ENG470 Engineering Honours Thesis

Battery Energy Storage System Control Algorithm Design

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Abstract

Microgrid is based on smaller decentralised low voltage system with the use of modern power technology puts different types of Distributed Energy sources solar power, wind power, and energy storage devices together, improving the electrical supply reliability, reducing the feeder loss and ensures the stability of the voltage. The current trend of incorporating energy storage devices in the microgrid is aimed to mitigate the power imbalance and improve the electrical supply reliability.

The thesis uses Kalbarri, Western Australia as a case study site with an aim to investigate the appropriate battery technology and formulate control algorithm for the microgrid.

The thesis starts by examining the Australian electrical market including the: socio-economic, political, and regulatory environment and presents the rationale of having an Energy Storage System in rural Australia. The thesis investigates the various available BESS battery technology options and suggests the most appropriate options for the BESS comprised Kalbarri microgrid model.

The MATLAB/Simulink BESS control algorithm design model is presented with an aim to test voltage and frequency regulation under different load condition, including the process of seamless transition from the grid-connected operation to a grid-disconnected operation of the microgrid.

The research presents a theoretical control model based on the Power Control theory and existing academic literature on the topic. The thesis examines the control algorithm design to regulate the frequency and voltage using the BESS system to connect to the main three phase AC grid. The overall site model includes a power conversion of two DC sources: BESS and PV system. The BESS control algorithm model comprises of a Power Conversion system that use three-phase full bridge Insulated Gate Bipolar Transistors (IGBTs) with LCL filter and a Power Control System based on Phased Lock Loop to synchronise with the grid frequency. The Power Control system uses a three-phase sinusoidal abc frame conversion to a DC reference signal dq0 frame to incorporate PI controller with an aim that the intermittence of the renewable energy generation Wind and PV system can be maintained to a balanced state in the grid within a short frame of time. The BESS control algorithm model uses a Current Controlled Voltage Source Converter for its simple controller design, better
performance during grid fault and the overall cost saving of the system. The thesis simulation utilized CCVSC for its tight regulation of the line current, mainly VSC protection against overcurrent and a high accuracy instantaneous current control.

However, the author acknowledges the simulation result indicate an anomaly with voltage control while using CCVSC in the control algorithm model in power source transition test condition. Hence, as a part of future improvement with a focus on the overcurrent, the author concludes possible testing with the VCVSC based control algorithm model for rapid and continuous response for smooth dynamic control and automated P and Q power control in both steady-state and dynamic system conditions.

Finally, the impact on the microgrid is presented with an in-depth analysis of the results, including the achievements, innovations, challenges and the suggestion for future improvement in the discussion section of the report.
Acknowledgements

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I am dedicating this thesis to my mother Ranjana Maskey and my father Narayan Kumar Maskey. I would thank my loving aunties Ratna Maskey Stephenson and Sita Maskey Subedi for all the support and life guidance. I am very blessed to have two more mother figures in my life. My girlfriend Christine Gozdalski for bringing love into my life. I will be forever grateful for the strong familial foundations my family has provided for me. My relationships with them is irreplaceable and without their encouragement, this journey would have been relentless. I would like to thank god for making it possible under all the personal challenges I faced during this period.

Lastly, I would like to mention words from my idol, late DR. Carl Sagan, ‘Somewhere something incredible is waiting to be known’. Life is challenging and beautiful at the same time, albeit, the hunt for the incredible unknown makes worth living.
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## Glossary

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
<tr>
<td>CCVSI</td>
<td>Current-Controlled Voltage Source Converter</td>
</tr>
<tr>
<td>VCVSI</td>
<td>Voltage-Controlled Voltage Source Converter</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resource</td>
</tr>
<tr>
<td>Li-on</td>
<td>Lithium Ion</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
<tr>
<td>CCVSC</td>
<td>Current Controlled Voltage Source Converter</td>
</tr>
<tr>
<td>VCVCC</td>
<td>Voltage Controlled Voltage Source Converter</td>
</tr>
<tr>
<td>P</td>
<td>Real Power</td>
</tr>
<tr>
<td>Q</td>
<td>Reactive Power</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
</tr>
<tr>
<td>dq</td>
<td>Direct Quadrature</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracker</td>
</tr>
<tr>
<td>V-f</td>
<td>Voltage Frequency</td>
</tr>
<tr>
<td>αβ</td>
<td>Alpha Beta</td>
</tr>
<tr>
<td>SWIS</td>
<td>South West Interconnected System</td>
</tr>
<tr>
<td>Pf</td>
<td>Power Factor</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
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Chapter 1: Introduction

The electric industry has undergone a significant amount of changes over the past decades. From the starting days of electricity with Thomas Edison’s Pearl Street, New York City DC distribution system, where for the first time the electricity was brought to the customer doors and to Nikola Tesla’s AC current discovery, that drove the electrical revolution of the nineteenth century exceeding the generation, transmission and distribution limit of Edison’s DC electricity [1]. The inception of AC electricity took the generation far from the settlements and powered the households and the industries through the poles and wires. The introduction of transformers into the distribution and transmission enabled supply over long distances, through stepping up the voltage in the transmission line reduced the losses on the transmission lines. The nineteenth century electrical achievement led the world into the industrial revolution.

However, technological advancement in the twentieth century created a high reliance on electricity. The conventional electrical infrastructure’s dependence with the supply through poles and wires have encountered issues with the interruption of the supply due to long distance of wire and poles that are more susceptible to aging, wear and tear, and harsh environmental conditions. In Western Australia, the issue mainly applies with the existing long-distance transmission, primarily, with the economic viability of the electricity supply chain. On the other hand, the increasing reliability issue with the electricity grew exponentially over the year, driving the necessity to transition out of the conventional electric network system.

The emerging renewable energies trend is playing a significant role to reduce the dependency on fossil fuels and tap the clean energy sources available to Western Australia such as solar and wind generation. Nonetheless, the inclusion of the renewable source to the existing electrical network requires a thorough analysis of the impact on the grid, particularly, the reliability and safety of the existing infrastructure. The research thesis starts with examining the overall components of the decentralised system with a focus on the concept of microgrids.
1.1 Microgrid

The microgrid technology is based on the effective inclusion of power, load, energy storage and control devices into a single controllable power supply system [2]. Microgrid is based on smaller decentralised low voltage system with the use of modern power technology puts different types of DER sources solar power, wind power, and energy storage devices together, improving the electrical supply reliability, reducing the feeder loss and ensures the stability of the voltage. The microgrid mainly operates on on-grid connection. However, it must be able to provide the required generation capacity and control after losing connection from the main grid [3].

The challenges of incorporating the renewable energy sources into the microgrid are that Distributed Generation takes place at the distribution side, when combined with the intermittent characteristics of the Renewable Energy sources limits the direct connection to the grid. Hence, power electronic interface of connecting (DC to AC or AC to DC) driven by the effective control system is required [2], and the energy storage system needs to store excess generation and inject power into the grid at the time of need.

1.1.1 Kalbarri Microgrid

The thesis is based on the microgrid in the regional town of Kalbarri, Western Australia. Kalbarri town site is serviced by 140 km long 33 kV radial feeder from Geraldton. Due to exposure to the environmental factor including wind-borne marine salt and dust on long distance feeder’s results long outages on the line [4]. Furthermore, Western Power’s Energy Modular Network report 2016 claims that the average customer without power for three hours each year at an average reliability 99.93 percent, but, on the other hand, the customers on the edge of the network in regional towns like Kalbarri face more extend and reoccurring outages [5].
Figure 1: Conceptual model for Kalbarri BESS centric microgrid [6]

The figure above is sourced from Western Power Study into the feasibility of a microgrid at Kalbarri found in [6]. The figure showcases a battery centric microgrid power flow including generation components - the existing Wind farm and newly added solar PV plant, power supply from Geraldton substation, a battery energy storage system and transmission to homes and businesses.

The detailed investigation of the Kalbarri microgrid generation and distribution can be found in the Chapter Methodology: Generation and Distribution.

