A CONTROL STRATEGY FOR A MICROGRID INTEGRATED WITH MULTIPLE SOLAR-PV UNITS AND A LARGE-SCALE BATTERY ENERGY STORAGE SYSTEM

by

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

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Abstract

This thesis presents a control strategy and its algorithms for a microgrid system that can operate in the grid-connected mode, in the islanded mode, and transfer between them. The microgrid includes three Solar-PV units and one large-scale Battery Energy Storage System (BESS). Performance evaluation of the microgrid is carried out in the time domain, using the PSCAD/EMTDC software platform, to demonstrate the effectiveness of the proposed control strategy. In the grid-connected mode, the three Solar-PV units are controlled to track their Maximum Power Points (MPPs) and the battery State of Charge (SOC) is maintained within a prespecified range. In the islanded mode, the BESS controls the voltage and frequency of the microgrid. The control system is also tested for other transient conditions such as load shedding, Solar-PV loss, temporary faults, reconnection to the utility grid and charge or discharge of the BESS in the case of low or high SOC, respectively.
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<th>Description</th>
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<tbody>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>ESS</td>
<td>Energy Storage System</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>SC</td>
<td>Supervisory Controller</td>
</tr>
<tr>
<td>LC</td>
<td>Local Controller</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>AC</td>
<td>Alternate current</td>
</tr>
<tr>
<td>SCR</td>
<td>Short Circuit Ratio</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>liFePo4</td>
<td>The lithium iron phosphate</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional and Integral</td>
</tr>
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</table>
# Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>P</td>
<td>Active power</td>
<td>W</td>
</tr>
<tr>
<td>Q</td>
<td>Reactive power</td>
<td>Var</td>
</tr>
<tr>
<td>V</td>
<td>Volts</td>
<td>V</td>
</tr>
<tr>
<td>F</td>
<td>Frequency</td>
<td>(\frac{1}{sec})</td>
</tr>
<tr>
<td>A</td>
<td>Amperes</td>
<td>A</td>
</tr>
<tr>
<td>G</td>
<td>Solar irradiance</td>
<td>(\frac{W}{m^2})</td>
</tr>
<tr>
<td>(\omega)</td>
<td>Angular frequency</td>
<td>(\frac{rad}{sec})</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>C°</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
<td>(\Omega)</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>H</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>F</td>
</tr>
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To my dear parents,

beloved husband,

& awesome kids....
Chapter 1

Introduction

Chapter 1 introduces the subject of this thesis and is organized as follows: Section 1.1 is an overview of the microgrid concept, including its definition and operational features. The main challenges to be addressed in this thesis are discussed under the problem statement in section 1.2. Section 1.3 provides the thesis’s objectives and the assumptions considered in this thesis are listed in section 1.4. The thesis outline is stated at the end of this chapter.

1.1 Background

Historically, electricity used to be generated at central generation stations, where the electrical power flowed from the conventional generation systems to the distribution substations through the utility transmission. In the last decades, the concept of microgrids has provided a new paradigm for the electricity system. A microgrid is a small version of the large, interconnected power systems and can operate independent of the utility grid as well as interoperate with it, i.e., it can provide electric power back to the utility grid. Based on the U.S. Department of Energy, a microgrid is defined as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the main grid. A microgrid can connect and disconnect from the main grid to enable it to operate in both grid-connected or islanded-mode”. One of the potential benefits of microgrids is the role they can play in making the electric grid more flexible and efficient, driven by the integration of Distributed Energy Resource (DER) units and controllable loads. A DER unit is either a Distributed Generator (DG) unit or an Energy Storage System (ESS) [1]. DG units are usually Renewable Energy Sources (RES), i.e., Solar Photovoltaic (PV) and wind power sources. ESS can be, for example, batteries,
flywheels, or supercapacitor storage systems. The declining cost of DG technologies, mounting environmental concerns and the governments’ policy initiatives have been the main drivers for acceptance of the microgrid concept.

Figure 1. 1: Total installed Solar-PV around the world for the past 15 years [2].

Fig. 1.1 shows that the global Solar-PV installation capacity has been exponentially increasing over the past two decades, recording 237.3 GW in 2015. This represents more than tripling of its global capacity in 2011[2]. Utilization of Solar-PV systems has gained global acceptance for several reasons, i.e., availability of solar irradiance in many regions, absence of moving parts in the generation system, decline of PV panel’s cost, and low operation and maintenance costs. However, Solar-PV units are intermittent source of power due to the unexpected solar irradiance change and temperature. Strategically, Battery Energy Storage System (BESS) can play a salient role in a microgrid by addressing any mismatch between the intermittent Solar-PV generation and power demand. BESS also can provide ancillary services such as voltage and frequency regulation, reactive power support, load leveling, peak shaving, and power quality improvement [3].
1.2 Motivation and Problem Statement

Unlike the conventional generation systems, Solar-PV units are variable source of power and produce Direct Current (DC) electricity; thus, they are interfaced to the host Alternate Current (AC) systems via power electronics converters [4]. One of the main operational problems of microgrids is the development of control strategies that are required for their interfaced DER units’ inverters to demonstrate the power flow and maintain the voltage and frequency of the microgrid [5]. Normally, the microgrid in the grid-connected mode is controlled to exchange power with the main utility grid, whether it imports the needed power from the utility grid or exports its surplus power to it. In the grid-connected mode, the microgrid’s voltage and frequency are often dominated by the host utility grid and considered constant. However, the Solar-PV units’ inverters are required to operate based on their MPPT strategy under different solar irradiance conditions. During transition from grid-connected mode to islanded mode, a mismatch between the output of Solar-PV units and microgrid’s demand results in frequency and voltage deviations. In the islanded mode, due to the absence of the main utility grid and the fact that Solar-PV units are variable and unpredictable [6], the microgrid’s voltage and frequency may deeply fluctuate [7] [8]. An BESS can be exploited to support the voltage and the frequency of a microgrid in a few cycles [9] [10]. However, this support lasts for only a certain amount of time because of the battery storage constraints such as its capacity and State of Charge (SOC) [11].

Therefore, there is a requirement for an effective control strategy that is capable of reliable operation of a microgrid integrated with multiple variable Solar-PV generation units (variable solar irradiance) and a BESS (considering the BESS SOC) and enables coordination with the utility grid in the grid connected mode, fast control of voltage and frequency of the microgrid in the islanded mode and seamlessly transfer from one mode to another.

1.3 Thesis Objectives

The main objective of this thesis is to develop a control strategy for a microgrid system which ensures its reliable operation under both modes of operation, i.e., grid-connected mode and islanded mode and enables the transition between them. The control strategy can take prompt actions, such
as load shedding or power curtailment in the case of insufficient or surplus power by the Solar-PV systems, and can charge or discharge the battery in the case of low or high battery SOC, respectively [12] [13]. The microgrid considered in this thesis includes three Solar-PV units and an BESS. The proposed control strategy comprises a Supervisory Control (SC) and four Local Controllers (LC) for each of the three Solar-PV units and the BESS. The objectives of this research are listed below:

1. Select, model, and integrate 2MW-4MWh Li-Ion BESS into a microgrid system that also includes three 1.5MW Solar-PV units.

2. Develop a LC for the BESS that retains a prespecified level of charge in the grid-connected mode and enables it to support the microgrid’s voltage and frequency in the islanded mode.

3. Deploy a LC for each of the three Solar-PV units to exchange power with the microgrid in both modes of operation. Each controller includes a Maximum Power Point Tracking (MPPT) to harvest the maximum output power under different irradiance conditions [14].

4. Develop a SC that can switch the control strategy from the grid-connected mode to the islanding mode and vice versa, and enables load shedding, Solar-PV power curtailment, and charging and discharging of the BESS.

5. Investigate the system dynamic performance based on the time-domain simulation, using the PSCAD/EMTDC software platform, in the islanded and grid-connected modes of operation.

1.4 Assumptions

The studies reported in this thesis are based on the following assumptions.

1- The BESS includes its own Battery Management System (BMS), which provides the battery SOC, estimation of the battery SOC is not considered in this thesis. This work assumes that the battery operating temperature is within the recommended range and considered constant, thus, parameters of the adopted battery model are functions of the battery SOC only.
2- Islanding detection mechanism and islanding detection strategy are not within the scope of this thesis.

3- The communication between the SC and LCs of each of the Solar-PV units and the BESS is assumed to be through fiber optics based on IEC 62351 protocol. Thus, the communication delay is assumed to be within 3 milliseconds [15].

4- The SC has access to the power generated by each Solar-PV unit and the BESS, the microgrid’s demand, the battery SOC and the status of the main circuit breaker at the Point of Common Coupling (PCC). Status of the main circuit breaker identifies grid-connected and islanded modes of operation.

5- Solar-PV inverters are operated at unity power factor, producing only real power.

1.5 Thesis Outline

The rest of this thesis is divided into four chapters:

Chapter 2 provides description and modeling of the study microgrid system including the Solar-PV units and the BESS and it also provides an overview of the proposed control strategy.

Chapter 3 presents case studies and evaluates a control strategy for a microgrid integrated with three Solar-PV units and one BESS in the grid-connected mode. A description of the LCs of the Solar-PV units and the BESS is also provided. Performance studies of the system under various scenarios, such as solar irradiance change, faults, and the battery charging and discharging modes are conducted based on time-domain simulation in the PSCAD software platform.

Chapter 4 presents, investigates and evaluates a control strategy for the study microgrid system subsequent the transition to the islanding mode of operation. The voltage and frequency restoration of the microgrid is carried out based on the proposed control strategy. Performance studies of the system under various scenarios, such as Solar-PV loss, load shedding, faults and reconnection to the grid are conducted in time-domain simulation in the PSCAD software platform.

Chapter 5 summarizes conclusions and contributions and suggests the future work.
Chapter 2

Study System Description, Model and Control Strategy

Chapter 2 introduces the study microgrid system and its model, including those of the Solar-PV units and the BESS. This Chapter also discusses the proposed control strategy for the grid-connected and islanded modes of operation of the microgrid system.

