Phasor Measurement Unit Enabled Power Dispatch and Autonomous Black Start of AC Microgrids

by

Amrit Singh

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
The Edward S. Rogers Sr. Department of Electrical and Computer Engineering
University of Toronto

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Abstract
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The aim of this thesis is to develop a mathematical model and control for black start and power dispatch of AC microgrids powered by converter interfaced distributed energy resources (DERs). This utilizes the development of microgrid controls in an asynchronous reference frame to maintain the operation of local current mode control regardless of synchronization of $dq$-frame across dispersed DERs. The viability of using Phasor Measurement Units (PMUs) to leverage the capabilities of existing and upcoming microgrids to provide grid support is also evaluated. This thesis develops controls for operation of DER-fed AC microgrids in both islanded and grid connected modes. A power dispatch mechanism is proposed to either supply local loads using PMU values to calculate load demand, or provide dispatchable power, when in grid connected mode. In doing so, this thesis establishes a microgrid that can both energize and operate autonomously while also providing network support when grid connected.
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Chapter 1

Introduction

1.1 Literature Review

The advent of renewable energy gave birth to the vision of “Green Grid” due to its ability to displace significant greenhouse gas emissions enabled by leveraging the smart grid infrastructure. Smart grids, as defined by North American Electric Reliability Corporation (NERC), are the “integration of real-time monitoring, advanced sensing, and communications, utilizing analytics and control, enabling the dynamic flow of both energy and information to accommodate existing and new forms of supply, delivery, and use in a secure and reliable electric power system, from generation source to end-user” [1].

As shown in Fig. 1.1, the main components of a smart grid are:
Chapter 1. Introduction

1. Intelligent Electronic Devices (IEDs): An integration of processor and communication capability used to control power system devices such as circuit breakers, relays etc.

2. Smart Meters: Energy meters using bidirectional communication between the utility and household for improved billing and accurate contingency detection.

3. Automated Substations: Supervisory control, monitoring and data acquisition using information gathered through effective communication schemes.

4. Optimizable Generation: The ability to optimize the generation to maintain grid frequency and voltage level on the basis of feedback from multiple nodes in the grid.

5. Self-optimizable Distribution: Self repairing distribution networks with the capability of separating/bypassing fault ridden regions in the grid to maintain continual power flow.

This thesis expands on the application of IEDs to distribution level networks to advance the capabilities of power system control and venture into the areas of optimizable generation and self optimizable distribution.

1.1.1 IEDs: A Microgrid Prospective

As stated above, IEDs are the integration of processors and communication. They are used to control, monitor, analyze power system operation with enhanced capabilities. Increasing complexity of distributed networks impacts the ability of the system to remain quasi-stationary [2]. Hence, [2], [3], suggest the significance of IEDs in applications in distribution level networks. The literature suggests that the information received from IEDs placed at multiple locations in the grid is used for the following applications:


The IED considered for this thesis is a Phasor Measurement Unit (PMU)-enabled protection relay. PMUs have been used for monitoring and support applications in power
systems. This thesis focuses on the application of phasor measurements to support microgrid operation. Due to their ability to communicate phasor information at higher baud rate, they provide an edge to control strategies and mode transfers. In the scope of this thesis, PMUs are placed upstream from the microgrid to monitor events and report to central control as depicted in Fig. 1.2. Phasor values transmitted by the PMU are used to predict the state of the microgrid operation (islanded or grid connected). The fast reporting rate of the PMU is leveraged to update the control strategies on the basis of changing operation mode in a microgrid to provide an autonomous smart microgrid.

Another application of interest is the mitigation of line and generator outages in the transmission network leveraging the support of smart grids formulated in this thesis. The agility of PMU operation allows the detection of any abnormal operation upstream, which can be leveraged to provide necessary grid support from the microgrid. This work will explore the application of PMU values for the above discussed operation and providing necessary grid support.

### 1.1.2 Review of Phasor Measurement Units (PMUs)

A Phasor Measurement Unit (PMU) is a device that measures electrical quantities along the grid and produces synchrophasor output(s) that are synchronized to the Coordinated Universal Time (UTC). A common sinusoidal signal representation is given by (1.1):

\[ x(t) = X_m \cos(\omega t + \delta) \]  

(1.1)
This is commonly represented as a phasor given by (1.2):

\[ X = \left( \frac{X_m}{\sqrt{2}} \right) e^{j\delta} \]  

(1.2)

Where, the magnitude of \( X_m \) is the rms value of \( x(t) \) and \( \delta \) is the offset at nominal system frequency synchronized to UTC. The schematic representation of (1.1) and (1.2) is given in Fig. 1.3(a) and 1.3(b) respectively. The output of a PMU is also known as a synchrophasor.

A generic PMU model is based upon the configuration in Fig. 1.4. The PMU inputs are the three phase voltages and currents at the location of its placement in the network. The input quantities pass through an anti-aliasing filter whose cut-off frequency is derived from the sampling rate chosen for the sampling process. In most practical cases, the value of cut-off frequency is set to half of the sampling rate to comply with the Nyquist criterion [20]. This step is followed by sampling of the outputs of the anti-aliasing filter at a specified sampling rate. This process takes place assuming that the sampling is synchronized to an absolute time reference (i.e. UTC in practical situations).

The sampling process is followed by complex demodulation which involves the multiplication of the input by a quadrature oscillator which gives sine and cosine terms separately. This is mathematically represented in (1.3) and (1.4), where the synchrophasor \( X \) of given signal \( x(t) \) at the \( m^{th} \) sample time is given as [21]:

\[ X(m) = \left( \frac{\sqrt{2}}{G_n} \right) \sum_{k=-N/2}^{N/2} x(m+k)W(k) \exp(-j(m+k)\Delta t\omega_0) \]  

(1.3)
Chapter 1. Introduction

\[ G_n = \sum_{k=-N/2}^{N/2} W(k) \]  

(1.4)

Where:
- \( W(k) \) - Low-pass Filter Coefficient
- \( N \) - FIR Filter Order
- \( \Delta t \) - \( 1/f_s \)
- \( f_s \) - Sampling Frequency
- \( x(m) \) - Sample of Waveform at time \( t = i\Delta t \)
- \( \omega_0 \) - \( 2\pi f_0 \)
- \( f_0 \) - Nominal Frequency (50 or 60 Hz)
- \( G_n \) - Low-pass Filter (Performance based on P or M class) Gain

The value of low-pass filter coefficients is selected on the basis of class of operation (i.e. P or M class) as given by (A.1) and (A.2) in Appendix A.2.

1.1.3 Phasor Data Concentrator (PDC) Architecture

A Phasor Data Concentrator (PDC) is a device that receives and processes synchrophasors from one or multiple Phasor Measurement Units (PMU). The PDC time synchronizes the PMU data received and produces a time aligned data stream as an output. The job of a PDC is to receive data from PMU, process it, reject bad data streams, and store the rest. The output of this device can either be utilized to assess a power system contingency or to be archived for diagnostic purposes.

PMUs are installed at substations in a power system. The location for placement of PMUs is selected on the basis of application(s) of the information provided by the device. [22] optimizes the PMU location selection algorithm to maximize the minimum distance among the set of outage signatures where the application of PMU values is for

Figure 1.4: Schematic of PMU Model
detecting line outages in wide-area transmission networks.

In Fig. 1.5 multiple PMUs are placed along the network and a single PDC exists at node 5 in an IEEE 14-bus test feeder system. PMUs measure voltage and current phasors and calculate frequency, rate of change of frequency (ROCOF), real and reactive power and store them in a local storage with exhaustable capacity. Data flagged important for the power system is stored permanently. The data collected by all PMUs is then transmitted to the PDC, situated at bus 5, through a bi-directional communication link. The data is available from local PMUs in real time for diagnostic purposes, but in most applications this data is transferred to a PDC to be further used for analysis. In a larger system, there can be a possibility of multiple PDCs and they are arranged in a hierarchical order. Hierarchy allows the data to be transferred from multiple PDCs to a master PDC where it can be analyzed.
1.1.4 PMU Standards

The scope of a common standard for PMUs was realized due to need for compatibility of PMUs developed by different manufacturers. The standards on PMUs can be split into two groups: (i) phasor measurement, and (ii) data transfer.

Phasor Measurement

The first synchrophasor standard, IEEE Std. 1344 [23] defined parameters and introduced inter-range instrumentation group-B (IRIG-B) time code for transferring timing information for synchronization purposes. This standard was superseded by IEEE Std. C37.118.1 [21] in 2011. It describes time tag and synchronization requirements for the measurement of electrical quantities and methods to evaluate these measurements under both static and dynamic conditions. It also describes the calculation mechanism used by synchrophasors and design of components of PMUs including the class of operation of the device on the following basis:

1. P Class - P stands for protection applications requiring fast response. It is intended for applications involving fast response and mandates no explicit filtering.

2. M Class - M stands for measurement applications requiring precise signals. It is intended for applications involving greater accuracy and low latency.

The concept of measurement evaluation is enforced by introducing the term called total vector error (TVE) which is defined as the difference between the theoretical and practical PMU value estimate given as [21]:

\[
TVE(m) = \sqrt{(\hat{X}_r(m) - X_r(m))^2 + (\hat{X}_j(m) - X_j(m))^2} \over X_r^2(m) + X_j^2(m)
\]  \hspace{1cm} (1.5)

Where:
\[\hat{X}_r(m)\text{ and } \hat{X}_j(m)\] - Actual values given by equipment under test (EUT)
\[X_r(m)\text{ and } X_j(m)\] - Estimated values at an instant of time

The error in the values of frequency and ROCOF are given by frequency error (FE):

\[FE = |f_{true} - f_{measured}|\]  \hspace{1cm} (1.6)

Furthermore, this standard states reporting rates for the transmission of synchrophasor estimates. Multiple reporting rates were suggested and compliance of a PMU to those values was proposed as stated in Table 1.1 and the latency of PMUs on the basis of their class of operation is as stated in Table A.3. This standard also specifies
Table 1.1: Required PMU Reporting Rates [21]

<table>
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<th>System Frequency</th>
<th>Reporting Rates ($F_s$ - Frames per second)</th>
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<tbody>
<tr>
<td>50 Hz</td>
<td>15/25/50</td>
</tr>
<tr>
<td>60 Hz</td>
<td>10/12/15/20/30/60</td>
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conditions and values to conduct compliance testing under steady state and dynamic conditions. Some amendments were made to the measurement time synchronization and performance requirement parameters of steady state and dynamic compliance tests in IEEE Std. C37.118.1a [24].

Data Transfer

A vital feature of PMUs is the ability to communicate the phasor values calculated at a remote location and transfer it to a PDC. Data transfer has two important concerns (i) ability to transfer without loss, (ii) latency; these are addressed using emerging communication technologies. The communication options for PMU can be classified as [26]:

1. Power Line Carrier (PLC)
2. Microwave
3. Fiber Optics
4. Pilot Wire

The data transfer standard IEEE Std. C37.118.2 [27] was approved in 2011 and it specifies the methods of exchange of PMU data along with the types, contents and data formats for real-time communication. It requires the contents are carried in their entirety when they are mapped into the communication protocol. It assures that the application receiving data is devoid of bad data stream. Availability, security, vulnerability, confidentiality and other issues are dependent on the protocol used. Synchrophasor mapping through serial and network communication is stated here along with the protocols that can be used:

1. Transmission Control Protocol(TCP)
2. User Datagram Protocol(UDP)
3. TCP/UDP Combined [20]
1.2 AC Microgrid Layout

The AC Microgrid used for this work has the following components:

1. Generation (solar, wind, energy storage, etc.)

2. Loads - Passive and Motor

3. Islanding switch ($S_{id}$)

4. Phasor Measurement Unit (PMU)

As shown in Fig. 1.6, there are multiple PMUs placed in the transmission network and this thesis takes the advantage of PMUs placed in close proximity to the islanding switch ($S_{id}$). The information from all PMUs is logged and processed using a PDC situated at the control center of the grid. The local distribution level PMU is used to transmit information about islanding of a microgrid with the transmission level PDC. This allows information sharing at the grid level which can be leveraged for load rescheduling or appropriate load shedding operation from the grid operator. The local PMU is also used for switching between islanded and grid-connected mode of operations to synchronize the microgrid with the grid voltage.

1.2.1 Existing Microgrid Control Strategies

There are many existing control schemes for distributed generation units in AC microgrids for standalone and grid-connected operation. The control in a microgrid can be classified as: (i) centralized and, (ii) decentralized. Many control strategies with a centralized control approach to maintain stable microgrid voltage and frequency follow the notion of a central control for controlling multiple units on the basis of communication between the central control unit and distributed generation units. The decentralized control strategies in [28]–[32] are based on distributed control schemes for independent distribution units in a microgrid using droop control for voltage and frequency regulation. In [28], a droop strategy for multiple distributed generation units within a microgrid is presented for an islanded operation. The advantage of this strategy is use of multiple current loop damping schemes to damp high frequency resonances and improve overall stability, particularly under light loading conditions. In [33], [34], an autonomous control strategy is presented for converter fed microgrids for islanded and grid connected operation along with load sharing schemes with the grid.
Figure 1.6: A high level layout of the AC Microgrid
A centralized control for microgrids requires a communication infrastructure to feed information to the central controller for control action on all microgrid units. In [35]-[38], hierarchical control strategies are presented. These involve multi-stage controllers with hierarchical level assigned to them. The higher level controls have more control parameters affected as a result of complex nested controls existing in the hierarchy.

