DC House Model Design and Construction

A Senior Project

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By

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Abstract

The purpose of this project is to construct a prototype of the DC House. More specifically, this project focuses on the development and construction of the power distribution system of the DC House. The system will be put in place starting from the source side model down to the load side modeling of the DC House. The result of this project serves as proof of concept or demonstration of the DC House system.

I. Introduction

There are many definitions for engineering, but a certain version is strongly considered in this project. Engineering consists of using science, mathematics and technology to make systems which will ultimately improve the quality of human life. The DC Power House project is one of humanitarian value. According to the Global Issues Organization, approximately 1.6 billion people (one quarter of humanity), mainly in Asian and African countries, currently live without electricity [1]. The only sensible solution to their energy problems is the use of renewable energy in an off-grid, autonomous home which is powered directly by direct current, rather than alternating current coming from a power line which probably cannot be found nearby. Using renewable energy can help the environment and foster the economy. New technology makes renewable energy (DC power) a promising source of electricity generation.

Why use DC power over AC power? To put it shortly, it is a sensible method for this application. Unlike the United States, where our electrical/geographical infrastructure and electronic appliance market is built on AC power production and transmission, it makes more sense to use DC power in developing countries since most places are geographically close and not as spread out as seen in larger countries. It is not necessarily dangerous to use DC power for short distance transmission in these developing countries, whereas it would be significantly dangerous to use it in large countries such as the U.S. where the distance between grid-tied energy sources and homes are much greater, i.e. the distance between a nuclear power plant and a home several miles away. Since renewable energy sources typically generate DC power, it is more viable to directly utilize this power in a stand-alone house nearby, eliminating the cost of large, expensive equipment such as alternators, inverters, AC-DC rectifiers, AC-DC converters inside appliances. Ultimately, this would eliminate the need for large transmission lines and

substations for distribution of AC power, which are unheard of in many villages and small towns in developing countries. 12V DC appliances are relatively inexpensive compared to AC appliances because they do not require buck AC-DC converters to step down 120VAC from the wall outlet to the 12VDC required by the appliance, for example. Current efficiencies in DC-DC converters, and the possibility of efficient Multi-Input Single-Output (MISO) DC-DC converters, allow small-scale DC power systems to efficiently provide power to homes which only demand the basic necessities such as low-power cooking devices and small refrigeration units.

There are many advantages for using DC power for short distance transmission. DC systems do not introduce a reactance in the line, thus reduce the amount of resistance in the line and reduce losses; power calculations and system analysis are simpler because there are no complex numbers – only a real component [2]. Frequency is zero in DC systems, thus no frequency variation to monitor, and network connection does not require synchronization or balance of system (BOS). There is no susceptance in the line of a DC system, thus the effects of charging current are negligible. Only two conductors are required in a DC system, rather than three for an AC system, thus reducing cost of copper wire. DC systems do not experience inductance, resulting in a smaller voltage drop than in AC systems for the same load; hence, DC systems have a better voltage regulation. DC systems do not experience the skin effect; therefore, the entire cross-sectional area of the line conductor can be utilized. AC systems require more insulation in the transmission lines than DC systems because of greater potential stress for the same working voltage; therefore, DC systems are less expensive in that aspect. The presence of capacitance in AC systems leads to greater power loss due to the charging/discharging of capacitance. As long as DC systems are able to efficiently transform voltages to other levels, DC transmission systems can be more efficient, more stable, as well as easier to monitor and analyze, as opposed to AC systems [2].

II. Background

DC House Project Overview

The model design of the DC House must consider several variables. The purpose of the DC House is to develop a low-cost method of generating DC power and providing it to small village homes in developing countries where electricity is not available or affordable. The hardware needed for the DC system must be affordable and feasible. Therefore, the specific components of the DC House must be chosen to appropriately accommodate the energy demand of the family while considering their fiscal circumstances. Ultimately, the DC House has the potential to improve the lifestyles of many unfortunate villages around the world. The basic model design of the DC House is shown in Figure 2-1, which illustrates the various types of DC power generation, including: photovoltaic, wind power, micro-hydroelectric, and human-generated.

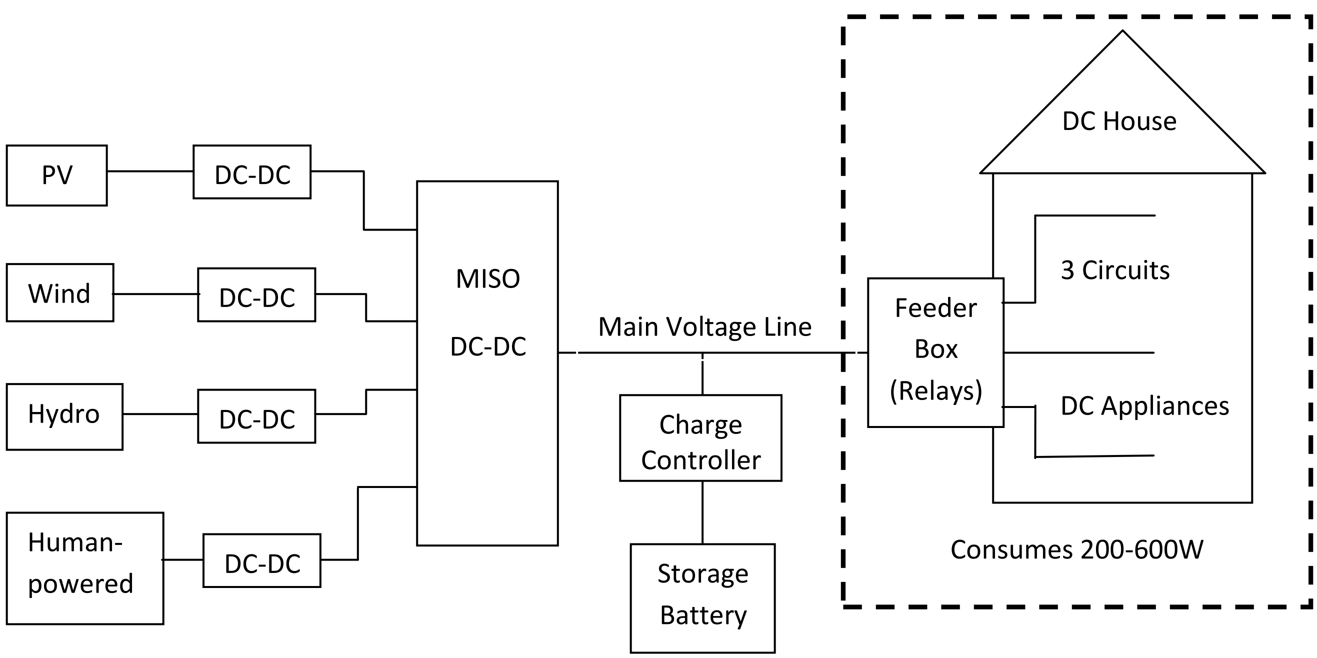

Figure 2-1: System Block Diagram of DC House Model Design

As seen in Figure 2-1, four renewable sources of energy are each connected to their respective boost DC-DC converters which step up the voltage from approximately 12V at the output of the renewable energy systems to an intermediate voltage of 24V. This intermediate voltage from the several outputs then becomes an input to the Multi-Input Single-Output (MISO) DC-DC converter, which sums the total power produced on the generation side and steps up the voltage again at the output while maintaining this power at certain efficiencies. However, since the MISO momentarily does not exist on the market (currently being designed by another student involved in the DC House project), another less-efficient design will be used to interface the generation side with the load side of the model in the mean time, which will be discussed later in this report. In this system, the main system voltage is 48V, which has been found to be the most efficient voltage for a system of this size. The main voltage line is connected to a charge controller and a battery with a certain capacity to store excess renewable energy produced not being used by the house. Therefore, if the residents of the home are using little or no power for a certain period of time, excess energy that is produced can be stored in the batteries for later use when certain resources such as the sun and wind are momentarily unavailable. The battery charge controller simply controls the charging and discharging of the battery according to energy production and current demand for consumption. The main voltage line is also connected to the house via a feeder box, which contains a few circuit breakers and fuses to control the distribution of power to home and protect the system from ground faults inside the home. It has been determined that three is the optimal number of circuits to be used for powering the appliances in the home. The DC appliances in the DC house must be chosen carefully to consume low power while sufficiently satisfying the basic needs for the residents.

III. Requirements

Objective

The objective is to design and construct a simple model of the DC House to exemplify its functionality. The main goal is to determine what major components are needed to make the DC system functional and affordable. Some of the major components that need to be identified in this project include: DC-DC converters, batteries storage and charge controller, feeder box with circuit breakers and fuse, and appliances. The momentary goal is not to design an efficient DC house, but to build one which is functional; the purpose is to prove that the system works.

Targets

In order to complete the objective of this project, the following targets must be addressed:

1. Choose a method to model the wind and hydro power generation systems.
2. Choose appropriate DC-DC converters to boost voltage from renewable energies.
3. Purchase batteries with enough capacity to store excess renewable energy and power the DC house for at least 12 hours without energy generation.
4. Purchase a battery charge controller to control the charging and discharging of current from the storage batteries.
5. Design the feeder box circuit which uses circuit breakers to distribute power to the circuits inside the DC house and to protect the entire system in case of a ground fault or short circuit inside the home.
6. Choose appropriate lighting and basic appliances that will be used inside the home. Appliances must be affordable and energy efficient.

Organization of Project

The timeline of milestones for this project have been organized in compliance with the targets set above. Figure 3-1 shows the general outline of the organization of this project.

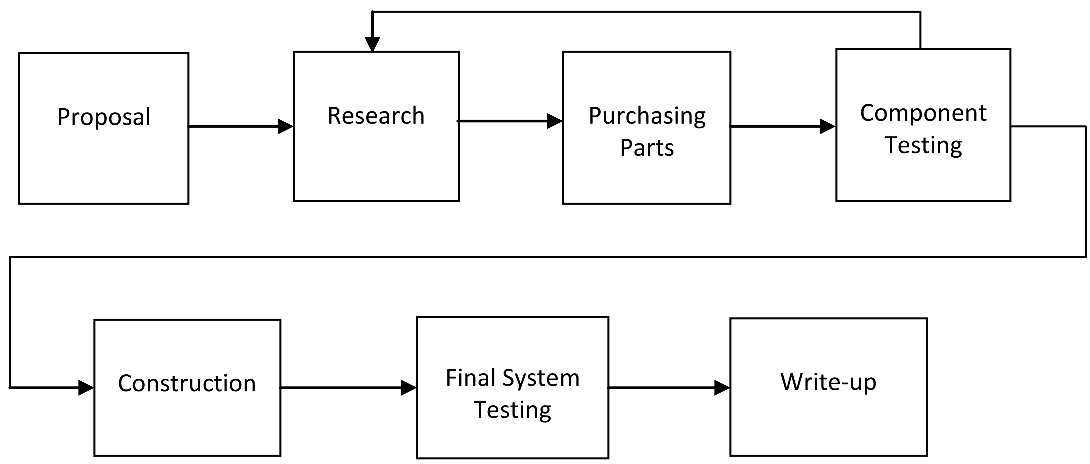

Figure 3-1: General Flow of Project Organization

Table 3-1 shows the dates for completion of each milestone.

