assumed to have different ratings, $P_{1\text{max}}$ and $P_{2\text{max}}$. The dispatched power in grid mode ($P_{10}$ and $P_{20}$) is defined at base frequency, $\omega_0$. The droop is defined to insure that both systems are at rated power at the same minimum frequency. During a change in power demand, these two sources operate at different frequencies, which cause a change in the relative power angles between them. When this change occurs, the two frequencies tend to drift toward a lower, single value of $\omega_1$. Unit 2 will have higher increase of its share of the total power needs than Unit 1. Each controller must have a restoration function to overcome the microgrid frequency decrease caused by droop regulation [2,3].
2.3.2 Centralized control

Centralized controls of microgrids can be explained based on hierarchical controls in Fig. 2.5. In fact, hierarchical systems may have centralized or decentralized controllers. The control level of hierarchical systems can be classified as fol-
lows [5, 40–42]:

- local controllers consisting of Microsource Controllers (MCs) and Load Controllers (LCs);
- Microgrid Cental Controllers (MGCCs); and
- Distribution Management System (DMS).

The MCs in centralized controls have similar principle as the local controllers discussed in the previous sub-section. In centralized controls, The MCs may also be enhanced with various degrees of intelligence. In addition, LCs are installed at the controllable loads to provide load control capabilities. LCs are commonly used for demand side management [5].

For each microgrid, there is an MGCC that interfaces between the DMS and the microgrid. The MGCC may have different roles ranging from simple coordination of the local controllers to the main responsibility of optimizing the microgrid operation. The difference between centralized and decentralized controls is defined by the centralization roles assumed by the MGCC; the level of decentralization can vary depending on the share of responsibilities assumed by the MGCC and the MCs and LCs. In a centralized control, MCs and LCs follow the orders of MGCC during grid-connected mode and have autonomy to perform their own controls during islanded mode [5].
DMS or Distribution Network Operator (DNO), to which several MGCCs are interfaced, has responsibility to manage the operation of medium and low voltage areas in which more than one microgrid may exist. In addition, one or more Market Operators (MO) will exist in the system if the microgrids participate in market operation. DNO and MO are not parts of microgrids but representatives of the utility [5].

Centralized control is best used for microgrids with the following characteristic [5, 43]:

- The owners of microsources and loads have common goals and seek cooperation in order to meet their goals,

- Small scale microgrids may be feasible to control with the presence of an operator.
2.3.3 Decentralized control

Decentralized controls have similar description to the centralized controls and can be explained based on Fig. 2.5. In decentralized controls, the main responsibility is given to MCs that compete to maximize their production in order to satisfy the demand and probably provide the maximum possible export to the grid taking into account current market prices. The decentralized control is aimed to maximize autonomy of the microsources and loads. Several intelligent methods based on peer-to-peer algorithm, such as multi-agent-based [4,44] and gossip-based algorithms [45], may be used for decentralized controls.

Decentralized control is best used for microgrids with the following characteristics [5]:

- microsources can have different owners in which case several decisions should be taken locally,

- microgrids operating in a market environment require that the action of the controllers of each unit participating in the market should have a certain degree of intelligence,

- local microsources may have other tasks besides supplying power to the local distribution networks, like producing heat for local installations, keeping the
voltage locally at a certain level or providing a backup system for local critical loads in case of main system failure.

2.4 Energy Storage Systems for Microgrid Applications

Microsources have small generating capacities and most microsources require inverters to convert their output to suit power system specifications [46]. Thus, the connections of small-size sources, dominated by power-electronic-interfaced sources, can be considered as an inertia-less system [36]. This inertia-less system cannot response to the initial or surge power or energy mismatch by using their machines inertia as commonly found in conventional grid systems. Therefore, a microgrid requires energy storage systems to solve the mismatch problems [16, 25–30].

Microgrids provide high opportunities to integrate small-scale RES into local power systems [32]. This integration will increase percentage of electricity produced from renewable energy sources to the overall electricity generations, hence will increase sustainability of electricity and ideally will also provide reliable, secure, flexible, affordable, and limitless electricity [16]. However, renewable energy is also naturally variable and intermittent [25, 28]. In addition, the connection of big amount of renewable energy sources to a local power system may cause a stability problem [26].

In order to utilize renewable energy optimally without having problems related
to variability and intermittency as well as instability, a properly designed storage system must be implemented in a local power system containing big amount of small-scale RES. This optimal utilization can be fully competitive either technically or economically to the utilizations of energy from the best fossil fuels or nuclear technologies [28].

Owing to the facts that different RES have different characteristics and the likeliness of hybrid energy sources in a microgrid, the design of versatile energy storage system (ESS) having capability to operate in wide ranges of power density and energy density is required. Since no single energy-storage technology has this capability, a combination of technologies such as supercapacitors, batteries, superconducting magnetic energy storage (SMES), and kinetic energy storage in flywheels is used [29].

The type and capacity of the energy storage inside the ESS depends upon the characteristics of compensation being provided. In case of short-time voltage sag which may draw higher currents for only few cycles, an energy storage element with smaller storage may be employed. However, additional backup source may be employed if sag continues for longer time interval leading to interruption of supply depending on the critical load. In case of harmonics elimination and reactive power compensation, suitable passive filter may be employed, thereby reducing the rating of the energy storage system [47].
2.5 Challenges in Microgrid Controls

Number of microgrids installed in LV distribution systems will continue to increase. Consequently, distribution systems will have different characteristics from the current conventional distribution systems. Thus, suitable control strategies must be designed to anticipate this difference [48].

Besides to optimize system operation electrically, microgrid controls also aim to optimize production and consumption of heat, gas, and electricity in order to improve overall efficiency [20]. Moreover, controlling a large number of microsources having different characteristics will be very challenging due to the possibility of conflicting requirement and limited communication [1].

Transitions from grid-connected to islanded modes of operation are likely to cause large mismatches between generation and loads, causing a severe frequency and voltage control problem. The plug-and-play capability may also create serious problem if the connection and disconnection processes involve big number of microsources at the same time [1].

2.6 Research Needs

Table 2.1 shows existing research work in microgrid energy management and control based on published papers. The table also shows limitation of these published
papers and scope for further research.

**Table 2.1: Research focus in microgrid energy management and control**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Focus</th>
<th>Operation Mode</th>
<th>Not Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>[49]</td>
<td>Distributed secondary control that requires measurement of other DGs</td>
<td>Islanded</td>
<td>Communication network failure, grid-connected, networked microgrids</td>
</tr>
<tr>
<td>[50]</td>
<td>Hybrid microgrid with an emphasis on dc controller and external dc system. DC power sources are modeled as ideal 650 V dc sources</td>
<td>Grid-connected</td>
<td>Islanded, networked microgrid, dynamic renewable source model</td>
</tr>
<tr>
<td>[51]</td>
<td>Circulating current and load-sharing between two parallel DGs</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrid, EMS</td>
</tr>
<tr>
<td>[52]</td>
<td>Centralized optimization to update power changes to the droop controller</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrids, communication networked failure</td>
</tr>
<tr>
<td>Reference</td>
<td>Description</td>
<td>Isolation Type</td>
<td>Network Type</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>----------------</td>
<td>---------------</td>
</tr>
<tr>
<td>[53]</td>
<td>Droop control with hybrid PV-battery and dispatchable DG. DGs act as spinning reserves</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrid, non spinning reserve DGs</td>
</tr>
<tr>
<td>[54]</td>
<td>Central controller to coordinate the operation of the hybrid unit with a diesel generator, in order to maintain the power balance</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrids, communication network failure</td>
</tr>
<tr>
<td>[55]</td>
<td>Dynamic modeling and control strategy for a sustainable microgrid primarily powered by wind and solar energy</td>
<td>Islanded &amp; grid-connected</td>
<td>Networked microgrid, ac power source</td>
</tr>
<tr>
<td>[56]</td>
<td>Complete description regarding the building and automation infrastructure of a lab-scale MG</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrid, ac power source</td>
</tr>
<tr>
<td>[57]</td>
<td>EMS for coordinating the power sharing among DGs. Different function of energy storage in islanded &amp; grid-connected modes</td>
<td>Islanded &amp; grid-connected</td>
<td>Networked microgrids, communication network failure</td>
</tr>
<tr>
<td>Reference</td>
<td>Description</td>
<td>System Type</td>
<td>Failure Type</td>
</tr>
<tr>
<td>-----------</td>
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<td>-------------</td>
<td>--------------</td>
</tr>
<tr>
<td>[58]</td>
<td>Single-object optimisation problem consisting of smart management of energy storage, economic load dispatch and operation optimisation of DG</td>
<td>Grid-connected</td>
<td>Islanded, networked microgrids, communication network failure</td>
</tr>
<tr>
<td>[59]</td>
<td>Robust EMS for a microgrid based on model predictive control</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrid, communication network failure</td>
</tr>
<tr>
<td>[60]</td>
<td>Two-stage optimization method to minimize the energy loss of microgrid with different penetration levels of plug-in hybrid electric vehicles (PHEVs)</td>
<td>Grid-connected</td>
<td>Islanded, networked microgrid, communication network failure</td>
</tr>
<tr>
<td>[61]</td>
<td>EMS consisting of two parts: a central energy management of the microgrid and a local power management at the customer side.</td>
<td>Grid-connected</td>
<td>Islanded, networked microgrids, communication network failure</td>
</tr>
<tr>
<td>Reference</td>
<td>Description</td>
<td>Grid-connected</td>
<td>Islanded, networked microgrids, communication network failure</td>
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</tr>
<tr>
<td>[62]</td>
<td>Off-line optimization approach for optimal off-line energy scheduling solution to devise a sliding-window based online algorithm for real-time energy management under the practical setup of noisy predicted net energy profile with arbitrary errors</td>
<td>Grid-connected</td>
<td>Islanded, networked microgrids, communication network failure</td>
</tr>
<tr>
<td>[63]</td>
<td>EMS based on a rolling horizon (RH) strategy for a renewable-based microgrid</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrid, communication network failure</td>
</tr>
<tr>
<td>[64]</td>
<td>Double-layer coordinated control approach for microgrid energy management consisting of two layers: the schedule layer and the dispatch layer.</td>
<td>Islanded &amp; grid-connected</td>
<td>Networked microgrids, communication network failure</td>
</tr>
<tr>
<td>[65]</td>
<td>EMS for a stand-alone droop-controlled microgrid, which adjusts generators output power to minimize fuel consumption and also ensures stable operation</td>
<td>Islanded</td>
<td>Grid-connected, networked microgrids, dynamic &amp; renewable source</td>
</tr>
</tbody>
</table>

### 2.7 Summary

This chapter has presented a review of microgrid and discussed several aspects of microgrid controls, specifically category, challenges, and energy storage applications of microgrids. Due to several differences, especially in term of inertia, conventional power system control cannot be used directly to microgrid. Some conventional power system controls, such as droop control, can be used for microgrid control after some modifications. Different types of control, such as centralized, decentralized, or hierarchical, can be applied to system level control depending on characteristics and objectives of microgrid.
2.8 References


[42] N. Hatziargyriou, “Active distribution network. the effect of distributed and renewable generation on power systems security round table; 2005.”


3.1 Introduction

This chapter discusses about microgrid modeling, including system and component modeling. The system modeling will discuss about the microgrid architectures and mode of operations. A single islanded microgrid will be discussed first, followed by the synchronous/asynchronous grid-connected microgrid, finally the networked microgrids will be discussed. The detail of the system specification, however, will be discussed in the next chapter. Modeling of the main components of microgrid, including PV and MPPT, battery, dispatchable DG(s), and load are also discussed.

3.2 Microgrid Architecture

The microgrid topology used in this paper is based on the CERTS microgrid architecture [1]. Fig. 3.1 shows the microgrid topology including all distributed energy resources (DERs) and converters. The microgrid topology in Fig. 3.1.a shows two point of common couplings (PCCs), $PCC_1$ and $PCC_2$. If the microgrid is connected to the grid synchronously, these two PCCs are connected directly to form a single
Fig. 3.1: Microgrid topology for a with/without tie-line converter microgrid: (a) Microgrid topology and (b) Tie-line converter.

PCC. If the microgrid is connected to the grid asynchronously, the tie-line converter in Fig. 3.1.b is installed between $PCC_1$ and $PCC_2$.

If there is no tie-line converter, the microgrid is actually part of the grid in grid-connected mode. The voltage magnitude and frequency are dictated by the grid. Any shortage and extra power will be automatically compensated by the grid. In term of power interchange, importing power from the grid occurs automatically through PCC without any intervention of microgrid central controller (MGCC); it happens just based on the electric circuit principle that current will flow if there is a closed loop connection. Exporting power from the microgrid to the grid, on the other hand, will occur automatically through PCC if the distributed generators (DGs) inside the microgrid have been committed to generate power. The decision which DG(s) to turn on
and how much power is generated depends on MGCC which may communicate with the grid’s distribution management system (DMS). Consequently, power interchange cannot be regulated directly, it is regulated through power generation.

The microgrid with tie-line converter, in contrast, has ability to regulate both power interchange and power generation independently. MGCC has responsibility to manage them and send the message to respective local controllers. For examples, the generation power request will be sent to DGs’ local control and the power transfer request will be sent to tie-line converter’s local control.

The tie-line converter is not only useful to form a regulated connection between the microgrid and the grid, but also useful to form the same connection between two neighboring microgrids. This kind of connection, if involving a group of neighboring microgrids, can form a networked microgrid system in which the neighboring microgrids have ability to interchange power. Fig. 3.2 shows the networked microgrid topology. The converter details will be discussed in Section 4.
Fig. 3.2: Networked microgrid.
3.3 Modeling of Renewable Generation

3.3.1 Modeling and Characteristics of Solar Cells

The simplest solar cell model consists of a diode and a current source connected in parallel as shown in Fig. 3.3. The current source is directly proportional to the solar radiation while the diode represents the p-n junction of a solar cell. Equations representing the ideal solar cell model can be represented in terms of current density as shown in (3.1) or current as shown in (3.2).

\[
J = J_{sc} - J_0 \left( e^{\frac{V}{VT}} - 1 \right)
\]  

(3.1)

\[
I = I_{sc} - I_0 \left( e^{\frac{V}{VT}} - 1 \right)
\]  

(3.2)

![Fig. 3.3: Simple physical model of solar cells](image-url)
where \( J \) is the photocurrent density \((A/m^2)\), \( J_{sc} \) is the short-circuit current density \((A/m^2)\), \( I \) is the photocurrent \((A)\), \( I_0 \) is the reverse saturation current \((A)\), \( V \) is the diode voltage \((V)\), \( V_T \) is thermal voltage \((V_{T} = 25.7 \text{ mV at } 25 \degree C)\).

The currents \( I_{sc} \) and \( I_0 \) relate to their current densities \( J_{sc} \) and \( J_0 \) as follows:

\[
I_{sc} = AJ_{sc},
\]

\[
I_0 = AJ_0.
\]

where \( A \) is the total area of the devices excluding the metal covered area.

The more accurate model of a solar cell, the general model, consists of a current source, two diodes connected in parallel, one shunt resistance and one series resistance shown in Fig. 3.4. The relationship between current and voltage for the general model is given in (3.4).

\[
I = I_L - I_{01} \left( e^{\frac{V+I R_s}{V_T}} - 1 \right) - I_{02} \left( e^{\frac{V+I R_s}{2 V_T}} - 1 \right) - \frac{V + I R_s}{R_{sh}}
\]

where \( I_L \) is the photo-generated current \((A)\), \( I_{01} \) is the reverse saturation current of
the first diode ($A$), $I_{02}$ is the reverse saturation current of the second diode ($A$), $n_1$ is the quality factor of the first diode, $n_2$ is the quality factor of the second diode, $R_s$ is the series resistance ($\Omega$), and $R_{sh}$ is the shunt resistance ($\Omega$).

General characteristics of solar cells represented by models in Figs. 3.3 and 3.4 are shown in Fig. 3.5. Fig. 3.5.a relates irradiance to the short circuit current and open circuit voltage of the solar cell. The increasing of irradiance leads to the increasing of the open circuit voltage logarithmically and the increasing of the short circuit current linearly. The arrow direction shows the increasing of irradiance. The influence of the cell temperature on the $I-V$ characteristics is illustrated in Fig.3.5.b. The increasing of the cell temperature significantly reduces the open circuit voltage while slightly increases the short circuit current.

**Fig. 3.5:** I-V Characteristics of solar cells.
3.3.2 Single Solar Cell Model

Simulations of the solar cell behavior for changing temperature and irradiance conditions are required for the purpose of modeling photovoltaic systems. The best way to simulate this behavior is by using a behavioral model [2]. This model assumes that the short circuit current has two main components. The first component relates to irradiance, \( G \), while the second component is function of cell temperature, \( T_{cell} \).