1.1.2 Battery Energy Storage System

Due to the varying generation level of the DER source, an energy storage device is needed to provide the required amount of power to maintain demand/supply in the off-grid operation mode and stabilise the microgrid [7]. Yallamilli et al. 2016 highlights that the aim to combat the intermittent
The nature of RES, the storage element have become the most essential part of microgrid is to enable the energy trading [8]. Riesz et al. [9] and Da Silva et al. [10] further support by pointing out BESS’s use in power application like voltage support, fast response and frequency regulation.

The conventional grid relies on a synchronous generator’s large rotational inertia to control frequency stability and fast voltage regulation to stabilise the voltage in the network [11]. Riesz et al. [12] claim that 12400 MW’s of inertia on SWIS grid from conventional fossil fuel plant can be largely reduced by the battery system providing voltage control without intrinsic rotational inertia. BESS maintained in a partially charged state have highly agile response rate and can give frequency stability capacity [13].

In the next Chapter, the thesis examines the Western Australia’s overall energy market and current BESS challenges perspective.

Chapter 2: Western Australia Energy Market

EPA claims that even though WA’s carbon emission is small by comparison to the global measure, WA still is one of the highest per capita emission regions in the world [14]. The large part of WA’s emission is from the retail, distribution, and generation of electricity and gas accounts for about 75 percent of the State’s greenhouse-gas emissions, out of which over 40 percent is purely from the electricity generation [15].

Western Power’s Energy Modular Network report 2016 claims that the average customer without power for three hours each year at an average reliability 99.93 percent, but, on the other hand, the customers on the edge of the network in regional WA face more extend and reoccurring outages [5]. Western Power’s Media Release in 2016 associate the power reliability in rural WA with the unavoidable issue faced with supplying electricity over very long transmission and distribution lines [16]. The added complexity with the WA’s geographical isolation limits the network’s prospect to
connect to its neighbouring systems, in hindsight, the challenging environment of WA’s isolation also presents an opportunity for the State to utilize the DER Wind and Solar energy to transition from the existing conventional centralised model to a decentralized model [17].

2.1 Western Australia Need for BESS

The motivation behind the implementation of Battery Energy Storage System (BESS) can vary based on regional needs. The topmost advantage of having a battery storage system is for clean energy, reaping benefits of reduced technology costs and mitigating potential future electricity price rise [18]. Besides the future electricity price rise, the customers within the WA’s South West Interconnected System (SWIS), the primary motivation is more linked with the BESS presenting an opportunity to move towards a flexible and secure electricity network [19].

Notably, the International Energy Agency (IEA) estimates globally the increase in installation of more than 78.0 GW of new solar and wind energy generation in 2016, which will further extend to project 378.1 GW over the next five years [20].

The reviewed literature incorporates the rationale on why BESS dissemination needs to overcome the economic, technical and regulatory hurdles that surround the overall Australian energy industry. IEA report 2014 lists a through details of the rationale for energy storage and barriers that hinder energy storage deployment [21]. Zhang et al. [22] provide a detailed barrier for energy storage markets [22]. The economic evaluation research thesis by Han et al. [23] contradicts that the true economics of the BESS requires more study on depreciation of the battery capacity through both electrical-chemical and mechanical mechanism, a result of the increase in battery’s inner resistance and a decrease in its efficiency prior to the battery’s end of life. Naumann et al. 2015 and Peterson et al. 2010 observed the BESS life cycle assessment is mainly limited to the State of Charge (SOC), with not enough focus given on the battery’s thermal exchange effect which largely impacts the internal resistance [24] [25] [26].
Nonetheless, the cost of infrastructure towards transmission and distribution of the electricity is largely reduced using DER model. DTI OFGEM report 2007 estimates that approximately 6.5 percent of generated electricity is lost during the electrical transmission and distribution to the consumers [27]. Allan et al. [28] specify the added benefit of DER with reduced inefficiencies and flexible electricity supply can minimize or eliminate the costly investments in existing centralised network with its aging infrastructure and capacity limitations.

2.1.1 BESS: Barriers

Even though there are research and tested benefits of the use of DER and BESS technology, there are still obstacles that act as a barrier in the implementation of BESS. The challenges can be list into below three main categories:

- Economical
- Regulatory
- Technical

2.1.1.1 Economical

From State of the Infrastructure report 2011/2012 suggests that the aging electrical transmission and distribution infrastructure led to increasing the frequency and severity of defects, causing reduced serviceability until repair or replacement is needed [29]. Manning et al. [26] highlight that according to the current regulatory structure for the National Electricity Market, the cost of electrical poles and wires is passed down to the customers. The customers within the WA’s SWIS network grid pay the same energy tariff, which in other words, the customers in Perth metro area cover the part of the cost of long power lines supplying power to the regional areas [30].

In a case study by Tayal et al. [17] concludes that the current model can provide a limited motive for the electricity utility Western Power to move away from existing area of operation. Additionally, the current model hinders the storage generation, instead of viewing the DER as an opportunity [31].
2.1.1.2 Regulatory

In the Australian National level, the complex nature of the legislative frameworks and absence of the long term policy is acting as a barrier towards the investment in the DER [32]. Zeh et al. 2016 acknowledge the increasing importance of the BESS integration with the electrical grid, nevertheless, notes that the market maturity is slow due to the lack legal framework and the initial high costs of the systems [33]. Council of Australian Governments Energy Council (COAG, 2015) identified the necessity to overcome the barriers in adopting the new technologies through clearer and consistent regulations [34].

The current legislation only allows Western Power to distribute energy through poles and wires and not generation, which a barrier for the battery storage system implementation for more reliable electricity at the end of the line regional areas [35].

2.1.1.3 Technical

There is an additional compliance requirement with selection and installation for the network operators to connect the grid [36]. In Western Australia, the compliance requirements extend to the selection and installation of the system, due to the concern of the customer’s true electricity demand may be masked by the battery storage and if BESS is not operational, there will be pressure on the existing electrical supply [37].

With the technological advancement, energy reform and increasing public awareness about the added benefits of energy storage technology, the above-mentioned barriers is gradually weaning off.

Furthermore, it is evident in the case by the UK government's Energy Review that a community network-based energy system increases the public awareness and social attitudes towards energy issues leading to higher efficiency in the way consumers use the energy resources [38].
2.2 SWIS Grid Future: The Modular Network

The modular network is reliant on consumer behaviour, technology advancement rates, regulation and policy [39]. Western power is aiming for a grid transformation by moving from the current fully integrated network, where everything is connected into a modular network made of battery storage systems, PV, microgrid and stand-alone battery system [40]. The vision is to have a flexible electrical network that will have a direct grid connection to the high load areas such as stadiums and mining, on the other hand, for the long distance end of the line consumer is serviced by more reliable stand-alone system and micro-grid [41]. The Western Power’s current BESS, microgrid and stand-alone systems in Stage 1 six projects in the Great Southern region and Stage 2 with 60 locations in the regional WA [42] is extensively studied in the thesis.

![Current SWIS model](image1.png) ![Future model with variable network types](image2.png)

*Figure 2: Western Power Network of the future [43]*

The figure above summarises transition from a centralised network to a modular network future with variable network where the network supply is diverse.
2.3 System Stability - Grid Code

The dissemination of battery storage system with proliferation using solar or wind energy will lead the industry from a centralised to a distributed model. This requires electrical networks to adapt to multi-flow paths and respond to increasing intermittency of generation [44].

The international standards are deployed by utility providers in different region worldwide to increase the operability and efficiency, including the safe and reliable connection of Distributed Generation into the power grid [45]. The most noteworthy DER interconnection standard is developed by IEEE Standard 1547 that clarifies the parameters in terms of performance, safety and maintenance [46]. Roy et al. 2013 summaries the primary attention areas of voltage regulation with this high inclusion of DER and stability relating to damping requirement caused by low inertia loads causing the voltage oscillation because of mismatch between the control interaction and the reactive power in the grid [47].