Table 3-1: Timeline of Project Milestones

Task	Start	End	Duration (Days)
Research	1/11/2012	2/27/2012	47
Adjustable Speed Drives	1/11/2012	2/27/2012	47
DC Generators	1/16/2012	2/27/2012	42
DC-DC Converters	1/16/2012	2/27/2012	42
Storage Battery	1/16/2012	2/27/2012	42
Circuitry and Appliances	1/16/2012	2/27/2012	42
DC Bus	1/23/2012	2/13/2012	21
Software Testing	2/27/2012	4/6/2012	39
Physical Construction	3/26/2012	5/18/2012	53
Senior Project First Draft	1/23/2012	5/11/2012	102
Introduction	1/23/2012	3/9/2012	46
Background	2/6/2012	3/9/2012	32
Requirements	2/6/2012	3/9/2012	32
Design	3/5/2012	5/11/2012	67
Test Plan	4/2/2012	5/11/2012	39
Development and Construction	4/9/2012	5/11/2012	32
Intergration and Test Results	4/16/2012	5/11/2012	25
Conclusion	4/30/2012	5/11/2012	11
Bibliography	2/6/2012	5/11/2012	95

Criteria

Several criteria will be considered in the model design of the DC House. Since the purpose of this project is to provide a feasible solution for the lack of electricity in small villages throughout developing countries, the economic, social, and environmental aspects must be taken into consideration. The first criteria are to identify which desired technologies actually exist on the market, and those which do not exist at the moment; this may have an effect on the final design, which will be slightly different from the original design. The appliances in the home must be limited to consume 600W, since each of the four renewable energy sources produce a maximum of 150W. Therefore, the appliances and lighting chosen for the DC House must be very efficient. Although efficiency of the system increases as voltage increases, the system voltages of the DC House will only range between 12V and 48V (multiples of 12), since this has previously been determined to be the most efficient, economic, and safest voltages for this application. Due to constraints posed by the technology of our time, the efficiency of the DC House model will not be as good as it can possibly be, so that factor will be considered, but will not be assessed in this project.

IV. DC System: Breakdown of the Model Design

This section of the report will go over every aspect of the DC House model design. This includes details of every connection between generation and load sides, models for wind and hydroelectric power generation, what types of appliances are being used for the model, and the wire gauge for each subsystem of the model.

Generation Side

Due to current technological constraints in the area of power electronics—absence of a MISO DC-DC converter—the generation side of the first DC House model will look similar to Figure 4-1 until a more sensible solution becomes available. Components must be chosen to interface with subsequent components. Details on the temporary parallel connection of the four DC-DC boost converters will be discussed later in this report.

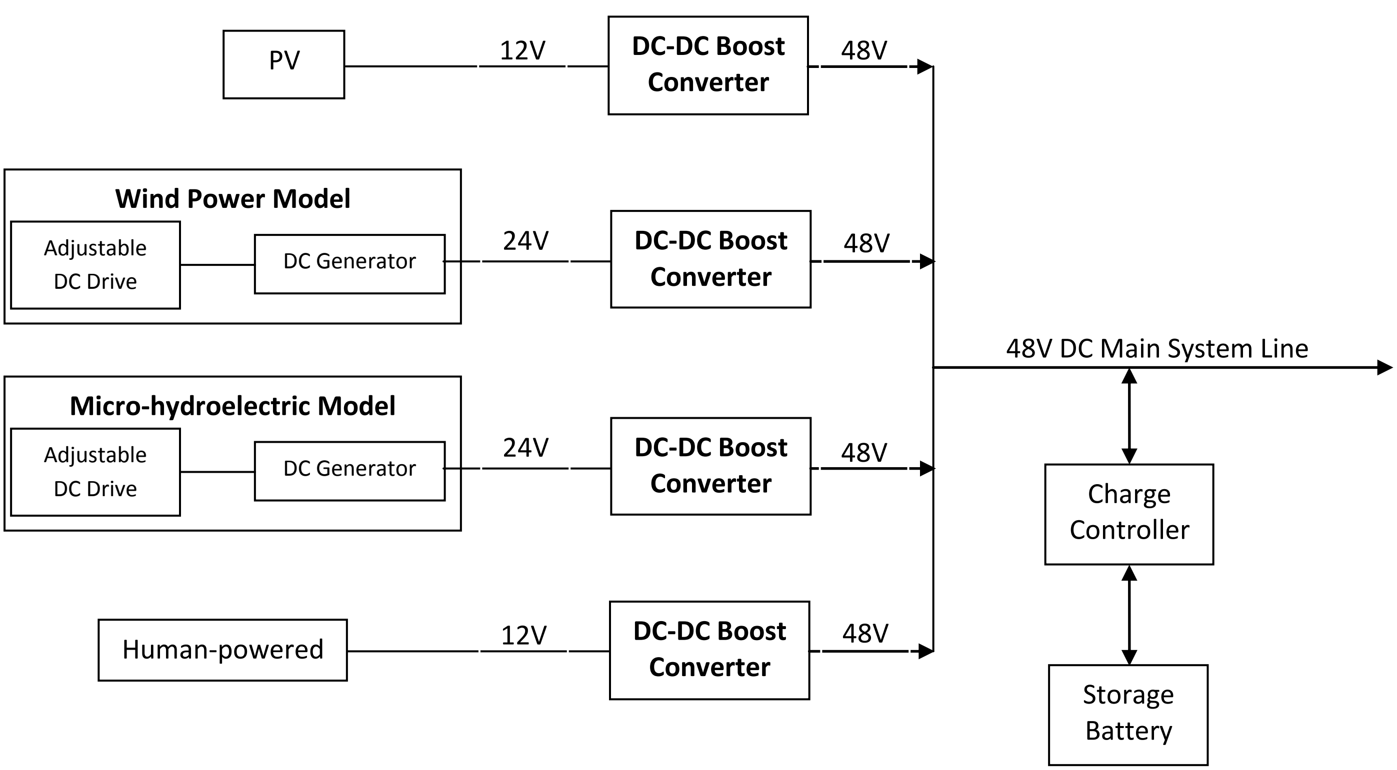

Figure 4-1a: Block Diagram of Generation Side

Modeling Wind and Hydroelectric Power Generation

In order to model the generation of energy from harvesting wind and hydro power, a permanent magnet (PM) DC generator will be used. The generators must be able to output 24V at a low speed of 100 RPM, in order to represent typical average speeds of wind and water in a stream, and at least 100W of power. The actual generators chosen for this project produce 150W from 24V at 100 RPM. Figure 4-2 shows the generators used for these models.

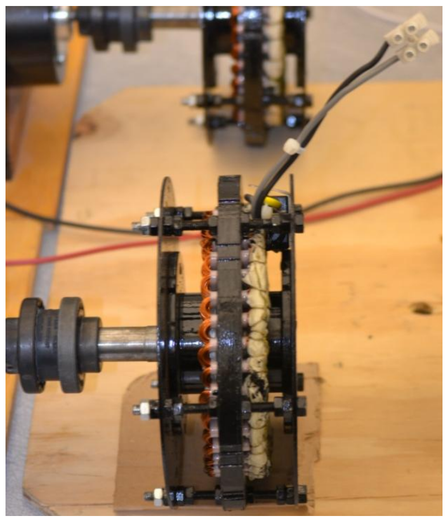

Figure 4-2: PM DC Generator

Next, a PM DC motor and a DC drive are needed to drive the generator. The best option for a PM DC motor for this project is the AP7402 BALDOR Industrial Motor, shown in Figure 4-3.

Figure 4-3: AP7402 BALDOR Industrial Motor

This motor has a rated armature voltage of 90VDC and rated power of ¼ HP, which equates to 186.4W (1 HP = 745.7W). The specifications for this motor are shown in Table 4-1.

Table 4-1: Specifications for AP7402 DC PM Motor

Specifications: AP7402

Catalog Number:	AP7402
Specification Number:	24A174Z107
Horsepower:	0.25
Armature Voltage:	90
Field Voltage:	90
Full Load Amps - Armature:	2.6
Full Load Amps - Field:	
RPM:	3450
Frame Size:	74-AHP-0
Service Factor:	n/a
Rating:	CONT
Insulation Class:	A
Form Factor:	n/a
Enclosure:	TENV
Baldor Type:	74P
DE Bearing:	
ODE Bearing:	
Electrical Specification Number:	24WGZ107
Mechanical Specification Number:	24LYA174
Base:	RG
Mounting:	SPL
Tach Mounting Kit:	n/a
Blower Kit:	n/a
Filter Kit:	n/a
Recommended SCR Control:	n/a

The DC drive chosen to run the PM DC motor must be selected to safely match the motor. The 15DV-E Adjustable Speed DC Drive made by Dart Controls, shown in Figure 4-4, is a perfect match for the BALDOR Industrial Motor.

Figure 4-4: 15DV-E Adjustable Speed DC Drive

The 15DV-E DC Drive requires an input of 120VAC in order to produce an output voltage of up to 90VDC, which is exactly the requirement for the armature of the AP7402 BALDOR Industrial Motor. This DC drive has a rating of 1/5 HP (149.2W) at 90VDC. Figure 4-5 shows the specifications for the 15DV-E DC Drive.

13DVE Rev.A /15DVE Rev.A MODEL SPECIFICATIONS

AC Input Voltage	± 10% Rated Line Voltage
Input Voltage - 13DVE Rev.A	12 VAC or 24 VAC
- 15DVE Rev.A	120 VAC or 240 VAC
Amps - DC Output	150mA to 3 Amps
Input Frequency	50 / 60 Hertz
I.R. Compensation	Adjustable - full range
Max. Speed	Adjustable (40 - 120% of Base Speed)
Min. Speed	Adjustable (0 - 30% of Max)
Output Voltage - 13DVE Rev.A(12 or 24 VAC Input)	0-12 or 0-24 VDC
- 15DVE Rev.A(120 or 240 VAC Input)	0-105 or 0-210 VDC
Overload Capacity	200% for 1 minute
Shunt Field Voltage - 13DVE Rev.A	.75 Amp max, 10 VDC at 12 VAC
	.75 Amp max, 20 VDC at 24 VAC
- 15DVE Rev.A	.75 Amp max, 100 VDC at 120 VAC
	.75 Amp max, 200 VDC at 240 VAC
Speed Control	5K Ohm Speed Potentiometer
Speed Range	25:1
Speed Regulation	± 1% of Base Speed
Temperature Range	-10° to 40° C. Ambient (15° to 105° F.)
Transient Protection	G-Mov
Dimensions	13DVE Rev.A / 15DVE Rev.A: 3.78" wide, 5.53" high, 3.49" deep
Weight	13DVE Rev.A / 15DVE Rev.A weighs 13.76 oz.

A-5-2728C-B
LT03

Figure 4-5: Specifications for 15DV-E DC Drive

All of the parts for the wind and hydro energy models have now been selected. The configuration of these models will be described in more detail in Chapter VI.

Photovoltaic System

The solar panel chosen for the DC House model is the BP SX 150S made by bp solar. This panel is rated at 150W. It provides a max power voltage V_{mp} of 34.5V and a max power current I_{mp} of 4.35A. These specifications are given in Table 4-2.