The equation for short circuit current is given by:

\[
I_{sc} = \frac{J_{scr}A}{1000}G + dJ_{sc} \frac{dT}{dT}(T_{cell} - T_r) \tag{3.5}
\]

where \( I_{sc} \) is the short circuit current (A), \( J_{scr} \) is the reference short circuit current density (A/m\(^2\)), \( \frac{dJ_{sc}}{dT} \) is the temperature coefficient of short circuit current (A/°C), and \( T_r \) is the reference temperature which is usually considered 25°C.

The diode component is represented by:

\[
I_d = \frac{I_{sc}}{V_{FCC}} \left( e^{\frac{V}{V_T}} - 1 \right) \tag{3.6}
\]

The cell temperature is derived from the NOCT (nominal operating conditions temperature) which is the temperature of the cell at 800 W/m\(^2\) of irradiance and 20 °C of ambient temperature, \( T_a \) [2]. That is,

\[
T_{cell} - T_a = \frac{NOCT - 20}{800}G \tag{3.7}
\]
The series resistance is derived as follows:

\[ R_s = \frac{V_{oc}}{I_{sc}} - \frac{P_{max}}{FF_0 I_{sc}^2} \]  

(3.8)

in which

\[ FF_0 = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{1 + v_{oc}} \]  

(3.9)

and

\[ v_{oc} = \frac{V_{oc}}{V_T} \]  

(3.10)

where \( P_{max} \) is the maximum power (W), \( FF_0 \) is the fill factor under ideal conditions, \( v_{oc} \) is the normalized value of the open circuit voltage (V).

The current and voltage for the maximum power point (MPP) is given by:

\[ I_m = I_{mr} \frac{G}{G_r} + A x \frac{delta J_{sc}}{delta T} (T_{cell} - T_r), \]

\[ V_m = V_T \ln \left(1 + \frac{I_{sc} - I_m}{I_{sc}} (e^{\frac{v_{oc}}{V_T}} - 1) \right) - I_m R_s. \]  

(3.11)

where \( I_m \) is the MPP current (A), \( I_{mr} \) is the reference MPP current (A), \( G_r \) is the reference irradiance (W/m²), \( V_m \) is the MPP voltage (V).

The behavioral model derived above is shown in Fig. 3.6. The upper figure shows the schematic form of the model consisting of the parameters derived in previous equations. The lower figure shows the parameter names for all terminals of the model.
Fig. 3.6: Schematic and block diagram of the solar cell behavioral model.

3.3.3 PV Module Model

A photovoltaic module consists of solar cells connected in series and in parallel. The connection of solar cells in a photovoltaic module is shown in Fig. 3.7. The behavioral model of a photovoltaic module is similar to the model for a solar cell. The series connection of solar cells in a photovoltaic module increases the voltage, while the parallel connection increases the current.
Fig. 3.7: Connection of solar cells in a photovoltaic module.

The equations below are derived based on the equations for a solar cell:

\[
I_{scM} = N_{pM}I_{sc},
\]
\[
V_{ocM} = N_{sM}V_{oc},
\]
\[
I_{mM} = N_{pM}I_{m},
\]
\[
V_{nM} = N_{sM}V_{m},
\]
\[
R_{sM} = \frac{N_{sM}}{N_{pM}R_s}.
\]

(3.12)

where the subscript M means module, \(N_{sM}\) is the number of cells connected in series, \(N_{pM}\) is the number of cells connected in parallel, \(I_{scM}\) is the short-circuit current of a PV module (A), \(V_{ocM}\) is the open-circuit voltage of a PV module (V), \(I_{mM}\) is the
MPP current of a PV module (A), $V_{mM}$ is the MPP voltage of a PV module (V) and $R_{sM}$ is the series resistance of a PV module (Ω).

### 3.3.4 PV Array Model

Similar to the relationship between a photovoltaic module and solar cells, a photovoltaic array consists of photovoltaic modules connected in series and in parallel as shown in Fig. 3.8. The behavioral model of a photovoltaic array is very similar to the model of a solar cell or a photovoltaic module. Instead of using index M, the model of a photovoltaic array uses index A that stands for array.
The relationships between array and module currents and voltages are given below:

\[ I_{scA} = N_{pA} I_{scM} = N_{PM} N_{pA} I_{sc}, \]
\[ V_{ocA} = N_{sA} V_{ocM} = N_{SM} N_{sA} V_{oc}, \]
\[ I_{mA} = N_{pA} I_{mM} = N_{PM} N_{pA} I_{m}, \]
\[ V_{mA} = N_{sA} V_{mM} = N_{SM} N_{sA} V_{m}, \]
\[ R_{sA} = \frac{N_{sA}}{N_{pA}} R_{sM} = \frac{N_{SM} N_{sA}}{N_{PM} N_{pA}} R_{s}. \] (3.13)

3.3.5 Maximum Power Point Tracking

The amount of power generated by a PV module depends on irradiance and ambient temperature. The I-V and P-V characteristic curves indicate the maximum power point (MPP) at which maximum possible power is available. The MPP is not static due to its dependency on atmospheric factors, irradiance and temperature. Hence, a technique called a maximum power point tracking (MPPT) is used to utilize the photovoltaic power effectively [2,3]. The basic principle of the MPPT is described in Fig. 3.9. The dc-dc converter is incorporated with an MPPT algorithm to ensure that the maximum power is delivered to the loads. The arrows on the P-V curve indicate the MPP is approached from both sides in order to track the exact point.

The purpose of the MPPT algorithm is to follow the MPP as it changes with
the ambient operating conditions of the PV generation system. In order to do such tracking, the terminal voltage of the PV array is manipulated. Many algorithms have been proposed for the MPPT application. Some widely adopted algorithms include: the Constant Voltage Method, the NonLinear Function Solution Method, the Perturbation & Observation or Hill Climbing Method and the Incremental Conductance Method. The PSCAD model implemented in this work is based on the Incremental Conductance Method algorithm because it is widely accepted as being efficient without incurring excessive computational burdens.

3.3.6 Algorithm Derivation

The Incremental Conductance Method is based upon the Hill Climbing Method (Perturbation & Observation Method) with a slight augmentation to this algorithm, which makes it slightly more robust. Details of the Perturbation & Observation
algorithm can be explained based on Fig. 3.10, which shows an arbitrary PV curve where the horizontal axis is the PV array terminal voltage, $V$, and the vertical axis is the arrays output power, $P$. When the array is operating at the MPP, $\frac{dP}{dv} = 0$. Hence, the objective of the MPPT algorithm is to seek the point where the $\frac{dP}{dv}$ value becomes zero. The PV arrays terminal voltage should be increased if $\frac{dP}{dv}$ is positive; conversely, the terminal voltage should be decreased if $\frac{dP}{dv}$ is negative.

Assume that the algorithm, through modification of a reference value, has just triggered an increase in the arrays terminal from $V_1$ to $V_2$. The resulting difference in the output power ($dP = P_2 - P_1$) is positive so the algorithm should continue to increase the terminal voltage beyond $V_2$ to $V_3$. Again, the resulting difference in output power ($dP = P_3 - P_2$) is positive and thus the algorithm will again trigger and
increase the terminal voltage beyond $V_3$ to $V_4$. Now the difference in output power $(dP = P_4 - P_3)$ is negative, hence the direction of movement in the terminal voltage reference is reversed and the terminal voltage is next moved from $V_4$ back to $V_3$. The resulting difference in $P$ $(dP = P_3 - P_4)$ is negative so the terminal voltage will be further decreased from $V_3$ to $V_2$. Now the difference in $P$ $(dP = P_2 - P_3)$ is again negative indicating that the direction in which the terminal voltage is moved should be reversed. The algorithm continues in this pattern reversing directions every time the PV output power decreases. Consequently, the algorithm will constantly fluctuate around MPP by a small increment/decrement of $V$.

To track the MPP for the current operating conditions of the PV array, the objective is to reach $\frac{dP}{dv} = 0$. It is useful to write $\frac{dP}{dv}$ in terms of voltages and currents, the two measured quantities at terminals of a PV array.

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = V \frac{dI}{dV} + I$$ (3.14)

The equation $\frac{dP}{dv} = 0$ can then be derived as shown in (3.15). Approximating $dI$ and $dV$ by $i(t)i(tt)$ and $v(t)vi(tt)$ respectively, (3.15) can be rewritten as (3.16).

$$V \frac{dI}{dV} + I = 0$$ (3.15)

$$\frac{i(t) - i(t - Deltat)}{v(t) - v(t - Deltat)} = -\frac{i(t)}{v(t)}$$ (3.16)
Equation (3.16) will be satisfied if the PV is operating at the MPP where \( dP/dV = 0 \). Similarly, the equivalent expressions for \( dP/dV < 0 \) and \( dP/dV > 0 \) are given in (3.17) and (3.18), respectively.

\[
\frac{i(t) - i(t - Deltat)}{v(t) - v(t - Deltat)} < -\frac{i(t)}{v(t)} \quad (3.17)
\]

\[
\frac{i(t) - i(t - Deltat)}{v(t) - v(t - Deltat)} > -\frac{i(t)}{v(t)} \quad (3.18)
\]

Under rapidly changing environmental conditions which trigger a change in the operating PV characteristic of the array, the sampled voltage does not change from one sample to another \( (dV = 0) \). The Hill Climbing method described above will fail to converge since (3.16), (3.17), and (3.18) would result in a division by zero. This problem can be solved by multiplying both sides of (3.14) by \( dV \), resulting in (3.19) and then simplify (3.19) to (3.20). This modification is known as the Incremental Conductance Method.

\[
dP = VdI + IdV \quad (3.19)
\]

\[
dP = VdI \quad (3.20)
\]

Equation (3.20) indicates that an increase in output power \( P \), when \( V \) is both positive and constant will be accompanied by an increase in the output current of the
array. Similarly, a decrease in $P$ will be accompanied by a decrease in $I$. As a result, the operating point can continue moving towards the MPP even though the terminal voltage is constant from one sampling period to the next. The flowchart in Fig. 3.11 summarizes this incremental conductance algorithm.

One of the difficulties of the Incremental Conductance MPPT algorithm is to
determine an initial value for the reference voltage, $V_{ref}$, so that it is the same or close to the actual terminal voltage of the PV array. Hence, any large transients in the PV array terminal voltage when the algorithm starts can be avoided. This issue can be addressed by having an initial waiting period during which its output should not be used and during which the model runs a moving average algorithm on its input voltage. Once this waiting period is over, the result of the average is used as the initial reference voltage for the algorithm. The voltage reference output from this algorithm is often used as an input to a regulator which in turn controls the duty ratio of a dc/dc converter.

### 3.4 Modeling of Battery

Energy storage elements are very important for a SAPV system due to the mismatch possibility between the PV power and the load demands. The PV power depends very much on the sunlight availability while the load demands do not. The most common type of storage is a battery, although other forms of storage are available. For instance, a flywheel or capacitor can be used for a small system with short term storage. The storage can also be non chemical, such as water for water pumping stand-alone PV systems [4].

The most commonly used battery in renewable energy system is lead-acid [2,5].
Other types of batteries: nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and lithium-ion (Li-ion) are relatively more expensive and not readily available [5]. A lead-acid battery is selected for the energy storage element due to its acceptable characteristics and cycle costs.

3.4.1 Battery Characteristics and Parameters

The main components of lead-acid batteries are two plates, positive (anode) and negative (cathode), immersed in a dilute sulphuric acid solution. The anode is made of lead dioxide (PbO2) and the cathode is made of lead (Pb) [2].

In the charge mode, the current flows into the battery at the positive terminal, so that the battery voltage and the stored charge increase gradually. While in the discharge mode, the current flows out of the positive terminal, causing the battery voltage and the stored charge to decrease. In addition, better battery models include two more modes: undercharge and overcharge modes [2].

The undercharge state is reached if the battery charge approaches the recommended minimum value and the circuit conditions force the battery to continue discharging. This state is characterized by a rapid decrease of the electrolyte internal density, which causes sedimentation at the bottom of the battery elements. This process cause a rapid reduce of the total battery capacity and may cause irreversible
When the battery charge goes beyond the maximum recommended value, the overcharge mode is reached. In this mode, the battery shows an effective reduction of the battery capacity. Further charging will take the battery to saturation and no more charge will be stored. Fig. 3.12 shows a voltage characteristic of a 2 V battery element along its different modes of operation.

There are three main parameters that usually define and rate a battery, specifically [2]:

1. the nominal capacity, $C_x$, for a rate of discharge of $x$ hours,
2. the charge or discharge rate,

3. the state of charge, SOC.

The nominal capacity is the nominal charge that can be stored. This parameter is provided by manufacturers for certain measurement conditions. Generally, the measured parameter is the charge delivered by the battery in a given period of time at a given discharge rate and temperature. The nominal capacity depends on the discharge duration. Mostly, the discharge duration provided by manufacturers are 5, 10 and 100 hours. Based on these time lengths, nominal capacities, $C_5$, $C_{10}$ and $C_{100}$ are defined and given in units of Ah.

The charge or discharge rates are the relationship between the nominal capacity of the battery and the charge or discharge currents. For discharge, the discharge rate is the time length required for the battery to discharge at a constant current. Due to the deeper electrolyte penetration into the battery plate material, the battery capacity increases for longer discharge rates [2].

The state of charge (SOC) is the ratio of the available charge at a given time divided by the maximum capacity. The SOC can be expressed as

$$SOC = \left(1 - \frac{Q}{C}\right),$$

(3.21)

$$0 \leq SOC \leq 1,$$

where $C$ (Ah) is the battery capacity and $Q$ (Ah) is the charge already delivered by the battery at the time of interest.
A parameter which is the complement of SOC is called depth of discharge, DOD, representing the fraction of discharge reached by the battery:

\[
DOD = 1 - SOC
\]  

(3.22)

Sometimes, the SOC is represented as the value of the remaining energy at a given time. There are some parameters for SOC: \(SOC_1\): initial battery state of charge in \(SOC_m\): maximum battery energy (Wh), \(SOC_n(t)(\%)\): normalized value of the remaining energy to \(SOC_m\).

### 3.4.2 Battery Model

The battery model in this thesis was developed by Lasnier and Tang [6] and revised by Castaer and Silvestre [2]. Input parameters for the model are:

- Initial state of charge: \(SOC_1\) (%), indicating available charge,
- Maximum state of charge: \(SOC_m\) (Wh), maximum battery capacity,
- Number of 2 V series cells: \(n_s\),
- Two empirical constants depending on the battery characteristics:
  - \(K\) (adimensional): charge or discharge battery efficiency,
  - \(D\) (h-1): battery self-discharge rate.
This battery model has only two modes of operation: charge and discharge. This electrical battery model shown in Fig. 3.13 consists of a voltage source $V_1$ in series with a resistor $R_1$. The values of $V_1$ and $R_1$ depend on the mode of operation.

The following equations are valid for the charge mode:

$$V_1 = V_{ch} = (2 + 0.148\beta)n_s, \quad (3.23)$$

$$R_1 = R_{ch} = \frac{0.758 + \frac{0.1309}{1.06-\beta}}{SOC_m}n_s, \quad (3.24)$$

with $\beta = \frac{SOC}{SOC_m}$. This $\beta$ is also used for the discharge mode.

The battery voltage is given by:

$$V_{bat} = V_{ch} + I_{bat}R_{ch}, \quad (3.25)$$
The following equations are valid for the discharge mode:

\[ V_1 = V_{dch} = (1.926 + 0.124\beta) n_s, \]  

\[ R_1 = R_{dch} = \frac{0.19 + \frac{0.1037}{\beta - 0.14}}{SOC_m} n_s, \]  

The battery voltage is given by:

\[ V_{bat} = V_{dch} + I_{bat} R_{dch}. \]  

The subindex \( ch \) stands for charge, while subindex \( dch \) means discharge. As discussed in the previous section, the battery current has a positive sign in the charge mode and a negative sign in the discharge mode.

