Design and Modeling of Centralized Distribution Network for the DC House
Project

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ABSTRACT

Design and Modeling of Centralized Distribution Network for the DC House Project

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This thesis focuses on the design, modeling, simulation, and performance evaluation of Centralized Distribution Network for the DC House Project. Power System Computer Aided Design (PSCAD) is used to model a Centralized PV Source, Battery Bank, and Distribution Network for 25 DC Houses. Design and modeling of each component in the proposed system are described. For the performance evaluation, emphasis is on voltage stability and system reliability under different operating conditions. Results from the simulation demonstrate the feasibility of the proposed Centralized Distribution Network for the DC House Project to support the houses during non-generation periods and distribution network voltage stability under different operating conditions. Cost analysis also shows the feasibility of the proposed system as compared to commonly used AC distribution network.

Keywords: DC House, Centralized Distribution Network, Solar Power, Boost Converter, Buck Converter, Maximum Power Point Tracking, Battery Bank, Voltage Stability, AC distribution network.

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CHAPTER 1

Introduction

More than 80% of world's energy supply comes from fossil fuel sources like petroleum, coal, and natural gas. Fossil fuels are nonrenewable energy sources since they take millions of years to form. When used, fossil fuels release carbon into the atmosphere which contributes to the greenhouse gases. Global CO₂ emissions are rising every year due to the increasing demand of energy consumption as shown in Figure 1-1 [1]. Figure 1-2 shows the CO₂ emissions by sectors of the energy consumption [1].

Figure 1-1: CO₂ emission by fuel [1]

The first study on CO₂ as greenhouse gas was published by Swedish scientist Svante Arrhenius in 1896. Before the large-scale use of fossil fuels, which was approximately 100 years ago, the atmosphere contained an average 275 ppm CO₂. Today

the estimate is 380 ppm CO₂ in the atmosphere which is a direct result of the combustion of fossil fuels. After 100 years of burning fossil fuels, the earth's average surface temperature has risen from 57°F to 58.3°F [2]. This is a small change in temperature, but potentially a large difference in climate which has led to glaciers melting and sea levels rising. If we continue to use fossil fuels until they run dry, the CO₂ concentration is expected to increase to about 550 ppm. The Intergovernmental Panel on Climate Change (IPCC) suggests that the average surface temperature will likely rise another 2.0 to 11.5 °F [2].

Figure 1-2: World CO₂ emission by sector in 2010 [1]

Global warming issue has made renewable sources of energy more attractive. Renewable energy is derived from natural processes (e.g. sunlight and wind) that are replenished at faster rate than they are consumed. Solar, wind, geothermal, hydro and some forms of biomass are common sources of renewable energy. Solar and wind have grown the most popular over the past decade. Global wind power capacity was 238

(GW) at the end of 2011, up from just 18 GW at the end of 2000. The advancements in electronics and renewable energy have enabled us to produce energy out of resources which was impossible 50 years ago. Renewable energy provides secure reliable power with economic productivity and with little to no environmental impact.

Solar photovoltaic (PV) directly converts solar energy into electricity using PV cell which is a semiconductor device. Figure 1-3 shows that the PV installation around the world has increased exponentially in the last decade. This exponential increase in PV installation is due to multiple variables that play a big role in the PV market. PV cell efficiency has increased, and simultaneously prices have been going down due to more manufacturer competition and government subsidies [3]. These advancements in the PV technology and reduction in the prices have made the exponential growth possible.

Figure 1-3: Cumulative installation of worldwide PV by the end of 2011 [3]

Renewable sources of energy also give us the chance to provide energy to rural areas mainly in under-developed countries which are not likely to be connected to electric grid. Still today there are about 1.3 billion people around the world who do not have access to electricity. About 587 million of this population lives in Africa, approximately 675 million in Asia, and 55 million in Eastern Europe/Eurasia [4]. Generally this population lives in rural areas which are farther away from the urban electric grid, thus connecting them to an electric grid is not economically viable. The capital required to build high voltage transmission system for longer distances is very expensive. According to Edison Electric Institute (EEI), from 2004-2008, United States invested \$4.6M/GW/year, New Zealand invested \$ 22.M/GW/year, and the Netherlands invested \$12.0M/GW/year in high voltage transmission [4]. The cost for lower than 230kV will be more for longer distance due to higher resistive losses (I^2R) in the grid. This is because as the transmission voltage is lowered, the resulting current increases proportionally and the losses in the system increase accordingly.

People who live in rural villages in underdeveloped countries are mostly poor and are deprived of most basics of human rights, and of economic opportunities to improve their standard of living without access to electricity. Undoubtedly rural electrification programs face major obstacles. Utility companies need to have high initial capital along with high operation costs because of the low population densities in rural areas. Therefore, it does not create a business advantage to invest on an expensive grid infrastructure to provide electricity to these people especially since their consumption will be very low (mostly for lighting). Moreover, building infrastructure for these areas

may often create conflicts with the local communities, and farmers due to rights of way for the construction and maintenance of electricity lines.

Renewable energy is an abundant source of energy which could be used to provide electricity for those unfortunate people in rural areas with no access to electricity. The good news is that many of these rural areas happen to be in locations where renewable energy sources are abundant. For example, majority of this poor population live within plus or minus 30 degrees of latitude around the world.

1.1 DC House Project

Local electrical network for the unfortunates seems to be a feasible option available through renewable sources of energy. The DC house project initiated at Cal Poly is an extension to that idea along with its futuristic benefits. DC house is a project for the unfortunates. It aims to deliver the most basic electric needs of the modern world to those in need by utilizing renewable energy sources. The DC house, as the name implies, operates fully on Direct Current.

Over the century scientific and economic developments have led to expansion of the electric grid around the world. But as mentioned earlier, still today, after 150 years of early inventions of electricity, there are approximately 1.3 billion people around the world who do not have access to electricity. Financial disadvantages and remote locations of these populations are the two main reasons for their governments not to have the incentive to connect them to their nations' grids. The DC house project aims to address

these problems and is divided into three phases. Phase 1, which was completed in June 2011, focused on the single DC house development as the basic unit. It included designs of generator sources such as: Hydro-power generator, a photovoltaic power generator, a human-powered generator and a wind-powered generator. Phase 1 also included the designs for multiple-input DC-DC converter, system level design of DC house (DC level and loads.)

Phase 2 of the project was concluded in June 2012. This phase looked at the optimization, protection, and implementation of single DC house. Several important milestones were completed during this phase such as a temporary DC house model at Cal Poly, DC Lightbulb, publications and presentations of DC house.

Now the project is in Phase 3, which will conclude in June 2013. Phase 3 of the project is focusing on a centralized DC System, where centralized PV panels are used to distribute power to a larger village rather than strictly to an individual house.

1.2 Thesis Objective

This thesis falls under the third phase of the DC House project which focuses on the design, modeling, simulation, and performance evaluation of the centralized distribution network for the DC House. Power System Computer Aided Design (PSCAD) is used to simulate the network. This network would include standalone solar PV source working with Maximum Power Point Tracker (MPPT) to maximize the power production under different weather conditions. The feasibility, operation, and performance of the

DC distribution system are the main goals of the study. Additionally as part of the study, the implementation of the PV sources with MPPT will consider various conditions that will affect the power generation and voltage stability in the local DC grid. Load flow analysis for as many as 25 houses of 500W and their different layouts will be modeled and analyzed. Backup batteries to provide stability to the grid and backup power during night and non-power generating conditions will also be studied and considered.

CHAPTER 2

Background

2.1: Motivation

The DC house project is a solution to challenges of rural electrification. It will provide self-sustaining DC power through various forms of renewable energy such as photovoltaic, hydropower, wind, and human-powered generation. The generated power is used to provide the most basic living necessities such as room lighting, electric stove for cooking, space heating, cooling and refrigeration. This renewable form of energy will replace liquid fuel, gas, biomass or animal waste, which currently help sustain the daily energy necessities of rural areas in poor nations. This chapter will discuss the commonly used AC distribution system and the advantages of choosing DC distribution for the DC house project.

2.2: AC Distribution

In the 1880s, Tesla and Edison went head to head with the “War of Currents” as it is called [18]. The biggest challenge was to set up an electrical-grid network that would send power over long distance with minimal losses. This required voltage step-up at the generation side and step-down on the distribution side. Westinghouse’s invention of the transformer made it possible for voltage to step-up and step-down in the alternating current, thus making it the stronger candidate out of the two. Tesla won his battle for

alternating current by proving it was the better choice at that time given all the electric equipment capabilities. This victory paved the way for the AC infrastructure to build over the past century.

2.2.1: AC Distribution Infrastructure

The grid “topology” used in an electrical energy distribution can vary according to practical constraints of budget, requirements for system reliability, and the load and generation characteristics. Figure 2-1 shows a typical power generation and distribution system used around the world [6]. The power generation sources include fossil fuels, nuclear, hydro, and renewables. Step-up transformers are used to step up the transmission grid voltage in hundreds of kilovolts in order to transmit power over long distances with minimum losses. The resistive power losses in electric transmission lines are directly related to the amount of current flowing through the conductor ($P_{\text{loss}} = I^2 R$). Once in the close proximity of the load, the voltage is stepped down and distributed at voltages required by the load (U.S domestic loads are supplied with 120Vac at 60 Hz). The infrastructure needed for this classic generation, transmission, and distribution requires high initial investment. Along with high initial costs, the AC system is also very complex and has many disadvantages in power distribution when compared to a DC system.

Figure 2-1: Transmission and Distribution Grid Structure within the Power Industry [6]

2.2.2: *Disadvantages of AC distribution*

One of the numerous disadvantages of an AC transmission line is its capacity to transmit power. The effective voltage of a conductor in an AC system is limited to 70.7% of the peak value. A similar conductor in DC transmission can transmit approximately 30% more power because the peak and RMS values in DC are same. Also, the current density of alternating electric current is non-uniform and more current flows near the surface of the conductor than the core, known as the “Skin Effect”. This condition decreases the amount of power that could be transmitted through a conductor because the

middle portion of the conductor is not being used. As shown in Figure 2-2, the current density for a DC conductor is uniform throughout, which is not true in AC conductor [6]. In an AC conductor, skin depth decreases as the frequency of current increases, thus current only flows mainly near the surface of the conductor [6].

Figure 2-2: Skin depth decreases with increasing frequency [6]

The Power Factor of the AC system is another variable that affects AC power transmission. The reactance of AC transmission lines lowers its Power Factor which leads to reactive power being drawn out of the generator, and subsequently less real power is delivered to the load. Another issue of an AC system is its frequency, which is required to be at 60 Hz for a stable system. An inaccurate frequency control does not allow efficient flow of power from multiple generators into the grid network. Another phenomenon in AC transmission is the Corona Discharge Effect in which electrical

breakdown is caused by ionization of surrounding air of conductors at voltage amounts greater than that of the critical breakdown voltage [7].

Many of the domestic loads such as home appliance, electronics, and entertainment systems require DC power for their operation. The incoming AC from the power outlet has to be converted to DC in order for these loads to work. This AC to DC power conversion introduces power losses into the system. Figure 2-3 shows the conversion stages which are required in an AC system for the DC loads [20]. Additionally, in case of renewable sources, which (generate DC power), the current AC system requires two conversion stages before power could be delivered to the load.

Figure 2-3: Conversion stages in an AC system [20]

A DC distribution system would eliminate the AC to DC conversion by more efficient DC-DC conversions. Another benefit of a DC system is that it is less costly since components are rated at lower voltages. Largely the DC distribution system is less complex, more efficient and consumes less space. However, AC system was preferred

over DC system for the past century because DC did not have the capability to step-up or step-down voltage without the power electronic technologies. The power electronic industry has since developed highly reliable and well-performing technologies capable of these tasks, and DC distribution is now considered as an optimal solution to improve distribution efficiency.

2.3: DC Distribution

The idea of incorporating one or multiple renewable energy sources to support the DC system is unique. DC system features lack of frequency stability, reactive power issues, skin effect, and conversion losses compared to AC power system. Using direct current to distribute power is not a new concept. As mentioned before, Edison was promoting DC distribution network during the “War of Currents” era in 1890’s. Also, RV, Telco and Data centers, aircraft, spacecraft, and ship already used DC distribution [11].

2.3.1: RV DC Distribution

First example of an existing small DC power distribution system in use is an RV’s electrical system, as illustrated in Figure 2.4 [5]. The RV’s motor drives an alternator that produces AC voltage, which is rectified to 12-volt DC to charge the on-board batteries and supply power to the DC appliances. This 12-volt DC distribution has its own fuses,

receptacle, and wiring. This system provides for the key components of an RV, such as light, water, heat, fans and motor, refrigeration, entertainment, and safety [5].

Figure 2-4: 110/120V – 30 Amp RV Wiring Configurations [5]

As displayed in Figure 2-4, there are cases when solar panels are also used to power the DC appliances and charge the batteries. In these cases, a charge regulator controls the power flow to the battery in order to protect from overcharging. Importantly, the DC system differentiates itself at this point because it is not necessary for the RV motor to be on as the basic appliances are running. This can be helpful in instances such as when the family is camping. Next example of a DC distribution system at a larger scale is Telco and Data Centers.

2.3.2: 400 VDC Distribution in Telco and Data Centers

Telco and Data Centers around the world are major consumers of power. In a typical 480 VAC data center (Figure 2-5), less than half of the power is delivered to the actual computer load, which includes microprocessors, memory and disk drives. The conventional power delivery architecture is burdened by many power conversion stages, as illustrated in Figure 2-5 [10]. Furthermore, each conversion stage creates inefficiency which wastes energy, produces heat, and increases the load on the center's cooling system.

Figure 2-5: Conventional 480Vac distribution in the United States [10]

In [10], a 400 VDC distribution in Telco and Data center was evaluated to improve energy efficiency of the system. The findings of this study showed that system efficiency improved significantly in power delivery architectures when power conversion stages were eliminated by directly feeding 400 VDC (Figure 2-6) [10]. Figure 2-7

displays the efficiency plots of power distribution architectures studied in [10] for the Telco and Data Centers. This study concluded that the two electrical architectures, 400 VDC and 48 VDC, yield the highest efficiency because the conversion stages are eliminated.

Figure 2-6: Proposed Facility-level 400V DC power distribution [10]

Figure 2-7: Comparison of calculated efficiencies as a function of load [10]

2.4: DC House Configurations

There are three different configurations of DC house: Individual DC house, Multiple DC Houses, and Centralized DC System. These configurations are based on multiple factors, such as the local population and the spread of the houses. The following sections discuss these configurations and their processes in further detail.