![Figure 3: Nominal Voltage level in Australia [48]](image-url)
2.3.1 Grid Stability in Western Australia

Western Power Ancillary report 2013, it can be seen that the suitability of energy storage technology within the SWIS network will be dependent on spinning reserve from fossil fuel generation due to the SWIS’s isolation from all other grid and the current lack of large-scale hydroelectric resources [49]. AEMO 2014 found the current SWIS network supply largely comes from the conventional fossil fuel station – with coal fired and gas fired generation [50]. Due to the existing SWIS electrical infrastructure is built based on the conventional centralised model, incorporating a multi-flow energy generation requires additional attention towards grid stabilisation.

The grid code practice in Australia is regulated by the Australian Energy Market Commission (AEMC) [51]. AEMO’s Power System report 2012 clarifies the frequency operating standard applies to the Western Australian grid. [52] The report includes frequency containment requirement in the majority of condition to be within ±1 Hz in both grid connected and islandic microgrid operation [53] and the voltage within the steady state accuracy of ±6 percent.

Chapter 3: BESS Battery Technology

Prior to examining the control algorithm of the BESS into the electrical network, the economics of the investment for an appropriate large-scale battery storage system type is studied. The battery storage system is primarily used to ensure the grid stabilisation and frequency regulation with the integration of the large scale solar and wind energy in the electrical grid. Divya et al. 2009, Zakeri et al. 2015 and Poullikkas et al. 2013 research thesis is found to have conducted a thorough analysis of the existing projects and the battery technology used [54] [55] [56]. Based on their research of the battery technology used in the sites similar to Kalbarri, below are the shortlisted three most widely used large scale battery technology:

1. Lead-acid battery
2. Lithium Ion (Li-ion) battery

3. Nickel Cadmium

A thorough detail on the working principle of behind each of battery technology listed above can be found in [57].

Below comparison chart is drawn based on battery technology research by Ibrahim et al. 2008, Poullikkas et al. 2013 and Zakeri et al. 2015 [58] [56] [55]:

<table>
<thead>
<tr>
<th></th>
<th>Lead-acid battery</th>
<th>Lithium-Ion battery</th>
<th>Nickel-Cadmium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power rating (in MW)</strong></td>
<td>Up to 20 [55]</td>
<td>Up to 0.01 [58]</td>
<td>Up to 40 [58]</td>
</tr>
<tr>
<td><strong>Response time</strong></td>
<td>Fast response [58]</td>
<td>Fast response [56]</td>
<td>Moderate [56]</td>
</tr>
<tr>
<td><strong>Efficiency (%)</strong></td>
<td>70 % to 90 % [56]</td>
<td>85 % - 95 % [55]</td>
<td>60 % - 73 % [55]</td>
</tr>
<tr>
<td><strong>Power density (W/kg)</strong></td>
<td>75 to 300 [58]</td>
<td>50 to 2000 [55]</td>
<td>50 to 1000 [58]</td>
</tr>
<tr>
<td><strong>Energy density (W/kg)</strong></td>
<td>30 to 50 [58]</td>
<td>150 to 350 [55]</td>
<td>15 to 300 [56]</td>
</tr>
<tr>
<td><strong>Total Capital cost (average per power rating in $/KW)</strong></td>
<td>Moderate at 2512 [55]</td>
<td>Moderate at 2140 [55]</td>
<td>High at 3376 [55]</td>
</tr>
<tr>
<td><strong>Life cycles (cycles)</strong></td>
<td>2000 to 4500 [55]</td>
<td>1500 to 4500 [58]</td>
<td>2000 to 2500 [58]</td>
</tr>
<tr>
<td><strong>Self-discharge (on a day)</strong></td>
<td>0.1 % to 0.3 % [55]</td>
<td>0.1 % to 0.3 % [55]</td>
<td>0.2 % to 0.6 % [55]</td>
</tr>
</tbody>
</table>

The feasibility study of the appropriate battery technology is examined in the Chapter 6 Methodology section Battery selection.
Chapter 4: BESS Control Algorithm

4.1 BESS Control Algorithm Aims

The requirement of the microgrid structure and control hierarchy is a necessity to understand the
BESS integration and examine the control algorithm into the microgrid. The thesis examined the
controlled strategies employed in the microgrid.

The thesis aims to conduct a thorough research in following areas:

- Voltage and frequency regulation in both grid-connected and islandic operation
- Synchronisation between microgrid and the main grid
- Microgrid resilience during the transient stage between change in power source conditions

4.2 BESS Control Algorithm Expectations

The control algorithm aims to provide more economical operation of the battery by not only
increasing reliability and reducing electrical cost but increasing the stability of the whole grid
network through reducing the electricity demand on the grid during the peak time [59]. The control
algorithm needs to level load, improve load factor and mitigate grid’s power system vulnerability
[60]. The BESS control algorithm primarily needs to regulate the frequency control, ensure the
power quality and the charge control is well maintained [61].

However, the research thesis is centred towards investigating the frequency and voltage stability of
the microgrid operation.

4.2.1 Frequency Control

Arun sawat wong et al. [62] stress that any misalignment of the generation and load creates a
development of the system frequency from the nominal value, and a significant deviation can result a
severe problem to the entire power system. The control algorithm model is challenged with
maintaining the frequency against the constantly varying active loads and mitigate the power
exchange errors [63]. The issues arise when the mismatch between the generation and the load can
cause the frequency to deviate. The predominant issue of intermittent generation nature of the renewable sources presents a constant design challenge on frequency control aspect [9]. During the off-grid operation of the microgrid, the active power variation affects the overall frequency, highlighting the necessity to dump the excess power on loads or the energy storage devices such as BESS that can improve the frequency regulation in the power generation [64].

Kalyani et al. 2012 examines both PI and PID controllers and concludes the PI controller effectively adjusts the frequency fluctuation with the change in load by actively damping the oscillation and quickly settling the system [65]. A thorough investigation into the use of PI controller is conducted in Chapter Methodology Section Control Algorithm model.

4.2.2 Voltage Control

Lu et al. [66] aligns power quality with BESS, claims the BESS’s ability to output both active and reactive at the same time combined with four quadrant operation ability. Azab et al. [67] further investigate that the PQ controller model is based on the generating a virtual quadrature signals that are orthogonal to the grid voltage and grid controller creating α and β coordinates.

Zhang et al. [68] suggests that the control is done by a decoupling of the active and reactive power separately leading to the output of the BESS equal to the reference value. Based on the assumption that regardless of the varying load and that the battery voltage is constant. Rouco et al. [69] further claims that the current in the d-axis of the reference frame and terminal voltage can control the active power and similarly, the current in the q-axis in the same frame controls the reactive power.

4.3 BESS Control Algorithm Objectives

Upon mapping the above Control Strategy Aims and Control Strategy Expectations against WA energy market and SWIS electrical network discussed in Chapter 2: WA Energy Market, the thesis objective is drawn as below:
• To design a resilient microgrid control algorithm, capable of handling transition between microgrid grid connected and grid disconnected mode. The resilience necessity is identified in the Chapter 2 Western Australia Energy market for the location such as Kalbarri.

• To mitigate the problem to the power system, a robust frequency control is required in Kalbarri microgrid with inclusion of DER - PV, Wind sources intermittent generation nature

• To investigate the real and reactive power in the network addressing the voltage control

The author recognises the above aims, expectations and objectives present a different significance and time period, that requires a hierarchical control approach to address the requirements.

![Microgrid control level hierarchy](image_url)

Figure 4: Microgrid control level hierarchy [70]

4.1.1 Primary Control

The primary control aims to stabilise the grid to enable the power trading between different generators, localised the control of the individual DER sources. The control primarily seeks to balance generation amongst DER sources with voltage and phase angle control [71]. The control primary provides active power and reactive power to converter used in the microgrid.
4.1.2 Secondary Control

The secondary control is a more centralised strategy focused on providing voltage and frequency stability in the microgrid. Hence, this is achieved by communicating the signal among the power converter in a microgrid. The control calculates the reference active power $P_{ref}$ and $Q_{ref}$ and provides the valve to the power converter to adjust control slope in the primary controller [3]. Due to potential frequency and voltage deviation issues with the primary control, the secondary control can compensate the incurred voltage and frequency deviations.