2.1 Study System Description and Model

A single-line diagram of the study system is shown in Figure 2.1. The 27.6 kV rural feeder is 26 km long and includes 28 buses. The study system includes three 1.5 MW Solar-PV units, one 2 MW (4 MWh) Li-ion BESS and a set of balanced and unbalanced loads. The Solar-PV units are located at buses B_{22}, B_{24}, and B_{28}. The BESS is located at B_{20}. As shown in Fig. 2.1, the distribution feeder has three step-down transformers, i.e., T_1, T_3, T_8, and one voltage regulating transformer T_2 between buses B_{12} and B_{13}. The system parameters are given in Appendix A.1. The microgrid under consideration is downstream to bus B_{15} of Fig. 2.1 and operates in the grid-connected mode and islanded mode based on the status of circuit breaker CB_1 between buses B_{14} and B_{15}. B_{15} is the Point of Common Coupling (PCC) of the microgrid. The system short-circuit capacity at the PCC is 56.7 MVA. The Short Circuit Ratio (SCR) at any AC bus is defined as the ratio of the short-circuit capacity of the AC bus to the rated DC power at that bus [16]. The SCR at PCC is 8.7. The SCR values at buses B_{22}, B_{24}, and B_{28} are 7.9, 7.4, and 5.4, respectively. Thus, the system is fairly “strong” with respect to the capacities of installed Solar-PV units and BESS. The Solar-PV penetration level of the microgrid system is 30% and calculated by

\[
\text{penetration} \% = \frac{P_{PV_{\text{max}}}}{P_{\text{demand}_{\text{max}}}} \times 100, \quad (2.1)
\]
where $P_{PV,\text{max}}$ is the maximum output power from the three Solar-PV units under Standard Test Conditions (STC) and $P_{\text{demand, max}}$ is the peak consumption of the microgrid [17].

Figure 2.1: Single-line diagram of the rural feeder.

STC corresponds to the scenario when Solar-PV units are exposed to solar radiation=1000 W/m², cell temperature = 25 °C, and the wind speed=1 m/s [18]. To study the microgrid performance, it is modeled in the time-domain using the PSCAD/EMTDC software platform [19]. Next sections describe models of the microgrid components that are used in the PSCAD software platform.
2.1.1 Transmission Lines, Loads, and Circuit Breaker Models

For the reported studies in this thesis, each overhead line of Fig. 2.1 is modeled as a $\pi$-section. The loads are considered as balanced loads and modeled as constant impedances. Parameters of the line models and loads are given in Appendix A.1. Each phase of a three-phase circuit breaker is modeled as ideal switch which can open at zero-crossing instants of the corresponding current.

2.1.2 AC Host System

The host utility grid to which the microgrid is connected, is represented by a three-phase, 27.6 kV, 20 MVA short circuit capacity source with $X/R$ ratio of 31.8. The rural feeder upstream to bus B12 of Fig. 2.1 is substituted by its Thevenin equivalent as shown in Fig. 2.2 and described in Appendix B.1.

![Figure 2.2: Simplified single-line diagram of the study system.](image)
2.1.3 Three Phase Transformers Models

Each of transformers T₄, T₅, T₆, T₇ and T₈ of Fig. 2.2 is modeled as a linear, three-phase, two-windings transformer. The winding interconnections are grounded-star at the high-voltage side and delta at the low-voltage side. Transformers T₂ and T₃ are modeled as linear, three-phase transformers with grounded-star windings at both sides. Transformers’ parameters are found in Table A.4 of Appendix A.

2.2 Solar-PV Units

Figure 2.3 shows a schematic diagram of the Solar-PV units which are connected to buses B₂₂, B₂₄ and B₂₈. Each Solar-PV unit is rated at 1.5 MW and consists of a Solar-PV array, a DC choke, a DC-link capacitor, a Voltage-Sourced Converter (VSC) with its LC filter and a step-up transformer [20]. Next sections provide model of each component of the Solar-PV unit.

![Schematic diagram of each Solar-PV system at B₂₂, B₂₄, and B₂₈.](image)

**Figure 2.3**: Schematic diagram of each Solar-PV system at B₂₂, B₂₄, and B₂₈.

2.2.1 Solar-PV Array Structure

A Solar-PV cell is a semiconductor diode that releases electricity when exposed to the light [21]. A PV panel (module) is typically 6×10 solar photovoltaic cells and ranges from 100 to 365 watts. A
Solar-PV array consists of interconnected Solar-PV panels (modules) in series and parallel to achieve the desired voltage, current and power. The output power of a Solar-PV array can be maximized using the Maximum Power Point Tracking (MPPT) control system as will be discussed in section 3.2.1 in Chapter 3. In this thesis, the Solar-PV array of each unit is assumed to be constructed from 6666 panels of the Canadian Solar module CS6K-270MM and modeled as explained in the next section.

2.2.2 Solar-PV Array Model

Figure 2.4 shows a single-diode model of a practical Solar-PV cell, which represents the non-linear $I$-$V$ characteristic of ideal Solar-PV cell based on solar irradiance ($G$) and temperature ($T$).

![Figure 2.4: Equivalent Circuit of a practical Solar-PV cell.](image)

The model consists of a DC current source $I_{irr}$ owing to the cell’s exposure to the solar irradiance, a diode at current $I_d$ representing the nonlinearity of the PV cell, a shunt resistance $R_p$, and a series resistor $R_S$ [22]. The characteristic $I$-$V$ curve of an ideal Solar-PV cell is the result of subtracting the diode current from the irradiance current as illustrated in Fig. 2.5 where $I_p$ is the shunt resistor $R_p$ current. Thus, the total output current from a Solar-PV cell is

$$I = I_{irr} - I_d - I_p, \quad (2.2)$$
Figure 2.5: The voltage and irradiance current, diode current, and output current characteristics curves of an ideal Solar-PV cell.

where $I_d$ is defined as

$$I_d = I_o \left[ e^{\frac{q(V+IR_S)}{nKT}} - 1 \right].$$ \hfill (2.3)

In (2.3) $q$ is the charge ($q = 1.602 \times 10^{-19}$ C), $k$ is the Boltzmann constant ($k = 1.380 \times 10^{-23}$ J/K), $n$ is the constant of the diode, $T$ is the temperature of the PV cell and $V$ is the output voltage of the Solar-PV cell. $I_p$ is

$$I_p = \frac{V + IR_S}{R_p}. \hfill (2.4)$$

Substituting for $I_d$ and $I_p$ from (2.3) and (2.4) into (2.2), $I$ can be expressed as

$$I = I_{irr} - I_o \left[ e^{\frac{q(V+IR_S)}{nKT}} - 1 \right] - \frac{V+IR_S}{R_p}, \hfill (2.5)$$

where $I_o$ is the diode saturation current and expressed as

$$I_o = I_{o,ref} \left[ \frac{T}{T_{ref}} \right]^3 e^{\left( \frac{E_{g,ref} - E_g}{KT_{ref}} \right)},$$ \hfill (2.6)

and $I_{irr}$ is given by

$$I_{irr} = I_{irr,ref} \left( \frac{G}{G_{ref}} \right) \left[ 1 + \alpha_T (T - T_{ref}) \right].$$ \hfill (2.7)

In (2.6) and (2.7), $I_{o,ref}$ is the saturation current at STC, $E_g$ represents the band gap energy of the PV cell material, $T_{ref} = 298 \text{ K}$, $G_{ref} = 1000 \text{ W/m}^2$, $I_{irr,ref}$ represents the short circuit current at
$G_{\text{ref}}$ and $\alpha_T$ is the temperature coefficient [23]. Values of $R_S, R_P, I_{\text{irr,ref}}$ and $I_{o,\text{ref}}$ are obtained from the Solar-PV data specifications. Considering series and parallel connections of the Solar-PV cells to form the Solar-PV array, the following scaling adjustment is considered during modeling, i.e.,

\[
I_{\text{irr,\text{array}}} = N_P I_{\text{irr}}, \quad (2.8)
\]

\[
I_{d,\text{array}} = N_P I_d, \quad (2.9)
\]

\[
R_{S,\text{array}} = \frac{N_S}{N_P} R_S, \quad (2.10)
\]

\[
R_{P,\text{array}} = \frac{N_S}{N_P} R_P, \quad (2.11)
\]

where $N_P$ and $N_S$ are the total number of Solar-PV panels connected in parallel and series, respectively.

---

**Figure 2.6**: Solar-PV array model in the PSCAD software platform.

Based on (2.2) to (2.11) and Fig. 2.4, Fig. 2.6. shows the Solar-PV array model adopted in the PSCAD software platform for the reported studies in this thesis. The Solar-PV array of each Solar-PV unit of Fig. 2.1 is rated at 1.5 MW and constructed from 6666 panels of the Canadian Solar module CS6K-270MM [14] for which $N_P = 303$ and $N_S = 22$. $N_P$ and $N_S$ are modeled in the PSCAD as inputs to control current sources, shunt and series resistors of Fig. 2.6. The current sources represent $I_{d,\text{array}}$ and $I_{\text{irr,\text{array}}}$ based on (2.3) and (2.7), respectively. Parameters of the Solar-PV panel under the study are given in Table 2.1.
Table 2. 1: The Canadian Solar panel electrical data at 1000 W/m² solar irradiance and cell temperature of 25°C.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Max Power (Pmax)</td>
<td>270 W</td>
</tr>
<tr>
<td>Opt. Operating Voltage (Vmp)</td>
<td>31.1 V</td>
</tr>
<tr>
<td>Opt. Operating Current (Imp)</td>
<td>8.67 A</td>
</tr>
<tr>
<td>Open Circuit Voltage (Voc)</td>
<td>38.2 V</td>
</tr>
<tr>
<td>Short Circuit Current (Isc)</td>
<td>9.19 A</td>
</tr>
</tbody>
</table>

2.2.3 DC Choke

The DC output from the Solar-PV array is connected to the VSC through the DC choke of Fig.2.3. The DC choke is used to block higher-frequency AC current from flowing back to the DC power source. In this thesis, the DC choke is modeled as a lossless air-core inductor of 5µH.