Table 4-2: Electrical Characteristics of BP SX 150S Solar Panel

	SX 150	SX 140[2]
Maximum power (P_{max})[3]	150W	140W
Voltage at P_{max} (V_{mp})	34.5V	34.0V
Current at P_{max} (I_{mp})	4.35A	4.11A
Warranted minimum P_{max}	140W	130W
Short-circuit current (I_{SC})	4.75A	4.5A
Open-circuit voltage (V_{OC})	43.5V	42.8V
Maximum system voltage[4]	600V	
Temperature coefficient of I_{SC}	(0.065±0.015)%/°C	
Temperature coefficient of V_{OC}	– (160±20)mV/°C	
Temperature coefficient of power	– (0.5±0.05)%/°C	
NOCT[5]	47±2°C	

This panel contains 72 multicrystalline silicon solar cells connected in series. The efficiency of this module is enhanced by improved cell coating. Each cell is laminated between sheets of ethylene vinyl acetate (EVA) and high-transmissivity low-iron 3mm tempered glass. Weatherproof DC-rated plug-and-socket connectors provide reliable low-resistance connections and eliminate wiring errors. Asymmetrical cables enable side-by- side or end-to-end module placement in arrays. The frame strength exceeds requirements of certifying agencies. A photo of the BP SX150S solar panel is shown in Figure 4-6.

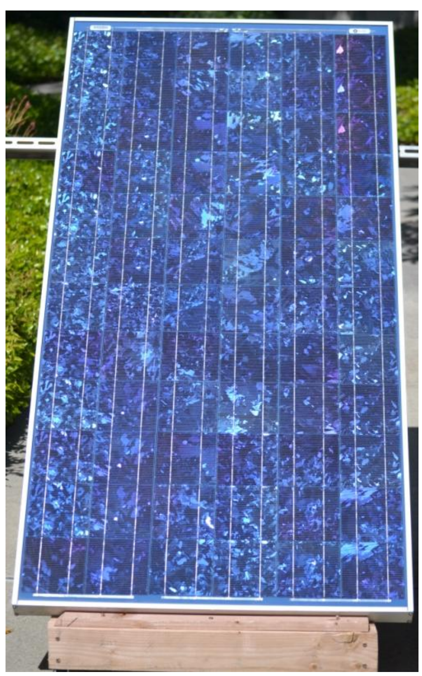

Figure 4-6: BP SX150S Solar Panel

Selecting Boost DC-DC Converters as Substitute for MISO

Since the MISO DC-DC converter is still in the design stage, an alternate configuration will be used as a temporary substitute until the MISO design is perfected. The requirement for the boost converters is to step up the voltage from 24VDC on the generation side to a regulated 48VDC on the main system line. Figure 4-7 shows the 24V-to-48V DC-DC converter being used for this task.

Figure 4-7: 24V-to-48V (Boost) DC-DC Converter

This converter has an input voltage range of 21V to 30V and a rated current of 5A, thus a power rating of 240W. This converter must have a higher power rating than the max power output of each energy source. Each energy source is designed to produce a maximum of 150W; therefore, this converter is adequate. To verify this power rating, consider the following voltage, which calculates the power rating based on regulated output voltage and output current rating:

$$P_{rated} = V_{out} \times I_{rated} = 48V \times 5A = 240W \tag{4-1}$$

where:
P_{rated}: rated power of the converter;
V_{out}: regulated output voltage;
I_{rated}: rated output current.

One method of transforming power from several different converters to a main system line is to use a parallel DC-DC converter configuration which involves the use of Super Barrier

Rectifier (SBR) diodes. The SBR diodes, which act as OR diodes, are used to protect each converter in case of a short at the output. OR FETs could alternatively be used to reduce power dissipation and voltage drop. However, this method will not be used for this project. Figure 4-8 illustrates the parallel configuration of the four DC-DC converters.

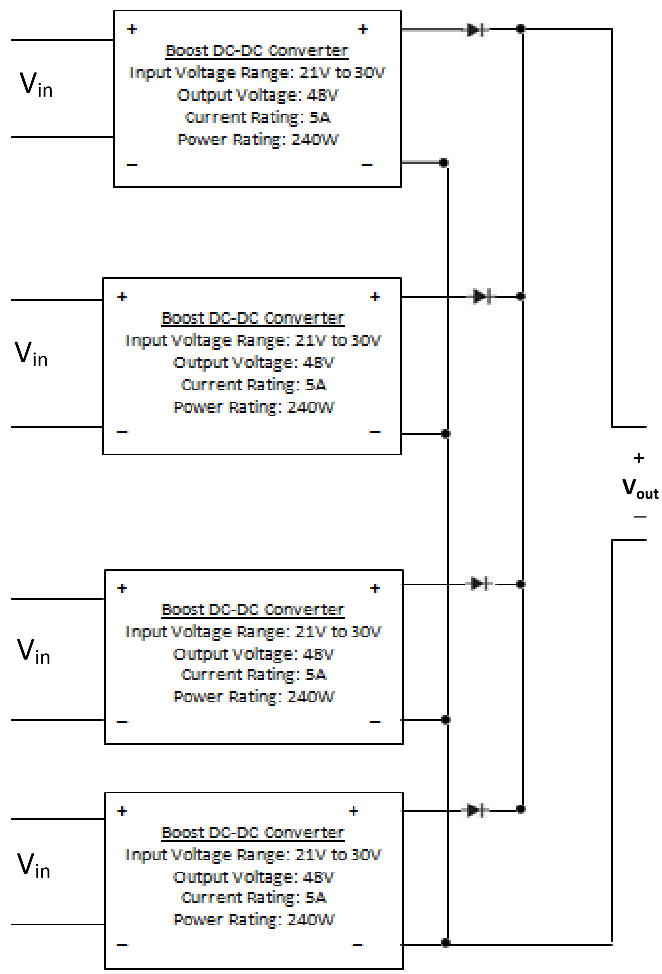

Figure 4-8: Parallel DC-DC Module Configuration

However, the main downside with this parallel DC-DC converter configuration is that only one source–the one with the highest input voltage–will transmit power to the output. The OR diodes detect which input is at a higher voltage and then allows current to flow through that diode. Another disadvantage of using diodes for protection is voltage drop across the diode (before the output) and power dissipation in the diode itself. Thus, this will have a negative, yet

small affect on the efficiency of the system. However, efficiency is not the scope of this project, so this factor will not be considered for now. One advantage to using this parallel configuration is redundancy to ensure that the system remains functional should a single module fail.

The part number for this SBR diodes used for this project is SBR30A40CT and the case number is TO-220AB. These SBR diodes come in pairs of two on each of these chips. Therefore, only two of these devices will be used for a total of four diodes. Figure 4-9 illustrates the packaging of the diode and the package pin out configuration.

Figure 4-9: SBR30A40CT Package Pin Out Configuration

Figure 4-10 shows the layout directly drawn on the packaging of the SBR.

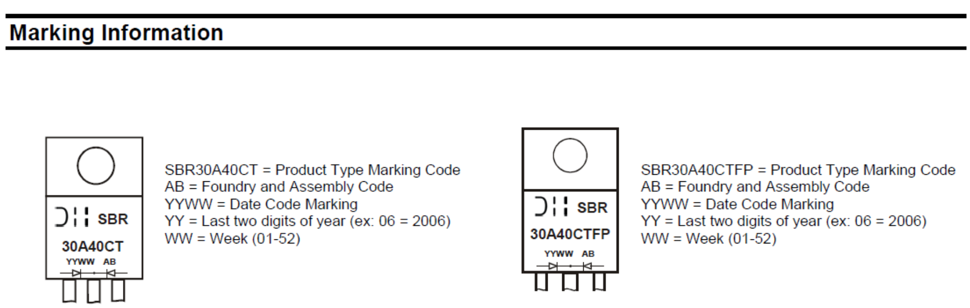

Figure 4-10: Marking Information for SBR30A40CT

This shows that the diodes are cathode-connected. The output will be connected at the cathode region which is in between the two diodes. In order to parallel the output of these diodes with another set of diodes, they must be connected to the output of another set of diodes.

Next, the voltage drop across the diodes must be checked to verify that it is within tolerance for the main system line. The rated output current of each boost DC-DC converter is 5A, which does not exceed the current rating of the SBR diodes, which is 30A. Table 4-3 lists all of the maximum ratings of the SBR30A40CT diodes and Table 4-4 lists its electrical characteristics such as forward voltage drop and leakage current.

Table 4-3: SBR30A40CT Maximum Ratings

Maximum Ratings @T_A = 25°C unless otherwise specified

Single phase, half wave, 60Hz, resistive or inductive load.
For capacitance load, derate current by 20%.

Characteristic	Symbol	Value	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_{RM}	40	V
Average Rectified Output Current @ T_C = 110ºC	I_O	30	A
Non-Repetitive Peak Forward Surge Current 8.3ms Single Half Sine-Wave Superimposed on Rated Load	I_{FSM}	250	A
Peak Repetitive Reverse Surge Current (2uS-1Khz)	I_{RRM}	3	A
Isolation Voltage (ITO-220AB Only) From terminal to heatsink t = 3 sec.	V_{AC}	2000	V

Table 4-4: SBR30A40CT Electrical Characteristics

Electrical Characteristics @T_A = 25°C unless otherwise specified

Characteristic	Symbol	Min	Typ	Max	Unit	Test Condition
Forward Voltage Drop	V_F	-	- 0.42	0.50 0.45	V	I_F = 15A, T_J = 25ºC I_F = 15A, T_J = 125ºC
Leakage Current (Note 4)	I_R	-	-	0.5 100	mA	V_R = 40V, T_J = 25ºC V_R = 40V, T_J = 125ºC

Notes: 4. Short duration pulse test used to minimize self-heating effect.

In order to estimate the maximum voltage drop that can be experienced across any particular diode, we must refer to Figure 4-11, which has a graph (left side) of the instantaneous forward current as a function of forward voltage drop at four different temperatures.

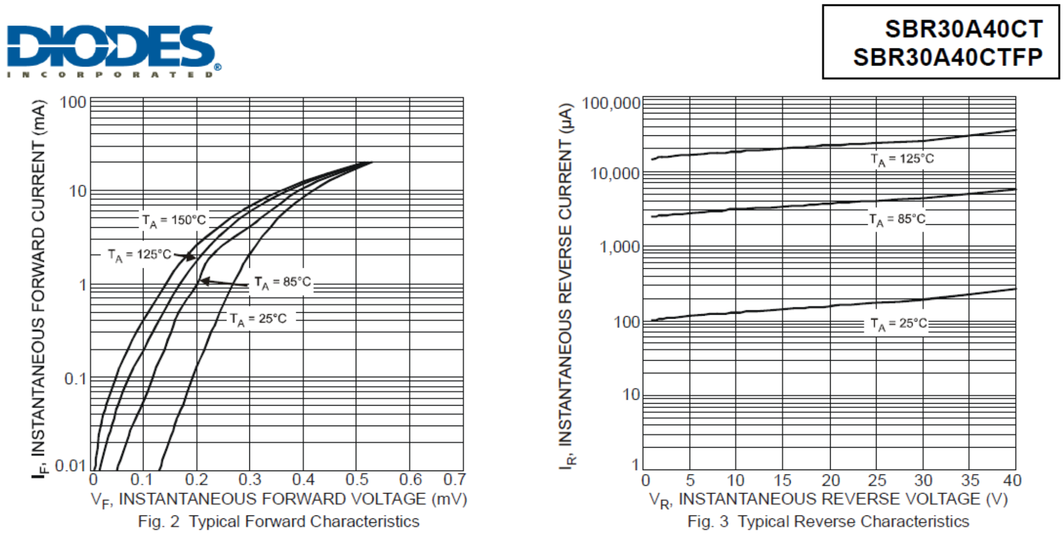

Figure 4-11: Forward and Reverse Characteristics of SBR30A40CT

Based on a max output current of 5A and choosing the worst case voltage drop temperature (T_A = 25°C), the maximum forward voltage drop across a given diode should be approximately 3.8mV. This worst case voltage drop is approximately 0.008% of the 48V DC system voltage; this is an insignificant voltage drop.

