Abstract — This paper presents modeling and simulation of a distributed network of DC Houses using MATLAB Simulink. The model will allow for sharing of power between houses within the network. The developed model consists of five separate DC House branches with local power generation. Each branch consists of a PV MPPT charge controller subsystem, a resistive load, and a bidirectional buck-boost converter subsystem. The performance of the individual components of the model is verified before constructing the network. The power sharing capability of the network was evaluated by measuring the efficiency transmission at varying wire gauges, distances, and high-end voltages. Results of the study show that for the most part, higher transmission voltage resulted in higher efficiency. However, this was not the case at some configurations due to different methods of power sharing.

Keywords — DC House, Residential Electricity, House Network

I. INTRODUCTION

In recent years, there have been constant efforts to provide clean and reliable energy to the whole world. In order to achieve this goal, it is important to be able to tailor these efforts towards the rural communities which have the most difficulty accessing power from the traditional AC grid. The DC House project is an example whose goal is to provide an alternative solution to off-grid rural electrification [1]-[3]. Through collaboration with other universities, there are also currently DC House prototypes in Indonesia and the Philippines [4]-[6].

The DC house can be considered a nanogrid, a smaller scale of a microgrid, powering only one house [9]. Unlike most nanogrids; however, the DC House is completely disconnected from the grid. The DC House runs on multiple different types of renewable energy sources such as solar, hydro, wind, and human generated power. In the standard DC House model, all of these inputs power a single DC load. Residential loads have become acclimated to the traditional AC grid, so any DC source will connect to AC power. However, most appliances and other loads within a household operate on DC power [10]. This means that before it can be used, the power must go through another conversion from AC back to DC. AC-DC conversion is inefficient and can cause a considerable amount of power loss. As can be seen in the model depicted in Figure 1, the DC House keeps the power as DC at all stages in order to eliminate the need for any AC-DC or DC-AC conversion. Instead, DC-DC conversion is used to step up or down the input voltages in order to match the desired nominal output voltage. DC-DC conversion is much more efficient than converting between AC and DC [11], which results in large savings in power loss. Energy efficiency is a crucial consideration in order to develop a more sustainable way to use energy as well as where energy sources are scarce. The model for the DC house has gone through multiple different iterations, fueled by student research in 3 key areas: small scale generation, interface, and loads [5].

Fig. 1. Simplified diagram of the DC House project

Due to the inconsistent nature of DC house energy sources, the voltage that each is supplying will vary with time. The result of this is requiring a DC-DC converter that will adjust the input voltages of each source to the nominal output voltage. All of these sources must also connect to a singular load, the DC House. This requires whatever converter to be used to be able to take in multiple inputs and produce a single output. As part of the DC House project, there have been many variations developed of the Multiple Input Single Output (MISO) converter [12]-[16].

In order to keep the maximum load of the DC House low, the loads included in the model are basic necessities and appliances. Using LEDs and an Edison screw base, past projects have been able to develop a DC model for lighting, the main load in rural residences [17][18]. Previous students have also...
been able to develop a smart DC wall plug that allows the connection of common appliances, such as refrigerators and TVs [5][19][20]. Another method of power supply researched by students is the USB-C power adapter [21]. This connector is an efficient way of powering electronic loads, like laptops.

Most existing distribution models are designed for AC, so the challenge becomes creating a feasible, efficient model for DC distribution. However, DC transmission does not require the use of transformers as its AC counterpart does, resulting in higher efficiency, lower cost, and lower component count [11]. For the standard DC House model, a transmission model had to be created for distribution from the Multiple Input DC-DC converter to the feeder box and for each of the load circuits within the house [20].

In many rural communities, it is common for families to live together in close clusters of houses. This allows for sharing of resources between houses, power only needing to be transmitted a short distance. In order to accommodate such rural communities, a solution must be developed to interconnect multiple DC Houses. The connection of multiple DC Houses is nearly synonymous to the connection of multiple microgrids [9]. There is an existing model for connection of multiple DC houses [10]; however, it is a centralized model in which power is produced at a central point and then distributed between DC Houses, as shown in Figure 2.

![Centralized Distribution Network for DC Houses](image)

In this paper, the development of an efficient model for distributed power distribution amongst a network of multiple DC Houses will be presented. All houses within a community would have their own sources of power generation, but they must be connected to a single DC bus. Various operating parameters such as the ideal voltage and wire gauge must be selected for the DC bus in order to minimize cost and power loss during transmission.

II. DESIGN REQUIREMENTS

In the network DC House model, each house has its own energy production and storage like that of a single DC House. All of the DC Houses in the network will now be connected together at a DC bus. This allows for sharing of power between houses which are producing more than they need and those which are producing less than they need. Developing the ideal model for a DC House network requires finding the best values for voltage and wire gauge. The best value for each may vary between network models depending on the size of the given network. The model allows us to investigate how the network operates at varying DC Bus voltages, configurations of houses for sharing power, average distance between houses, and the resulting effect on efficiency, cost, and cable size. Figure 3 depicts the block diagram of the DC House network mode.

