Design of a 380 V/24 V DC micro-grid for residential DC distribution

Victor-Juan Webb
The University of Toledo

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A Thesis

entitled

Design of a 380 V/24 V DC Micro-Grid for Residential DC Distribution

by

Victor-Juan Webb

Submitted to the Graduate Facility as partial fulfillment of the requirements for the Master of Science Degree in Electrical Engineering

______________________________
Dr. Lingfeng Wang, Committee Chair

______________________________
Dr. Roger King, Committee Member

______________________________
Dr. Weiqing Sun, Committee Member

______________________________
Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo
May 2013
This research will investigate a direct current (DC) micro-grid for power distribution in residential households. DC distribution has a long history, being considered at the beginning with alternating current (AC) distribution; however, due to the ease of distributing AC power over a long distance using transformers, it won against DC. Today, with the majority of electronics and appliances being used in the household using DC voltage, DC distribution is being studied as a viable alternative to AC. DC distribution also benefits renewable energy generation that generate DC power, such as photovoltaic (PV), by reducing the number of energy conversion steps.

The practicability of the proposed DC micro-grid is investigated by comparing to the existing 240 V AC system of homes. The primary goal is to design an energy efficient household to reduce the impact on the current power grid from increasing energy demand, and to manage local electricity generation and storage systems at the household level. Most previous works
investigate a low voltage (LV) household, with a distribution voltage range from 24 V to 48 V, with imposed restrictions on available power and appliances used. This research will look at maximizing energy efficiency with a solution that is scalable through a large range of households, allowing for application in households with low power demands and households with high power demands. This is accomplished through the use of both high voltage (HV) DC at 380 V and low voltage DC at 24 V. The implementation of the DC micro-grid and current AC system takes into consideration the losses due to converters and rectifiers, standby power, and wiring. Power consumption measurements for typical household equipment and appliances (e.g. TVs, lighting, refrigerator, air-conditioning systems, washer, dryers, etc.) are used for evaluation of the proposed micro-grid. The validity of the DC micro-grid is obtained through simulations in both PSIM and Simulink. It is concluded that a 380/24 V DC micro-grid is a more economical solution versus the existing AC system.
Acknowledgements

Throughout my graduate career, I have been privileged to know many people who have provided me with a great learning experience and inspiration. Dr. Lingfeng Wang and Dr. Roger King have provided me with those gifts and I express great appreciation for the guidance they have provided. I also thank my fiancé and family for providing the motivation and inspiration to help me complete my studies.
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Chapter 1

Introduction

The demand for energy is constantly increasing, which is pushing the limitations of the current grid, increasing reliance on fossil fuels, and increasing CO$_2$ emissions. These concerns have renewed interest in discovering ways to reduce power demand on the grid through renewable energy, building automation, direct current (DC) distribution, and more. The result has led to fast implementation of photovoltaic (PV) power systems. With the majority of electronics and appliances operating on DC and renewable energy systems, such as PV power systems, generating DC power, energy usage can potentially be reduced by having DC sources and appliances directly connected. This savings in energy is achieved by reducing the number of conversions between DC to and alternating current (AC).
1.1 **Historical Overview**

The dispute between DC and AC has been going on since the late 1800s [1]. Initially, DC was the standard in the US, but faced concern for large distribution. The voltage levels for DC could not easily be converted and the transmission loss through the cables was too much. When Tesla introduced AC transformers and generators, the expansion DC distribution became nothing more than a dream. Through the use of transformers, AC voltage level could be easily changed, allowing for low loss when transmitting over a great distance.

While AC had advantages over DC for energy distribution when the national power grid was created, that balance began to shift in favor of DC with the power electronics revolution. The power electronics revolution began in 1948 with the creation of the silicon transistor, followed by a second revolution with the introduction of the commercial thyristor by GE [2]. Since the components of power electronics require DC voltage, DC's role began to continuously rise. Today, most electronics and appliances used in residential households operate on DC voltage.

1.2 **Background**

Recently, a multitude of research projects have been conducted to maximize energy efficiency in the U.S. to minimize the negative impact on the current power grid from the increasing energy demands and the influx of plug-in hybrid electric vehicles (PHEVs). There are different proposals, with
some suggesting an overhaul of the current power grid for DC distribution and others are looking at DC in buildings while maintaining the current AC grid. The majority of DC distribution studies have been in data centers and commercial buildings. Though the benefits for DC distribution commercial buildings have shown to be beneficial, less focus has been put into residential DC distribution. Residential households would require a different approach compared to what has been researched for commercial buildings and renewable energy generation is less likely to be utilized in the residential segment.

Most residential households are currently supplied with 240 V\text{AC}, requiring rectifiers for DC operated appliances to convert the AC voltage to usable DC, leading to power losses in the conversion. Standby power loss also factors into AC distribution for DC electronics and appliances, since the rectifiers will continue draw power even if the device is in standby. DC distribution in a building would require rectification only from the grid to the internal grid in the household, or micro-grid, and would use DC-DC converters for the rest.

With the interest in reducing dependency on foreign petroleum and CO\text{2} emissions, renewable energy has been a rapidly expanding area. Renewable energy generation helps strengthen the case for DC distribution since renewable energy sources generate DC power. With DC distribution, DC-DC conversion is all that is required to interface with the grid and
battery storage to a micro-grid compared to AC, which would require AC-DC conversions in addition. By maximizing energy efficiency with renewable energy sources, the demand on the power grid is also reduced, which leads to less reliance on foreign petroleum and reduced CO₂ emissions.