Battery Sizing and Selection of Charge Controller

The purpose of the charge controller is to control the power flow between the main voltage line and the storage/back-up battery. The battery stores excess renewable energy that is not consumed by the DC House. The battery must be able to provide enough power to the house in case the renewable sources are not producing enough energy to power the demands of the DC House. The battery must be able to supply 200W for at least 12 hours, which is approximately the average amount of time that any point on the Earth spends without sun. Therefore, the battery chosen for this model must be able to supply a minimum of 200W for 12 hours straight. The calculation for this goes as follows:

$$\text{kilowatt hours} = \text{Power} \times \text{Time} = 200\text{W} \times 12 \text{ hours} = 2.4\text{kWh} \quad (4\text{-}2)$$

where:
kilowatt hours: unit of energy supplied by battery;
Power: maximum power demanded by the load;
Time: minimum amount of time that the battery must be able to supply to the load.

This calculation establishes that the battery must have a rating of 3 kilowatt-hours. The unit chosen to meet this demand is a 12-V, Lead Calcium battery rated at 200Ah. The specifications for this battery are shown in Figure 4-12.

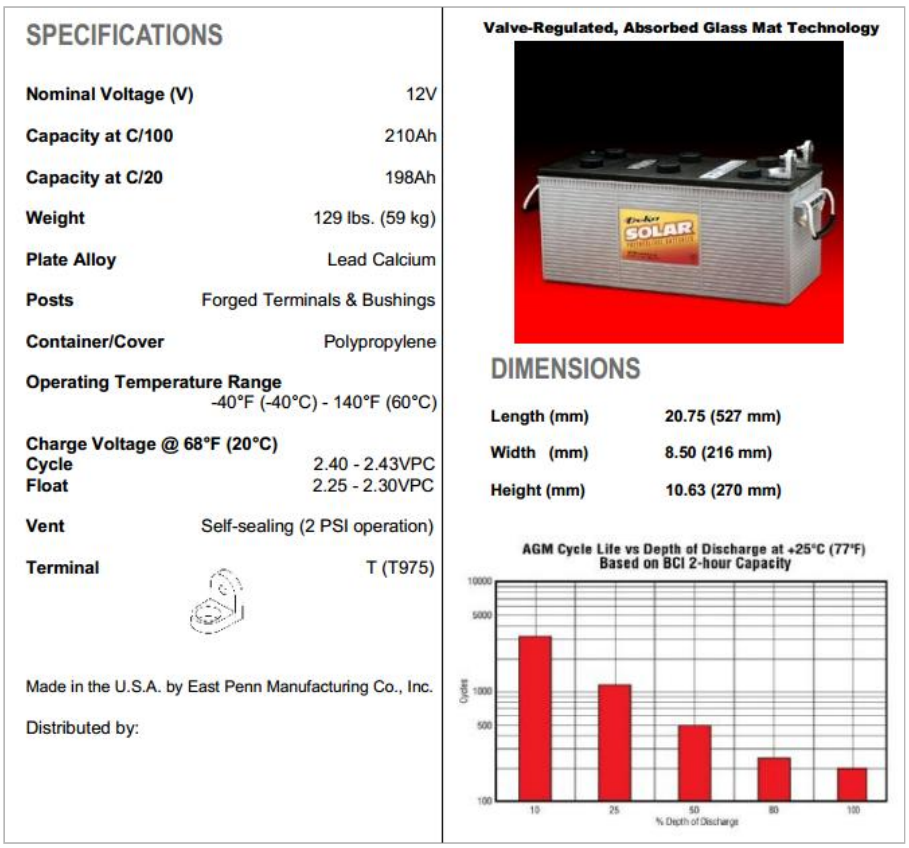

Figure 4-12: Specifications for 8A4DLTP-DEKA Battery

The following kilowatt-hour calculation proves that this battery meets the demands of the DC House:

$$\text{kilowatt hours} = \text{Voltage } \times (\text{Amp hours}) = 12\text{V } \times 200 \text{ Ah} = 2.4\text{kWh} \quad (4\text{-}3)$$

where:
kilowatt hours: unit of energy supplied by battery;
Voltage: battery voltage;
Amp hours: battery ampacity rating.

The charge controller must be able to take in power from the 48V DC bus and charge up the 12V battery, as well as discharge in the reverse order when renewable energy sources are unavailable but the DC House still demands power. The charge controller must also be able to support a certain amount of current in order to meet the demands of the DC House power consumption. The following calculation shows the maximum amperage requirement of the charge controller for 12 hours of operation, based on the capacity of the battery:

$$\text{Amperage} = \frac{\text{Amp hour rating}}{\text{Hours of operation}} = \frac{200\text{Ah}}{12 \text{ hours}} = 16.67 \text{ Amperes} \quad (4\text{-}4)$$

where:
Amperage: maximum current based on amp hour rating and required hours of battery operation.

The calculation shown in equation (4-4) shows that the charge controller must be able to discharge a minimum of 16.67A from the battery at peak demand. Therefore, the charge controller chosen for the DC House model is the VS2048N ViewStar Solar Controller, shown in Figure 4-13.

Figure 4-13: VS2048N ViewStar Solar Controller

The VS2048N is chosen for this battery because it can handle up to 20A flowing in and out of the battery, which is above the 16.67A calculated in equation (4-3). This charge controller has an input port for the solar panel or source of power, a bidirectional port for the battery to allow current to flow in and out of the battery, and an output port to power the load. The specifications table for this charge controller model is shown in Table 4-5.

Table 4-5: VS2048N ViewStar Solar Controller

Model No:	VS1048N	VS2048N	VS3048N	VS4048N	VS5048N	VS6048N
Electrical Parameters						
Nominal SystemVoltage	12V/24V/36V/48V Auto work					
Maximum Battery Voltage	32V					
Maximum PV Voltage	48V					
Rated Battery Current (A)	10A	20A	30A	40A	50A	60A
Charge Circuit Voltage Drop	≤0.24V					
Discharge Circuit Voltage Drop	≤0.16V					
Self-consumption	≤44mA					
Communication	TTL232 level /RJ45 interface					
Remote temperature sensor interface	2ERJ—3.81					
Ground	Negative to the ground					
Working temperature	-20℃~ +55℃					
Storage temperature	-30℃~ +80℃					
Enclosure	IP30					

As seen in the table above, this charge controller works automatically for systems in the range from 12V to 48V and all multiples of 12 in between. This means it will work properly between a 48V DC bus and a 12V battery. This charge controller is for off-grid (stand-alone) systems such

as the DC House. Figure 4-14 shows the features of this VS2048N ViewStar charge controller, which includes high-efficiency series pulse-width modulation (PWM) charging with temperature compensation.

Features:

- 32 bit MCU with high speed and high performance
- 12 bit A/D high-precision sampling to ensure accuracy
- Excellent EMC design
- Nominal system voltage automatic recognition
- High efficient Series PWM charging with temperature compensation
- Use MOSFET as electronic switch, without any mechanical switch
- Widely used, automatically recognize day/night
- Adopt graphics dot-matrix LCD screen and HMI (human-machine interface) with 4 buttons, integrated menu displaying and operation
- Humanized design of browser interface, undertake every operating conveniently
- Full control parameters setting and modification, diversified load control mode
- Gel, Sealed and Flooded battery type option

Figure 4-14: Features of VS2048N ViewStar Solar Controller

Distribution/Load Side

The load side is where the generated energy is distributed among three appliance circuits inside the DC House. From the 48V system line, the power is distributed to the loads inside the home via circuit breakers. Appliances are spread apart as evenly as possible into three circuits, where appliances are connected in shunt form. Figure 4-1b illustrates the general load side distribution at a high level; this does not show exact configurations of circuit breakers and appliances. Figure 4-1b is a continuation of Figure 4-1a.

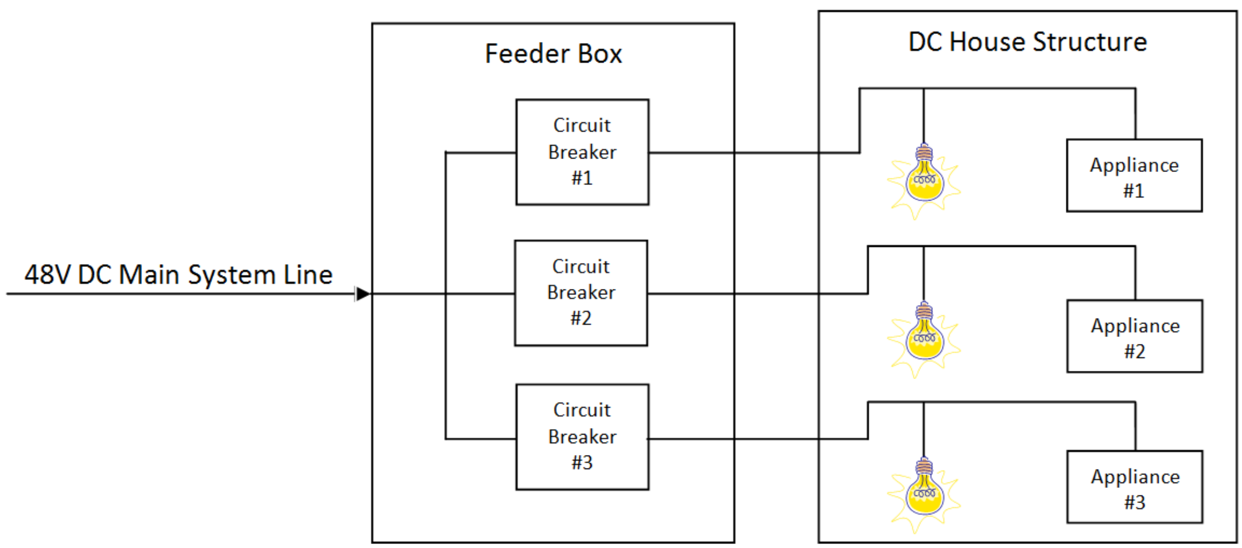

Figure 4-1b: Block Diagram of Load Side

Selecting Appropriate Appliances

Most DC appliances are 12V. The appliances chosen for the DC House must be very efficient, consume very low power, and must be practical for everyday use. These appliances include three DC lighting sources and four basic home appliances, including a small refrigerator/warmer, fan, smoke detector, and TV with AM/FM radio. There is no limit to the number of appliances that can be placed on a certain branch circuit inside the house, as long as

their current sums do not exceed circuit breaker ratings. As previously mentioned, the appliances chosen for the DC House must have some practical purpose. The mini-fridge could be used for storing medicines and important liquids; the fan is good for cooling off after a long day of work on a warm day; the smoke detector is a good safety precaution in case of a fire; the TV/radio device is a form of entertainment.

