Design and Simulation of a DC Microgrid for a Small Island in Belize

Jordon Grant

Thesis of 60 ECTS credits
Master of Science (M.Sc.) in Sustainable Energy Engineering – Iceland School of Energy

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by

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Thesis of 60 ECTS credits submitted to the School of Science and Engineering at Reykjavík University in partial fulfillment of the requirements for the degree of Master of Science (M.Sc.) in Sustainable Energy Engineering – Iceland School of Energy

May 2018

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May 2018
A microgrid based on direct current (DC) was designed and simulated for a small island in Belize. The energy generated in the microgrid will come from DC sources and the loads on the island will also be DC. Therefore, it was proposed to design a microgrid based on DC to reduce the amount of conversion losses between AC-DC. A microgrid based on DC will have no power factor losses, less corona discharges due to the absence of the skin effect and allow for a cheaper and simpler system. DC microgrids are already widespread in the telecoms industry for data centres, airplanes, submarines and remote locations. MATLAB/Simulink was used to design and simulate the individual components of the microgrid. Power electronic converters were designed and simulated for use with photovoltaic (PV) modules and maximum power point trackers (MPPT) in order to extract maximum power from the solar resource. The perturb and observe (P&O) algorithm was coded into the MATLAB environment for the MPPT. A bidirectional converter (BDC) was also designed to allow power to flow from/to the battery which was controlled by a PI controller. A traditional buck or boost converter could not be used for the bidirectional converter due to the presence of diodes in their designs. The charge controller successfully controlled the bidirectional converter allowing power to flow from/to the battery to achieve voltage stabilization. A lead-acid battery was found to be the most cost effective option for integration into the microgrid.

The solar and wind resources for the island were modelled along with the predicted load profiles of the island. A financial analysis was conducted using the Hybrid Optimization Model for Electric Renewables (HOMER) software. It was found that a DC microgrid could meet the load requirements with 20% less generation than an AC microgrid due to the absence of losses in inverters reducing the costs. An AC microgrid with diesel only generation which is currently in use resulted in the highest overall costs, an AC hybrid microgrid resulted in a cheaper system than the diesel only system and a DC microgrid resulted in the lowest costs. A long term, medium term and short term analysis of the DC microgrid was conducted. A 100% renewable microgrid was found to generate excess electricity throughout a year because the system needs to be sized to meet the load on periods of low renewable energy generation. Batteries can be used to decrease the excess electricity but they eventually increase the cost of the system and create battery disposal problems. The medium and short term analysis verified the functionality of the charge controller on a good day and bad day for renewable energy generation. Both simulations shown that the voltage was stabilized and the bidirectional converter functioned correctly. The microgrid would require 15.7% island cover from PV panels and 10 containers for the batteries. Therefore, it was proposed to size the solar generation to meet the base load and diesel generators to meet the peak load with hydrogen storage.
Hönnun og hermun á DC örneti fyrir litla eyju í Belize.

Jordon Grant

maí 2018

Útdráttur

Í verkefninu var jafnstraums örnet (DC microgrid) hannað og hermt fyrir litla eyju í Belize. Gert er ráð fyrir að öll orka sé framleidd sem (DC) og allt álag sé jafnframt DC álag. Af þessum sökum er lagt til að hann örnetið alfarið sem DC net til að koma að mestu í veg fyrir tóp vegna af og áriðlunari. Í slíkt örneti er ekki um að ræða tóp vegna aflstuðulsls og einnig eru tóp vegna útleiðslu (corona töp) lægri sökum minni yfirbordsáhrið í leiðara (skin effect). Hugmyndin er að slíkt kerfi geti leitt til einfaldara og ódýrara orkuleiðsstillings geymslas fyrir eyjuna. Örnet sem rekin eru sem DC net eru þegar útbreidd innan símakerfa, gagnavera, kafláta og annarra einangræðra kerfa. MATLAB/Simulink var notað við hönnun og hermun einstakra hluta örnetsins. Kraftrafeindabúnaður var hannað og hermdur ásamt sólarsellum með stýringum sem hámörkuðu afl frá sólarorkunni. Þessi stýring var útfærð og forrituð í MATLAB. Einnig var aflrafeindabúnaður hannaður sem stýrði aflflæði til og frá rafhlöðu en sú stýring var útfærð sem PI stýring. Virkni þeirrar hleðslustýringar var mjög góð sem aftur leiddi til góðrar og stöðugrar spennustýringar í kerfinu. Lead-acid rafhlöða var notuð þar sem hún þótti hagstæðust til notkunar í þessu kerfi.

Möguleg sólar og vindorka eyjunnar var hermd ásamt áætlun í álagi hennar. Hagræn orku athugun var framkvæmd með notkun Hybrid Optimization Model for Electric Renewables (HOMER) forritinu. Niðurstöður sýndu að DC örnet gat annað álagi eyjunnar með 20% minni orkuframleiðslu samanborið við AC net vegna minni tapa af völdum af og áriðl. Niðurstöður sýndi einnig að AC örnet þar sem eingöngu er um dísel rafala að ræða í framleiðslunum þ.e. eins og staðan er í dag, var heildarkostnaðurinn hæstur í þessum útreikningum. Í því tilviki sem um samþættis AC framleiðslu er að ræða var kostnaðurinn minni en ódýrasta útgáfan var þegar kerfið var alfarið útfærð sem DC kerfi. DC kerfi sem byggði á 100% endurnýjanlega orkuleiðsstillingsgjafans framleiðslu þótti þarf um orku en þóf um þar sem aflgetan var ákvörðuð út frá álagi þegar aflgeta endurnýjanlega orkugjafans er í lágmarsi. Rafhlöður má nota til að minnka þessa aflpörf en notkun af þeirra gæti þetta rituð heildarkostnað kerfisins. Tæknið athugun á stýringum kerfsins sýndu fram á virkni þess þegar aflgetað ódýrasta og skemum degi m.t.t. framleiðslu á endurnýjanlegum rafti. Báðar hermaninn þá var þar sem aflgetan var stöðug og rafeindabúnaðurinn sem stýrir hleðsluninn virkaði sem skylti. Örkerfi sem byggði á 100% endurnýjanlega orku myndi þurfa sólarsellur sem þekja 15,7% eyjunnar og 10 gáma af rafhlöðum. Því er lagt er til að ákvarða stærð sólarorfumframleiðslunnar út frá grunnnotkun og nota dísel rafala til að mæta aflþörf í afltopum ásamt einhverskonar framleiðslu, geyslum og notkun á vetnisorku.
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date

Jordon Grant
Master of Science
I dedicate this to my nephew.
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List of Abbreviations

AC       Alternating Current
ACSR     Aluminium Conductor Steel Reinforced
BDC      Bidirectional Converter
DC       Direct Current
DER      Distributed Energy Resources
DOD      Depth of Discharge
GHG      Greenhouse Gas
HVDC     High Voltage DC
LCOE     Levelized Cost of Electricity
MSc      Masters of Science
MPPT     Maximum Power Point Tracker
NPC      Net Present Cost
O&M      Operations and Maintenance
P&O      Perturb and Observe
PI       Proportional Integral
PV       Photovoltaic
PWM      Pulse Width Modulation
SOC      State of Charge
VPP      Virtual Power Plant
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<tr>
<td>$E$</td>
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<td>$J$</td>
</tr>
<tr>
<td>$L$</td>
<td>Inductance</td>
<td>$H$</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
<td>gram</td>
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<tr>
<td>$R$</td>
<td>Resistance</td>
<td>$\Omega$</td>
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<tr>
<td>$c$</td>
<td>Speed of Light</td>
<td>$2.99 \times 10^8 \text{ m s}^{-1}$</td>
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<tr>
<td>$V$</td>
<td>Voltage</td>
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Chapter 1

Introduction

1.1 Introduction

A direct current (DC) Microgrid will be designed and simulated for a small island in Belize. Currently, the island is powered by expensive and polluting diesel generators operating with alternating current (AC). The developer intends to build an 100-room hotel, 100 dwellings and other services such as golf cart charging stations which will significantly increase the load demand of the island therefore new investment is needed in the ageing microgrid. A DC microgrid will help to facilitate the integration of renewables and positively add to the image of the island.

1.1.1 Caye Chapel

The island of Caye Chapel is a small privately owned island located offshore Belize with coordinates 17° 41’ 24” N, 88° 03’ 36” W. Figure 1.1(a) shows an image of the island and Figure 1.1(b) shows its location on a map located offshore Belize. The island features a private airstrip and a golf course. A mexican investment company has purchased the island and would like to develop the microgrid in accordance to the anticipated increase in the load profile. To improve the image of the island and to promote sustainable tourism a state of the art microgrid based on DC will be proposed.

![Picture from above](image1.png)

(a) Picture from above

![Location on map](image2.png)

(b) Location on map

Figure 1.1: The island of Caye Chapel in Belize
1.1.2 Thesis Objectives

The objective of this master thesis is to propose a design for a DC microgrid consisting of renewable energy generation. A cost effective system will be selected in order to meet the load requirements of the island and the financial benefits of a DC microgrid will be quantified over an AC microgrid. The components of the microgrid will be modelled and the whole DC microgrid will finally be simulated.

1.2 Background

1.2.1 Microgrids

A microgrid is a local electrical grid containing sources and loads [1]. The definition of a microgrid is a cluster of distributed resources which have the ability to operate autonomously [2]. Microgrids are being used to bring electricity into areas where transmission lines cannot reach. A traditional system with generation in one place and then distribution at high voltages is designed for high energy density fossil fuels [3]. Distributed generation can be used to increase the reliability of a system and allow for the integration of renewables. Distributed generation is a much more suitable method of electricity distribution for renewables due to their lower energy density as compared to fossil fuels and since the power generation is on site losses due to transmitting electricity are proportionally eliminated [4]. Energy storage can be used in microgrids to improve the power quality and smooth out the fluctuations of renewable energy generation. The recent trend in renewables is to use distributed power sources and energy storage to form a microgrid [5].

1.2.2 History of DC Transmission

Power transmission was initially carried out using DC in the early 1880’s but was quickly replaced by AC with the development of the transformer, induction motor and synchronous generator. Since then the power system has been dominated by AC transmission [6].

In order for power to be transmitted over long distances the voltages were elevated using a transformer which works with AC however there was no DC equivalent. Therefore, using AC enabled power to be sent over long distances with less losses due to the current being kept at a lower level whereas DC transmission would have required a generating plant closer to each load making AC much more cost effective. However, we now have power electronics which are able to step up and down DC voltages. The induction motor was widely used and works with AC so having an AC system reduced the need for a conversion step. However, now we have efficient DC motors therefore using a DC grid would reduce the need for a conversion step. The synchronous generator was used to convert fossil fuel energy into AC electricity but now with the increase in renewable energy a lot of electricity generated is in DC. Therefore, to use renewable energy more efficiently they should directly supply DC loads [5]. Evidently, many of the reasons why we originally opted for an AC transmission system are no longer valid today.
Chapter 2

Theory

2.1 DC Microgrids

DC transmission is making a comeback and has the potential to provide many benefits especially with microgrids. Photovoltaic (PV) cells generate DC electricity and with the majority of electronic loads requiring DC, a DC microgrid would eliminate the conversion steps between AC and DC [6]. A traditional system would require the PV energy to be inverted from DC to AC so that the energy can be sent to the grid and then another conversion step inside the electronic load rectifying the electricity back from AC to DC so that the energy can be used. Therefore, because each conversion step introduces losses to the system, eliminating these two conversion steps has the potential to improve the efficiency of the DC microgrid by 10-25% [7]. Also wind, small scale hydro and tidal power generation use variable speed turbines which involves converting the variable AC energy from AC to DC and then back to AC at the required frequency as shown in Figure 2.1. Variable speed turbines are used to let the turbine rotate at a particular speed to extract maximum power from the resource. Due to the varying frequency the energy is converted to DC and then the electricity can be converted back to AC at 50 Hz. Therefore, using a DC microgrid with these systems would still reduce a conversion step from DC to AC and improve the efficiency of the system [8].