The estimation of the instantaneous value of the SOC (Wh) is an important part of the battery model. The following equation describes the SOC at time \((t + dt)\):

\[ SOC(t + dt) = SOC(t) \left(1 - \frac{D}{3600} dt\right) + k \left(\frac{V_{bat} I_{bat} - R_1 I_{bat}^2}{3600}\right) dt. \]  

The above equation can be simplified by substituting \( V_{bat} = V_1 + I_{bat} R_{bat} \) yielding:

\[ SOC(t + dt) = SOC(t) \left(1 - \frac{D}{3600} dt\right) + \left(\frac{kV_1 I_{bat}}{3600}\right) dt, \]  

which can be further simplified to:

\[ \frac{SOC(t + dt) - SOC(t)}{dt} = \frac{kV_1 I_{bat}}{3600} - \frac{D \times SOC(t)}{3600}. \]
The above equation can be solved by using a time domain integral. The SOC value for the battery model can be then evaluated as follows:

$$SOC_n(t) = SOC_1 + \frac{1}{SOC_m} \int \left( \frac{kV_1 I_{bat}}{3600} - \frac{D \times SOC_n(t)SOC_m}{3600} \right) dt$$  \hspace{1cm} (3.32)

where $SOC_1$ is the initial battery state of charge in %, $SOC_m$ is the maximum battery state of charge in Wh units, and $SOC_n(t)$ is the SOC normalized to the battery state of charge $SOC_m$. Therefore $SOC_n$ the SOC in % is the internal time step in simulation to simplify the numerical resolution [2].

The battery model described above can be simplified by assuming the resistance $R_1$ has the same value for the charge and discharge modes. This assumption will result in a more compact model.

### 3.5 Modeling of Dispatchable Distributed Generator

Dispatchable DG is modeled as positive power injection. Considering that the bus voltage where the DG is located is well regulated, the power injection can be modeled as current injection. The dq-currents to be injected ($i_d(t)$ and $i_q(t)$) can be calculated based on the requested DG power ($P_{DG}(t)$ and $Q_{DG}(t)$) as shown in (3.33), considering that the dq-voltages at that respective bus ($v_d$ and $v_q$) are constant. Then, the dq-currents are transformed to abc-current as given in (3.34). To represent the time constant of the DG, a time delay is used when calculating current from power.
The DG model is represented in Fig. 3.14.

\[
i_d(t) = \frac{2}{3v_d} P_{DG}(t),
\]
\[
i_q(t) = -\frac{2}{3v_d} Q_{DG}(t).
\] (3.33)

\[
\begin{bmatrix}
i_a(t) \\
i_b(t) \\
i_c(t)
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta \\
\cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\
\cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3})
\end{bmatrix}
\begin{bmatrix}
i_d(t) \\
i_q(t)
\end{bmatrix}
\] (3.34)

### 3.6 Modeling of Load

Load model is similar to the DG model. Instead of positive power injection as DG, the load is modeled as negative power injection. The load power is also assumed to have immediate response so that the time delay on the DG model is removed and replaced by -1 for the load model. The load model is shown in Fig. 3.15.
3.7 Simulation Model

The networked microgrid system is modeled and simulated in PSCAD. The networked microgrid model is shown in Fig. 3.16. The hybrid system as the main source in the microgrid including its controls is shown Fig. 3.17. Finally, the VSC as the converter between the dc and ac systems including its control is shown in Fig. 3.18.
Fig. 3.16: Networked microgrid model in PSCAD.
Fig. 3.17: Hybrid system model in PSCAD: (a) circuit, (b) PV converter control, and (c) battery converter control.
Fig. 3.18: VSC model in PSCAD: (a) circuit, (b) droop control, (c) voltage control, and (d) current control.
3.8 Summary

This chapter has presented system and component modeling of microgrid. The microgrid can have different modes of operation: single islanded microgrid, synchronous grid-connected microgrid, asynchronous grid-connected microgrid, and networked microgrids. Main component models, including PV and MPPT, battery, dispatchable DG and load are also discussed. Finally, simulation models in PSCAD are presented.
3.9 References


CHAPTER 4. VOLTAGE AND FREQUENCY CONTROL IN A MICROGRID

4.1 Introduction

Microgrid can be defined as a group of interconnected loads and distributed energy resources (DGs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect/disconnect from the grid to enable it to operate in both grid connected or island mode. Due to its location next to the consumers, microgrids have opened opportunity for the consumer to produce electricity. This type of consumers, which is not a net consumer, is commonly known as prosumer. Consequently, different type and ownership of DGs is common in a microgrid. Different type usually causes different dynamic characteristics which require suitable control and energy management, which works in short time frame. Different ownership will require suitable energy management in rather longer time frame.

Due to different energy sources in the microgrid, it requires power conditioning units, or commonly known as converters, to convert the energy/power from its
primary sources to electricity. The controller for power converters are commonly designed based-on small-signal model in which the controller is designed in the vicinity of its nominal operating point. This approach is taken by linearizing the system around its equilibrium point [1, 2]. Due to several causes, such as the intermittency and variability of RES, large changes in loads or generations, and microgrid reconfigurations, however, it is very common that the converter must operate beyond this region of linearization. Consequently, the controller may not work as expected in this region. To solve this problem, this work uses large-signal model approach to design the controller. In this approach, the system model is derived directly from the original system without linearization. Then, the controller is designed based on this original plant. Due to its wide range of applications and easiness of design, this work uses Proportional-Integral (PI) controller. Even though PI controller is a linear controller, it will work well in various operating points since the changing in operating point is sensed and feedback/fed-forward to the controller. The controller is designed just based on the plant transfer function which is considerably constant for the entire operating points. The controller will compensate for the operating point changes based on the feedback/feedforward signals measured directly from the system. The block diagram of each controller is presented in detail to show the controller and converter parts, including the feedback(s)/feed-forward(s).

The controller design in this work is presented in a simple and consistent man-
ner. Even though the microgrid has different types of converters, such as dc-dc converter and voltage source converter (VSC), the design procedures can be made to be general. In general, the controller design follows the following procedures: 1) the inner-loop controller design procedures: define the plant transfer function, calculate the controller gains based-on open-loop transfer function, and fine-tune the controller by using reliable tools; 2) the outer-loop controller design: define the plant transfer function, include the closed-loop gain of the inner-loop in calculating the open-loop transfer function, calculate the control gains based-on the open-loop transfer function (make sure that the outer-loop controller is much slower than the inner-loop controller), and fine-tune the controller by using reliable tools.

Droop-based primary control, combined with a secondary frequency/voltage restoration control, have been proposed for power sharing among parallel inverter-based distributed generators (DGs) in a microgrid [3, 4]. The droop is based on the maximum power capacity of each DG. However, a renewable-based DG, as mentioned previously, does not have a constant maximum power capacity; its power capacity depends on the atmospheric conditions. Hence, the primary droop-based control as well as the secondary frequency/voltage restoration is not suitable for this kind of DGs. The renewable energy sources that depends on the atmospheric conditions, such as solar and wind energy, cannot be scheduled to generate power/energy whenever it is needed. Hence, the energy management and control should be designed to harvest
maximum available power through a maximum power point tracking (MPPT) algorithm and to store the extra energy to the energy storage element(s), such as battery, available in the microgrid. The energy management and control also schedules dispatchable DG(s) and regulates power transfer between grid and microgrid based-on state of charge (SOC) of the battery.

The responsibility to regulate power transfer between grid and microgrid can be given to individual VSC as discussed in . However, this approach does not show a microgrid as an entity when dealing with the main grid, which is the main concept of microgrid. It just shows grid-integrated DG(s) since each DG deal directly with the main grid. In addition, this approach also enforces strict integration requirements to be followed. The integration can be made more flexible through a tie-line control in which two ac systems can be integrated asynchronously through a dc-link. In this second approach, the microgrid will present as an entity when dealing with the main-grid. These both approach will be presented and compared in this work. The microgrid topology, based on the CERTS microgrid architecture, with tie-line converter is shown in Fig. 3.1.

The controller design for each converter in Fig. 3.1 will be addressed separately in the following sections. Section I will discuss about a hybrid photovoltaic (PV)-battery system, consisting of two converters: PV converter and bidirectional converter. Then, the controller design for a VSC will be discussed in section III. Sec-
Fig. 4.1: Microgrid topology.

Section IV will continue the discussion with the controller design for a tie-line converter. All these converters will be put together and the role of each converter in the microgrid, including its energy management, will be discussed in Section V. The simulation results and discussions will be presented in Section VI to verify the controller design. Finally, the conclusion will sum up this chapter.

4.2 Design of Multi-Layer Control Architecture

The control architecture developed in this work has multiple layers as shown in Fig. 4.2 and the outer layer is slower than the inner layer. The layers are developed based on combination of common voltage source converter (VSC) control and analogy
of conventional grid control as follows:

1. current control, this layer is responsible to regulate the current flowing on the VSC’s inductor filter. If a VSC functions as a voltage source, this current control works together with the next layer voltage control to form a complete VSC control. If the VSC does not have responsibility to regulate its output voltage, on the other hand, the current control can work independently without the voltage control;

2. voltage control, this layer is responsible to regulate the voltage across VSC’s capacitor filter. This voltage control works together with the previous layer current control so that the VSC can function as a voltage source;

3. primary frequency control, this droop control layer is responsible to regulate frequency of the microgrid based on detected power mismatch and energy availability. The droop control will regulate the frequency in three categories:

   - nominal frequency if there is no power mismatch detected or battery SOC is within its limits,
   - high off-nominal if the generated power is more than the consumed power plus losses and the SOC is reaching its upper limit,
   - low off-nominal if the generated power is less than the consumed power plus losses and the SOC is reaching its lower limit,
Control Emphasis for Each Mode

Level 0 (Inner Loop)
- Internal current control
- External voltage control

Level 1 (Primary Control)
- Droop Control

Level 2 (Secondary Control)
- Voltage & frequency restoration
- Synchronization

Level 3 (Tertiary Control)

---

**Fig. 4.2:** Multi-layer control for microgrid.

4. secondary frequency restoration control, this layer is responsible to restore the frequency to its nominal after the off nominal frequency is detected. This control function is given to local controllers of dispatchable DGs and MPPT;

5. tertiary power interchange control, this layer is responsible to regulate power interchange between grid and microgrid or between two neighboring microgrids. This control function is given to tie-line converter.
4.3 Hybrid Photovoltaic-Battery Systems

In this section, the controller designs for a hybrid PV-battery system will be discussed. The system under studies is shown in Fig. 4.3. This figure shows that the hybrid system contains two converters:

- the PV converter that controls $I_{PV}$ (through the inductor current ($I_{LPV}$)) and $V_{PV}$,
- the battery bidirectional converter that controls $I_{LBi}$ and $V_{dc}$.

These two converters are basically a single two-leg bridge, in which each converter utilizes one leg. The controller design is based on large-signal model that considers wide range of operating points of the system. The use of two-leg bridge converter and large-signal model is similar to the approach in [5]. The use of large signal model for voltage source converter (VSC) in [6] inspired the authors to use this approach. Voltage and current relationships between two sides of each converter are based-on averaged converter model as shown in Fig. 4.4.

In designing the controllers for these two converters, the following considerations are applied:

- the PV controller design considers that the output terminal voltage $V_{dc}$ is constant due to the control action of the battery bidirectional converter,
Fig. 4.3: Complete circuit of the PV-battery system.

Fig. 4.4: Averaged buck-boost converter model.
• the battery bidirectional controller design considers variations on the load and PV converter terminals. Each source of variation can be represented by a current source.

4.3.1 PV Converter

The PV converter shown in Fig. 4.3 is a unidirectional converter in which the output power can flow from the PV arrays to the dc-link only. The ultimate goal of this PV converter is to harvest maximum power from the PV arrays. Due to the dependency of the PV output power \( P_{PV} \) on the PV voltage \( V_{PV} \) and PV current \( I_{PV} \), \( P_{PV} \) can be regulated by regulating \( V_{PV} \) or \( I_{PV} \). In this work, both \( V_{PV} \) and \( I_{PV} \) are regulated in a dual control loop in which voltage control is in the outer loop and current control is in the inner loop. This dual loop control is shown in Fig. 4.5. Since the output of the PV converter is connected to the dc-link which is regulated by the battery converter, the PV converter is responsible to regulate its input side to operate at maximum power point (MPP) by tracking the reference signal which comes from a maximum power point tracking (MPPT) algorithm and leaves the output side to be regulated by the battery converter. The MPPT algorithm used in this work is the incremental-conductance-based MPPT algorithm [7].

The controller design of the PV converter starts with the inner control loop.
Fig. 4.5: Block diagram of the PV converter’s dual control loops.

Fig. 4.6: PV side circuit of the PV-battery system.

Fig. 4.6 shows the PV side circuit of the PV-battery system and its averaged model that can be used to derive the plant transfer function given in (4.1).

\[
\frac{I_{LPV}}{V_{LPV}} = \frac{1}{L_{PV}.s + R_{PV}}; \tag{4.1}
\]

where: \( V_{LPV} = V_{PV} - D_{PV}V_{dc} \).

The transfer function shows that the inductor current of the PV converter \((I_{LPV})\) is controlled through the inductor voltage \((V_{LPV})\). Based on the transfer function and the circuits, the block diagram of the inner loop of the PV converter
is shown in Fig. 4.7. The block diagram shows the PI controller generate the expected inductor voltage as the control signal \((u_c)\). This expected inductor voltage is not identical as the actual inductor voltage. To show the difference, the control signal expresses the inductor voltage with an index \(\text{ctrl}\) as shown in (4.2). However, a well designed controller should lead an actual variable to follow its expected value. Based on this block diagram, the open loop transfer function of the PV converter’s inner loop can be derived and is given in (4.3). This open-loop transfer function can be obtained by considering the compensator and plant transfer functions only from Fig. 4.7. The feed-forwards and other blocks should be ignored. This transfer function can be used to find the time constant of the converter by using the pole-zero cancellation principal as shown in (4.4) [6].

\[
\begin{align*}
   u_c &= \left(\frac{K_{pc}s + K_{ic}}{s}\right)(I_{LPV}^* - I_{LPV}) \\
   &= (V_{LPV})_{\text{ctrl}} = (V_{PV} - D_{PV}V_{dc})_{\text{ctrl}}
\end{align*}
\]  

(4.2)
where: \( L_{PV} \) and \( R_{PV} \) are the inductor and resistor of the PV converter, \( K_{pc} \) and \( K_{ic} \) are the control gains, \( K_{ic} \) is the inner control gain, \( K_{pc} \) is the outer control gain, and \( K_{ic} \) is the voltage gain of the PV converter.

This equation can be used directly to calculate the inner control gains, \( K_{pc} \) and \( K_{ic} \). The inner control gains can also be found by using (4.3) to draw its Bode plot. Some fine tuning tools, such as a PID tuning tools from Matlab [8], can be used for convenience.

Based on the above derivations, the inner loop of the PV converter control can be summarized as follow:

- the main variable to control is the inductor current of the PV converter (\( I_{LPV} \)),
- the inductor current of the PV converter (\( I_{LPV} \)) is controlled through the inductor voltage (\( V_{LPV} \)),
- finally, the controller regulates duty cycle of the PV converter based on the following equation: \( D_{PV} = \frac{V_{PV} - V_{LPV}}{V_{dc}} \).

After deriving the inner controller, next step is deriving the outer controller. The averaged model of the outer control loop can be drawn based on Kirchhoff’s current law (KCL) at the PV capacitor’s node and is shown in Fig. 4.8. The KCL
is used because the PV capacitor voltage, i.e. the PV voltage ($V_{PV}$), is regulated by regulating the PV capacitor current ($I_{CPV}$). Based on this averaged model, the transfer function of this outer loop’s plant can be derived and shown in (4.5). Based on the transfer function and the averaged model, the block diagram of the outer control loop is given in Fig. 4.9. The block diagram shows the PI controller generates the expected capacitor current as the control signal ($u_v$). In this block diagram, the inner control loop is represented by its closed loop transfer function ($G_{inner-cl} = \frac{1}{\tau_c s + 1}$).