### 1.2.2 Existing Microgrid Black Start Strategies

The microgrid operation is facilitated by black start control in islanded mode to support autonomy. The majority of existing black start strategies are based upon utilization of a synchronized voltage and frequency value for non collocated distributed energy resource (DER) units. This is achieved by designing a central control to facilitate the operation. In [28], [39]-[41], a central control is utilized to support microgrid black start and grid synchronization process. The central control utilizes high bandwidth communication to provide synchronized signals to distributed generation units. In [42], a master-slave cooperative control is established. Here, the operation in islanded mode is facilitated by a master DER unit which will act as a central control to black start the microgrid. Another method to black start a multi-DER fed microgrid is by utilizing locally generated frequency signal [43], [44]. This is facilitated by internal crystal oscillators, where the locally generated frequency signal is assumed to converge with the microgrid frequency, based on fabricated nonlinear dynamics that are integrated into each controller. Since these controls are designed only for single-phase DERs, no mechanism for providing balanced three-phase output is available.

### 1.3 Technical Standards

Technical organizations have established standards for the construction, interconnection prerequisites, communication technologies and testing of equipments for Distributed Generation (DG). Some of the most prominently used standards are given by the Institute of Electrical and Electronics Engineers (IEEE), UL safety organization and International Electro-technical Commission (IEC). The objective of this section is to present an overview of some standards relevant for the interconnection of DGs and focus on the future of successful exploitation of renewable energy based DGs.
1.3.1 IEEE 1547: Standard for Interconnecting Distributed Resources with Electric Power Systems (EPS)

IEEE Std. 1547 [45] was first introduced in 2003 by IEEE to establish the criteria and requirements for the interconnection of distributed energy resources (DERs) with electric power systems. It was introduced to address issues related to increasing deployment of DER units in the modern grid. This standard provides technical information relevant to performance, operation, testing, safety considerations, and maintenance of the interconnection.

The original standard included tests for over and under frequency detection and directs for a complete disconnection of the DER unit under such conditions. Due to the aforementioned issues and to provide an application guide for the original standard, IEEE Std. 1547.2 [46] was introduced in 2008. It gave a background and rationale behind the requirements and criteria for interconnected operation of DER and the grid. This standard was applicable for DER technologies of aggregate capacity of 10 MVA or less at the PCC.

The series of interconnection standards state that the DER unit should not take part in regulating voltage at the PCC and should not cause the voltage of the local electric power system to go outside of the requirements specified in ANSI Std. C84.1 [47]. DER units are allowed to absorb or supply reactive power, but are controlled by the EPS operator. This requirement was redacted by IEEE with the introduction of IEEE Std. 1547a [48] in 2014 as an amendment to some sections of the original IEEE Std. issued in 2003. This amendment permits DER operators to actively participate in voltage regulation at PCC with the consent of the utility operator. When the voltage range at the PCC is as given in Table A.1 in Appendix A.1, the DER unit shall discontinue to energize the EPS within the clearing time (s) indicated. It also suggests that for units of capacity more than 300 W, the voltage set points and clearing time may be adjustable. As for the under-frequency and over-frequency operation, the clearing time and frequency set points (stated in Table A.2 in Appendix A.1) may be adjustable on agreement with the utility operator.

In 2015, IEEE Std. 1547.1a [49] was introduced as an amendment to the IEEE Std. 1547.1 issued in 2005. It included type tests for equipment under response to abnormal voltage and frequency conditions. It also covered power variation test to verify the power response of the equipment as specified by the manufacturer.

The IEEE committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage is working on the IEEE Std. 1547.8 which builds upon the IEEE Std. 1547.7
and is expected to address challenges related to storage with respect to DER units in smart grids, including plug-in electric vehicles (EV). It has also proposed to include low frequency Fault ride-through (LFRT) under agreement between the DER and utility operator with the set points and clearing time(s) specified in Table A.2 in Appendix A.1. Furthermore, the inclusion of volt/var compensation using DER units facilitating the ability to deal with the impacts of increasing footprint of distributed generation in the modern grid is also a part of this update.

1.3.2 UL 1741: Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources

UL Std. 1741 [50] reviews construction, performance and protection aspects of DER and interconnecting equipment. This standard specifies that for utility interactive equipment, the requirements specified by the this standard are used as a supplement or in conjunction with the IEEE Std 1547 series. Unlike the other standards that primarily define technical parameters and requirements, this standard covers the physical and design aspect of building blocks of distributed generation in detail.

The second edition updated in 2016 added requirements and testing for grid support inverters. It provides specifications for anti-islanding protection along with voltage and frequency ride through capability of DERs along with the testing procedures. Furthermore, this update discusses volt/var control in order to maintain stable grid voltage. It gives the provision of prioritizing volt/var control operation for DERs upto a certain kW/kVar limits specified by the utility operator. It also defines the volt/var operation in terms of strength of aggressiveness of reactive power (Q) as: (i) Most Aggressive, (ii) Average, (iii) Least Aggressive.

1.3.3 IEEE 519: IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power System

IEEE Std. 519 [51] is the most widely accepted standard across utilities and countries for establishing the recommended voltage and current harmonics specifications for individual customers [52]. The limits specified in this standard attribute to steady-state operation and stated for the worst case scenario. The application of the limitations stated are applied at the point of interconnection between the distributed generation and the grid, also known as the point of common coupling (PCC).
This standard defines multiple parameters for the evaluation of the effect of harmonic limits for any particular application. The parameters are given for both current and voltage. The relevant parameters are: (i) Individual harmonic distortion (IHD), (ii) Total harmonic distortion (THD), and (iii) Total demand distortion (TDD).

**Total Harmonic Distortion**

\[
\text{THD} = \sqrt{\sum_{h=2}^{50} \frac{V_h^2}{V_1}} \times 100\% \tag{1.7}
\]

Where, \(V_h\) is the rms value of voltage of harmonic \(h\), \(V_1\) is the rms value of the voltage of fundamental harmonic. The value of upper bound of the sum can be chosen to be any value up to infinity. As a common practice this value is chosen to be 50.

**Total Demand Distortion**

\[
\text{THD} = \sqrt{\sum_{h=2}^{50} \frac{I_h^2}{I_L}} \times 100\% \tag{1.8}
\]

Where, \(I_h\) is the rms value of current of harmonic \(h\), \(I_L\) is the rms value of the maximum load current demand. The value of upper bound of the sum can be chosen to be any value up to infinity. As a common practice this value is chosen to be 50.

### 1.4 Motivation

An ideal microgrid should be able to black start autonomously and provide seamless transfer between standalone and grid-connected modes of operation. Although, existing microgrid control scheme allow the operation of an AC microgrid in grid-connected and islanded modes, they offer limited ability to black start autonomously with multiple DER units operating. This is attributed to the deficit in the availability of synchronized voltage and frequency for non-collocated DER converters. A suitable approach to facilitate black start in a multi-DER microgrid is to maintain the operation of local current control regardless of synchronization of consistent \(dq\)-frame creation across the dispersed DER units. Thus, it is of value to investigate the design of microgrid controls in asynchronous reference frames.

Autonomous microgrids must also be able to perform: (i) grid connection, (ii) islanding, (iii) grid re-connection, (iv) grid power dispatch. The literature review also reveals the use of Phasor Measurement Units (PMUs) in various research areas concerning estimation and detection. PMUs can be leveraged towards a stronger interconnection between
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low voltage distribution network and the grid by virtue of data sharing and effective communication.

Figure 1.7: Layout of (a) high level grid infrastructure, (b) centralized high bandwidth microgrid control, (c) fully distributed microgrid control, (d) fully distributed control augmented with low bandwidth PMU communication

1.5 Thesis Objectives

The primary objective of this thesis is to design and develop a black start control architecture for a microgrid powered by multiple dispersed DER units which operate independent of global synchronization signal. This is achieved by leveraging asynchronous reference frame theory to encourage continuous operation of local DER converter controls at black start. The thesis further extends and investigates the operation of the microgrid in grid-connected mode. It does so by leveraging the capabilities of a PMU to support synchronization operation and power dispatch in grid-connected mode. This is achieved by establishing a hierarchy as shown in Fig. 1.7d where the microgrid distributed control is augmented with low bandwidth PMU communication. The existing transmission
networks can currently leverage only a small number of the capabilities of distributed
generation powered by renewable sources of energy. This can be further strengthen by
the use of communication abilities of PMUs to facilitate bidirectional flow of energy and
information.

The primary objectives of this thesis can be summarized as follows:

1. Develop black start control reinforced by voltage and frequency control for operation
   of microgrid in standalone mode by:

   (i) Modelling and designing a single-DER converter fed microgrid with local cur-
   rent control in an asynchronous $\alpha\beta$-frame.

   (ii) Scaling the microgrid and investigating black start and power sharing control
        for multiple DER converters.

2. Develop PMU based control for synchronization and power dispatch with the grid
   and demonstrate the efficacy of AC microgrids in utilizing the capabilities of PMUs
   to establish grid support and autonomy.

1.6 Thesis Outline

The content of this thesis is organized as follows:

Chapter 2 presents an overview of a single-DER converter fed microgrid along with
the current mode control design in an asynchronous $\alpha\beta$-frame. This chapter is further
expanded to develop voltage and frequency control for both autonomous and black start
operation developed in $dq$-frame.

Chapter 3 presents an overview of the experimental setup for a single-DER converter
fed microgrid. This chapter provides results for the experimental validation of the control
schemes developed in the previous chapter.

Chapter 4 presents the modeling and design of voltage and frequency control for a
scaled microgrid along with the grid-connected operation and power sharing using PMUs.

Chapter 5 presents results for experimental validation of the control schemes devel-
oped for a dual-DER converter fed microgrid, that leverages PMU data.

Chapter 6 summarizes this thesis, presents its contributions and future works.
Chapter 2

Single DER Converter Microgrid Modelling

To gain insight into the operation of a PMU and supervisory control within a microgrid, it is vital to simulate a study system. Thus, the aim of this chapter is to discuss in detail the topology and modeling parameters of the AC microgrid system and associated local control strategies used for implementation in PSCAD/ETMDC simulation environment, as a basis for further analysis throughout this thesis. The microgrid is designed to operate in standalone and grid connected mode of operation. This chapter models the microgrid in standalone mode to devise a voltage and frequency control for PCC synchronization in $dq$-frame.

2.1 Microgrid Configuration

This section entails the layout and design details of the microgrid developed for this work. The local control strategies for the converter are also discussed here. The single line diagram of the three-phase AC microgrid developed for this work is depicted in Fig. 2.1. It consists of the following key components:

1. Converter interfaced DER
2. Bus capacitor, $C_B$
3. Passive and motor loads
4. Islanding switch ($S_{id}$)
The microgrid supplies a variety of adjustable passive loads (R, L, C) and a three-phase induction motor load rated at 5 hp. The bus $B$ is connected to the grid through an isolating $Y - Y_g$ transformer. The system can either be operated in grid-connected or islanded mode using the islanding switch $S_{id}$. The following sections describe the details about modeling and control design for converter interfaced DER used in this system. The analysis was done under the following set of assumptions:

1. The system is nominally balanced

2. The DER provides a stiff dc source

3. The DER voltage, $v_{dc}$, is sufficiently high to avoid saturation of the converter controller

4. The DER converter employs high frequency pulse width modulation (PWM) to control the output currents, and injects minimal low order harmonics into the grid

Figure 2.1: Schematic of single DER converter fed microgrid
In order to model the dynamics of DER converter fed microgrid as depicted in Fig. 2.1, the components of the microgrid shown in Fig. 2.2 are modelled in this work. This is done by modelling each component of this microgrid separately and connecting them together. It is then followed by the development of a supervisory control architecture to control the bus voltage and frequency in standalone mode. The following sections discuss each of these models in detail.

![Diagram of Single DER Converter Microgrid Model](image)

Figure 2.2: Components of the single-DER converter interfaced microgrid model

### 2.2 Space Vector: Definitions and Conversions

The control and modelling of this microgrid utilizes different reference frames and this section gives conversions between them. All measurements for the DER converter parameters are made in the \( abc \)-frame. The DER converter output current, \([i_1]\), is described as:

\[
[i_1] = \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix}
\]  

(2.1)
Let, $i_{1\alpha}$ and $i_{1\beta}$ represent the $\alpha\beta$-frame DER converter output current which can be calculated using Clarke’s transform as given by (2.2).

\[
\begin{bmatrix}
    i_{1\alpha} \\
    i_{1\beta} \\
    i_{1o}
\end{bmatrix}
= \frac{2}{3}
\begin{bmatrix}
    1 & -\frac{1}{2} & \frac{1}{2} \\
    -\frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2} \\
    \frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\begin{bmatrix}
    i_{1a} \\
    i_{1b} \\
    i_{1c}
\end{bmatrix}
\] (2.2)

The DER converter output current can also be defined as:

\[
\vec{i}_1 = i_{1\alpha} + j i_{1\beta}
\] (2.3)

The current-mode control design will require the conversion of reference values in $dq$-frame to be converted to $\alpha\beta$-frame using the relation given by (2.4).

\[
\begin{bmatrix}
    i_{1\alpha} \\
    i_{1\beta} \\
    i_{1o}
\end{bmatrix}
= \frac{2}{3}
\begin{bmatrix}
    \cos(w_o t) & -\sin(w_o t) & 0 \\
    \sin(w_o t) & \cos(w_o t) & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    i_{1d} \\
    i_{1q} \\
    i_{1o}
\end{bmatrix}
\] (2.4)

Where, $w_o$ denotes the angular frequency corresponding to the grid frequency ($f_o$).
2.3 DER Interfaced Converter Model

In this microgrid, a two-level converter interfaced DER is implemented with an LCL filter as depicted in Fig. 2.4. The LCL filter is one of the most commonly used topology in the industry for grid connected distributed generation units. Here, the dc voltage, ac bus voltage and grid voltage are given by $v_{dc}$, $v_B$, $v_g$ respectively.