![Figure 2.1: Wind energy conversion](image)

Most electronic loads, LED lighting, telecommunication equipment, electric vehicles and HVAC systems are operated on DC. They contain a rectifier in a traditional system to rectify from AC to DC so that the energy can be used [9]. Therefore, utilising a DC microgrid again reduces conversion losses on the load side. DC Microgrids are already in use inside commercial buildings, data centers, space craft, ships, rural electrification systems and EV charging centers [10]. Devices which are inherently AC where an induction motor is needed for loads such as dishwashers and washing machines will require an inverter for connection to the DC grid [11]. A report by the Lawrence Berklely National Laboratory shown that due to the reduction in conversion losses with a DC microgrid for use in data centers a DC microgrid could achieve up to 28% in energy cost savings. A DC microgrid is thought to be safer on the human body because it does not give involuntary contractions and the electromagnetic fields are reduced [11]. DC microgrids only have active power because the voltage and current are always in phase and there are no power factor losses. Therefore, no reactive power or harmonics exist in a DC microgrid increasing the power quality and efficiency of the system compared to an AC microgrid [12]. There are no standards for DC microgrids [13] and many voltage levels have been used such as 480V, 326V, 230V, 120V and 48V. The higher voltage levels have the advantage in that they have lower power losses and voltage drops. The lower voltages have the advantage in that they are safer and can function without grounding. When using 350, 326, 230 and 120V it is possible to substitute AC and DC using the same cables [11]. A voltage level of 350V is thought to be optimal from a technical and economical perspective and it has the ability to operate with existing systems and cables. Appliances designed to work on 230/240V AC are able to function with 350V DC but tests need to be done for long term functionality [14]. Consequently, we can see that DC distribution results in reduced losses, increased safety, reduced electromagnetic fields and power quality improvements [7]. One of the disadvantages of DC microgrids is that traditional short circuit protection equipment cannot be used. This is because the current does not cross zero [15]. However, AC breakers can be used in low voltage DC equipment by adjusting the ratings by proper correction factors [11]. Electronic circuit breakers have been shown to outperform mechanical circuit breakers but when an electronic circuit breaker is activated it does not provide complete isolation. Also, due to the lack of inertia in a microgrid a large scale deployment of DC microgrids based on solar generation could lead to instability of the grid. There has also been problems with arcing when plugging and unplugging home electrical applications with DC systems. This has been solved by adding a shunt diode/capacitor branch to the plug socket [7].

2.2 System Architecture

DC microgrids are not very widespread but have the potential to present many advantages in terms of facilitating renewable energy integration and improving power quality. DC microgrids usually contain distributed energy resources (DER), loads and energy storage [16]. Figure 2.2 shows the typical architecture of a DC microgrid.

Renewable energy sources such as photovoltaic modules and wind turbines are typically connected to the DC bus via power electronic converters. These converters have the ability to control the output voltage of DER in order to stabilize the bus voltage and extract maximum power. There are power electronic converters that have the ability to increase or decrease the output voltage. DC loads can be directly connected to the DC bus and if an AC load is required an inverter would be needed in order to invert the DC bus voltage into a usable AC voltage. Batteries are typically used in DC microgrids due to their relatively cheap price.
2.3 Power Transmission

DC Power is transmitted via underground cables or overhead lines consisting of conductors, insulators and support structures [17]. Aluminium is frequently used as a conductor because it has a low resistance, low cost, high weight to strength ratio and is widely available. The resistance of a DC cable can be calculated by Equation 2.1. The aluminium is typically reinforced with steel to make it stronger. Aluminium conductor, steel-reinforced (ACSR) is manufactured in strands to make it easier to manufacture. Overhead transmission lines are not covered with an insulator to help with the dissipation of heat. Insulator discs are typically used with AC transmission to separate the bundles of cables. The higher the voltage level used the more insulator material needed. Support structures are used to suspend the cables at height at a safe distance away from the public and can be made of wood or metal.

\[ R_{DC} = \frac{\rho l}{A} \]  

Where \( \rho \) is the resistivity of the conductor at a specific temperature, \( l \) is the conductor length and \( A \) is the cross sectional area of the conductor.

and longer backup times as shown in Table 2.1 [16]. A longer backup time and low losses are desirable for energy storage technologies for microgrids which contain renewable energy generation in order for the load to be met. The problem with batteries is that their service life is relatively short and therefore they need to be changed out more often. Charge controllers are used in order to control the flow of power in the microgrid. Devices are needed to control when power is sent to the batteries or sent to power the load. These controllers also help to improve the power quality in the microgrid.

Table 2.1: Energy storage comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>Battery</th>
<th>Flywheel</th>
<th>Supercapacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backup Time</td>
<td>5-30 min</td>
<td>10-30 sec</td>
<td>10-30 sec</td>
</tr>
<tr>
<td>Losses</td>
<td>Very low</td>
<td>Variable</td>
<td>High</td>
</tr>
<tr>
<td>Energy Price ($/kWh)</td>
<td>150-800</td>
<td>3000-4000</td>
<td>4000-5000</td>
</tr>
<tr>
<td>Service Life (Years)</td>
<td>5</td>
<td>20</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

Figure 2.2: Typical DC microgrid architecture
2.4 Power Quality

Power quality is a measure of the reliability and stability of a power source in terms of the voltage, frequency and waveform. The reason why DC systems exhibit higher power quality than AC systems is because the frequency is zero for DC systems therefore it is much easier to achieve a signal that is within specifications. A microgrid should be able to supply power to the loads without damaging them, which is a greater concern with the increase in digital equipment. The term power quality is used but the measurement is actually the quality of the voltage. The DC power can be calculated by Equation 2.2. DC systems have no phase angle between the voltage and current therefore exhibit no reactive power increasing the power quality. Also, because the frequency is zero of a DC waveform there is no harmonic distortion. Harmonics appear in multiples of the power supply frequency. Voltage stability is the main focus in DC systems and power electronic converters and batteries can be utilized in order to maintain DC voltage stability.

\[ P = VI = \frac{V^2}{R} = I^2R \]  

(2.2)

2.5 Load Flow Analysis

Iterative methods can be used in order to evaluate the flow of power in AC systems until a certain convergence criteria is met. Two widely used methods for load flow analyses are:

- Gauss-Seidel
- Newton-Raphson

The Gauss-Seidel method is conducted using Equation 2.3 which converges relatively fast with few iterations and takes up less memory space. In a DC grid the reactive power \( Q \) would be zero.

\[ V_k(i + 1) = \frac{1}{Y_{kk}} \left[ \frac{P_k - jQ_k}{V_k^*(i)} - \sum_{n=1}^{k-1} Y_{kn}V_n(i + 1) - \sum_{n=k+1}^{N} Y_{kn}V_n(i) \right] \]  

(2.3)

The Gauss-Seidel method is used to solve linear algebraic equations and there are some cases where the Gauss-Seidel method causes the solution to diverge. The Newton-Raphson method can be used to solve nonlinear equations and can solve equations with less iterations than Gauss-Seidel. The convergence time is independent of the dimension of the matrix. The Newton-Raphson method is based on the power mismatch for the convergence criteria and is calculated in 4 steps:

Step 1:

Compute the power mismatch \( \Delta y(i) \).

\[ \Delta y(i) = \begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix} = \begin{bmatrix} P - P[x(i)] \\ Q - Q[x(i)] \end{bmatrix} \]  

(2.4)
Step 2:

Calculate the Jacobian matrix elements.

for n \neq k

\[ J_{1kn} = \frac{\partial P_k}{\partial \delta_n} = V_k V_n \sin(\delta_k - \delta_n - \theta_{kn}) \] (2.5)

\[ J_{2kn} = \frac{\partial P_k}{\partial V_n} = V_k V_n \cos(\delta_k - \delta_n - \theta_{kn}) \] (2.6)

\[ J_{3kn} = \frac{\partial Q_k}{\partial \delta_n} = -V_k V_n \cos(\delta_k - \delta_n - \theta_{kn}) \] (2.7)

\[ J_{4kn} = \frac{\partial P_k}{\partial V_n} = V_k V_n \sin(\delta_k - \delta_n - \theta_{kn}) \] (2.8)

for n = k

\[ J_{1kk} = \frac{\partial P_k}{\partial \delta_n} = -V_k \sum_{\substack{n=1\\ n \neq k}}^N V_n \sin(\delta_k - \delta_n - \theta_{kn}) \] (2.9)

\[ J_{2kk} = \frac{\partial P_k}{\partial V_n} = V_k Y_{kk} \cos\theta_{kk} + \sum_{n=1}^N V_n \cos(\delta_k - \delta_n - \theta_{kn}) \] (2.10)

\[ J_{3kk} = \frac{\partial Q_k}{\partial \delta_n} = V_k \sum_{\substack{n=1\\ n \neq k}}^N V_n \cos(\delta_k - \delta_n - \theta_{kn}) \] (2.11)

\[ J_{4kk} = \frac{\partial Q_k}{\partial V_n} = -V_k Y_{kk} \sin\theta_{kk} + \sum_{n=1}^N V_n \sin(\delta_k - \delta_n - \theta_{kn}) \] (2.12)

Step 3:

Solve for the change in voltage and phase.

\[
\begin{bmatrix} J_{1(i)} & J_{2(i)} \\ J_{3(i)} & J_{4(i)} \end{bmatrix} \begin{bmatrix} \Delta \delta(i) \\ \Delta V(i) \end{bmatrix} = \begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix}
\] (2.13)

Step 4:

Solve for the voltage and phase for the next iteration.

\[
x(i+1) = \begin{bmatrix} \Delta \delta(i+1) \\ \Delta V(i+1) \end{bmatrix} = \begin{bmatrix} \delta(i) \\ V(i) \end{bmatrix} + \begin{bmatrix} \Delta \delta(i) \\ \Delta V(i) \end{bmatrix}
\] (2.14)
CHAPTER 2. THEORY

The load flow techniques described above are used for AC power flow. The DC power flow problem is much simpler due to many factors. A DC cable can be considered to be ideal but with an AC cable there are losses due to the skin effect and the PI model is typically used to represent the line due to its inductive and capacitive properties. Furthermore, in AC systems the amplitude is not constant but oscillates therefore more equations are needed to represent this wave response. In a DC system the voltage is constant and there is no reactive power. Therefore, the power flow problem has transformed from a non-linear complex issue to a much simpler calculation where the magnitudes of the voltages are constant and the reactive power is zero. The power flow problem is now a simple linear equation which is non-iterative only requiring a single calculation therefore is much faster to calculate but is less accurate due to the use of assumptions which generally don’t hold in real life. The following assumptions are made with DC power flow:

• The voltage angle differences are very small
• The voltage profile is flat and therefore voltages are set to 1 p.u.
• The line is lossless

So in order to get the DC power flow equation we take the AC power flow problem and simplify it into a linear equation. A simplified relationship of the active power distributed on a line can be given by Equation 2.15.

\[
P_{\text{Line}} = \left| V_s \right| \left| V_r \right| \left| X_{\text{Line}} \right| \sin(\theta_{sr})
\]

Consequently, if we assume the line is lossless, set the voltage magnitudes to 1 p.u. and remove the sine expression the power distributed on a DC line becomes Equation 2.16 and labelling the line impedance as susceptance we get a simplified linear expression on the right. The whole system can then be modelled by Equation 2.17

\[
P_{\text{Line}} = \frac{\theta_{sr}}{X_{\text{Line}}} = B_{\text{Line}} \cdot \theta_{sr}
\]

\[
\Delta P = \sum_{n=1}^{n} B_{sr} \cdot (\theta_s - \theta_r)
\]

2.6 Smart Grids

A smart grid has the ability to intelligently integrate the actions of many distributed resources in order to efficiently deliver power [8]. The concept of the virtual power plant (VPP) is being utilized in smart grids to efficiently deliver power to loads. The conventional power system works with a large scale power plant in one location and then the power is transmitted and distributed over large distances. Distributed generation is usually in small uncoordinated amounts that work on an individual basis [18]. The concept of the virtual power plant is to group all the small distributed units into an aggregate unit in order to coordinate their responses. A smart grid can be equipped with information and communication technologies, sensing and control technologies and also power electronics and energy storage to add benefits to the grid. One technique in order to meet the load in a day is with load shifting. If energy generation has a surplus during the day which is usually the case with a solar microgrid this excess energy can be stored and used at a later time in the day when
solar generation is low as shown in Figure 2.3. The difference between a smart grid and microgrid is that a microgrid refers to a smaller grid and has the ability to meet the loads without connection to the macrogrid. A smart grid refers to a grid that is automated and is able to respond to disturbances automatically.

![Figure 2.3: Load shifting](image)

### 2.7 High Voltage Direct Current

High Voltage DC (HVDC) systems are being used to transmit renewable energy over long distances to load centers. The first commercial application of HVDC was between the Swedish mainland and the island of Gotland in 1954 [19]. High voltages are used to decrease the amount of losses during transmission and direct current is used to decrease the amount of corona discharge due to the absence of the skin effect. More power per conductor can be distributed with DC transmission [20] decreasing the right-of-way requirements which reduces the variable costs of the lines [21].

The skin effect is a phenomena in AC systems where the current has a tendency to distribute within the conductor such that the current density is larger near the surface of the conductor and the current density decreases as you approach the center as shown in figure 2.4(a). The higher the frequency the stronger the skin effect and more current is distributed near the surface of the conductor. When the frequency drops to zero the current is evenly distributed throughout the conductor and there is no skin effect [9].

Corona discharge is when the air around a conductor is ionised. A corona discharge will occur when the electric field strength around a conductor is high enough to form a conductive region around the conductor but not high enough to cause arcing to a nearby object. It is often viewed as a blueish color as seen in figure 2.4(b). A corona discharge results in real power losses. Therefore, AC systems which are prone to the skin effect have greater amounts of corona discharge because the electric field is higher at the surface of the conductor. DC systems do not have a skin effect therefore the electric field is lower at the surface of the conductor reducing the amount of corona discharge. This helps DC systems to be more efficient. HVDC has shown to be a solution for asynchronous connections between power systems with different frequencies or synchronous speeds and also underwater connections [22]. Conversion stations for HVDC work with multiple switches. Due to the high voltages required (greater than 150 kV) which are much greater than the semiconductor device ratings
CHAPTER 2. THEORY

(a) The skin effect  
(b) Corona discharge

Figure 2.4: Losses in an AC system

(approx 5\text{ kV}) multiple switches are connected in series to form a composite switch called a valve [8]. HVDC has shown that with the use of power electronic conversion stations DC systems can be used to provide additional benefits.
Chapter 3

Methods

In this chapter the operation of the individual components of the microgrid will be analyzed using MATLAB/Simulink. Simulink has an environment called Simscape which can be used to model dynamical systems. The Simscape language shows its strength with physical modelling by using equation based representation and allows for bidirectional energy flows [23]. DC-DC converters, solar modules, wind turbines, batteries and a charge controller will be analyzed.

3.1 Power Electronics

3.1.1 Introduction

DC-DC converters use switched mode power supplies in order to convert one voltage to another level with high efficiencies [24]. Power electronic converters can be used for [25]:

- Voltage control
- Power flow control
- System balancing
- Maximum power point tracking
- Fault protection

Linear voltage regulators can also be used to convert one DC voltage to another level but at much lower efficiencies. For example, if we have the circuit in Figure 3.1(a) with $V_S = 100 \, \text{V}$ and we need $25 \, \text{V}$ at the output with $R_L = 10 \, \Omega$. We would make the variable resistance $30 \, \Omega$ so that $R_L$ absorbs a quarter of the input power. The current in the circuit would be $I = V/R = 100/(30+10) = 2.5 \, \text{A}$ and the output voltage would be $V_O = I \times R = 2.5 \times 10 = 25 \, \text{V}$. In this circuit the efficiency would be $\eta = V_{out}/V_{in} = 25/100 = 25\%$ with the majority of the power being dissipated as heat through the variable resistor. The lower the output voltage required the lower the efficiency of the circuit. A switched mode converter uses a transistor instead of a variable resistor to control the output voltage as shown in Figure 3.1(b). When the switch is closed $V_O = V_S$ and when the switch is open $V_O = 0 \, \text{V}$. The duty cycle is adjusted which is the fraction of a period that the switch is on in order to control the output voltage. In the switched-mode converter all of the power is absorbed by the load assuming that the switching transistor is ideal. Therefore, the switching circuit of figure 3.1(b) is theoretically 100\% efficient.
3.1.2 DC-DC Converters

DC-DC converters will be used in conjunction with components of the microgrid to help stabilize the voltage and generate maximum power [26]. Three DC-DC converter types will be investigated:

- Buck converter
- Boost converter
- Buck-Boost converter

These DC-DC converters operate by periodically opening and closing a switch. The buck converter reduces the input voltage and the boost converter increases the input voltage. It is called a boost converter because the output voltage is larger than the input voltage [24]. The buck-boost converter has the ability to increase or decrease the input voltage but with a polarity reversal. These DC-DC converters can be seen in Figure 3.2.

![DC-DC Converter Circuits](image)

**Figure 3.2: DC-DC converter circuits**

The converters contain a low pass filter after the switch at the output in order to obtain a purely DC output. The output voltage is changed by varying the duty cycle. The output of the buck, boost and buck-boost converters are calculated by Equations 3.1 to 3.3 respectively with the responses plotted in Figure 3.3.

\[
V_O = V_S D \quad (3.1)
\]

\[
V_O = \frac{V_S}{1 - D} \quad (3.2)
\]

\[
V_O = -V_S \left( \frac{D}{1 - D} \right) \quad (3.3)
\]
3.1. POWER ELECTRONICS

The boost converter works by storing energy in an inductor when the switch is closed and delivering that energy to the load when the switch is open to boost the output voltage. The inductor needs to be large enough in order to keep the current positive and in continuous operation. When choosing the inductor size Equation 3.4 was used to find the minimum inductor size required in order for the current to be continuous. A larger inductor was chosen to ensure that the current stays positive when the switch is open. The voltage ripple can be minimised by having a larger capacitor on the output. The voltage ripple can be calculated using Equation 3.5.

\[
L_{\text{min}} = \frac{D(1 - D)^2 R^2}{2f} \tag{3.4}
\]

where \(L_{\text{min}}\) is the minimum inductance required for continuous operation, \(D\) is the duty cycle, \(R\) is the load resistance and \(f\) is the switching frequency.

\[
\frac{\Delta V_O}{V_O} = \frac{D}{RCf} \tag{3.5}
\]

where \(V_O\) is the output voltage and \(C\) is the capacitance.

The boost converter of Figure 3.2(b) was simulated in Simulink. The inductor value was calculated using Equation 3.4. Figure 3.4 shows the required minimum inductance versus the duty cycle for a load of 10 \(\Omega\) at 5 kHz. As you can see the largest minimum inductance is 150 \(\mu H\) when the duty cycle around 0.35. A larger inductance of 240 \(\mu H\) was chosen to ensure that the boost converter operated in continuous current mode.

![Figure 3.3: DC-DC converter outputs](image)

The circuit of Figure 3.5(a) was simulated with a duty cycle of 0, 0.2 and 0.4. The simulation results can be seen in Figure 3.5(b). As you can see when the duty cycle is increased the output voltage also increases. When the duty cycle is 0.4 the output voltage was 600 V as can be confirmed using Equation 3.2.
\[ V_O = \frac{V_S}{1-D} = \frac{360}{1-0.4} = 600V \]
3.1. POWER ELECTRONICS

3.1.1 Design in Simulink

3.1.2 Simulink output

Figure 3.7: Buck-Boost converter in simulink

The output voltage is below the input voltage. When the duty cycle is 0.7 the output voltage was 840 V as can be confirmed using Equation 3.3.

\[ V_O = -V_S \left( \frac{D}{1-D} \right) = -360 \left( \frac{0.7}{1-0.7} \right) = -840V \]

3.1.3 The Bidirectional Converter

A converter is required to allow the flow of power from and to the batteries in the microgrid. The previous buck and boost converters do not have the capability for bidirectional power flow. This is because they all have diodes in their designs which prevent reverse current flow [27]. A bidirectional converter can be designed by combining the capabilities of the buck and boost converters and replacing their diodes with switches as shown in Figure 3.8. The top switch is used to operate the converter as a buck converter, transferring power from the high voltage side to the low voltage side and the bottom switch is used to operate the converter as a boost converter, transferring power from the low voltage side to the high voltage side.

Figure 3.8: Bidirectional converter construction

The design was simulated in Simulink as shown in Figure 3.9. The bidirectional converter will be controlled by a charge controller which will determine whether energy needs to be sent to or from the battery in order to smooth out the fluctuations of renewable energy sources and stabilize the voltage. The same values as the buck converter design was used
for the bidirectional converter except for the inductor value. It was found that having a large inductor value inhibits the voltage stability of the system therefore a lower value was chosen. The lower ripple will help to charge and discharge the batteries with higher efficiencies increasing their lifetime.

![Bidirectional converter in Simulink](image)

Figure 3.9: Bidirectional converter in Simulink

### 3.2 Photovoltaic Cell

#### 3.2.1 Introduction

PV cells convert sun light into a voltage by the photoelectric effect [28]. A load connected across a PV array will draw current from the device and the PV array will deliver power to the load [28]. The PV array is constructed of n-type and p-type material in order to generate current flow in an external circuit. When light hits the PV cell a photon is absorbed which generates an electron-hole pair. Due to the external circuit connecting the n-type and p-type material the electron will travel from the n-type material to the p-type material via a connection by an external circuit creating current flow. Figure 3.10 shows the definition of a single cell to the construction of a PV array. A single cell only generates a voltage in the range of 0.5 - 0.8 V which is not enough to power the load therefore many cells are connected in series and parrellel to increase the voltage and current respectively [29] as shown in Figure 3.11.