Next, the open-loop transfer function for this outer control loop is given in (4.7).

$$\frac{V_{PV}}{I_{CPV}} = \frac{1}{C_{PV}s},$$ (4.5)

where: $I_{CPV} = I_{PV} - I_{LPV}$. In which, $I_{PV}$ is set based on the MPP current ($I_{MPP}$), while $I_{LPV}$ is regulated in the inner control loop.
Fig. 4.9: Block diagram of the outer control loop of the PV converter.

\[
\begin{align*}
u_v &= \left( \frac{K_{pu}s + K_{iv}}{s} \right) (V_{PV}^* - V_{PV}) \\
&= (I_{CPV})_{ctrl} = (I_{PV} - I_{LPV})_{ctrl}.
\end{align*}
\]

(4.6)

\[
G_{outer-cl} = \left( \frac{K_{pu}s + K_{iv}}{s} \right) \left( \frac{1}{\tau_c s + 1} \right) \left( \frac{1}{C_{PV} s} \right).
\]

(4.7)

In designing the outer control loop, it is assumed that the inner control loop is much faster than the outer control loop so that the outer control loop sees that the actual current tracks its reference current immediately. In other words, the closed loop transfer function of the inner control loop can be assumed to be unity \( G_{inner-cl} = \frac{1}{\tau_c s + 1} \approx 1 \). This assumption can be realized by defining that the inner control loop’s bandwidth is around ten time of the outer control loop’s. The inner control loop’s bandwidth can be defined based on the inner control loop’s time constant as given in 4.8. The outer control gains, \( K_{pu} \) and \( K_{iv} \), can be found by using 4.7 to draw its Bode plot. As previously discussed, the Matlab’s PID tuning tools can
be used to fine tuned these gains.

\[
BW_{inner} = \frac{1}{\tau_c}, \quad BW_{outer} = \frac{BW_{inner}}{10}.
\] (4.8)

Based on the above derivations and assumptions, the outer loop of the PV converter control can be summarized as follow and the summary is used to draw the detail block diagram shown in Fig. 4.10:

- the main variable to be controlled is the PV voltage \((V_{PV})\),
- the PV voltage \((V_{PV})\) is controlled through the PV capacitor current \((I_{CPV})\),
- finally, the outer loop controller generates the PV inductor reference current \((I_{LPV})\) based on the following equation: \(I_{LPV} = I_{PV} - I_{CPV}\).
4.3.2 Bidirectional Battery Converter

Different from the PV converter, the battery converter shown in Fig. 4.11 is a bidirectional converter in which its current can flow in two directions: from the battery to the dc link or vice versa. The main objective of this converter control is to regulate dc-link voltage \( V_{dc} \) around the nominal value of 850 V. However, \( V_{dc} \) is not the only variable to be regulated, the inductor current \( I_{LBi} \) needs also to be regulated due to the limit of the charging/discharging current of the battery and the inductor current. Hence, the battery converter requires a dual-loop bidirectional converter, similar to the block diagram in Fig. 4.5.

The transfer function of the inner control loop’s plant can be derived based on the averaged model on the right side of Fig. 4.11 and is given in (4.9). The transfer function shows that the inductor current \( I_{LBi} \) is controlled through the inductor
Fig. 4.12: Block diagram of the inner control loop of the bidirectional converter.

Voltage ($V_{LBi}$). Based on the transfer function, the block diagram of the inner loop of the battery bidirectional converter is shown in Fig. 4.12. Similar to the previous converter, the control signal is given in (4.10). Based on this block diagram, the open loop transfer function of the bidirectional converter can be derived and is given in (4.11). This transfer function can be used to find the time constant of the converter by using the pole-zero cancellation as discussed in the previous subsection.

$$\frac{I_{LBi}}{V_{LBi}} = \frac{1}{L_{Bi}s + R_{Bi}},$$  \hspace{1cm} (4.9)

where: $V_{LBi} = V_{Batt} - D_{Bi}V_{dc}$.

$$u_c = \left( K_{pc}s + K_{ic} \right) \left( I_{LBi}^* - I_{LBi} \right)$$

$$= (V_{LBi})_{ctrl} = (V_{Batt} - D_{Bi}V_{dc})_{ctrl},$$ \hspace{1cm} (4.10)

$$G_{inner-ol} = \left( K_{pc}s + K_{ic} \right) \left( \frac{1}{L_{Bi}s + R_{Bi}} \right).$$ \hspace{1cm} (4.11)

Based on the above derivations, the inner loop of the battery bidirectional con-
verter control can be summarized as follow:

- the main variable to be controlled is the inductor current \(I_{LBi}\),
- the inductor current \((I_{Bi})\) is controlled through the inductor voltage \((V_{LBi})\),
- finally, the controller regulates duty cycle of the bidirectional converter based on the following equation: \(D_{Bi} = \frac{V_{Batt} - V_{LBi}}{V_{dc}}\).

The battery bidirectional converter is a dual loop control. The inner control loop derived above will be driven by the outer control loop. In other words, the reference inductor current \((I_{LBi}^*)\) is generated by the outer control loop. The averaged model of the outer control loop is shown in Fig. 4.13. The figure assumed that the dc-link voltage \((V_{dc})\) is regulated through the dc-link’s capacitor current \((I_{C,dc})\). Hence, the transfer function of this outer control loop’s plant is given by (4.12). The figure also shows that variations on the load and PV sides are represented by the current sources. Based on the transfer function and the averaged model, the block diagram of the outer control loop is given in Fig. 4.14. Similar to the previous converter, the control signal \((u_e)\) is given in (4.13). The outer control design of the bidirectional converter also considers that the inner loop control is around ten time faster than the outer loop control. Next, the open-loop transfer function for this outer control loop is given in (4.14).
Fig. 4.13: Averaged model of the outer control loop of the bidirectional converter.

Fig. 4.14: Block diagram of the outer control loop of the bidirectional converter.

\[
\frac{V_{dc}}{I_{Cdc}} = \frac{1}{C_{dc}s}, \tag{4.12}
\]

where: \( I_{Cdc} = (D_{Bi}I_{LBi} + D_{PV}I_{PV} - I_{Load}) \).

\[
u_v = \left( \frac{K_{pv} + K_{iv}}{s} \right) (V_{dc}^* - V_{dc})\]

\[
= (I_{Cdc})_{ctrl} = (D_{Bi}I_{LBi} + D_{PV}I_{PV} - I_{Load})_{ctrl}, \tag{4.13}
\]

\[
G_{outer-ol} = \left( \frac{K_{pv}s + K_{iv}}{s} \right) \left( \frac{1}{\tau_c s + 1} \right) \left( \frac{1}{C_{dc} s} \right). \tag{4.14}
\]

Based on the above derivations, the outer loop of the battery bidirectional converter control can be summarized as follow and the summary is used to draw the
**Fig. 4.15:** Detail block diagram of the bidirectional converter’s dual control loops.

detail block diagram shown in Fig. 4.15:

- the main variable to be controlled is the dc-link voltage ($V_{dc}$),

- the dc-link voltage ($V_{dc}$) is controlled through the dc-link’s capacitor current ($I_{Cdc}$),

- finally, the controller regulates the reference inductor current of the inner loop ($I_{LBi}$) of the bidirectional converter based on the following equation: $I_{LBi} = \frac{I_{Cdc} + I_{Load} - D_{PV} I_{LPV}}{D_{Bi}}$.

**4.4 Voltage Source Converter**

Due to the demand and motivation to utilize renewable energy sources (RES), it is very common that a microgrid has several converters which interact one another. It is also common that a VSC does not connect to a primary energy source directly.
It rather connects to a dc-link which is the output of other converters. Hence, an assumption that the VSC input is an ideal dc source is not valid anymore. This work considers that the VSC connects to a dc-link which is an output of two converters discussed in the previous section.

This work uses the large signal model to derive the converter model and to design controller. The derivation is mainly follow the procedures in [6] and the controller design combined the approach in [6] and [9]. This section will discuss about VSC model and control modes used in this work.

4.4.1 VSC Model

The 3-phase VSC model is shown in Fig. 4.16. The VSC is connected to an ideal dc source on one side and an unknown ac system on the other side. The ac system can be a grid, ac loads, or a combination of grid and ac loads. Each phase of the converter represent a half-bridge converter. This half-bridge converter model can be represented by (4.15) and the relationship of modulation index and the VSC terminal voltage can be represented by (4.16). These two equations can be represented by Fig. 4.17.

\[ L_j \frac{di}{dt} + R_f i = v_t - v_s \]  (4.15)
Fig. 4.16: 3-phase VSC model.

Fig. 4.17: Diagram block of the VSC model.

\[ v_t = m \frac{V_{dc}}{2} \]  

(4.16)

4.4.2 Control Mode

VSC controllers can be designed based on the model presented in the previous subsection and the dual-loop approach presented in the previous section about hybrid system. Depending on the needs, the VSC controllers can be designed for the following
variable: dc-side voltage, ac-side voltage (including its frequency), ac-side current, and active/reactive power. Considering that the dc-side voltage, i.e. dc-link voltage, is controlled by the bidirectional converter, it is not discussed in this section.

Considering the advancement of a rotating-reference-frame (dq-frame) based control and its nature to decouple between active power (P) and reactive power (Q), the authors use the dq-frame based control. Hence, (4.15) needs to be transformed to its rotating reference frame which resulted in (4.17). Based on these dq current equation and the VSC model, the diagram block of the VSC current control is shown in Fig. 4.18. As previously discussed in the hybrid system, for this current mode control, the main objective is to control the inductor current through inductor voltage. Hence, the control signal \( u_c \) is the expected inductor voltage. This control signal will be processed by using (4.17) and (4.16) to produce modulation indexes, \( m_d \) and \( m_q \). Then, the modulation indexes will be processed by the converter represented by Fig. 4.17 to produce a regulated output current.

\[
\begin{align*}
L_f \frac{di_d}{dt} + R_f i_d &= \omega L_f i_q + v_{td} - v_{sd}, \\
L_f \frac{di_q}{dt} + R_f i_q &= -\omega L_f i_d + v_{td} - v_{sd},
\end{align*}
\]

(4.17)

The converter can be designed based on the open-loop transfer function of the current-mode control. The open-loop transfer function is given in (4.18).
The inner-loop current-mode control can also be extended with an outer-loop voltage-mode control. The extension involves calculation of another pair of controller gains for the outer-loop, $K_{pv}$ and $K_{iv}$. As previously mentioned, for the current-mode control, the inductor current is regulated through the inductor voltage, whereas the capacitor voltage is regulated through the capacitor current for the voltage-mode control. Hence, both controls has different plants so that they both require different controller gains.

The outer-loop voltage-mode control can be derived by taking KCL on the filter capacitor node. The KCL in abc-frame for each phase can be represented as (4.19).
The equivalent equation in dq-frame is represented in (4.20). Based on the dq-frame equation for the KCL entering/leaving the capacitor node, the block diagram of the outer-loop voltage-mode control is shown in Fig. 4.19. Next, the open-loop transfer function of the outer-loop voltage-mode control is given in (4.21).

\[ C_f \frac{dv_s}{dt} = i(t) - i_{Load}(t). \]  

(4.19)

\[ C_f \frac{dv_d}{dt} = \omega C_f v_q + i_d - i_{Load-d}, \]  

(4.20)

\[ C_f \frac{dv_q}{dt} = -\omega C_f v_d + i_q - i_{Load-q}. \]
The frequency control is included in the current and voltage control when the modulation index for three phase signal ($m_{abc}$) is produced from the dq-frame modulation index ($m_{dq}$). The frequency of the output voltage can be controlled directly either by generating ideal frequency of 377 rad/sec (60 Hz) or by referring to the grid frequency. The frequency control can be implemented as shown in Fig. 4.20.

\[
G_{outer-ol} = \left( \frac{K_p}{s} + K_i \right) \left( \frac{1}{\tau_c s + 1} \right) \left( \frac{1}{C_f s} \right).
\]

(4.21)

The frequency control is included in the current and voltage control when the modulation index for three phase signal ($m_{abc}$) is produced from the dq-frame modulation index ($m_{dq}$). The frequency of the output voltage can be controlled directly either by generating ideal frequency of 377 rad/sec (60 Hz) or by referring to the grid frequency. The frequency control can be implemented as shown in Fig. 4.20.

4.5 Control Roles and System Specifications

The controller discussed in the previous sections work in a micro seconds to seconds time frame. It deals with voltage and frequency control as well as fast power balancing based on local measurement. Specifications of the dc-dc converters are presented in Table 4.1, while specifications of the VSC are presented in Table 4.2.
The proposed control functions as follows:

- the PV converter is to regulate the output voltage of PV, i.e. the input voltage of the converter, in order to harvest maximum available power from the PV;

- the bidirectional dc-dc converter is to maintain dc-link voltage and also charging/discharging current at a specified values;

- the VSC is to maintain magnitude, phase angle and frequency of the ac output in off-grid operation and to regulate power transfer between grid and microgrid if there is no tie-line converter.
Table 4.1: Specifications of the dc-dc converters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PV Converter</th>
<th>Bidirectional Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{PV}$ or $R_{Bi}$</td>
<td>75.3 mΩ</td>
<td>75.3 mΩ</td>
</tr>
<tr>
<td>$L_{PV}$ or $L_{Bi}$</td>
<td>1 mH</td>
<td>1 mH</td>
</tr>
<tr>
<td>$C_{PV}$</td>
<td>10 mF</td>
<td>N/A</td>
</tr>
<tr>
<td>$C_{dc}$</td>
<td></td>
<td>1.45 mF</td>
</tr>
<tr>
<td>$K_{pc}$</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>$K_{ic}$</td>
<td>75.3</td>
<td>416.67</td>
</tr>
<tr>
<td>$K_{pv}$</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>$K_{iv}$</td>
<td>10</td>
<td>33.33</td>
</tr>
<tr>
<td>$V_{PV}$ or $V_{Batt}$</td>
<td>480 V</td>
<td>480 V</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td></td>
<td>850 V</td>
</tr>
</tbody>
</table>
Table 4.2: Specifications of the VSC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_f$</td>
<td>3.26 mΩ</td>
</tr>
<tr>
<td>$L_f$</td>
<td>200 µH</td>
</tr>
<tr>
<td>$C_f$</td>
<td>2 mF</td>
</tr>
<tr>
<td>$K_{pc}$</td>
<td>0.4</td>
</tr>
<tr>
<td>$K_{iv}$</td>
<td>6.52</td>
</tr>
<tr>
<td>$K_{pv}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$K_{iv}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>850 V</td>
</tr>
<tr>
<td>$V_{s,L-L}$</td>
<td>480 V</td>
</tr>
</tbody>
</table>
4.6 Simulation Results and Discussions

4.6.1 Current Control

In a current mode control, the VSC output voltage is not control. Hence, the VSC must be connected to a voltage-controlled bus, usually a grid bus or PCC. In this dissertation, the inverter output is connected to a PCC whose voltage is controlled by the grid. The purpose of this simulation is to verify the dynamic characteristics of the VSC for step changes of the direct and quadrature currents. There are three values tested: positive nominal, zero, and negative nominal. For direct current, the test values are 204 A, 0 A, and -204 A, while for quadrature current, the values are 21 A, 0 A, and -21 A.

The simulation results in Fig. 4.21 show that the actual currents track their references very well. The settling time is also fast enough at around one 60 Hz cycle. The only concern is the big overshoot of quadrature current when the direct current changes 2 pu from 1 pu to -1 pu. The changes does not only involves the magnitude, but also phase reversal. However, it is obvious that this big changes rarely happens.
Fig. 4.21: The abc and dq load currents: (a) 3-phase abc current, (b) actual and reference direct current, and (c) actual and reference quadrature current.

4.6.2 Voltage Control: No Load Condition

In the voltage control simulation, the bus voltage is controlled by the VSC. To verify the control performance, the bus should not be connected to the grid. Otherwise, the grid will keep the voltage constant and the voltage controller of the VSC cannot be verified. Right after the controller is activated at 0.2 s, the instantaneous voltage builds up to track its reference. The simulation results in Fig. 4.22 shows that the settling time is around two 60 Hz cycles and the maximum peak overshoot is less than 20%.
Fig. 4.22: Instantaneous and peak load voltage: (a) instantaneous voltage, and (b) peak voltage.

4.6.3 Voltage Control: Loading Condition

The loading conditions is simulated to verify the stability of the VSC terminal voltage when there is a rapid change of the load. The loading conditions include exporting nominal power of 120 kW, importing nominal power of 120 kW, and no power transfer. All the waveforms in Fig. 4.23 shows that the VSC works well in rapid power changes. The power changes from 120 kW to -120 kW shows that the phase angle of the current switches from in phase with the voltage to 180° out of phase with the voltage.
Fig. 4.23: VSC performance in loading condition: (a) load power, (b) load voltage, (c) load current, and (d) phase-a voltage and current.
4.6.4 Frequency Control

The frequency control is simulated by changing the frequency of the input signal to the phase-locked loop (PLL) block. The frequency is varied ±2 Hz around 60 Hz, or it is ranging from 58 to 62 Hz. The simulation results show that the actual frequency tracks its reference value with acceptable transient at the beginning of every frequency change. The settling time is around 200 ms. The PCC voltage does not show any distortion due to these frequency changes.
Fig. 4.24: Frequency control responses: (a) actual and reference frequency; (b) phase-a PCC voltage.
4.7 Summary

Controller design based on large-signal model for a wide-range of operating points has been discussed. The controllers are designed for dc-dc converters and voltage source converter. Several scenarios have been simulated to verify the controller design. The simulation results shows that the controllers function as expected.
4.8 References


5.1 Introduction

This chapter focuses on power interchange. The power interchange can be among DGs inside a microgrid, between microgrid and grid, and among neighboring microgrid. The power interchange is based on power control which is an extension of current mode control. Power interchange algorithm for microgrid depends on the type and ownership of microgrid. This chapter will continue the discussions on the derivation of power control and tie-line converter. Simulation results and discussions will verify the design. Finally, a summary will sum up this chapter.