2.4.1: Individual DC House Configuration

In the Individual DC house configuration, a single DC house operates in islanding mode, as illustrated in Figure 2-8 [20]. This type of configuration is suitable for villages with widely disperse population and it can have one or multiple renewable sources generating DC power. In order to have regulated input into the Multiple Inputs DC-DC converter (MISO), the renewable sources are followed by the DC-DC converter. This MISO conversion translates to a single DC bus voltage at 48V which is used to power the house and charge the battery bank for the night-time use. The completed DC house projects under this configuration are discussed in the next section.

Figure 2-8: Single DC house Configuration [20]

In [14] a bicycle power generator was designed and implemented. The goal was to have a cost effective human-powered DC generator which could be used in times when other renewable sources would not be generating power. A car's alternator, with modified internal wiring, was attached to the bike's back tire in order to convert the mechanical energy into electrical energy. As Figure 2-8 illustrates, this electrical energy then could be used to provide power straight to the DC house or charge the batteries. The findings of the study showed that the alternator's efficiency to convert mechanical energy to electrical energy is highly dependent on its RPM in conjunction with its internal resistance. At around 1800 RPM, the alternator's efficiency was close to 35%. It was also

concluded that there is plenty of room for improvements in the lower RPM efficiency. Other projects focused on additional renewable sources such as wind power [18] and hydro-electric [19].

In [8] the main DC bus voltage feeding to the house was analyzed for the highest efficiency. The goal of the project was to determine the adequate DC bus voltage that would generate the highest system efficiency. It accounted for variables such as mesh and radial distribution systems, wire size, different loads, and 500W maximum power input. Subsequently, it was concluded that 48V bus would give the best results in efficiency and cost of the components [8].

In [9] research was conducted on available DC loads that can be used in the DC house. A system was designed, modeled, and characterized in steady state using Simulink toolbox in MATLAB. The selection strategy for the loads were mainly based on fulfilling the basic humanitarian needs of daily life such as lighting, cooking appliances, and food storage. Further detailed study was conducted on the individual loads to determine the best available option in the market, given the capabilities and limitation of DC house. For example, two types of compressors were studied for the refrigerator load. It was determined a conventional compressor would not be a good choice of load for the DC house because it typically requires large amount of start-up current which would exceed the capabilities of the source given that most of the renewable sources are constant current source. An alternative swing-compressor available in the market was determined a better fit because it requires a low startup current. Based on these findings, a refrigerator available in the market was selected and further studied by creating a model

in Simulink based on the characteristics given in the datasheet. To maximize efficiency, and simultaneously reduce the cost of the system, different circuit configurations were studied to connect the loads within the DC house while varying the feeder bus voltages and size of wire used for the circuit [9].

In [4] an economical and energy-efficient DC light bulb was designed and implemented. This DC Light Bulb was to operate at input voltage ranging from 24 VDC to 72 VDC as shown in Figure 2-9. Test in the lab showed the DC light bulb is capable of producing illumination intensities equivalent to a standard 100W A19 incandescent light bulb at one-tenth the total power consumption. This study demonstrated the feasibility of the DC Light Bulb in terms of overall efficiency, line regulation, load regulation, power consumption, total lumens, and thermal profile.

Figure 2-9: Fully DC Light bulb at full load from 48 VDC input [4]

In [16] Multiple-Input and single output DC-DC converter was studied to integrate multiple renewable energy sources for a single DC house as illustrated in Figure 2-8. Full bridge topology was chosen because only one winding per input source in the transformer is required, which helps to keep the transformer size small. The controller is sensing current at the primary winding and voltage at the output to auto adjusts its PWM duty cycle. Figure 2-10 illustrates a prototype board that was built and tested in the lab. The design had three different inputs and single output with a maximum of 80 Watts of output power capability. The MISO board design was further improved in [17] which increased its power capability to 150W. The 500W requirement for a single DC house can be met by having multiple converters in parallel configuration.

Figure 2-10: Multiple Input Single Output board [16]

2.4.2: Multiple DC Houses Configuration

Second configuration of the DC house is illustrated in Figure 2-11 [20]. This configuration allows the exchange of power in a small cluster of DC houses. It is suitable for more concentrated pockets of remote villages. Flexibility of sharing power further improves the reliability of the system because there are fewer chances of power outages, in case the renewable sources for one house stop working.

Figure 2-11. Multiple DC houses configuration [20]

2.4.3: Centralized Distribution Network for DC Houses

The third configuration for the DC house project is a centralized distribution network illustrated in Figure 2-12 [20]. This configuration can be implemented in a small clustered village with ten or more houses. This approach offers better system reliability, yet lowers the cost of the project. This thesis focuses on the design, modeling, simulation, and performance evaluation of this centralized distribution network, which will be presented in greater detail in the following chapters.

Figure 2-12: Centralized distribution network for dc houses [20]

CHAPTER 3

System Design

3.1: PSCAD Software

The electric grid has remained unaffected since the 20th century's technological advancements. But the recent integration of power electronics and communication devices into the grid is changing this hundred-year-old infrastructure into a smarter grid. In the so-called "Smart Grid" infrastructure, energy would be generated, distributed and used more efficiently. However these new power electronic and communication devices pose problems for most of the existing power system design software because the scope of their capabilities to simulate behavior of these new electronic devices is very limited. These simulation challenges are resolved by using Power System Computer Aided Design (PSCAD) software package developed by Manitoba HVDC Research Center. The PSCAD simulation tool can duplicate the response of power electronic devices in time steps ranging from nanoseconds to seconds [31]. Other power electronic simulation software packages, such as PSpice, are general purpose analog and mixed-signal simulator used to verify circuit design and to predict circuit behavior. Whereas, PSCAD is specifically targeted to simulate power systems and power electronic circuits [31]. Since the simulation model of the Centralized DC House Distribution Network will have power systems and power electronic components,

PSCAD was chosen as the best available option to simulate the behavior of the centralized DC house distribution network.

3.2: High Level System Design

The centralized DC House distribution network is a solution to provide electricity to rural and isolated populations with low cost and high system reliability. As mentioned in the previous chapter, multiple renewable sources can be used to generate power for the DC house as well. But this study only focuses on solar power generation as the source of power for the centralized DC House distribution network. Figure 3-1 illustrates the fundamental block diagram of the proposed design for the centralized DC House distribution network.

Figure 3-1: Basic block diagram of proposed design

The power generated by PV array varies according to the solar irradiance, temperature, and load demand. These three variables control the voltage operating point of the PV array, which determines the amount of power generated. A Maximum Power Point Tracking device is used to keep the voltage operating point of the PV array around the knee of the I-V curve, which extracts maximum amount of power. Battery bank stores the excess power generated during the peak sunlight hours, and supplies it to the load at night or in cloudy weather conditions.

Figure 3-2 illustrates further a detailed block diagram of the proposed system design. PV array is a constant current source and the main requirement of any switch mode DC-DC converter used in the MPPT scheme is for it to have low input current ripple. Buck Converter or its derived topologies has a switch at the input which leads to higher input current ripple and requires a big capacitor at the input. On the other hand, the input current for a Boost Converter is continuous due to the inductor at the input. Therefore, Boost Converter topology is a better choice for the MPPT scheme. The second DC-DC converter in the system needs to convert the varying output voltage of the Boost Converter to a stable 48V DC bus distribution voltage. Additionally this converter must have low output current ripple, so smooth power is delivered to the DC bus. The Buck Converter topology fulfills both of these requirements. It has low output current ripple due to the inductor at its output. The following sections will discuss each component operation in further detail.

Figure 3-2: Detailed block diagram of the proposed design

3.3: *PV Cell Circuit Model*

The electrical equivalent model of PV cell is shown in Figure 3-3. This model contains a current source anti-parallel with a diode, a shunt resistance and a series resistance [28]. PV cells consist of silicon p-n junction which releases electrons when exposed to light. These electrons are then free to move across the junction in closed circuit loop due to the voltage potential V_d . This phenomenon is modeled by the light generated current source I_{ph} in the equivalent circuit. The diode in the equivalent circuit corresponds to the silicon p-n junction characteristics. Without the sunlight, PV cell does not produce power; instead it works as a diode i.e. a p-n junction. The resistor R_{sh} represents the leakage current, and R_s represents the connection losses and is usually not significant [21].

Figure 3-3: PV Cell Equivalent Circuit [28]

The output current of the current source is directly proportional to the light falling on the cell. The photon generated current source I_{ph} is defined as:

$$I_{ph} = [I_{SC} + k_1(T - 298)] \left(\frac{G}{k_2} \right) \quad (3-1)$$

where:

k_1 = 0.00017 A/°C Cells' short-circuit temperature (A/°C)

I_{SC} = Cell short-circuit current at 25°C (°C)

T = Cell temperature (°C)

G = Solar radiation (W/m²)

k_2 = 1000 (W/m²), (reference Solar radiation)

Figure 3-4 illustrates the non-linear characteristics of the PV cell which are mainly due to the current, I_d , flowing through the anti-parallel diode, i.e. p-n junction.

Figure 3-4: The I-V characteristics of a PV cell [21]

The basic equation to characterize the solar cell I-V relationship is derived from analyzing the equivalent circuit in Figure 3-3. The following equation is obtained using circuit's Kirchoff's current law:

$$I = I_{ph} - I_d - I_{sh} \quad (3-2)$$

Next, the substitution of relevant expressions for the diode current I_d and the shunt branch current I_{sh} provides equation 3-3:

$$I = I_{ph} - I_{sd} \left[\exp \left(\frac{V + IR_s}{\frac{nkT}{q}} \right) - 1 \right] - \left(\frac{V + IR_s}{R_{sh}} \right) \quad (3-3)$$

where:

I_{sd} = diode's saturation current (A)

$k = 1.3807 \times 10^{-23}$, Boltzmann constant, (JK⁻¹)

$q = 1.6022 \times 10^{-19}$, electric charge, (C)

n = diode's quality factor

The open-circuit voltage of PV cell is obtained by letting $I = 0$ and $R_{sh} \rightarrow \infty$ as:

$$V_{oc} = V_d - \frac{nkt}{q} \ln \left(\frac{I_{ph}}{I_{sd}} + 1 \right) \approx \frac{nkt}{q} \ln \left(\frac{I_{ph}}{I_{sd}} \right) \quad (3-4)$$

Short-circuit current of the cell is obtained by applying a short at the cell's output voltage $V = 0$ and average current through diode is neglected, so the short circuit current I_{sc} is stated as:

$$I_{sc} = \frac{I_{ph}}{1 + \frac{R_s}{R_{sh}}} \cong I_{ph} \quad (3-5)$$

The output power P of the PV cell is defined as

$$P = VI \quad (3-6)$$

Substituting (2) into (6) yields

$$P = VI_{ph} - I_{sd} \left[\exp \left(\frac{q}{nkt(R_s + I)} \right) - 1 \right] V - \frac{(R_s I + V)V}{R_{sh}} \quad (3-7)$$

A single solar cell is the simplest component of a PV module. The current generated by this cell is very small. Therefore a solar module is a combination of multiple solar cells that are connected in series and/or parallel to generate usable current and voltage.

3.3.1: PV module PSCAD Implementation

Figure 3-5 illustrates the custom library component, available in PSCAD, to emulate PV behavior. This component was developed by Dr. Athula Rajapakse from the University of Manitoba, Canada. This module implements behavior of equation 3-3 based on temperature and irradiance inputs. Figure 3-6 illustrates the default parameters of the individual PV cell that were used in the simulation. One can obtain these parameters from PV manufacturer's data sheet, and modify them accordingly in the PSCAD to emulate the behavior of a particular PV cell that will be used.

Figure 3-5: PV Module Components available in PSCAD

Figure 3-6: PV Cell Default Parameters

Figure 3-7 illustrates the PV array configuration used for the simulation. In the PV array parameters, one can change the number of cells in a module in series or parallel configuration as well as can configure the PV array with series or parallel connect PV modules as needed. The Standard Operating Condition (SOC) test for PV is performed at 800 W/m^2 and 25°C . The SOC I-V and Power characteristics of the individual module used in the simulation are shown in Figure 3-8. The power generation of the module varies with the operating voltage and maximum power generation point occurs around the knee of the curve when module is operating around 24V. In this configuration 400 PV panels are connected in parallel. A single panel could produce 45W of maximum power, which means in this configuration PV array is capable of producing 18kW of power.

Figure 3-7: PV Module and PV Array Parameters

1.

Figure 3-8: PV Module I-V and Power Characteristics

3.4: PV Maximum Power Point Tracking

As shown in Figure 3-8, the PV power generation characteristics are non-linear, which vary with solar irradiation, temperature and load. The amount of power a PV module can generate depends on the operating point on the I-V curve. There is only one point of maximum power (MPP – Maximum Power Point), which occurs around the knee point of the curve. A maximum power point tracking device is required in order to keep the system operating on the knee of the I-V curve with the changing weather and temperature. A maximum power point tracker (MPPT) is a power electronic DC-DC converter used to obtain maximum amount of power from PV array. It uses an intelligent algorithm to ensure PV is always operating at the maximum power point as the solar radiation, temperature and load fluctuate. Figure 3-9 shows the custom library component available in PSCAD for MPPT. This custom component offers two peak power tracking schemes: Perturb and Observe and Incremental Conductance.

Figure 3-9: PSCAD MPPT Component (left), and Parameters (right)

Perturb and Observe (P & O) scheme is carried out by changing the duty cycle of the power converter connected to the PV array and observing the output power. In this case, changing the duty cycle of the power converter changes the input current from the PV array accordingly. Consequently, this changes the operating voltage of the array. Figure 3-8 shows when operating to the left of the MPP, incrementing the voltage increases the power, and when operating to the right of the MPPT, incrementing the voltage decreases the output power. Table 3-1 below summarizes the perturbation steps taken to reach maximum power point of the PV array. The table shows that if the PV output power increases after perturbation, then the subsequent perturbation is kept the same; but if the output power decreases after perturbation, then the previous perturbation should be reversed. The down side of this periodic process is that the system oscillates about the MPP. This oscillation can be reduced using smaller perturbation size, which however slows down the MPPT process [30].