![PV definitions](image)

Figure 3.10: PV definitions
3.2. PHOTOVOLTAIC CELL

3.2.2 Modelling

Photovoltaic cells can be modelled in Simulink either by implementing the equations that represent the functionality of a solar cell or by using the Simulink environment which has pre-defined solar arrays for many different models. The solar array modelled was a Canadian Solar CS6X-310P. The corresponding I-V and P-V curves for this module under varying irradiance and temperatures are shown in Figure 3.12. The upper graph of Figure 3.12(a) shows the current versus the voltage for the Canadian Solar CS6X-310P. The I-V curves show that the output current drops with decreasing irradiance. The curves also show that the current produced by the module is constant with increasing voltage until a certain voltage is reached and then the current produced by the module decreases substantially with increasing voltage. The bottom graph of Figure 3.12(a) is a plot of the power versus the voltage where power is the product of the voltage and current. The P-V curves show that the output power drops with decreasing irradiance. The power increases with increasing voltage for all the curves until a certain voltage is reached and then the power begins to decrease with voltage. The knee of the P-V curve is where we want to operate at in order to extract maximum power from the array. The graphs in Figure 3.12(b) show the same response but for a variance in temperature. The I-V plot shows that a change in temperature has a much lower effect on the current generated from the PV array. The P-V curve also shows that the power delivered from the PV array is also not affected as much. The maximum power point decreases with increasing temperature because as the temperature increases the conductivity of the semiconducting material increases rapidly. The current increases but the voltage decreases much more rapidly decreasing the power.

The PV cell can be modelled by Equations 3.7 to 3.13 using the two-diode model. The two diode model is shown in Figure 3.13. The single diode model assumes a constant diode ideality factor, which is how close a diode follows an ideal diode. In reality the diode ideality factor changes with voltage therefore the two-diode model allows for a better approximation at higher and lower voltages. Equation 3.7 represents the current at the terminals of the PV cell. Equation 3.8 is the photo current produced by the cell and is dependent on the...
irradiance and temperature. The current is then produced due to the photoelectric effect [28]. Equations 3.9 and 3.10 represent the diode currents. The shunt and series currents are shown in Equations 3.11 and 3.12. The series resistance represents the contact resistance between the metal and silicon and reduces the cell current. The shunt resistance is due to manufacturing defects and gives a different path to the photocurrent reducing the current at the PV terminals resulting in power losses. A lower value decreases the output voltage because a less resistive path will be present for the photocurrent. An ideal PV cell will have $R_s = 0$ and $R_{sh} = \infty$. Equation 3.13 represents the reverse saturation current. The parameter definitions are summarized in Table A.1 in Appendix A.

\begin{align*}
I & = N_p I_{ph} - N_p I_{D1} - N_p I_{D2} - I_{sh} \\
I_{ph} & = [I_{sc} + K_i(T - T_{ref})]G/1000 \\
I_{D1} & = I_s \left[ e^{\frac{V}{N_p} + \frac{IR_s}{N_p}} \right]^{-1} \\
I_{D2} & = I_s \left[ e^{\frac{V}{2N_p} + \frac{IR_s}{N_p}} \right]^{-1}
\end{align*}
3.2. PHOTOVOLTAIC CELL

\[ I_{sh} = \frac{N_{pv}}{N_s} + IR_s \]

(3.11)

\[ I_s = I_{rs} \left( \frac{T}{T_{ref}} \right)^{3} e^{\frac{qE_{g}}{N_s kT_{ref}} (\frac{1}{T_{ref}} - \frac{1}{T})} \]

(3.12)

\[ I_{rs} = \frac{I_{sc} e^{\left( \frac{qV_{oc}}{N_s kT} - 1 \right)}}{e^{\left( \frac{qV_{oc}}{N_s kT} - 1 \right)}} \]

(3.13)

A photovoltaic cell can be modelled as a current source. The simulink block for the PV cell is based on the two diode model [28]. Figure 3.14 shows the input panel for the PV array in Simulink. The array data tab lists the number of parallel and series strings in order to modify the PV array voltage and current. The Module data tab has specific operating information for the PV array. This data can be selected from many manufacturers or you can manually enter the specific data. The model parameters tab then lists the specific parameters for the PV array.

![Figure 3.14: Simulink PV array block parameters](image)

3.2.3 Simulation

The circuit of Figure 3.15(a) was simulated in Simulink under standard test conditions with an irradiance of 1000 W/m² and at 25°C. The PV curves under these conditions are shown in 3.15(b). The circuit was simulated with different loads to investigate the power delivered by the PV array and to investigate the principle of maximum power transfer. Figure 3.16 shows the outputs from the simulations with the load at 0.75 Ω, 1 Ω and 3 Ω respectively. The results are summarized in Table 3.1.

![Table 3.1: Simulation Results](image)

When the load is at 0.75 Ω the current, voltage and power are at 360.8 A, 270.6 V and 97.6 kW respectively. On the curves of Figure 3.15(b) the PV array is operating at point A. When the load is at 1 Ω the current, voltage and power are at 349.7 A, 349.7 V and 122.3 kW respectively. On the curves of Figure 3.15(b) the PV array is operating at point B. When the load is at 3 Ω the current, voltage and power are at 142.5 A, 427.4 V and 60.88 kW respectively. On the curves of Figure 3.15(b) the PV array is operating at point C. As you can see the power delivered by the PV array can be adjusted by varying the load...
resistance. Maximum power is transferred when the load resistance is equal to the resistance of the PV array.

Figure 3.15: PV array simulation in Simulink under standard test conditions

Figure 3.16: PV output parameters with different loads

Table 3.1: PV output vs change in load

<table>
<thead>
<tr>
<th>Load (Ohms)</th>
<th>Current (Amps)</th>
<th>Voltage (Volts)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>360.8</td>
<td>270.6</td>
<td>97.6</td>
</tr>
<tr>
<td>1</td>
<td>349.7</td>
<td>349.7</td>
<td>122.3</td>
</tr>
<tr>
<td>3</td>
<td>142.5</td>
<td>427.4</td>
<td>60.88</td>
</tr>
</tbody>
</table>
Maxium power point trackers (MPPT) can be used to find the operating point at which maximum power can be extracted from the PV array under varying irradiance and temperature [30]. MPPT’s use a simple structure with a few variables for implementing an iterative method to achieve impedance matching between the load and output impedance of the PV array [31]. The MPPT modelled was the perturb and observe (P&O) algorithm. This is a commonly used MPPT algorithm and works by perturbing the voltage in a certain direction and observing the change in power. If the power is increased the voltage is perturbed in the same direction [20]. Figure 3.17 shows how the MPPT connects to the PV system. The input to the MPPT is the voltage and current from the PV Array. The algorithm determines whether the voltage needs to be increased or decreased in order to increase the power from the PV array. The MPPT then outputs a change in the duty cycle which is converted to a PWM signal and fed to the boost converter so that the voltage can be increased or decreased.

Figure 3.18 shows the logic for the perturb & observe algorithm. The voltage and current are read and the product is taken to give the power. The first conditional statement checks if the power is the same as the previous reading. If there is no change in power we must be operating at the knee of the P-V curve and no change in operating voltage is needed. The next conditional statement compares the power of the previous sample to the current sample. Then the voltage is compared to the previous sample and from this information we can determine in which direction the maximum power point is in. The duty cycle is then perturbed in the direction that will increase the power. The change in duty cycle is fed into a PWM generator which operates the boost converter to perturb the voltage. The P&O algorithm was written in a MATLAB .m file and embedded inside Simulink using the function block. The MATLAB code for the perturb and observe algorithm is shown in Appendix B.

### 3.2.3.1 PV connected with MPPT and Boost converter

The Canadian Solar CS6X-310P PV array was connected to a boost converter and MPPT P&O algorithm and was simulated in Simulink. The circuit diagram is shown in Figure 3.19. In order to suppress high frequency ripples of the PV output voltage a capacitor is added to the PV terminals [32]. The output parameters for a load of 0.75 Ω, 1 Ω and 3 Ω are shown in Figure 3.20. The results are summarized in Table 3.2.

When the load is at 0.75 Ω the MPPT algorithm sets the duty ratio to 0 and the power delivered is the same as when the boost converter and MPPT algorithm were not connected as in Table 3.1. This is also the case for when the load is 1 Ω. The reason for this is because with these 2 scenarios the PV array is operating at points A and B in Figure 3.15(b) and in order for the maximum power to be increased the output voltage needs to be decreased so that the input power of the PV array can be increased. However, because we have a boost converter this is not possible because it only has the ability to increase the output voltage and not decrease. If we examine the case when the load is 3 Ω the original power from the
PV array was 60.88 kW when the MPPT was not connected in Table 3.1 and now with the MPPT connected the power is increased to 122.2 kW as can be seen in Table 3.2. The MPPT increased the power in this case because the PV operating voltage needed to be decreased which is achieved by an increase in the output voltage. In order to have an MPPT that can operate in both regions with this design we need a converter that can increase or decrease the output voltage which is achievable with the buck-boost converter.
3.2. PHOTOVOLTAIC CELL

Figure 3.19: Connected PV, MPPT & Boost converter in Simulink

Figure 3.20: MPPT output parameters with different loads (Boost)

Table 3.2: MPPT output vs change in load

<table>
<thead>
<tr>
<th>Load (Ohms)</th>
<th>MPPT (Duty Cycle)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>0</td>
<td>97.6</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>122.2</td>
</tr>
<tr>
<td>3</td>
<td>0.393</td>
<td>122.7</td>
</tr>
</tbody>
</table>
3.2.3.2 PV connected with MPPT and Buck-Boost converter

To give the MPPT the ability to increase or decrease the voltage in order for the perturb and observe algorithm to achieve maximum power with any load the Canadian Solar CS6X-310P PV array was connected to a buck-boost converter instead of a boost converter. The circuit diagram is shown in Figure 3.21 and the output parameters for a load of 0.75 Ω, 1 Ω and 3 Ω are shown in Figure 3.22. The results are summarized in Table 3.3.

![Figure 3.21: Connected PV, MPPT & Buck-Boost converter in Simulink](image)

![Figure 3.22: MPPT output parameters with different loads (Buck-Boost)](image)

In this scenario with a buck-boost connected the power is increased in each scenario because the buck-boost converter has the ability to increase or decrease the operating voltage. Table 3.3 shows that the output for each load case is operating at maximum power at around point B of figure 3.15(b). In real applications a boost converter is sufficient because most loads are much higher than this simulated case.
Table 3.3: MPPT output vs change in load

<table>
<thead>
<tr>
<th>Load (Ohms)</th>
<th>MPPT (Duty Cycle)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>0.462</td>
<td>122.5</td>
</tr>
<tr>
<td>1</td>
<td>0.495</td>
<td>122.9</td>
</tr>
<tr>
<td>3</td>
<td>0.622</td>
<td>122.9</td>
</tr>
</tbody>
</table>

3.3 Wind Turbine

3.3.1 Introduction

Wind power is produced by extracting energy from wind through aerodynamic forces on the blades of the wind turbine. The blades are connected to a drive shaft which rotates through a generator creating variable AC electricity. The blades rotate at a variable speed to extract maximum power from the wind resource therefore the power is usually converted from AC to DC and then back to AC at a specific frequency. The wind resource originates from the uneven heating of the atmosphere by the sun, irregularities in the earths surface and the rotation of the earth [29]. The uneven heating of the atmosphere causes air in the heated regions to expand decreasing its pressure. This causes a pressure gradient and air will flow from the high pressure regions to the low pressure regions.