2.2.4 Voltage-Sourced Converter (VSC)

Fig. 2.7 illustrates the VSC system which converts the output Direct Current (DC) from the Solar-PV array into the Alternating Current (AC) for the grid [24]. The VSC is rated at 0.7 kV DC / 0.37 kV AC. The VSC consists of six IGBTs switch modules connected with antiparallel diodes, DC-side capacitor C₁, and an AC-side LC Filter. The switch modules are controlled based on a Sinusoidal Pulse Width Modulation (SPWM) scheme with switching frequency of 2.4 kHz as will be discussed in Chapter 3. The DC capacitor C₁ is rated at 280 mF and connected to the DC-side of the inverter to minimize the ripple of the DC Source.
2.2.5 LC Filter

The AC-side series reactor of the VSC and a three-phase capacitor bank constitute the VSC AC-side filter as shown in Fig. 2.7. The LC filter attenuates the switching frequency ripple of the output voltage of the VSC [25]. The LC filter is modeled as a three-phase reactor and three-phase capacitor banks. The inductance of each reactor is $37\mu$H with an internal resistance of 0.02 mΩ and the capacitance of each capacitor is $C = 5.1$ mF.

2.2.6 Step-up Transformer

The AC output voltage of the VSC filter is stepped up to the voltage of the feeder via 1.7 MVA-0.37 kV/27.6 kV transformer. The transformer is modeled as a linear three-phase transformer and configured as delta at low-voltage side and grounded-star at high-voltage side as depicted in Fig. 2.3. Parameters of the step-up transformers are given in Appendix A.1.
2.3 Battery Energy Storage System

Figure 2.8 shows a schematic diagram of the BESS located at bus $B_{20}$ of Fig. 2.1 which includes a battery array, a DC choke, DC-link capacitor, a VSC with its LC filter and a step-up transformer.

![Schematic Diagram of BESS](image)

**Figure 2.8**: Schematic diagram of the BESS interfaced to the microgrid system at $B_{20}$.

The BESS is rated at 2 MW- 4 MWh. The structure of BESS is the same as that of the Solar-PV unit with the exception that in the BESS, the power flow is bidirectional (charging and discharging). The DC output of the battery array is interfaced to the VSC through a 20µH DC choke. The DC choke is selected based on the reported analysis of [26]. The VSC output voltage is filtered through an LC filter and stepped up to the voltage of the microgrid system through the step-up three-phase transformer. Parameters of VSC and its interfaced LC filter and step-up transformer are included in Table 2.2.

**Table 2.2**: The values of the VSC, LC filter, and the step-up transformer of the BESS.

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSC</td>
<td>0.7 kV DC/0.37 kV AC</td>
</tr>
<tr>
<td>DC Capacitor</td>
<td>0.04 (F)</td>
</tr>
<tr>
<td>L Filter</td>
<td>37 (µH)</td>
</tr>
<tr>
<td>C Filter</td>
<td>5.1 (mF)</td>
</tr>
<tr>
<td>$r_L$ Filter</td>
<td>2 (mΩ)</td>
</tr>
<tr>
<td>Step-up transformer</td>
<td>2.3 MVA- 0.37 kV/27.6 kV</td>
</tr>
</tbody>
</table>
2.3.1 Battery Array Structure

Batteries are electrochemical devices that store electric energy in electrochemical form and deliver Direct Current electricity [27]. Each battery cell has its operating voltage and maximum current capability, i.e., the voltage of a lithium-ion battery cell is 3.7 V. Battery cells are interconnected in series and parallel in each module and these modules are connected in parallel and series forming battery arrays to achieve higher voltage and current ratings. For this thesis, the battery module is assumed to be constructed from twenty-four of 120 Ah Li-ion batteries in parallel and the battery array is assumed to be constructed from four-hundred and twenty battery modules in parallel and series [28] [29].

2.3.2 Battery Array Model

Figure 2.9 shows the Voltage Source-Resistor battery model which is adopted in this thesis [30]. The battery model consists of a DC voltage source representing the battery open circuit voltage at no load \( V_{ocv} \), and series resistors \( R_{ch} \) and \( R_{dis} \) representing the power loss during charging and discharging operation, respectively. \( V_{ocv}, R_{ch} \) and \( R_{dis} \) are functions of the battery SOC and its operation temperature \( (T) \). A battery SOC is defined as the ratio of the remaining power to its rated capacity [31]. The rated capacity is given by the manufacturer and represents the maximum amount of charge that can be stored in the battery.

![Battery Array Model Diagram](image)

**Figure 2.9:** Equivalent circuit of a battery cell represented by a DC voltage, and two resistors representing the charging and the discharging operation of the Battery.
This thesis assumes constant battery operating temperature, thus, $V_{ocv}, R_{ch}$ and $R_{dis}$ of the battery are functions of only the SOC. Three lookup tables based on experimental data of [32] are used to determine $V_{ocv}, R_{ch}$ and $R_{dis}$ as functions of the battery SOC as shown in Fig. 2.10 and Fig. 2.11 and the open circuit voltage of each battery module is set from 770 V to 833 V corresponding to SOC from 10% to 100%.

**Figure 2.10:** Experimental data of the battery open circuit voltage as a function of the SOC [32].

**Figure 2.11:** Experimental data of the battery internal resistors as functions of the SOC [32].
Based on Fig. 2.9, the battery voltage is expressed as

$$V_{bat} = V_{ocv} - R_{bat} I_{bat}, \quad (2.12)$$

where $R_{bat}$ represents either $R_{ch}$ or $R_{dis}$ as shown in (2.13) and determined from Fig. 2.11 as

$$R_{bat} = \begin{cases} R_{ch} = f(SOC) & \text{for charging} \\ R_{dis} = f(SOC) & \text{for discharging}. \end{cases} \quad (2.13)$$

SOC must be respected to its upper and lower limitations ($SOC_{min}$, and $SOC_{max}$) to protect the battery from overcharging and over discharging incidents. The battery SOC is expressed as

$$SOC = SOC_{ini} - \int \frac{\eta I_{bat}}{Q_b} dt, \quad (2.14)$$

where $SOC_{ini}$ is the initial state of charge of the battery, $Q_b$ is the battery energy capacity (kAh) and $I_{bat}$ is the output current of the battery (A). In this thesis, $I_{bat}$ is indicated as positive or negative for discharging or charging, respectively. The battery efficiency $\eta$ is defined as the amount of power discharged by the battery divided by the amount of power delivered to the battery. The battery efficiency depends on the rate of charging or discharging operations. i.e., higher rate of charging/discharging operation reduces efficiency. Efficiency is calculated from (2.15) and (2.16), where $\eta_{ch}$ is the charging efficiency and $\eta_{dis}$ is the discharging efficiency.

$$\eta_{ch} = \frac{V_{ocv}}{V_{ocv} - I_{bat} R_{ch}}, \quad (2.15)$$

$$\eta_{dis} = \frac{V_{ocv} - I_b R_{dis}}{V_{ocv}}. \quad (2.16)$$

Considering series and parallel connections of the battery cells to form the battery array, the following scaling adjustment is considered in the adopted model, i.e.,

$$V_{ocv, array} = N_s V_{ocv}, \quad (2.17)$$

$$R_{ch, array} = \frac{N_s}{N_p} R_{ch}, \quad (2.18)$$

$$R_{dis, array} = \frac{N_s}{N_p} R_{dis}, \quad (2.19)$$
where \( N_p \) and \( N_s \) are the total number of battery modules connected in parallel and series, respectively. Fig. 2.12 shows the battery array model, implemented in the PSCAD software platform for the reported study, based on (2.17) to (2.19) and Fig. 2.9.

![Battery array model in the PSCAD software platform.](image)

The battery array of the study system of Fig. 2.1 is rated at 2MW-4MWh, i.e., it can give a maximum power of 2MW for a maximum of two hours and constructed from 42 of 100 kWh (LiFePo4) Li-ion battery modules in parallel, for which \( N_p = 42 \) and \( N_s = 1 \). \( N_p \) and \( N_s \) are modeled in the PSCAD as inputs to control voltage source and \( R_{ch} \) and \( R_{dis} \) of Fig. 2.9. Parameters of the BESS under study are given in Table 2.3.

<table>
<thead>
<tr>
<th>Single battery capacity</th>
<th>120 Ah (two of 60 Ah batteries in parallel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery module</td>
<td>Twenty-four of 120 Ah batteries in series</td>
</tr>
<tr>
<td>100 kW-100kWh</td>
<td>Ten battery modules in series</td>
</tr>
<tr>
<td>2MW-4MWh</td>
<td>Forty-two of 100 kWh battery modules in parallel</td>
</tr>
<tr>
<td>Minimum working voltage</td>
<td>696 V</td>
</tr>
<tr>
<td>Maximum working voltage</td>
<td>840 V</td>
</tr>
</tbody>
</table>
2.4 Microgrid Control Strategy

The control strategy adopted in this thesis is based on one Supervisory Control (SC) and four Local Controllers (LCs) corresponding to each of the three Solar-PV units and the BESS. The SC sets the reference values for the four LCs, detects the status of CB₁ in Fig. 2.1, and decides on switching the control from the grid-connected mode to the islanded mode and vice versa.

In the grid-connected mode, the three Solar-PV inverters are controlled to be in active and reactive (P-Q) control mode. Each Solar-PV unit includes its MPPT. The MPPT provides reference real power for the LC of the corresponding Solar-PV unit. The BESS inverter also operates under the P-Q control mode while maintaining the battery SOC within prespecified range. Based on the battery SOC, the reference real power of the LC of the BESS is set. For the reported studies in this thesis, it is assumed that there is no reactive power support provided by the Solar-PV units or the BESS in the grid-connected mode, i.e., reactive power demand is provided by the grid. Thus, the reference reactive power is set to zero by the SC for all the Solar-PV units and the BESS.

In the Islanded (autonomous) mode, when CB₁ of Fig 2.1 is open, LC of the BESS switches from P-Q control mode to Voltage/Frequency (V-F) control mode to support the voltage and the frequency of the microgrid in the absence of the utility grid. The three Solar-PV units are kept under the P-Q control mode tracking their MPPs.

2.5 Summary

In this chapter, the study system is described, including the Solar-PV units and the Battery Energy Storage System. Also, the modeling of the study system apparatuses was provided in this chapter, including transmission lines models, AC host system model, loads models, transformers models, Solar-PV units models, and the BESS model. Finally, the microgrid control strategy adopted for this thesis is briefly discussed.
Chapter 3

Grid-Connected Microgrid

Chapter 3 provides a control strategy for the study microgrid system when it is connected to the utility grid. The grid-connected mode requirements are also briefly discussed. The solar-PV units control is explained, including the MPPT, the DC voltage control, and the VSC system control. Then, the BESS control and the battery SOC constraints’ logic are presented. Based on time-domain case studies in PSCAD platform, the performance of the microgrid and associated control are evaluated and verified.