Table 3-4: Summary of Perturb & Observe Algorithm

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

The next maximum power point tracking scheme available in the PSCAD MPPT component is the Incremental Conductance method. This scheme focuses on the slope of

the PV array power curve. The slope of the PV array power curve is zero at the MPP, positive on the left of the MPP and negative on the right, as given by:

$$\left. \begin{aligned} dP/dV &= 0, & \text{at MPP} \\ dP/dV &> 0, & \text{left of MPP} \\ dP/dV &< 0, & \text{right of MPP} \end{aligned} \right\} \quad (3-8)$$

Since

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \cong I + V \frac{\Delta I}{\Delta V} \quad (3-9)$$

Equation 3-8 can be rewritten as:

$$\left. \begin{aligned} \Delta I/\Delta V &= -I/V, & \text{at MPP} \\ \Delta I/\Delta V &> -I/V, & \text{left of MPP} \\ \Delta I/\Delta V &< -I/V, & \text{right of MPP} \end{aligned} \right\} \quad (3-10)$$

Therefore, MPP can be tracked by comparing the instantaneous conductance (I/V) with the incremental conductance ($\Delta I/\Delta V$). Figure 3-10 illustrates the incremental conductance base algorithm used by the PSCAD MPPT component. The operating point of the PV array is V_{ref} which is equal to V_{mpp} at MPP. Once MPP has been reached, the PV array is maintained at this point unless a change in ΔI is noted. No oscillation around the MPP point is the advantage incremental conductance has over P & O algorithm.

Figure 3-10: Incremental Conductance Based Algorithm MPPT [30]

The PI controller used to drive the DC-DC converter for maximum power point tracking is illustrated in Figure 3-11. Instantaneous PV array voltage and current are measured to calculate the optimum operating voltage point (V_{mpp}) of the PV array which generates the maximum power.

Figure 3-11: The Controller used to drive the Boost Converter Switch for MPPT

3.5: Boost Converter Operation

Figure 3-12 illustrates the basic block diagram of the Boost Converter. DC-DC converters can operate in three conduction modes: Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM), and Boundary Conduction Mode (BCM) [32]. In Continuous Conduction Mode, the inductor current remains positive throughout the switching period. In Discontinuous Conduction Mode, the inductor current reaches zero for portion of the switching period. In Boundary Conduction Mode, the inductor current is at the edge of the CCM before going to the DCM (special case of CCM). Figure 3-13 illustrates the three different conduction modes of the DC-DC converters. Since the Boost Converter will be connected to the PV array (constant current source), the desired mode of operation for the converter is the Continuous Conduction Mode.

Figure 3-12: Boost Converter Block Diagram [32]

Figure 3-13: Conduction Modes of DC-DC Converters [32]

In the CCM mode, boost converter has two states per switching cycle. During the switch ON state (Figure 3-14), switch is forward biased and diode is reversed biased. The current flows through the inductor in clockwise direction and the inductor stores energy in its magnetic field. The polarity on the left side of the inductor is positive during this state (storing energy). During the switch OFF state (Figure 3-15), switch is open, and

diode is forward biased, which increases the impedance of the circuit. Consequently the inductor resists the change in the circuit current due to higher impedance; thus the polarity of the inductor is reversed (positive polarity on the right side of the inductor). As a result two sources in series supply the load at higher voltage and charge the output capacitor simultaneously. Also the output capacitor is sized to supply sufficient power to the load during the switch OFF state [33].

Figure 3-14: Boost Converter CCM Switch ON State [32]

The voltage across the inductor during switch ON state can be written as:

$$V_L = V_S = L \frac{di_L}{dt} \text{ or } \frac{di_L}{dt} = \frac{V_S}{L} \quad (3-11)$$

The increasing inductor current during the switch ON state is given by:

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_S}{L} \quad (3-12)$$

$$\Delta i_{L-Closed} = \frac{V_S}{L} DT \quad (3-13)$$

Figure 3-15: Boost Converter CCM Switch OFF State [32]

The voltage across the inductor during switch OFF is calculated as:

$$V_L = V_S - V_O \quad (3-14)$$

$$V_L = L \frac{di_L}{dt} \text{ or } \frac{di_L}{dt} = \frac{V_S - V_O}{L} \quad (3-15)$$

The change in the inductor current is computed as:

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_S - V_O}{L} \quad (3-16)$$

$$\Delta i_{L-Open} = \frac{(V_S - V_O)(1-D)T}{L} \quad (3-17)$$

As stated earlier, in steady state conditions the change, when inductor current is increasing (switch ON) and decreasing (Switch OFF), are equal. This implies that the net change in inductor current over one period is zero. Therefore in CCM mode the output voltage of the Boost Converter can be equated to:

$$\Delta i_{L-Closed} + \Delta i_{L-Open} = 0 \quad (3-18)$$

$$\frac{V_S DT}{L} + \frac{(V_S - V_O)(1 - D)T}{L} = 0 \quad (3-19)$$

$$\overline{V_O} = \frac{V_S}{1 - D} \quad (3-20)$$

Figure 3-16: Boost Converter Inductor, Switch and Diode Current [32]

The Boost Converter waveforms in CCM are illustrated in Figure 3-16. The waveform $I_{sw(t)}$ represents, the current through the switch during T_{ON} , and waveform $I_{D(t)}$ represent the current through the diode during T_{OFF} . Furthermore, the current through the inductor $I_{L(t)}$ is equal to the combination of the switch and diode currents.

3.5.1: Boost Converter PSCAD Implementation

Figure 3-17 illustrates the block diagram of Boost Converter implemented in PSCAD. An input capacitor is used for a stable voltage input from the PV array. The duty cycle of the switch is controlled by the MPPT controller shown in Figure 3-11. The MPPT varies the duty cycle according to the solar irradiance, temperature and load conditions in order to extract maximum power out of the PV array. The switching frequency of the DC-DC converter can be selected from a range starting at 5 kHz to over 100 kHz. A higher switching frequency requires smaller energy storage components (inductor and capacitor), which makes the converter compact. However, the trade-off is that the simulation runs very slow because of the lower time step required by high switching frequency. As a result, switching frequency of 20 kHz was selected to keep the balance between the two trade-offs.

Figure 3-17: Boost Converter connected to the PV Array in PSCAD

The critical inductance that yields Continuous Conduction Mode is determined from the minimum value of inductor current I_{L-min} as:

$$L_c = \frac{D(1-D)^2 R}{2f} \quad (3-21)$$

In 3-21 “R” represents the load resistance. Minimum of five DC houses will be consuming 2.5 kW of power almost entirely. Load in terms of resistance for five houses is calculated to be:

$$R = \frac{V^2}{P} = \frac{48^2}{2500} = .9216 \Omega \quad (3-22)$$

And, for a 50% duty cycle the Critical inductance is calculated to be:

$$L_C = \frac{.5(1 - .5)^2 * .9218}{2 * 20 \times 10^3} = 2.88 \mu H \quad (3-23)$$

The duty cycle of the converter varies according to the weather and load conditions. Therefore, a higher value for the inductor is preferred to ensure that the converter is working in CCM mode at all time. The inductor of 20μH was tested and chosen to keep the converter in CCM mode under varying weather and load conditions.

The output capacitor value is determined by:

$$C = \frac{D}{Rf} \times \frac{V_o}{\Delta V_o} \quad (3-24)$$

A 50% duty cycle at 25V input voltage will boost the output voltage to 50V, and the output capacitor required in this case would be:

$$C = \frac{.5}{.1884 * 20 \times 10^3} \times \frac{50}{1} = 6.7 mF \quad (3-25)$$

The output voltage ripple has an inverse relationship with the output capacitor value, so a lower output ripple will require a bigger capacitor. As mentioned, this

converter will have varying duty cycle according to the different weather and load conditions. A 10 mf capacitor was chosen for different operating conditions.

3.6: Buck Converter Operation

As mentioned earlier, the second DC-DC converter in the system needs to convert the varying output voltage of the Boost Converter to a stable 48V DC bus distribution voltage. Additionally this converter must have low output current ripple, so smooth power is delivered to the DC bus. The Buck Converter topology fulfills both of these requirements. It has low output current ripple due to the inductor's location in the circuit, as illustrated in Figure 3-18 [32]. The cascading of Boost and Buck converter provides good input and output current characteristics. As mentioned in the previous section, the desired mode of operation for these converters is the Continuous Conduction Mode. Therefore, all the following equations are derived in the Continuous Conduction Mode.

Figure 3-18: Buck Converter Block Diagram [32]

Similar to Boost, Buck converter also has two states in the Continuous Conduction Mode: Switch ON and Switch OFF. In the switch ON state, the diode is reverse biased (Figure 3-19), and the voltage across the inductor is:

$$V_L = V_S - V_O \quad (3-26)$$

Figure 3-19: Buck Converter CCM Switch ON State [32]

The change in the inductor current is calculated as:

$$\frac{di_{Lt}}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_S - V_O}{L} \quad (3-27)$$

$$\Delta i_{L-closed} = \frac{(V_S - V_O)}{L} DT \quad (3-28)$$

The second state of the Buck converter is illustrated in Figure 3-20. In this state switch is turned off and the voltage across inductor is:

$$V_L = -V_O = L \frac{di_L}{dt} \quad (3-29)$$

Figure 3-20: Buck Converter CCM Switch OFF State [32]

The change in the inductor current is computed as:

$$\frac{\Delta i_L}{t_{off}} = \frac{\Delta i_L}{T - DT} = \frac{\Delta i_L}{(1 - D)T} = -\frac{V_o}{L} \quad (3-30)$$

$$\Delta i_{L-open} = -\frac{V_o}{L}(1 - D)T \quad (3-31)$$

In steady state operation the net change in the inductor current is zero. Therefore the output voltage of the Buck Converter is:

$$\Delta i_{L-1period} = \Delta i_{L-closed} + \Delta i_{L-open} = 0 \quad (3-40)$$

$$0 = \frac{V_s - V_o}{L}DT - \frac{V_o}{L}(1 - D)T \quad (3-41)$$

$$0 = \frac{V_s}{L}DT - \frac{V_o}{L}DT - \frac{V_o}{L}T + \frac{V_o}{L}DT \quad (3-42)$$

$$V_o = DV_s \quad (3-43)$$

Figure 3-21: Buck Converter CCM Waveforms [34]

The Buck Converter waveforms are shown in Figure 3-21. As mentioned earlier, when the switch is ON, the inductor current increases linearly and the capacitor is charged. And, when the switch is OFF, the inductor current decreases linearly and the capacitor discharges to supply the load. The net change in the inductor current in the steady state is zero. The output voltage ripple is a function of the output capacitor. A bigger capacitor at the output will result in low ripple in the output voltage ripple [32].

3.6.1: Buck Converter PSCAD implementation

In PSCAD the Buck Converter is cascaded with the Boost Converter as shown in Figure 3-22. The output voltage of the Buck Converter is regulated at 48V while the input voltage varies depending on the solar irradiance, temperature and load. Figure 3-23 illustrates the PI controller used for the output voltage regulation. In order to get a regulated 48V at the DC bus, the controller compares the output voltage of the Buck Converter (DC bus voltage) to the reference 48V. If the output voltage is lower than 48V, the switch turns on to charge the output capacitor; if the output voltage is higher than 48V, the switch turns off to discharge the output capacitor. The switching frequency of the converter is 20 kHz.

Figure 3-22: Buck Converter Cascaded with Boost Converter in PSCAD

Figure 3-23: Buck Converter Switch Controller for Regulating Output Voltage at 48V

The critical inductance of the converter is computed as:

$$L_c = \frac{(1 - D) R_{max}}{2f} \quad (3-44)$$

$$L_c = \frac{(1 - .5) * .9218}{2 * 20000} = .011mH$$

But a .1mH was selected because the load resistance can go higher and duty cycle can go lower under different test conditions.

The minimum capacitor required at the output is computed as:

$$C_o = \frac{1 - D}{\frac{\Delta V}{V_o} 8Lf^2} \quad (3-45)$$

$$C_o = \frac{1 - .2}{\frac{1}{48} 8 (.0001)(20000)^2} = .12mf \quad (3-46)$$

3.7: Battery Bank

PV power generation varies with the amount of sunlight shining on the panels at an instance, which results in lack of power generation during night time and cloudy weather. At such times, a battery bank is needed in order to provide smooth power to the load continuously. There are four major types of rechargeable batteries used as energy storing devices: Lead Acid, Nickel-51Cadmium (NiCD), Nickel-metal-hydride (NiMH), Lithium-ion (Li-ion). Figure 3-25 shows the discharge characteristics of an individual cell for the batteries.

Figure 3-25: Cell Discharge Characteristics of Four Battery Types

In order to determine the optimal battery type, the major attributes to focus on are the specific energy, years of service life, load characteristics, price, safety, self-discharge, environmental issues, and disposal. NiCD, NiMH, and Li-ion batteries are usually used in

critical and extreme temperature applications [23]. However the reason they are not likely candidates for use in PV systems is because their high initial costs and unavailability offset their advantageous characteristics.

Lead Acid batteries are one of the oldest rechargeable battery systems created by French Physicist Gaston Plante in 1859 [24]. Their low cost, high tolerance to over-charge and over-discharge characteristics make them ideal for isolated PV systems. There are three different types of lead acid batteries available in the market today: flooded lead-acid, gelled electrolyte, and absorbed glass mat (AGM). Gelled electrolyte and AGM are also commonly referred to as sealed or valve-regulated lead acid batteries (VRLA). The advantages and disadvantages of these two different battery types are compared in Table 3-2.

Table 3-2: Comparison of Flooded Lead-Acid and VRLA Battery Types [23]

Battery Type	Advantages	Disadvantages
Flooded Lead-Acid		
Lead-Antimony	low cost, wide availability, good deep cycle and high temperature performance, can replenish electrolyte	high water loss and maintenance
Lead-Calcium Open Vent	low cost, wide availability, low water loss, can replenish electrolyte	poor deep cycle performance, intolerant to high temperatures and overcharge
Lead-Calcium Sealed Vent	low cost, wide availability, low water loss	poor deep cycle performance, intolerant to high temperatures and overcharge, can not replenish electrolyte
Lead Antimony/Calcium Hybrid	medium cost, low water loss	limited availability, potential for stratification
Captive Electrolyte Lead-Acid		
Gelled	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Absorbed Glass Mat	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability

These Gelled and AGM (VRLA) batteries are designed to minimize the required maintenance over the life of the battery. In the small PV systems, VRLAs are the most popular because of their low maintenance requirements, even though their cost is higher than the Flooded Lead-Acid batteries. Other differentiating attributes include the impossibility of adding an electrolyte to the VRLA batteries due to their seal construction type. The sealed construction makes VRLA batteries extremely intolerant to overcharging and high temperatures [23]. Hence, the Flooded Lead-acid batteries are the most ideal battery type for the centralized DC House distribution system. In the next section, the implementation of Lead-acid battery model is discussed.