3.3.2 Wind Terminology

The power generated by a wind turbine is shown in Equation 3.14. The power generated from a wind turbine is proportional to the cube of the wind speed therefore wind turbines should be placed in areas of high mean annual wind speeds. If wind speeds are too high pitch control can be applied where the angle of the blades are adjusted to reduce the speed of the blades. The Simulink diagram of a wind turbine is shown in Figure 3.23 which is based on Equation 3.14.

\[
P_m = \frac{1}{2} \rho A C_p(\lambda, \beta) V_\omega^3
\]

(3.14)

where \(\rho\) is the air density, \(A\) is the rotor area that is swept, \(V_\omega\) is the wind speed and \(C_p(\lambda, \beta)\) is the power factor coefficient. \(C_p(\lambda, \beta)\) is a measure of the amount of energy extracted from the wind resource and is a function of the tip speed ratio \(\lambda\) and the pitch angle \(\beta\). The Betz limits states that the power factor coefficient has a limit of 59.7%. The tip speed ratio is the relative speed of the rotor and the wind speed. The pitch angle is the relative angle between the rotor and its axis.
CHAPTER 3. METHODS

Figure 3.23: Simulink model of a wind turbine

Wind turbines start to produce power at wind speeds of around 3-4 m/s and are stopped in high wind speeds approximately above 20-25 m/s [33]. Figure 3.24 shows an example power curve of a pitch regulated wind turbine. The power starts to increase from the cut-in speed until it reaches its rated power where extra wind speeds create a steady power output until the wind speeds reach a maximum that is safe for the wind turbine therefore it is cut-out. Wind speed measurements were downloaded from the NREL database for the area of interest in Caye Chapel. The wind speeds are generally in the area of 3-6 m/s which may not be high enough to make wind turbines feasible for the microgrid as compared to the solar resource because wind speeds are the critical factor in regards to wind power generation [5].

Figure 3.24: Pitch regulated wind turbine power output

3.4 Energy Storage

3.4.1 Introduction

Energy storage is a critical component in a microgrid that is based on renewable energy [34]. Energy storage will help to maintain voltage stability and smooth out the fluctuations of renewable energy generation. Batteries which make use of a reversible chemical reaction to store energy and convert chemical energy into electrical energy will be used as the energy storage element in this DC microgrid [35]. Batteries are not as fast at responding than super capacitors but they have the ability to store more energy which is a critical design
consideration in microgrids [10]. The response time is quicker with supercapacitors because
the electrical energy can be stored directly without a chemical process [36]. The response
time is not as critical in a DC microgrid because we don’t have to worry about frequency
regulation. Batteries can be damaged due to deep discharge therefore the state of charge
should be limited to a reasonable region [37].

3.4.2 Battery Terminology

A battery can be modelled as a non-linear voltage source where the output voltage depends
on the current and also the battery state of charge (SOC). The SOC is a non-linear function
of the current and time [32]. The internal resistance and voltage depend on the battery SOC.
The SOC can be defined as the ratio of the ampere-hour remaining in the battery to the
total ampere-hour of the battery [38]. The internal resistance of a battery is nearly constant
until the SOC reaches 90% then it increases exponentially. A diffusion capacitance builds
up within a battery due to concentration difference between chemical species. The two
diffusion layers have opposite charges with the electrolytes behaving as a dielectric which
produces a capacitance effect called the diffusion capacitance. When a battery is charged
faster than the chemical energy conversion process can handle side reactions take place. This
causes the battery to be heated and hydrogen and oxygen gasses are produced in a process
known as gassing [38]. The battery for the DC microgrid was modelled in Simulink based
on the Shephred Model as shown in Figure 3.25. This model has a controlled voltage source
with a series resistance [39]. Figure 3.26(a) and (b) shows the discharge characteristics of the
battery. The output voltage is given by Equation 3.15 and the SOC is given by Equation 3.16.
The discharge curves are sloping indicating that the power delivered by the batteries will fall
throughout a discharge cycle. Lithium-ion batteries have a flatter discharge characteristic
curve but the extra cost makes lead-acid batteries more widely used [29].

Figure 3.25: Battery model in Simulink

\[
V_b = V_0 + R_b \times i_b - K \times \left( \frac{Q}{Q - \int i_b dt} \right) + A \times \exp(B \int i_b dt)
\]  

\[SOC = 100 \times \left( 1 + \frac{\int i_b dt}{Q} \right)\]

Simulink has a built-in component for a battery as shown in Figure 3.27(a). Figure
3.27(b) shows that when current is being delivered to the battery the SOC increases and
CHAPTER 3. METHODS

3.5 Charge Controllers

3.5.1 Introduction

Charge controllers are used to regulate the flow of current to and from batteries in a microgrid [29]. They are essential to protect the batteries and regulate the DC bus voltage. In this DC microgrid project a charge controller will control a bidirectional converter lowering the PV output voltage produced to the level required by the batteries and when the PV output drops to zero the charge controller will activate the bidirectional converter to send the power from the batteries to the microgrid. Figure 3.28 shows the proposed logic for a charge controller in a DC microgrid. Most batteries are designed to operate in the region of 30-90%. Therefore, the logic in the controller will check if the batteries are in the region of 30-90% and if they are depending on the power balance between the generation and load.
the batteries will either charge or discharge. If the batteries are at a low SOC of below 30% and if the power generated is greater than the required load the batteries will be charged but if the load is higher than the power generated load shedding should be considered to protect the batteries. The last case is if the batteries are at a high SOC of above 90%. In this case if the microgrid is generating excess power the current will be sent to a dump load to protect the batteries from overcharging and the DC bus voltage from increasing.

\[
\begin{align*}
SOC > 0.9 & \rightarrow P_{PV} > P_{Load} \rightarrow \text{Charge} \rightarrow \text{DumpLoad} \\
SOC < 0.3 & \rightarrow P_{PV} > P_{Load} \rightarrow \text{Charge} \\
0.3 \leq SOC \leq 0.9 & \rightarrow P_{PV} > P_{Load} \rightarrow \text{LoadShedding} \rightarrow \text{Charge} \rightarrow \text{Discharge}
\end{align*}
\]

Figure 3.28: Charge controller logic

### 3.5.2 PI Controller

A microgrid can be controlled by voltage-based droop control or communication-based control [40]. In this project we will use the communication based control method based on a proportional-Integral (PI) controller. A PI controller will be used as the control mechanism for the charge controller. A block diagram of a PI controller is shown in Figure 3.29. This is a commonly used control mechanism which calculates the error \( e(t) \) between the output \( y(t) \) and the desired set point \( Ref \). A proportional and integral correction is made to the error signal and the combination of these corrections forms the control variable \( u(t) \). This control variable is used to reduce the error in the system and the process is continued to decrease the error. In the DC microgrid design the reference will be the desired DC voltage of 350 V and the monitored output \( y(t) \) will be the DC bus voltage. The control variable \( u(t) \) will operate the bidirectional converter which will control the flow of power between the microgrid and battery in order to stabilize the DC bus voltage. The proportional term generates a proportional response relative to the error. If there was no error signal in a proportional only controller the bidirectional converter would not be activated and the DC voltage would deviate once a zero steady state error is reached due to inertia in the system. Therefore, we also use an integral response which adds a control based on the past errors. A P controller will exhibit a faster response but a PI controller has a better power regulation and zero steady-state error [9].
3.5.2.1 PI Controller Design

The PI controller was implemented into Simulink using objects as shown in Figure 3.30. The proportional block was selected to be 0.02 and the integral block was selected as 3. The terms where added together and a limit was applied between 0.95 and -0.95 because the output will operate a bidirectional converter which has a maximum duty ratio of 1 but problems occur with infinity at 1 so 0.95 was chosen for the limits. The output is fed to the outport $y$ and the error is fed back into the inport $u$. The output $y$ will either be positive or negative depending on if the DC voltage needs to be increased or decreased. Therefore, logic will be used to transmit the positive signals to the boost control and the negative signals to the buck control of the bidirectional converter.

![Figure 3.29: PI controller block diagram](image)

![Figure 3.30: Simulink PI controller topology](image)
Chapter 4

Results

In this chapter the results will be presented for the final proposed microgrid design. Firstly, the resources and components for the microgrid and list their specifications will be described. Secondly, the results from the financial analysis which was conducted in order to select the most economical system that can meet the load requirements will be presented. Finally, a technical analysis of the DC microgrid will be presented.

4.1 System Description

4.1.1 Resources

4.1.1.1 Solar Resource

The solar data for Caye Chapel was loaded from the Hybrid Optimization Model for Electric Renewables (HOMER) [41] database by specifying the locations coordinates of 17° 41’ 24” N, 88° 03’ 36” W. Caye Chapel has a relatively strong solar resource with a daily radiation annual average of 4.75 kWh/m²/day. A graph of the global horizontal radiation is shown in Figure 4.1(a). The months from March to May have the greatest amounts of solar radiation but coexist with a greater amount of cloud cover indicated by the red line which is the clearness index. The average daily profile of solar radiation for each month is shown in Figure 4.1(b). As you can see the solar radiation starts to increase from 6am, peaking at around 12pm and returning to zero just after 6pm for all months but with variations in magnitude.

![Figure 4.1: Caye Chapel solar resource](image)
4.1.1.2 Wind Resource

The wind data for Caye Chapel was downloaded from the NREL database and was edited into an appropriate format in order to upload it into the HOMER software. The wind resource for Caye Chapel is not so strong with an annual average wind speed of 3.39 m/s. Figure 4.2(a) shows the average wind speeds for each month. Very low wind speeds can be seen in the months from August to October of below 3 m/s. The wind profile for the first week of January is shown in Figure 4.3. As you can see the wind resource profile is much more random than the solar resource. The weibull k distribution for the wind resource is 3.68. Weibull k factors indicate the data distribution with lower k values corresponding to broader distributions of wind speeds and higher k values corresponding to smaller wind speed distributions. The weibull distribution of 3.68 is relatively high indicating that the region of Caye Chapel has a wide variance in wind speeds typical in gusty areas without a strong constant wind resource. Figure 4.2(b) shows the scaled data for each month. The stongest wind speeds are in December with maximum wind speeds exceeding 6 m/s.