Appliance #1: Refrigerator

The first appliance selected is a little refrigerator. The brand and model chosen is the RoadPro RPSF5235 12-Volt SnackMaster Deluxe Family Size Cooler/Warmer. This is a 12-Volt appliance rated at 4.2 Amps; consumes 50.4 Watts. Its features include thick insulated walls and a double pane Plexiglass door which will hold the interior temperature constant for quite some time. With a 48-Liter (1.7 ft^3) holding capacity, this refrigerator, weighing at 18.5 lbs., is large enough to fit important medicines and liquids which need refrigeration, or other substances which even require warm temperatures such as family dinners. The dimensions are 20"H x 11 1/2"W x 12 1/4"D. The cooler/warmer takes some time (approximately 30 minutes) to cool/warm depending upon the ambient temperature. The cooler/warmer will always perform best if filled with food/beverages which have been pre-chilled or pre-heated. When the cooler/warmer has reached the desired temperature, the 12V power cord may be unplugged and taken anywhere while holding its internal temperature for quite some time. Figure 4-15 exemplifies the use of the RoadPro RPSF5235 12-Volt Cooler/Warmer.

Figure 4-15: RoadPro RPSF5235 12-Volt SnackMaster Deluxe Cooler/Warmer

Appliance #2: Fan

The next appliance chosen for the DC House is the RoadPro RP73002 10” 12-Volt portable fan. This fan can be run by plugging it into a 12V socket or by 8 D-cell batteries for up to 40 hours. There is the option of Hi or Low fan speed and the adjustable base to fine tune the air flow. The hanging hook allows secure elevated use. This fan is small with the dimensions 15"H x 11.75"W x 3"D (max depth with base flipped out 9.5"), so it can be stored just about anywhere. This 12V appliance has a rated current of 0.5A, so it only consumes a maximum of 6W. Figure 4-16 shows what the RoadPro RP73002 10” 12-Volt portable fan.

Figure 4-16: RoadPro RP73002 10” 12V Portable Fan

Appliance #3: Smoke Detector

The next appliance chosen is the ESL 429C Photoelectric 2-Wire 12/24VDC Smoke Detector. The 2-wire smoke detectors continually monitor their own sensitivity and operational status and provide a visual trouble indication if they drift out of sensitivity range or fail internal diagnostics. The ESL 429 is easily cleaned by replacing the proprietary field replaceable optical chamber. It is designed to reduce false alarms from dust, insects, RFI, and external light. An integrated silicon heat sensor and a dedicated microprocessor are used to detect heat and perform the rate-of-rise calculations. Figure 4-17 shows the ESL 429C smoke detector.

Figure 4-17: ESL 429C 12/24V Smoke Detector

This device is a 12V appliance and consumes 60mA. Therefore, the power consumption of this device is 0.72W. Table 4-6 lists the specifications of this model.

Table 4-6: ESL 429C 12/24V Smoke Detector Specifications

2-wire compatibility	S10A
Alarm Current Consumption[Nominal]	60.0 mA
Detector Head Depth[Nominal]	1.85 in
Detector Head Diameter[Nominal]	6.1 in
Field Wiring Size[Minimum]	14.0 AWG
Field Wiring Size[Maximum]	24.0 AWG
Heat Detection Specifications - Fixed[Nominal]	135.0 °F
Heat Detection Specifications - Rate of Rise	>105°F and Rate of Rise 15°F/min
Height[Nominal]	1.85 in
Maximum Ripple[Maximum]	10.0 %
Operating Humidity[Minimum]	0.0 % RH
Operating Humidity[Maximum]	95.0 % RH
Operating Temperature[Minimum]	32.0 °F
Operating Temperature[Maximum]	120.0 °F
Operating Voltage[Minimum]	6.5 V
Operating Voltage[Maximum]	20.0 V
Packaging Basis[Nominal]	10.0 per carton
Regulatory Approval	UL 268 MEA CSFM
Relay @ Contact Rating	2.0 A @ 28.0 V
Sensitivity - Photoelectric[Minimum]	0.05 %
Sensitivity - Photoelectric[Maximum]	3.1 %
Sensitivity - Photoelectric[Nominal]	3.1 %
Standby Current Consumption[Nominal]	70.0 µA

Appliance #4: TV/Radio

The last appliance being used for the DC House model is the GPX TVP2K TV/Radio. This entertainment appliance has a screen with dimensions 5.5"B × 5.5"W. It covers all UHF and VHF channels, and has a built-in AM/FM radio tuner with an antenna. This is a 12V appliance but can be powered by 10 C-cell batteries for fully portable operation. The device has dimensions 7"B × 9"W × 7"H and weighs 5 lbs. Figure 4-18 shows the GPX TVP2K Portable TV with AM/FM Radio.

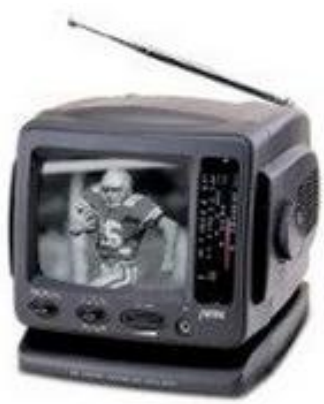

Figure 4-18: GPX TVP2K Portable TV with AM/FM Radio

LED Lighting

The DC House model needs to have a source of light for night hours. The most efficient form of lighting is through the use Light Emitting Diodes (LEDs). LED is more efficient than Compact Fluorescent (CFL) and incandescent light bulbs. Three LED strips will be used to light up the DC House. However, the lumens emitted by these LED strips must be appropriate for the size of the model. The LED strip chosen is the WLF-CW60SMD, which is 24 inches (2 feet) long, emits a cool white color, contains 60 LEDs, illuminates 180 lumens per foot (360 per unit), operates at 12V, draws 355mA, and consumes 4.26W each. Figure 4-19 shows the specification table for the WLF series LED strips.

WLF Waterproof Light Fixture

SPECIFICATIONS

All WLF series Fixtures use 3528SMD LEDs with 120° viewing angle

Part NO	Number of LEDs on Bar	Total Length Unit: cm(in)	Emitting Color	Color Temperature Unit: Kelvin	Single LED Luminous Flux Unit: lumen	Lumen / Foot	Total Lumen per Unit	Current Draw @ 12 Volts Unit: mA	Price Each** Unit: USD
WLF-CW30SMD	30	30cm (12in)	Cool White	6100	6.0	180	180	210	24.95
WLF-WW30SMD	30	30cm (12in)	Warm White	3200	5	150	150	205	24.95
WLF-CW60SMD	60	60cm (24in)	Cool White	6100	6.0	180	360	355	39.95
WLF-WW60SMD	60	60cm (24in)	Warm White	3200	5	150	300	350	39.95

* White LED Note: Correlated Color Temperature measured in Kelvin, higher numbers indicate blue/purple tint (similar to HID lamps), standard incandescent bulbs are around 3000K - all LEDs are 3528SMD LEDs with 120° viewing angle
** The following quantity discounts are available: 10% at 50+ pcs, 20% at 100+ pcs, 25% at 500+ pcs, 30% at 1000+ pcs. Click here for for info on quantity discounts
All specifications are subject to change without notice

Average Rated Life: 10,000 Hours Waterproof Rating: IP67

Figure 4-19: Specifications for WLF Series Waterproof LED Light Fixture

Next, the lumens emitted by the LED strips must be sufficient enough to light up the DC House model. The typical appropriate number of lumens required to properly light up a room is 15 lumens/ft^2. The DC House model structure has dimensions 8"L × 8"W × 8"H; however, only the length and width need to be considered. The following equation calculates the minimum number of lumens required to properly light up the room:

$$\text{Required Lumens} = \text{Length} \times \text{Width} \times 15\,\frac{\text{lumens}}{\text{ft}^2} \qquad (4\text{-}5)$$

where:
Required Lumens: the minimum amount of lumens required;
Length: the length of the room in feet;
Width: the width of the house in feet.

For a width and length of 8 feet, the minimum amount of lumens required for the DC House model structure is 960 lumens. With three LED strips, each emitting 360 lumens, the total amount of lumens provided by the LED strips is 1,080 lumens; this is 120 lumens greater than the minimum requirement. Therefore, these LED strips will sufficiently light up the room.

Overall, the main goal in choosing appropriate appliances and lighting is to choose practical ones which consume very low power. Table 4-7 outlines a summary of the power consumption of all the appliances and lighting, which sums up the total maximum power consumption of all the appliances used in the DC House model to be 70.62W.

Table 4-7: Load Summary

Appliance	Voltage (V)	Current (A)	Power (W)
Refrigerator	12	4.2	50.4
Fan	12	0.5	6
Smoke Detector	12	0.06	0.72
TV/Radio	12	0.06	0.72
3 LED Strips	12	3 × 0.355	3 × 4.26
Total:	--	5.885	**70.62**

Feeder Box Panel

The feeder box is a panel located on the outside of the DC House and contains the 48V DC distribution panel and circuit breakers. If a circuit breakers trips for one of the branch circuits in the house, then the resident knows where to go to reset the breaker.

DC Power Distribution Panel

The DC distribution panel for the DC House must be able to connect the 48V system bus to three circuit breakers, which will be connected to three branch circuits to power the appliances inside the home. The distribution panel being used for the DC House model is the NEWMAR DST-FB Combination DC Power Distribution Panel. Figure 4-20 shows the NEWMAR DST-FB DC Power Distribution Panel.

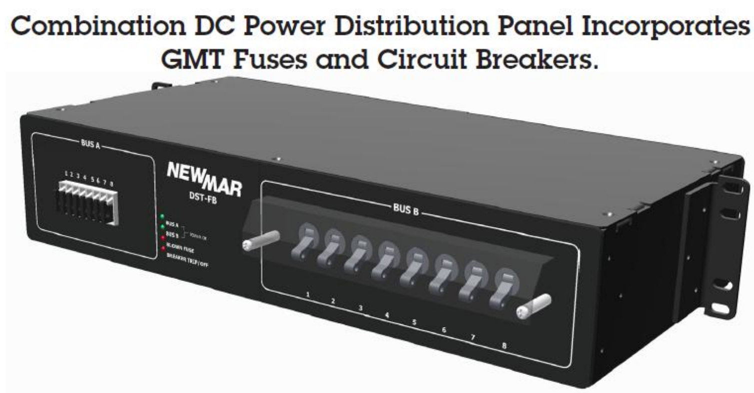

Figure 4-20: NEWMAR DST-FB DC Power Distribution Panel

This combinatorial DC power distribution panel incorporates up to eight GMT fuses on Bus A and up to ten circuit breakers on Bus B. The panel has three nominal input voltages of 12, 24, or 48VDC (positive or negative ground). Figure 4-21 shows the electrical characteristics for the NEWMAR DST-FB Combination DC Power Distribution Panel.