![Higher Voltage DC Bus](image)

From previous work [22][24], it has already been determined that the most optimum nominal operating voltage on the house side is 48V. Now, multiple DC Houses are being connected together at a single DC bus, whose voltage has yet to be determined. In power distribution, it is ideal to transmit power at a high voltage and low current.

To minimize power transmission loss, lower current is desirable. Voltage and current are inversely related, meaning that as current decreases, the voltage increases. This relation shows why it is ideal to transmit power at a high voltage when creating an efficient system. In order to step up the voltage for transmission, the proposed DC network will utilize a bidirectional buck-boost converter. It is necessary for the converter to be bidirectional so that the direction of power flow may be determined by whether a house is sending power to the DC Bus when it has excess or receiving power when it has a lack. The transmission side voltage will affect the components values needed for the buck-boost converter, which in turn may affect the size and cost of the converter.

The system model may vary depending upon the number of houses in the community, the distance between houses, and priority between cost and efficiency. This study will primarily focus on developing a system of 5 houses, varying which houses are sharing power analyzing what changes must be made to the system in order to maintain high performance and low cost at all configurations. The distance between houses will alter the distance that power must be transmitted. Transmission distance is directly related to the resistance of the wire, and therefore to the power loss. Increasing the transmission distance will also increase the length of wire which must be purchased and installed. For this project, three different reasonable distances will be chosen to compare results at. In order to preserve the balance between cost and efficiency, the chosen wire gauge may vary for each system dependent upon this analysis. Based upon previous work conducted on the MISO converter[12]-[16], the initial maximum load of each house was chosen to be 150W.

In many cases, cost is directly related to performance of the DC House network. Larger wire gauge has less resistance and provides greater efficiency but will also increase the cost. The voltage chosen for the DC Bus will also affect the cost in the same way. In order to receive the same performance at higher current levels, a lower (more expensive) wire gauge must be used. The design requirements for this project must be balanced.
with the cost of the network, in order to maintain an affordable price. While maintaining a low price point, all parts of the system must be dependable and robust. Aside from just the initial cost, this will help to keep the cost of maintenance down for the customer.

III. DESIGN

The distributed DC house network model was designed and constructed using MATLAB Simulink. The Simulink model will contain five individual DC Houses, each with their own source of power generation. The source of power generation for each DC House will be modeled as a PV array utilizing maximum power point tracker and a charge controller. All of the houses in the network will be connected through which they will be able to share power. In order to connect from between this high voltage DC bus and the lower voltage DC Houses, a power conversion stage will be needed for each house. The modeling of a DC-DC converter that can meet the requirements necessary for this system will also be covered in this chapter. The operation of the proposed converter design will then be verified for a range of voltages from 100V-300V.

For simplicity, the model uses only PV sources. Solar power is a relatively common renewable source, which has been rapidly growing in popularity in recent years. Due to this popularity, there is a higher availability of resources on PV systems than many other systems, making it an ideal candidate for modeling. In addition, Also, an energy storage component must be added which enables the system to charge the battery when solar energy is at a surplus and discharge to supply power to the house when solar energy is at a deficit. Another key component of the photovoltaic system design is the maximum power point tracker (MPPT). A tracker will allow the component of the photovoltaic system design to find the best voltage operation point of the PV cell and ensure the highest possible power yield. The perturb and observe algorithm increments the voltage of the PV system in small steps and observes the power at each point to track the maximum power point. This method of maximum power point tracking is accurate and relatively simple to implement. The implementation of the perturb and observe algorithm in MATLAB Simulink is done through the use of built-in block functions and is shown in Figure 5. The MPPT takes in the operating voltage and current of the array and outputs the current PV power. Internally, the MPPT performs the necessary logic operations to determine if the maximum power has been reached and set the size of the next voltage increment.

Fig. 4. Buck Converter from PV MPPT Charge Controller

This MPPT charge controller uses a lead acid battery for energy storage. The charge controller component uses a charging method with three stages: the constant current charging stage, the constant voltage charging stage, and the float charging stage [24]. Constant current charging charges the battery at its rated capacity and occurs when the MPPT is enabled. Constant voltage charging occurs when the MPPT is disabled. Float charging occurs when the battery is fully charged and simply maintains the state of charge at 100% so that the battery is not overcharged. Overcharging of the battery could cause overheating or a battery gassing reaction which could lead to component failure. As shown in Figure 6, the battery charge controller takes in the battery current, voltage, and state of charge conditions as the inputs. The state of charge condition allows the charge controller to determine if the float stage needs to be enabled. If the charge controller does not enter the float stage, then it will decide to enter the constant current stage if the voltage of the battery is below the constant voltage set point. Otherwise, it will enter the constant voltage stage. The voltage state of the battery also determines the PWM signal which is sent to the gate of the MOSFET in the MPPT charge controller buck converter.