4.1.3 Tertiary Control

Tertiary control is based on the economic aspect to optimise the microgrid operation and manages the power flow between on-grid and off-grid operation [72]. The primary aim is to choose the operating point of the active power of each DER sources to enable the power flow control in a microgrid. Whilst operating in an off-grid mode, the microgrid needs to stabilise the voltage and supply power [3]. The examination of the different level control expectation sets a design aim for the BESS control algorithm.

4.4 BESS Modelling

4.3.1 Battery

A Battery’s main characteristics is determined by its voltage, supply current, the time constants, and internal resistances. The bi-directional charge exchanges due to discharging and charging of the battery in the project required the understanding of the dynamic behaviour of the battery.
The battery model includes a voltage source (Vo), an internal resistance (Rs), combined capacitance (Co) and (Ro) mimics the transient behaviour of the battery.

A thorough analysis of the suitable battery technology type discussed in Chapter 4: BESS technology and Chapter 7: Methodology battery Section Battery Technology Decision matrix.

4.3.2 Voltage Source Converter

Dong et al. 2014 highlights that the majority of the DERs converter-based connection to the microgrid, enabling the effective converter control resulting in the stability of the entire microgrid [74]. VSC allows the energy transfer from the DC sources Battery and PV system to output a smooth AC to connect to the main grid. During the grid connected mode, the voltage and frequency stabilization is completed by the main grid supply. Hence, the DER sources act as a current source and achieve a constant power output known as a PQ control method. However, during the off-grid mode, the microgrid is required to have the capacity to deliver frequency and voltage source, known as a V-f droop control method. The switching between the control methods have an impact on the operation mode conversion failure [74].
4.3.3 Converter Control Strategy with BESS

BESS is used as a constant DC source in the grid. The VSC is used to capture a suitable DC voltage and the voltage is then converted into grid-referenced AC signal [75].

Zhang et al. 2015 summarises the secondary control in microgrid can be conducted through PV mode (Active and Voltage regulation) with P and Q of the generation sources follows the active power interchange or voltage set point at the microgrid point of common coupling (PCC) or PQ mode (Active Power and Reactive Power regulation) where the P and Q of the generation sources follow the Pref and Qref measured at the PCC [76].

The thesis aims to use the PQ control mode for the BESS where the generation sources follow the Pref and Qref. The use of VSC enables the control of the phase and magnitude of outputting voltage, allows to regulate the injection of P and Q from the BESS.

During the grid connected operation of the microgrid, the VSC operates in PQ mode and the voltage and frequency reference is guided by the main grid. The VSC operates as a current source with exchanging P and Q, including supporting the main grid, however, during the islandic operation the VSC is required to operate in V-f mode to regulate voltage and frequency while sharing the P and Q.

If all the connected DG sources operate in the PQ control mode during the microgrid transition from the main grid to islandic mode, the challenge of instability arises.

Okedu et al. 2011 suggests that compared to Voltage Controlled VSC, Current Controlled VSC provides a lesser complicated controller design, a better performance during the grid fault and no necessity of DC-link protection reducing the overall cost of the system [77].

The author concludes the CCVSC converter is deemed more suitable upon mapping against the rural area necessity discussed in Chapter 2 Section Western Australian Energy Market.
4.3.3.1 Current Controlled Voltage Source Converters

A dedicated current controller scheme tightly regulates CCVSC line current through AC side terminal voltage. P and Q are controlled by the phase angle and the amplitude of the VSC line current with respect to the grid voltage [78].

Due to the current regulation scheme, the VSC is protected against overcurrent and have a high accuracy instantaneous current control [79]. Also, the current control includes robustness against variation in VSC and AC system parameters and superior dynamic performance and higher control precision.

The two main converter control strategies are discussed below:

**PQ Control Strategy**

PQ control is based on the DER sources specified P and Q according to the reference P and Q, mainly with the frequency and voltage of the grid with which the VSC is connected change within a certain range with the P and Q of the DER sources staying the same [67]. The strategy can be simplified as a constant power control method to match the P and Q of the DER sources with the reference power. PQ control is based on the decoupling P and Q and outputting the control in the dq frame. [80].

![Figure 6: Schematic diagram of PQ Control](image)

The change in the microgrid frequency within an allowed frequency minimum and frequency maximum value maintains the P of the converter to the reference P value of the grid. Likewise, the
change in the microgrid voltage within the allowed range maintains the Q of the converter to reference Q value of the grid.

**V-f control**

Microgrid transition from on-grid connected to the islanded mode creates an issue of instability with VSC staying in the PQ control mode. Hence, to adjust the grid frequency and voltage to the VSC must transition to the V-f mode [80]. The frequency can be controlled via power balance between the generation and the consumption by using the ESS, which requires a grid-forming unit with the V-f control strategy.

![Figure 7: V-f Control algorithm](image)

**Switching control mode**

Zhou et al. 2015 summarises the switching mode challenges possessed with the loss of the voltage and frequency support from the grid and highlights the switching process [2]. Upon discussion of the different P-Q and V-f control in the microgrid, Zhang et al. 2013 highlights the significance of the seamless control strategy transfer, however, criticises the lack of adequate research on the mode conversion [81].
In the Chapter 7 Section Control Algorithm model, the dual-mode converter examines the mode conversion from grid connected mode to islandic mode, while focusing on voltage and frequency control.

Chapter 5: Methodology

The testing of the control algorithm is based on the generation and load profile of Kalbarri, Western Australia. Kalbarri is a regional town located 569 kilometres from Perth [82]. Based on the Kalbarri microgrid information, a Simulink model including main grid source, BESS, PV system and Wind farm system is implemented [83].

Before commissioning the design and modelling, the suitable battery technology is examined using the Decision-matrix tool. The thesis thoroughly weighs the main necessity of the project site and based on the decision-matrix tool devise the most appropriate option. Upon selection of the battery technology, the battery technology type is used in the design simulation.

5.1 Battery Model

5.1.1 Battery Technology Selection

In Chapter 2 Section WA perspective on BESS, the necessity of the network is briefly discussed and the Chapter 4: BESS Battery Technology touched upon the existing battery system, and comparison amongst the most widely used system is made. A decision matrix tool is widely used in the engineering sector to evaluate compelling solutions through identifying key factors, criteria, and suggesting the most suitable option [84].

5.1.1 Decision Matrix

A decision matrix tool subjective measure of attributes is assigned:
Table 2: Battery Technology - Attributes and Value table

<table>
<thead>
<tr>
<th>No.</th>
<th>Attributes</th>
<th>Assigned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extremely low</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>Very low</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>Below Average</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>Average</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>Above Average</td>
<td>0.6</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>Very High</td>
<td>0.8</td>
</tr>
<tr>
<td>9</td>
<td>Extremely high</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The attributes table is mapped against the battery key factors in Chapter 4 Technology Selection and the finding of the WA perspective market requirements highlighted in Chapter 2 WA Energy Market. Also, the research thesis on rural Australia electrical network by Uski et al. 2018 and Wolfs et al. 2015 is examined [85] [86]. The author has prepared below value table:

Table 3: Battery Technology - Key factors value table

<table>
<thead>
<tr>
<th>Key factors</th>
<th>Attributes measure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating (in MW)</td>
<td>Very high</td>
<td>0.8</td>
</tr>
<tr>
<td>Response time</td>
<td>Very High</td>
<td>0.8</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>Extremely High</td>
<td>1.0</td>
</tr>
<tr>
<td>Lifetime (yr)</td>
<td>High</td>
<td>0.7</td>
</tr>
<tr>
<td>Power density (W/kg)</td>
<td>Above average</td>
<td>0.6</td>
</tr>
<tr>
<td>Energy density (W/kg)</td>
<td>Above average</td>
<td>0.6</td>
</tr>
<tr>
<td>Total capital cost (average per power rating in $/KW)</td>
<td>Average</td>
<td>0.5</td>
</tr>
<tr>
<td>Life cycles (cycles)</td>
<td>Below average</td>
<td>0.4</td>
</tr>
</tbody>
</table>
The battery comparison table prepared in Chapter 4: BESS Technology is revised below. The author assigned weigh score out of 1 to 5 for each battery technology type against its key factors:

**Table 4: Battery Technology - Weight allocation table**

<table>
<thead>
<tr>
<th>Key Factors</th>
<th>Lead-acid</th>
<th>Lithium-Ion battery</th>
<th>Nickel-Cadmium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Details</td>
<td>Weight</td>
<td>Details</td>
<td>Weight</td>
</tr>
<tr>
<td>Power rating (in MW)</td>
<td>Up to 20 [55]</td>
<td>4</td>
<td>Up to 0.01 [58]</td>
</tr>
<tr>
<td>Response time</td>
<td>Fast response [58]</td>
<td>5</td>
<td>Fast response [56]</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>70 % to 90 % [56]</td>
<td>4</td>
<td>85 % - 95 % [55]</td>
</tr>
<tr>
<td>Power density (W/kg)</td>
<td>75 to 300 [58]</td>
<td>2</td>
<td>50 to 2000 [55]</td>
</tr>
<tr>
<td>Energy density (W/kg)</td>
<td>30 to 50 [58]</td>
<td>2</td>
<td>150 to 350 [55]</td>
</tr>
<tr>
<td>Total capital cost</td>
<td>Moderate at 2512 [55]</td>
<td>4</td>
<td>Moderate at 2140 [55]</td>
</tr>
<tr>
<td>(average per power rating in $/KW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life cycles (cycles)</td>
<td>2000 to 4500 [55]</td>
<td>5</td>
<td>1500 to 4500 [58]</td>
</tr>
<tr>
<td>Self-discharge (on a day)</td>
<td>0.1 % to 0.3 % [55]</td>
<td>3</td>
<td>0.1 % to 0.3 % [55]</td>
</tr>
</tbody>
</table>

The self-discharge (on a day) for the battery is very low, with a score of 0.2.
The decision matrix table is prepared using the assigned value in Table 3 and assigned weight in Table 4 for each battery technology type. The score is calculated using:

\[ \text{Score} = \text{Value} \times \text{Weight} \]

**Table 5: Decision Matrix table**

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
<th>Lead-acid</th>
<th>Lithium-Ion</th>
<th>Nickel-Cadmium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weight</td>
<td>Score</td>
<td>Weight</td>
</tr>
<tr>
<td>Power rating (in MW)</td>
<td>0.8</td>
<td>4</td>
<td>3.2</td>
<td>3</td>
</tr>
<tr>
<td>Response time</td>
<td>0.8</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>1.0</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Lifetime (year)</td>
<td>0.7</td>
<td>4</td>
<td>2.8</td>
<td>4</td>
</tr>
<tr>
<td>Power density (W/kg)</td>
<td>0.6</td>
<td>2</td>
<td>1.2</td>
<td>5</td>
</tr>
<tr>
<td>Energy density (W/kg)</td>
<td>0.6</td>
<td>2</td>
<td>1.2</td>
<td>5</td>
</tr>
<tr>
<td>Total Capital cost (average per power rating in $/KW)</td>
<td>0.5</td>
<td>4</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Life cycles (cycles)</td>
<td>0.4</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Self-discharge (on a day)</td>
<td>0.2</td>
<td>3</td>
<td>0.6</td>
<td>3</td>
</tr>
<tr>
<td>Total Score</td>
<td></td>
<td></td>
<td>21</td>
<td>25.3</td>
</tr>
</tbody>
</table>
The result of assessment tool is tabulated below:

![Battery Technology Decision-Matrix result](image)

**Figure 8: Battery Technology Decision-Matrix result**

From the decision matrix analysis, Lithium-Ion battery type is deemed to be the most suitable for the project. Simulink’s Lithium-Ion battery for BESS with the voltage of 415 V with 4.5 MWh capacity is used:

![Simulink Lithium Ion battery equivalent circuit](image)

**Figure 9: Simulink Lithium Ion battery equivalent circuit [88]**
The battery operates by sensing the current through the internal resistance. The battery current \(I_{\text{batt}}\) is passed through the time integrator, enabling tracking of the current amount during the specific period of time. The battery’s Open Circuit Voltage \(V_{\text{oov}}\) is formulated using the below equation [89]:

\[
V_{\text{batter}} = V_{\text{oov}} - K \left[ \frac{Q \cdot I_{\text{batt}}}{Q - I_{\text{batt}} \cdot t} \right] + A \cdot e^{-B \cdot I_{\text{batt}}}
\]

5.2 Generation

Kalbarri microgrid is serviced by a 140 km 33KV three-phase voltage source from Geraldton, WA. The microgrid is additionally serviced with an existing 1.6 MW wind farm located 25 km south of the Kalbarri, a 4.5 MWh BESS and a proposed a 1 MW concentrated solar PV [6]. A 33 kV three phase voltage source Simulink block is used to replicate the grid source.

5.2.1 Distributed Generation Sources

5.2.1.1 Wind Generation Model

The existing 1.6 MW Wind farm is simulated using pre-defined Simulink block Wind Turbine Induction Generator with a base speed of 12 metre per second and pitch angle controller gain of \(K_p\) and \(K_i\) 25. The details of the Wind Turbine modelled can be found in the Appendix Wind.

5.2.1.2 PV Generation Model

The proposed PV generation is mimicked using a PV array block SunPower SPR-305E-WHT-D module with a capacity of 305.226 W per solar cell available in Simulink, with using the information available at the standard condition of 1000 W per square metres is calculated. The information on the PV array used in the simulation can be found in the Appendix PV. 1 MW solar generation is simulated using 75 parallel strings with 44 series connected modules per string to generate 1 MW power supply.

A maximum power point tracking (MPPT) algorithm is based on maximizing the power through impedance matching between PV array and the load via DC-DC boost converter [90]. MathWorks
MPPT Controlled Grid-connected PV array example model is used as a reference in designing the PV model for the project. Detailed information can be found in [91].

5.3 Distribution

The distribution modelled in the Simulink with a pi three phase line. The three-phase power source feed is located 140 km from the Geraldton and Wind farm located 25 km south of the Kalbarri. The transmission line details:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive and zero sequence resistances (r1 r0)</td>
<td>[0.01273 0.3864]</td>
</tr>
<tr>
<td>Positive and zero sequence inductances (l1 l0)</td>
<td>[0.9337e-3 4.1264e-3]</td>
</tr>
<tr>
<td>Positive and zero sequence capacitances (c1 c0)</td>
<td>[12.74e-9 7.751e-9]</td>
</tr>
</tbody>
</table>

5.4 Load Model

A three-phase load is modelled using three-phase series RLC load block in the Simulink design. The information can be found in Appendix Load.

Chapter 6: BESS Control Algorithm Model

The control algorithm model used comprise of conversion system and control algorithm system. BESS system is capable of providing voltage and frequency stability to the grid. The system stores energy during the energy surplus in the grid and alternatively, during the islandic microgrid operation acts as a voltage source. The BESS system undergoes charge and discharge phase during the transition from on-grid power supply and off-grid islandic operation of the microgrid. However, the control algorithm model design in the project is primarily connected to the BESS only.
6.1 Control System

Control system is used for managing State of Charge (SOC) and managing the active and reactive power also known as PQ method [92]. The project involved the control algorithm of the active and reactive power, hence, the Control System used is focused on using the PQ method, involving decoupling using direct quadrature reference to control the converter. Simulink’s Park transformation block is used to convert abc phase to dq axes.

When the microgrid is connected to the main grid, the BESS is not involved in maintaining the frequency and voltage of the microgrid. During the off-grid operation of the microgrid, the BESS system controls the V-f control mode [81]. The main aim of the thesis is to examine the BESS control algorithm controlling the voltage and frequency of the microgrid.

The control algorithm is comprised of Phase Locked Loop, Current Controller and PWM signal generator. The park transformation is used to convert the abc frame V and I into the dq0 frame V
and I. The conversion into the dq frame simplifies the control of the AC by using a PI controller tracking a constant DC reference rather than sinusoidal reference of αβ frame and abc frame.