3.7.1: Battery Bank PSCAD Implementation

The battery is modeled by a controlled voltage source in series with a constant resistance, as shown in Figure 3-26.

Figure 3-26: Battery Equivalent Circuit Diagram [18]

This basic equivalent battery circuit is represented by shepherd's equation as:

$$E_{bat} = E_o - K * \frac{(1 - SOC)}{SOC} * Q + Ae^{-B(1-SOC)Q} \quad (3-46)$$

The voltage at the battery terminal is calculated as:

$$V_{bat} = E_{bat} - R_{bat} * I_{bat} \quad (3-47)$$

where:

E_{bat} : internal voltage (V)

E_o : battery voltage constant (V)

K: polarization constant (V/Ah) or polarization resistance (Ω)

SOC : State of charge (%)

Q: battery capacity (Ah)

A: exponential Zone amplitude (V)

B: exponential zone time constant inverse (1/Ah)

V_{bat} : terminal voltage (V)

I_{bat} : battery current (A)

Figure 3-27 illustrate the custom battery component available in PSCAD, which implements equation 3-46.

Figure 3-27: Battery Custom Component in available in PSCAD

where:

- **I_{bat}**: The current of the battery, input signal.
- **Reset**: The control signal used to control charge or discharge of the battery, input signal.
- **SOC**: State of charger, output signal

The five battery type options available in PSCAD model are: Li-ion, Lead acid, Ni-Cd, Ni-MH and User defined. As discussed in the previous section, Lead-acid battery type is the optimum choice for the isolated PV backup system. The parameters of the Lead-acid model are illustrated in Figure 3-28.

The screenshot shows a dialog box titled "[battery:Battery] id='1140155040'". It has a dropdown menu set to "Lead acid". Below the menu is a "General" section with a table of parameters. At the bottom, there is a section for "internal resistance (ohm)" with a description of its properties. The dialog has "Ok", "Cancel", and "Help..." buttons.

General	
nominal voltage (V)	40
reated capacity (Ah)	1250
nominal capacity (Ah)	1000
Initial capacity (Ah)	1000
Maximum voltage (V)	48
voltage at exponential point (V	42.5
internal resistance (ohm)	.1

internal resistance (ohm)
Type=Real, Symbol=Rbat2, min=, max=, unit=,
Content=Variable, Intent=Input

Figure 3-28: Lead-Acid Battery Parameters

- **Nominal Voltage (V):** End of the linear zone of the discharge characteristics
- **Rated Capacity (Ah):** Rated capacity of the battery
- **Initial Capacity (Ah):** Initial condition for the simulation and does not affect the discharge curve
- **Nominal capacity (Ah):** The amount of current that can be extracted from the battery before it needs to recharge
- **Voltage at exponential point (V):** The exponential point corresponds to the end of the exponential zone
- **Maximum Voltage (V):** Battery voltage when its fully charged
- **Internal Resistance (Ω):** Internal resistance of the battery

The voltage of battery cell varies in accordance with its charge state (Figure 3-25). Similarly, the terminal voltage of the battery bank will decrease as its SOC (state of charge) goes down. But the battery bank needs supply power to the load consistently at 48V during the non-generation periods. A DC-DC converter with regulated output helps to meet this design requirement. Figure 3-29 illustrates the battery bank design implemented in PSCAD. The top path is used for charging the battery and it is discharged through the bottom path. Boost Converter (sub-module “Boost-Bat1”) steps-up the battery terminal voltage to 48V DC Bus voltage when the load is supplied from the battery. Figure3-30 illustrates the Boost Converter and controller with-in the sub-module.

Figure 3-29: Complete Battery Bank Design

Figure 3-30: Boost Converter (top) and Controller (bottom) within the Sub-Module Battery Cascaded

3.8: Distribution Network

The centralized distribution network for the DC houses is illustrated in Figure 3-31. This network consists of overhead distribution cables, five feeders and a total of 25 DC houses. The layout is modeled in PSCAD using common feeder characteristics that system planners use in suburban residential regions [15]. Figure 32 illustrates a magnified view of individual feeder with five houses. A single DC House load can be varied from 100-500W.

Figure 3-31: Distribution Network Design for 25 DC Houses

Figure 3-32: Magnified view of Feeder C Supplying Power to 5 DC Houses

Figure 3-33 shows the power flow in a basic DC circuit. The power loss in a DC circuit is directly proportional to the conductor resistance and the amount of current flowing through the conductor as shown by following equation:

$$P_{Loss} = P_{source} - P_{Load} = V_{DC} * I - V_2 * I = I^2 * R \quad (3-48)$$

Figure 3-33: DC Equivalent Circuit Diagram [8]

At full load, the minimum current will be:

$$I_{full-load} = \frac{P}{V_{DC-Bus}} = \frac{25 * 500}{48} = 260.42A \quad (3-49)$$

Equation 3-49 shows distribution network will have high currents due to the low distribution voltage, therefore minimum resistance is desired in the distribution conductors in order to minimize distribution losses. Aluminum Conductor Steel Reinforced (ACSR) cables are frequently used for overhead power distribution. Their performance is highly reliable for many years even under adverse weather conditions. Table 3-3 shows the characteristics of the different ACSR cables. Waxing conductor at 266.9 kcmil is selected based on the ampacity rating, DC resistance, and cost. The cable distances labeled in orange (Figure 3-31) corresponds to Waxwing conductor type. The

cable distance labeled in purple corresponds to Raven 1/0 AWG which is selected to connect a single DC House to the distribution network.

Table 3-3: ASCR Conductor Specifications Chart

ACSR & All Aluminum Cable Specification Chart															
Code Word	Size (AWG or kcmil)	Strand- ing (Al/Stl)	Diameter (ins.)				Weight Per 1000 ft. (lbs.)			Content (%)		Rated Strength (lbs.)	Resistance OHMS/1000 ft.		Allowable Ampacity+ (Amps)
			Individual Wires		Steel Core	Complete Cable							DC@ 20°C	AC@ 75°C	
			Al	Stl			Al	Stl	Total	Al	Stl				
Turkey	6	6/1	.0661	.0661	.0661	.198	24	12	36	67.88	32.12	1190	.641	.806	105
Swan	4	6/1	.0834	.0834	.0834	.25	39	18	57	67.87	32.12	1860	.403	.515	140
Swanate	4	7/1	.0772	.103	.103	.257	39	28	67	58.1	41.9	2360	.399	.519	140
Sparrow	2	6/1	.1052	.1052	.1052	.68	62	29	91	67.9	32.1	2850	.254	.332	184
Sparate	2	7/1	.0974	.1298	.1298	.325	62	45	107	58.12	41.88	3460	.251	.338	184
Robin	1	6/1	.1181	.1181	.1181	.354	78	37	115	67.88	32.12	3550	.201	.268	212
Raven	1/0	6/1	.1327	.1327	.1327	.398	99	47	145	67.89	32.11	4380	.159	.217	242
Quail	2/0	6/1	.1489	.1489	.1489	.447	124	59	183	67.88	32.12	5310	.126	.176	276
Pigeon	3/0	6/1	.1672	.1672	.1672	.502	156	74	230	67.87	32.13	6620	.100	.144	315
Penguin	4/0	6/1	.1878	.1878	.1878	.563	197	93	291	67.89	32.12	8350	.0795	.119	357
Waxwing	266.8	18/1	.1217	.1217	.1217	.609	250	39	289	86.43	13.57	6880	.0643	.0787	449
Partridge	266.8	26/7	.1013	.1013	.1013	.642	251	115	367	68.51	31.49	11300	.0637	.0779	475
Ostrich	300	26/7	.1074	.1074	.1074	.68	283	130	412	68.51	31.49	12700	.0567	.0693	492
Merlin	336.4	18/1	.1367	.1367	.1367	.684	315	49	365	86.43	13.57	8680	.0510	.0625	519
Linnet	336.4	26/7	.1137	.1137	.1137	.72	317	146	462	68.5	31.5	14100	.0505	.0618	529
Oriole	336.4	30/7	.1059	.1059	.1177	.741	318	209	526	60.35	39.65	17300	.0502	.0613	535
Chickadee	397.5	18/1	.1486	.1486	.1486	.743	373	58	431	86.43	13.57	9940	.0432	.0529	576
Brant	397.5	24/7	.1287	.0858	.2574	.772	374	137	511	73.21	26.79	14600	.0430	.0526	584
Ibis	397.5	26/7	.1236	.0962	.2885	.783	374	172	546	68.51	31.49	16300	.0428	.0523	587
Lark	397.5	30/7	.1151	.1151	.3453	.806	375	247	622	60.35	39.65	20300	.0425	.0519	594
Pelican	477	18/1	.1628	.1628	.1628	.814	447	70	517	86.45	13.56	11800	.0360	.0442	646
Flicker	477	24/7	.141	.094	.2819	.846	449	164	614	73.21	26.79	17200	.0358	.0439	655
Hawk	477	26/7	.1354	.1053	.316	.858	449	207	656	68.51	31.49	19500	.0356	.0436	659
Hen	477	30/7	.1261	.1261	.3783	.883	450	296	746	60.35	39.65	23800	.0354	.0433	666
Osprey	556.5	18/1	.1758	.1758	.1758	.879	522	82	603	86.43	13.57	13700	.0308	.0379	711

The DC resistance of the conductors leads to voltage drop in the network that varies with the distance and the amount of current flowing in the cable ($V_{\text{drop}} = I \times R_{\text{cable}}$). Therefore, DC-DC converters are required at strategic locations in the distribution network in order to boost the voltage back to 48V. Boost Converter typology is selected and its output voltage is regulated at 48V with the PI controller as shown in Figure 3-34. The distribution network layout (Figure 3-31) shows the boost converter and controller sub-module placed at strategic locations.

Figure 3-34: Boost Converter (top), and its Switch Controller (bottom) used in Distribution Network

This completes the basic model for Centralized Distribution Network for DC House Project. Next chapter will focus on performance evaluation of the proposed design.

Chapter 4

System Validation

In this chapter, the proposed design model for the centralized DC distribution network is validated. First, the operation of the Boost Converter and the MPPT controller is validated under varying solar radiation, temperature, and load. Then the operation of the Buck Converter is verified. The next steps involve the testing of the voltage stability of the network under different circumstances and the verification of battery charging with excessive PV power. Lastly, the PV source is turned off and battery bank is used to supply power to load to emulate night and cloudy conditions.

4.1: MPPT and Boost Converter Validation

The I-V (current versus voltage) characteristics of the PV module are nonlinear as shown in Figure 3-8. The operating voltage of the PV module determines the amount of power generated by the PV module. The maximum power is extracted from the PV when the module's operating voltage is around the knee of the I-V curve. For example, if the PV module is operating at 25V, then it generates close to 45W. Instead if the same PV module is operating at 5V, then it generates only 10W (Figure 3-8). Therefore, the desired operating voltage is around the knee of the module's I-V curve, where the maximum PV power is utilized. The maximum power extraction is achieved by dynamically alternating the duty cycle of the Boost Converter (Figure 4-1), which forces

the PV array to operate around the knee of the I-V curve. Boost Converter's duty cycle is controlled by a maximum power point controller, which alternates the converter's duty cycle in accordance with three parameters: solar radiation, temperature and load. Next, three simulation test case results are presented. These depict the behavior of three different scenarios where V_{mpp} of the array alters and MPPT controller's response to the variations is analyzed.

Figure 4-5: Complete System Design Implemented in PSCAD

Figure 4-2 shows the I-V characteristics of PV module with varying irradiance and temperature. Solar radiation primarily influences the output current of the PV module, while temperature mainly changes the output voltage of the PV module. These two parameters alternate the V_{mpp} of the PV module dynamically.

Figure 4-6: PV Module I-V Characteristic with Varying Solar Radiation (left) and Temperature (right) [35]

As the temperature increases, the V_{mpp} point of the PV module shifts to the left on the I-V curve (Figure 4-2) which needs to be tracked by the MPPT controller. In order to verify the response of the MPPT controller to temperature variations, the first test case is performed with the system operating at full load (25 DC houses consuming 500W each) while the temperature is varied from 5°C to 45°C in increments of 10°C. The results of this simulation test case are shown in Figure 4-3.

Figure 4-7: PV Array output Voltage (top), Current (middle), and Power (bottom) with Varying Temperature

Table 4-5: PV Output Voltage, Current, and Power with Varying Temperature

Time (seconds)	Temperature (°C)	V _{mpp} (V)	Current (A)	Power (kW)
0.1	5	27.6	608	16.8
0.3	15	26.9	624	16.79
0.5	25	26.3	638	16.8
0.7	35	25.8	651	16.8
0.9	45	25.15	668	16.8

Table 4-1 summarizes the PV voltage, current, and power measurements with incrementing temperature. The voltage operating point of the PV array shifted to the left with increasing temperature as anticipated. The dips in the current and power graph represent the response time of the MPPT controller between the temperature change and the implementations of the necessary modifications to the Boost Converter's duty cycle.

For the second simulation test case, solar radiation is varied from 400W/m^2 to 1000W/m^2 in steps of 200 W/m^2 , while temperature remains constant at 25°C . The results of the simulation test case are shown in Figure 4-4.

Figure 4-8: PV Array output Voltage (top), Current (middle), and Power (bottom) with Varying Solar Irradiance

Table 4-6: PV Output Voltage, Current, and Power with Varying Irradiance

Time (seconds)	Irradiance (W/m ²)	PV V _{mpp}	PV current (A)	PV power (kW)
0.15	400	25.9	109	2.83
0.35	600	26.4	273	7.21
0.55	800	27.1	428	11.6
0.75	1000	27.8	604	16.8

Table 4-2 summarizes the PV voltage, current and power measurements with incremented solar radiation. The power generating capability of the PV array increases with incrementing solar radiation. As the solar radiation is increased, PV array is able to generate more current and its voltage operating point moves slightly to the right as anticipated by Figure 4-2.

For the third simulation test case, the load is varied while the other two parameters remain constant at 800 W/m^2 and 25°C . Figure 4-5 shows that when the load is increased, the voltage operating point shifts to the left on the I-V curve. Figure 4-6 shows the results from the third simulation test case where the load of the individual DC house is varied from 100W to 500W in steps of 100W. As expected, the PV voltage drops as its output power increases.