Fig. 6. Battery Charge Controller from PV MPPT Charge Controller

The basic layout of the bidirectional buck-boost converter designed for this project is shown in Figure 7. The design uses

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two MOSFET switches, each with an antiparallel diode. The switching signal to the top diode is controlled by the voltage measurement at the low voltage input. The switching signal to the bottom diode is controlled by the voltage measurement at the high voltage input. The Simulink model uses PID controls in order to modulate the pulse width of the signal, changing the duty cycle while maintaining the switching frequency.

As the inductor charges and discharges, it controls the current waveforms of the converter. After testing the converter with multiple inductance values, the converter achieves the proper boost operation at a high-end voltage of 300V with an inductance of about 15μH. This inductance value proved to work fine for all other voltage levels as well, in both buck and boost mode operations. The capacitance at the low voltage end of the converter is varied from 1000μF-5500μF as the high-end voltage is increased from 100V-300V. The capacitance at the high end of the converter is maintained at 900μF for all high-end voltages. Each capacitance has a modeled series resistance of 1mΩ.

Fig. 7. Simulink Model of Bidirectional Buck-Boost Converter

For testing, the initial full load is considered to be 150W, but this may increase as in the future if multiple sources are added into the design. The nominal input voltage during buck operation is the high-end DC voltage which is varied between 100V-300V in 50V increments. The nominal input voltage during boost operation is 48V, which as previously mentioned is the operating voltage of a DC House. The high and low input voltage used in all cases are ±15% of the nominal input voltage.

The final design of the distributed DC House network is provided in Figure 8. This model contains five separate DC House branches, labeled as A-E going from top to bottom. On the very left of each load there is a subsystem block. This subsystem contains the PV array and PV MPPT charge controller as previously described. Each DC House is modeled as a 15.36Ω resistive load so that the DC House will consume 150W at 48V. The next subsystem is the bidirectional buck-boost converter, labeled as “BiDC-DC.” This will step up the voltage from 48V to the voltage of the High Voltage DC bus, which will be varied during testing. The converter will also allow current to flow through from either direction. This model contains the distribution line from each house, which will connect to the upper distribution network line. The distance of the distribution line will be maintained at 2 meters, while the distance of line between houses will be varied during testing. On the very right of the model is a battery.

Fig. 8. System Model of Distributed Network with Five DC Houses

The operation of the bidirectional buck-boost converter was able to be verified with high-end voltage of 100V, 150V, 200V, 250V, and 300V. These are the voltages which will be tested for the high voltage DC bus, in order to compare efficiencies. Two different wire gauges will also be selected to observe the potential benefits of different gauges. The plan for testing the distributed network of DC Houses is to determine the network efficiency while utilizing different combinations of houses supplying and demanding power for all different high-end voltages, distances, and wire gauges.

IV. SIMULATION RESULTS

There were three states for the DC House branches during testing: supplying, demanding, and off. Houses which are supplying are considered to be strictly providing power and not demanding any within their own branch. In order to represent this in the model, the resistive load that represents the power demand of the house is commented out of the model. The irradiance and temperature inputs to the supplying PV modules were set to 1000W/m² and 25°C. The load of each demanding branch is set to absorb 150W at 48V. Branches which are considered to be in the off state represent branches which are either supplying and demanding no power or branches whose supply and demand are perfectly matched.

With the states of operation for the DC House branches defined, ten different configurations for testing were defined. The first four configurations all had the topmost branch in the supplying state. The bottom four branches were as follows for these four configurations: bottom most branch demanding with the rest off, bottom two demanding with the rest off, bottom three demanding with the other branch off, and all four demanding. The next three configurations were with the top two branches supplying. These configurations followed a similar pattern as before for the rest of the three branches: bottom most branch demanding with the other two branches off, bottom two branches demanding with the remaining branch off, and all three
demanding. For the next two configurations the top three branches were all supplying power. The bottom two branches were set as follows for these configurations: bottom most demanding with the other off and both demanding. The final configuration was with the top four branches all supplying and the bottom branch demanding. 

The notation of these configurations was simplified for the purpose of recording data. In the shortened notation, supplying branches were denoted as 1, demanding branches as 1’, and off branches as 0. Using this notation, the corresponding number for each DC House branch is written from left to right, representing the branches from top to bottom, respectively. For example, the first configuration where only the top branch is supplying and only the bottom branch is demanding while the rest are off is represented by the notation 10001’. These configurations will provide a comprehensive set of test points to validate that the model will operate properly in all current-sharing scenarios.