![Figure 2.4: Schematic of DER converter with Modified LCL Filter](image)

2.3.1 LCL Filter Design

The DER converter is interfaced with an LCL filter. The resonant frequency of the plant model is given by equation 2.5. A modified filter is used with a damping resistor ($R_d$) to damp the resonance in the $L_2C_f$ circuit. Detailed design and rationale behind this design is discussed in Appendix B.

$$
\omega_{res} = \sqrt{\frac{L_1 + L_2}{L_1L_2C_f}} \tag{2.5}
$$

2.3.2 DER Converter Mathematical Model

The DER converter output voltage and current are given by $v_t$ and $i_1$ as depicted in the average model as shown in Fig. 2.5. Now, the time-domain analysis of the average model gives the following state equations:

$$
[i_C] = [i_1] - [i_2] \tag{2.6}
$$

$$
L_1 \frac{d[i_1]}{dt} = [v_t] - [v_C] - R_d[i_1] + R_d[i_2] \tag{2.7}
$$
Figure 2.5: Averaged model of DER converter with modified LCL filter

\[ L_2 \frac{d[i_2]}{dt} = [v_C] - [v_s] + R_d[i_1] - R_d[i_2] \]  

(2.8)

\[ C_f \frac{d[v_C]}{dt} = [i_C] \]  

(2.9)

Subject to the following constraints:

\[ i_{1a} + i_{1b} + i_{1c} = 0 \]  

(2.10)

\[ i_{2a} + i_{2b} + i_{2c} = 0 \]  

(2.11)

\[ i_{Ca} + i_{Cb} + i_{Cc} = 0 \]  

(2.12)

The frequency-domain analysis of (2.6)-(2.9) reduces the relevant transfer functions of DER filter network as given by (2.13)-(2.18).

\[ \frac{i_{1\alpha}}{v_{1\alpha}} = \frac{L_2C_fs^2 + R_dC_fs + 1}{L_1L_2C_fs^3 + C_fR_d(L_1 + L_2)s^2 + (L_1 + L_2)s} \]  

(2.13)

\[ \frac{i_{1\beta}}{v_{1\beta}} = \frac{L_2C_fs^2 + R_dC_fs + 1}{L_1L_2C_fs^3 + C_fR_d(L_1 + L_2)s^2 + (L_1 + L_2)s} \]  

(2.14)
\[
\frac{i_{2\alpha}}{v_{t\alpha}} = \frac{R_d C_f s + 1}{L_1 L_2 C_f s^3 + C_f R_d (L_1 + L_2) s^2 + (L_1 + L_2) s} \tag{2.15}
\]
\[
\frac{i_{2\beta}}{v_{t\beta}} = \frac{R_d C_f s + 1}{L_1 L_2 C_f s^3 + C_f R_d (L_1 + L_2) s^2 + (L_1 + L_2) s} \tag{2.16}
\]
\[
\frac{v_{C\alpha}}{v_{t\alpha}} = \frac{L_2 s}{L_1 L_2 C_f s^3 + C_f R_d (L_1 + L_2) s^2 + (L_1 + L_2) s} \tag{2.17}
\]
\[
\frac{v_{C\beta}}{v_{t\beta}} = \frac{L_2 s}{L_1 L_2 C_f s^3 + C_f R_d (L_1 + L_2) s^2 + (L_1 + L_2) s} \tag{2.18}
\]

The selection of plant transfer function is based on the evaluation of stabilizability and controllability. The plant equation (2.13) is stable due to the presence of two complex conjugate poles. As explained in Appendix B, the addition of damping resistor \((R_d)\) improves the stabilizability of transfer function (2.15). Also, the control developed using plant equation (2.15) does not have to consider reactive power correction to account for the current absorbed by filter capacitor \((C_f)\), but the use of (2.15) is discouraged without the presence of a damping resistor as it approaches instability. Hence, plant is modelled using (2.13).

### 2.3.3 Current-Mode Control Design

The closed-loop control is designed for the converter interfaced DER as shown in Fig. 2.6. The control is implemented in \(\alpha\beta\)-frame attributing to simple feedback and decoupled components as compared to the \(dq\)-frame. A proportional-resonant (PR) control is used for the design of current-mode control is as represented by (2.19) in general form.

\[
C(s) = \frac{k_a s^2 + k_b s + k_c}{s^2 + w_o^2} \tag{2.19}
\]

Where,
- \(\omega_o\) - angular frequency of nominal grid (rad/s)
- \(k_a, k_b, k_c\) - Control gains

In order to keep the control design practical, the converter control latency is simulated with the delay block, representing the latency of digitally implemented PWM block. The converter latency is approximated as:

\[
H(s) = e^{-s T_d} \approx \frac{1}{1 + s T_d} \tag{2.20}
\]

The control is implemented with feed-forward loop to improve the accuracy of oper-
imation and optimize performance. The output of the actual control loop is $u_{tαβ}$ which is converted to a modulation index as per (2.21). The validation of current mode control is carried out using PSCAD as discussed in Appendix C.

$$\vec{m}_{αβ} = \frac{\vec{u}_{tαβ}}{\vec{V}_{dc}/2}$$

(2.21)

Where,

- $\vec{V}_{dc}$ - The measured dc voltage at the input port
- $\vec{u}_{tαβ}$ - DER converter’s requested output voltage in $αβ$-frame
- $\vec{m}_{αβ}$ - Modulating index ($ε[-1,1]$) in $αβ$-frame
- $\vec{v}_{tαβ}$ - Actual output converter voltage

### 2.4 Dynamic Microgrid Model

This section describes the mathematical model of the microgrid shown in Fig. [2.7]. Here, $v_t$ represents the DER converter output voltage, $v_B$ represents the bus voltage, and $i_L$ represents the load current modelled as a current source. The bus voltage control scheme is derived from this mathematical model. The microgrid model is presented in a state-space representation in this section.

#### 2.4.1 Dynamic Model of Islanded Microgrid

A simplified electrical model of the microgrid is shown in Fig. [2.7]. Here, the load at microgrid bus is modelled as a current source ($i_L$) and resistance ($R_l$). The model considers the presence of a bus capacitor ($C_B$) at the microgrid bus to facilitate synchronization of microgrid voltage and frequency. Applying Kirchoff’s voltage law in islanded mode, gives (2.22).

$$C_B \frac{dv_B}{dt} = -\frac{v_B}{R_l} + i_2 - i_L$$

(2.22)
The system equations can be represented in $dq$-frame rotating with the angular frequency of $\omega_{dq}$, which can be variable. Using the transformation matrices in (2.2) and (2.4), the equations in $dq$-frame are derived as follows:

\begin{align}
\frac{dv_{Bd}}{dt} &= -\frac{v_{Bd}}{R_tC_B} + \frac{i_{2d}}{C_B} - \frac{i_{Ld}}{C_B} + \omega_{dq}v_{Bq} \\
\frac{dv_{Bq}}{dt} &= -\frac{v_{Bq}}{R_tC_B} + \frac{i_{2q}}{C_B} - \frac{i_{Lq}}{C_B} - \omega_{dq}v_{Bd}
\end{align}

(2.23) (2.24)

Where,

$v_{Bdq}$ - $dq$-axis component of $v_B$

$i_{2dq}$ - $dq$-axis component of $i_2$

$i_{Ldq}$ - $dq$-axis component of $i_L$

The microgrid parameter to be regulated is bus voltage ($|\vec{v}_B|$) which is given by the following expression:

\[ |\vec{v}_B| = \sqrt{v_{Bd}^2 + v_{Bq}^2} \]  

(2.25)

For control design it is desirable that the $dq$-frame rotate with the same frequency as the grid. In case of an islanded grid this can be an issue as the grid voltage and frequency regulation is conducted by the DER converter. This issue can be resolved by aligning the d-axis of the reference frame with $v_{Bd}$ which implies that $v_{Bq}$ and $\frac{dv_{Bq}}{dt}$ is zero in (2.23)-(2.24). Substituting this in (2.23)-(2.24) gives the following equations:

\[ \omega_{dq} = \frac{i_{2q} - i_{Lq}}{C_Bv_{Bd}} \]  

(2.26)
\[
\frac{dv_{Bd}}{dt} = -\frac{v_{Bd}}{R_lC_B} + \frac{i_{2d}}{C_B} - \frac{i_{Ld}}{C_B} \tag{2.27}
\]

The system outputs to be regulated are bus voltage \(v_B\) and bus frequency \(\omega\) given by (2.28) and (2.29) respectively.

\[
|\vec{v}_B| = v_{Bd} \tag{2.28}
\]

\[
\omega = \omega_{dq} \tag{2.29}
\]

### 2.4.2 Steady-State Solutions

The steady-state solutions for microgrid system equations are given by the following relations:

\[
v_{Bd} = R_l(i_{2d} - i_{Ld}) \tag{2.30}
\]

The system output corresponding to the steady state input are given as follows:

\[
|\vec{v}_B| = v_{Bd} \tag{2.31}
\]

\[
\omega = \frac{i_{2q} - i_{Lq}}{C_B v_{Bd}} \tag{2.32}
\]

### 2.4.3 State-Space System Model

The microgrid system equations can be represented in state-space form using state vector \(x\), input vector \(u\), disturbance vector \(d\), and output vector \(y\):

\[
\dot{x} = Ax + Bu + Ed \tag{2.33}
\]

\[
y = Cx + \frac{1}{x}\left\{Du + Fd\right\} \tag{2.34}
\]

Where,

\[
x = \begin{bmatrix} v_{Bd} \end{bmatrix} \tag{2.35}
\]
Chapter 2. Single DER Converter Microgrid Modelling

The state matrices can be represented as follows:

\[ \mathbf{A} = \left[ -\frac{1}{R_C C_B} \right] \] (2.39)

\[ \mathbf{B} = \left[ \frac{1}{C_B} \quad 0 \right] \] (2.40)

\[ \mathbf{E} = \left[ \frac{1}{C_B} \quad 0 \right] \] (2.41)

\[ \mathbf{C} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \] (2.42)

\[ \mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{C_B} \end{bmatrix} \] (2.43)

\[ \mathbf{F} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_B} \end{bmatrix} \] (2.44)

2.5 Supervisory Voltage and Frequency Control

The microgrid operates in standalone mode using a supervisory voltage and frequency control developed from the microgrid model derived above. This control is responsible for operating the local current mode control developed for the DER interfaced converter, which is developed in \( \alpha \beta \)-frame. The controls are designed in different reference frames to keep the current control operational regardless of synchronization of consistent \( dq \)-frame creation across non-collocated DER units.

This section entails the design of voltage and frequency control from the microgrid model. As shown in (2.33)-(2.44), the voltage and frequency of the standalone microgrid are the outputs of the model developed using output currents of DER interfaced converter \( i_{2 \alpha \beta} \) as the system inputs. The schematic representation of this model is shown in Fig.
2.8, where the supervisory operation of bus voltage \( v_B \) and frequency \( \omega \) control drives the DER interfaced converter’s current control.

\[
\begin{bmatrix}
i_{2d} \\
i_{2q}
\end{bmatrix} \rightarrow \text{Dynamic Microgrid Model (2.33)-(2.34)} \rightarrow \begin{bmatrix} v_B \\ \omega \end{bmatrix}
\]

Figure 2.8: Voltage and Frequency Control Overview

Based on the representation of voltage and frequency control as shown in the block diagram in Fig. 2.8, the dynamics of supervisory controls is embedded in the state space model represented in (2.33)-(2.34). The dynamics of the plant of frequency control will be coupled with the voltage control plant and PI control parameters. A systematic approach is used to decouple the dynamics of these controls as demonstrated in the following sub-sections.

### 2.5.1 Voltage Control

The voltage control is used to regulate the bus voltage of the islanded microgrid shown in Fig. 2.7. The model shown in Fig. 2.8 is taken as a starting point for determining the voltage control plant along with the state-space model in Section 2.4.3. The voltage control will set the reference value for \( i_{2d} \) to compensate the active power demand at the bus, \( B \). Using the model from (2.33)-(2.44), the expression for voltage control in s-domain can be given as:

\[
\frac{v_B}{i_{2d}} = \frac{1}{s + 1/R_l C_B} \tag{2.45}
\]

The voltage control plant of (2.45) will become unstable as the value of \( R_l \) approaches zero. This can be verified in Fig. 2.9, where different eigenvalues are plotted for changing value of \( R_l \) and as the value approaches zero, the system eigenvalues move towards the imaginary axis.

In order to ensure that the plant is stable when \( R_l \) approaches zero, a virtual impedance is added to the voltage control plant as depicted in Fig. 2.11. This virtual impedance \( (R_v) \) allows the voltage control plant to be stable when the resistive load at the bus is low. It can be verified from Fig. 2.10 that the eigenvalues of the plant are stable even when \( R_l \) is zero.
Chapter 2. Single DER Converter Microgrid Modelling

Figure 2.9: Eigenvalue analysis on voltage control plant without virtual impedance for different values of $R_l$

Figure 2.10: Eigenvalue analysis on voltage control plant (with virtual impedance ($R_v$)) for different values of $R_l$

The open loop transfer function used to regulate microgrid bus voltage with a virtual impedance ($R_v$) included is given as in (2.46).

$$\frac{v_B}{u_1} = \frac{1/C_B}{s + 1/ReqC_B} \tag{2.46}$$

Where,

$$Req = \frac{R_lR_v}{R_l + R_v} \tag{2.47}$$

Let the proportional and integral gain of the PI control be given by $K_{pv}$ and $K_{iv}$. The closed loop transfer function of voltage control is represented by (2.48).
2.5.2 Frequency Control

As established in the last section, the frequency control plant is coupled with the voltage control. Using the state-space model from (2.33)-(2.44), the expression for bus frequency control plant can be given as:

\[
\frac{\omega}{i_{2q}} = \frac{(1/R_{eq}C_B)s + 1/C_B}{v_{Bd}[s^2 + s(1/R_{eq}C_B + K_{pv}C_B) + k_{iv}C_B]}
\]

Figure 2.12: Frequency control block diagram

The frequency control can be represented as a block diagram shown in Fig. 2.12. The frequency control plant in the block diagram is given by (2.49). Let the proportional and integral constants of frequency PI controller be \(K_{p\omega}\) and \(K_{i\omega}\) respectively. The closed loop transfer function is given by (2.50).

\[
\frac{\omega}{\omega^{ref}} = \frac{(k_{p\omega}s + k_{i\omega})[(1/R_{eq}C_B)s + 1/C_B]}{s^3 + s^2(1/R_{eq}C_B + K_{p\omega}C_B + k_{p\omega}R_{eq}C_Bv_{Bd}) + s(k_{i\omega}C_B + k_{p\omega}K_{p\omega}C_B + k_{i\omega}C_BR_{eq}v_{Bd}) + k_{i\omega}k_{p\omega}C_Bv_{Bd}}
\]
2.6 Microgrid Model Validation

The mathematical microgrid model developed in (2.33)-(2.34) is validated by comparing the response of bus voltage \( (v_B) \) and frequency in simulations carried out in PSCAD. A switching model is used to simulate the DER converter in PSCAD. The PSCAD model considers the delays associated with pulse width modulation as experienced in an experimental setup. The bus voltage \( (v_B) \) and frequency \( (\omega) \) directly influence \( i_{2d} \) and \( i_{2q} \) respectively. The outputs of voltage and frequency control are used to initialize the reference for \( dq \)-frame current control which are converted to \( \alpha\beta \)-frame reference using (2.4). The dependence of \( dq \)-frame currents on voltage and frequency controls can be explained by capturing the response of change in \( i_{2d} \) and \( i_{2q} \) on the bus voltage \( (v_B) \) and frequency \( (\omega) \).