3.1 Grid-Connected Mode Control Strategy

In the grid-connected mode of operation, the microgrid’s voltage and frequency are determined by the utility grid. The grid supplies any power deficit and absorbs any surplus power of the microgrid system. The proposed control strategy regulates the solar-PV units to exchange real and reactive power with the microgrid through the current controller of their VSC systems while tracking their MPPs. The control strategy also controls the BESS to satisfy its SOC constraints while regulating the active and reactive power through the current controller of its VSC system. The control strategy in the grid-connected mode has two main functions. i) extracting the maximum output power from the three Solar-PV units based on their MPPT controls. ii) controlling the battery SOC at a certain level which can support the microgrid voltage and frequency in the islanded mode. The proposed control strategy attempts to keep the BESS in the grid-connected mode in an idle state, i.e., neither charging nor discharging, which reduces the number of charging/discharging cycles and extends battery life [33].
Figure 3.1: The proposed control strategy for the microgrid system in the grid-connected mode.

Fig. 3.1 shows the closed-loop process of the three Solar-PV units and the BESS which are in the P-Q control mode. The battery SOC is controlled to be within a pre-specified range ($SOC_{\text{min}}$ & $SOC_{\text{max}}$). A wider SOC range is also considered ($SOC_{\text{max-H}}$ & $SOC_{\text{min-L}}$) as shown in Fig. 3.2. The zone between the two ranges prevents repeated charging/discharging operations over the pre-
specified range, thus, improves the battery output power profile by considering the battery losses in the control strategy.

**Figure 3.2:** The initial SOC range of the BESS in the grid connected mode control strategy.

The logic of charging and discharging the BESS based on its initial SOC:

1- If the battery initial SOC is within the pre-specified range, i.e., \( SOC_{\min} \leq SOC \leq SOC_{\max} \). The LC sets the reference real power of the battery to zero \( (P_{\text{batt,ref}} = 0) \). Therefore, the BESS is kept in idle state in the P-Q control mode and available to support the microgrid in the islanded mode.

2- If the battery initial SOC is less than \( SOC_{\min-L} \), the LC orders the battery to charge at its rated power \( \|P_{\text{rated}}\| \) until it reaches the pre-specified range.

3- If the battery initial SOC is greater than \( SOC_{\max-H} \), the LC orders the battery to discharge at the rated power \( \|P_{\text{rated}}\| \) until it reaches to the pre-specified range.

4- If the battery initial SOC is within the range of \( SOC_{\min-L} < SOC < SOC_{\min} \), the LC orders the battery to charge with \( \|P_{\text{loss}}\| \) to compensate for the battery losses, thus, preventing the hysteresis band that results from charging and discharging around \( SOC_{\min-L} \) due to the battery losses.
If the battery initial SOC is within the range of $SOC_{\text{max}} < SOC < SOC_{\text{max-H}}$, the LC of the BESS disables any charging orders.

### 3.1.1 Grid-Connected Mode Requirements

In the grid-connected mode, based on the international standards of IEEE 1547/UL 1741 and IEC 61727, the maximum voltage amplitude variations at the Point of Common Coupling (PCC) must be less than $\pm 10\%$ and the microgrid frequency variations must be less than $\pm 1\%$ [34]. These requirements shall be met at the PCC of the microgrid, even though the DER units, which are used to meet these requirements are located elsewhere. The microgrid needs to be disconnected from the utility grid in case of any voltage and frequency outside of these specified ranges [35].

### 3.2 Solar-PV Unit Control

Figure 3.3 shows the LC of each Solar-PV unit which includes a Maximum Power Point Tracking (MPPT) control, a DC Voltage controller and the VSC system control. The MPPT provides the reference DC voltage to the DC voltage controller. The DC voltage controller generates the reference real power ($P_{s,\text{ref}}$) for the VSC system control. The current controller of the VSC system controls the VSC output power to track the AC power reference generated from the DC voltage controller by providing the modulation indexes for the SPWM scheme of the VSC. In this thesis, it is assumed that there is no reactive power support provided by the Solar-PV units, i.e., the SC sets the reference reactive power ($Q_{s,\text{ref}}$) of the Solar-PV units to be zero.
3.2.1 Maximum Power Point Tracking (MPPT)

Figure 3.4 shows the Power-Voltage (P-V) characteristic of a Solar-PV unit under constant irradiance. The P-V characteristic shows that the Solar-PV terminal voltage is used to vary its output power. For instance, if the operating terminal voltage of a Solar-PV unit is below the optimal operating point (Maximum Power Point), by increasing the terminal voltage, the output power is increased until the maximum power is extracted. If the terminal voltage further increases, the output power will decrease. Hence, to extract the maximum power from a Solar-PV unit, the terminal voltage must be retained at the optimal value.
In this thesis, each Solar-PV unit is combined with an MPPT algorithm based on the Incremental Conductance (IC) tracking algorithm developed in [14]. An MPPT receives the terminal voltage and currents of the Solar-PV unit and generates the optimal DC voltage ($V_{DC_{,ref}}$) required for the DC voltage controller of Fig. 3.3 [36]. There are several algorithms to track the MPP of a Solar-PV unit [37] [38]. Details of the adopted MPPT logic are given in Appendix A.4.

3.2.2 DC Voltage Controller

The DC output power of the Solar-PV is related to the AC output power of the inverter through the DC capacitor voltage, i.e., voltage of $C_1$ in Fig. 2.3, based on [39]

$$P_C = C_1 \, V_{DC_{,PV}} \, \frac{dV_{DC_{,PV}}(t)}{dt}. \quad (3.1)$$

If the input DC power is larger than the output AC power, the voltage across the DC capacitor increases. Similarly, if the output AC power is larger than the input DC power, the voltage across the capacitor decreases. As shown in Fig. 3.5, the DC voltage reference $V_{DC_{,REF}}$ generated from the MPPT is compared to the Solar-PV terminal voltage $V_{DC_{,PV}}$. The Proportional-Integral (PI) controller receives the error and generates the AC real power reference $P_{s_{,ref}}$ for the VSC control system accordingly. The PI control parameters of the DC voltage controller are included in Appendix A.2.
3.2.3 VSC System Control

Figure 3.6 shows the implementation of the AC power controller and the current controller in the PSCAD software platform based on the dq frame representation of VSC [40] [41]. The AC power controller receives the reference real and reactive power from the DC voltage controller and the SC, respectively. In this thesis, the limits of the \( P_{s_{\text{ref}}} \) limiter are determined as \( P_{s_{\text{min}}} = 0 \) and \( P_{s_{\text{max}}} = 1 \) pu, and it is assumed that the Solar-PV units operate at unity power factor. Thus, \( Q_{\text{ref}} = 0 \). The current reference limits of \( I_{td} \) and \( I_{tq} \) are determined by the inverter power rating. The PI controller parameters are given in Appendix A.2.
Figure 3.6: Diagram illustrating the real and reactive (P-Q) power control mode implemented in the PSCAD in per-unit to compute the reference currents $I_d$ and $I_q$ and to generate modulation indexes $m_d$ and $m_q$.

Each Solar-PV unit must be synchronized to the microgrid terminal voltage at their point of connection, i.e., B22, B24 and B28 of Fig. 2.3. Therefore, all abc/dq and dq/abc transformations of each Solar-PV unit controller are based on a reference angle that is provided by a Phase-Locked Loop (PLL) of the Solar-PV unit [42]. A PLL generates a ramp signal theta that varies between 0 and 360°, synchronized or locked in phase, to the input voltage, which in this case is the low voltage side of the step-up transformer of Fig. 2.3. The parameters of the PLL used in this thesis are found in Appendix A.2. Figure 3.7 shows the SPWM switching strategy for the VSC. The SPWM strategy is implemented by comparing modulating indexes $m_a$, $m_b$, and $m_c$ against 2.4 kHz triangle waveform carrier. The intersections of the carrier signal and the modulating signals determine the switching instants of the IGBTs switch modules of the VSC.
3.3 BESS Control

Figure 3.8 depicts the control structure of the BESS. The LC comprises a SOC constraints logic and the VSC system control. The SOC constraints logic provides the reference real power while the SC provides the reference reactive power to the VSC system. In this thesis, it is assumed that there is no reactive power support provided by the BESS in the grid connected mode, therefore, the SC sets the reference reactive power ($Q_{s,\text{ref}}$) of the BESS to zero.

In the grid-connected mode of operation, the BESS is controlled to operate in the P-Q control mode while maintaining the battery SOC within a pre-specified range. The implemented LC uses the battery SOC to satisfy the limits while regulating the active power. This means that based on the
battery SOC, the reference real power $P_{s\_ref}$ is generated for the VSC system and the VSC system controls its output power to track this reference value.

3.3.1 Battery SOC Constraints Logic

In this thesis, a battery SOC constraints logic is developed to monitor the BESS SOC, prevent over-charge and over-discharge incidents, ensure safe use of the battery and extend its service life. This logic keeps the battery in an idle state in the grid-connected mode and controls its SOC to be between 70\% and 75\%. Based on the assumption that a lithium-ion battery can be charged/discharged up to a SOC of 90\% and 30\%, respectively. Therefore, the battery will be able to discharge up to 45\% of its capacity and to be charged up to 20\% of its capacity in the islanded mode of operation.

Figure 3. 9: Battery SOC constraints logic implemented in the PSCAD for the grid-connected microgrid.
In addition, this logic considers the battery losses by considering a wider range of SOC, which in this case is between 69% and 76% [43]. This extra range prevents the hysteresis condition that results from the repeated charging/discharging around the pre-specified range (70% and 75%). Figure 3.9 shows the implementation of the SOC constraints logic in the PSCAD/EMTDC software platform. In this thesis, it is assumed that the BESS includes its own Battery Management System (BMS). The BMS provides the battery SOC to the SOC constraints logic. Accordingly, the SOC constraints logic generates the reference real power for the LC of the BESS.

3.4 Supervisory Control

The Supervisory Controller (SC) is responsible for the coordination between LCs of each Solar-PV unit and the BESS, the reactive power control of Solar-PV units and BESS and the transition from the grid-connected mode to the islanded mode and vice versa [44]. The SC, through fast fiber-optic communication infrastructure, has access to electrical signals at the point of connections of Solar-PV units and the BESS [45]. The SC also has access to the status of the circuit breaker (CB1 of Fig. 2.1) to determine islanded mode and grid-connected mode of operation and to switch the control strategy from one mode to another.