5.2 Current Mode and Power Mode Control

In dq-frame, the current-mode control can be turned directly to a power-mode control by using the relationship between voltages, currents, and powers as in (5.1). This relationship can be expressed for real and reactive power delivered to the ac
Assuming that the PCC dq-frame voltage components, $v_{sd}$ and $v_{sq}$, are fully controlled by another converter and the phase-locked loop (PLL) is in steady state, in which $v_{sq} = 0$, the reference currents in Fig. 4.18 can be generated by the reference powers as in (5.2). These equations turn the current-mode control directly to power-mode control without any change in the controller gains, $K_{pc}$ and $K_{ic}$.

\[
\begin{align*}
   i_d^*(t) &= \frac{2}{3v_{sd}} P_s^*(t), \\
   i_q^*(t) &= -\frac{2}{3v_{sd}} Q_s^*(t).
\end{align*}
\]  

### 5.3 Impact of Microgrid Ownership on Power Interchange

From the utility grid point of view, microgrids have different type and ownership. A microgrid can be owned by a utility company in which the utility company can have full control on the microgrid. In this case, power transfer between the utility grid and the microgrid can be dictated by the utility and the amount is just based on the extra power availability, demand need, and available distribution line capacity. A microgrid can also be owned by a community or private company. Hence, the relationship between the microgrid and utility grid is as two area systems in which
Fig. 5.1: Relationship of a utility grid and microgrids.

each area has its own energy management and control. In this case, power transfer between the utility grid and the microgrid is based on an agreement between both parties. Thus, a tie-line regulator, such as a back-to-back converter, is required to regulate this power transfer. The relationship between utility grid and microgrids is shown in Fig. 5.1.
If there is no tie-line converter, the responsibility to regulate power transfer between grid and microgrid can be given to individual DG as discussed in [1]. However, this approach does not show a microgrid as an entity when dealing with the main grid. It just shows grid-integrated DG(s) since each DG deal directly with the main grid. In addition, this approach also enforces strict integration requirements to be followed. The integration can be made more flexible through a tie-line control in which two ac systems can be integrated asynchronously through a dc-link. In this second approach, the microgrid will present as an entity when dealing with the main-grid. The microgrid topology, based on the CERTS microgrid architecture, with tie-line converter is shown in Fig. 3.1.

### 5.4 Tie-Line Converter

To have a smooth and seamless integration between two ac systems, the following requirements must be fulfilled:

- rms voltages of the two systems must be the same,
- frequencies of the two systems must be the same,
- phase sequences of the two systems must be the same.

In the case of a microgrid that can operate both grid-connected and islanded modes of operation, the microgrid is responsible to fulfill these requirements. This
responsibility can be given to a VSC that operates in a voltage-mode control to regulate the PCC voltage. However, this integration can be made more flexible through a back-to-back tie-line converter that enables the two ac systems to integrate asynchronously through a dc-link. The tie-line converter as shown in Fig. 5.2 consists of two VSC discussed in the Chapter 4. The first VSC regulates power transfer between the main grid and the dc-link based on the power-mode control discussed previously, while the second VSC regulates the dc-link voltage and can also be embedded with a reactive power control.

The dc-link voltage control uses an energy-based dc-link voltage control \cite{2}. The energy stored in or required to charge the dc-link capacitor is expressed in (5.3). The dc power related to this energy is given in (5.4). Based on (5.4), the required power by the dc-link capacitor to charge from actual voltage \(v_{dc}\) to the reference voltage \(V_{dc}^*\) can be expressed in (5.5). The plant transfer function for the dc-link voltage control can be derived based on (5.4) and is given in (5.6).

\[
W_{dc} = \frac{1}{2} C_{dc} V_{dc}^2. \tag{5.3}
\]

\[
P_{dc} = \frac{dW_{dc}}{dt} = \frac{1}{2} C_{dc} \frac{d}{dt} \left( V_{dc}^2 \right). \tag{5.4}
\]
\[ P_{dc} = \frac{1}{2T_{rpl}} C_{dc} \left( V_{dc}^* - V_{dc}^2 \right) . \]  
(5.5)

where: \( T_{rpl} \) is the ripple period of the dc-link capacitor voltage, which, in general, is half the period of the ac system on the other side of the VSC.

\[ \frac{V_{dc}^2}{P_{dc}} = \frac{2}{C_{dc}s}. \]  
(5.6)

Based on Fig. 5.2, the power balance can be used to relate between the input powers of the two VSC and the power stored in the dc-link capacitor. Considering that the VSC losses is negligible, the power balance can include the power at PCC of VSC2 as in (5.7). Hence, the controller can be used to regulate \( P_{s2} \) which finally can
regulate $i_{d2}$ in the inner loop. The block diagram of this control is shown in Fig. 5.3.

The figure also shows that the grid side VSC also regulates reactive power through the quadrature current. The quadrature current control is just shown in general form in which the reference current ($i_q^*$) will result in the actual current ($i_q$). The detail control is the same as the current mode control of VSC in Fig. 4.18 Chapter 4.

$$P_{dc} = -P_{in1} - P_{in2} = P_{eq} - P_{in2},$$

$$P_{dc} = P_{eq} - Ps2.$$  \hspace{1cm} (5.7)

Based on the Fig. 5.3, the open-loop transfer function of the dc-link voltage control is given in (5.8). This open-loop transfer function can be used to fine-tune the controller gains. For initial check, the controller gains given in (5.9) can be used [2].
\[
G_{outer-ol} = \left( \frac{K_{pv}s + K_{iv}}{s} \right) \left( \frac{1}{\tau_c s + 1} \right) \left( \frac{2}{C_{dc}s} \right).
\]

(5.8)

\[
K_{pv} = \frac{C_{dc}}{2T_{rpl}},
\]

(5.9)

\[
K_{iv} = \frac{K_{pv}}{2}.
\]

5.5 Control Roles and System Specifications

The system specifications for the dc-dc converter as well as VSC in this chapter are the same as the system specifications in the previous chapter. The specifications of the back-to-back converter are given in Table 5.1. The addition of the tie-line converter introduces some changes in the controller roles. The proposed control functions as follows:

- the PV converter is to regulate the output voltage of PV, i.e. the input voltage of the converter, in order to harvest maximum available power from the PV;

- the bidirectional dc-dc converter is to maintain dc-link voltage and also charging/discharging current at a specified values;

- the VSC is to maintain magnitude, phase angle and frequency of the ac output voltage in all operation modes;
• the tie-line back-to-back converter is to regulate power transfer between main grid and microgrid and among adjacent microgrids in a networked microgrid system.

The roles of each controller for a microgrid without a tie-line converter is shown in Fig. 5.4, while the roles of each controller for a microgrid with a tie-line converter is shown in Fig. 5.5. In a microgrid with a tie-line converter, the VSC is always responsible to regulate voltage magnitude, phase angle and frequency. The responsibility to regulate power transfer between grid and microgrid is taken by the tie-line converter.
Fig. 5.5: Microgrid with tie-line converter.
Table 5.1: Specifications of the back-to-back converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( VSC_1 )</td>
</tr>
<tr>
<td>( R_f )</td>
<td>3.26 m( \Omega )</td>
</tr>
<tr>
<td>( L_f )</td>
<td>200 ( \mu )H</td>
</tr>
<tr>
<td>( C_{dc} )</td>
<td>10 mF</td>
</tr>
<tr>
<td>( K_{pc} )</td>
<td>0.4</td>
</tr>
<tr>
<td>( K_{ic} )</td>
<td>6.52</td>
</tr>
<tr>
<td>( K_{pv} )</td>
<td>N/A</td>
</tr>
<tr>
<td>( K_{iv} )</td>
<td>N/A</td>
</tr>
<tr>
<td>( V_{dc} )</td>
<td></td>
</tr>
<tr>
<td>( V_{s,L-L} )</td>
<td>480 V</td>
</tr>
</tbody>
</table>
5.6 Simulation Results and Discussions

In islanding mode of operation, the VSC of the hybrid PV-battery will function as a voltage source that is responsible to regulate voltage magnitude and frequency of the microgrid. Active and reactive power will be supplied automatically based on the impedance of the load(s) seen by the VSC. Due to the capacity limit of the DG(s) inside the microgrid, it is very important to manage power balancing inside the microgrid. Hence, the hybrid PV-battery cannot supply the load(s) more than its own capacity since there is no reserved kinetic energy as in synchronous machines. However, depending on its state of charge (SOC), the battery can supply extra power temporarily as long as the VSC has enough rating to supply this extra power.

When the microgrid is in grid connected, the voltage magnitude and frequency is dictated by the grid if the microgrid is connected to the grid without a tie-line converter. In this case, the DG(s) inside the microgrid, including the hybrid PV-battery, acts as a current source that supplies the load according to control signal received from MGCC. Individual DG(s) sees the rest of the system beyond its output terminal as Thevenin equivalent circuit.

Active and reactive power transfer between the hybrid PV-battery and the rest of the system, including the rest of microgrid and the grid is presented in Fig. 5.6. Since this power control is an extension of the current control in the previous chapter,
the controller performance is similar between the current control and this power control. The settling time is around one 60 Hz cycle and the biggest overshoot occurs when the power changes from 1 pu (120 kW) to -1 pu (-120 kW), or 2 pu change in magnitude and reverse phase angle.

For a microgrid that connects to the grid through a tie-line converter, the simulation results are shown in Figs. 5.7, and 5.8. Fig. 5.7(a) and (b) show the active and reactive power transfer on the microgrid side VSC. Positive power indicates that microgrid imports power from the grid and vice versa. The simulation results show that the power transfer is regulated well by the microgrid side VSC except for the transient right after the controller is activated at 0.2 s. The active power is trans-

Fig. 5.6: Active and reactive power transfer: (a) active power, and (b) reactive power.
ferred in the range between -1 pu (-120 kW) and 1 pu (120 kW). Even though the HVDC has functionality to transfer reactive power, the reactive power is regulated at 0 kVAr. If required, however, reactive power can be regulated to other values. The PCC voltage and output current in Fig. 5.7(c) shows that the PCC is stiff enough and microgrid will relatively not be susceptible to any changes in the grid or HVDC.

Fig. 5.8(a) shows the reflection of the power transfer on the grid side VSC, while Fig. 5.8(b) shows that the reactive power is regulated at 0 kVAr. The main function of the grid side VSC is to regulate dc-link voltage of the tie-line converter. The dc-voltage regulation is based on energy stored in the dc-link capacitor. Hence, dc-link voltage will not reaches its steady state value of 850 V unless some power are transferred to the dc-link. When 120 kW was transferred from the grid to microgrid at 0.5 s, the dc-link voltage starts increasing and reaches its steady state value of 850 V at 0.575 s.

The third case study is grid-connected networked microgrids. Active power is interchanged between microgrid 1 (MG1) and microgrid 2 (MG2) while grid is in idle condition. The power transfer between MG1 and MG2 is 60 kW, less than the power transfer between grid and microgrid. The simulation results are shown in Figs. 5.9 and 5.10. Fig. 5.7(a) and (b) show the active and reactive power transfer of power control VSC, MG1 side VSC. Positive power indicates that MG1 imports power from MG2 and vice versa. The simulation results shows that the power transfer is regulated well
Fig. 5.7: Active/reactive power transfer and PCC voltage and current on the microgrid side VSC.

Fig. 5.8: Reflection of the active/reactive power transfer and dc-link voltage on the grid side VSC.
by the MG1 side VSC except for the transient right after the controller is activated at 0.2 s. The active power is transferred in the range between -60 kW and 60 kW. The reactive power is regulated at 0 kVAr. The PCC voltage and output current in Fig. 5.9(c) shows that the PCC is stiff enough and MG1 will relatively not be susceptible to any changes in MG2.

Fig. 5.10(a) shows the reflection of the power transfer on the MG2 side VSC, while Fig. 5.10(b) shows that the reactive power is regulated at 0 kVAr. The main function of the MG2 side VSC is to regulate dc-link voltage at 850 V. The dc-link voltage reaches its steady state value of 850 V at 0.3 s.
Fig. 5.9: Active/reactive power transfer and PCC voltage and current on the power control VSC.

Fig. 5.10: Reflection of the active/reactive power transfer and dc-link voltage on the dc-link control VSC.
5.7 Summary

Controller design based on large-signal model for a wide-range of operating point has been discussed. Power control as well as power exchange has been simulated. The power exchanges include microgrid with and without tie-line converter connection to the grid as well as networked microgrids. The simulations results show that the converter controls function as expected.
5.8 References


CHAPTER 6. FREQUENCY-RESPONSE-BASED DECENTRALIZED CONTROL

6.1 Introduction

This chapter discusses about decentralized control for power balancing based on frequency response generated by a droop controller. In contrast to the common droop control function for power sharing between parallel DGs, the droop control in this chapter is used as an indicator by the dispatchable DG(s) or MPPT of PV to act accordingly, including start generating power, increase power generation, decrease power generation, or stop generating power. This decentralized control is very essential in case of communication network failure.

6.2 Overview of Droop Control

The droop control for microgrid is derived based on the droop control for conventional power systems. In contrast to the droop control in conventional power system that relies on reserved kinetic energy inside the inertia, the droop control in
Fig. 6.1: Circuit and phasor diagram for droop derivation.

The active and reactive powers flowing into the line are expressed in (6.3).

\[
P = \frac{V_1^2}{Z} \cos \theta - \frac{V_1 V_2}{Z} \cos(\theta + \delta),
\]
\[
Q = \frac{V_1^2}{Z} \sin \theta - \frac{V_1 V_2}{Z} \sin(\theta + \delta),
\]
with \( Z e^{j\theta} = R + jX \), (6.3) can be rewritten as follow:

\[
P = \frac{V_1}{R^2 + X^2} (R(V_1 - V_2\cos\delta) + XV_2\sin\delta),
\]
\[
Q = \frac{V_1}{R^2 + X^2} (-RV_2\sin\delta + X(V_1 - V_2\cos\delta)),
\]

(6.4)

By using elimination method, (6.4) can be rewritten as follows:

\[
V_2\sin\delta = \frac{XP - RQ}{V_1},
\]
\[
V_1 - V_2\cos\delta = \frac{RP + XQ}{V_1}.
\]

(6.5)

Based on the ratio \( R/X \), the droop characteristics in (6.5) can be classified as follows [1]:

1. **Highly inductive lines**

For overhead lines, \( X \gg R \), which means that \( R \) may be neglected. If the power angle \( \delta \) is small, then \( \sin\delta \approx \delta \) and \( \cos\delta \approx 1 \). The above equations then become:

\[
\delta \approx \frac{XP}{V_1V_2},
\]
\[
V_1 - V_2 \approx \frac{XQ}{V_1}.
\]

(6.6)

The above equations show that the angle \( \delta \) can be controlled by regulating \( P \), whereas the inverter voltage \( V_1 \) is controllable through \( Q \). Control of the frequency dynamically controls the power angle and, thus, the real power flow. Thus, by adjusting \( P \) and \( Q \) independently, frequency and amplitude of the grid
voltage are determined. Hence, the droop characteristics can be written as

\[ f - f_0 = -k_p(P - P_0), \]
\[ V_1 - V_0 = -k_q(Q - Q_0). \]  

(6.7)

\[ f_0 \text{ and } V_0 \text{ are rated frequency and grid voltage respectively, and } P_0 \text{ and } Q_0 \text{ are the set points for active and reactive power of the inverter.} \]

2. Highly resistive lines/cables

Low voltage cable grids usually have mainly resistive line impedances. Ultimately, \( X \) could be neglected instead of \( R \).

\[ \delta \approx -\frac{RQ}{V_1V_2}, \]
\[ V_1 - V_2 \approx \frac{RP}{V_1}. \]  

(6.8)

In this case, adjusting active power \( P \) influences the voltage amplitude, while adjusting reactive power \( Q \) influences the frequency. Hence, the droop characteristics can be written as

\[ f - f_0 = -k_q(Q - Q_0), \]
\[ V_1 - V_0 = -k_p(P - P_0). \]  

(6.9)

3. General case with a specified \( R/X \)

In the general case, both \( X \) and \( R \) are to be considered. Hence, both active power \( P \) and reactive power \( Q \) influence the voltage magnitude and frequency.
An additional linear transformation can be introduced to decouple this relationship.

\[
\begin{bmatrix}
P' \\
Q'
\end{bmatrix} = T \begin{bmatrix}
P \\
Q
\end{bmatrix}
\]  
(6.10)

where 
\[
T = \begin{bmatrix}
sin\theta & -cos\theta \\
cos\theta & sin\theta
\end{bmatrix}
\] \text{ and } = tan^{-1}\left(\frac{X}{R}\right)

Hence,

\[
\begin{bmatrix}
P' \\
Q'
\end{bmatrix} = \begin{bmatrix}
\frac{X}{Z} & \frac{R}{Z} \\
\frac{R}{Z} & \frac{X}{Z}
\end{bmatrix} \begin{bmatrix}
P \\
Q
\end{bmatrix}
\]  
(6.11)

or

\[
P' = \frac{XP - RQ}{Z},
\]
\[
Q' = \frac{RP + XQ}{Z}.
\]  
(6.12)

Hence the decoupled relationship can be maintain as follows

\[
V_2 sin\delta = \frac{ZP'}{V_1},
\]
\[
V_1 - V_2 cos\delta = \frac{ZQ'}{V_1}.
\]  
(6.13)

\(P'\) and \(Q'\) can be determined by knowing the ratio \(R/X\) only; the exact values of \(R\) and \(X\) are not necessarily known. Hence, the general droop characteristics can be written as follows

\[
f - f_0 = -k_p(P' - P^0'),
\]
\[
V_1 - V_0 = -k_q(Q' - Q^0').
\]  
(6.14)
The droop coefficient can be designed as follows [2]:

\[
    k_p = \frac{\Delta \omega}{P_{\text{max}}},
\]

\[
    k_q = \frac{\Delta V}{2Q_{\text{max}}},
\]

(6.15)

where \(\Delta \omega\) and \(\Delta V\) are the maximum frequency and voltage deviation allowed, while \(P_{\text{max}}\) and \(Q_{\text{max}}\) are the maximum active and reactive power delivered by the inverter.