Table 2.1: System parameters chosen to validate microgrid mathematical model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>p.u. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base voltage</td>
<td>( V_{\text{peak base}} )</td>
<td>V</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Base current</td>
<td>( I_{\text{peak base}} )</td>
<td>A</td>
<td>35.4</td>
<td></td>
</tr>
<tr>
<td>Base impedance</td>
<td>( Z_{\text{base}} )</td>
<td>Ω</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>Rated voltage</td>
<td>( V_{\text{peak rated}} )</td>
<td>V</td>
<td>170</td>
<td>1.0</td>
</tr>
<tr>
<td>Rated current</td>
<td>( I_{\text{peak rated}} )</td>
<td>A</td>
<td>35.4</td>
<td>1.0</td>
</tr>
<tr>
<td>DC voltage</td>
<td>( V_{dc} )</td>
<td>V</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>Switching frequency</td>
<td>( f_s )</td>
<td>kHz</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Grid frequency</td>
<td>( f )</td>
<td>Hz</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Bus voltage</td>
<td>( \bar{v}_{Bd} )</td>
<td>V</td>
<td>170</td>
<td>1.0</td>
</tr>
<tr>
<td>Load resistance</td>
<td>( R_l )</td>
<td>Ω</td>
<td>10</td>
<td>2.1</td>
</tr>
<tr>
<td>Bus capacitance</td>
<td>( C_B )</td>
<td>μF</td>
<td>50</td>
<td>11.05 ( (X_c) )</td>
</tr>
</tbody>
</table>

Figure 2.13: Bode plot of open loop transfer function
The parameters chosen for simulating the microgrid in PSCAD are as shown in Table 2.1. Similar values are selected to gather the responses from the mathematical model. Figure 2.13 depicts the bode plot of the open loop system transfer function for the current mode control. The SISOTOOL application was used in MATLAB/Simulink to tune the PR-controller to provide desired step response with transfer function, $C(s)$, as shown by (2.19).

Table 2.2: PR controller gains

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_a$</td>
<td>3.2</td>
</tr>
<tr>
<td>$k_b$</td>
<td>2048</td>
</tr>
<tr>
<td>$k_c$</td>
<td>428480</td>
</tr>
</tbody>
</table>

As shown in Fig. 2.14, the response of various microgrid parameters is depicted with change in the bus voltage reference ($v_B^{ref}$) as simulated in PSCAD and obtained from the mathematical model. It can be observed that change in bus voltage will impact the $d$-frame DER output current ($i_{2d}$) as shown in Fig. 2.14b. This shows the dependence of $d$-frame DER output current on the voltage at the bus, $B$. Due to the coupling between the $dq$-frame voltage and frequency control, any change in bus voltage will produce a transient dip in frequency as shown in Fig. 2.14e.

Now that the dependence of $i_{2d}$ on bus voltage is verified, Fig. 2.15 shows the response of microgrid parameters with change in bus frequency reference ($f^{ref}$) as simulated in PSCAD and obtained from the mathematical model. Here, it can be observed that change in bus frequency will impact the $q$-frame DER output current ($i_{2q}$) as shown in Fig. 2.15c. This shows the dependence of $q$-frame DER output current on the frequency at the bus, $B$. Due to the coupling between the $dq$-frame voltage and frequency control, any change in bus frequency will produce a transient change in voltage as shown in Fig. 2.15d. These responses also show the precision between the mathematically developed model and the simulated microgrid.
Figure 2.14: Depicting the response of PSCAD simulation model to step change in bus voltage reference: (a) bus voltage reference \(v_{B}^{ref}\), (b) DER \(d\)-frame output current \(i_{2d}\), (c) DER \(q\)-frame output current \(i_{2q}\), (d) Bus voltage \(v_{B}\), (e) Frequency \(f\)
Figure 2.15: Depicting the response of PSCAD simulation model to change in frequency reference: (a) bus frequency reference ($f_{\text{ref}}$), (b) DER $d$-frame output current ($i_{2d}$), (c) DER $q$-frame output current ($i_{2q}$), (d) Bus voltage ($v_B$), (e) Frequency ($f$)
2.7 Chapter Summary

This chapter presents the simplest case of AC microgrid model used for this work. First, a brief introduction regarding the topology and layout of the system is presented followed by the design of DER interfaced converter model in Section 2.3. This includes the representation of mathematical model of DER interfaced converter along with the current mode control design in $\alpha\beta$-frame.

In Section 2.4, the design of dynamic microgrid model is presented. This includes the state-space model of the simplest case of microgrid used in this thesis. This is followed by the formulation of supervisory voltage and frequency control for the proposed microgrid. Finally, the mathematical model is validated against a model simulated in PSCAD with similar design conditions as that of the mathematical model.
Chapter 3

Validation of Single DER Converter Microgrid

This chapter presents the experimental results to validate the responses of control schemes modelled in the previous chapter. It starts with a brief description of the experimental setup layout. It then describes the control programming environment and the criteria for selection of control parameters. Finally, the experimental results are presented and compared with simulation results gathered from $PSCAD^{TM}/EMTDC$.

3.1 Experimental Setup Layout

This section provides detailed description of the simplified microgrid model as shown in Fig. 3.1. This setup is used for the verification of models derived in the previous chapter. The microgrid experimental measurements are also compared to the $PSCAD^{TM}$ simulation results.

Both the microgrid local and supervisory controls are programmed into the National Instruments CompactRIO (NI 9035) which is a real time controller interfaced with LabVIEW as the programming environment. It uses a combination of physical layouts and graphical programming for data acquisition, instrument control and industrial automation on the Windows platform. The CompactRIO is connected to the PC for visualizing the control graphical user interface using LabVIEW. It is also connected to an oscilloscope to record microgrid results at the bus, $B$. The compactRIO outputs the gating pulses to drive the switches of the voltage source converter.

For the DER converter, voltage and current sensors are used to sense the dc voltage ($V_{dc}$), three-phase bus voltage ($v_B$), and output current ($i_1$) and ($i_2$). These sensed values are fed to a National Instruments CompactRIO.
The Phasor Measurement Unit (PMU) is connected to sense the three-phase grid voltage \(v_g\) and current \(i_g\). The PMU values are used for synchronization of \(v_B\) when the reconnection from islanded to grid connected mode takes place. The PMU is also connected to the CompactRIO and the PC using IEEE C37.118.1 communication protocol.

A switched model, with six controllable switches, is used for simulating the DER interfaced converter. The voltage and frequency controllers use the value of bus voltage magnitude \(|v_B|\) and grid frequency \(\omega\) which are calculated as shown in Fig. 3.2 and using (3.1a)–(3.1c).

\[
|\vec{v}_B| = \sqrt{(v_{B\alpha})^2 + (v_{B\beta})^2}
\]  

(3.1a)
\[ \theta = \angle \vec{v}_B \] (3.1b)

\[ \omega = \frac{d\theta}{dt} \] (3.1c)

The outputs of voltage and frequency controller drive the reference for current mode control in \( \alpha\beta \)-frame. The \( dq \)-frame references are converted to \( \alpha\beta \)-frame references using the following relation matrix:

\[
\begin{bmatrix}
  i_d \\
  i_q \\
  i_o
\end{bmatrix}
= \frac{2}{3}
\begin{bmatrix}
  \cos(\omega t) & -\sin(\omega t) & 0 \\
  \sin(\omega t) & \cos(\omega t) & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  i_d \\
  i_q \\
  i_o
\end{bmatrix}
\] (3.2)

![Diagram](image)

Figure 3.2: Measurement and Conversion Unit

### 3.2 Control Parameters

The control parameters for microgrid controls are chosen under the following constraints:

1. The transient deviation in bus voltage \((v_B)\) should be less than 10 % and steady state change should be less than 5 % as stated in ANSI C84.1 - 2011 [47].

2. The transient deviation in frequency \((\omega)\) should be less than 5 % as stated in IEEE Std 1547a - 2014 [48].

3. The recovery time for voltage and frequency deviations should be in conformity with IEEE Std 1547a - 2014 [48] as indicated in Appendix A.3.

The control parameters for both voltage and frequency control are selected such that the microgrid operates in islanded mode with different load variations. The microgrid model requires a certain amount of resistance on the bus to damp oscillations amongst storage elements. As suggested in the last chapter, the voltage control has a virtual impedance \((R_v)\) to compensate for load resistance in its absence. The value of \(R_v\) is selected on the basis of DER interfaced converter rating such the microgrid operation is
Table 3.1: Experimental Control Parameters of single-DER converter microgrid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>p.u. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base voltage</td>
<td>$V_{base}$</td>
<td>V</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Base current</td>
<td>$I_{base}$</td>
<td>A</td>
<td>35.4</td>
<td></td>
</tr>
<tr>
<td>Base impedance</td>
<td>$Z_{base}$</td>
<td>Ω</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>VSC rated voltage</td>
<td>$V_{peak}$</td>
<td>V</td>
<td>170</td>
<td>1.0</td>
</tr>
<tr>
<td>VSC rated current</td>
<td>$I_{peak}$</td>
<td>I</td>
<td>35.4</td>
<td>1.0</td>
</tr>
<tr>
<td>DC voltage</td>
<td>$V_{dc}$</td>
<td>V</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_s$</td>
<td>kHz</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Grid frequency</td>
<td>$f$</td>
<td>Hz</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Load resistance</td>
<td>$R_l$</td>
<td>Ω</td>
<td>10</td>
<td>2.1</td>
</tr>
<tr>
<td>Load inductance</td>
<td>$L$</td>
<td>mH</td>
<td>16</td>
<td>1.26 ($X_l$)</td>
</tr>
<tr>
<td>Load capacitance</td>
<td>$C_l$</td>
<td>µF</td>
<td>30</td>
<td>18.4 ($X_{cl}$)</td>
</tr>
<tr>
<td>Bus capacitance</td>
<td>$C_B$</td>
<td>µF</td>
<td>50</td>
<td>11.05 ($X_{cB}$)</td>
</tr>
<tr>
<td>Voltage proportional gain</td>
<td>$K_{pv}$</td>
<td>-</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Voltage integral gain</td>
<td>$K_{iv}$</td>
<td>-</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Virtual impedance</td>
<td>$R_v$</td>
<td>Ω</td>
<td>14.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Frequency proportional gain</td>
<td>$K_{pω}$</td>
<td>-</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>Frequency integral gain</td>
<td>$K_{iω}$</td>
<td>-</td>
<td>53.1</td>
<td></td>
</tr>
</tbody>
</table>

not affected under low or no load conditions. For this experimental setup it is chosen to be $R_v = 14.5$ Ω (3.0 p.u.) which is sufficient to keep the voltage and frequency plants stable.

The voltage and frequency control parameters chosen for the single-DER converter microgrid along with the load parameters are as stated in Table 3.1.

### 3.3 Phasor Measurement Unit (PMU) - SEL 451-5

A protection relay equipped with a Phasor Measurement Unit (PMU) manufactured by Schweitzer Engineering Labs (SEL-451) is used for grid reconnection and power sharing controls in the microgrid. SEL 451-5 is a protection relay which has the capabilities of a PMU embedded inside. This device can be used in multiple applications, such as:

1. Substation protection
2. Fault detection
3. Identifying line and generator outages
4. State estimation
Table 3.2: SEL-451 relay parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE standard level</td>
<td>IEEE C37.118.1a</td>
</tr>
<tr>
<td>Compliance level</td>
<td>Level 1 - TVE and frequency range</td>
</tr>
<tr>
<td>Protocols</td>
<td>DNP3, Modbus, SEL Fast Message</td>
</tr>
<tr>
<td>Message Rate</td>
<td>1-60 mps</td>
</tr>
<tr>
<td>CT Inputs</td>
<td>6</td>
</tr>
<tr>
<td>PT Inputs</td>
<td>6</td>
</tr>
<tr>
<td>Analog Inputs</td>
<td>16</td>
</tr>
<tr>
<td>Digital Inputs</td>
<td>64</td>
</tr>
<tr>
<td>Baud rate</td>
<td>57600</td>
</tr>
</tbody>
</table>

SEL 451-5 works on the principle of sensing analog values using CTs and PTs which are then time synchronized using a high priority time signal generated by a GPS antenna. This time synchronized information is then transmitted to a workstation or a Phasor Data Concentrator (PDC) using a communication scheme compliant with the IEEE Std. C37.118.1a [24] or IEC 61850 [25]. Fig. 3.3 shows the front and back panel of this relay.

![Figure 3.3: SEL 451-5: Protection, automation, bay control system (a) front view, (b) back view](image)

As stated in Table 3.2, IEEE C37.118.1a communication protocol for synchrophasors is used for connecting the relay to a workstation using an Ethernet cable. The human ma-
Chapter 3. Validation of Single DER Converter Microgrid

The human machine interface as shown in Fig. 3.4 is used to interact with the PMU using a workstation. The HMI is accessible with SEL-5030 AcSELerator™ QuickSet software.