![Wind Resource](image)

(a) Average daily wind speeds for each month

![Monthly wind distribution](image)

(b) Monthly wind distribution

Figure 4.2: Caye Chapel wind resource

![Wind speeds for the first week of January](image)

Figure 4.3: Wind speeds for the first week of January

4.1.2 Load Profiles

4.1.2.1 Residential load

An estimate of the residential load was modelled and loaded into HOMER. A typical daily load profile is shown in Figure 4.4(a) and can be seen to increase around 7 AM and maintain stable throughout the day until peaking at 6pm. Figure 4.4(b) shows the full distribution of the load for each month and the results are summarized in table 4.1. The average daily energy consumption is 13,464 kWh/day and the average power is 561 kW with a maximum power consumption of 1,821 kW. The spread between the average power and the peak power can be quantified by the load factor in Equation 4.1. The load factor of the residential load is
0.308 showing that the load is highly variable. The peak load ultimately decides the sizing of the system [42]. Therefore, it is ideal to have load factors close to one in order to reduce unnecessary investment in peaker plants.

\[
\text{Load Factor} = \frac{\text{Average Load}}{\text{Peak Load}} \tag{4.1}
\]

![Typical daily profile](image1.png) ![Monthly distribution](image2.png)

Figure 4.4: Residential load

<table>
<thead>
<tr>
<th><strong>Residential load</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ((kWh/d))</td>
</tr>
<tr>
<td>Average ((kW))</td>
</tr>
<tr>
<td>Peak ((kW))</td>
</tr>
<tr>
<td>Load factor</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of residential load

### 4.1.2.2 Commercial load

An estimate of the Commercial load is shown in Figure 4.5(a) and a typical weekly profile is shown in Figure 4.5(b). The weekly profile shows that the plant is in full production from Monday to Friday with decreased operations on Saturday and the plant is closed on Sunday. A summary of the commercial load profile is presented in table 4.2. The commercial load starts to increase around 7am and is then constant until 5pm when the load starts to decrease until the idle rate of power consumption.

![Typical daily profile](image3.png) ![Typical weekly profile](image4.png)

Figure 4.5: Commercial load
4.1.3 Generation

4.1.3.1 Caterpillar C32 Diesel Engine

A Caterpillar C32 diesel engine was modelled for the microgrid with its specifications listed in Table 4.3. The diesel engine costs $135,000 for a 1,000 kW module [43]. Diesel engines are currently used to power the island of Caye Chapel therefore an initial base case financial analysis will be conducted of a diesel only microgrid.

![Caterpillar C32 Diesel Engine](image)

<table>
<thead>
<tr>
<th>Caterpillar C32 Diesel Engine Specifications [43]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
</tr>
<tr>
<td>Active Power (kW)</td>
</tr>
<tr>
<td>Apparent Power (KV A)</td>
</tr>
<tr>
<td>Price ($)</td>
</tr>
</tbody>
</table>

4.1.3.2 Canadian Solar CS6X-310P Solar Panel

Canadian Solar CS6X-310P solar panels were modelled for the microgrid with the specifications listed in Table 4.4. The solar panels cost $305.4 for a 0.31 kW panel [44]. These panels have been used in a wide range of projects worldwide and are capable of delivering large amounts of power with 310 W under STC.

4.1.3.3 Aeolos-H 10 kW Wind Turbine

An Aeolos-H 10 kW wind turbine was modelled for the microgrid with its specifications listed in Table 4.5. The wind turbine costs $19,770 for a 10 kW turbine [45]. These horizontal axis wind turbines have a low RPM generator allowing electricity to be produced at wind speeds as low as 3.5 m/s. The wind turbine has yaw control with a DC output of 110-380V.

4.1.4 Energy Storage

4.1.4.1 Trojan L16P-AC Lead Acid Batteries

The batteries selected for the microgrid were the Trojan L16P-AC lead acid batteries with their specifications listed in Table 4.6. The batteries cost $280 per battery [46]. Batteries
help to reduce the wasted energy and stabilize the voltage. Adding batteries into the microgrid will allow renewable energy sources to be oversized, allowing them to be charged when renewable energy is abundant and discharged when renewable energy generation decreases. Oversizing batteries also helps to increase their lifetime because the depth of discharge (DOD) is significantly reduced. The Trojan L16P-AC Lead Acid Batteries are designed for use with renewable energy hybrid systems. The minimum lifetime of the batteries is 4 years but the actual lifetime is modelled in HOMER and depends on many factors such as the depth of discharge and number of cycles. Lead acid batteries are the most widely used type of batteries for energy storage in microgrids due to their availability in many sizes, low cost and well determined performance characteristics [29].

### 4.1.5 Power Converter

#### 4.1.5.1 Delta H7U Photovoltaic Multimode Inverter

A Delta H7U photovoltaic multimode inverter was modelled for the microgrid with its specifications listed in Table 4.7. The converter costs $1,500 for a 7 kW module [47]. The inverter has 4 built in MPPT trackers to help extract maximum power from the PV arrays under different shading conditions. Conventional converters are configured with one MPPT
setting for all of the panels but with the H7U inverter arrays in different locations can be configured separately as shown in Figure 4.6 in order to extract maximum power from all the modules under different shading conditions.

Table 4.6: Battery specifications

<table>
<thead>
<tr>
<th>Trojan L16P-AC Lead Acid Batteries Specifications [46]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
</tr>
<tr>
<td>Nominal Capacity (Ah)</td>
</tr>
<tr>
<td>Voltage (V)</td>
</tr>
<tr>
<td>Batteries per string</td>
</tr>
<tr>
<td>Minimum SOC (%)</td>
</tr>
<tr>
<td>Minimum lifetime (Years)</td>
</tr>
<tr>
<td>Price ($)</td>
</tr>
</tbody>
</table>

Table 4.7: Converter specifications

<table>
<thead>
<tr>
<th>Delta H7U Photovoltaic Multimode Inverter Specifications [47]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
</tr>
<tr>
<td>Max Capacity (kW)</td>
</tr>
<tr>
<td>Voltage Range (V)</td>
</tr>
<tr>
<td>Efficiency (%)</td>
</tr>
<tr>
<td>lifetime (Years)</td>
</tr>
<tr>
<td>Price ($)</td>
</tr>
</tbody>
</table>

Figure 4.6: Separate MPPT settings for each area

4.2 Financial Analysis

A financial analysis was conducted using HOMER, which uses the enumeration and comparison method in order to optimize the capacities of components [37]. The most cost effective solution that was able to satisfy the load requirements was calculated for the three following scenarios:

- An alternating current microgrid with diesel only generation.
- An alternating current microgrid with renewable energy generation, batteries and a converter.
• A direct current microgrid with renewable energy generation and batteries.

The microgrids were ranked by net present cost (NPC) and the system with the lowest levelized cost of electricity (LCOE) was chosen. Table 4.8 lists the sizing of the components for the most cost effective microgrid for each scenario from 42,600 simulations with the one-line diagrams shown in Figure 4.7. A hybrid microgrid combines two or more sources of renewable energy generation [48]. Note that both hybrid microgrids contain mostly solar generation. This is because the wind resource in Caye Chapel is relatively low and the solar resource is strong. Also, the price of solar panels are very cheap compared to the same amount of power from wind turbines ($9,840 vs $19,770) per 10 kW of generation. Despite this, the developers plan to install two 10 kW wind turbines to gather knowledge on wind generation. These turbines may help to provide energy at night when the solar panels are redundant and add to the energy diversity of the system.

When determining total NPC’s the capital, replacement, operations & maintenance (O&M), fuel and salvage costs were calculated. The capital costs are the initial investment required to purchase the equipment. The replacement costs are the expenses on new equipment to replace the retired equipment during the lifetime of the project. The O&M costs are the costs to operate and maintain the equipment and the salvage costs refer to the value of the equipment at the end of the project [49].

Table 4.8: Microgrid optimized sizing

<table>
<thead>
<tr>
<th>Component</th>
<th>AC Diesel Microgrid</th>
<th>AC Hybrid Microgrid</th>
<th>DC Hybrid Microgrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Generator (kW)</td>
<td>4,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV Array (kW)</td>
<td></td>
<td>37,050</td>
<td></td>
</tr>
<tr>
<td>Wind (kW)</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Batteries (Units)</td>
<td></td>
<td>31,780</td>
<td></td>
</tr>
<tr>
<td>Converter (kW)</td>
<td></td>
<td>3,955</td>
<td></td>
</tr>
<tr>
<td>PV Array (kW)</td>
<td></td>
<td>29,400</td>
<td></td>
</tr>
<tr>
<td>Wind (kW)</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Batteries (Units)</td>
<td></td>
<td>32,180</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.7: Microgrid options

4.2.1 AC Diesel Only Microgrid

Table 4.9: AC Diesel only microgrid net present costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O&amp;M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
<th>Total ($)</th>
<th>LCOE ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Engine</td>
<td>540,000</td>
<td>3,873,500</td>
<td>22,396</td>
<td>107,634,344</td>
<td>-50,328</td>
<td>112,019,928</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>540,000</td>
<td>3,873,500</td>
<td>22,396</td>
<td>107,634,344</td>
<td>-50,328</td>
<td>112,019,928</td>
<td>0.637</td>
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</tbody>
</table>
The current microgrid in Caye Chapel uses diesel generators in order to provide electricity to the island. The price of diesel in Belize is relatively expensive at $1.27 per liter as of 20\textsuperscript{th} November 2017 [50]. Therefore, although the diesel generators are relatively inexpensive the total costs are increased substantially due to diesel fuel usage. A summary of the net present costs for the microgrid are summarized in Table 4.9 with a graph of the results in Figure 4.8. The initial investment for the diesel generators is low at $540,000 but because of the high price of diesel fuel the greatest expenditure throughout the lifetime of the project is on diesel fuel at $107,634,344. The levelized cost of electricity for the system is high at $0.637/kWh.

![Cash Flow Summary](image)

Figure 4.8: AC Diesel microgrid cash flow summary

The diesel only microgrid has a high total NPC but also because the system is AC there will be additional losses in the loads for electronic devices which work with DC. Diesel engines are also an emitter of pollutants into the atmosphere. A summary of the emissions over the lifetime of the project are shown in Table 4.10.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>17,458,512</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>43,094</td>
</tr>
<tr>
<td>Unburned Hydrocarbons</td>
<td>4,773</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>3,249</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>35,060</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>384,530</td>
</tr>
</tbody>
</table>

### 4.2.2 AC Hybrid Microgrid

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O&amp;M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
<th>Total ($)</th>
<th>LCOE ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>36,492,256</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>36,492,256</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>39,540</td>
<td>0</td>
<td>12,783</td>
<td>0</td>
<td>-1,535</td>
<td>50,788</td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>8,898,400</td>
<td>16,022,441</td>
<td>8,125,107</td>
<td>0</td>
<td>-1,718,872</td>
<td>31,327,074</td>
<td></td>
</tr>
<tr>
<td>Converter</td>
<td>847,500</td>
<td>353,632</td>
<td>722,260</td>
<td>0</td>
<td>-65,822</td>
<td>1,857,570</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>46,277,696</td>
<td>16,376,073</td>
<td>8,860,149</td>
<td>0</td>
<td>-1,786,229</td>
<td>69,727,688</td>
<td>0.397</td>
</tr>
</tbody>
</table>

Table 4.11: AC Hybrid microgrid net present costs
Due to the high cost of diesel fuel an economic analysis was made with HOMER to find the most economical AC hybrid system that could meet the load requirements without using any diesel generation. The analysis shown that due to the low wind resource and the fact that solar panels have significantly dropped in price the most economical AC hybrid microgrid is a system containing mostly photovoltaic generation with batteries and a converter. The optimized system architecture is shown in Table 4.8. A summary of the net present costs are shown in Table 4.11 with a graph of the NPC shown in Figure 4.9. The initial investment for the AC hybrid microgrid is high at $46,277,696 but because the system is composed of mainly PV generation which have a long lifetime of 25 years the total replacement costs are relatively low as compared to the capital costs which mostly consist of the battery replacement charges. Also, because the system is composed of renewable energy generation there are no fuel costs and the total NPC of the microgrid is $69,727,688. The LCOE for the microgrid is $0.397/kWh.