Figure 11: Control System overview

Figure 12: Control Algorithm
6.1.1 Phase Locked Loop

To maintain the frequency of PV and Wind source in synchronize with the grid frequency and lock on to that the matching frequency, the Simulink three-phase PLL block is used. To track the frequency and the phase angle of the three phase signal a Simulink block Phase Locked Loop (PLL) is used to track the frequency and phase of the voltage through an internal oscillator.

![Battery Control System - Phase Locked Loop](image)

The PLL primarily includes the three parts: phase detector, low pass filter, and voltage-controlled oscillator. The voltage-controlled oscillator (VCO) operates in reference the voltage received and outputs frequency accordingly, i.e. increased voltage results increase in frequency and vice versa. The VCO feedbacks the outputted frequency to the Phase detector, which compares with the input frequency and produces an error voltage. The error voltage is then sent to the low pass filter that only passes low frequency voltage. After the incoming frequency and the output frequency value is same, the loop is locked, resulting the internal oscillating frequency to maintain the phase difference to zero.

The output reference frequency from the PLL block is sent to the converter to match the PWM output signal to be in line with the system reference frequency.
6.1.2 Park Transformation

The park transformation converts abc frame into the dq0 frames through conversion of abc frame into αβ frame and then, converted into dq frame. The abc frame consists of the three sinusoidal frames, which are simplified with the use of the rotating frame of αβ frame vector with two sinusoidal frames, the αβ frame is then converted into the dq0 space vector, making it static from the point of view of the new rotating reference frame [94] [95]. The d and q component are called direct and quadrature that are constant since both the vector and frame are rotating at the same speed angular speed.

The use of dq representation in the thesis simplifies the control of the AC by using a PI controller tracking the constant DC reference rather than sinusoidal reference of αβ frame and abc frame.

Simulink abc to dq0 block is used to carry out the transformation. The dq frame is used to rotate the AC reference frames to replicate into a DC signals.

Figure 14: Battery Control System - Park Transformation [96]
Yazdani et al. 2010 Chapter 4 provides the below $\alpha\beta$ frame representation and control of three-phase signals and system [79].

\[
\begin{pmatrix}
V(0) \\
V(\alpha) \\
V(\beta)
\end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix}
\frac{1}{\sqrt{2}} & 1 & 0 \\
\frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\
\frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{pmatrix} \begin{pmatrix}
V(a) \\
V(b) \\
V(c)
\end{pmatrix}
\]

Carnieletto et al. 2009 provides the equation of the frame conversion [97]:

\[
\begin{pmatrix}
V(d) \\
V(q)
\end{pmatrix} = \begin{pmatrix}
cos\theta & sin\theta \\
-sin\theta & cos\theta
\end{pmatrix} \begin{pmatrix}
V(\alpha) \\
V(\beta)
\end{pmatrix}
\]

6.1.3 Idref and Iqref Calculation
With the two PI controllers is utilized to control the instantaneous value of P and Q with respect to the reference P and Q signals. The operation of the P PI controller is the reference grid current Idref in the d-axis of the dq reference frame and similarly, the operation of the Q PI controller is the reference grid current Iqref in the q-axis of the dq reference frame [67].
6.1.4 Grid Connected PQ Operation

The converter side in the Power Conversion system block is connected to the BESS – a DC power source. The current controller adjusts the d – direct and q – quadrature components of the current. The model is devised on the equation devised by Bidram et al 2017 [70] for the PQ control:

\[
V_{i_d}(out) = -w \times L_f \times I_q + Kp1 \times (I_{dref} - I_d) + Ki1 \times (I_{dref} - I_d) \\
V_{i_q}(out) = w \times L_f \times I_d + Kp2 \times (I_{qref} - I_q) + Ki2 \times (I_{qref} - I_q)
\]

Where Kp1 is the proportional term and Ki1 is the integral term of the PI controller 1 in the inner loop;

Kp2 is the proportional term and Ki2 is the integral term of the PI controller 2 in the outer loop;

Id and Iq are the d – direct and q – quadrature current from the power conversion system block

Vd and Vq are the d – direct and q – quadrature voltage from the power conversion system block

Idref is generated from the P error by comparing the calculated values of the generated P with the grid’s Pref. Similarly, Iqref is generated through the Q components comparison.
Furthermore, Yazdani and Irvani 2010 provides a detailed relationship of the dq frame voltage and current with the active power (P) and reactive power (Q) equations below [79]:

\[ P(t) = \frac{3}{2} [Vd * Id + Vq * Iq] \]

\[ Q(t) = \frac{3}{2} [-Vd * Iq + Vq * Id] \]

With the use of PLL, during the steady operation, Vsq is equal to zero, hence the above equations can be rewritten as:

\[ P(t) = \frac{3}{2} [Vd * Id] \]

\[ Q(t) = \frac{3}{2} [-Vd * Iq] \]

The P and Q equation is deployed to calculate the reference P and reference Q.

6.1.5 V-f Control Operation

Guerrero et al. 2011 defines droop control method as [98]:

\[ \omega = \omega_{ref} - m * P \]

\[ V = V_{ref} - n * Q \]

Where \( \omega_{ref} \) and \( V_{ref} \) are the grid rated angular frequency and voltage

\( m \) and \( n \) are the droop coefficients
The DER sources designated the P and Q according to the stability at $\omega$ and $V$. Katiraei et al. 2006 claim that the formation of the voltage formation block with the P flow is dependent on the phase angle difference and the Q flow is dependent on the voltage magnitude difference.

Hajilu et al. 2015 highlight the V-f control current equation as below:

$$V_{id}(out) = -w \cdot L_f \cdot i_q + Kp1 \cdot (I_{dref} - I_d) + Ki1 \cdot (I_{dref} - I_d)$$

$$V_{iq}(out) = w \cdot L_f \cdot I_d + Kp2 \cdot (I_{qref} - I_q) + Ki2 \cdot (I_{qref} - I_q)$$

The detailed of the equation calculation can be found in [80].

### 6.1.6 Pulse Width Modulation

The control system generated abc frame signal is fed into the IGBT’s of the converter. Each of the pulses consists of 1s and 0s, controlling the converter operation by switching the individual IGBTs on and off.
Figure 18: Control Algorithm - PWM signal generation

Figure 19: PWM generation switching signals
6.2 Conversion System

The conversion system is connected both ways flow DC battery from/to an AC grid.

6.2.1 Three Phase Full Bridge Converter and LCL Filter

The bidirectional converter method is used for its direct conversion from DC voltage to an AC voltage and AC voltage to DC voltage. An LCL filter is connected to the VSC to filter the harmonics, followed by transformer to increase the voltage level.

The converter used in the thesis consists of 3 leg, 6 IGBTs with switching dependent on the Pulse Width Modulation signal received from the Battery Control System, converts between the AC and DC signal. The S1, S2, S3, S4, S5 and S6 distinct PWM signals are formed during the DC to AC conversion in figure 19 is fed into individual IGBT.

![Figure 20: Power Conversion System](image)
LCL filter is placed to mitigate frequency harmonics and to level the pulse outputted from the inverter.

Figure 22: LCL filter

Reznik et al. 2014 summarises the equation to calculate the base impedance L1 L2 and base capacitance that can be found in [99].
The voltage reading after PWM converter, LCL filter and transformer is shown below:

**Figure 23: Voltage after PWM converter**

**Figure 24: Voltage post LCL filter**

**Figure 25: Voltage post transformer**

In the next section, the overall design model is presented.
Chapter 7: Model Analysis

The model includes BESS, PV system, Wind Generation, Main grid connection and Load as described in the Chapter 1 section Introduction to the Kalbarri Microgrid. The DER generation model, distribution model and Load model is discussed in depth in Chapter 6 Methodology Section Generation. The current controlled PQ controller compares the generated $P$ and $Q$ to the grid $P_{ref}$ and $Q_{ref}$ providing the PWM signal to the converter. The internal components for BESS, PV, Wind generation, Load and Maingrid can be found in the Appendix 13.2, Appendix 13.5, Appendix 13.6, Appendix 13.7 and Appendix 13.8 respectively. The control algorithm model detail is discussed in Chapter 7 BESS Control Algorithm Model sections: Control system and Conversion system.