SEL 451-5 can be used to transmit the following as synchrophasors:

1. Instantaneous quantities
   - Three-phase, sequence voltages and currents
2. Power and energy metering
3. Demand and peak metering
4. Synchrophasors
   - Three-phase voltages and currents
   - Frequency ($\omega$)
   - Rate of change of frequency (ROCOF)

### 3.4 Voltage and Frequency Control Response

This section presents the results of voltage and frequency control response in the presence of loads at the microgrid bus, $B$. Firstly, the response of microgrid to a step change in
bus voltage reference \( (v_B^{ref}) \) is discussed, followed by the impact of load switching on the microgrid bus voltage \( (v_B) \) and frequency \( (\omega) \). The control and load parameters are selected as stated in Table 3.1.

In this case, the microgrid response to a step in bus voltage reference \( (v_B^{ref}) \) is analyzed with a resistive \( (R_l) \) load present at the bus, \( B \). As shown in Fig. 3.5, the response of microgrid bus voltage has no overshoot and a rise time \( (t_r) \) of 20ms. Due to the coupling between \( dq \)-frame control, the microgrid frequency experiences a transient dip of 0.4 Hz. It also shows consistency amongst the simulation and experimental results.

![Graph 1](image1.png)

**Figure 3.5:** Response of microgrid to step in bus voltage reference \( (v_B^{ref}) \): (a) Bus voltage \( (v_B) \), (b) Bus frequency \( (f) \)

Now, assuming the same loading structure, the microgrid response to a step change in bus frequency reference \( (f^{ref}) \) is analyzed. In Fig. 3.6a, the experimental and simulation results show that the step response of microgrid bus frequency \( (f) \) has no overshoot and a rise time \( (t_r) \) of 70ms.

This section also examines the transient response of the microgrid with the introduction of a passive load on the microgrid bus. The response of bus voltage and frequency upon switching a resistive, inductive and capacitive load are shown in Fig. 3.7. The voltage response remains well damped and stable for all cases, but the transient dip experienced in the bus voltage is most prominent in the case of switching a capacitive load.
Chapter 3. Validation of Single DER Converter Microgrid

Figure 3.6: Response of microgrid to step in bus frequency reference ($f_{ref}$): (a) Bus frequency ($f$), (b) Bus voltage ($v_B$)

The bus voltage changes from 170 V to 167 V with a recovery time, $t_{rec} = 40$ms.

The maximum deviation in frequency is experienced due to switching of a capacitive load ($C_l$) as shown in Fig. 3.7c. The bus frequency changes experiences a deviation of 0.6 Hz with a recovery time, $t_{rec} = 80$ms. On the contrary, as shown in Fig. 3.7a, the switching of a resistive load causes a deviation of 0.2 Hz with a recovery time, $t_{rec} = 10$ms. This contrast in the response is attributed to the dependence of $q$-frame current reference on the supervisory frequency controller.

This section also examines the operation of microgrid without resistive load ($R_l$). As shown in Fig. 3.8, the microgrid bus voltage remains stable and well damped after the removal of resistive loads from the microgrid bus. The response for bus frequency ($f$) is well damped and stabilizes to its original values after a transient deviation of 0.8 Hz. This verifies the purpose and effectiveness of damping resistor in the bus voltage controller to maintain stable voltage in the absence of resistive load at the bus.
Figure 3.7: Transient response of microgrid parameters to switching of: (a) resistive load, (b) inductive load, (c) capacitive load
3.5 Black Start Response

This section presents the simulation and experimental results for black start operation of the proposed microgrid. The following are the existing conditions before the microgrid is black started:

1. The microgrid bus, \( B \), is disconnected from the grid

2. Motor loads are not connected to the bus

The black start operation is initiated by the supervisory voltage and frequency control as shown in Figs. (3.9a) and (3.9b) respectively. The microgrid voltage and frequency control synchronizes with the bus capacitor (\( C_B \)) to energize the microgrid at \( v_B = 170 \text{ V (peak)} \) and \( f = 60 \text{Hz} \) at \( t = 0 \text{s} \). The voltage control response at black start is stable and well damped with a settling time of \( t_s = 50 \text{ ms} \). The frequency control response has an overshoot of 8.3% with a settling time of \( t_s = 100 \text{ ms} \). The response of three-phase bus voltage to black start is as shown in Fig. 3.10.
Figure 3.9: Response of microgrid to black start operation: (a) Bus voltage ($v_B$), (b) Bus frequency ($f$)

Figure 3.10: Three-phase bus voltage, $v_B$, response at black start: (a) Simulated, (b) Experimental
3.6 System Response to Motor Starting

This section examines the response of grid voltage and frequency to starting of an induction motor. The motor used for this test has the parameters indicated in Table 3.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>$P_r$</td>
<td>kW</td>
<td>4.6</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>$p$</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>AC Motor Type</td>
<td>-</td>
<td>-</td>
<td>Induction</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>$V_s$</td>
<td>V</td>
<td>220-420</td>
</tr>
<tr>
<td>Phase</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Output Speed</td>
<td>$n_s$</td>
<td>rpm</td>
<td>1725</td>
</tr>
<tr>
<td>Mounting Type</td>
<td>-</td>
<td>-</td>
<td>Flange Mount</td>
</tr>
<tr>
<td>Maximum Output Torque</td>
<td>$T_{max}$</td>
<td>N-m</td>
<td>26.7</td>
</tr>
<tr>
<td>Current Rating</td>
<td>$I_{rated}$</td>
<td>A</td>
<td>8.7</td>
</tr>
</tbody>
</table>

The microgrid bus voltage ($v_B$) and frequency ($\omega$) is 170 V and 376.9 rad/s prior to the introduction of a motor load on the bus, $B$. Also, the motor is not mechanically coupled to any load when it is started. As shown in Fig. 3.11a, the bus voltage ($v_b$) shows a slight dip to the introduction of a motor load. The voltage dips from 170 V to 140 V and recovers back with a recovery time, $t_{rec} = 40$ ms. The frequency control shows a transient change from 60 Hz to 55 Hz in Fig. 3.11b. The frequency control response has a recovery time, $t_{rec} = 60$ ms. The microgrid operation remain stable and well damped. The presence of a motor impacts both voltage and frequency control, but these electrical parameters reach an steady state before the motor reaches the mechanical steady state. Hence, the motor current demand takes longer to reach steady state.
Figure 3.11: Response of microgrid to motor starting operation: (a) Bus voltage ($v_B$), (b) Bus frequency ($f$)
3.7 Chapter Summary

This chapter validates the models developed for voltage and frequency control in the last chapter. A detailed explanation of the experimental setup is given in this chapter along with the control parameters chosen for simulation and experimental validation of the mathematical models. This chapter systematically provides the responses of voltage and frequency control schemes to black start operation, passive and motor load transients. The microgrid remains stable and responses well damped under all the test conducted to maintain optimal operation of the proposed microgrid.
Chapter 4

Multi DER Converter Microgrid Modelling

Chapter 2 presented the modelling and control of a small scale microgrid with a single DER. The aim of this chapter is to develop the model and control for a scaled version of the microgrid model. Furthermore, this chapter uses the scaled model of the microgrid to introduce real and reactive power sharing control between paralleled DER units. Finally, this is followed by the operation of the microgrid in grid connected mode and development of a power sharing scheme to provide grid support, which leverages a PMU placed at the substation. This chapter allows to leverage and enhance the capabilities of a microgrid with the utilization of PMUs.

4.1 Multi Converter interfaced DER Microgrid

In this chapter, the single converter interfaced DER fed microgrid model is expanded to a multiple DER fed microgrid model. A simple layout of a multi-DER microgrid is shown in Fig. 4.1. The main components of this microgrid are:

1. Converter interfaced DERs

2. Bus capacitor, $C_B$

3. Passive and motor loads

4. Islanding switch, $S_{id}$
The dynamics of DER fed microgrid shown in Fig. 4.1 are modelled using the scaled component model as shown in Fig. 4.2. Each DER model used for scaling the microgrid is as developed in Chapter 2.

For analysis of the model of a multi-DER fed microgrid, Fig. 4.3 shows the simple case considered in this work, where all reactive and motor loads are conglomerated into a single equivalent current source. The dynamic equations of the microgrid are an extension of the model derived for the single-DER fed system in Chapter 2 but with the additional inputs from $n$ DER converters to the bus B. The microgrid system equations are as represented in $dq$-frame by (4.1)-(4.2):

$$
\begin{align*}
\frac{dv_{Bd}}{dt} &= -\frac{v_{Bd}}{R_dC_B} + \sum_{m=1}^{n} \frac{i_{2d,m}}{C_B} - \frac{i_{Ld}}{C_B} + \omega_{dq}v_{Bq} \\
\frac{dv_{Bq}}{dt} &= -\frac{v_{Bq}}{R_qC_B} + \sum_{m=1}^{n} \frac{i_{2q,m}}{C_B} - \frac{i_{Lq}}{C_B} - \omega_{dq}v_{Bd}
\end{align*}
$$

Where,

$v_{Bd}, v_{Bq}$ - $dq$-axis component of $v_B$

$i_{2d,m}$ - $dq$-axis component of $i_2$ for $m^{th}$ DER converter

$i_{Ld_q}$ - $dq$-axis component of $i_L$
Instantaneous synchronization to the bus voltage, as proposed for microgrid control in [55] is employed. The $d$-axis of the reference frame is aligned with $v_{Bd}$. This is achieved by substituting $v_{Bq}$ and $\frac{dv_{Bq}}{dt} = 0$ in (4.1)-(4.2).

\[
\omega_{dq} = \frac{(\sum_{m=1}^{n} i_{2q,m}) - i_{Lq}}{C_B v_{Bd}}
\]  

(4.3)

\[
\frac{dv_{Bd}}{dt} = -\frac{v_{Bd}}{R_i C_B} + \frac{\sum_{m=1}^{n} i_{2d,m}}{C_B} - \frac{i_{Ld}}{C_B}
\]  

(4.4)

The microgrid outputs to be regulated are the bus voltage and frequency as shown by (4.5)-(4.6).

\[|\vec{v}_B| = v_{Bd}\]  

(4.5)

\[\omega = \omega_{dq}\]  

(4.6)
4.1.1 Steady-State Solutions

The steady state solution for the microgrid system of equations is given by the following relations:

\[ v_{Bd} = R_l \left[ \sum_{m=1}^{n} i_{2d,m} \right] - i_{Ld} \]  
(4.7)

The steady state solutions for outputs to be regulated are as shown by (4.8) and (4.9):

\[ |\overrightarrow{v_B}| = v_{Bd} = R_l \left[ \sum_{m=1}^{n} i_{2d,m} \right] - i_{Ld} \]  
(4.8)
\[ \omega = \frac{\left( \sum_{m=1}^{n} i_{2q,m} \right) - i_{Lq}}{C_B v_{Bd}} \] (4.9)

### 4.1.2 State-Space System Model

The microgrid system equations can be represented in state-space form using state vector \((x)\), input vector \((u)\), disturbance vector \((d)\), and the output vector \((y)\):

\[
\dot{v}_{Bd} = -\frac{1}{R_l C_B} \begin{bmatrix} v_{Bd} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_B} & 0 \\ \sum_{m=1}^{n} \frac{i_{2d,m}}{C_B} & \sum_{m=1}^{n} \frac{i_{2q,m}}{C_B} \end{bmatrix} + \begin{bmatrix} -\frac{1}{C_B} & 0 \\ \sum_{m=1}^{n} \frac{i_{2d,m}}{C_B} & \sum_{m=1}^{n} \frac{i_{2q,m}}{C_B} \end{bmatrix} \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} (4.10)
\]

\[
\omega = \frac{1}{v_{Bd}} \left\{ \begin{bmatrix} 0 & \frac{1}{C_B} \\ \sum_{m=1}^{n} \frac{i_{2d,m}}{C_B} & \sum_{m=1}^{n} \frac{i_{2q,m}}{C_B} \end{bmatrix} + \begin{bmatrix} 0 & -\frac{1}{C_B} \\ \sum_{m=1}^{n} \frac{i_{2d,m}}{C_B} & \sum_{m=1}^{n} \frac{i_{2q,m}}{C_B} \end{bmatrix} \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \right\} (4.11)
\]

\[
\dot{x} = A_m x + B_m \sum_{m=1}^{n} u + E_m d (4.12)
\]

\[
y = C_m x + \frac{1}{x} \left\{ D_m \sum_{m=1}^{n} u + F_m d \right\} (4.13)
\]

Where,

\[
x = \begin{bmatrix} v_{Bd} \end{bmatrix} (4.14)
\]

\[
u = \begin{bmatrix} i_{2d,m} & i_{2q,m} \end{bmatrix}^T (4.15)
\]

\[
d = \begin{bmatrix} i_{Ld} & i_{Lq} \end{bmatrix}^T (4.16)
\]

\[
y = \begin{bmatrix} v_B & \omega \end{bmatrix}^T (4.17)
\]

The state matrices can be represented as follows:

\[
A_m = \begin{bmatrix} -\frac{1}{R_l C_B} \end{bmatrix} (4.18)
\]

\[
B_m = \begin{bmatrix} \frac{1}{C_B} & 0 \end{bmatrix} (4.19)
\]

\[
E_m = \begin{bmatrix} -\frac{1}{C_B} & 0 \end{bmatrix} (4.20)
\]
\[ C_m = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \]  
(4.21)

\[ D_m = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{c_B} \end{bmatrix} \]  
(4.22)

\[ F_m = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{c_B} \end{bmatrix} \]  
(4.23)

### 4.2 Dual DER Converter Microgrid Supervisory Voltage and Frequency Control

The voltage and frequency control is developed for a dual converter microgrid \( m = 2 \) as shown in Fig. 4.4. It shows that the voltage and frequency control of each DER converter has a nested current mode control. The DER output currents, in \( dq \)-frame are the inputs to the dynamic microgrid model as shown by (4.15). The outputs are bus voltage \( v_B \) amplitude and frequency \( \omega \) as shown by (4.17).