Table 4.12 shows a summary of the losses within the converter. The converter is responsible for losses of 1,527,266 kWh/year. These losses result in more investment being required in solar panels to meet the load requirements which increases the NPC of the microgrid. The AC hybrid microgrid has zero emissions because it consists of renewable energy generation.

<table>
<thead>
<tr>
<th>Converter losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (kW)</td>
</tr>
<tr>
<td>Capacity Factor (%)</td>
</tr>
<tr>
<td>Energy in (kWh/year)</td>
</tr>
<tr>
<td>Energy out (kWh/year)</td>
</tr>
<tr>
<td>Losses (kWh/year)</td>
</tr>
</tbody>
</table>
4.2.3 DC Hybrid Microgrid

Table 4.13: DC Hybrid microgrid net present costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O&amp;M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
<th>Total ($)</th>
<th>LCOE ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>28,957,420</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>28,957,420</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>39,540</td>
<td>0</td>
<td>12,783</td>
<td>0</td>
<td>-1,535</td>
<td>50,788</td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>9,010,400</td>
<td>13,133,608</td>
<td>8,227,372</td>
<td>0</td>
<td>-461,521</td>
<td>29,909,858</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>38,007,360</td>
<td>13,133,608</td>
<td>8,240,156</td>
<td>0</td>
<td>-463,057</td>
<td>58,918,068</td>
<td>0.335</td>
</tr>
</tbody>
</table>

The optimized system architecture for the DC microgrid is shown in Table 4.8. Because the DC microgrid does not require a converter there are less losses which enables the load requirements to be met with 7,650 kW less PV generation. A summary of the net present costs for the DC microgrid are summarized in Table 4.13 with a bar chart of the results in Figure 4.10. The capital investment is lower than that of the AC hybrid microgrid because a decreased investment is required in solar panels and converters. The replacement and O&M costs are also reduced because the sizing of the system is smaller. The total NPC of the system is only $58,918,068 with an LCOE of $0.335/kWh.

Figure 4.10: DC Hybrid microgrid cash flow summary

4.2.4 Financial Summary

Table 4.14: Summary of microgrid net present costs

<table>
<thead>
<tr>
<th>Microgrid</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O&amp;M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
<th>Total ($)</th>
<th>LCOE ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Diesel</td>
<td>540,000</td>
<td>3,873,500</td>
<td>22,396</td>
<td>107,634,344</td>
<td>-50,328</td>
<td>112,019,928</td>
<td>0.637</td>
</tr>
<tr>
<td>AC Hybrid</td>
<td>46,277,696</td>
<td>16,376,073</td>
<td>8,860,149</td>
<td>0</td>
<td>-1,786,229</td>
<td>69,727,688</td>
<td>0.397</td>
</tr>
<tr>
<td>DC Hybrid</td>
<td>38,007,360</td>
<td>13,133,608</td>
<td>8,240,156</td>
<td>0</td>
<td>-463,057</td>
<td>58,918,068</td>
<td>0.335</td>
</tr>
</tbody>
</table>

A financial analysis was conducted using HOMER to find the most economical microgrid in terms of NPC. HOMER models the system components, energy resources and loads on an hourly basis [41]. The financial results for each microgrid are listed in Table 4.14. The AC diesel microgrid has the lowest initial capital costs but because of the high price of diesel fuel the systems overall NPC are the highest at $112,019,928 resulting in an LCOE of
$0.637/\text{kWh}$. The AC hybrid microgrid is an improvement from the diesel only system but has the highest initial capital costs because more renewable generation and converters are needed to be purchased. The AC hybrid microgrid results in an overall NPC of $69,727,688$ and a LCOE of $0.397/\text{kWh}$. The DC hybrid microgrid has the lowest overall NPC. This is because the efficiency of the microgrid is increased due to there being no conversion losses. This means that the load requirements can be met with less PV generation decreasing the capital costs. The decreased sizing of the microgrid in turn reduces the replacement and O&M costs. The DC hybrid microgrid has a total cost of $58,918,068 resulting in a LCOE of $0.335/\text{kWh}$. The DC hybrid microgrid is $10,809,620$ cheaper than the AC hybrid microgrid. Furthermore, the DC hybrid microgrid was shown to be more cost effective by only modelling the inverter losses on the generation side. In reality, DC circuits have been shown to provide energy savings in solar PV microgrids with battery storage by 14-25% [13] therefore the DC system would have a reduced load profile providing extra cost savings on generation. The use of renewable energy generation results in zero emissions being released into the atmosphere. If carbon credits where to be issued in the future at $20$ per ton of greenhouse gases (GHG) [51] this microgrid could earn $349,160$/year as a result of avoiding 17,458 tons/year of GHG’s. Over the project lifetime of 25 years this would bring in $8,729,000$.

### 4.3 Technical Analysis

The financial analysis shown that a DC microgrid with the sizing in Table 4.8 is the most cost effective solution to meet the load requirements for the island of Caye Chapel. A technical analysis will be conducted of the DC microgrid design. A long term analysis will be conducted over a period of one year to monitor the power generation and energy balance. A medium term analysis will be conducted over a period of 24 hours to analyze the voltage stability and energy storage usage. Finally, a short term analysis will be conducted over a period of a couple of seconds to analyse the DC microgrids transient behavior [25].

#### 4.3.1 Long Term Analysis

The long term analysis will look at the electricity production and consumption throughout a year. Table 4.15 summarizes the energy flows in the microgrid throughout a year. The microgrid produces a lot of excess electricity which is not being utilized. This is because the microgrid is based on 100% renewable energy and an excess amount of energy is needed throughout the year in order to meet the load on days when the solar radiation is low. If the system was sized to have zero wasted energy throughout the year the load would not be met in a period when the renewable energy generation is low. This is because the microgrid needs to be sized to meet the load in a period with low generation therefore the difference between the worst day and best day of renewable energy production results in wasted energy. This can be reduced by adding more batteries to the system but because of the cheaper price of solar panels compared to that of batteries the most economical design is to have more generation and less storage increasing the wasted energy but creating a microgrid with the lowest costs. The extra generation does not increase the LCOE because the marginal cost of renewable energy generation is zero. However, the excess generation could negatively effect the microgrid by overcharging the batteries. This can be prevented by installing a dump load. The charge controller can request that excess energy is sent to the dump load in order
to protect the batteries. If diesel generators were added to the microgrid to meet the peak load the excess electricity production would be decreased but the LCOE would increase.

Table 4.15: Electricity production and consumption in a year

<table>
<thead>
<tr>
<th>Microgrid Production</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array (kWh/yr)</td>
<td>42,040,128</td>
</tr>
<tr>
<td>Wind turbines (kWh/yr)</td>
<td>2,440</td>
</tr>
<tr>
<td>Total Production (kWh/yr)</td>
<td>42,042,568</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Microgrid Consumption</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Consumption (kWh/yr)</td>
<td>13,745,701</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Microgrid Excess</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess Electricity (kWh/yr)</td>
<td>28,296,867</td>
</tr>
<tr>
<td>Excess Electricity (%)</td>
<td>67.3</td>
</tr>
</tbody>
</table>

The DC hybrid microgrid makes use of batteries in order to meet the load requirements when there is no solar energy present. In order to preserve the lifetime of the batteries the state of charge (SOC) of the batteries is kept above 30%. Figure 4.11 shows the battery SOC throughout the project lifetime of 25 years and you can see that the depth of discharge (DOD) is controlled to increase the lifetime of the batteries. The usable nominal capacity of the batteries is 48.6 MWh. This enables the microgrid to run autonomously without any generation for 31 hours as shown in Table 4.16. This autonomy period is based on the average load therefore during periods of high demand the length of autonomy would decrease but at times of low energy consumption this number would increase. The battery has a max charge rate of 18 A. Therefore, if the battery bus is at 120 V the load power can be easily met with a maximum power output of 50 MW.

Figure 4.11: State of charge of the batteries

<table>
<thead>
<tr>
<th>Battery autonomy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery capacity (kWh)</td>
<td>48,600</td>
</tr>
<tr>
<td>Average Load (kW)</td>
<td>1,570</td>
</tr>
<tr>
<td>Autonomy (h)</td>
<td>31</td>
</tr>
<tr>
<td>Yearly throughput (MWh)</td>
<td>13,745</td>
</tr>
</tbody>
</table>
4.3.2 Medium Term Analysis

Two simulations will be presented in the medium term analysis of 24 hours. The first case will be on a sunny day when renewable energy is abundant and the second case will be on a cloudy day when there is not much generation. Figure 4.12 shows the amount of energy produced for each month. As you can see the month with the highest generation is in March and the month with the lowest generation is in December therefore these two cases will be analyzed.

![Figure 4.12: Monthly energy production of the DC microgrid](image)

The DC microgrid was constructed in Simulink as shown in Figure 4.13. The DC microgrid consists of solar generation, wind generation, a commercial load and a residential load. The power flow is controlled by a charge controller which controls the flow of power between the microgrid and the battery by activating the bidirectional converter. A scope was set up in order to view the response of the microgrid as shown in Figure 4.14. The scopes were setup in order to view the flow of power in the microgrid and monitor relevant parameters. The power from the renewable energy sources was received from HOMER and entered into Simulink via lookup tables. The Simulink data then drives a current controlled source to turn the values into current for use within Simulink. The load data was also entered into Simulink via lookup tables.

![Figure 4.13: The DC Microgrid in Simulink](image)

Figure 4.15 shows the simulated results for the month of March. Figure 4.15(a) shows that the power generated by the microgrid far exceeds the load requirements throughout the day except at the start and end of the day when there is no solar generation. Figure 4.15(b) shows that the voltage is held stable throughout the day. The bidirectional converter is delivering power to the battery indicated by positive power increasing the SOC of the battery.
CHAPTER 4. RESULTS

Figure 4.14: Scope setup in Simulink

and keeping the voltage stable in the microgrid even though there is excess generation that would increase the DC bus voltage if the battery was not included.

Figure 4.15: Power flow in March

Figure 4.16 shows the simulated results for the month of December. Figure 4.16(a) shows that the power required by the load is greater than the power generated by the microgrid throughout most of the day except between 10 AM and 2 PM where the solar generation
is at its peak and meets the load requirements. Figure 4.16(b) shows that the voltage is held stable throughout the day. The bidirectional converter is delivering power to the microgrid indicated by negative power reducing the SOC of the battery and keeping the voltage stable in the microgrid even though there is not enough energy generation.

![Power Flow in December](image)

Figure 4.16: Power flow in December

**4.3.3 Short Term Analysis**

The short term analysis will see how the DC microgrid reacts to sudden changes in power generation. The device controlling the microgrids response is the charge controller which is based on a PI controller as shown in Figure 4.17. The charge controller was designed and simulated in Simulink and works by comparing the DC bus voltage to a reference value. The DC bus reference voltage in this microgrid was set to 350V. The difference between the DC bus voltage and the reference value is taken and the error signal is fed into a PI controller. The PI controller calculates the change needed to reduce the error and the output DC bus voltage is again fed back into the controller. If the DC bus voltage needs to be increased the boost control is activated and if the DC bus voltage needs to be decreased the buck control is activated.