3.5 Performance Evaluations

To investigate dynamic performance of the microgrid system under the grid-connected mode control strategy, four case studies are conducted based on time-domain simulation using the PSCAD/EMTDC software platform. The cases demonstrate operation of the microgrid system when Solar-PV units are exposed to variable solar irradiance and i) battery initial SOC is within the pre-specified range, i.e., BESS in an idle state ii) battery initial SOC is lower than the pre-specified range, i.e., BESS starts charging from the utility grid until it reaches the accepted SOC range, iii) battery initial SOC is higher than the pre-specified range, i.e., BESS starts discharging at its rated power until it reaches the accepted SOC range, iv) battery losses considered in the SOC constraints logic to prevent the charging and discharging hysteresis band.
3.5.1 Variable Solar Irradiance

Figure 3.10 (a) shows real power exchange of the three Solar-PV units and the BESS with the utility grid. The three Solar-PV units operate under similar conditions and thus, their output power curves are overlapped. The simulation starts, when each Solar-PV unit supplies 0.4 pu to the microgrid, the utility grid supplies 0.51 pu to the microgrid and the battery initial SOC is 0.73, which is within the pre-specified range (70% - 75%). Thus, the BESS output power is zero during this case and the SOC remains constant as shown in Fig. 3.10 (b). The three Solar-PV arrays are exposed to an increasing solar irradiance as per data of Appendix A.3. Each Solar-PV unit is controlled to track its MPP, recording 0.6 pu at $t = 16$ sec. While each Solar-PV unit increases its output power based on its MPPT control, the utility grid reduces its power supply until it provides zero power at $t = 13$ sec. After that, the surplus power of the microgrid is exported to the utility grid. For example, at $t = 20$ sec the microgrid supplies -0.19 pu back to the utility grid. Figure 3.10 (c) shows that the variation of the $V_{PCC}$ is within the accepted limit of IEEE 1547. Fig 3.10 (d) shows that the system frequency during the simulation is constant around 60.0 Hz.

Figure 3.11 shows the steady state instantaneous output currents from each Solar-PV unit and the BESS under the grid-connected mode of operation. The three Solar-PV are in the P-Q control mode, their currents are balanced. The BESS is an idle state based on the SOC constraints logic and hence its currents are zero.
(a) Real power exchange between the three Solar-PV systems, the utility grid, and the BESS when the battery is idle (pu)  

(b) Battery SOC is within the pre-specified range (0.73)  

(c) The voltages of PCC (pu)
(d) The microgrid system frequency during the grid-connected mode (Hz)

Figure 3.10: Variable solar irradiance.
3.5.2 BESS Charging Mode

Figure 3.12 (a) shows the active power exchange of the three Solar-PV units and the BESS with the utility grid. In this case, the simulation starts when each Solar-PV unit supplies 0.4 pu to the microgrid system, the grid supplies 1.35 pu, and the BESS initial SOC is 0.6817 which is lower than the specified $\text{SOC}_{\text{min}}(0.69)$. Consequently, the battery starts charging at the rated power as shown in Fig. 3.12 (a) until SOC meets the lower limit at $t = 20.4$ sec and becomes constant again as shown in Fig. 3.12 (b). After that, the battery output power is kept at zero as per the grid-connected mode control strategy. Fig. 3.12 (c) shows the voltages of $V_{\text{PCC}}$. As shown in Fig. 3.12 (c), at $t = 20.4$ sec...
the voltage variation is still within the accepted standards regulation of IEEE 1547. Fig. 3.12 (d) shows that the system frequency variation due to the transient from the charging mode to the idle mode is about 0.8%, which is still within the accepted standards of IEEE 1547.

(a) Real power of the three Solar-PV systems, the utility grid, and the BESS when the battery is under the charging mode (pu)

(b) Battery is charging under the SOC control scheme till it reaches the pre-specified range,
(c) The voltages of the PCC in (pu)

(d) The microgrid system frequency in (Hz)

Figure 3.12: BESS Charging Mode.

Figure 3.13 shows the steady state instantaneous output currents from the Solar-PV units and the BESS under the grid-connected mode of operation. The three Solar-PV units in the P-Q control mode and their currents are balanced. The BESS returns to the idle state after the charging mode and its currents go to zero at at $t = 20.4$. 

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Figure 3.13: Steady State Instantaneous Currents of the three Solar-PV units and the instantaneous currents of BESS in the grid-connected mode under the SOC constraints logic (SOC\textsubscript{initial} = 0.681).

3.5.3 BESS Discharging Mode

Figure 3.14 (a) shows the active power exchange of the three Solar-PV units and the BESS with the utility grid. The simulation starts when each Solar-PV unit supplies 0.39 pu to the microgrid, the utility grid absorbs 0.33 pu from the microgrid and the battery initial SOC is 0.7679, which is higher than the SOC\textsubscript{max-H} (0.7600). Consequently, the battery discharges at rated power until the SOC meets the accepted limit SOC\textsubscript{max-H}. The power delivered by the microgrid increases while the BESS discharges and the output power from each Solar-PV unit increase based on their MPPT until the battery becomes idle at $t = 17$ sec when the SOC reaches the accepted limit as shown in Fig. 3.14 (b). After the BESS reaches the idle state and the output power from the Solar-PV units become constant, the surplus power of the microgrid becomes constant around 0.15 pu. Fig. 3.14 (c) and Fig. 3.14 (d) shows the voltages of the PCC, $V_{PCC}$, and the microgrid system frequency, respectively, and both fulfill the grid-connected mode requirements.
(a) Real power of the three Solar-PV systems, the utility grid, and the BESS when the battery is discharging with rated power (+2 MW)

(b) Battery is discharging under the SOC control scheme till it reaches the pre-specified range
Figure 3.15 shows the steady state instantaneous output currents from the Solar-PV units and the BESS under the grid-connected mode of operation. The three Solar-PV units in the P-Q control mode and their currents are balanced. The BESS returns to the idle state after the discharging mode and its currents go to zero at $t = 17$. 

Figure 3.14: BESS Discharging Mode.
3.5.4 BESS Hysteresis Band

This case is conducted to show the effects of considering the battery losses in the developed SOC constraints logic. In Figs. 3.16 (a) the simulation starts when the BESS is initialized at a SOC less than the \( \text{SOC}_{\text{min-L}} (0.69) \), thus, based on the grid-connected control strategy the BESS starts charging at the rated power until it reaches the specified SOC range \( (0.69 < \text{SOC} < 0.7) \) and it becomes idle at \( t = 0.8 \) sec. However, due to the battery losses, the SOC decreases below the \( \text{SOC}_{\text{min-L}} (0.69) \) at \( t = 3.2 \), hence the battery charges again until it reaches back to above \( \text{SOC}_{\text{min-L}} \). This process forms a hysteresis band as shown in Fig. 3.16 (a). In Fig. 3.16 (b) the battery losses are considered in the SOC constraints logic by constantly compensating for it instead of charging with the rated power. This eliminates the hysteresis band and increases the battery service life. Figure 3.16 (c) shows the BESS SOC without considering the losses in the control strategy and Fig. 3.16 (d) shows the BESS SOC increasing due to the charging of the battery to compensate for the losses based on the SOC constraint logic.
(a) The BESS output power without considering the losses causing hysteresis band

(b) The BESS output power while considering the BESS losses to prevent the hysteresis band

(c) The BESS SOC without considering the losses
3.6 Operation of Microgrid During Faults

This section investigates the behavior of the microgrid in the grid-connected mode during symmetrical and asymmetrical faults. As discussed earlier in this Chapter, all grid-connected mode requirements shall be met at the PCC of the microgrid. For this reason, this section discusses the results for three-phase to ground (LLLG) and single-phase to ground (LG) faults occurring at the PCC. In this thesis, the fault resistance is 0.01Ω and is cleared at the first zero current-crossing of each faulted phase after 6 cycles (100 ms).

3.6.1 Temporary Three-Phase-to-Ground Fault

Figure 3.17 shows the $V_{PCC}$ and $I_{PCC}$ when a LLLG fault occurs at the PCC at $t = 2.1$ sec. The fault is cleared after 6 cycles at $t = 2.2062$ sec. $I_{PCC}$ increases from a steady value of 0.05 p.u to 0.27 pu because of the transient experienced by the fault. After the fault is cleared, another transient occurs in $I_{PCC}$ which reaches -0.48 pu and eventually dies out and returns to the steady state at $t = 2.2125$ sec.
During the LLLG fault, the microgrid system does not remain balanced, consequently, $I_{PCC}$ does not remain balanced during the fault. Upon clearing the fault, control actions eventually return the voltages and currents of the PCC to their normal ranges after 12.5 $msec$. A zoomed version of $V_{PCC}$ is shown in Figure 3.18, the clearing of phase b of $V_{PCC}$ occurs at $t=2.2007$ sec. At $t=2.2032$ sec the system goes from a single-phase to two-phase and finally returns to a three-phase version by $t=2.2062$ sec when all phases of the fault are cleared.
3.6.2 Temporary Single-Line-to-Ground Fault

In Fig. 3.19, a LG fault occurs at phase c of the PCC at $t = 2.1$ sec and the fault is cleared after a fault duration of 0.1 sec. An initial transient of $I_{PCC}$ occurs at $t = 2.104$ sec as $I_{PCC}$ drops to -0.3 pu then increases to 0.65 pu and eventually dies out at $t = 2.205$ sec after the clearing of the LG fault. The microgrid system becomes unbalanced during the fault, consequently, $I_{PCC}$ also becomes unbalanced during the fault. The voltage of phase c severely drops during the fault and upon clearing the fault control actions eventually return the voltage to its normal range at $t = 2.209$ sec.
Figure 3.19: $V_{PCC}$ and $I_{PCC}$ during a LG fault at the PCC bus when the microgrid is in the grid-connected mode.