With two DER converters connected to the PCC, the microgrid bus voltage is regulated by the \( d \)-frame current outputs from both DER converters. Similarly, the bus frequency is regulated by the \( q \)-frame output currents from both DER converter. In order to facilitate a collaborative sharing of the \( d \)- and \( q \)-frame currents to regulate bus voltage and frequency, the following sections discuss active and reactive power sharing using voltage and frequency droop respectively. Here, the voltage is drooped corresponding to the \( d \)-frame current output and the frequency is drooped corresponding to the \( q \)-frame current output.
Figure 4.4: Control model for multi-DER converter microgrid model with \( n = 2 \)
4.2.1 Active Power Sharing: Voltage Droop

The voltage control for each converter is responsible for determining the reference of $d$-frame current ($i_{2d,m}^{ref}$) and hence, controlling the active power output of that converter. Voltage reference droop is applied to the space vector bus voltage amplitude reference to balance the active power shared by each converter in a dual-converter microgrid as given by (4.24) and (4.25).

\[
v_{B1,droop}^{ref} = v_{B1}^{ref} - i_{2d,1} D_{v1} \tag{4.24}
\]

\[
v_{B2,droop}^{ref} = v_{B2}^{ref} - i_{2d,2} D_{v2} \tag{4.25}
\]

Where, $D_{v1}$ and $D_{v2}$ are droop factors for DER converter 1 and 2 respectively.

The voltage control output for each DER converter with a drooped voltage reference can be expressed as (4.26).

\[
u_1 = \left( K_{pv} + \frac{K_{iv}}{s} \right) \left( \frac{v_{B1}^{ref} - i_{2d,1} D_{v1}}{v_{B1,droop}^{ref}} - |\rightarrow v_B| \right) \tag{4.26}
\]

\[
i_{2d,1} = u_1 - \frac{|\rightarrow v_B|}{R_v} \tag{4.27}
\]

Where,

$K_{pv}$ - Proportional constant for voltage control

$K_{iv}$ - Integral constant for voltage control

$R_v$ - Virtual impedance

Figure 4.5 shows the voltage control for the dual converter microgrid along with the voltage droop control for active power sharing among the DER converters. It can also be inferred that the output current ($i_{2d,m}$) of each converter is inversely proportional to the droop factor ($D_{vm}$) as also shown by (4.24) and (4.25). The ratio of active power shared by each converter can be given as a ratio of currents shared between them as expressed in (4.28a).

\[
P_m = \frac{3}{2} v_B i_{2d,m} \tag{4.28a}
\]

\[
i_{2d,m} \propto \frac{1}{D_{vm}} \tag{4.28b}
\]

It can be deduced from (4.28a) and (4.28b) that the ratio of active power shared between two converters can be expressed as a ratio of droop factors as stated in (4.29).

\[
\frac{P_1}{P_2} = \frac{D_{v2}}{D_{v1}} \tag{4.29}
\]
The maximum value of droop factors that can be selected for power sharing between converters is 5% as standardized by NERC BAL-011-TRE-1 [56].

### 4.2.2 Reactive Power Sharing: Frequency Droop

The frequency control for each converter is responsible for determining the reference of \( q \)-frame current \( (i_{2,q,m}^{ref}) \) and hence, controlling the reactive power output of that converter. Frequency reference droop is used to balance the reactive power shared by each converter in a multi-converter fed microgrid as given by (4.30) and (4.31).

\[
\omega_{1,\text{droop}}^{\text{ref}} = \omega_{1}^{\text{ref}} - i_{2,q,1} D_{\omega 1} \tag{4.30}
\]

\[
\omega_{2,\text{droop}}^{\text{ref}} = \omega_{2}^{\text{ref}} - i_{2,q,2} D_{\omega 2} \tag{4.31}
\]

Where, \( D_{\omega 1} \) and \( D_{\omega 2} \) are droop factors for DER converter 1 and 2 respectively.

The frequency control output for each DER converter with a drooped frequency reference can be expressed as (4.32).

\[
i_{2,q,1} = \left( K_{p\omega} + K_{i\omega} \frac{1}{s} \right) \left( \omega_{1}^{\text{ref}} - i_{2,q,1} D_{\omega 1} - \omega \right) \tag{4.32}
\]

Where,

- \( K_{p\omega} \) - Proportional constant for frequency control
- \( K_{i\omega} \) - Integral constant for frequency control

Figure 4.5 shows the frequency control for the dual converter microgrid along with the frequency droop control for reactive power sharing among the DER converters. It can also be inferred that the output current \( (i_{2,q,m}) \) of each converter is inversely proportional to the droop factor \( (D_{\omega m}) \) as also shown by (4.30) and (4.31). The ratio of reactive power shared by each converter can be given as a ratio of currents shared between them as expressed in (4.33a).

\[
Q_{m} = \frac{3}{2} v_{Bd} i_{2,q,m} \tag{4.33a}
\]

\[
i_{2,q,m} \propto \frac{1}{D_{\omega m}} \tag{4.33b}
\]

It can be deduced from (4.33a) and (4.33b) that the ratio of reactive power shared between converters can be expressed as a ratio of droop factors as stated in (4.34).

\[
\frac{Q_1}{Q_2} = \frac{D_{\omega 2}}{D_{\omega 1}} \tag{4.34}
\]
Figure 4.5: Voltage and frequency control of dual converter microgrid with active and reactive power sharing
4.3 Grid-Connected Operation

The dual-converter microgrid discussed in the previous sections is modeled to operate in islanded state with supervisory voltage and frequency control. As shown in Fig. 4.6 during islanded mode, bus, $B$, and grid parameters are not identical. The switch, $S_{id}$, is used to execute microgrid mode transfers. The connection of islanded microgrid to a stable grid can be made subsequent to the following conditions:

1. Bus voltage ($|v_B|$) – Grid voltage ($|v_g|$) ≤ $\epsilon_v$
2. Bus frequency ($\omega$) – Grid frequency ($\omega_g$) ≤ $\epsilon_\omega$
3. Bus theta ($\theta$) – Grid theta ($\theta_g$) ≤ $\epsilon_\theta$

![Figure 4.6: High level operation mode transfer logic](image)

The grid connection control takes the remote, GPS time-stamped grid parameters as projected by the Phasor Measurement Unit (PMU). It operates by comparing the grid and bus parameters as mentioned above and switches mode. The supervisory voltage and frequency control will change upon transition to grid connected operation.

Upon interconnection with the grid, the voltage and frequency is controlled by the utility ($v_g, \omega_g$). The microgrid bus voltage and frequency changes to grid voltage ($v_g$) and frequency ($\omega_g$) as expressed in (4.35) and (4.36):

\[ |v_B| = |v_g| \] (4.35)

\[ \omega = \omega_g \] (4.36)
Upon interconnection, the microgrid is controlled using current mode control for each DER converter. Hence, the $d$ and $q$-frame current upon connection to the grid for DER converters is calculated using the relations represented in (4.37) and (4.38) respectively.

$$i_{2d}^{ref} = \frac{2}{3} \frac{P^{ref}}{v_{Bd}} \quad (4.37)$$

$$i_{2q}^{ref} = -\frac{2}{3} \frac{Q^{ref}}{v_{Bd}} \quad (4.38)$$

Where,
- $v_{Bd}, v_{Bq}$ - local $dq$-frame component of grid voltage
- $P^{ref}, Q^{ref}$ - Active and reactive power reference provided by the PMU

With the microgrid operating in grid connected mode, the voltage and frequency are constants. Thus, $i_{2dq}$ are the state variables in the microgrid system model. The following conclusions can be deduced:

1. The $dq$-frame currents upon connection to the grid are set to the load demands in islanded state

2. The power demand reference is specified by the grid operator at the substation

In order to facilitate power sharing between the microgrid and bulk power system, the following sections develop a power sharing mechanism.

### 4.4 Grid Power Dispatch Mechanism

The active and reactive power demand in an islanded microgrid is met indirectly by voltage and frequency controls developed in the previous sections. In the grid connected mode, the conventional method to regulate the power demand is by changing the remote power references to the utility specified values. The DER current demand reference is then locally decided on the basis of the relations (4.37)-(4.38). The proposed microgrid is capable of operating in the following modes:

1. Islanded mode operation using voltage and frequency control

2. Grid connected operation using current mode control ($P - Q$ control) by utility dispatch

All load changes in microgrid are supplied by the utility unless the grid operator specifies the updated active and reactive power demand. This thesis proposes to augment
power dispatch from the microgrid by leveraging the capabilities of a phasor measurement unit (PMU) placed at the substation. The following section explains the functionality of a new mechanism to supply power demand in grid connected mode from dispatchable generation.

4.4.1 PMU Enabled Power Dispatch

The microgrid operates in $P - Q$ control subsequent to grid connection. As shown in Fig. 4.6, the PMU is connected on the grid side of the microgrid islanding breaker ($S_{id}$). The voltage and current measurements from the PMU can be leveraged to detect and supply real and reactive power demand in grid connected mode. The microgrid will supply the power demand according to the reference specified by the PMU. Hence, the microgrid is capable of operating in standalone and grid-connected mode using respective control strategies as shown in Fig. 4.7.

![Figure 4.7: Microgrid operating modes](image)

Figure 4.8 depicts the sequence of execution of the PMU power dispatch mechanism along with power direction at each step. The addition of load on the microgrid bus will instantaneously draw current demand from the grid ($i_g$). During this step, the direction
of power flow will be from the grid to the load. As the PMU detects this current demand, it will update the microgrid control about the updated total power demand at the bus. This is followed by the microgrid controller updating the power supplied to the load. Hence, the load power demand will be compensated by the microgrid by virtue of the updated microgrid output current \( i_2 \). In the final step, the direction of power will be from microgrid to the load. The operation of this mechanism is under the following conditions:

1. Initiated only in grid connected mode
2. The microgrid will supply loads depending on the available dispatchable generation
3. The mechanism ceases to operate when the microgrid reaches its rated power capacity as it enters power clipping
4. In the case of an islanding detection, the microgrid control ceases PMU power dispatch and switches to voltage-frequency control to operate in islanded mode
5. In the case of PMU malfunction, the microgrid switches to direct dispatch from the grid operator

This mechanism can also be utilized to compensate current demand for transient load additions anywhere in the feeder system on the basis of measurements from non-collocated PMUs. It can also be leveraged to provide active and reactive power support to mitigate transmission level contingencies. This will help alleviate the stress on transmission level networks and allow better utilization of existing and upcoming microgrids.
Chapter 4. Multi DER Converter Microgrid Modelling

(a) Microgrid supplies local load current demand in islanded mode

(b) Immediately after grid re-connection the microgrid continues to supplies local load current demand

(c) Microgrid DERs update the PMU about their output power
(d) Immediately after addition of microgrid load ($\Delta i_L$) grid supplying additional load current ($\Delta i_L$) instantaneously

(e) PMU transmits updated power demand information to the microgrid

(f) microgrid supplies updated current demand ($i_L + \Delta i_L$)

Figure 4.8: Sequence of execution of PMU power dispatch mechanism
4.5 Chapter Summary

This chapter presents an extension of the single-DER fed microgrid controls to a scaled multi-DER fed microgrid. First, a model is developed for voltage and frequency control of a multi-DER fed microgrid along with a state-space model. This is followed by the development of active and reactive power for a dual-DER fed microgrid which is chosen to validate all derived models in this chapter. Finally, a grid connection operation and grid power dispatch mechanism is developed using the available resource of a substation based phasor measurement unit.
Chapter 5

Experimental Results

This chapter presents the experimental results to validate the responses of control schemes modeled in the previous chapter for a multi-DER fed microgrid. It starts with a brief description of the experimental setup layout. It then describes the control programming environment and the criteria for selection of control parameters. This chapter discusses standalone operation, power sharing, and grid-connected operation.

Finally, the experimental results are presented and compared with the simulation results gathered from $PSCAD^{TM}/EMTDC$.

5.1 Experimental Setup Layout

This section provides the detailed description of the experimental setup used for validating the dual-DER fed microgrid control in islanded and grid-connected mode as shown in Fig. 5.1. This setup is also extended to verify active and reactive power sharing schemes amongst the existing DER converters. This setup is an extension of the experimental setup described in Chapter 3. Another DER interfaced converter with LCL filter is added to the existing setup to verify the voltage and frequency control schemes developed for a dual-DER fed microgrid in Chapter 4.

The control schemes developed for a dual-DER fed microgrid are programmed in National Instruments CompactRIO using LabVIEW interface. It uses real-time FPGA to program data acquisition, control design and pulse width modulation (PWM) generation. It is also connected to a PC for visualizing the control graphical user interface using LabVIEW. The compactRIO outputs the gating pulses to drive the switches of the DER converter.
Figure 5.1: Layout of the experimental setup for a dual-DER converter microgrid.
Chapter 5. Experimental Results

The gating signal outputs for each DER converter are generated from a separate CompactRIO unit to drive each converter independently. The compactRIO is also used to program active and reactive power sharing developed in the previous chapter. For the DER converter, voltage and current sensors are used to sense dc voltage \(v_{dc}\), three-phase bus voltage \(v_B\), and output currents \(i_2\) for each DER converters. These sensed values are sent to the compactRIO (NI-9035) as control feedback parameters.

The Phasor Measurement Unit (PMU) is connected to sense the three-phase grid voltage \(v_g\) and current \(i_g\). The PMU values are used for synchronization of bus voltage, \(v_B\), when the reconnection from islanded to grid connected mode takes place. The PMU is also connected to the CompactRIO hardware and the PC using IEEE C37.118.1 communication protocol. The PMU is also used to gather information to implement a power sharing mechanism that transfers or shares the load supplied by the grid when the microgrid is operating in grid-connected mode depending upon the available microgrid generation.