![Charge controller topology based on a PI controller](image)

Figure 4.17: Charge controller topology based on a PI controller
The short term analysis was conducted in a 1.5 s period and the output is shown in Figure 4.18. The curves show that initially when the microgrid is generating enough power to stabilize the voltage and meet the load demands there is no power transfer between the batteries and microgrid and the bidirectional current is 0. Then the microgrid power is reduced so that the microgrid demands power. The controller responds by sending power from the batteries to the microgrid indicated by negative power on the bidirectional converter. The controller does this by activating the boost control on the bidirectional converter. Then the power is increased so that the microgrid produces excess energy. The charge controller responds by activating the buck control and sending the excess power to the batteries indicated by positive power on the bidirectional converter. Throughout the transitions in microgrid power generation the voltage has been kept stable because of the response of the charge controller.

![Figure 4.18: Short term analysis](image)

### 4.3.4 Equipment Installation

#### 4.3.4.1 PV Installations

The solar capacity needed for the island is ambitious at 29.4 MW. However, the technical feasibility of such an installation is achievable and many projects worldwide have huge solar capacities with a 1,547 MW installation in China and a 1,000 MW installation in India. Table 4.17 summarizes the area needed for the installation. To install the solar capacity 15.7% of the island would need to be covered with solar panels. The developers are also considering buying a large area on the bigger island of Caye Cauker nearby and creating a solar farm and bringing that power to Caye Chapel. Figure 4.19 shows the sun position throughout a typical day. As you can see the sun is positioned to the south therefore PV panels should be placed on all the dwellings and buildings south facing to increase exposure.

![Figure 4.19: Sun position](image)

#### 4.3.4.2 Battery Installations

Table 4.18 summarizes the number of containers needed to store the required amount of batteries. A total of 10 containers would be needed to house the required batteries.
4.3. TECHNICAL ANALYSIS

Table 4.17: PV installation information

<table>
<thead>
<tr>
<th>Solar Panel Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV capacity (kW)</td>
</tr>
<tr>
<td>PV Area (m²)</td>
</tr>
<tr>
<td>Island Area (m²)</td>
</tr>
<tr>
<td>Island cover (%)</td>
</tr>
</tbody>
</table>

Figure 4.19: Caye Chapel sun position

Though, lead acid batteries are a cost effective way of providing storage their lower energy density requires that more containers are needed leading to space restrictions. The space requirements of the microgrid could be reduced by using lithium-ion batteries but the LCOE would increase and the issue of battery disposal would still be a problem. Lithium-ion batteries have an energy density 3 times greater than lead-acid batteries but are 5 times more expensive [52]. A proposal for a next project was to investigate the use of hydrogen storage. Excess PV power could be supplied to an electrolyzer to generate hydrogen which could be delivered to hydrogen storage tanks through a compressor [48]. The hydrogen could then be converted to electricity via a hydrogen fuel cell.

Table 4.18: Battery installation information

<table>
<thead>
<tr>
<th>Battery Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries</td>
</tr>
<tr>
<td>Battery Volume (m³)</td>
</tr>
<tr>
<td>Container Volume (m³)</td>
</tr>
<tr>
<td>Containers</td>
</tr>
</tbody>
</table>
Chapter 5

Discussion

5.1 Summary

5.1.1 Component Modelling

Simulink models were developed for the essential components of a microgrid. Power electronic converters were designed which would be used in conjunction with the solar panels. A buck, boost and buck-boost converter were designed. Then the bidirectional converter was designed and simulated which is needed to work in conjunction with a battery in order for it to charge and discharge. The modelling of PV modules was then presented and a maximum power point tracker based on the perturb and observe algorithm was coded in MATLAB. In order for maximum power to be extracted from a PV module it was connected up to a boost converter and MPPT tracker. The modelling of wind turbines was also presented. The microgrid would need energy storage to smooth out the fluctuations of renewable energy generation and provide voltage stability. The modelling of lead-acid batteries was presented and a demonstration simulation was shown in Simulink. An algorithm for a charge controller was presented which would be used in order to protect the batteries. The charge controller was designed to operate the bidirectional converter in order to control the flow of power between the batteries and microgrid. The control was based on a PI controller in order to smoothly bring the voltage to the desired set point and keep it there with minimum steady state error.

5.1.2 Financial Analysis

A financial analysis was conducted using HOMER energy software in order to quantify the financial benefits of using a DC microgrid over an AC hybrid microgrid and an AC diesel only microgrid which is currently installed on the island. The AC diesel only microgrid resulted in the highest LCOE of $0.637/kWh. This was because of the high price of diesel fuel in Caye Chapel. Also, the AC diesel only microgrid was a big emitter of greenhouse gasses. The AC hybrid microgrid had the highest initial capital costs because more generating equipment was needed to be purchased to meet the load requirements because of losses in the converters. The extra equipment resulted in increased replacement and O&M costs. The AC hybrid microgrid resulted in an LCOE of $0.397/kWh. Finally, the DC hybrid microgrid was able to meet the load requirements with 7,650kW less of solar generation due to the absence of losses in converters. This reduced the initial capital costs, replacement and O&M costs resulting in an LCOE of $0.335/kWh.
5.1.3 Technical Analysis

A long term, medium term and short term technical analysis was conducted in order to verify the technical viability of the DC microgrid design. Finally, the physical size of the system was considered for installation. The long term analysis analyzed the energy flows in the microgrid and it was noted that the majority of the energy generation in the microgrid was from the solar resource. This was found to be the case not only because the solar resource was much stronger than the wind resource but also because the price of solar panels were much cheaper than wind turbines for the same generation capacity. The amount of excess generation in the microgrid was large at 67.3%. This is because when designing an 100% renewable microgrid it has to be sized to meet the load on a day when renewable generation is the lowest and therefore when generation increases this results in excess electricity. The best technical solution would be to have a hybrid system with diesel generators where the renewable generation is sized to meet the base load and the diesel generators meet the peak loads.

The medium term analysis was conducted over a period of a day and two scenarios were presented. One case on a sunny day and the other on a cloudy day. The analysis shown that in both simulations the charge controller properly activated the bidirectional converter in order to send power to the microgrid when the renewable energy generation was insufficient in order to meet the load and to the batteries when the renewable energy generation was in excess of the load demand. In both occasions the DC microgrid bus voltage was held stable. The short term analysis was conducted over an interval of 1.5 seconds in order to see the functionality of the charge controller. The controller was seen to activate the boost control when energy was needed to be sent to the microgrid and activate the buck control when power was needed to be sent to the battery. The amount of PV capacity needed for the island was aggressive at 29.4 MW which would result in 15.7% of the island being covered in solar panels. The size of the battery required for a 100% renewable energy microgrid was a concern for the developers. Future projects will evaluate the possibility of buying space on a nearby island to create a solar park and send the power to Caye Chapel. The possibility of using hydrogen storage was proposed to be investigated.

5.2 Conclusion

The following conclusions can be made from this thesis:

- Power electronic converters can be used in conjunction with solar modules and maximum power point trackers to increase the extracted energy from the solar resource by achieving impedance matching between the source and load.

- A bidirectional converter can be used in between a microgrid and battery in order for power transfer to occur between the microgrid and battery. A PI controller can adequately control the operation of the bidirectional converter in order to achieve a stable DC bus voltage with a low steady-state error.

- A lead-acid battery can be modeled in Simulink using the Shephred Model. Lead-acid batteries have a lower energy density than lithium-ion batteries but due to their low price they are frequently used in microgrids. However, due to their lower energy density they take up more space.
• The developers plan to build two 10 kW wind turbines to develop the wind resource. The analysis of the wind resource in HOMER suggests that further investment should not be made on wind turbines. The technical analysis shown that more energy can be extracted from solar panels in conjunction with batteries at a cheaper price.

• A DC hybrid microgrid provides overall cost savings as compared to an AC diesel only microgrid because the high price of diesel fuel increases the LCOE of a diesel only system.

• A DC hybrid microgrid requires a lower initial capital investment as compared to an AC hybrid microgrid due to the absence of losses in the inverters. This enables the DC microgrid to meet the load requirements with less generation which also reduces the replacement and O&M costs.

• Designing a microgrid based on 100% renewable energy can create a large system in order to meet the load on days when renewable energy generation is low. This creates an excess amount of energy generation throughout the year. A trade-off could be to design the system so that the renewable component meets the base load and diesel generators are activated in order to meet the peak load. A larger battery could be used but this would increase the LCOE of the system.

• Space restrictions and disposal issues can occur when using batteries for storage in a microgrid. If renewable energy generation is low in the region of weeks the size of the battery required for autonomy would be significantly large.
Bibliography


## Appendix A

### Tables

Table A.1: Photovoltaic cell parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$</td>
<td>Energy band gap</td>
<td>$1.3 , eV$</td>
</tr>
<tr>
<td>$G$</td>
<td>Sun irradiance</td>
<td>$W/m^2$</td>
</tr>
<tr>
<td>$I$</td>
<td>Output current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_{D1}$</td>
<td>Diode 1 current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_{D2}$</td>
<td>Diode 2 current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>Photon current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_{rs}$</td>
<td>Reverse saturation current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_s$</td>
<td>Saturation current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>Short circuit current</td>
<td>$A$</td>
</tr>
<tr>
<td>$I_{sh}$</td>
<td>Shunt current</td>
<td>$A$</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann constant</td>
<td>$1.38 \times 10^{23} , J/K$</td>
</tr>
<tr>
<td>$K_i$</td>
<td>Current temperature coefficient</td>
<td>$A/°C$</td>
</tr>
<tr>
<td>$n_1$</td>
<td>Diode 1 ideality factor</td>
<td>1</td>
</tr>
<tr>
<td>$n_2$</td>
<td>Diode 2 ideality factor</td>
<td>1</td>
</tr>
<tr>
<td>$N_p$</td>
<td>Number of paralleled connected cells</td>
<td>$N$</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Number of series connected cells</td>
<td>$N$</td>
</tr>
<tr>
<td>$q$</td>
<td>Electron charge</td>
<td>$1.6 \times 10^{-19} , C$</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Series resistance</td>
<td>$Ω$</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>Shunt resistance</td>
<td>$Ω$</td>
</tr>
<tr>
<td>$T$</td>
<td>Cell temperature</td>
<td>$°C$</td>
</tr>
<tr>
<td>$T_{ref}$</td>
<td>Cell reference temperature</td>
<td>$°C$</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>Open circuit voltage</td>
<td>$V$</td>
</tr>
</tbody>
</table>
Appendix B

Code

Perturb and Observe Algorithm

```matlab
function D = PandO(V, I)

% Perturb and Observe algorithm

persistent Dprev Pprev Vprev % record values for next recall

if isempty(Dprev)
    Dprev = 0.7;
    Vprev = 360.8;
    Pprev = 97.6e3;
end

% Delta duty cycle
deltaD = 0.001;

% Calculate the power
P = V*I;

% P&O logic to increase or decrease duty cycle
if(P−Pprev) ~= 0
    if(P−Pprev) > 0
        if(V−Vprev)
            D = Dprev−deltaD;
        else
            D = Dprev+deltaD;
        end
    else
        if(V−Vprev) > 0
```

```
\[ D = D_{prev} + \delta D; \]

\[ \text{else} \]

\[ D = D_{prev} - \delta D; \]

\[ \text{end} \]

\[ \text{end} \]

\[ \text{else} \]

\[ D = D_{prev}; \]

\[ \text{end} \]

\[ \% \text{ Make current } n = \text{The next } (n - 1) \]

\[ D_{prev} = D; \]

\[ V_{prev} = V; \]

\[ P_{prev} = P; \]