### 6.3 Droop Control for Microgrid Applications

Power transfer inside a microgrid and between microgrid and grid or neighboring microgrid(s) must be managed well in order not to overload any DG or to overcharge/deep discharge any energy storage element. If the communication network is available, the power transfer can be managed by MGCC based on the data received from local measurements. However, the controller must also be designed to anticipate the communication network problem that leads to unavailable control signal from MGCC. In this case, the power transfer must rely on local controller based on local measurement only. Droop based control has been proposed as decentralized control for power sharing among parallel inverters and among DGs inside a microgrid. The conventional droop characteristics as shown in (6.16) is used for \(P - \omega\) and \(Q - V\) control for highly inductive transmission line. However, microgrid is located in distribution system with significant \(R/X\) ratio of distribution line. Hence, \(P - V\)
and $Q - \omega$ control is used instead of $P - \omega$ and $Q - V$ control. To include the effect of both $R$ and $X$, [1] proposed that the conventional droop characteristics in (6.16) can be used by replacing $P$ with $P'$ and $Q$ with $Q'$ obtained from the transformation in (6.17). In order to use this general droop characteristics, $R/X$ ratio must be known in advance.

$$\omega = \omega_0 - k_p (P - P_0);$$

$$V = V_0 - k_q (Q - Q_0).$$

(6.16)

$$P' = \frac{XP - RQ}{Z},$$

$$Q' = \frac{RP + XQ}{Z}.$$  

(6.17)

In this paper, the droop control is used for active power balance inside the microgrid. Hence, only $P - \omega$ or $P' - \omega$ control is considered, while the magnitude voltage is controlled by the external voltage-mode control explained in Section 4.4. The proposed droop control will be derived and explained based on Fig. 6.2. The conventional and generalized droop characteristics discussed above focus on the droop of the $\omega$ of $v_s$ every unit increase of $P_s$ and were derived based on the power transfer in the distribution line, between PCC and grid. Considering that $R_f \ll X_f$, the active power loss inside the filter ($P_f$) can be ignored. Hence, the active power delivered to the distribution line from the PCC can be expressed as (6.18). Therefore, the droop characteristics can be considered based on $P_t$ instead of $P_s$ and the influence of the
distribution line can be ignored. If the droop characteristics is derived by considering the area where $P_t$ flows (or the area between the VSC output and PCC), the power coupling can be ignored since the filter is highly inductive and the conventional droop characteristics in (6.16) can be applied.

$$P_s = P_t; P_f \approx 0.$$  \hspace{1cm} (6.18)

### 6.3.1 Scenario 1: Hybrid PV-Battery has less power than load

Since the PV array operates in maximum power mode and the microgrid is regulated to utilize maximum power from hybrid PV-battery, the conventional droop characteristics in Fig. 6.3 is not suitable. The conventional droop will automatically dictate DGs to share power even though the hybrid PV-battery still have enough power to supply local loads. Instead of direct use of the droop characteristics for
power sharing, this paper proposes the droop characteristics for unbalance power indicator inside the microgrid, indicated by off nominal frequency. Hence this conventional droop characteristics is split into two modified droop characteristics that has a threshold power ($P_0$). To anticipate the shortage power of the hybrid PV-battery, the modified droop characteristics indicated by the term "shortage power" is used. The frequency of the PCC voltage ($v_s$) with this modified droop can be expressed in (6.19). This threshold power can be selected accordingly. In this paper, the PV output power is selected as the threshold power. The main reason for this selection is to keep the frequency constant as long as the PV arrays have enough power to supply the loads. Since the battery is also available to support the PV array in supplying the load, this modified droop characteristics will not be activated until the SOC reached its minimum limit of 40%. When the droop is activated, the frequency will decrease accordingly. Since the frequency is global inside the microgrid, it becomes an indicator for other controllers that the microgrid needs to import power from the grid in grid-connected mode or neighboring microgrid(s) in networked microgrid mode or to turn on the dispatchable DG(S) in islanded mode. In case all of this does not work to stabilize the frequency, the final option is to shade the load(s) gradually.

$$\omega = \begin{cases} 377, & \text{if } P_t \leq P_0 \\ 377 - k_p(P_t - P_0), & \text{if } P_0 < P_t \leq P_{t_{max}} \end{cases}$$

(6.19)
6.3.2 Scenario 2: Hybrid PV-Battery has more power than load

Similar to the shortage power case, the modified droop indicated by the term "extra power" is used for the extra power condition. The main idea is to enable droop when the PV power is more than the load power. The frequency of the PCC voltage \( v_s \) with this modified droop can be expressed in (6.20). Since the battery is also available to store the extra power from PV arrays, this modified droop characteristics will not be activated until the SOC reached its maximum limit of 90%. When the droop is activated, the frequency will increase accordingly. Since the frequency is global inside the microgrid, it becomes an indicator for other controllers that the microgrid is ready to export power to the grid in grid-connected mode or neighboring...
microgrid in networked microgrid mode or to disable the MPPT in islanded mode.

\[ \omega = \begin{cases} 
377 - k_p(P_t - P_0), & \text{if } P_t \leq P_0 \\
377, & \text{if } P_0 < P_t \leq P_{t_{\text{max}}} 
\end{cases} \]  
(6.20)

6.3.3 Scenario 3: Combination of Scenario 1 and Scenario 2

The shortage and extra power conditions may occur interchangeably. The above modified droop characteristics may be combined with a conditional check. The combined modified droop characteristics is shown in Fig. 6.4 and expressed in (6.21). Hence, all off nominal frequency deviations, whether it is frequency decrease or increase, can be used as an off nominal operation indicator for decentralized control.

\[ \omega = \begin{cases} 
377 - k_p(P_t - P_0), & \text{if } P_t \leq P_0 \& SOC \geq SOC_{\text{max}}, \\
or P_t > P_0 \& SOC \leq SOC_{\text{min}}, \\
377, & \text{if } P_t > P_0 \& SOC < SOC_{\text{max}}, \\
or P_t \leq P_0 \& SOC > SOC_{\text{min}}.
\end{cases} \]  
(6.21)
6.3.4 Frequency Restoration

After the droop is activated, the microgrid will work in off nominal frequency. This off nominal operation will continue unless there is a frequency restoration action taken. Since the off nominal frequency operation is activated as an indicator for a power mismatch inside the microgrid, the frequency restoration action is responsible to correct this mismatch. This control function is given to the local controllers of dispatchable DG and MPPT of PV.

If the low off nominal frequency is detected, the local control of the dispatchable DG will generate $P_{DG_{min}}$ to supply the microgrid. If this generated power is more than or equal to the shortage power, the droop will be deactivated and frequency
will return to nominal. If this generated power is less then shortage power, the low
off nominal frequency will persist and the DG will increase its power by a predefined
increment of $\Delta P_{DG}$ as long as the DG maximum capacity ($P_{DGmax}$) has not been
reached.

If the high off nominal frequency is detected, the local control of the DG will
check if the DG still generates power. If this generated power is more than $P_{DGmin}$,
the generated power will decrease until it reaches $P_{DGmin}$. If the high off nominal
frequency is still detected when $P_{DG} = P_{DGmin}$, the DG will be turned off. If the
high off nominal frequency is still detected after the DG turned off, then local MPPT
control which has time delay function will detect this high off nominal frequency and
will deactivate the MPPT algorithm. The new reference voltage for the PV converter
will be generated manually by the MPPT transfer algorithm which is part of the local
control of PV converter. The process to start or stop the dispatchable DG is shown
in Fig. 6.5, while the process to deactivate MPPT of PV is shown in Fig. 6.6.
Fig. 6.5: The process of frequency restoration by utilizing DG.
Fig. 6.6: The process of frequency restoration by deactivating MPPT.
6.4 Power-Balancing Cases

Considering different $SOC$ and power balance, the microgrid can operate in different cases below. The equations related to each cases are summarized in Table 6.1.

1. Case 1: Normal ($SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}}$). In this case, the only source supplying power is the hybrid system so that the generated power ($P_g$) equals the VSC power ($P_t$). Hence, the entire load power ($P_{\text{Load}}$) is supplied by the VSC.

$$P_g = P_t,$$
(6.22)

$$P_{\text{Load}} = P_t.$$

The power mismatch between the PV and the VSC output power is expressed as the battery output power:

$$P_t - P_{PV} = P_{\text{Bat}},$$
(6.23)

where $P_{\text{Bat}}$ is positive when the battery is discharged if the PV power is less than the load power, and negative when the battery is charged if the PV power is more than the load power.

This case is shown in Fig. 6.7. Fig. 6.7.a shows that PV power matches the load power. Hence, the battery SOC will not change since the battery is not charged or discharged. Self-discharge may be ignored because it occurs in a very slow rate. Fig. 6.7.b shows that the PV power is less than the load power so that
the battery must discharge to supply additional power to the load ($P_{Bat} > 0$). Fig. 6.7.c shows that the PV power is more than the load power so that the battery must be charged to store the extra generated power ($P_{Bat} < 0$).

2. Case 2: Deep-discharged ($SOC \leq SOC_{min}$). Before this condition is reached, the following conditions are satisfied:

\[
\begin{align*}
P_{PV} & < P_t, \\
P_{Bat} & > 0,
\end{align*}
\] (6.24)

\[
SOC_{min} \leq SOC \leq SOC_{max}.
\]

Hence, the battery will discharge and $SOC$ will decrease. Normally, $SOC$ will not decrease below $SOC_{min}$, but the time delay as the accumulation of the processing time may cause it to decrease slightly below $SOC_{min}$.

Depending on the DG status whether it is still off or already on, the generated power can be only from the hybrid system or the hybrid system and DG as shown in (6.25). In steady state, the generated and load powers are balanced.
Hence, the load power is also expressed by the same equation. Normally, when $SOC$ is within its minimum and maximum limit, generated power is only from the hybrid system. However, there is a condition when the DG is already on and not yet turned off so that both sources supplying the load. The DG power does not increase to match the power mismatch since the battery has higher priority for matching this mismatch in case of shortage power. Hence, $SOC$ will decrease until it reaches the minimum limit.

$$P_g = P_{\text{Load}} = \begin{cases} P_t, & \text{if the DG is still off,} \\ P_t + P_{DG}, & \text{if the DG is already on.} \end{cases}$$

(6.25)

If the conditions in (6.26) are satisfied, the droop control will be activated and the frequency will decrease. This off nominal frequency will be sensed by the local DG control which orders DG to turn on or increase its output power, depending on the DG status whether it is still off or already on. The detail power balancing process is shown in Figs. 6.8 and 6.9. Fig. 6.8 shows that only hybrid system supplies power before the droop is activated, while Fig. 6.9 shows that both hybrid system and DG supply load(s). Figures (a) show the condition before the droop is activated, figures (b) show the condition after the droop is activated, and figures (c) show the condition after the frequency is restored.

$$P_{PV} < P_t,$$

(6.26)

$$SOC \leq SOC_{\text{min}}.$$
After the frequency is restored, the SOC will increase gradually or stay at its minimum limit. Since the EMS is designed to maximize power utilization from hybrid PV-battery, the supply from DG is only requested if required; the DG should be turned off when it is not required anymore or the power from DG should be decreased if less power is required. However, in order to avoid SOC chattering around $SOC_{\text{min}}$, a lower threshold, $SOC_{\text{thrLow}}$, is required to check whether it is suitable to turn off or decrease the DG power or not. When this threshold is reached, the DG will be turned off if $P_{PV} > P_t$. The DG will continue on until $SOC = SOC_{\text{max}}$ if $P_{PV} \leq P_t$.

3. Case 3: Over-charging ($SOC \geq SOC_{\text{max}}$). Before this condition is reached, the

\[ SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}} \]

\[ SOC = SOC_{\text{min}} \]

\[ SOC_{\text{thrLow}} \leq SOC \leq SOC_{\text{max}} \]

\[ SOC = SOC_{\text{max}} \]

\[ SOC_{\text{thrLow}} \leq SOC \leq SOC_{\text{max}} \]

\[ SOC = SOC_{\text{max}} \]
Fig. 6.9: Power balancing with droop control and frequency restoration for $SOC = SOC_{min}$ and $P_{g-initial} = P_l + P_{DG}$.

Following conditions are satisfied:

$$P_{PV} > P_l,$$

$$P_{Bat} < 0,$$

$$SOC_{min} \leq SOC \leq SOC_{max}.$$

Hence, the battery will be charged and $SOC$ will increase. Normally, $SOC$ will not exceed $SOC_{max}$, but the time delay as the accumulation of the process may cause it to increase slightly beyond $SOC_{max}$. Similar to case 2, the generated power can be only from the hybrid system or the hybrid system and DG.

If the conditions in (6.28) are satisfied, the droop control will be activated and the frequency will increase. This off nominal frequency will be sensed by the local DG control which orders DG to turn off or decrease its output power. The step-by-step power balancing process is shown in Fig. 6.10. Fig. 6.10.a shows the condition before the droop is activated, Fig. 6.10.b shows the condition after
the droop is activated, and Fig. 6.10.c shows the condition after the frequency is restored. The top figures show that DG power is still required after the frequency is restored so that the DG power is only decreased by $\Delta P_{DG}$, while the bottom figures show that the frequency restoration requires DG to be off.

$$P_{PV} > P_t, \quad (6.28)$$

$$SOC \geq SOC_{max}.$$  

After the frequency is restored, the SOC will decrease gradually or stay at its maximum limit. To maximize power utilization from the hybrid system and to avoid SOC chattering around $SOC_{max}$, the DG power will be kept constant until $SOC$ reaches its minimum limit, unless the power balance condition is disturbed by instantaneous change in operating points.

Sometimes, turning off DG still does not restore the frequency as shown in Fig. 6.11.b. Hence, an additional action, deactivating MPPT, is required. This condition can happen if the microgrid is lightly loaded. When MPPT is deactivated, the reference voltage for the PV converter will be decreased so that the PV power will decrease by $\Delta P_{PV}$ as shown in Fig. 6.11.c. As a result, the battery stops charging and $SOC$ will decrease gradually or stay at its maximum. To avoid chattering around $SOC_{max}$ while also trying to generate maximum power from the PV, an upper threshold is introduced. This threshold is similar to the lower threshold in Case 2.
Fig. 6.10: Power balancing with droop control and frequency restoration by decreasing DG power for SOC at maximum limit.