Figure 4-5: PV Array Voltage Operating Point as the Load Increases

Figure 4-6: PV Array operating Voltage (top), Current (middle), and Power (bottom) with Varying Load

Table 4-3: PV Output Voltage, Current and Power with Varying Load

Time (seconds)	House Load (W)	Vmpp (V)	Current (A)	Power (kW)
0.15	100	29.37	95	2.8
0.25	200	28.98	196	5.68
0.45	300	28.46	318	9.05
0.65	400	27.85	442	12.31
0.85	500	26.70	614	16.4

Data from Table 4-3 show that the V_{mpp} (operating point of the PV array) moves to the left with increasing load as predicted.

Figure 4-7 depicts the input (PV voltage) and output voltage of the Boost Converter as the load is increased at standard operating conditions (800W/m^2 @ 25°C). The output voltage of the Boost Converter is dependent upon its duty cycle, which is controlled by the MPPT controller. Table 4-4 summarizes the input and output voltages and duty cycle of the Boost Converters. The duty cycle of the converter is calculated according to equation 4-1. The duty cycle of the converter decreases as the load increases which accounts for more power transferred to the output.

Figure 4-7: Boost Converter Input and Output Voltages with increasing Load

Table 4-4: Summary of the Boost Converter Voltages and Duty Cycle with Increasing Load

Time (seconds)	Load	V _{mpp} (V)	Boost V _o (V)	Duty Cycle (%)
0.15	100	29.37	147.3	80.1
0.25	200	28.98	143.9	79.9
0.45	300	28.46	139.29	79.56
0.65	400	27.85	134.47	79.29
0.85	500	26.70	126.4	78.87

$$\%Duty\ Cycle_{Boost} = \left(1 - \frac{V_{PV}}{V_{oBoost}}\right) \times 100\% \quad (4-1)$$

The Continuous Conduction mode of the converter is verified by Figure 4-8. The top graph (Figure 4-8) shows the increasing current through the inductor as the load increases. The bottom graph displays a magnified view of the charging and discharging of the inductor at full load (500W). The inductor is charging for approximately 80% of the total period and discharging for about 20% of the total period as it was calculated from the input and output voltages of the converter (Table 4-4). Next, the operation of the Buck Converter is verified.

Figure 4-8: Boost Converter Inductor Current (top) and Magnified View of Inductor Current at Full Load (bottom)

4.2: Buck Converter Validation

The Buck converter needs to step-down its input voltage (which is the output voltage of the Boost Converter) to 48V DC bus voltage. Thus, the Buck Converter's output is dynamically regulated at 48V by the PI controller. Figure 4-9 depicts the input and output voltages of the Buck Converter with increasing load. The graph data is summarized in Table 4-5 and verify that the Buck Converter is regulating its output voltage at 48V (also the DC bus voltage) with varying input voltage as might be the case in many situations.

Figure 4-9: Buck Converter Input and Output Voltages with increasing Load

Table 4-5: Summary of the Buck Converter Voltages and Duty Cycle with Increasing Load

Time (seconds)	Load	Buck Vin or Boost Vo (V)	Buck Vo or DC Bus (V)	Duty Cycle (%)
0.15	100	147.3	48.38	32.84
0.25	200	143.9	48.26	33.54
0.45	300	139.29	48.15	34.57
0.65	400	134.47	48.06	35.74
0.85	500	126.4	48.02	37.99

$$\%Duty\ Cycle_{Buck} = \left(\frac{V_o}{V_{in}} \right) \times 100\% \quad (4-2)$$

Figure 4-10 illustrates the output power of the PV array and the output power of the Buck Converter. Table 4-6 summarizes the data from the power graphs and the efficiency of the converter is calculated according to equation 4-3. The efficiency of the converter increases with increasing load as expected except at the full load.

Figure 4-10: PV Output Power (green) and Buck Converter Output Power (blue) with Varying Load

Table 4-6: *Efficiency Summary of the Buck and Boost Converters with Increasing Load*

Time (seconds)	Load (kW)	PV Pout (kW)	Buck Pout (kW)	Efficiency (%)
0.1	2.5	2.96	2.63	88.85
0.3	5	5.85	5.3	91.45
0.5	7.5	8.87	8.2	92.45
0.7	10	12.1	11.31	93.47
0.9	12.5	16.01	14.8	92.44

$$Efficiency = \frac{Buck P_{out}}{PV P_{out}} \times 100\% \quad (4-3)$$

4.3: Voltage Stability of the Distribution Network

Figure 4-11 depicts the centralized power distribution model of the 25 houses. As mentioned in the previous chapter, the resistors in the layout represent the DC resistances of the cable conductors. The farthest house in the layout will see the maximum voltage drop due to the resistive losses of the conductors. Therefore, the Boost Converters are needed to boost the decreased bus voltage back to 48V before it can be distributed to the DC Houses. Next, voltage drop and stability of the distribution layout is tested under different operating conditions.

Figure 4-11: Centralized Distribution Network Design for 25 DC Houses

4.3.1: Full Load

Figure 4-12 illustrates the voltages at five different locations when the system is operating at full load (500W) and PV array is generating power at standard operating conditions (800 W/m² and 25°C).

Figure 4-12: Voltages at Five locations in the Distribution Network at Full Load

The top graph (Figure 4-12) shows voltages across the main distribution conductor. The voltage at location A (which is at same location as source) is averaging around 48.7V. Location B is 500ft away from the main source. Two Waxwing (2×266.1 kcmil) conductors are used to transmit power across this distance. There is a 4V drop across the Waxwing conductors due to its DC resistance, and the voltage at location B is 44V. Location C is at 500ft from location B and only one Waxwing (1×266.1 kcmil) is used to transmit power across this distance because it carries only about half as much current as the first conductors. Moreover, the voltage at location C is around 40V. This portrays that these voltage drops are dependent upon three variables: distance, load, and cable resistance.

The middle graph (Figure 4-12) depicts the voltage difference between Location B (beginning of Feeder D) and the voltage supplied to the individual house at location D (at the end of the Feeder D). The voltage from location B is boosted back to 48V by the Boost Converter and distributed to the DC Houses in Feeder D. Similarly, voltage at location C is boosted back to 48V and is distributed to the DC Houses in Feeder C, as depicted in bottom graph of Figure 4-12.

Figure 4-13 shows the current in the main conductors and into the two individual houses at Locations D and E. As anticipated location A conducts the maximum current of about 310A, followed by location B current of about 260A, and then the current at location C is about 130A. The individual houses are supplied with 10.4A, which proves that they are consuming about 500W when operating at 48V. The current ripple significantly depends on the inductor value of the Buck Converter (on the source side).

The inductor with lower value closer to the boundary conduction mode leads to higher ripple in the system.

Figure 4-13: Current at Five Locations in the Distribution Network at Full Load

Figure 4-14 depicts the power flow in the distribution network. The bottom graph (Figure 4-14) validates that the individual houses are consuming about 500W. In the steady state (around .2 seconds), the source is supplying approximately 14.6 kW and all of the houses combined are consuming little over 12.5 kW. So, approximately 2 kW of

power is consumed by the distribution network, mainly by the losses in the distribution cables. These losses can be minimized by decreasing the distance if possible, or by using higher gauge cables which will have less resistance.

Figure 4-14: Power in the main DC Distribution Cable (Top) and Power delivered to 2 individual Houses (bottom)

4.3.2: Varying Load

In the second simulation test, the house load is incremented from 100W to 500W in steps of 50W every 0.1 seconds. Figure 4-15 illustrates voltage measurements of the network as the load is varied. Higher load yields higher current in the system which contributes to higher voltage drops across the distribution conductors ($V_{\text{drop}} = I \cdot R_{\text{cable}}$). However, the dynamic response of the Boost Converters keeps the distributed house voltage close to 48V ($\pm 0.5V$) consistently, as depicted on the bottom two graphs of Figure 4-15.

Figure 4-15: Voltage Measurements as Load is incremented from 100W to 500W in steps of 50W

The current flow in the system increases in accordance with the load, as depicted in Figure 4-16. The current ripple increases as the amount of current in the system increases.

Figure 4-16: Current Measurements at Five Locations as load is incremented from 100W to 500W in steps of 50W

Figure 4-17 depicts the power flow increases with the increasing load. The losses in the distribution network increase as well with the increasing current ($P_{\text{loss}} = I^2 \cdot R_{\text{cable}}$). Next, the number of houses operating at full load is incremented from 5 to 25 in step of 5.

Figure 4-17: Power measurements at 5 different locations as load incremented from 100W to 500W in steps of 50W

4.3.3: Varying Number of Houses Operating

Figure 4-18 shows voltage stability in the network as the number of houses consuming power at full load is increased from 5 to 25 in steps of 5. Table 4-7 summarizes the voltage measurements at the five locations in the system. The current in the system increases in accordance with the number of houses consuming power, which leads to the voltage drops at locations B and C. These voltage drops are compensated by the Boost Converters and the voltage at locations D and E is kept stable at 48V.

Similarly, Figure 4-19 and 4-20 show the current and power flow in the system with five houses added to the network every 0.2 seconds.

Figure 4-18: Voltage Measurements at Five Locations as Number of Houses is incremented

Table 4-7: Distribution Network Voltages with 5 to 25 Houses at 500W

Time (sec)	Houses	Location A (V)	Location B (V)	Location C (V)	Location D (V)	Location E (V)
0.1	5	48.7	48.2	48.2	48.4	48.3
0.2	10	48.5	47.1	47.5	48.2	48.2
0.4	15	48.2	46.2	44.5	48.1	48
0.6	20	48	45.2	43.1	47.9	47.9
0.8	25	47.8	44.1	40.1	47.8	47.7

Figure 4-19: Current Measurements at Five Locations as Number of Houses is incremented

Figure 4-20: Power Measurements at Five Locations as Number of Houses is incremented

4.4: PV Charging the Battery and Supplying the Load

Figure 4-21 illustrates the peak sun hour power generation capacity of the PV source. During the peak sun hours, the PV array produces more power than the load demands and this excess power is used to charge the battery bank.

Figure 4-21: Battery Storage during Peak Sun Hours (dark yellow) and Battery Supplying Load (green)

For night time operation (approximately 14 hours of non-generation period), battery bank will require approximately 48 kWh of energy in order to supply the DC houses, which will consume 100W-150W each. A test case is run where the excess power from the PV array during peak sun hours is used to charge the battery bank. Figure 4-22 shows that 6.8 kW of energy is supplied to the battery and at this rate, 7 peak sun hours

will provide the battery bank with enough energy to last through the night time. Figure 4-23 illustrates the battery current and voltage.

Figure 4-22: Power Supplied to the Battery from PV Array

Figure 4-23: Battery Current (blue) and Voltage (green)

Figure 4-24 illustrates the voltage stability in the network while the battery bank is charging. Figures 4-25 and 4-26 show the current and power in the network and verify that the operation of the distribution network is not compromised when the batteries are charging.

Figure 4-24: Voltage Measurements of the Distribution Network at Five Locations While the Battery Bank is being charged

Figure 4-25: Current Measurements of the Distribution Network at Five Locations While the Battery Bank is being charged

Figure 4-26: Power Measurements of the Distribution Network at Five Locations While the Battery Bank is being charged

4.5: Battery Bank Supplying the Load

4.5.1: Varying Load

Similar to the test case in section 4.3.2, the load is varied from 100W to 500W with steps of 50W every 0.1 seconds; however, the load is supplied from the battery bank instead of PV (emulating night time or cloudy weather conditions). The input parameters of the battery bank are shown in Figure 3-38 (previous chapter). Figure 4-27 shows the voltage stability in the network as the load is increased. The DC bus voltage is regulated at 48V by the Boost Converter, which is cascaded with the battery bank (Figure 4-1). The voltage for the DC Houses (Locations D and E) is observed at 48V. Figures 4-28 and 4-29 show the current and power flow in the network with the increasing load. Furthermore, Figure 4-30 shows the decreasing SOC (state of charge) of the battery with time, which shows that power is being drawn from the battery. This test case verifies that the battery bank is able to provide smooth power to the DC Houses during non-generation periods.

Figure 4-27: Voltage Measurements of Distribution Network at Five Locations as Load is increased from 100W to 500W in steps of 50W (Powered from Battery)

Figure 4-28: Current Measurements of Distribution Network at Five Locations as Load is increased from 100W to 500W in steps of 50W (Powered from Battery)

Figure 4-29: Power Measurements of Distribution Network at Five Locations as Load is increased from 100W to 500W in steps of 50W (Powered from Battery)

Figure 4-30: Battery Bank State of Charge (SOC)

4.5.2: Varying Number of Houses Operating

In this test case, the number of houses consuming power is increased from 5 to 25 in steps of 4 every .2 seconds. Figure 4-31 shows voltage stability in the network as the number of houses consuming power is increased. As more houses start consuming power, the voltage at locations B and C dropped. But Boost Converters keep the distributed house voltage at 48V (Locations D and E). Similarly Figures 4-32 and 4-33 show the current and power flow in the network. This test case verifies that the battery bank is able to provide smooth power as the number of houses consuming power increase.

Figure 4-31: Voltage Measurements of Distribution Network at Five Locations as number of houses is incremented (Powered from Battery)

Figure 4-32: Current Measurements of Distribution Network at Five Locations as number of houses is incremented (Powered from Battery)

Figure 4-33: Power Measurements of Distribution Network at Five Locations as number of houses is incremented (Powered from Battery)

4.6: System Cost Analysis

The major factor driving the growth of the renewable energy sources such as photovoltaic is their competitive cost, which has been decreasing for the past two decades. The DC distribution method is chosen for our system because it is more efficient and requires fewer components than an AC distribution method. In the following sections, a DC vs. AC distribution cost analysis is performed for a system that could range from 10 kW to 100 kW.

4.6.1: PV Array and MPPT Charge Controller Cost

The adequate sizing of PV array is important to prolong the life of the system components, house appliances, and battery bank. PV array sizing is based on the lowest insolation month (critical month) of the place where system will be implemented. Since the DC house project is to be mainly used in developing countries, the insolation data of Jakarta, Indonesia, will provide for system sizing. From the data in Figure 4-34, it is clear that the lowest insolation month in Jakarta is January when the average insolation is 4.25 kWh/m²/day.