Electrical

Nominal Input: 12, 24 or 48 VDC, Positive or Negative ground

Total Circuit Capacity (16 total): 8 GMT fuses & 8 breakers

Dual Bus: Bus rating - 100 Amps each max.
Bus A: Feeds 8 x GMT fuses, 15 Amps max., fuse rating
Bus B: Feeds 8 x plug-in circuit breakers, 30 Amps max., breaker rating

Circuit Breaker Values: 5, 10, 15, 20, 25 & 30 amp., easy plug-in via panel front (sold separately)

GMT Fuse Values: 1, 3, 5, 7.5, 10 & 15 amp, (sold separately)

Figure 4-21: Electrical Characteristics for NEWMAR DST-FB DC Power Distribution Panel

This panel contains LEDs on the front side, which indicate whether there is power available to a certain bus, as well as if there is a blown fuse or a tripped/off circuit breaker. This panel can hold up to ten circuit breakers with values ranging from 5A to 30A.

Circuit Breakers

Power is distributed among the three appliance circuits via the DC distribution panel, which contains three circuit breakers. These circuit breakers protect the system from inrush (input surge) current caused by the loads inside the DC House. These circuit breakers are very important for protection of the system. Appliances will be shunt-connected to one of three branch circuits inside the DC House. Therefore, since current add up when loads are placed in parallel, the DC circuit breakers are chosen based on the maximum current required to power the appliances on a certain branch. The goal here is to choose a circuit breaker size just above this maximum current rating so that it trips and open-circuits that particular branch if a short circuit occurs. Another goal is to evenly split up the appliances between the three circuits based on their current ratings so that the three circuit breakers can have the same current rating. My estimation is that the current on each branch will not exceed 5A. There are four appliances and three LED strips. Each branch circuit will have a combination of an appliance (or two) and an LED strip in order to evenly space them out. The two appliances with the smallest current ratings will be placed on one circuit with an LED strip. The remaining two appliances will be placed on separate branches, each with an LED strip. Branch #1 will consist of the two appliances with the smallest current ratings are the smoke detector and the TV radio. According to Table 4-7, their currents combined with the current of one LED strip add up to 475mA; this definitely does not exceed 5A. Branch #2 will consist of the fan and an LED strip; their currents

add up to 855mA. Branch #3 will consist of the cooler/warmer and an LED strip; their currents add up to 4.555A, which is below 5A. This confirms that 5A circuit breakers will be adequate for the DC distribution panel. Figure 4-22 shows the type of plug-in circuit breaker that will be used on the DC Distribution Panel, which is rated at 5A.

Figure 4-22: Plug-in, 5A Circuit Breaker

Buck DC-DC Converters

Buck DC-DC converters are needed to step down the system voltage (48V) from the distribution panel to 12V for the appliances on the branch circuits inside the home. Each branch circuit needing 12V for the appliances requires one of these. Since each branch consists of 12-V appliances, three of these buck converters will be needed. Figure 4-23 shows the buck converter being used for the appliances.

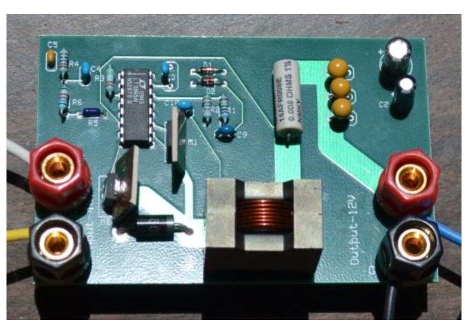

Figure 4-23: Buck Converter for Appliances (48V to 12V)

Wire Sizing

The goal in choosing wire size is to choose the gauge which will provide sufficient ampacity and power, as well as minimum voltage drop. By rule of thumb, the voltage drop across a wire should not exceed 2% of the system voltage. For short distances, the larger the wire, the less voltage drop occurs due to insignificant resistance in the wire; this is the case for the DC House. Smaller wire gauge, as well as smaller distance the wire is required to extend, results in lower cost for wiring the system. The following equation is used to calculate appropriate wire sizes for the direct current system.

$$\%VD = \frac{0.2Id(\frac{\Omega}{kft})}{V_S} \qquad (4\text{-}6)$$

where:
%VD: voltage drop based on the percentage of the main system voltage;
I: maximum ampacity of the wire in amperes;
d: distance that the wire extends in one direction;
V_S: system or source voltage;
(Ω/kft): wire resistance per kilofoot.

The maximum current coming out of any section of this system is based on the maximum output power and the output voltage. The maximum output current from the PV is 4.35A. The maximum output current from the permanent magnet DC generators is 6.25A (150W/24V_{out}). The output current rating of the boost DC-DC converters is 5A. Since the main system line only takes power from the boost DC-DC converter with the highest output voltage, the maximum current that can exist on the main system line is 5A. With the current arrangement of appliances on the branch circuits inside the home, the current on each branch should not exceed 5A. It was previously calculated that the current between the battery and the charge controller should not exceed 16.67A. However, this would require a large wire size. As seen in Table 4-7, the total currents of the appliances in the DC House add up to 5.855A. Therefore, the

maximum possible current being drawn from the battery and onto the main system line should not exceed 5.9A. The goal here is to choose one wire size that will work for the entire DC system. Table 4-8 shows the American Wire Gauge (AWG) cable/conductor sizes, which is based on the National Electrical Code (NEC).

Table 4-8: American Wire Gauge (AWG) Cable/Conductor Sizes and Properties

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
0000 (4/0)	0.46	11.684	107	0.049	0.16072	302	125 Hz
000 (3/0)	0.4096	10.40384	85	0.0618	0.202704	239	160 Hz
00 (2/0)	0.3648	9.26592	67.4	0.0779	0.255512	190	200 Hz
0 (1/0)	0.3249	8.25246	53.5	0.0983	0.322424	150	250 Hz
1	0.2893	7.34822	42.4	0.1239	0.406392	119	325 Hz
2	0.2576	6.54304	33.6	0.1563	0.512664	94	410 Hz
3	0.2294	5.82676	26.7	0.197	0.64616	75	500 Hz
4	0.2043	5.18922	21.2	0.2485	0.81508	60	650 Hz
5	0.1819	4.62026	16.8	0.3133	1.027624	47	810 Hz
6	0.162	4.1148	13.3	0.3951	1.295928	37	1100 Hz
7	0.1443	3.66522	10.5	0.4982	1.634096	30	1300 Hz
8	0.1285	3.2639	8.37	0.6282	2.060496	24	1650 Hz
9	0.1144	2.90576	6.63	0.7921	2.598088	19	2050 Hz
10	0.1019	2.58826	5.26	0.9989	3.276392	15	2600 Hz
11	0.0907	2.30378	4.17	1.26	4.1328	12	3200 Hz
12	0.0808	2.05232	3.31	1.588	5.20864	9.3	4150 Hz
13	0.072	1.8288	2.62	2.003	6.56984	7.4	5300 Hz
14	0.0641	1.62814	2.08	2.525	8.282	5.9	6700 Hz
15	0.0571	1.45034	1.65	3.184	10.44352	4.7	8250 Hz
16	0.0508	1.29032	1.31	4.016	13.17248	3.7	11 k Hz
17	0.0453	1.15062	1.04	5.064	16.60992	2.9	13 k Hz
18	0.0403	1.02362	0.823	6.385	20.9428	2.3	17 kHz
19	0.0359	0.91186	0.653	8.051	26.40728	1.8	21 kHz
20	0.032	0.8128	0.518	10.15	33.292	1.5	27 kHz
21	0.0285	0.7239	0.41	12.8	41.984	1.2	33 kHz

According to Table 4-8, AWG No. 14 has an ampacity of 5.9A, which is the maximum current on the main system line. This wire size will be used for every segment of the system. Next, the maximum length of wire that can be used for the model will be calculated using Equation 4-6. Solving for d, assuming a voltage drop of 2%, a system voltage of 12V (worst case), a maximum current of 5.9A, and given a wire resistance of 2.525 Ω/kft for AWG No. 14, the maximum allowable wire distance for the model is 8 kft or 8,000 feet. The model will not use anywhere near this amount of wire since everything component, including the solar panel and generators,

will be located in close proximity to the DC House model. Therefore, wire size AWG No. 14 will be a sufficient wire size for this model and voltage drop can be considered negligible.

Final System Design

The final system design consists of all of the previous parts mentioned in that general order. Figure 1-a connected with Figure 4-1b shows the completed system block diagram of the DC House model. Figure A-1, found in Appendix A, illustrates the general connection of components for the DC House model. More details on the construction of this model will be described in Chapter V.

V. Component Testing

In order to have a good understanding of the system, each component must be tested for their electrical and/or mechanical characteristics. Such components which require immediate testing include the appliances and LED lighting, solar panel, parallel (boost) DC-DC converters, and the generators (wind and hydro models). These characteristics will help determine if the system will work.

Testing Appliances and LED Lighting

The 12-Volt appliances and LED light strips were tested by applying 12VDC to them with a power supply. Each appliance was tested on each setting and intensities for ten minutes; all appliances functioned properly.

Testing the Solar Panel

The solar panel was tested by loading the output of the panel with a series of power resistors and measuring the voltage across that particular resistance. From that voltage, the current and power were calculated. All relationships were plotted afterwards. The data points that were recorded are displayed in Table 5-1.

Table 5-1: Data for Electrical Characteristics of BP SX150S Solar Panel

Load Resistance (Ω)	Current (A)	Voltage (V)	Power (W)
22.5	1.75	39.38	68.91
18.4	1.93	35.51	68.54
16.3	2.14	34.88	74.65
13.8	2.43	33.53	81.49
13	2.78	36.14	100.47
10.9	3.32	36.19	120.14
7.4	3.91	28.93	113.13
5	4.05	20.25	82.01
2.9	4.15	12.04	49.95
0	4.47	0.00	0.00

Table 5-2 shows the measured short-circuit current and open-circuit voltage. The short circuit current is very close to what is on the PV nameplate, but the measured open circuit voltage is off by 5.8V of what is on the nameplate.

Table 5-2: Measured Open-circuit Voltage and Short-circuit Current of BP SX150S Solar Panel

Measured Data	
I_{SC} (A)	4.47
V_{OC} (V)	37.7

Figure 5-1 plots the output power of the BP SX150S solar panel as a function of resistance.