3.7 Conclusions

This chapter proposes a control strategy for a microgrid system integrated with multiple Solar-PV units and BESS when it is connected to the utility grid. The control strategy ensures that the BESS is always charged at a certain SOC in the grid-connected mode which enables it to support the voltage and frequency of the microgrid after any islanding events. Performance evaluations verify the proposed control strategy in all the possible states of the BESS, i.e., idle state, charging or discharging mode based on the developed SOC constraints logic. The control strategy also considers
the variable solar irradiance for the Solar-PV units in all performance evaluations. Coordination between Solar-PV units and the BESS was verified during power exchange with the utility grid, i.e., power imports and exports, under changing solar irradiance and all possible states of the BESS. The voltage variation of the microgrid at the PCC in pu (V_{PCC}) is within \( \pm 10\% \) in all simulated cases as per the grid-connected mode requirements of IEEE 1547, i.e., 0.4\% in the first case, 1.37\% in the second case and -1.3\% in the third case. The microgrid frequency variation is within \( \pm 1\% \) in all simulated cases, i.e., 0.83\% in the second case and -1\% in the third case. The behavior of the microgrid during symmetrical and asymmetrical faults is also investigated, the microgrid system does not remain balanced under fault scenarios due to the lack of fault ride through capability of Solar-PV units and BESS. However, upon clearing the fault, control actions eventually return the voltages and currents of the PCC to their normal ranges after 12.5 \textit{msec} and 9 \textit{msec} in the case of symmetrical and asymmetrical faults, respectively.
Chapter 4

Islanded Microgrid

Chapter 4 provides the control strategy for the microgrid system when it is disconnected from the utility grid and operates as an autonomous island. An explanation of the islanded mode requirements and voltage and frequency control of the microgrid is also provided. Practical scenarios are studied to demonstrate dynamic performance of the islanded microgrid including the reconnection to the utility grid case.

4.1 Islanded Mode Control Strategy

In this thesis, the microgrid switches from the grid-connected mode to the islanded mode when the main circuit breaker, CB1 of Fig. 2.1, opens. The proposed supervisory control assigns the BESS to maintain the voltage and frequency of the microgrid in the islanded mode of operation. The supervisory control checks the SOC of the BESS and takes prompt actions such as load shedding and power curtailment of the Solar-PV units in the case of insufficient or surplus power of the islanded microgrid, charging and discharging of the BESS in the case of low or high SOC and reconnecting to the utility grid [46] [47]. Figure 4.1 provides a flowchart of the proposed control strategy in the islanded mode of operation. As shown in the flowchart, the three Solar-PV units are kept in the P-Q control mode tracking their MPPs while the BESS switches from the P-Q to the V-F control mode subsequent to the islanding event. In the case that the BESS SOC is within the controlled range, i.e., BESS is available to charge/ discharge to support the voltage and frequency of the islanded microgrid, two scenarios are addressed based on the comparison between the microgrid demand (P_{Load}) and the net generated power by the three Solar-PV units (P_{3PV}). When P_{3PV} < P_{Load}, the SC orders the LC of the BESS to discharge the battery with |P_{load}-P_{3pv}| to compensate for the power deficit and restore the frequency. If P_{3PV} > P_{Load}, the SC orders the LCs of the BESS to be charged with |P_{3pv}-P_{load}|. In the case that the BESS SOC is not within the controlled range, i.e., BESS is not
available to support the voltage and the frequency of the islanded microgrid, four different scenarios are addressed based on the BESS SOC and the comparison between $P_{\text{Load}}$ and $P_{3PV}$. i.e., If $P_{3PV} < P_{\text{Load}}$ and $\text{SOC} < \text{SOC}_{\text{min}}$, SC gives an order for load shedding of non-critical loads. If $\text{SOC} > \text{SOC}_{\text{max}}$ and $P_{3PV} > P_{\text{Load}}$, Solar-PV units will go under power curtailment.

![Flowchart of the proposed control strategy for the microgrid in the islanded mode.](image)

**Figure 4.1:** Flowchart of the proposed control strategy for the microgrid in the islanded mode.

### 4.1.1 Islanded Mode Requirements

Figure 4.2 shows two characteristics [48] indicating the DER capability of withstanding abnormal voltage and frequency events before tripping based on the IEEE 1547 standard [49]. In this thesis, these two characteristics are used for voltage and frequency evaluation during the transition from grid-connected mode to the islanded mode and in the islanded mode. The islanded mode
requirements considered for this thesis is to ensure that the voltage and frequency are within the IEEE 1547 envelope as shown in Fig. 4.2.

**Figure 4.2:** DER voltage and frequency sensitivity to disturbance based on the IEEE 1547 standard [49].
4.2 Circuit Breaker Opening and Communication Delay

In this thesis, the transition from the grid-connected mode to the islanded mode occurs by opening all the three phases of CB₁ in Fig. 2.1. After that, the SC switches the control strategy from the grid-connected mode to the islanded mode. Figure 4.3 shows the instantaneous currents of the three-phase breaker CB₁ depicting the time of the first and last phase opening instants. As shown in Fig. 4.3, at time $t = t₁$ the first phase of CB₁ opens and at time $t = t₂$ the last phase of CB₁ opens. In this thesis, the time delay between the opening of the first and last phase is found to be ($Δt = 9$ milliseconds).

Figure 4.4 shows the PSCAD implementation of the switching signal that the SC uses to switch from one mode to another.

If the communication between the SC and CB₁ is through fiber optics based on IEC 62351 protocol. Another time delay of 3 milliseconds is considered and represented by the time delay block of Fig. 4.4. The control strategy of this work switches from the grid-connected mode to the islanded mode based on the switching signal of Fig. 4.4.

![Figure 4.3: Instantaneous currents of the three-phase breaker CB₁.](image-url)
4.3 Voltage and Frequency Control

In the islanded mode of operation, the microgrid’s voltage is regulated by the BESS based on voltage feedback from the BESS inverter. The VSC control within the BESS is switched from the P-Q control mode to the V-F control mode upon receiving the switching signal from Fig. 4.4.

Figure 4.4: PSCAD implementation of the switching signal from the grid-connected mode to the islanding mode.

Figure 4.5: Schematic diagram of the BESS control system for both modes of operation: P-Q control and Voltage control modes.
Figure 4.5 shows a schematic diagram of the P-Q control and the voltage control within the LC of the BESS. The control mechanism is done in the d-q frame in the per unit system where $V_{s,\text{ref}}$ is set to 1 pu and $V_{sq}$ is set to 0. The BESS has an internal oscillator [50] that generates and imposes the frequency of the microgrid in the islanded mode, i.e., the frequency is set to $(\omega_0 = 2\pi f_{ref})$, where $f_{ref} = 60$Hz. The Solar-PV units are synchronized to the microgrid by their PLLs using their terminal voltages.

4.4 Performance Evaluations

To investigate the dynamic performance of the microgrid system in the islanded mode of operation, six case studies are conducted using the PSCAD/EMTDC software platform. The first case demonstrates the operation of the microgrid system as per the control strategy ensuring the transition from the grid-connected mode to the islanded mode. The second and third cases are examining transients due to Solar-PV power loss and load shedding in the islanded mode. The fourth case studies the microgrid during the reconnection to the utility grid. The last two cases examine the behavior of the islanded microgrid during symmetrical and asymmetrical faults.

4.4.1 Islanding Transition

Figures 4.5 show the microgrid transient response to the transition from the grid-connected mode to the islanded mode when the islanding event occurs at $t = 5$ sec. Figure 4.6 (a) shows the real power of the three Solar-PV units, utility grid, and BESS in both modes of operation. Prior to the islanding event, the utility grid supplies 0.41 pu to the microgrid and each of the three Solar-PV units supplies 0.43 pu and the BESS exchanges no power as per the grid-connected mode control strategy. Upon receiving the switching signal from Fig 4.4, the BESS starts discharging at the rated power to fast control the microgrid voltage and frequency and the three Solar PV units are kept tracking their MPPs. Figure 4.6 (b) shows the BESS SOC constant in the grid-connected mode and decreasing while the BESS discharges in the islanded mode of operation. Figure 4.6 (c) shows the microgrid frequency is maintained around 60Hz in both modes of operation, even though it reaches 8% of its nominal value at the transition instant, however, it is still within acceptable region of IEEE 1547.
standard characteristic. Finally, Figure 4.6 (d) shows the voltages of the PCC showing that the transition variation is also within the safe region of IEEE1547 standard characteristic. As concluded from Figures 4.5, BESS control system keeps the microgrid’s voltage at 1 pu, and maintains its frequency at 60 Hz during the islanded mode of operation.
Figure 4.6: (a) The active power exchanged between the Solar-PV units, the BESS, and the utility grid under the islanded mode control strategy (pu), (b) BESS SOC under the islanded mode of operation, (c) The microgrid system frequency in (Hz) and (d) The voltages of the PCC in (pu).

Figure 4.7 shows the steady state instantaneous output currents of each Solar-PV unit and the BESS under the islanded mode control strategy.
Figure 4.7: Steady state instantaneous currents of the three Solar-PV units and the BESS in the islanded mode of operation (pu).

4.4.2 Solar- PV loss

Figures 4.8 show transients in the islanded mode of operation when one of the Solar-PV units, PV$_2$, provides zero output power at $t = 5$ sec due to a passing cloud. Prior to this power loss, each Solar-PV unit was supplying the microgrid with an output power of 0.43 pu and the BESS was supporting the microgrid by an output power of 0.42 pu. Fig. 4.8 (a) shows that the moment PV$_2$ output power drops to zero, the BESS output power increases to balance the supply-demand of the microgrid. Also, while the output powers of PV$_2$ and PV$_3$ increases (tracking their MPPs), the BESS decreases its output power accordingly. Figure 4.8(b) shows the BESS SOC decreases while discharging in the islanded mode and its slope even decreases faster after the loss of PV$_2$ at $t = 5$ sec. Figure 4.8(c) shows that the microgrid frequency is maintained at 60Hz in the islanded mode of operation even during the power loss of PV$_2$ due to the support of the BESS. Finally, Figure 4.8(d) shows that the voltages of PCC are maintained within the IEEE 1547 envelope of Fig. 4.2.
Figure 4.8: (a) The active power exchanged between the Solar-PV units, the BESS, and the utility grid under the islanding mode control strategy during the power loss of PV2 (pu), (b) BESS SOC under the proposed control strategy, (c) The microgrid system frequency in (Hz) and (d) The voltages of the PCC in (pu).