5.2 Control Parameters

The control parameters are selected as specified in Table 5.1. The proportional and integral gains are selected to have the same value for both DER converters. The voltage and frequency parameters used in this experimental setup are identical to the ones described for a single DER converter microgrid model in Chapter 3 (also shown in Table 5.1), and are consistent with IEEE Std 1547.1a [49].

5.3 Load Sharing Response

In this section, the response of active and reactive power sharing is discussed. All DER units in the multi-DER fed microgrid can be black started individually sequentially or in tandem, regardless of synchronization of consistent \(dq\)-frame creation across all units. Here, to demonstrate the load sharing response, the microgrid is black started using the supervisory voltage and frequency control applied to a single DER converter. The other DER converter connected at the bus is energized later and power sharing occurs autonomously using the active and reactive power sharing schemes developed in Chapter 4. The following sequence of steps are executed to test the response of power sharing:

1. The supervisory voltage and frequency control operate to black start the single DER converter in the microgrid.
2. The second DER is energized and active and reactive power sharing operates by drooping voltage and frequency references against the $d$- and $q$-frame DER converter output currents respectively.

3. The power required by the load at the PCC is finally shared by the DER converters in a ratio depending on their droop coefficients.

The droop coefficients selected for active and reactive power control in this work are as stated Table 5.1. This selection is based on the type of generation from Table 5.2 as specified by NERC BAL-001-TRE-1 [56].

As shown in Fig. 5.2, the system is black started with voltage and frequency control. The total active power demand at the bus $B$ is supplied by DER converter 1. Hence, $P_1 = 4.25$ kW and $P_2 = 0$ kW from time $t = 0s$ to $t = 0.1s$. The response of three-phase bus voltage ($v_B$) and frequency ($f$) at black start requires 1 to 2 cycles, as shown in Fig. 5.2, if no motor load exist. At time $t = 0.1s$, the active power sharing starts to operate and the load demand is shared equally between DER converter 1 and 2 by virtue of power sharing control as shown in Fig. 5.3. The bus voltage response is as shown in Fig. 5.3.

After the power sharing control is initiated, the power shared by each DER converter is
Table 5.2: Droop coefficient specifications for different types of generation

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>Maximum Droop Setting (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>5</td>
</tr>
<tr>
<td>Nuclear</td>
<td>5</td>
</tr>
<tr>
<td>Coal and Lignite</td>
<td>5</td>
</tr>
<tr>
<td>Combustion Turbine (Simple Cycle and Single-Shaft Combined Cycle)</td>
<td>5</td>
</tr>
<tr>
<td>Combustion Turbine (Combined Cycle)</td>
<td>4</td>
</tr>
<tr>
<td>Steam Turbine (Simple Cycle)</td>
<td>5</td>
</tr>
<tr>
<td>Steam Turbine (Combined Cycle)</td>
<td>5</td>
</tr>
<tr>
<td>Diesel</td>
<td>5</td>
</tr>
<tr>
<td>Wind Powered Generator</td>
<td>5</td>
</tr>
<tr>
<td>DC Tie Providing Ancillary Services</td>
<td>5</td>
</tr>
<tr>
<td><strong>Renewable (Non-Hydro)</strong></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

given by (5.1)-(5.2).

Similarly, for testing the reactive power sharing control, initially $Q_1 = -0.9 \text{kVar}$ and $Q_2 = 0 \text{kVar}$ from time $t = 0s$ to $t = 0.1s$ as shown in Fig. 5.2. At time $t = 0.1s$, the reactive power sharing starts to operate and the load demand is shared equally between DER converter 1 and 2 by virtue of power sharing control as shown by the bottom plot in Fig. 5.3. The bus frequency response is shown in Fig. 5.3. After the power sharing control is initiated, the reactive power shared by each DER converter is given by (5.3)-(5.4). The zoomed in response of the initial transient after engaging the second DER with load sharing is shown in Fig. 5.4. It also depicts the voltage and frequency responses at these initial transients.

$$P_1 = \frac{3}{2}(v_{rB1}^{ref} - i_{2d1}Dv_1)i_{2d1}$$

$$P_2 = \frac{3}{2}(v_{rB2}^{ref} - i_{2d2}Dv_2)i_{2d2}$$

$$Q_1 = -\frac{3}{2}(v_{rB1}^{ref} - i_{2d1}Dv_1)i_{2q1}$$

$$Q_2 = -\frac{3}{2}(v_{rB2}^{ref} - i_{2d2}Dv_2)i_{2q2}$$

At time $t = 1.8s$, the active and reactive power shared by both DER converters is equalized as shown in Fig. 5.3. Hence, $P_1 = P_2 = 2.125 \text{kW}$ and $Q_1 = Q_2 = -0.4 \text{kVar}$ after the control reaches steady state. Now, the instantaneous value of bus voltage and frequency is $v_B = 170V - 0.05(8.3A) = 169.6 \text{V}$ and $f = 60 Hz - 0.05(1.6) = 59.92 \text{Hz}$ respectively.
Figure 5.2: Black start response of microgrid from single DER (a) Three-phase bus voltage ($v_B$), (b) Bus frequency ($f$), (c) Active power of DER converters, (d) Reactive power of DER converters
Figure 5.3: Response depicting power sharing: (a) active power of DER converters, (b) three-phase bus voltage ($v_B$), (c) reactive power sharing, (d) bus frequency ($f$)
Figure 5.4: Zoomed in transient response due to power sharing: (a) active power of DER converters, (b) bus voltage ($v_B$), (c) reactive power of DER converters, (d) bus frequency ($f$)
5.4 Microgrid Mode Switching Response

In this section the bus voltage \( v_B \) and frequency \( \omega \) response is discussed when the dual-DER fed microgrid is (i) re-connected to the grid, and (ii) islanded from the grid. This is used to verify the validity of voltage and frequency control for a dual-DER fed microgrid during mode transitions.

5.4.1 Grid Re-connection Transients

In this test the microgrid operating in islanded mode is re-connected to the grid. The operation takes place by connecting the microgrid to the grid by synchronizing to the grid voltage values received from the PMU situated after the islanding switch \( (S_{id}) \). Prior to grid re-connection, the current demand is shared uniformly between DER converters connected at the bus, \( B \), by virtue of power sharing control as discussed in the previous sections. The re-connection to the grid requires the transfer of voltage and frequency control to a \( P - Q \) control where the \( dq \)-frame current reference is calculated using (5.5)-(5.6).

\[
\begin{align*}
    i_{2d}^{ref} &= \frac{2}{3} \frac{P^{ref}}{v_{Bd}} \\
    i_{2q}^{ref} &= -\frac{2}{3} \frac{Q^{ref}}{v_{Bd}}
\end{align*}
\]

Where,
\( P^{ref}, Q^{ref} \) - Active and reactive power reference provided by the PMU
\( v_{Bd}, v_{Bq} \) - Locally measured \( dq \)-frame component of bus voltage
\( i_{2d}, i_{2q} \) - Locally computed \( dq \)-frame component of DER output current reference

As shown in Fig. 5.5, the microgrid bus voltage \( (v_B) \) and frequency \( (\omega) \) is maintained using the voltage and frequency control before re-connecting to the grid. At \( t = 0s \), the islanding switch \( (S_{id}) \) is closed to re-connect the microgrid to the grid. The microgrid bus voltage and frequency after grid connection are determined by the grid, thus given by (5.7)-(5.8).

\[
\begin{align*}
    |\vec{v}_B| &= |\vec{v}_g| \\
    \omega &= \omega_g
\end{align*}
\]

Where,
$v_g$ - Grid voltage measured by PMU

$\omega_g$ - Grid frequency measured by PMU

As shown in Fig. 5.5, the bus voltage ($v_B$) experiences a transient change from 169.6 V to 168 V as a result of grid connection. This value settles to grid voltage at 169.6 V with a recovery time of $t_{rec} = 20ms$. Similarly, the bus frequency ($\omega$) will experience a transient change from 60 Hz to 59.2 Hz as shown in the middle plot in Fig. 5.5. This is because minor phase error must be accommodated. Subsequent to grid re-connection, the microgrid operates with $P-Q$ control.

Figure 5.5: The experimental transient response to grid re-connection (a) bus voltage ($v_B$), (b) bus frequency ($\omega$), (c) three-phase bus voltage
5.4.2 Islanding Transients

In this test the grid connected microgrid is transferred to islanded mode by opening the islanding switch ($S_{id}$). This operation deprives the bus, $B$, of any voltage and frequency reference from the grid. The PMU sends a request to the DERs to start operation in standalone mode. This leads to commencement of transfer to operation using supervisory voltage and frequency control. The transfer to islanded microgrid results in the load demand being supplied by DER converters. Prior to transfer from grid connected mode to islanded mode, the DER converter output currents are controlled by $P - Q$ control, after islanding they operate in power sharing control.

As shown in Fig. 5.6, the disconnection of grid causes bus voltage ($v_B$) to experience a transient deviation from 170 V to 170.2 V, with a recovery time of $t_{rec} = 4 ms$. Similarly, the bus frequency ($\omega$) also experiences a deviation of 0.2 Hz at the time of grid disconnection with a recovery time, $t_{rec} = 4 ms$. 
Figure 5.6: The experimental transient response to islanding: (a) bus voltage \(v_B\), (b) bus frequency \(\omega\), (c) three-phase bus voltage
5.5 PMU Based Power Dispatch

The case of the grid power sharing mechanism was tested on the single-DER fed microgrid setup. The PMU based power dispatch is tested for various test cases as stated in Table 5.3. The grid voltage \( v_g \) and current \( i_g \) are obtained from the PMU and visualized on an oscilloscope. The test cases are discussed as follows:

1. **Grid re-connection**: In this case, the microgrid operation switches from islanded to grid connected mode as in Section 5.4.1 but here we observe the PMU measured grid quantities vs. the DER output quantities. The control operation changes from voltage-frequency to \( P - Q \) control. As shown in the top plot in Fig. 5.7, the three-phase grid current \( i_g \) depicts a transient change upon grid connection at \( t = 0s \). The local load demand is supplied by the microgrid. The power output of the DER converter shows a transient dip at \( t = 0s \), attributed to the transient dip in microgrid voltage and current transient upon grid connection. The PMU interface depicts grid voltage \( v_g \) and currents \( i_g \) after the operation as shown in the bottom plot in Fig. 5.7.

2. **Transient load addition**: In this case, the microgrid is operating in grid connected mode with a load demand rising from 3850W to 4950W due to addition of microgrid load. Fig. 5.8 shows transient as the load is introduced on the bus, \( B \) at \( t = -0.025s \). The grid instantaneously supplies the load demand as seen from the grid currents. The PMU dispatch detects the change in load and directs the microgrid DER to supply the additional load. As a result, the microgrid power output changes (refer to Fig. 5.8c) at time, \( t = 0s \). Thus, the microgrid supplies the existing and additional load with minimal grid contribution.

3. **Transient load removal**: In this case, the microgrid is operating in grid connected mode with a load demand of 4950W as shown in Fig. 5.9. A load is transiently removed from the microgrid bus, \( B \). As a result, the microgrid load demand drops from 4950W to 4250W as shown in the bottom plot in Fig. 5.9. This shows that the microgrid is able to regulate its power demand due to changing loading conditions.

4. **Over rated operation**: In this case, the rated power of the DER converter is set to \( P_{\text{1 rated}} = 5kW \) due to the current limit of the converters used for the experimental setup. The microgrid is operating at rated capacity power as shown in Fig. 5.10. A transient load is switched on the microgrid bus. The grid currents instantaneously supplying the load current demand. The microgrid reference reference depicts a
change in power demand as shown in Fig. 5.10, but the microgrid power does not increase due to operation at rated capacity.

These results validate and summarize the effectiveness of PMU based microgrid power dispatch mechanism as a way to leverage the capacity of microgrids to supply power in grid connected mode.

Table 5.3: Test cases for PMU enabled power dispatch mechanism

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grid connection</td>
</tr>
<tr>
<td>2</td>
<td>Transient load addition</td>
</tr>
<tr>
<td>3</td>
<td>Transient load removal</td>
</tr>
<tr>
<td>4</td>
<td>Over rated operation</td>
</tr>
</tbody>
</table>
Figure 5.7: The response to grid re-connection: (a) grid currents ($i_g$), (b) DER converter output current ($i_2$), (c) DER converter active power ($P_1$), (d) AccSELeator interface depicting current and voltages supplied by the grid
Figure 5.8: The response to transient resistive load step: (a) grid currents \((i_g)\), (b) DER converter output current \((i_2)\), (c) DER converter active power \((P_1)\), (d) AccSELerator interface depicting current and voltages supplied by the grid.
Figure 5.9: The response to transient resistive load removal: (a) grid currents \(i_g\), (b) DER converter output current \(i_2\), (c) DER converter active power \(P_1\), (d) AccSELerator interface depicting current and voltages supplied by the grid.
Figure 5.10: The response to resistive load step of 500 W above rated capacity: (a) grid currents ($i_g$), (b) DER converter active power ($P_1$), (c) AccSELerator interface depicting current and voltages supplied by the grid.
5.6 Chapter Summary

This chapter validates the models developed for voltage and frequency control for multi-DER converter fed microgrids by considering a case of $n=2$. A detailed explanation of the testing process is explained in this chapter for respective tests. It also gives an explanation of the complete experimental setup along with the control parameters chosen for simulation and experimental validation of the mathematical models. This chapter systematically provides the responses of voltage and frequency control schemes to black start operation, power sharing, grid interconnection, islanding and PMU power dispatch. The microgrid remains stable and responses well damped under all the test conducted to maintain optimal operation of the proposed microgrid.
Chapter 6

Conclusion

Existing and upcoming microgrid infrastructure at the distribution level has the potential of operating autonomously and in cooperation with the transmission level network. AC microgrids provide an opportunity for increasing the footprint of renewable distributed energy resource (DER) powered generation. Development of infrastructure can enable a superior utilization of renewable energy on the distribution and transmission level networks.