Variable	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Insolation, kWh/m ² /day	4.25	4.75	5.19	5.22	5.10	4.93	5.26	5.92	6.29	5.81	5.00	4.45
Clearness, 0 - 1	0.40	0.45	0.50	0.53	0.56	0.57	0.60	0.63	0.62	0.55	0.47	0.43
Temperature, °C	26.08	26.03	26.26	26.75	27.01	26.92	26.54	26.45	26.49	26.47	26.39	26.27
Wind speed, m/s	3.19	3.15	2.41	2.65	3.60	4.05	5.00	5.06	4.34	3.17	2.72	2.63
Precipitation, mm	406	298	245	195	173	100	77	77	93	146	174	225
Wet days, d	16.9	13.8	15.5	15.5	13.7	11.5	8.6	7.9	8.0	12.3	17.0	18.4

These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center; New et al. 2002

Figure 4-34: Jakarta Indonesia Monthly Insolation [36]

The total daily energy demand for the system is based on 4 hours at full load, 12 hours at 60% of the load and 8 hours at 30% of load (night). Total energy demand for a 10 kW system is calculated using:

$$\frac{\text{Energy demand}}{\text{day}} = 10kW \times 4hrs + 6kW \times 12hrs + 3kW \times 8hrs$$

$$= 136kWh$$
(4-4)

These energy demand calculations take into consideration the energy required to charge the battery bank. Table 4-8 shows the PV array sizing and cost calculations based on 85% system efficiency.

Table 4-8: PV Array Sizing and Cost Calculations

PV Sizing_Insolation_4.25 W/m^2	
	10 kw system
	Max eff
C1 Total energy demand per day (C5*48) (W)	136000.00
C2 System efficiency	0.85
C3 Required array output per day (W) (C1 / C2)	160000.0
C4 Selected PV module max power voltage at STC (x.85)	36.08
C5 Selected PV module guaranteed power output at STC	285
C6 Peak sum hours at design tilt for design month	4.25
C7 Energy output per module per day (C5xC6)	1211.25
C8 Module energy output at operating temperature (DFxC7)	
DF = 0.80 for hot climates and critical applications.	
DF = 0.90 for moderate climates and non-critical applications.	1090.125
C9 Number of modules required to meet energy requirements (C3 / C8)	146.77
	147.00
C10 Number of modules required per string (A2 / C4)	2
C11 Number of strings in parallel (C9 / C10) rounded	74
C12 Number of modules to be purchased (C10 x C11)	148
Individual Panel Price	\$ 193.80
Total Cost	\$ 28,682.40

JAP6- 285W solar module is selected for the system due to its competitive price per watt (Appendix A). Table 4-9 summarizes the cost for a system ranging from 10 kW to 100 kW with 85% and 75% system efficiencies. The data from the table are plotted in Figure 4-35. The plot shows that improving the system efficiency is significant in reducing the high initial cost for a PV system.

Table 4-9: *Summary of PV Cost for 85% and 75% System Efficiency*

System kW	85% eff	75% eff
10	\$ 28,682.40	\$ 32,558.40
20	\$ 56,977.20	\$ 64,729.20
30	\$ 85,659.60	\$ 96,900.00
40	\$ 113,954.40	\$ 129,070.80
50	\$ 142,249.20	\$ 161,241.60
60	\$ 170,931.60	\$ 193,800.00
70	\$ 199,226.40	\$ 225,970.80
80	\$ 227,908.80	\$ 258,141.60
90	\$ 256,203.60	\$ 290,312.40
100	\$ 284,498.40	\$ 322,483.20

Figure 4-35: DC Distribution PV Cost with 85% and 75% Efficiency

The MPPT charge controller selected for the system is Outback FM-80 Flexmax (Appendix B). This charge controller takes the varying voltage from the PV array and produces a stable 48V voltage for the DC bus. A Single FM-80 controller has output power rating of 3840W and costs \$584. Table 4-10 lists the number of controllers required and their corresponding costs.

Table 4-10: *MPPT Charge Controller Cost*

System kW	MPPT controllers required	Total Cost
10	3	\$1,752
20	6	\$3,504
30	8	\$4,672
40	11	\$6,424
50	14	\$8,176
60	16	\$9,344
70	19	\$11,096
80	21	\$12,264
90	24	\$14,016
100	27	\$15,768

4.6.2: Battery Bank Cost

The storage capacity required for the battery bank depends on the number of days batteries can provide power to the load without recharging. Depth of Discharge (DOD) is the amount of energy drawn from a battery compared to its total storage capacity. For a PV system, two common terms related to DOD are maximum DOD and average daily DOD. Maximum DOD is the maximum amount of charge that can be drawn out of the battery. It is also related to the autonomy capacity required to operate the system loads

for given number of days with no generation from PV. A system designed with very low DOD will have most of the battery energy available to the load but with a trade-off for longer battery life. The average daily DOD is the amount of energy drawn from battery's full capacity with the average daily load profile. A system designed for longer autonomy periods (more capacity) will have lower average daily DOD. For this system, DOD of 80% is selected, which is typical for isolated PV storage systems. For the battery bank, Trojan T105-RE Flooded lead-acid battery is selected (Appendix C), which has 225A of capacity with 6V terminal voltage. Table 4-11 shows the calculations for the number of batteries required for a 10 kW to 100 kW system and their corresponding costs, assuming two days of autonomy storage are required.

Table 4-11: Battery Bank Sizing for 2 Days of Autonomy Storage

2 Cloudy Day		Daily Amp hour		Autonomy Capacity Ah		DOD		DOD Ah		Battery (Ah)		Paralleled		Series		Total Batteries		Bat Kwh capacity		Cost	
System	Kw	Max (Ah/day)	Min (Ah/day)	Max (Ah)	Min (Ah)			Max (Ah)	Min (Ah)			Max	Min			Max	Min	Max	Min	Max	Min
10	2833.33	2562.50	2	5666.67	5125.00	0.8		7083.3	6406.3	225	225	31.48	28.47	8		252	228	272	246	\$ 32,760.00	\$ 29,640.00
20	5666.67	5125.00	2	11333.33	10250.00	0.8		14166.7	12812.5	225	225	62.96	56.94	8		504	456	544	492	\$ 65,520.00	\$ 59,280.00
30	8500.00	7687.50	2	17000.00	15375.00	0.8		21250.0	19218.8	225	225	94.44	85.42	8		756	684	816	738	\$ 98,280.00	\$ 88,920.00
40	11333.33	10250.00	2	22666.67	20500.00	0.8		28333.3	25625.0	225	225	125.93	113.89	8		1008	912	1088	984	\$131,040.00	\$118,560.00
50	14166.67	12812.50	2	28333.33	25625.00	0.8		35416.7	32031.3	225	225	157.41	142.36	8		1260	1139	1360	1230	\$163,800.00	\$148,070.00
60	17000.00	15375.00	2	34000.00	30750.00	0.8		42500.0	38437.5	225	225	188.89	170.83	8		1512	1367	1632	1476	\$196,560.00	\$177,710.00
70	19833.33	17937.50	2	39666.67	35875.00	0.8		49583.3	44843.8	225	225	220.37	199.31	8		1763	1595	1904	1722	\$229,190.00	\$207,350.00
80	22666.67	20500.00	2	45333.33	41000.00	0.8		56666.7	51250.0	225	225	251.85	227.78	8		2015	1823	2176	1968	\$261,950.00	\$236,990.00
90	25500.00	23062.50	2	51000.00	46125.00	0.8		63750.0	57656.3	225	225	283.33	256.25	8		2267	2050	2448	2214	\$294,710.00	\$266,500.00
100	28333.33	25625.00	2	56666.67	51250.00	0.8		70833.3	64062.5	225	225	314.81	284.72	8		2519	2278	2720	2460	\$327,470.00	\$296,140.00

Furthermore, Table 4-12 summarizes the variations in the battery cost as the size of the system and number of days are varied. Data shows that the battery cost is significantly higher as the autonomy storage days are increased. This is because battery prices have not dropped like the PV module prices. Additionally Figure 4-36 shows a 3D graph of the battery cost.

Table 4-12: *Battery Cost Varied with System Size and Storage Capacity*

System Size (KW)	Cloudy day storage				
	0 (14 hr night)	1	2	3	4
10	\$ 5,850.00	\$ 14,820.00	\$ 29,640.00	\$ 44,460.00	\$ 59,280.00
20	\$ 11,570.00	\$ 29,640.00	\$ 59,280.00	\$ 88,920.00	\$ 118,560.00
30	\$ 17,420.00	\$ 44,460.00	\$ 88,920.00	\$ 133,250.00	\$ 177,710.00
40	\$ 23,140.00	\$ 59,280.00	\$ 118,560.00	\$ 177,710.00	\$ 236,990.00
50	\$ 28,990.00	\$ 74,100.00	\$ 148,070.00	\$ 222,170.00	\$ 296,140.00
60	\$ 34,710.00	\$ 88,920.00	\$ 177,710.00	\$ 266,500.00	\$ 355,420.00
70	\$ 40,560.00	\$ 103,740.00	\$ 207,350.00	\$ 310,960.00	\$ 414,570.00
80	\$ 46,280.00	\$ 118,560.00	\$ 236,990.00	\$ 355,420.00	\$ 473,850.00
90	\$ 52,000.00	\$ 133,250.00	\$ 266,500.00	\$ 399,750.00	\$ 533,000.00
100	\$ 57,850.00	\$ 148,070.00	\$ 296,140.00	\$ 444,210.00	\$ 592,280.00

Figure 4-36: Battery Bank Cost with Increasing System Size and Storage Capacity

4.6.3: Distribution Cost

The selection criteria for the distribution conductors is their DC resistance and prices. For the main distribution lines, ASCR Waxing (266.8 kcmil) conductor is chosen and Raven (1/0 AWG) is selected to connect single house to the main conductors. Table 4-13 shows the calculated cost for the 10 kW. Table 4-14 shows the total distribution cost for the wiring and Boost Converter (Appendix D) for a 10 kW -100 kW system.

Table 4-13: *Distribution Wiring Cost for a 10 kW System.*

10 KW Wiring Min Cost				
		Length(kft)	Price/kft	Cost
Waxwing	1x266.8	1.35	842.45	\$1,137.31
Raven	1/0. AWG	1.625	370.52	\$ 602.10
			Total	\$1,739.40

Table 4-14: *Distribution Wiring and Boost Converter Cost*

Distribution Cost		
System Size (KW)	Wiring Cost	Boost Converter Cost
10	\$ 1,739.40	\$1,400
20	\$ 3,478.81	\$2,800
30	\$ 5,218.21	\$4,200
40	\$ 6,957.61	\$5,600
50	\$ 8,697.01	\$7,000
60	\$ 10,436.42	\$8,400
70	\$ 12,175.82	\$9,800
80	\$ 13,915.22	\$11,200
90	\$ 15,654.62	\$12,600
100	\$ 17,394.03	\$14,000

Table 4-15 shows the total cost of the Centralized DC Distribution System for the DC House. The battery cost is for the best case scenario, which is only accounting for

enough storage for the night-time operations. This cost will multiply if more autonomy storage capacity is desired.

Table 4-15: Total DC System Cost

System kW	PV Cost	MPPT Cost	Battery Cost	Distribution		Total DC cost
				Wiring	Boost	
10	\$ 28,682.40	\$1,752	\$ 5,850.00	\$ 1,739.40	\$1,400	\$ 39,423.80
20	\$ 56,977.20	\$3,504	\$11,570.00	\$ 3,478.81	\$2,800	\$ 78,330.01
30	\$ 85,659.60	\$4,672	\$17,420.00	\$ 5,218.21	\$4,200	\$ 117,169.81
40	\$113,954.40	\$6,424	\$23,140.00	\$ 6,957.61	\$5,600	\$ 156,076.01
50	\$142,249.20	\$8,176	\$28,990.00	\$ 8,697.01	\$7,000	\$ 195,112.21
60	\$170,931.60	\$9,344	\$34,710.00	\$10,436.42	\$8,400	\$ 233,822.02
70	\$199,226.40	\$11,096	\$40,560.00	\$12,175.82	\$9,800	\$ 272,858.22
80	\$227,908.80	\$12,264	\$46,280.00	\$13,915.22	\$11,200	\$ 311,568.02
90	\$256,203.60	\$14,016	\$52,000.00	\$15,654.62	\$12,600	\$ 350,474.22
100	\$284,498.40	\$15,768	\$57,850.00	\$17,394.03	\$14,000	\$ 389,510.43

4.6.4: AC System Cost

In order to justify the DC distribution method a comparison study was prepared for the AC distribution cost. The AC system is less efficient because of the extra conversion stages, which are not required in the DC distribution. The AC system requires an inverter to convert DC to AC on the source side. SMA Sunny Boy 10000TLUS-10 10 kW inverter is selected (Appendix E). The common AC distribution voltage is 12.4 kV, which means transformers are required to step-up the voltage at the source end and step-down on the house side to supply the house at 120V. The transformer selected for the AC network is ABB Single phase overhead distribution transformer (Appendix F). Table 4-16 details the cost analysis for the AC system. The PV cost for the AC system is calculated assuming system efficiency of 75%. The cost for MPPT charge controller and

battery bank remains unchanged from the DC system. But the wiring cost is half of the DC system because smaller cable conductors are needed for the high voltage distribution.

Table 4-16: Total AC System Cost

System kW	PV Cost	MPPT Cost	Battery Cost	Inverter Cost	Transformer Cost	Distribution		Total AC Cost
						Wiring	Transformer	
10	\$ 32,364.60	\$1,752	\$ 5,850.00	\$3,305	\$3,500	\$ 869.70	\$5,000	\$ 52,641.30
20	\$ 64,535.40	\$3,504	\$ 11,570.00	\$6,610	\$5,250	\$ 1,739.40	\$7,500	\$ 100,708.80
30	\$ 96,900.00	\$4,672	\$ 17,420.00	\$9,915	\$7,000	\$ 2,609.10	\$10,000	\$ 148,516.10
40	\$ 129,070.80	\$6,424	\$ 23,140.00	\$13,220	\$8,750	\$ 3,478.81	\$12,500	\$ 196,583.61
50	\$ 161,241.60	\$8,176	\$ 28,990.00	\$16,525	\$10,500	\$ 4,348.51	\$15,000	\$ 244,781.11
60	\$ 193,606.20	\$9,344	\$ 34,710.00	\$19,830	\$12,250	\$ 5,218.21	\$17,500	\$ 292,458.41
70	\$ 225,777.00	\$11,096	\$ 40,560.00	\$23,135	\$14,000	\$ 6,087.91	\$20,000	\$ 340,655.91
80	\$ 257,947.80	\$12,264	\$ 46,280.00	\$26,440	\$15,750	\$ 6,957.61	\$22,500	\$ 388,139.41
90	\$ 290,312.40	\$14,016	\$ 52,000.00	\$29,745	\$17,500	\$ 7,827.31	\$25,000	\$ 436,400.71
100	\$ 322,483.20	\$15,768	\$ 57,850.00	\$33,050	\$19,250	\$ 8,697.01	\$27,500	\$ 484,598.21

Figure 4-36 graphs the cost difference between the DC and AC distributions. In this figure, the DC system is assumed to be at 85% efficiency and AC system to be at 75% efficiency. The cost difference between the two distribution methods grows larger as their efficiency gap increases.