4.4.3 Load Shedding

Figures 4.9 show the system transient response to a load shedding in the islanded mode of operation. The load shedding is done by disconnecting loads of B19 of Fig. 2.1 at $t = 3$ sec. Figures 4.9 verify
that the V-F control of BESS maintains the operation of the system subject to load change in the islanded mode of operation. Figure 4.9 (a) shows the real output power of the three Solar-PV units and the BESS in the islanded mode of operation when a load shedding is done at $t = 3$ sec. A zoomed view of the BESS’s output power during the instant of load shedding is shown in Figure 4.10. Prior to the load shedding, the BESS supplies 0.466 pu to the islanded microgrid. After the load shedding, the BESS reduces its output power to 0.455 pu at $t = 3.05$ sec. Figure 4.9 (b) shows the BESS SOC in the islanded mode during the load shedding. Figure 4.9 (c) shows the microgrid frequency is maintained at 60Hz in the islanding mode of operation and during the load shedding. Finally, Figure 4.9 (d) shows that the voltage of the PCC is maintained within an acceptable range and not significantly disturbed by the load shedding.
Figure 4.9: (a) The active power exchanged between the Solar-PV units, the BESS, and the utility grid under the islanding mode control strategy when a load shedding occurs (pu), (b) BESS SOC under the proposed control strategy, (c) The microgrid system frequency in (Hz) and (d) The voltages of the PCC in (pu).
Figure 4.10: A close up of BESS’s output power during the load shedding instant.

4.4.4 Reconnection to the Grid

Figures 4.11 show the system transients due to the reconnection of the islanded microgrid to the utility grid. At time $t = 4.0$ sec, the microgrid is commanded to re-connect to the utility grid by the SC and the control strategy is switched from the islanded mode to the grid-connected mode. Prior to the re-connection, each Solar-PV unit supplies output power of 0.43 pu and the BESS supplies 0.41 pu to the islanded microgrid. Figure 4.11 (a) shows the real power exchange of the three Solar-PV units, the BESS, and the utility grid in both modes of operation and it shows that the same instant the re-connection occurs, the BESS output drops to zero again as per the grid-connected control strategy. Figure 4.11 (b) shows the BESS SOC discharging in the islanded mode and in an idle state in the grid-connected mode as per the proposed control strategy. Figure 4.11 (c) shows the microgrid frequency is maintained around 60Hz in both modes of operation with an acceptable transient during the re-connection process. Finally, Figure 4.11 (d) shows the voltages of the PCC are maintained within the acceptable range in both modes of operation with an acceptable transient during the reconnection process.
(a) Real Power Exchange

(b) BES SOC
Figure 4.11: (a) The active power exchanged between the Solar-PV units, the BESS, and the utility grid during the reconnection of the islanded microgrid to the utility grid (pu), (b) BESS SOC under the proposed control strategy, (c) The microgrid system frequency in (Hz) and (d) The voltages of the PCC in (pu).
4.5 Operation of Islanded Microgrid During Faults

This section investigates the behavior of the microgrid in the islanding mode during symmetrical and asymmetrical faults occurring at B19 of the microgrid. The fault resistance is 0.01Ω and is cleared at the first zero current-crossing of each faulted phase after 6 cycles (100 ms).

4.5.1 Three-Phase-to-Ground Fault

A LLLG fault occurs at bus B19 of the islanded microgrid at $t = 5$ sec and the fault is cleared after a fault duration of 0.1 sec at $t = 5.1$ sec. $I_{B19}$ increases from a steady value of 0.75 p.u to 5 pu because of the transient experienced by the fault. After the fault is cleared, another transient occurs in $I_{B19}$ which reaches 3 pu at $t = 5.108$ sec, the transient gradually decreases and reaches the steady state again at $t = 5.6$ sec. As shown in Fig. 4.13, the clearing of phase a occurs at $t = 5.101$ sec. At $t = 5.102$ sec the system goes from a single phase to two phase version and finally returns to a three-phase version by $t = 5.108$ sec when all phases of the fault are cleared. Consequent to the clearing of the LLLG fault, the islanded microgrid system does not reach the steady before a period of 500 msec of time.

4.5.2 Single-Line-to-Ground Fault

In Figure 4.14, a LG fault occurs at phase a of bus B19 at $t = 5$ sec and the fault is cleared after a fault duration of 0.1 sec at $t = 5.1$ sec. During the LG fault, the voltage of (phase a) severely drops and the other two phases (b and c) become unbalanced during the fault. Fig. 4.14 shows that even after the clearance of the fault, $V_{B19}$ does not return to its normal range until $t = 5.3$ sec. An initial transient of $I_{B16}$ occurs at $t = 5.05$ sec, $I_{B19}$ increases from a steady state value of 0.75 pu to 2.5 pu and becomes unbalanced during the fault as it increases gradually until it dies out at $t = 5.15$ sec. The islanded microgrid system becomes unbalanced during the LG fault, consequently, $I_{B19}$ and $V_{B19}$ are unbalanced during the LG fault. Control actions eventually return $V_{B19}$ and $I_{B19}$ to their normal range at $t = 5.3$ sec.
Figure 4.12: $V_{B19}$ and $I_{B19}$ during LLLG fault at bus B19 of the islanded microgrid.
Figure 4.13: A close up of $V_{B19}$ during the clearing of an LLLG fault at bus B19 of the islanded microgrid.
Figure 4.14: $V_{B19}$ and $I_{B19}$ during LG fault at bus B19 of the islanded microgrid.

4.6 Conclusions

This chapter proposes a control strategy for a microgrid system integrated with multiple Solar-PV units and BESS when it is disconnected from the utility grid. The control strategy enables the transfer from the grid-connected mode to the islanded mode, assigns the BESS to maintain the voltage and frequency of the islanded microgrid and reconnects to the utility grid. Section 4.4.1 verifies the microgrid transition from the grid-connected mode to the islanded, i.e., upon receiving the switching signal from SC, the BESS starts discharging at the rated power to fast control the microgrid voltage and frequency. Microgrid frequency is maintained around 60Hz in both modes of operation, even though it reaches 8% of its nominal value at the transition instant, still this value is within the IEEE1547 FRT envelop of Fig 4.2 as it occurs in less than 0.16 sec. The voltages of the PCC during the transition reaches 22%, however it falls within the IEEE VRT envelope of Fig 4.2.

Section 4.4.2 verifies the coordination between the BESS and Solar-PV units, i.e., when Solar-PV2 output power drops to zero, the BESS increases its output power to maintain the frequency. In section 4.4.3, the microgrid frequency and voltage of the PCC are maintained within acceptable ranges and
are not significantly disturbed by the load shedding. Section 4.4.4 verifies the microgrid reconnection to the utility grid upon receiving the grid-connection signal from the SC, i.e., the BESS returns to its idle state again. As concluded from performance evaluations, BESS control system keeps the microgrid’s voltage at 1 pu and maintains its frequency at 60 Hz during the islanded mode of operation under all test cases.

The behavior of the microgrid during symmetrical and asymmetrical faults is also investigated, the microgrid system, does not remain balanced under fault scenarios due to the lack of fault ride through capability of Solar-PV units and BESS. However, upon clearing the fault, control actions eventually return the voltages and currents of the PCC to their normal ranges after 500 $msec$ and 200 $msec$ in the case of symmetrical and asymmetrical faults, respectively.
Chapter 5

Conclusions

In this thesis, the operation and control of a typical microgrid system are studied. The microgrid system integrated with multiple Solar-PV units and BESS. The models of the microgrid system including Solar-PV systems and BESS are presented. The control strategy for both modes of operation are given in a closed loop feedback flowchart. Also, fast control of microgrid frequency and voltage is done with the employment of strategically placed BESS. The approach used in this thesis is the implementation of one centralized supervisory controller and four local controllers into the Solar-PV units and BESS with the utilization of communications between them. The microgrid system is simulated in both modes of operation: grid-connected and islanded. The transients due to islanding process are illustrated and it is proved that the proposed control strategy maintains frequency and voltage close to their nominal values for varying solar irradiance during islanded mode of operation. Furthermore, the stability of the microgrid is ensured in both modes of operation by maintaining the standard requirements. The controllers are developed in the dq-frame reference based on the per-unit system. Hence, it is easy to use the same controllers for differently sized power converters and to avoid performing very complicated parameter tunings. The chosen control parameters in the proposed control strategy are, however, dependent on the Solar-PV, BESS, and external power grid conditions. These parameters can be adaptively achieved with the changing system conditions which could be a very promising future direction of this work.
5.1 Specific Conclusions

- The microgrid system, including three 1.5MW Solar-PV units and one 2MW(4MWhr) BESS were modeled, controlled, and operated in the offline time-domain simulation PSCAD software platform in both modes of operation: grid-connected and islanded.

- Two closed-loop feedback control strategies were developed for real power exchange between microgrid with the utility grid in the grid connected mode and the fast control of microgrid in the islanded mode.

- Three local controllers for the Solar-PV units were implemented to keep the Solar-PV units in the P-Q control mode tracking their MPP under the changing solar irradiance data in both modes of operations.

- One local controller for the BESS was implemented to keep it idle in the grid connected mode while supporting the microgrid’s voltage and frequency in the islanded mode.

- An SOC constraints logic was developed and adopted in the control strategy to ensure the battery availability to support the islanded microgrid, prevents formation of hysteresis band and extends the battery service life.

- Reliable operations of the microgrid in both modes of operation were verified in performance evaluation as per the requirements of IEEE 1547, taking into consideration variable solar irradiance, charging and discharging the BESS, islanding event, voltage and frequency control, load shedding, and power loss.

- Seamless transition from the grid-connected mode to Islanded mode and vice versa was ensured through the developed control strategy.
5.2 Contributions

The contributions of this thesis are as follows:

- Proposes control strategy that capable of operating microgrid system integrated with multiple Solar-PV units and BESS in the grid-connected mode, in the islanded mode and can transfer between them. The control strategy provides the optimum response in terms of power balance and voltage/frequency stability, even though, voltage rise and voltage unbalance during the transients in the performance evaluations, these variables were maintained within the appropriate limits.

- Explores practical scenarios of the microgrid operation such as the variable Solar-PV generation due to the irradiance change, considering the BESS SOC constraints, exporting surplus power to the utility grid, load shedding and power loss. Moreover, the practical modeling of the Solar-PV and BESS based on industrial data sheets.

  ✓ The BESS was modeled and sized based on the Voltage Source-Resistor battery model and the experimental data of (LiFePo4) Li-ion Battery Energy Storage System.