In this thesis, an AC microgrid is modelled for multi-mode operation. This is achieved through the development of black start control for DER converter fed microgrids. Thus, the microgrid operates in standalone mode by utilizing voltage-frequency control. Furthermore, the thesis leverages modular communication capabilities of phasor measurement units (PMUs) to facilitate the synchronization of the microgrid with the grid upon re-connection. PMUs are further utilized to develop a power dispatch mechanism as an alternative to utility dispatch. Thus, this thesis undertakes the modelling and control infrastructure design of an AC microgrid.

6.1 Contributions

This thesis models an AC microgrid powered by DER interfaced converters with voltage and frequency control developed to facilitate black start operation in standalone mode. This is undertaken in different reference frames to: (i) maintain current control operation regardless of synchronization of dq-frame across the non-collocated DER units, (ii) simplify the grid synchronization process upon grid re-connection, and (iii) operate the microgrid in grid-connected mode. The operation of the microgrid is validated using PSCAD/EMTDC\textsuperscript{TM} simulation environment and an experimental setup.

The microgrid controls developed are utilized to scale the microgrid for multi-DER
interfaced converter operation. This is achieved by designing a droop based control to facilitate parallel operation of DER converters. In this way, the microgrid is operated in standalone mode with the capability to share power depending upon the rating of DER units. The thesis leverages modular communication to transfer between operation mode using a Phasor Measurement Unit (PMU). A synchronization control is designed to ensure soft transfer between modes. Nominally, the microgrid operates in grid-connected mode using P-Q control also known as utility dispatch.

Finally, this thesis utilizes PMU values from the transformer substation to facilitate power dispatch to the microgrid in grid-connected mode of operation. This control mechanism allows the microgrid to operate under option of either utility or PMU dispatch. This thesis discusses PMU dispatch wherein the PMU measurements are used to detect transient change in loading at the microgrid bus. This mechanism can utilize available dispatch-able generation to supply local loads. Hence, the microgrid capacity is utilized to relieve the stress on the transmission level networks. A further extension of this scheme is towards alleviating the impacts of outages and contingencies in the transmission level feeding reactive power from distribution level microgrids.

The controls are modelled and developed in MATLAB design tools and PSCAD is used to assess the controls developed. Results are further validated using an experimental setup comprising of dual-DER converter fed microgrid. The PMU used in the development of this work is embedded in a relay, placed at the transformer substation. This thesis validates the autonomous black start of multi-DER fed microgrids and investigates its operation in grid-connected mode using strategically placed PMUs, modular communication and sophisticated control. The primary contributions of this thesis are summarized as follows:

1. Development of autonomous black start enabled by voltage and frequency control for operation of microgrid in standalone mode.

2. Demonstration of utilization of asynchronous $\alpha\beta$-frame to facilitate black start operation of multi-DER fed microgrid without the need to synchronize using phase locked loop (PLL).

3. Utilizing modular communication of the Phasor Measurement Unit (PMU) to establish microgrid synchronization with the grid.

4. Development of a power dispatch mechanism using PMUs as an alternative to utility dispatch. Hence, venturing into self-optimizable distribution networks with continual power flow.
6.2 Future Work

The work proposed in this thesis can be expanded in the following potential areas:

1. The impact of unpredictability of renewable generation (like solar, wind etc.) needs to be examined on the control schemes and communication infrastructure.

2. Investigating operation with nonlinear and unbalanced loads.

3. Investigating the impact of EV charging (G2V, V2G) infrastructure with existing proposed control.

4. Investigating the potential of PMUs to mitigate grid level outages, through automatic PMU dispatch of incremental real and reactive power commands.
Bibliography


Appendices
Appendix A

Standard Technical Requirements

A.1 IEEE 1547: Fault Ride-Through Parameters

Table A.1: Default Response of DER to Abnormal Voltages

<table>
<thead>
<tr>
<th>Voltage Range (% of base voltage)</th>
<th>Clearing Time (s)</th>
<th>Clearing Time: adjustable up to and including (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V &lt; 45</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>45 ≤ V &lt; 60</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>60 ≤ V &lt; 88</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>110 ≤ V &lt; 120</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>V ≥ 120</td>
<td>0.16</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table A.2: Default Response of DER to Abnormal Frequencies

<table>
<thead>
<tr>
<th>Function</th>
<th>Default Settings</th>
<th>Ranges of Adjustability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (Hz)</td>
<td>Clearing Time (s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UF 1</td>
<td>&lt; 57</td>
<td>0.16</td>
</tr>
<tr>
<td>UF 2</td>
<td>&lt; 59.5</td>
<td>2</td>
</tr>
<tr>
<td>OF 1</td>
<td>&gt; 60.5</td>
<td>2</td>
</tr>
<tr>
<td>OF 2</td>
<td>&gt; 62</td>
<td>0.16</td>
</tr>
</tbody>
</table>

1Base Voltages are the nominal system voltages stated in ANSI C84.1 - 2011
A.2 IEEE Std. C37.118.1: Parameters

The filter coefficient $W(k)$ is given for P and M class filter is given in equation A.1 and A.2 as:

$$ W(k) = 1 - \frac{2}{N + 2|k|} $$  \hspace{1cm} (A.1)

$$ W(k) = \frac{\sin(2\pi k \cdot \frac{2F_{fr}}{F_{sampling}})}{2\pi k \cdot \frac{2F_{fr}}{F_{sampling}}} h(k) $$  \hspace{1cm} (A.2)

Where:

- $k$ - $-N/2 : N/2$ (integer values only)
- $N$ - filter order
- $F_{fr}$ - low-pass filter reference frequency
- $F_{sampling}$ - sampling frequency of the system
- $h(k)$ - Hamming function
- $W(0)$ - 1

Table A.3: Reporting Latency of PMUs

<table>
<thead>
<tr>
<th>Performance Class</th>
<th>Maximum PMU Reporting Latency (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Class</td>
<td>$2/F_s$</td>
</tr>
<tr>
<td>M Class</td>
<td>$7/F_s$</td>
</tr>
</tbody>
</table>
A.3 IEEE Std. 519-2014: Voltage and Current Distortion Limits

Table A.4: Voltage Distortion Limits

<table>
<thead>
<tr>
<th>Bus Voltage $V$ at the PCC (kV)</th>
<th>Individual Harmonic (%)</th>
<th>Total Harmonic Distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \leq 1.0$</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>$1.0 &lt; V \leq 60$</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$69 &lt; V \leq 161$</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$161 &lt; V$</td>
<td>1.0</td>
<td>1.5(^2)</td>
</tr>
</tbody>
</table>

Here, $I_{SC}$ is the maximum short-circuit current at PCC and $I_L$ is the maximum demand load current at the PCC under normal load operating conditions.

Table A.5: Current Distortion Limits for Systems Rated 120 V through 69 kV

<table>
<thead>
<tr>
<th>Individual Harmonic Order (Odd Harmonics)(^4)</th>
<th>Maximum Harmonic Current Distortion of Maximum Demand Current (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{SC}/I_L$</td>
<td>3≤h&lt;11</td>
</tr>
<tr>
<td>&lt;20</td>
<td>4.0</td>
</tr>
<tr>
<td>20&lt;50</td>
<td>7.0</td>
</tr>
<tr>
<td>50&lt;100</td>
<td>10.0</td>
</tr>
<tr>
<td>100&lt;1000</td>
<td>12.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
</tr>
</tbody>
</table>

\(^2\)High-voltage systems can have up to 2.0 % THD where the cause is an HVDC terminal whose effects will attenuate at points in the network where future users may be connected.

\(^3\)Even harmonics are limited to 25% of the odd harmonic limits above.

\(^4\)Current distortions that result in a dc offset are not allowed.
Appendix B

LCL Filter Design

A typical voltage source converter (VSC) with an LCL filter is designed for this work. The design is based on the schematic shown in Fig. B.1. The parameters given in Table B.1 were chosen on the basis of the following design consideration:

1. The current through the capacitor \( i_c \) should be less than 1% of the fundamental output current.

2. The largest harmonic of the output current should be less than 1% of the fundamental output current.

3. The sizing of \( L_1, L_2, C_f \) should consider minimizing the energy stored in them.

In addition to the above stated considerations, the design was carried out for specific parameters of the grid as stated in Table B.2

![Figure B.1: Schematic of LCL Filter](image)

The LCL filter parameters as stated in Table B.1 were used to implement a VSC in MATLAB/SIMULINK. The VSC current controller response to unit step as represented in Fig. B.2. The resonance in the plot is due to the LC circuit formed by \( L_2 \) and \( C_f \).
Appendix B. LCL Filter Design

Table B.1: LCL Filter Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>1.6 mH</td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.81 mH</td>
</tr>
<tr>
<td>$C_f$</td>
<td>9.81 µF</td>
</tr>
</tbody>
</table>

Table B.2: System Ratings

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Voltage ($V_{LL}^{bus}$)</td>
<td>208 V</td>
</tr>
<tr>
<td>DC Voltage ($V_{dc}$)</td>
<td>380 V</td>
</tr>
<tr>
<td>VSC Current Rating ($I_{rated}$)</td>
<td>35.4 A</td>
</tr>
<tr>
<td>Grid Frequency ($f_g$)</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Switching Frequency ($f_s$)</td>
<td>6 kHz</td>
</tr>
</tbody>
</table>

Figure B.2: Step response of VSC current controller without damping resistor

The response of this LCL filter is exacerbated by the presence of a capacitive load ($C_l$) due to the additional resonance of new LC circuit formed at the VSC grid side. This problem can be dealt with the introduction of a damping resistor ($R_d$) in the LCL filter design as depicted in Fig. (B.3) [54]. The frequency-domain analysis gives the transfer functions as given in (B.1), (B.2), (B.3) for the LCL filter. The plant transfer function is represented by $\frac{i_1}{v_t}$ as given by (B.1):

$$\frac{i_1}{v_t} = \frac{L_2 C_f s^2 + R_d C_f s + 1}{L_1 L_2 C_f s^3 + R_d (L_1 + L_2) C_f s^2 + (L_1 + L_2) s}$$
\[
\begin{align*}
\frac{i_2}{v_t} &= \frac{R_d C_f s + 1}{L_1 L_2 C_f s^3 + R_d (L_1 + L_2) C_f s^2 + (L_1 + L_2) s} \\
\frac{i_C}{v_t} &= \frac{L_2 C_f s^2}{L_1 L_2 C_f s^3 + R_d (L_1 + L_2) C_f s^2 + (L_1 + L_2) s}
\end{align*}
\] (B.2) (B.3)

Figure B.3: Schematic of LCL filter with damping resistor \( (R_d) \)

The presence of a damping resistor \( (R_d) \) changes the characteristics of the filter at resonant frequency and high frequency (HF) region with less attenuation with increasing values of \( R_d \) as shown in Fig. B.4. This will reduce the resonance that exists in the LC circuit formed by the addition of a capacitive load and hence, maintain stability. For a given switching frequency, the introduction of damping resistance will lead to change in the following aspects of filter design:

1. Power loss
2. Cost

The value of \( R_d \) is selected by analyzing the response shown in Fig. B.4 and optimizing the above stated impacts on the VSC design. It is chosen to damp the resonance of the LCL filter and for this work, the value of \( R_d = 1.5 \Omega \).
Figure B.4: Bode plot for (B.1) with various values of $R_d$
Figure B.5: Step response of VSC current controller with damping resistor ($R_d$) = 1.5 Ω
Appendix C

Current Mode Control: Results

The current mode control is designed for every DER interfaced converter with LCL filter connected to the microgrid bus in $\alpha\beta$-frame. As explained in Chapter 2, current control is designed to regulate the current demand of voltage and frequency black start control. This section presents the results for current control response to active and reactive power demand. The output current reference is calculated using (C.2) and (C.3) corresponding to reference active ($P_{\text{ref}}$) and reactive ($Q_{\text{ref}}$) power and bus voltage ($v_{Bdq}$). The output current used for operation in this thesis can be given as:

$$i_1 = i_{1\alpha} + i_{1\beta}$$ (C.1)

$$i_{d1}^{\text{ref}} = \frac{2}{3} \frac{P_{\text{ref}}}{v_{Bd}}$$ (C.2)

$$i_{q1}^{\text{ref}} = -\frac{2}{3} \frac{Q_{\text{ref}}}{v_{Bd}}$$ (C.3)

The $dq$-frame reference obtained from (C.2) and (C.3) is converted to $\alpha\beta$-frame using the transformation shown in (C.4).

$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ i_{o} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(wt) & -\sin(wt) & 0 \\ \sin(wt) & \cos(wt) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{d} \\ i_{q} \\ i_{o} \end{bmatrix}$$ (C.4)

Where, $w$ denotes the angular frequency corresponding to the grid frequency ($f$). The active and reactive power references are selected with time as shown in Table C.1. As shown in Figs. C.2a and C.2b, the $\alpha\beta$-frame change in accordance with the changing values of active and reactive power.
Table C.1: Active and reactive power demand with time

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>0≤t&lt;0.5</th>
<th>0.5≤t&lt;0.7</th>
<th>0.7≤t&lt;1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{ref}$</td>
<td>kW</td>
<td>2.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>$Q_{ref}$</td>
<td>kVar</td>
<td>0</td>
<td>0</td>
<td>-0.45</td>
</tr>
</tbody>
</table>

Figure C.1: Response of: (a) three-phase grid voltage, (b) VSC output current

The effectiveness of LCL filter in filtering the output current harmonics is shown in Fig. C.1b. Also, the total harmonic distortion of the designed filter is below 1% as shown in Fig. C.2d for all steady state measurements.
Figure C.2: Response of: (a) $\alpha$-frame converter output current, (b) $\beta$-frame converter output current, (c) total harmonic distortion (THD) for output current, (d) zoomed-in view depicting a THD of less than 1% during steady state operation.