Figure 4-37: DC System Cost at 85% Efficiency and AC System 75% Efficiency

Chapter 5

Conclusion and Future Work

5.1: Summary and Conclusion

This thesis focuses on the design, modeling, simulation, and performance evaluation of a DC House centralized distribution network. The complete system was modeled in PSCAD. The simulation results proved that the design meets the DC bus voltage stability requirements under different operating conditions. Different variations in the weather patterns can affect the PV generation. Simulation results further verified that the MPPT controller responds to the different weather patterns accordingly. The PV source is kept at its maximum power generating point by the MPPT controller and the buck converter by regulating the DC bus voltage at 48V. The PV source is able to supply the load and charge the battery bank during the peak sun hours without having any voltage instability at the DC bus. In addition, during night-time operation the battery bank is able to supply the load at stable 48V.

The distribution network layout was modeled with 25 houses (Figure 4-11). The voltage drops in the network were caused by the resistive losses of the conductors (Figure 4-12). The boost converters in the distribution network kept the voltage supplied to the load at 48V (Figure 4-12).

The efficiency of the power converters at the source side was observed to range from 88.85% to 93.47%, based on the load demand (Table 4-6). On the other hand, the efficiency of the distribution network depends on the distance that the network has to cover and the conductor type utilized. The losses in the distribution network can be minimized by choosing higher gauge conductors and reducing the distance if possible.

DC vs. AC cost analysis showed that the isolated DC centralized distribution system is more cost effective of the two systems. The AC distribution is burdened by the extra conversion stages which require extra components and reduce efficiency. Other factors, such as power factor correction and frequency stability, are not relevant in the DC system. The factors together provide for a simple, efficient and cost effective system.

5.2: *Future Work*

For simplicity, this study only included PV renewable source as part of the system but the concept of the DC House includes many other renewable sources such as: wind, hydro, human-powered generator. In the future work these sources can also be integrated into a larger simulation model.

More thorough study can also be performed on the performance of the battery bank by looking at the charge, discharge cycle and the battery health over its life. A battery bank is a heart of isolated this isolated distribution system therefore more thorough study will help improve the performance of the whole system.

This system is at a low voltage distribution which leads to high currents in the network. To ensure reliable operation of the distribution network, it is important to have a

good protection system. Future simulations could create a protection scheme for the system by integrating current interruption devices in case of faults, relays and proper grounding schemes. Future study should also be conducted to determine the most optimum distribution voltage for the DC house network.

Overall this thesis produced a basic simulation model for the centralized DC house distribution system which will be further built upon in the future.

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Appendices

- A. JAP6 PV Module Data Sheet
- B. FLEXmax Continuous MPPT Controllers Datasheet
- C. Trojan T105 Battery Data Sheet
- D. Boost Converter for the Distribution network and Battery Bank Specifications
- E. SMA SUNNY BOY 10000TL-US Inverter Datasheet
- F. ABB Single Phase Overhead Distribution Transformer

Appendix A

JAP6 PV Module Data Sheet

JAP6

72/280-310/3BB

MULTICRYSTALLINE SILICON MODULE

JA Solar Holdings Co., Ltd. is a world-leading manufacturer of high-performance photovoltaic products that convert sunlight into electricity for residential, commercial, and utility-scale power generation. The company was founded on May 18, 2005, and was publicly listed on NASDAQ on February 7, 2007. JA Solar is one of the world's largest producers of solar cells and modules. Its standard and high-efficiency product offerings are among the most powerful and cost-effective in the industry.

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Key Features

- Multicrystalline modules designed for commercial and solar farm grid-tied applications
- High output, 15.48% highest conversion efficiency
- Designed for UL 600V or ETL 1000V, IEC 1000V applications
- Anti-reflective and self-cleaning surface reduces power loss from dirt and dust
- Outstanding performance in low-light irradiance environments
- Excellent mechanical load resistance: Certified to withstand high wind loads (2400Pa) and snow loads (5400Pa)
- High salt and ammonia resistance certified by TÜV NORD

Reliable Quality

- Positive power tolerance: 0~+5W
- 100% EL double-inspection ensures modules are defects free
- Modules binned by current to improve system performance
- Potential Induced Degradation (PID) free

Superior Warranty

- 10-year product warranty
- 25-year linear power output warranty

www.jasolar.com

Comprehensive Certificates

- IEC 61215, IEC 61730, UL1703, CEC Listed, MCS and CE
- ISO 9001: 2008: Quality management systems
- ISO 14001: 2004: Environmental management systems
- BS OHSAS 18001: 2007: Occupational health and safety management systems
- Environmental policy: The first solar company in China to complete Intertek's carbon footprint evaluation program and receive green leaf mark verification for our products

Specifications subject to technical changes and tests. JA Solar reserves the right of final interpretation.

Figure A-1: JAP6 PV Module Datasheet Page 1

Engineering Drawings

MECHANICAL PARAMETERS

Cell (mm)	Poly 156x156
Weight (kg)	22.5 (approx)
Dimensions (LxWxH) (mm)	1956x991x45
Cable Cross Section Size (mm ²)	4
No. of Cells and Connections	72 (6x12)
No. of Diodes	3 or 6 (2 in parallel)
Junction Box Connector	MC4 Compatible
Packaging Configuration	22 Per Pallet

WORKING CONDITIONS

Maximum System Voltage	DC 1000V (TÜV) / 600V (UL) / 1000V (ETL)
Operating Temperature	-40°C ~ +85°C
Maximum Series Fuse	15A
Maximum Static Load, Front (e.g., snow and wind)	5400Pa (112 lb/ft ²)
Maximum Static Load, Back (e.g., wind)	2400Pa (50 lb/ft ²)
NOCT	47±2°C
Application Class	Class A

I-V CURVE

ELECTRICAL PARAMETERS

TYPE	JAP6 72-280/3BB	JAP6 72-285/3BB	JAP6 72-290/3BB	JAP6 72-295/3BB	JAP6 72-300/3BB	JAP6 72-305/3BB	JAP6 72-310/3BB
Rated Maximum Power at STC (W)	280	285	290	295	300	305	310
Open Circuit Voltage (Voc/V)	45.38	45.41	45.72	45.9	46.08	46.20	46.30
Maximum Power Voltage (Vmp/V)	35.99	36.08	36.39	36.60	36.82	36.97	37.04
Short Circuit Current (Isc/A)	8.29	8.38	8.42	8.48	8.53	8.60	8.69
Maximum Power Current (Imp/A)	7.78	7.90	7.97	8.06	8.15	8.25	8.37
Module Efficiency [%]	14.44	14.70	14.96	15.22	15.48	15.73	15.99
Power Tolerance (W)	-0~+5W						
Temperature Coefficient of Isc (dIsc/dT)	+0.062%/°C						
Temperature Coefficient of Voc (dVoc/dT)	-0.330%/°C						
Temperature Coefficient of Pmax (dPmp/dT)	-0.450%/°C						
STC	Irradiance 1000W/m ² , Module Temperature 25°C, Air Mass 1.5						

Electrical data in this catalog do not refer to a single module and they are not part of the offer. They only serve for comparison among different module types.

JA Solar 10.2012

Figure A-2: JAP6 PV Module Datasheet Page 2

Appendix B

FLEXmax Continuous MPPT Controllers Datasheet

FLEXmax™

Continuous Maximum Power Point Tracking Charge Controllers

- Increases PV Array Output by up to 30%
- Advanced Continuous Maximum Power Point Tracking
- Full Power Output in Ambient Temperatures up to 104°F (40°C)
- Battery Voltages from 12 VDC to 60 VDC
- Fully OutBack Network Integrated and Programmable
- Programmable Auxiliary Control Output
- Built-in 128 days of Data Logging
- Standard 5 Year Warranty

The FLEXmax family of charge controllers is the latest innovation in Maximum Power Point Tracking (MPPT) charge controllers from OutBack Power Systems. The innovative FLEXmax MPPT software algorithm is both continuous and active, increasing your photovoltaic array power yield up to 30% compared to non-MPPT controllers. Thanks to active cooling and intelligent thermal management cooling, both FLEXmax charge controllers can operate at their full maximum current rating, 60 Amps or 80 Amps respectively, in ambient temperatures as high as 104°F (40°C).

Included in all of the FLEXmax Charge Controllers are the revolutionary features first developed by OutBack Power, including

support for a wide range of nominal battery voltages and the ability to step-down a higher voltage solar array to recharge a lower voltage battery bank. A built-in, backlit 80 character display shows the current status and logged system performance data for the last 128 days at the touch of a button. The integrated OutBack network communications allows FLEXmax series Charge Controllers to be remotely programmed and monitored via a MATE system display and provides unrivaled complete system integration.

FLEXmax MPPT Charge Controllers are the only choice when you demand a high performance, efficient and versatile charge controller for your advanced power system.

OutBack
Power Systems™

www.outbackpower.com

Figure B-1: FLEXmax Continuous MPPT Controllers Datasheet Page 1

FLEXmax Specifications

	☉FLEXmax 80 - FM80-150VDC	☉FLEXmax 60 - FM60-150VDC
Nominal Battery Voltages	12, 24, 36, 48, or 60 VDC (single model - selectable via field programming at start-up)	12, 24, 36, 48, or 60 VDC (single model - selectable via field programming at start-up)
Maximum Output Current	80 amps @ 104° F (40°C) with adjustable current limit	60 amps @ 104° F (40°C) with adjustable current limit
Maximum Solar Array STC Nameplate	12 VDC systems 1250 Watts / 24 VDC systems 2500 Watts / 48 VDC systems 5000 Watts / 60 VDC Systems 7500 Watts	12 VDC systems 900 Watts / 24 VDC systems 1800 Watts / 48 VDC systems 3600 Watts / 60 VDC Systems 4500 Watts
NEC Recommended Solar Array STC Nameplate	12 VDC systems 1000 Watts / 24 VDC systems 2000 Watts / 48 VDC systems 4000 Watts / 60 VDC Systems 5000 Watts	12 VDC systems 750 Watts / 24 VDC systems 1500 Watts / 48 VDC systems 3000 Watts / 60 VDC Systems 3750 Watts
PV Open Circuit Voltage (VOC)	150 VDC absolute maximum coldest conditions / 145 VDC start-up and operating maximum	150 VDC absolute maximum coldest conditions / 145 VDC start-up and operating maximum
Standby Power Consumption	Less than 1 Watt typical	Less than 1 Watt typical
Power Conversion Efficiency	97.5% @ 80 Amps in a 48 VDC System - Typical	98.1% @ 60 Amps in a 48 VDC System voltage - Typical
Charging Regulation	Five Stages: Bulk, Absorption, Float, Silent and Equalization	Five Stages: Bulk, Absorption, Float, Silent and Equalization
Voltage Regulation Setpoints	10 to 60 VDC user adjustable with password protection	10 to 60 VDC user adjustable with password protection
Equalization Charging	Programmable Voltage Setpoint and Duration - Automatic Termination when completed	Programmable Voltage Setpoint and Duration - Automatic Termination when completed
Battery Temperature Compensation	Automatic with optional RTS installed / 5.0 mV per °C per 2V battery cell	Automatic with optional RTS installed / 5.0 mV per °C per 2V battery cell
Voltage Step-Down Capability	Can charge a lower voltage battery from a higher voltage PV array - Max 150 VDC input	Can charge a lower voltage battery from a higher voltage PV array - Max 150 VDC input
Programmable Auxiliary Control Output	12 VDC output signal which can be programmed for different control applications (Maximum of 0.2 amps DC)	12 VDC output signal which can be programmed for different control applications (Maximum of 0.2 amps DC)
Status Display	3.1" (8 cm) backlit LCD screen - 4 lines with 80 alphanumeric characters total	3.1" (8 cm) backlit LCD screen - 4 lines with 80 alphanumeric characters total
Remote Display and Controller	Optional Mate or Mate2 with RS232 Serial Communications Port	Optional Mate or Mate2 with RS232 Serial Communications Port
Network Cabling	Proprietary network system using RJ 45 Modular Connectors with CAT 5e Cable (8 wires)	Proprietary network system using RJ 45 Modular Connectors with CAT 5e Cable (8 wires)
Data Logging	Last 128 days of Operation - Amp Hours, Watt Hours, Time in Float, Peak Watts, Amps, Solar Array Voltage, Max Battery Voltage, Min Battery Voltage and Absorb for each day along with total Accumulated Amp Hours, and KW Hours of production	Last 128 days of Operation - Amp Hours, Watt Hours, Time in Float, Peak Watts, Amps, Solar Array Voltage, Max Battery Voltage, Min Battery Voltage and Absorb for each day along with total Accumulated Amp Hours, and KW Hours of production
Hydro Turbine Applications	Consult factory for approved Turbines	Consult factory for approved Turbines
Positive Ground Applications	Requires two Pole Breakers for switching both positive and Negative Conductors on both Solar Array and Battery Connections (HUB 4 and HUB 10 can not be used for use in positive ground applications)	Requires two Pole Breakers for switching both positive and Negative Conductors on both Solar Array and Battery Connections (HUB 4 and HUB 10 can not be used for use in positive ground applications)
Operating Temperature Range	Minimum -40° to maximum 60° C (Power capacity of the controller is automatically derated when operated above 40° C)	Minimum -40° to maximum 60° C (Power capacity of the controller is automatically derated when operated above 40° C)
Environmental Rating	Indoor Type 1	Indoor Type 1
Conduit Knockouts	One 1" (35mm) on the back; One 1" (35mm) on the left side; Two 1" (35mm) on the bottom	One 1" (35mm) on the back; One 1" (35mm) on the left side; Two 1" (35mm) on the bottom
Warranty	Standard 5 year / Available 10 Year	Standard 5 year / Available 10 Year
Weight	- Unit 1220 lbs (556 kg) - Shipping 1575 lbs (710 kg)	1165 lbs (53 kg) 1455 lbs (64 kg)
Dimensions	- Unit 16.25" x 5.75" x 4" (41.3 x 14 x 10 cm) - (H x W x D) - Shipping 21" x 10.5" x 9.75" (53 x 27 x 25 cm)	13.5 x 5.75 x 4" (40 x 14 x 10 cm) 18 x 11 x 8" (46 x 30 x 20 cm)
Options	Remote Temperature Sensor (RTS), HUB 4, HUB 10, MATE, MATE 2	Remote Temperature Sensor (RTS), HUB 4, HUB 10, MATE, MATE 2
Menu Languages	English & Spanish	English & Spanish

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Phone: +34.93.654.9568

www.outbackpower.com

Available From:

7/02/08

Figure B-2: FLEXmax Continuous MPPT Controllers Datasheet Page 2

Appendix C

Trojan T105 Battery Data Sheet

T105-RE DATA SHEET

MODEL: T105-RE with Bayonet Cap
DIMENSIONS: inches (mm)
BATTERY: Flooded/wet lead-acid battery
COLOR: Maroon (case/cover)
MATERIAL: Polypropylene

PRODUCT SPECIFICATION WITH T2 TECHNOLOGY™

BCI GROUP SIZE	TYPE	CAPACITY ^A Amp-Hours (AH)			ENERGY (kWh)	TERMINAL Type	DIMENSIONS ^B Inches (mm)			WEIGHT lbs. (kg)
		5-Hr Rate	20-Hr Rate	100-Hr Rate			100-Hr Rate	Length	Width	
6 VOLT DEEP CYCLE BATTERY										
GC2H	T105-RE	185	225	250	1.50	5	10-3/8(264)	7-1/8(181)	11-3/4(299)	67(30)

A. The amount to Amp-hours (AH) a battery can deliver when discharged at a constant rate at 80°F (27°C) for the 20-Hour and 100-Hour rates and 86°F (30°C) for the 5-Hour rate and maintain a voltage above 1.75V/cell. Capacities are based on nominal performance.
B. Dimensions are based on nominal size. Dimensions may vary depending on type of handle or terminal.
C. Dimensions taken from bottom of the battery to the highest point on the battery. Height may vary depending on type of terminal.
Trojan's battery testing procedures adhere to both BCI and IEC test standards.