In the next chapter, grid-connected and grid-disconnected operations of the microgrid is studied.
Chapter 8: Contingency Analysis

The contingency analysis is conducted to investigate the resilience of the microgrid. The model is operated under different test conditions to observe the output and fitness of the control algorithm.

Under this section, power source switching between grid connected to grid disconnected operations and the varying load conditions is tested. The two types of analysis are summarised below:

1. Power Source Transition
2. Varying Load Condition

Switching operation is achieved by connecting a Simulink step onto the external control of the three-phase circuit breaker block in Simulink.

8.1 Power Source Transition

One of the main implications is the power source transitioning if there is a fault with connection from the maingrid. The transition is modelled in the Simulink via introducing a time step block connecting it to the circuit breaker to disconnect the microgrid from the power source in the figure below:

![Figure 27: Contingency Analysis - Power Source transition](image-url)
8.1.1 Power Source Switching Rationale

The switch controlling the operation on the above diagram will open at \( t_1 = 5 \) seconds and close at \( t_2 = 10 \) seconds. The step value 0 indicates a switch close and the step value 1 indicates a switch open condition. The switching rationale is shown below Figure 32.

![Figure 28: Contingency Analysis - Power Source Switching logic](image)

8.1.2 Observation

The simulation result below reflects the outcome of the transition in the microgrid frequency and voltage:
From the result obtained in the simulation, frequency and voltage fluctuation is identified during the microgrid transition from grid connected to grid disconnected mode. The switching occurs:

- At time \( t1 \) 5 seconds, the switch opens causing the microgrid to go offline from the main grid. A fuzzy behaviour in both frequency and voltage is noted indicating the transition into maingrid disconnection.

- At time \( t2 \) 10 seconds, the switch closes causing the microgrid to go back online with the main grid. Both frequency and voltage are stable after the maingrid takes control of frequency and voltage regulation.

The PID controller parameters can be found in Appendix 12.10. The result from the simulation is compared to the result obtained on the research paper conducted by Nguyen et al 2015 [100] on the grid power transition:
8.1.3 Result Analysis

The obtained result’s frequency and voltage behaviour are compared during the grid-connected and grid-disconnected operation, with fuzzier reading during the grid-disconnected operation. Both simulated results and Nguyen et al 2015 outcome indicates a finer frequency and voltage regulation during the maingrid connected microgrid operation [100].

The slightly out of range voltage fluctuation in comparison to the parameter discussed in Chapter Section System Stability – Grid Code, indicates a potential issue with the overall control system design prompt response to the power source transition operation.
8.2 Load Variation

A similar approach to the power source transition section of using a time step block connecting it to the circuit breaker is simulating the varying load conditions. The grid-connected load variation conditions are tested by removing the external control in the main grid connected circuit breaker. The microgrid is operated under different load conditions. The summary of the load conditions is highlighted below:

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Load capacity</th>
<th>Time duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load A</td>
<td>Normal Load condition</td>
<td>5 MW</td>
</tr>
<tr>
<td>Load B</td>
<td>Reduced Load condition (30 percent reduction)</td>
<td>5 MW X 0.7 = 3.5 MW</td>
</tr>
<tr>
<td>Load C</td>
<td>Added Load condition (30 percent added)</td>
<td>5 MW X 1.3 = 6.5 MW</td>
</tr>
</tbody>
</table>

8.2.1 Load Value Variation Rationale

A shorter time transition period is used to simplify the observation reading between the switching of the load values. The time duration can be easily altered by the user via changing the step value. Below table represents the load value switching operation in the model:
The step value 0 indicates load offline and the step value 1 indicates load online in figure 34. The load variation is conducted by step function block value between 0 and 1 injected in the respective Load A, B and C circuit breakers. The load switching occurs:

- At time $t_1$ 5 seconds: Normal load A is only active while both Load B and Load C are inactive.
- At time $t_2$ 10 seconds: Load B is active, while Load A is turned off and Load C continues to stay inactive.
- At the time $t_3$ 10 seconds: Load C is active, Load B is turned off and Load A continues to stay inactive.

Below step operation result illustrates the varying load condition:
8.2.2 Observation

The simulation reading below highlights the catchment time frame whilst the load variation occurs.
The variation in frequency and voltage is observed during the load transit time frame of $t_1 = 5$ seconds and $t_2 = 10$ seconds. The frequency deviation is the highest level at 50.5 Hz and lowest level at 49.1 Hz and the voltage deviation at the lowest point 400 V is observed. Due to the event of the load switching at $t_1$ and $t_2$, the frequency and voltage deviation is noticed. During $t_1$ there is a brief shift in both voltage and frequency. However, the continual increased frequency and voltage fluctuation after $t_2$ under the additional load condition stands out compared to Load A and Load B conditions.
8.2.3 Result Analysis

The result obtained from the simulation, there is a frequency and voltage deviation behaviour difference during the transition from Load A to Load B and Load C respectively. The switching occurs:

- During Load A and Load B, the voltage and frequency reading is steady. However, in transition to the high value Load C, a significant fluctuation in both frequency and voltage is observed.
- At each transit event t1 and t2, a brief fluctuation in voltage and frequency is observed. The shift is expected due to the change in load value. The control algorithm model adjusts the fluctuation promptly.
- From the result obtained above, the expected performance of the microgrid is steadier during the normal load condition and reduced load condition than during the additional load condition.

Chapter 9: Discussion

A summary of the achievements and the issues of the thesis are outlined below:

9.1 Achievements

The research achievements are listed as below:

9.1.1 Research

A thorough analysis of Western Australia’s electrical energy market with a focus on rural community energy expectations and alignment of the future of SWIS network is conducted. The detailed findings are presented in the thesis. The thesis further provides insight to the distributed energy sector in Australia, examining the added benefit brought upon application of energy storage technology. The thesis also assessed the BESS related current projects, evaluating its use, potential barriers, and possible benefits to the existing electrical infrastructure.
9.1.2 Technical

The decision matrix tool weighed key factor criterion of available battery types suggesting the most suitable Battery technology: Lithium-Ion for Kalbarri microgrid.

The design model systematically used the power theory and the VSI converter techniques to maintain stability in terms of incorporating the inclusion of DER sources: PV generation, Wind generation, and the energy storage element. The model investigated used a power control system with a three-phase sinusoidal abc frame to dq0 frame conversion to incorporate PI controller to mitigate the intermittence of renewable energy generations, Wind and PV system, within a short timeframe. The control model proves a method to simulate operation of the microgrid under transition between grid-connected to grid-disconnected condition and vice versa. Furthermore, the model touched upon the measure to simulate varying load condition in the microgrid.

Finally, the thesis incorporates frequency and voltage behaviour under power source transition and load variation condition. The author listed observations, including shortcomings and anomalies found in the simulation and mapped it against the expected result.

9.2 Innovation

9.2.1 Decision Matrix Analysis

The thesis utilised a decision matrix tool to determine the most suitable battery technology. Thorough analysis of key factors was conducted and systematically assigned weight value for each shortlisted option in terms of its importance. The tool provided an insight to the Kalbarri microgrid battery technology requirement and finding the best fit.
9.2.2 Utilization of the Simulink Externally Controlled Circuit Breaker
The model utilised by adding a step block into the externally controlled circuit breaker successfully simulate the microgrid power source transition from grid-connected to the islandic mode and vice-versa. The same measure was used in simulating the load variation condition of stepping up and stepping down the load.

9.2.3 Switching Control
Zhang et al. 2013 criticises the lack of adequate research on the control mode switch conversion [68]. The thesis attempted to add an insight into the control mode switch area, the simulation conducted in the Chapter 9 Contingency Analysis Section Power Source transition examined the switching control from grid-connected to islandic mode.

9.2.4 Q Injection
The control algorithm design investigated the use of the PQ control mode for the BESS where P and Q of the generation sources follow Pref and Qref measured at PCC. The use of VSC enables the control of the phase and magnitude of outputting voltage allowing to regulate the injection of P and Q from the BESS.