Fig. 6.11: Power balancing with droop control and frequency restoration by deactivating MPPT for SOC at maximum limit.
Table 6.1: Power balancing cases with the droop control

<table>
<thead>
<tr>
<th>Cases</th>
<th>Figure</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
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<tbody>
<tr>
<td>$SOC_{min} \leq SOC \leq SOC_{max}$</td>
<td></td>
<td>$P_g = P_{Load} = P_t$</td>
<td>$P_t = P_{PV} + P_{Bat}$</td>
<td>$P_{Bat} = 0$ $P_{Bat} &lt; 0$ $P_{Bat} &gt; 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_g = P_{Load} = P_t$</td>
<td>$P_t = P_{PV} + P_{Bat}$</td>
<td>$P_{DG} = P_{DG_{min}}$ $P_{Bat} = 0$ $P_{DG} = P_{DG_{min}}$ $P_{Bat} &lt; 0$</td>
</tr>
<tr>
<td>$SOC \leq SOC_{min}$</td>
<td></td>
<td>$P_{DG} = P_{DG1}$ $P_{Bat} &gt; 0$</td>
<td>$P_{DG} = P_{DG1}$ $P_{Bat} \to 0$</td>
<td>$P_{DG} = P_{DG1} + \Delta P_{DG}$ $P_{Bat} = 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{DG} = P_{DG1}$ $P_{Bat} &gt; 0$</td>
<td>$P_{DG} = P_{DG1}$ $P_{Bat} \to 0$</td>
<td>$P_{DG} = P_{DG1} - \Delta P_{DG}$ $P_{Bat} = 0$</td>
</tr>
<tr>
<td>$SOC \geq SOC_{max}$</td>
<td></td>
<td>$P_{PV} = P_{PV1}$ $P_{Bat} &lt; 0$</td>
<td>$P_{PV} = P_{PV1}$ $P_{Bat} \to 0$</td>
<td>$P_{PV} = P_{PV1} + \Delta P_{PV}$ $P_{Bat} = 0$</td>
</tr>
</tbody>
</table>

Fig. 6.7

$P_g = P_{Load} = P_t$
$P_t = P_{PV} + P_{Bat}$
$P_{Bat} = 0$ $P_{Bat} < 0$ $P_{Bat} > 0$

Fig. 6.8

$P_g = P_{Load} = P_t$
$P_t = P_{PV} + P_{Bat}$
$P_{DG} \geq P_{DG_{min}}$
$P_{Bat} > 0$
$P_{Bat} \to 0$
$P_{DG} = P_{DG_{min}}$

Fig. 6.9

$P_g = P_{Load} = P_t + P_{DG}$
$P_t = P_{PV} + P_{Bat}$
$P_{DG} = P_{DG1}$
$P_{Bat} > 0$
$P_{Bat} \to 0$
$P_{DG} = P_{DG1} + \Delta P_{DG}$
$P_{Bat} = 0$

Fig. 6.10

$P_g = P_{Load} = P_t + P_{DG}$
$P_t = P_{PV} + P_{Bat}$
$P_{DG} = P_{DG1}$
$P_{Bat} < 0$
$P_{Bat} \to 0$
$P_{DG} = P_{DG1} - \Delta P_{DG}$
$P_{Bat} = 0$

Fig. 6.11

$P_g = P_{Load} = P_t$
$P_t = P_{PV} + P_{Bat}$
$P_{PV} = P_{PV1}$
$P_{Bat} < 0$
$P_{Bat} \to 0$
$P_{PV} = P_{PV1} + \Delta P_{PV}$
$P_{Bat} = 0$
6.5 Droop Control Implementation

The droop control can be implemented based on the frequency control in Section 4.4. In contrast to the frequency control in which the measured frequency is directly compared to the reference frequency, the droop control generates frequency deviation that will be subtracted from the reference frequency. This frequency deviation is based on the load power. To make sure that the frequency is within the limit, a limiter is added after the deviation is subtracted from the reference frequency. The conventional droop control implementation is shown in Fig. 6.12. This conventional droop control does not implement the proposed droop characteristics. The proposed droop control implementation, including the conditional check to enable or disable the droop, is shown in Fig. 6.13.

Fig. 6.12: Implementation of the conventional droop control.
Fig. 6.13: Implementation of the proposed droop control.
6.6 Simulation Results and Discussions

The comparison between the conventional droop control and the proposed modified droop control is presented in 6.14. For simplicity, in this comparison 50 kW is used the nominal power. The droop coefficient is defined as \( \frac{2\pi}{P_{\text{nominal}}} \). This droop coefficient relates \( \omega \) and \( P_{\text{Load}} \). Hence, for the conventional droop, the microgrid frequency will decrease by 1 Hz for every load power increase by 50 kW. The conventional droop characteristics, however, defines that the nominal frequency only occurs at the nominal power. The simulation result show the droop characteristics precisely. The modified droop characteristics, on the contrary, will depend on the battery SOC. When the upper limit of the battery SOC and the threshold power \( (P_{\text{Load}} \leq P_{\text{nominal}}) \) are reached, the droop control will be activated for the extra power region. Similarly, when the lower limit of the battery SOC and the threshold power \( (P_{\text{Load}} \geq P_{\text{nominal}}) \) are reached, the droop control will be activated for the shortage power region. These both droop regions are presented in the middle and bottom figures of Fig. 6.14.

The above comparison was made simple to show the comparison only. Next, the detail consideration is taken to show how this modified droop control is applied in the microgrid. The main different between this droop control and the simplified one is the adaptive droop characteristics based on the PV power. Since the main factor in the droop design is the availability of PV output power and battery stored energy,
Fig. 6.14: Conventional and modified droop characteristics: (a) conventional droop, (b) modified droop with an extra power case, and (c) modified droop with a shortage power case.
the droop coefficient is defined as $\frac{2\pi}{P_{pv}}$. Due to variability of the PV output power, the measured PV power is used instead of the nominal PV power. The other important thing is how to design the controller of dispatchable DG(s) and MPPT to response to the droop frequency. To avoid chattering after the dispatchable DG(s) is online to supply the shortage power, a hysteresis gap is used to define the range of frequency to turn on/off the dispatchable DG(s). The dispatchable DG or MPPT states just change if the upper or lower hysteresis limit is crossed.

Two scenarios discussed in Section 6.3 are simulated and analyzed. In the first scenario, the hybrid PV-battery has less power than the load. Fig. 6.15(a) shows that PV generates its maximum power of 114 kW. To supply the 150 kW loads, battery will discharge so that the VSC output power matches the load power. However, this discharge will reduce SOC until its lower limit of 0.4 is reached at 5.63 s. As a result, the droop is activated, and the frequency decreases to 59.69 Hz. After the low off-nominal frequency is detected, the DG will generate power and it becomes available after five cycles. Due to the time delay of the DG response, the DG still senses the low frequency after producing 50 kW and increases its power to 60 kW to restore the frequency. After the system reaches the steady state, the microgrid already has extra power of around 25 kW. This power is used to charge the battery indicated by increasing SOC in Fig. 6.15(c) and negative $I_{bat}$ in Fig. 6.16(c). Fig. 6.16(a) shows that $V_{PV}$ tracks $V_{mpp}$ very well. The dc-link is relatively stable at 850 V as shown
in Fig. 6.16(b), while the PCC voltage and VSC output current in Fig. 6.16(d) also confirms that the PCC is regulated well.

In the second scenario, the hybrid PV-battery has more power than the load. Fig. 6.17(a) shows that PV generates its maximum power of 114 kW and DG generates 60 kW, while only 100 kW loads are connected to the microgrid. At around 10 s, the upper limit of SOC, 0.9, is reached as shown in Fig. 6.17(c), while the generated power is still surplus. Hence, the droop is activated and the frequency increases to 60.75 Hz as shown in Fig. 6.17(b). The DG reduces its power to $P_{DGmin} = 50$ kW, but the generated power is still surplus. At 10.4 s, the DG stop supplying the microgrid. However, PV power is still more than the load power. Hence, the MPPT must be deactivated. Fig. 6.18(a) shows that starting at 10.5 s PV voltage ($V_{PV}$) does not track MPPT voltage anymore. Fig. 6.18(c) shows that battery charging current decreases significantly and gradually crosses zero and then switches to discharging mode. During all this process, the dc-link voltage is relatively constant at around 850 V. The PCC voltage is also relatively constant with the peak value of 391.92 V. The output current of the hybrid PV-battery also confirms that the system is stable.

Finally, the simulations are conducted to compare between a system with the proposed droop and without the proposed droop. The simulation results of the system with the proposed droop control are shown in Fig. 6.19, while the simulation results of the system without the proposed droop control are shown in Fig. 6.20. Since the
Fig. 6.15: Power, frequency, and SOC when hybrid PV-battery has less power than the load.

Fig. 6.16: Voltages and currents of the converters when hybrid PV-battery has less power than the load.
Fig. 6.17: Power, frequency, and SOC when hybrid PV-battery has more power than the load.

Fig. 6.18: Voltages and currents of the converters when hybrid PV-battery has more power than the load.
SOC is within the minimum and maximum limit, the proposed droop control disable the droop and continue working in nominal frequency. The battery will discharge to supply power mismatch. The dispatchable DG will not be turned on. Hence, all power is from renewable and free power sources.

In contrast, Fig. 6.20 shows the microgrid operates in off nominal frequency even though the SOC is within its minimum and maximum limit. Hence, the dispatchable DG is turned on. The load is supplied by both the hybrid PV-battery and DG. Nonrenewable and not-free power source is turned on even though the hybrid PV-battery is still able to supply the load.
6.7 Summary

In this chapter, droop characteristics for microgrid application has been derived. The proposed droop is a modification of the conventional droop by considering PV power and battery SOC. Instead of merely for power sharing between parallel DGs, the proposed droop is used as an indicator that power mismatch occurs inside the microgrid. In order to request power support form dispatchable DG(s) or power decrease from MPPT or already committed DG(s), an off nominal frequency operation is used. This off nominal frequency can convey the message about power mismatch in case of communication network failure.
6.8 References


CHAPTER 7. ENERGY MANAGEMENT SYSTEM

7.1 Introduction

This chapter discusses about energy management system (EMS), the proposed system level control. For a single microgrid, microgrid central controller (MGCC) is responsible for this energy management and assumes the highest priority in the hierarchical control. If two or more microgrids form a networked microgrid system, a networked microgrid central controller (NMGCC) assumes this highest hierarchy and coordinates with MGCCs of all networked microgrids. The proposed control and EMS architecture are verified using for economic and resilient operation.

7.2 Energy Management Architecture

The controller discussed in the previous chapters work in short time frame, around micro seconds to seconds. It deals with voltage and frequency control as well as fast power balancing based on local measurement. For longer time-frame, such as in minutes, and on system level, an energy management is responsible to make sure
that critical loads are supplied in all possible conditions and power/energy is utilized optimally by managing power transfer with other DGs, feeder(s), grid, or neighboring microgrid(s). The complete description about energy management time frame based on [1] can be seen in Fig. 7.1.

The proposed control has hierarchical structure with microgrid central controller (MGCC) in the highest hierarchy for each microgrid. When operates in islanded mode, MGCC will receive important data/information from lower level controls, process these data, and send request/order to the lower level control(s) to change the set point of the respective controller(s). In grid-connected mode, MGCC will communicate with distribution management system of the grid’s distribution system to initiate power transfer between grid and microgrid. If both parties agree, MGCC will send the request/order to tie-line converter to change the set point of the tie-line converter. For a networked microgrid system, another layer, networked microgrid central controller (NMGCC) is added. This layer will interact with MGCC, DMS, and tie-line control as shown in Fig. 7.2.
Fig. 7.1: Energy management time-frame.
Fig. 7.2: Control architecture of a networked microgrid system.
7.3 Energy Management for Power Balancing

The proposed energy management is a modification of the energy management in [2]. The main objective of the energy management is to maintain power balancing inside the microgrid while maximizing the power utilization from renewable energy sources, hybrid PV-battery. The main governing factor for the energy management is the battery SOC and mismatch between the PV power \( P_{PV} \) and the VSC output power \( P_t \).

7.3.1 Islanded Microgrid

In islanded mode, the generated power inside the microgrid comes from the following:

1. the VSC output power \( P_t \) that is originally from the renewable and free hybrid PV-battery power, and

2. the DG output power \( P_{DG} \).

\[
P_g = P_t + P_{DG}. \tag{7.1}
\]

The VSC output power \( P_t \) can be expressed as:

\[
P_t = P_{PV} \pm P_{Bat}. \tag{7.2}
\]
where the $P_{Bat}$ sign is positive when the battery is discharged and negative when the battery is charged.

Considering that generation cost of the hybrid PV-battery is free of charge, the only generation cost in the islanded microgrid is of DG power:

$$C(P_g) = C(P_{DG}).$$ \hspace{1cm} (7.3)

Hence, the cost can be minimize if the DG generation cost is minimum. For each bus $i$ where generator is located, the DG generation cost is expressed by a quadratic function given in (7.4). The rate of change of the generation cost with respect to $P_{DG}$ is expressed by (7.5). Since it is a linear function, the minimum cost will be reached when $P_{DG} = 0kW$. Hence, the energy management will just request power from DG when it is required.

$$C(P_{DGi}) = aP_{DGi}^2 + bP_{DGi} + c.$$ \hspace{1cm} (7.4)

$$\frac{dC(P_{DGi})}{d(P_{DGi})} = 2aP_{DGi} + b.$$ \hspace{1cm} (7.5)

The microgrid power-balance conditions depends on the state of charge of the battery and balancing between the VSC output power ($P_t$) and PV power ($P_{PV}$). Hence, the power-balance can be classified into the cases below. The equations for each cases are the same as the equations for cases in Chapter 6 and presented again in Table 7.1.
In an islanded mode, whenever the SOC reaches its minimum limit of 40%, MGCC will request dispatchable DG to supply power to the local loads. If the required power is less than $P_{DG_{min}}$, the DG will generate power at its minimum limit ($P_{DG_{min}}$). Hence, PV will operate in maximum power mode, while DG will operate in constant power mode. The extra power supplied by the DG will force VSC to reduce its output and provide more power to charge the battery. If the required power is more than $P_{DG_{min}}$, the DG will generate the required power. This operation will continue until the SOC reaches 60% when MGCC will check whether $P_{PV} \geq P_t$. If $P_{PV} \geq P_t$, MGCC will request the DG to stop supplying power. If SOC still decreases from its 40% limit even though the DG already reaches its rating, a load shedding is required.

If SOC reaches its maximum limit of 90%, in islanded mode, the MPPT algorithm will be disable and the reference voltage will decrease so that PV can generate less power. All this process can be seen in Fig. 7.8.

1. Case 1: Normal ($SOC_{min} \leq SOC \leq SOC_{max}$). In this case, the entire load power is supplied by the VSC:

\[ P_g = P_t, \]

\[ P_{Load} = P_t. \]  

(7.6)

(7.7)

The power mismatch between the PV and the VSC output power is expressed as the battery output power:

\[ P_t - P_{PV} = P_{Bat}, \]
where $P_{Bat}$ is positive when the battery is discharged if the PV power is less than the load power, and negative when the battery is charged if the PV power is more than the load power. Since $SOC$ is between its minimum and maximum limit, MGCC is not required for power balancing.

This case is shown in Fig. 7.3. Fig. 7.3.a shows that PV power matches the load power. Hence, the battery SOC will not change since the battery is not charged or discharged. Self-discharge may be ignored because it occurs in a very slow rate. Fig. 7.3.b shows that the PV power is less than the load power so that the battery must discharge to supply additional power to the load ($P_{Bat} > 0$). Fig. 7.3.c shows that the PV power is more than the load power so that the battery must be charged to store the extra generated power ($P_{Bat} < 0$).

2. Case 2: Deep-discharged ($SOC \leq SOC_{min}$). This case is similar to the same case in the droop control in Chapter 6. The only different is the droop control is disable for this case since MGCC is available to manage the microgrid. The
Fig. 7.4: Power balancing for SOC at minimum limit, $P_{g-initial} = P_l$.

Fig. 7.5: Power balancing for SOC at minimum limit, $P_{g-initial} = P_l + P_{DG}$.

power balancing process is given in Figs. 7.4 and 7.5.

3. Case 3: Over-charging ($SOC \geq SOC_{max}$). Similar to the previous case, this case is also based on the same case in Chapter 6. The droop control is disable and MGCC is responsible to manage the microgrid. The power balancing process is given in Fig. 7.6. If SOC continues increasing after the DG is turned off, the MPPT control must be deactivated as shown in Fig. 7.7.
Fig. 7.6: Power balancing for SOC at maximum limit by decreasing $P_{DG}$.