  ✓ The BESS SOC constraints were considered by developing a SOC constraints logic which can handle the battery SOC limits in both modes of operation to protect it against any accidental overcharge or over discharge events and it also prevents the unwanted hysteresis band by considering the battery losses. Evaluated in Chapter 3.

  ✓ The variable Solar-PV generation was considered by exposing the Solar-PV units to solar irradiance data from Arizona weather station.

  ✓ Practical scenarios such as load shedding, power loss, temporary faults and reconnection to the grid were conducted in the performance evaluations of Chapter 4.
5.3 Future Work

There are several issues which require further investigation based on the context of this thesis such as:

- Islanding detection algorithms and verifications.

- Protection strategies and relay coordination to prevent unwanted equipment tripping during and after islanding process.

- Impact of single-phase and unbalanced loads on the control, protection, and behavior of the microgrid and these issues may be more noticeable with the weak microgrid system.

- Reactive power control to address stability problems of the islanded microgrid with significant Solar-PV penetration.

- RTDS implementation of the developed controllers to reduce the simulation time and to ensure its industrial application.
Bibliography


Appendix A

A.1 Study System Parameters

Table A. 1: Source Parameters.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
<td>(MVA)</td>
<td>20</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>(kV)</td>
<td>27.6</td>
</tr>
<tr>
<td>Positive sequence resistance</td>
<td>(Ohm)</td>
<td>0.027</td>
</tr>
<tr>
<td>Positive sequence reactance</td>
<td>(Ohm)</td>
<td>0.86</td>
</tr>
<tr>
<td>Zero sequence resistance</td>
<td>(Ohm)</td>
<td>0.078</td>
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<tr>
<td>Zero sequence reactance</td>
<td>(Ohm)</td>
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Table A. 2: Overhead lines Parameters.

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<tr>
<th>Line Type</th>
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<th>X1  (ohms/km)</th>
<th>B1  (uS/km)</th>
<th>R0  (ohms/km)</th>
<th>X0  (ohms/km)</th>
<th>B0  (uS/km)</th>
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<td>0.4852</td>
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### Table A. 3: Loads Parameters.

<table>
<thead>
<tr>
<th>Load Bus Name</th>
<th>Load Name</th>
<th>VL_L (kV)</th>
<th>VL_G (kV)</th>
<th>R_a (Ohm)</th>
<th>R_b (Ohm)</th>
<th>R_c (Ohm)</th>
<th>X_a (Ohm)</th>
<th>X_b (Ohm)</th>
<th>X_c (Ohm)</th>
<th>L_a (H)</th>
<th>L_b (H)</th>
<th>L_c (H)</th>
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<tr>
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<td>B2</td>
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<td>0</td>
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### Table A. 4: Transformers Parameters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Ratings (MVA)</th>
<th>Phases</th>
<th>High Voltage (kV)</th>
<th>Low Voltage (kV)</th>
<th>SC impedance (%)</th>
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<tbody>
<tr>
<td>T1</td>
<td>3.6</td>
<td>3</td>
<td>27.6</td>
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<td>T3</td>
<td>1</td>
<td>3</td>
<td>27.6</td>
<td>Y0</td>
<td>8.3</td>
</tr>
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<td>3</td>
<td>27.6</td>
<td>Y0</td>
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<tr>
<td>T5</td>
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<td>27.6</td>
<td>Y0</td>
<td>0.37</td>
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<td>27.6</td>
<td>Y0</td>
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<td>T7</td>
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<td>3</td>
<td>27.6</td>
<td>Y0</td>
<td>0.37</td>
</tr>
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</table>
A.2 Controller Parameters

The Proportional Integral (PI) values within the current controller and the DC voltage controller of the three Solar-PV systems are included in Table A.5 and A.6.

Table A. 5: Current Controller of the Solar-PV.

<table>
<thead>
<tr>
<th>Proportional Gain</th>
<th>$K_{p,v}$</th>
<th>0.1</th>
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</thead>
<tbody>
<tr>
<td>Integral Time Constant</td>
<td>$\tau_{i,v}$</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table A. 6: DC Voltage Controller of the Solar-PV.

<table>
<thead>
<tr>
<th>Proportional Gain</th>
<th>$K_{p,v}$</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral Time Constant</td>
<td>$\tau_{i,v}$</td>
<td>0.1</td>
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</table>

Table A. 7: Current Reference Limits.

<table>
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<tr>
<th>$I_{d\text{d,max}}$</th>
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</thead>
<tbody>
<tr>
<td>$I_{d\text{d,min}}$</td>
<td>0</td>
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<tr>
<td>$I_{tq\text{,max}}$</td>
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<tr>
<td>$I_{tq\text{,min}}$</td>
<td>-1</td>
</tr>
</tbody>
</table>

The PI values within the current controller of the BESS are included in Table A.8.
### Table A. 8: BESS Current Controller.

<table>
<thead>
<tr>
<th>Proportional Gain</th>
<th>K_{p,v}</th>
<th>0.1</th>
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</thead>
<tbody>
<tr>
<td>Integral Time Constant</td>
<td>\tau_{i,v}</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Table A. 9: PLL Parameters within Each Solar-PV Unit.

<table>
<thead>
<tr>
<th>Proportional Gain</th>
<th>50</th>
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</thead>
<tbody>
<tr>
<td>Integral Gain</td>
<td>900</td>
</tr>
<tr>
<td>Base Volt</td>
<td>370 [V]</td>
</tr>
<tr>
<td>Base Frequency</td>
<td>60 [Hz]</td>
</tr>
<tr>
<td>Angle input/output</td>
<td>Radians</td>
</tr>
<tr>
<td>Upper Tracking Limit</td>
<td>1.2</td>
</tr>
<tr>
<td>Lower Tracking Limit</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### A.3 Solar Irradiance Data

The solar irradiance data used in this thesis is taken from a site of installation in Arizona, USA. The global horizontal irradiance is measured in 1 second sample intervals. The magnitude of irradiance change from one second to the next is analyzed and binned into 0.25 W/m² values [14]. Three data files of the solar irradiance were used in the PSCAD software platform as input to three Solar-PV systems. Figure A.1 plots of the measured irradiance data used in this thesis.
A.4 MPPT Logic

Figure A.2 explains the MPPT algorithm developed in [14]. The logic observes the solar-PV power change, if it is larger than a certain threshold ($\Delta P_{\text{large}}$) in one iteration, the algorithm concludes it as a rapid change in irradiance and enters an interrupt as explained next.

“The sampled power level is used to refer to a look-up table for a voltage step size (V step). The new voltage reference is given and the MPPT algorithm waits for a time ($\Delta t_{\text{large}}$) until the next iteration. After one iteration of the interrupt, the algorithm develops an iteration of classical IC method so that $\Delta P$ can be evaluated based on the voltage step size of 1 V (rather than the variable voltage step size, V step). $\Delta P_{\text{large}}$ represents a large change in power that is due to irradiance change, the voltage step-size is selected from a look-up table based on the solar-PV power output”.
Figure A.2: MPPT Incremental Conductance logic of [14].
Appendix B

B.1 Thevenin Equivalent

Thevenin equivalent was used to reduce the study system network from buses B1 to B12 as depicted in Figure B.1. To calculate the equivalent voltage source parameters, symmetrical fault (3L-G) and asymmetrical fault (L-G) are applied at Bus B12.

The magnitude of the positive sequence impedance is calculated as per the following equation

\[ Z^1 = \frac{V_{3LG/ph}}{I_{3LG/ph}} \, , \]  

(B.1)
where $V_{3LG/ph}$ is the pre-fault voltage per phase in rms and $I_{3LG/ph}$ is the steady state three line to ground fault current per phase. The angel of the positive sequence impedance was calculated from the phase shift between the pre-fault voltage and steady state fault current.

The magnitude of the zero-sequence impedance is calculated as per the following equation

$$I_{LG/ph} = \frac{3 * V_{LG/ph}}{z^0 + z^1 + z^2}, \quad (B.2)$$

where $V_{LG/ph}$ is the pre-fault voltage per phase in rms and $I_{LG/ph}$ is the steady state single line to ground fault current per phase. If $z^1 = z^2$, where $z^1$ and $z^2$ are the positive and negative sequence impedances, respectively. Then, the magnitude of the zero-sequence impedance can be calculated from (B.3).

$$z^0 = \frac{V_{LG/ph}}{I_{LG/ph}} + 2 * z^1. \quad (B.3)$$

The angel of the zero-sequence impedance can be obtained by trials and error and it was found to be 73.3° for this thesis. The values of the equivalent source are enclosed in Table B.1.

<table>
<thead>
<tr>
<th>Table B. 1: Equivalent Source Parameters</th>
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<tbody>
<tr>
<td><strong>Magnitude (Ω)</strong></td>
</tr>
<tr>
<td>Positive Sequence Impedance</td>
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<tr>
<td>Zero Sequence Impedance</td>
</tr>
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</table>
Appendix C

Extra Results when Faults Applied at PCC and B19 in Grid-connected mode and Islanded mode

C.1 Temporary Three-Phase-to-Ground Fault applied at the PCC in the Grid-Connected mode
C.2 Temporary Single-Line-to-Ground Fault at the PCC in the Grid-Connected mode
C.3 Temporary Three-Phase-to-Ground Fault applied at B19 in the islanded mode
C.4 Temporary Single-Line-to-Ground Fault at B19 in the islanded mode

![Graph showing current waveform](image_url)

- $I_{PV1}$
- $I_{PV2}$

Time (sec)
Appendix D
Extra Results for Solar-PV and BESS
Currents in Grid-connected mode and
Islanded mode

D.1 Variable Solar Irradiance
D.2 BESS Charging Mode

\[ PV_1 \]

\[ T_{PV1} (pu) \]

\[ PV_2 \]

\[ T_{PV2} (pu) \]
D.3 BESS Discharging Mode

PV\textsubscript{1}

PV\textsubscript{2}

Time (sec)

Time (sec)

I_{PV1} (pu)

I_{PV2} (pu)
D.4 Islanding Transition

\[ \text{PV}_1 \]

\[ \text{PV}_2 \]

Time (sec)

\[ I_{\text{PV}1} \text{ (pu)} \]

\[ I_{\text{PV}2} \text{ (pu)} \]