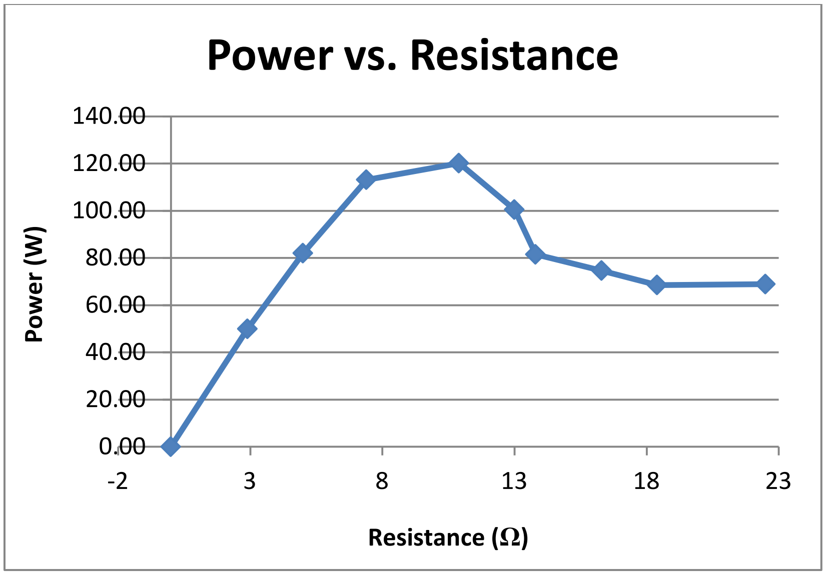

Figure 5-1: Power vs. Resistance Plot of BP SX150S Solar Panel

The panel was tested with a resistance ranging from 0 to 22.5Ω. From this plot, it is apparent that the power peaks at 120.14W at a voltage of 36.19V, a current of 3.32A, and a resistance of 10.9Ω. Figure 5-2 plots the output current of the BP SX150S solar panel as a function of resistance, which correlates to Figure 5-1.

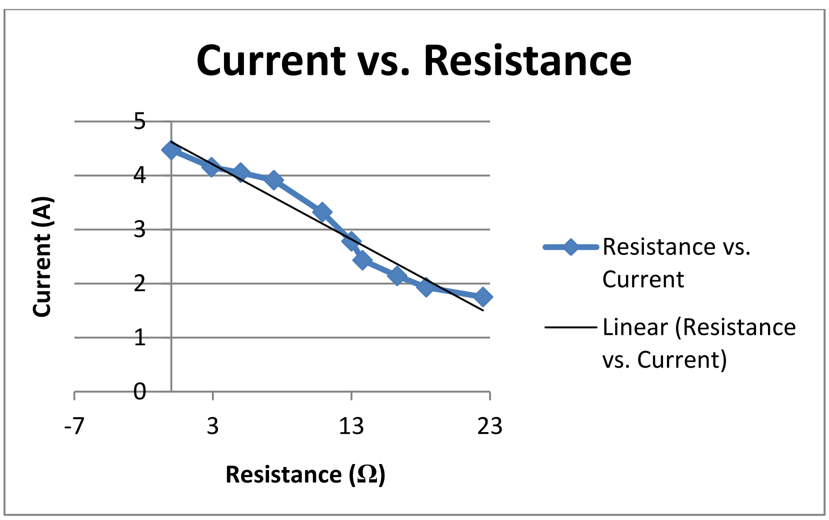

Figure 5-2: Current vs. Resistance Plot of BP SX150S Solar Panel

Figure 5-3 plots the output current for the BP SX150S solar panel as a function of voltage.

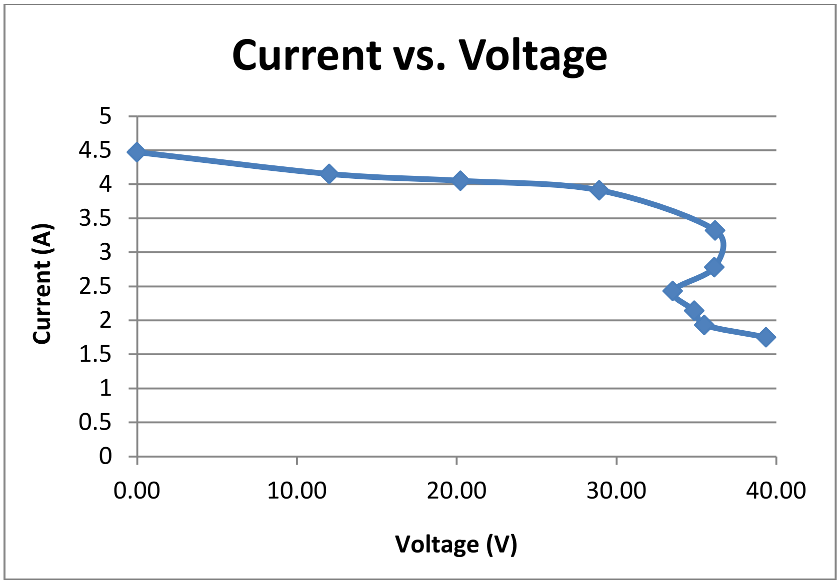

Figure 5-3: Current vs. Voltage Plot of BP SX150S Solar Panel

Testing the Parallel DC-DC Converter Configuration

Once the boost DC-DC converters are arranged in parallel with four inputs and one output, it must be tested to verify that the module will output 48V when there is an input to one of the booster modules. The tests consist of using the generators to provide a 24V input to parallel converters. First, one generator was hooked up to one of the boost converters in the parallel DC-DC converter configuration. Using a digital multimeter, the speed of the motor must be adjusted to approximately 100 RPM so that the output voltage of the generator is 24V. Then, a digital multimeter is used to check the output voltage of the parallel DC-DC converters. With one or two generators connected, the output voltage ranges between 47.2V and 47.8V. This voltage drop is caused by the voltage drop across the diodes in the parallel DC-DC converter configuration (Figure 4-8). The maximum voltage dropped that was recorded at the output of the parallel DC-DC converter configuration was 0.8V. This voltage drop is less than 2% of the system voltage (48V); a 2% voltage drop in this system would be 0.96V. Therefore, this 0.8V voltage drop will not affect the functionality of the system.

Testing the Generators

The generators must be tested to verify that they output 24V and 150W at 100 RPM at full load. The speed of the generator was tested to see what the speed is when providing 24V to full load. The Ametek 1891 Digital Tachometer, shown in Figure 5-4, was used to measure the rotor speed of the permanent magnet DC generators.

Figure 5-4: Ametek 1891 Digital Tachometer

Both generators were tested and verified that they output 24V at 100 RPM with no load and full load. Both generators tested consistent with the specifications. A multimeter was used to test the voltage at the output of each generator.

VI. Development and Construction

The construction of the DC House model mainly consists of preassembling subcomponents together to make the main components, then piecing together all main components. The first step is to assemble the boost DC-DC converters in parallel using the SBR diodes in the configuration shown in Figure 4-8. Figure 6-1 shows the completed setup of the parallel DC-DC converters.

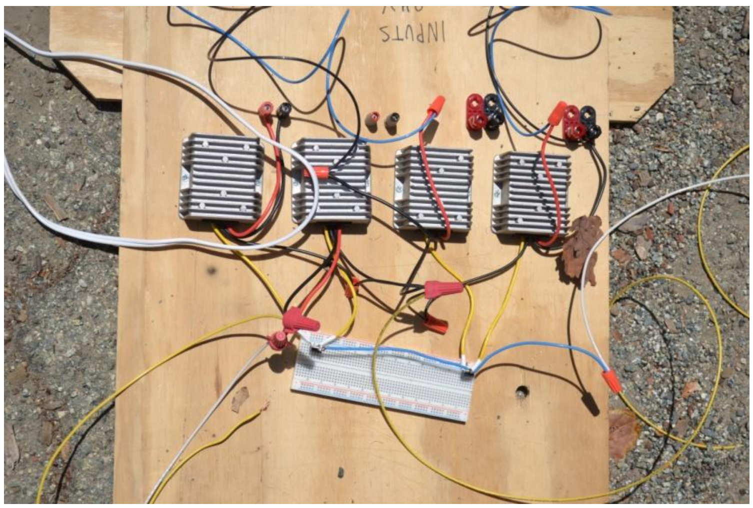

Figure 6-1: Assembled Setup of Parallel DC-DC Converters

The next step is to complete the setup of the wind and hydro models. Each model consists of its own adjustable speed DC drive, permanent magnet (PM) DC motor, and permanent magnet (PM) DC generator. First, the DC drives are assembled and connected to a 120VAC wall outlet. The armature wires of the DC drive then get connected to the armature of the PM DC motors. Then the motor gets coupled with the PM DC generator. This same procedure is done for both the wind and hydro power models. Each of the outputs of these models, which come from the output of the generators, become inputs to one of the boost converters in the parallel DC-DC converter setup, as illustrated in Figure A-1. Figure 6-2 shows the assembled wind and hydro models.

Figure 6-2: Assembled Wind and Hydro Models

The next step is to connect the solar panel (PV) to one of the inputs of the parallel DC-DC converters. Figure 6-3 shows wire nuts being used to connect wires between the output of the PV to the input of one of the boost converters.

Figure 6-3: PV Wiring to Boost Converter

For the construction of the DC House model, only three energy sources will be used to demonstrate functionality. These energy sources include the PV, as well as the wind and hydro models. Human-generated power will not be included in these steps.

The next step is to connect the 48V output from the parallel DC-DC converter configuration to what will become the 48V main system line. As seen in Figure A-1, the single output from the parallel DC-DC converter module must be the input to the “PV” input port on the charge controller. Then the battery must be connected to the “Battery” port on the charge controller. Finally, the “Load” output port of the charge controller must be connected to the 48V DC power distribution panel in order to complete the 48V main system line. The way this charge controller works is that it allows energy to flow in from the 48V main system line into the “PV” input port on the charge controller and flows into the battery. Energy that is not being used by the appliances flows into the battery until it is fully charged. When appliances are being used inside the DC House, energy flows out of the battery and out of the charge controller through the “Load” output port at 48V. Therefore, the “Battery” port on the charge controller acts as a bidirectional gateway for energy flow, both into and out of the battery. This means that the charge controller has its own buck-boost converters to allow a certain input voltage, charge up the battery with maximum power point tracking (MPPT), and then provide energy back to the 48V main system line, which is essentially fed to the appliances. Figure 6-4 vaguely shows the wiring of the charge controller with the battery.

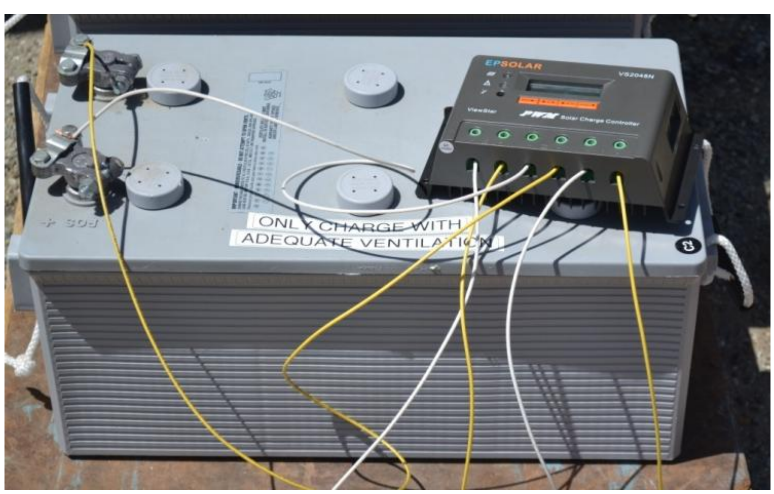

Figure 6-4: Wiring of Charge Controller

Next, the output from the "Load" port on the charge controller must be connected to the input port of the -48V DC power distribution panel, which is PORT B (circuit breakers) on the distribution panel; PORT B is the port on the DC power distribution panel which consists of the circuit breakers. Since the nominal input voltage for the DST-FB distribution panel is -48VDC, this means the wiring must be in reverse polarity. So the positive "+" wire from the charge controller must be connected to the return "RTN" on the BUS B input of the panel, and the negative "–" wire from the charge controller must be connected to "HOT" on the BUS B input of the distribution panel. Therefore, this reverse-polarity wiring must stay consistent for wiring the branch circuits to the outputs of the distribution panel. Figure 6-5 shows the input and output ports of BUS B on the back side of the DC power distribution panel.