Fig. 7.7: Power balancing for SOC at maximum limit by deactivating MPPT.
Fig. 7.8: Energy management of an islanded microgrid.
Table 7.1: Power balancing cases without the droop control

<table>
<thead>
<tr>
<th>Cases</th>
<th>Figure</th>
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<tbody>
<tr>
<td>$SOC_{min} \leq SOC \leq SOC_{max}$</td>
<td></td>
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<tr>
<td>Fig. 7.3</td>
<td>$P_g = P_{Load} = P_t$</td>
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<tr>
<td></td>
<td>$P_t = P_{PV} + P_{Bat}$</td>
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<tr>
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<tr>
<td>Fig. 7.4</td>
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<td>$P_{Bat} \rightarrow 0$</td>
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<tr>
<td></td>
<td>$P_{DG} \geq P_{DG_{min}}$</td>
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<td></td>
<td>$P_{Bat} = 0$</td>
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<tr>
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<tr>
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<td>$P_{Bat} &lt; 0$</td>
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<tr>
<td>$SOC \leq SOC_{min}$</td>
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<td>Fig. 7.5</td>
<td>$P_g = P_{Load} = P_t + P_{DG}$</td>
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<td>$P_t = P_{PV} + P_{Bat}$</td>
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<td>$P_{Bat} \rightarrow 0$</td>
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<td>$P_{DG} = P_{DG1} + \Delta P_{DG}$</td>
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<tr>
<td>$SOC \geq SOC_{max}$</td>
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<td>Fig. 7.6</td>
<td>$P_g = P_{Load} = P_t + P_{DG}$</td>
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<td></td>
<td>$P_t = P_{PV} + P_{Bat}$</td>
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<td></td>
<td>$P_{Bat} \rightarrow 0$</td>
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<tr>
<td></td>
<td>$\Delta P_{DG} &lt; P_{DG1}$</td>
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<tr>
<td></td>
<td>$P_{Bat} = 0$</td>
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<td>$SOC \geq SOC_{max}$</td>
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<tr>
<td>Fig. 7.7</td>
<td>$P_g = P_{Load} = P_t$</td>
</tr>
<tr>
<td></td>
<td>$P_t = P_{PV} + P_{Bat}$</td>
</tr>
<tr>
<td></td>
<td>$P_{PV} = P_{PV1}$</td>
</tr>
<tr>
<td></td>
<td>$P_{Bat} &lt; 0$</td>
</tr>
<tr>
<td></td>
<td>$P_{Bat} \rightarrow 0$</td>
</tr>
<tr>
<td></td>
<td>$P_{PV} = P_{PV1} + \Delta P_{PV}$</td>
</tr>
<tr>
<td></td>
<td>$P_{Bat} = 0$</td>
</tr>
</tbody>
</table>
7.3.2 Grid-Connected Microgrid

For a grid-connected microgrid, the same process as the islanded microgrid is applied. The main difference between the islanded microgrid and the grid-connected microgrid is the grid-connected microgrid has a connection to the grid that allows power exchange between the microgrid and the grid. Hence, the possibility to import/export power from/to the grid must be included in the generated power equation.

\[ P_g = P_t + P_{DG} \pm P_{tie}. \]  \hspace{1cm} (7.8)

where \( P_{tie} \) is the power transferred between the microgrid and the grid through the tie-line converter. \( P_{tie} \) sign is positive if the power is imported from the grid, and negative if the power is exported to the grid.

Similar to the DG power, the cost generation of the grid power also a quadratic function. The only difference between these two cost functions is the coefficient. Hence, the rate of change of the grid generation cost is also a linear function. Consequently, the minimum cost will be obtained if \( P_{DG} = 0 kW \) and \( P_{tie} = 0 kW \). If the following conditions is reached:

\[ P_{PV} \leq P_t, \]  \hspace{1cm} (7.9)
\[ SOC \leq SOC_{min}, \]

additional power is required. To decide whether to import power from the grid or to turn on the DG, an economic analysis is run and the result is executed by MGCC.
In grid-connected operation, whenever the SOC reaches its minimum limit of 40%, an optimization algorithm will decide whether to import power from the grid or to turn on the dispatchable DG(s). If it is decided to import power from the grid, minimum and maximum power transfer limit is applied. If the requested power is less than the maximum power transfer limit of $P_{\text{tie-min}}$, the microgrid will import constant power of $P_{\text{tie-min}}$ from the grid. If the required power is more than $P_{\text{tie-min}}$, the imported power can be flexible between the minimum and maximum limit. This operation will continue until the SOC reaches 60% when the microgrid will check whether the PV power is enough to supply the microgrid so that the import power from the grid can be stopped. If SOC still decreases from its 40% limit even though the maximum power transfer limit is reached, the dispatchable DG(s) will be supplying at $P_{DG_{\text{min}}}$ and will increase up to its maximum capacity if needed. If it is decided to turn on the dispatchable DG(s) without importing power from the grid, the same procedures as the islanded mode will apply. Furthermore, the power transfer from the grid will also be requested if the thermal DG reaches its maximum capacity, while the SOC still decreases. The procedures continue to load shedding if required. The grid connected process is shown in Fig. 7.9. The EMS also has additional processes: Turn-on DG, Buy from Grid, and Sell to Grid. Theses additional processes are shown is Figs. 7.10, 7.11, and 7.12. The Buy From Grid process is very similar to Sell To Grid process. The main different is the set point for Buy From Grid is positive, while
the set point of Sell To Grid is negative. In grid connected mode, the extra power will be sent to the grid if DMS agrees. However, the power transfer between grid and microgrid must be in the range of minimum and maximum limit, $P_{tie-min}$ and $P_{tie-max}$. 
Fig. 7.9: Energy management of a grid-connected microgrid.
Fig. 7.10: Process of starting a DG in grid-connected operation.

Fig. 7.11: Process of importing power from grid in grid-connected operation.
Fig. 7.12: Process of exporting power to grid in grid-connected operation.

7.3.3 Networked Microgrid

The networked microgrid system is shown in Fig. 7.13. A networked microgrid central controller (NMGCC) is responsible to manage the networked microgrid system. Hence, MGCCs of the connected microgrids are responsible to send important information of each microgrid, such as SOC, $P_{PV}$, $P_t$, and $P_{DG}$. This information will be processed in NMGCC to output new set points of each DG and tie-line converter. Before sending important information to NMGCC, each MGCC is responsible to check whether its microgrid has connection to another microgrid or not. The energy management and control architecture for a networked microgrid system is shown in Fig. 7.2.
Fig. 7.13: Networked microgrid architecture


7.4 Economic Operation

The main objective of the system is to minimize the cost of power generation. This formulation considers generation from dispatchable DG(s) as well as import power from the grid through tie-line converter. The objective function can be presented as:

\[
\min \left( \sum_{k=1}^{N} C(P_{DGk}) + C(P_{tie}) \right).
\]  

(7.10)

where \( C(P_{DG}) \) is a quadratic function for generation real power output. For each bus \( i \) if the generator is connected, the cost function can be written as (7.11). The considerations in Section 7.3 are also applied is this economic operation.

\[
C(P_{DGi}) = aP_{DGi}^2 + bP_{DGi} + c.
\]  

(7.11)

The three-phase current injection method (TCIM)-based optimal power flow (OPM) [3] is used to calculate the economic and technical solution for the system. The TCIM is utilized in this OPF formulation as it applies some significant advantages to using a conventional power flow computation. TCIM OPF is applicable to three-phase balance and unbalanced systems. Since it uses rectangular coordinates instead of polar, it can achieve better convergence for distribution systems. This TCIM provides accurate results for both radial and mesh network architectures. The optimization
results for economic operation is executed by the rule based energy management as shown in Fig. 7.9 to decide the action whether to buy turn of dispatchable DG or to import from grid.

7.5 Resilient Operation

In case of emergency, such as wind storm, intentional attack, etc., the microgrid or networked microgrid system must be able to supply critical load(s). In order to guarantee this continuous supply, the critical load(s) must always have connection to the renewable DG, dispatchable DG, or the grid [4]. The resilient operation does not consider economic operation unless the critical load(s) can be supplied by more than one source or through more than one path. In this case, the economic operation as discussed above will be applied. The resiliency algorithm is shown in In order to find resilient solution to the system, the following processes are applied:

1. graph representation. The system network is represented by a graph that uses edge and vertex to represent, line and bus respectively.

2. path finding. After the graph representation is complete, a search algorithm is used to find all valid path connecting between the critical load(s) and source(s).

3. economic operation is run if there are more than one path connecting between the critical load(s) and the source(s) or there are more than one source available
to supply the critical load(s).

4. the solution is verified by conducting simulation to make sure that all technical requirement is fulfilled

The following factors are considered in this work for computing the resiliency of the microgrid:

1. Edge count: This is represented as the ratio of total number of connected edges for each path in a possible configuration to the number of critical loads.

2. Overlapping Edges: It is the total number of common closed edges in each path for the reconfigured system.

3. Switching operations: It is the total number of switching operations required to create the reconfigured network.

4. Path Redundancy: This is the total number of paths available to supply the critical load.

5. Probability of availability: This factor considers the probability of supplying the critical load from different sources. For this system, the PV system is assigned a probability of 0.8, the grid is assigned a probability of 0.9, while the gas unit is assigned a probability of 0.95, and the aux generator is assigned a probability of 1.
6. Penalty factor: This factor imposes a penalty on different sources based on availability and cost of operation. The auxiliary diesel generator has the highest penalty factor of 1, while the PV has the least penalty factor of 0.5. The penalty factors for the grid and the gas unit are 0.8 and 0.9 respectively.

**Fig. 7.14:** The algorithm to determine the resiliency of the network.
7.6 Simulation Results

7.6.1 Case study 1: Islanded Microgrid

The islanded microgrid simulation results is shown in Fig. 7.15. The simulation is used to verify control action taken if the generated power from hybrid PV-battery is less than the microgrid load. Since there is no connection to external network, including the main grid, the only option is turning on the dispatchable DG. Consequently, economic operation is not an option in this case. The simulation results show that the lower limit of SOC is reached at 0.75 s and the dispatchable DG is ready to supply power of $P_{DGmin} = 50\text{kW}$ at 0.85 s. The phase-a PCC voltage show that the system voltage is stable.

7.6.2 Case study 2: Grid-Connected Microgrid

The grid-connected operation is simulated to show the control action taken when the microgrid has less generated power than the load and at the same time has two options to buy from the grid or to turn on the dispatchable DG. Based on an offline optimization algorithm, the MGCC decides to buy power from the grid. The decision also considers the generating limit of DG and the transfer limit of tie-line converter.
Fig. 7.15: Islanded microgrid responses: (a) active power; (b) SOC; (c) phase-a PCC voltage
Due to the power mismatch inside the microgrid, the lower limit of SOC is reached at 1 s. MGCC send the new set point to the tie-line controller. Hence the tie-line converter orders the requested power from the grid based on this new set point. The microgrid receive the transfer power of $P_{tie-min} = 60kW$. This power transfer is more than the shortage power inside the microgrid. Hence, the extra power is used to force the VSC to decrease its output power and provide more power to charge the batter. As a results, SOC increases gradually.
7.6.3 Networked Microgrids

The following simulation results show a fault occurs on the main feeder from the main grid. Hence, the networked microgrids are isolated from the main grid. Then, microgrid 1 load increases beyond its available power generation. At the same time, microgrid 2 has low load and high reserved generation power. Hence, microgrid 1 requests power from microgrid 2. Microgrid 1 responses for this load increase and power import from microgrid 2 are shown in Fig. 7.17. Microgrid 2 responses for this power export to microgrid 1 are shown in Fig. 7.18.
Fig. 7.17: MG-1 responses for load increases beyond generation
Fig. 7.18: MG-2 responses for sending power to MG-1
7.7 Summary

The developed energy management system is based on hierarchical control. The system level controls, or EMS, interact with the lower level control to receive important information and to change the set points of these controllers. For individual microgrid, MGCC is responsible to run energy management. In a networked microgrid system, a higher level control, NMGCC, is added to communicate with all MGCCs of participating microgrids. Economic and resiliency analyses are conducted to verify that the proposed control accommodates economic and resilient operation.
7.9 References


8.1 Introduction

This chapter concludes the dissertation and provides contributions of this research work and also discusses future work. The goal of this dissertation is to design an energy management and multi-layer control of networked microgrid for all possible operation modes and to have seamless transition from one mode to another.

8.2 Conclusions and contributions

In order to design the energy management and control, a good understanding of the system and its component is very important. The design process has been conducted step-by-step by increasing complexity from the control design for a dc-dc converter, a single VSC, an islanded microgrid, a synchronously grid-connected microgrid, an asynchronously grid-connected microgrid, to a networked microgrid system. The design of energy management and multi-layer control for networked microgrids has been addressed in detail.

Following contributions have been made in this dissertation work:
1. Proposed a novel multi-layer control architecture that works in wide range of operating points, based on large signal model. Inner layer is designed for current, voltage and frequency control while outer layer is designed for secondary frequency control and power exchange control. To compensate for operating point changes, such as variability of the renewable sources, large-signal model is used to design the controller. The feedforward measured system response augments the linear PI control to compensate for the nonlinear characteristics of the system. The dq-based control that works in constant trajectory and can decouple control variables to create a SISO system from a MIMO system is used for voltage source converter (VSC) control. The simulations for large load changes show that current reaches steady state in one cycle and voltage reaches steady state in two cycles. These big load changes do not cause significant overshoot to voltage due to well-designed control. Control architecture utilizing different type of converters:

- two leg dc-dc converter that represents two converters:
  - uni-directional dc-dc boost converter that controls maximum power generation from PV arrays,
  - bidirectional dc-dc buck-boost converter for battery that controls dc-link voltage.
• a voltage source converter (VSC) for PCC voltage control that is responsible to regulate voltage magnitude and frequency of the microgrid,
• a pair of back-to-back converter that controls power interchange between grid and microgrid or neighboring microgrids as well as dc-link voltage of the back-to-back converter.

2. Proposed back-to-back converter to integrate non-utility microgrids to enable controlled power transfer with the grid to minimize the uncertainty at DMS. A networked microgrid concept is proposed to enable power interchange between grid and non-utility microgrids as well as among neighboring microgrids with controlled power transfer. The connection through tie-line converter is used based on the understanding that in the future the number of private owned microgrids will increase, that the utility grid does not have full access to control directly or indirectly using microgrid energy management system.

3. Proposed a new modified droop based control for decentralized power sharing inside the microgrid which supports maximum power point operation of renewable DG in case of communication network failure. This modified droop based control is used in slightly different way compared to conventional droop for power sharing. The droop will be activated adaptively based on the mismatch between power generated by the hybrid PV-battery and PV power as well as
the state of the charge of the battery. When activated, the droop is used to indicate power mismatch through off-nominal frequency as a global variable without the need of communication network. Frequency restoration algorithm is also proposed. The secondary control for frequency restoration algorithm in the dispatchable DG local controller and MPPT local controller for PV will act to restore the frequency. The frequency restoration algorithm is distributed and acts depending on the local controller. In the developed control algorithms, the droop control does not need to have prior knowledge about the impedance of distribution line. Simulation results show that the frequency deviation when the droop is activated is around 0.5% or 0.3 Hz. Depending on the time response of the dispatchable DG and additional time delay given to the dispatchable DG and MPPT algorithm, the frequency can be restored within 5 cycles. The droop activation and the frequency restoration action cause minimal impact on the voltage magnitude.

4. Developed a multiple-mode microgrid energy management architecture for economic or resilient operation that works with multi-layer centralized control. The proposed energy management has multiple modes for economic or resilient operation at system level. The energy management is decentralized inside the microgrid based on rule-based algorithm. The system level control is designed to require minimum number of data from local controllers. MGCC as the central
controller does not know and does not need to know the detail of local system. However, it receives summary of the respective subsystem from the local control. This minimum information will be enough to manage power balance inside the microgrid. A simulation also shows that the energy management can be used to regulate the microgrid in emergency conditions after reconfiguration algorithm.

8.3 Future Work

This research will open great opportunity for future works. An immediate future work will be developing an optimization algorithm for the energy management since the current energy management is a rule-based algorithm. Next, hardware in the loop will be an important future work to test the algorithm in real-time with RSCAD/RTDS. Control techniques should be extended without battery energy systems and how other kind of storage or no storage will be integrated into developed control architecture. Research work can be further extended for more complex and larger system.
8.4 Summary

In this dissertation, energy management and multi-layer control for networked microgrid was designed. Within this chapter, conclusion and contribution of this research are provided. Furthermore, the possible future work in continuum with this research are suggested.