9.2.4 Incorporated the Proposed PV System
Based on the Western Power Kalbarri microgrid feasibility study, the proposed 1 MW PV system have been incorporated in the project to provide more insight into the impact of an additional DER source into the existing microgrid [44].

9.3 Challenges

9.3.1 Voltage Drop
The simulation design observed the voltage drop in the network at the PCC site. Upon investigation of the issue, the author concludes instability potentially occurred in the VSC with the current
saturating under large disturbances. The research by Huang et al. 2019 on Control Design of Voltage Source Converter supports the instability issue with the current limitation can be found in [101].

9.3.2 Simulation Speed

Due to the extensive use of PLL (Phase Locked Loop), including the relational operators and the power electronic converters devices in the model, the model could not be operated in the Phasor mode. The model is simulated in the discrete powergui to simulate the EMT (Electro-magnetic transient) mode that simulates in a slower speed in comparison to the Phasor powergui mode; however, discrete mode is claimed to be more accurate than the Phasor mode on Simulink [102].

9.3.3 Limited Existing Research on Control Mode Conversion

The author found the most of the existing microgrid control academic research thesis are aimed on the grid-connected converter control. Zhang et al. 2014 supports the author’s claim by highlighting few researches on the mode conversion [81].

9.3.4 Simulink Design

The author claims to experience the complication in terms of designing the system on the Simulink software with experiencing rigidity and lack of resource clarity in terms of the operation of the elements and blocks with the software’s source library.

9.3.5 Software Resources

The author found the lack of adequate resources with the VSI controlled microgrid to assist in developing the model. The author claims the existing resources available to be mainly theoretical based with limited resource example on the modelling BESS design on the Simulink software.
9.4 Future Improvements

9.4.1 PI Controller Alternatives

The research control model uses PI controller is widely used in the industrial sector and power systems due to the simple structure, robust operation and reliability. However, PI controller have a limited capacity in terms of optimally tuning the PI gains for complex systems and it is highly dependent on the PI parameter values [103].

9.4.2 Voltage Controlled Voltage Source Converter

The thesis used Current Controlled Voltage Source Converter to devise the BESS control algorithm model. A dedicated current controller scheme tightly regulates CCVSC line current through AC side terminal voltage. Due to the current regulation scheme, the VSC is protected against overcurrent and has a high accuracy of instantaneous current control [79]. Also, the current control includes robustness against variation in VSC and AC system parameters and superior dynamic performance and higher control precision.

However, the noted issue of the voltage control result from the CCVSC used in the model is observed. Based on the research thesis by Reed et al. 2013 and Zhou et al. 2015 summarising the VCVSC advantage of rapid and continuous response for smooth dynamic control and automated P and Q power control in both steady-state and dynamic system conditions, the author advises the model can be further improved by testing the use of VCVSC [104] [2].

9.4.3 Simulation Speed

The simulation model can be improved by operating in a Phasor model to substantially increase the simulation speed.
Chapter 10: Conclusion

The thesis laid a successful foundation in examining the necessities of existing Western Australian electrical network with an aim to focus in Kalbarri. The thesis presented the justification on why Energy Storage System is important in the Australian electricity market. The thesis provides a snapshot of benefits and hurdles of the BESS technology. The thesis utilizes ‘Decision Matrix’ tool to assess the available battery technologies and suggest the most suitable solution after examining the important parameters of the project site area. Upon selection of battery technology, the thesis presented a BESS control algorithm on power theory and existing literature on VSC driven microgrid. The thesis suggests a theoretical model of the BESS control algorithm. The model extensively used power electronics element: Three-phase full bridge Insulated Gate Bipolar Transistor (IGBTs) and filters to convert DC into AC and AC into DC conversion. The suggested model uses the Power Control System based on Phased Lock Loop to synchronise with the grid frequency. The power control system uses Park transformation to convert the three-phase sinusoidal abc frame conversion to a DC reference signal of dq0 frame to incorporate PI controllers.

The model is tested under power source transition and varying load condition. The power source transition performance of the proposed model establishes an expected dip in both voltage and frequency during the transition state from maingrid connected to maingrid disconnected condition. However, the voltage drop during a small period time is slightly outside the voltage range of ±6 percent. Based on observed results, the author concludes control design to develop further to enable prompt voltage regulation response during the transition state between maingrid connected to maingrid disconnected condition.

During varying load, the model operates within the satisfactory range under the normal load and reduced load condition. However, under the added load condition there is both increased voltage and frequency fluctuation. The added load condition’s frequency fluctuation is up to ±0.6 Hz which is within the acceptable ±1 Hz range.
The thesis simulation utilised CCVSC for its simple controller design, better performance during grid fault overcurrent, a high accuracy instantaneous current control, and the overall cost saving of the system for tight regulation of the line current. However, to improve the voltage regulation as a part of future improvement with a focus on the overcurrent, the model can be revised with the use of VCVSC for rapid and continuous response for smooth dynamic control and automated P and Q power control. Both steady-state and dynamic system conditions are identified as an improvement compared to the performance of CCVSC driven control in the thesis simulation.

The discussion section summarises the achievements and innovation made, with an inclusion of the challenges and shortcomings of the design devised. The thesis presented a thorough explanation of the power theory used and the simulation result obtained, with a summary of the future improvements.

Chapter 11: Bibliography


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Chapter 12: Appendices

12.1 BESS Battery Model

12.2 BESS Control Model
12.3 Load Variation Model

12.4 Power Source Transition
12.5 PV Array

Array type: SunPower SPR-305E-WHT-D
44 series modules; 75 parallel strings

Parallel strings: 75
Series-connected modules per string: 44

Module data:
- Maximum Power (W): 305.226
- Short-circuit current (A): 9.66
- Open circuit voltage (V): 45.2
- Maximum power point voltage (V): 54.7
- Current at maximum power point (A): 5.18
- Temperature coefficient of Voc (%/deg.C): -0.27269
- Temperature coefficient of Isc (%/deg.C): 0.06767

Model parameters:
- Light generated current II (A): 0.0002
- Diode saturation current I0 (A): 0.0041
- Diode ideality factor: 0.6504
- Shunt resistance Rsh (ohms): 2881504
- Series resistance Rs (ohms): 0.17152
12.6 Wind Turbine Model
12.7 Load
12.7 Main Grid Source

12.8 LCL Filter Calculation
List of parameters needed:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_g$</td>
<td>Grid frequency</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>Switching frequency</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Active Power</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>Dc voltage</td>
</tr>
<tr>
<td>$V_{ph}$</td>
<td>Output phase voltage</td>
</tr>
<tr>
<td>$K_a$</td>
<td>Desired attenuation</td>
</tr>
<tr>
<td>$V_n$</td>
<td>Line-to-line RMS output voltage</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Inductance on the inverter side</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Inductance on the grid side</td>
</tr>
</tbody>
</table>

$Z_b = \left(\frac{V_n^2}{P_n}\right)$

$C_b = \frac{1}{\omega_g Z_b}$

$I_{max} = \frac{P_n V_L}{3 V_{ph}}$

$L_1 = \frac{V_{DC}}{6 f_{sw} A_{l_{max}}}$

$L_2 = \frac{\sqrt{\frac{K_a}{T}} + 1}{\epsilon f/\nu_{sw}^2}$
12.9 IGBT

**Internal resistance Ron (Ohms):**

1e-3

**Snubber resistance Rs (Ohms):**

1e5

**Snubber capacitance Cs (F):**

inf

- Show measurement port

---

12.10 PID Controller Parameters

- **Controller parameters:**
  - Controller:
    - Proportional (P):
    - Integral (I):
    - Derivative (D):

- **Select Tuning Method:** Transfer Function Based (PID Tuner App)

- **Initial conditions:**
  - Source:
  - Reset:

- **External reset:**
  - Input:
  - Derivative:

- **Ignore reset when integrating:** Yes

- **Enable zero-crossing detection:** Yes

---
12.11 Transformer

12.11.1 BESS Transformer

12.11.2 Maingrid Transformer
12.11.3 PV Transformer

12.11.4 Wind Transformer