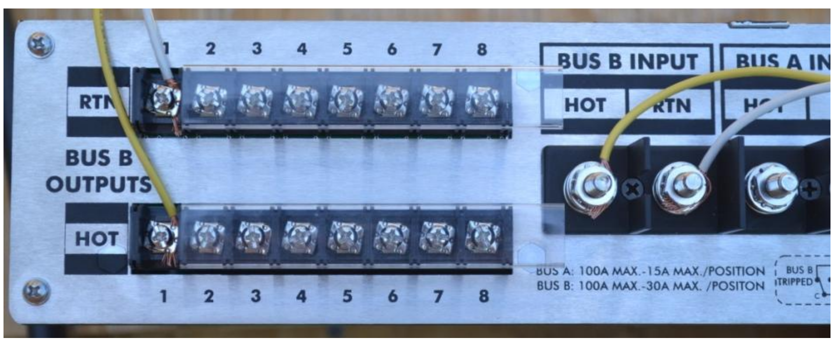

Figure 6-5: I/O Ports on BUS B of DST-FB

Figure 6-6 shows the three circuit breakers on BUS B located on the front side of the DST-FB DC power distribution panel. The green LED on BUS B indicates that this bus has available power.

Figure 6-6: Front Side of DST-FB DC Distribution Panel

The next step in the construction process is to wire the three outputs of the DC distribution panel to the three branch circuits inside the DC House. Since all of the appliances in the DC House model require a 12V input, buck converters are needed to convert the 48V from the distribution panel down to 12V for the appliances. If 48V appliances are also being used, one branch can be reserved for these 48V appliances, meaning the buck converter is not required for that branch, and the branch gets 48V directly from an output of the distribution panel. Figure 6-7 shows the input port (left) of the buck converter wired to one of the output ports on BUS B of the distribution panel, and its output port (right) connected to the start of one of the branch circuits inside the home.

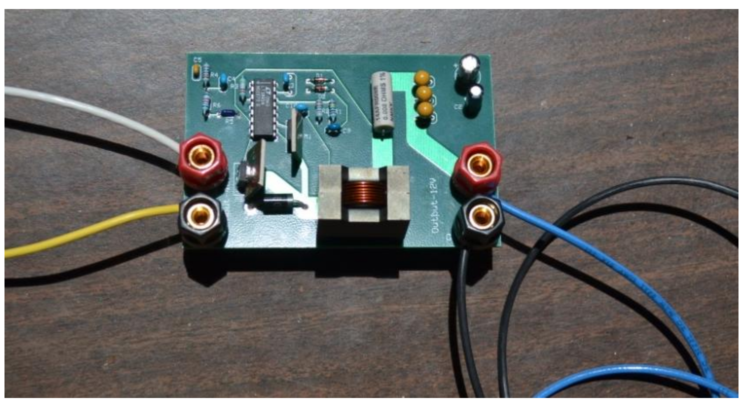

Figure 6-7: 48V-to-12V Buck Converter for 12V Appliances

The final step in the construction process of the DC House model is to connect all appliances to the branch circuits inside the home. All appliances are shunt-connected, or connected in parallel, as previously stated in the load/distribution side of the model design breakdown. Figure 6-8 shows some of the appliances connected to one branch circuit inside the DC House model; LED strips are on, fan is on, and radio is on.

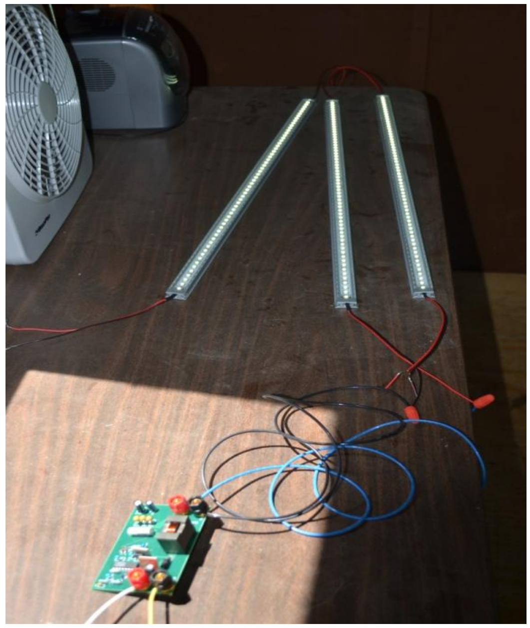

Figure 6-8: Appliances Shunt-connected to Branch Circuit #1

This concludes the construction process of the DC House model. All appliances were tested to verify functionality of the DC House model. All four appliances and three LED strips were tested on all three branch circuits; all appliances and LED strips were receiving power and functioning properly in tandem. Figure 6-9 shows the entire DC House model.

Figure 6-9: DC House Model

Conclusion

As previously stated, the purpose of this project is to prove that the DC House concept could work. Components for the model were chosen based on the design. All subcomponents, such as DC-DC converters required testing to verify their functionality. Then the other components, such as the parallel DC-DC converters, were assembled and tested to verify that they function properly for their purpose. Once all main components were selected, each one was tested to verify their functionality for the DC House model. Some of these other tests included testing the solar panel, DC drives, motors, generators, charge controller with battery, DC power distribution panel, buck converter, and appliances.

Cost and efficiency were not taken into account in the design or development of the DC House model. However, the concept was proven to work. With more improvements in the design, the model can be tested for long periods of time to see how much energy can be generated and stored in the battery. The optimal wire size that was chosen for this model is AWG No. 14. However, the wire size will change based on the size of the load and how much power is being generated by the renewable energy sources. The appliances that were chosen for this model were small and consumed very low power. This was done on purpose to guarantee a working model with a small load, in case a generator (wind or hydro) failed or the PV did not receive enough sun.

Over time, with improvements in the design and advancements in power electronics, the efficiency of the DC house design will be improved and new models will be developed with smarter choices on which subcomponents should be used. The development of the MISO will greatly improve the efficiency of this DC system because the MISO is not selective about which energy source to use; the MISO sums up all of the power generated from the energy sources and feeds it to the main system line.

Recommendation

Further tests should be done on the DC House model. Minor improvements in the design such as implementing the Multiple-Input Single-Output (MISO) DC-DC converter would greatly improve the efficiency and functionality of the DC House model. Buck boost converters could be used to regulate the output from the solar panel and other renewable sources of energy before it is input to the MISO. The model could be tested with larger loads to see how much the model can handle in terms of energy demand. The DC House model should be tested for long periods of time using computers to measure how much energy it can generate to power the home and store excess energy in the battery as back up. Once a stronger model design is implemented, calculations and tests should be conducted on the actual model to demonstrate its efficiency and cost-effectiveness.

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Appendix A

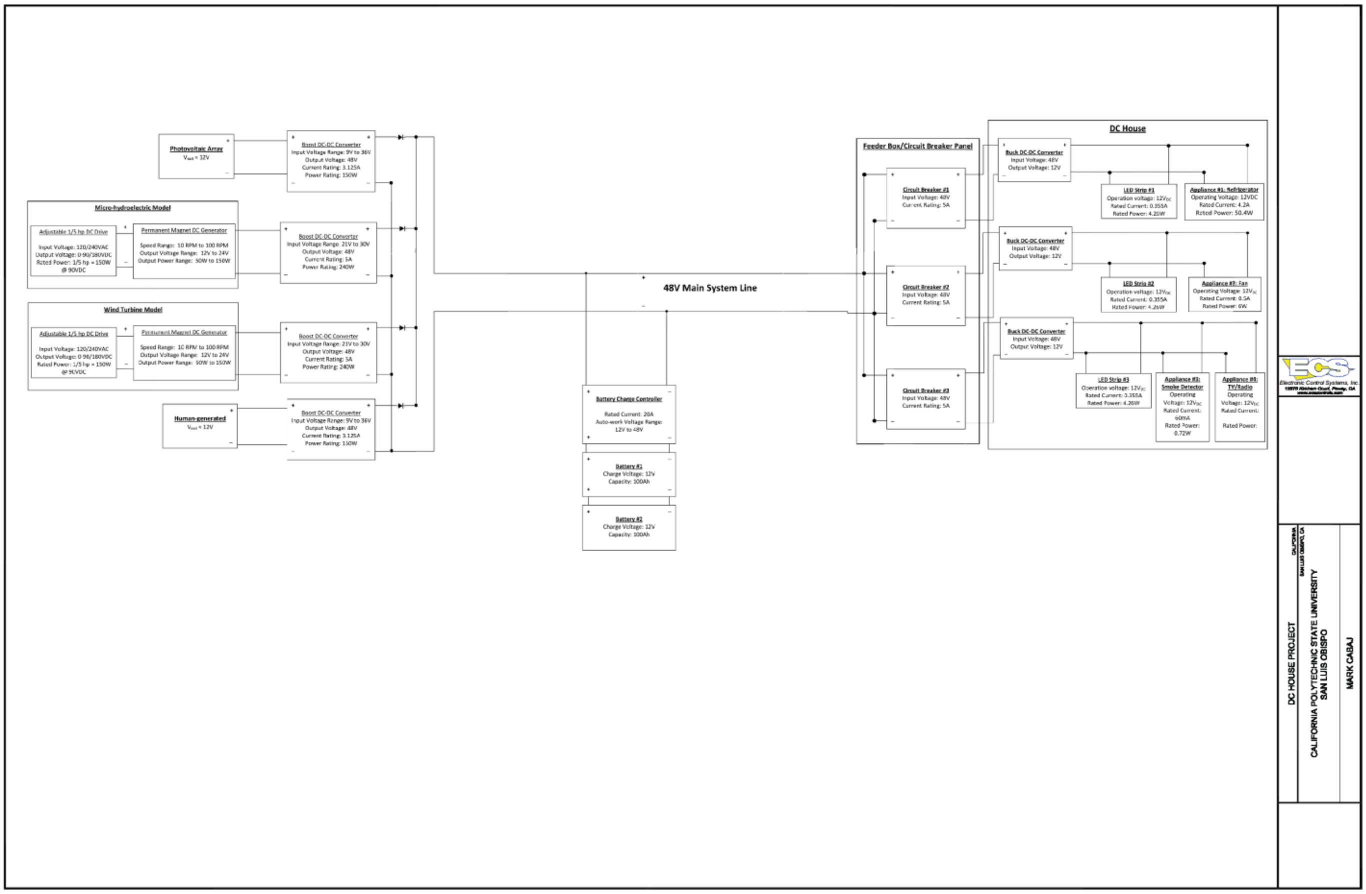

Figure A-1: DC House Model Design and General System Layout