CHARGING INSTRUCTIONS

CHARGER VOLTAGE SETTINGS (AT 77°F/25°C)					
System Voltage	6V	12V	24V	36V	48V
Daily Charge	7.2 – 7.35	14.4 – 14.7	28.8 – 29.4	43.2 – 44.1	57.6 – 58.8
Float	6.60	13.2	26.4	39.6	52.8
Equalize	7.75	15.5	31.0	46.5	62.0

.028 VPC for every 10°F (5.55°C) above or below 77°F (25°C) (add .028 VPC for every 10°F (5.55°C) below 77°F and subtract .028 VPC for every 10°C above 77°F).

CHARGING TEMPERATURE COMPENSATION

.028 VPC for every 10°F (5.55°C) above or below 77°F (25°C) (add .028 VPC for every 10°F (5.55°C) below 77°F and subtract .028 VPC for every 10°C above 77°F).

OPERATIONAL DATA

Operating Temperature	Self-discharge
-4°F to 113°F (-20°C to +45°C). At temperatures below 32°F (0°C) maintain a state of charge greater than 60%.	5 – 15% per month depending on storage temperature conditions.

TERMINAL CONFIGURATIONS

5	LT	L-Terminal
		Terminal Height Inches (mm) 1-3/4 (43) Torque Value in-lb (Nm) 100-120 (11-14) Through-hole Diameter (mm) 3/8 (10)

Figure C-1: Trojan T105 Battery Data Sheet Page 1

T105-RE DATA SHEET

BATTERY DIMENSIONS (shown with LT)

TROJANT105-RE PERFORMANCE

PERCENT CAPACITY VS. TEMPERATURE

Trojan batteries are available worldwide through Trojan's Master Distributor Network. We offer outstanding technical support, provided by full-time application engineers.

For a Trojan Master Distributor near you,
call 800.423.6569 or + 1.562.236.3000 or visit www.trojanbattery.com
12380 Clark Street, Santa Fe Springs, CA 90670 • USA

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Page 2 of 2

Figure C-2: Trojan T105 Battery Data Sheet Page 2

Appendix D

Boost Converter for the Distribution network and Battery Bank Specifications

Product Description

Specification:

Module Properties: Step-up / Boost DC-DC Converter

Input Voltage: DC 10 ~ 60 V

Output Voltage: DC 12 ~ 80 V (adjustable, O/p Voltage > I/p Voltage by 2V)

Output Current: 10A Max

Input Current: 15 A Max(Under normal circumstances please 12A Current)

The minimum voltage difference: 2V

Output Power: input 12V Max 120W, in 24V Max 240W, in 60V Max 600W ($P=U * I$)

Efficiency: 95% Max (eg input :30V output: 40V 5A n: 93%)

Output Short-circuit Protection : yes

Input Reverse Protection: None

Size: 85 x 63 x 64 mm (L*W*H)

Weight: 250g

Figure D-1: Boost Converter for the Distribution network and Battery Bank description

Appendix E

SMA SUNNY BOY 10000TL-US Inverter Datasheet

SUNNY BOY 8000TL-US / 9000TL-US / 10000TL-US

SB 8000TLUS-10 / SB 9000TLUS-10 / SB 10000TLUS-10

TRANSFORMERLESS TECHNOLOGY

Efficient <ul style="list-style-type: none">• Maximum efficiency of 98.3%• Transformerless, with H5 topology	High Yields <ul style="list-style-type: none">• Superior yield with OptiTrac MPP tracking• OptiCool™ active temperature management	Safe <ul style="list-style-type: none">• SMA Power Balancer for three-phase grid connection• Integrated DC load disconnect and combiner box• UL 1741/IEEE-1547 compliant	
--	--	---	--

SUNNY BOY 8000TL-US / 9000TL-US / 10000TL-US

Transformerless design, maximum yields

The new Sunny Boy TL-US series is UL-listed for North America and features SMA's innovative H5 topology, resulting in superior efficiencies of up to 98 percent and unmatched solar yields. The transformerless design reduces weight, increases the speed of payback and provides optimum value for any decentralized, commercial PV system. The Sunny Boy TL-US series for North America is the ideal choice for mid-size and large plants from 24 kWp up to the megawatt range.

Figure E-1: SMA SUNNY BOY 10000TL-US Inverter Datasheet Page 1

Technical data	Sunny Boy 8000TL-US	Sunny Boy 9000TL-US	Sunny Boy 10000TL-US
	208 V AC	208 V AC	208 V AC
Input (DC)			
Max. recommended PV power (@ module STC)	10000 W	11250 W	12500 W
Max. DC power (@ cos φ =1)	8400 W	9400 W	10500 W
Max. DC voltage	600 V	600 V	600 V
DC nominal voltage	345 V	345 V	345 V
MPP voltage range	300 V - 480 V	300 V - 480 V	300 V - 480 V
Min. DC voltage / start voltage	300 V / 360 V	300V / 360 V	300 V / 360 V
Max. input current / per string (at DC combiner box)	28 A / 28 A	31 A / 31 A	35 A / 35 A
Number of MPP trackers / fused strings per MPP tracker	1 / 6 (@ Combiner Box)	1 / 6 (@ Combiner Box)	1 / 6 (@ Combiner Box)
Output (AC)			
AC nominal power	8000 W	9000 W	10000 W
Max. AC apparent power	8000 VA	9000 VA	10000 VA
Nominal AC voltage / adjustable	208 V / –	208 V / –	208 V / –
AC voltage range	183 V - 229 V	183 V - 229 V	183 V - 229 V
AC grid frequency; range	60 Hz; 59.3 - 60.5 Hz	60 Hz; 59.3 - 60.5 Hz	60 Hz; 59.3 - 60.5 Hz
Max. output current	40 A	44 A	49 A
Power factor (cos φ)	1	1	1
Phase conductors / connection phases	1 / 2	1 / 2	1 / 2
Harmonics	< 4%	< 4%	< 4%
Efficiency			
Max. efficiency	98.3%	98.3%	98.3%
CEC efficiency	98%	98%	97.5%
Protection devices			
DC reverse-polarity protection	●	●	●
AC short circuit protection	●	●	●
Galvanically isolated / all-pole sensitive monitoring unit	–/●	–/●	–/●
Protection class / overvoltage category	I / IV	I / IV	I / IV
General data			
Dimensions (W / H / D) in mm (in)	470 / 615 / 240 (18.5 / 24 / 9)		
DC Disconnect dimensions (W / H / D) in mm (in)	187 / 297 / 190 (7 / 12 / 7.5)		
Packing dimensions (W / H / D) in mm (in)	390 / 580 / 800 (16 / 23 / 31.5)		
DC Disconnect packing dimensions (W / H / D) in mm (in)	370 / 240 / 280 (15 / 9 / 11)		
Weight / DC Disconnect weight	35 kg (77 lb) / 3.5 kg (8 lb)		
Packing weight / DC Disconnect packing weight	40 kg (88 lb) / 4 kg (9 lb)		
Operating temperature range / full power range	-25 °C ... +60 °C (-13 °F ... +140 °F) / -25 °C ... +45 °C (-13 °F ... +113 °F)		
Noise emission (typical)	≤ 46 dB(A)	≤ 46 dB(A)	≤ 46 dB(A)
Internal consumption at night	≤ 0.25 W	≤ 0.25 W	≤ 0.25 W
Topology	transformerless H5	transformerless H5	transformerless H5
Cooling concept	OptiCool	OptiCool	OptiCool
Electronics protection rating / connection area	NEMA 3R / NEMA 3R	NEMA 3R / NEMA 3R	NEMA 3R / NEMA 3R
Features			
Display: text line / graphic	●/–	●/–	●/–
Interfaces: RS485 / Bluetooth	o/o	o/o	o/o
Warranty: 10 / 15 / 20 years	●/o/o	●/o/o	●/o/o
Certificates and permits (more available on request)	UL1741, UL1998, IEEE 1547, FCC Part 15 (Class A & B), CSA C22.2 No. 107.1-2001		
NOTE: US inverters ship with gray lids.			
● Standard features o Optional features – Not available			
Revised August 2010 Data at nominal conditions			
Type designation	SB 8000TLUS-10	SB 9000TLUS-10	SB 10000TLUS-10

Accessories

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SMA America, LLC

Figure E-2: SMA SUNNY BOY 10000TL-US Inverter Datasheet Page 2

Appendix F

ABB Single Phase Overhead Distribution Transformer

Power and productivity
for a better world™ **ABB**

Figure F-1: ABB Single Phase Overhead Distribution Transformer Datasheet Page 1

Product overview

Application

The ABB overhead transformer may be used alone for the supply of a single phase load or as one of three units in a bank for the supply of a three phase load. The unit may be direct-mounted to a wooden or concrete pole, or cluster mounted on a pole for three phase use. The ABB transformers are designed for servicing residential overhead distribution loads. They are also suitable for light commercial loads, industrial lighting and diversified power applications.

Standards

All units are built in accordance with both CAN CSA C2.1-06 and CAN CSA C2.2-06, except as modified to comply with customer specifications. IEEE C57.12.20 or International Electrotechnical Commission Standard (IEC) may apply if required.

Features

- Core and coils designed for an optimum Total Ownership Cost (TOC)
- Wound core with step-lap joints for increased efficiency and lower noise levels
- "Low-high-low" windings for increased short circuit strength, efficiency and thermal strength
- Computer aided design for mechanical & electrical calculations (C.A.D.)
- Dual voltage designed to meet BIL and short circuit requirements on both connections
- Low voltage leads with embossed markings on all units with 3 LV bushings for easy reading and permanent identification on selected ratings
- Paint system meeting or exceeding the performance of the IEEE C57.12.28 Standard (para. 5.3 to 5.5 included), including the salt spray test
- Lifting lugs meeting all of the requirements of the CSA C2.1-06 and CSA C2.2-06 Standard (including feature to prevent sling slippage)
- Multiple cover clamps to ensure proper sealing and to minimize water retention on the cover edge
- Cover or sidewall mounted high voltage bushing(s) as required
- Low voltage spade or clamp type (basket) terminals as required
- Provision for surge arrester bracket, bracket available as an option
- Automatic self-resealing pressure relief valve

Dual Voltage Transformers and Taps

Dual voltage transformers have proven to be very useful for their versatility which allows lower inventories for the electric utilities

and saves on change out costs in the event of upgrading to higher system voltage. Because taps are also in common use, it is appropriate that dual voltage transformers with taps be considered. As the transformer reliability is adversely affected by the increased number of HV leads introduced by dual voltage designs, ABB recommends the following:

- Dual Voltage transformers without taps should be limited to a 4:1 ratio (eg 2.4 x 8.0 kV)
- If taps are required on both connections, the voltage ratio should be 2:1

Accordingly, ABB recommends that:

- (1) dual voltage transformers without taps be limited to a maximum HV spread of 2400V x 8000V, or 4800V x 16000V, and that
- (2) transformers with taps (for both connections) be limited to a maximum spread of 2:1, for example 7200V x 14400V, or 8000V x 16000V.

Pole Mounted Transformers, Rating Details

General technical information is listed below. Information on less common requirements can be obtained through your ABB sales representative.

- kVA: 10, 15, 25, 37, 50, 75, 100, 167
- Temperature rise : 65 °C
- Cooling type : ONAN
- Single Phase
- Hertz : 60, 50
- Polarity : Additive or Subtractive
- Primary Voltage : 2400V through 34500 GrdY / 19920V
- Secondary Voltage : 120 / 240V, 240 / 480 V, 347V, 600V
- Insulation Class : 25kV (150kV BIL) and below
- Taps: none, or as an option, 4 x 2.5% HV (any combination of full capacity above nominal and /or reduced capacity below nominal)

Options

- Four HV winding taps complete with externally operated tapswitch
- Dual voltage primary complete with externally operated voltage switch
- Extra creep bushing
- Surge arrester bracket
- Internal Fault Detector (IFD)
- Non conductive transformer cover
- Biodegradable vegetable oil (BIOTEMP®)
- Stainless steel tank and cover

2 Single phase overhead distribution transformers

Figure F-2: ABB Single Phase Overhead Distribution Transformer Datasheet Page 2

Outline Drawings

The influence of the loss evaluation formulae on transformer designs will lead to a wide variety of sizes and weights, thereby making it difficult, for the purpose of this information sheet, to cover the broad range of dimensions.

Typical Dimensions (mm) for grain oriented electrical design

KVA	A	B	C	D	Mass (kg)	Oil (litres)
10	885	560	500	525	100	22
25	935	610	560	590	160	30
50	1035	710	635	675	260	60
75	1035	710	745	840	375	90
100	1135	815	770	965	555	100
167	1335	1015	795	890	690	160

Single phase overhead distribution transformers 3

Figure F-3: ABB Single Phase Overhead Distribution Transformer Datasheet Page 3