Figures 9(a) to 9(c) were created for testing the system with 13AWG, one plot for each distance between neighboring houses. At each distance and wire gauge five different high-end transmission voltages were used to test each different configuration of the DC House branches.

The results show when multiple branches were supplying, they would “smartly” share power. This means the supplying branches which were closer to the demanding branches would supply a higher portion of the power needed. The only transmission voltage that this behavior was not seen at was the highest 300V set point. The most likely explanation is that this difference is introduced by the converter. When designing the converter, it was initially difficult to get the converter to reach a high-end voltage of 300V when in boost operation mode. Since the converter has more difficulty supplying power at this voltage, the supplying branches split the power evenly to share this burden. This can be corroborated by the results from testing with a configuration of 11’1’1’, where one branch must supply power to all four others at full load. Efficiencies at 200V and 250V specifically are much closer to and even higher than the efficiency at 300V than expected for some configurations of the DC House branches.

Results from the same testing process using 12AWG are shown in Figures 10(a) to 10(c). From all of these plots, we see that they follow the same trends over the different configurations and transmission voltages as were seen when using 13AWG. The efficiency of transmission with 12AWG at every point was.
slightly higher than the efficiency seen at the corresponding point with 13AWG. This is to be expected as 12AWG wire has a larger cross-sectional area than 13AWG wire and therefore less resistance for the same length of wire. The trend of efficiencies seen at both 13AWG and 12AWG should translate to all other wire gauges within a reasonable range and this should provide a good basis for the design of future distributed network systems.

The test results provide sufficient validation of the model for a distributed network of DC Houses. This model should provide a good basis for future design and construction of networks of different sizes and parameters. As expected, the simulation results showed that the efficiency decreases with increase in the distance between houses and increase in the wire gauge. The only unexpected result was seen from the trends of efficiencies over the range of high-end transmission voltages. It was expected that at all points higher transmission voltage would result in higher efficiency. This was the case at most points; however, there were some configurations of the DC House branches which resulted in higher efficiencies at 200V or 250V than at 300V. This was due to the different methods of power sharing at the different transmission voltages. Because the efficiencies are so close at 250V and 300V, there is less benefit to using 300V for transmission. In the previous chapter, slightly better performance of the converter was also seen with a high-end voltage of 250V. From this information 250V seems to be an ideal choice for the high-end transmission voltage for this model. This may vary in future models if the layout and size of the system is changed.

V. CONCLUSION

The proposed model for a distributed network of DC Houses consisted of five separate DC House branches. Each branch had its own local power generation in the form of a solar photovoltaic array. With every PV array subsystem in the model, a MPPT charge controller is included which keeps the PV system operating at its maximum power point and maintains an output voltage at the nominal 48V of the low voltage DC bus. In order to convert this low voltage to a voltage and current more suitable for transmission, this model utilizes a bidirectional buck-boost converter which allows current to flow both into and out of the branch. Through the transmission line, all of the branches are connected at a single point in the middle of the model which represents the high voltage DC bus. At the high voltage DC bus, there is a battery connected for energy storage.

The performance of the bidirectional buck-boost converter was verified in both buck and boost mode operation at 100V, 150V, 200V, 250V, and 300V high-end voltages with a full load of 150W. In buck mode operation, the converter had a voltage ripple of about 0.02V, load regulation between 0.08%-0.25%, and line regulation between 0.125%-4.60%. In boost mode operation, the converter had a voltage ripple of 1.5V at most, load regulation between 0.04%-0.10%, and line regulation between 0.05%-0.20%. For most of these performance measurements, all of the high-end voltages provided good results, but the best results were typically seen with a high-end voltage of 200V or 250V.

Ten configurations of the DC House branched in the network were selected to represent a range of possible power sharing requirements. All of these configurations were tested with: 13AWG and 12AWG transmission line; 4 meters, 6 meters, and 8 meters transmission distance between houses; 100V, 150V, 200V, 250V, and 300V high-end transmission voltage. Over the range of voltages tested, generally the efficiency was seen to increase with voltage as expected. However, there were some configurations at which the efficiencies at 200V and 250V were extremely close or even higher than at 300V. This was found to be attributed to different methods of power sharing at the different voltages. At the lower voltages, it was seen that the supplying branches which were closer to the demanding branch or branches would supply a greater portion of the power needed. At 300V, the supplying branches would provide equal portions of the power demanded regardless of their position in relation to the demanding branches. The same trends of efficiencies were followed using both wire gauges and over all distances, with decreasing efficiency at higher wire gauge and transmission distance. Overall, the three highest transmission voltages all provided similar and any of them would be suitable for the design. Using a lower wire gauge will provide less losses in transmission but will increase the price of the system.

REFERENCES