1.3 Research Approach

This research will look into the advantages and design of a DC micro-grid in residential households. The DC micro-grid approach is preferred when compared to replacing the entire grid with DC. The idea is that this DC micro-grid can be implemented in new households, or modified into existing, with minimal impact on other users relying on AC power.

The DC distribution proposed is a micro-grid that provides DC voltage at two levels, 380 V and 24 V. Research has been performed in residential DC distribution that shows favorable results for a low-voltage (LV) only solution of either 24 V or 48 V. While low-voltage can power a fair number of electronics, there are restrictions on high power devices due to present day high current and safety regulations [3]. Those restrictions require sacrificing the comfort of living that many are accustomed to from high power electronics such as centralized air conditioning, high-power microwaves, dryers, etc. By introducing a high-voltage (HV) component, this allows high power to be utilized in a DC-powered home. The low-voltage level was chosen to be 24 V because DC voltage over 30 V is considered “not safe” and requires specific insulation requirements [4]. The high-voltage level was chosen to be
380 V for the micro-grid because the EMerge Alliance has chosen 380 V\textsubscript{DC} as standard for data centers, which will help develop standardize connectors, ports, and insulation requirements [4].

The viability of the DC micro-grid will be determined through design and simulation in this research. Wiring and a variety of loads will be researched and implemented into AC and DC household models for comparison. The DC micro-grid has multiple options to be sourced, but is expected to be provided power through the use of multiple, centralized rectifiers which converts 240 V\textsubscript{AC} from the grid to 380 V\textsubscript{DC}, and LV electronics will be provided voltage through via a high efficiency DC-DC converter which will convert 380 V\textsubscript{DC} to 24 V\textsubscript{DC}. The DC voltage can also be provided by renewable energy systems such as PV and wind energy systems. The grid rectifiers will also support generation to allow batteries and renewable energy sources to generate power for the grid.

1.4 Thesis Layout

The remainder of the document is laid out as follows:

- Chapter two summarizes the current household situation and discusses the energy usage and design. This chapter will consist of details on the AC household and DC household models, the loads for each household, and the calculations and results of the models to
compare energy usage. This chapter will also summarize the benefits of the DC household.

- Chapter three will consist of the simulation model of the micro-grid and results from both PSIM and Simulink/SimPowerSystems. This will include the schematic and implementation of the grid rectifier and Ćuk converter, discussion of custom subsystems and masks, and the results of the simulations.

- Chapter four completes the document with conclusions and prospective future research directions.
Chapter 2

AC vs. DC for Residential Energy Distribution

2.1 The Typical Household

2.1.1 Present Household Power Distribution

In the US, power is distributed to households through an AC power grid. When the power reaches the household, it is provided at 240 V\textsubscript{AC}, which is distributed through two “hot” and a neutral wire. The two “hot” wires provide 120 V\textsubscript{AC} that have a phase difference of 180°. This allows two different voltage levels to be distributed through the household, 240 V\textsubscript{AC} between the two “hot” wires and 120 V\textsubscript{AC} between a “hot” and neutral wire. Most appliances operate on 120 V\textsubscript{AC} while higher-powered electronics (e.g. washer, dryer, central air conditioner, etc.) operate on the 240 V\textsubscript{AC}.
2.1.2 Average Household Energy Usage

2.1.2.1 Wiring and Power Loss

Households will have wiring feed throughout most of the house so electronics and appliances can be powered in every required room, with the power supply usually within a short distance of the appliances requiring the highest amount of power. The wiring used in households has a resistance which causes voltage drop and power loss as the current flows through it. Manufacturers design electronics to handle a certain amount of voltage drop, but the recommend voltage drop for residential households is less than 5% [3].

In order to minimize power loss and voltage drop, the proper wiring size has to be chosen based off the design of the household. The resistance \( R \) of the wiring is determined by its resistivity \( \rho \), length \( l \), and cross-sectional area \( A \), which is shown in Equation 2-1.

\[
R = \frac{\rho \times l}{A}
\]  

Typically, copper conductors are used for household wiring due to copper’s low resistivity and high-power appliances are placed closer to the power supply to reduce the resistance of the wiring. This becomes more apparent when in larger households; wiring from the feeder can reach up to 80 m in length [3]. Thus, minimizing the resistance of the wire directly affects the power loss and express in the following equation:
Where:

\[ P = I^2 \times R \]  \hspace{1cm} (2-2)

P: Power  
I: Current  
R: Resistance

### 2.2 The AC and DC Household Models

When designing a house, the length of the wiring varies depending on where the power supply is located from the appliances and electronics that need to be powered, and the power requirements of them. For the scope of this research, an average length of 30 m will be used.

#### 2.2.1 Loads

To model the loads, day-to-day household appliances and electronics, and their ratings, were acquired from [5], [6], and [7]. The loads are selected as standard loads that can be found in a family-sized AC household. The DC household will be designed to work with the selected loads to ensure that it can maintain the same comfort of living. The power rating of the modeled loads range from 4 W to 5000 W, with some very popular appliances having significant energy requirements, such as air conditioning, clothes dryer, hair dryer, and dishwasher. The lighting is modeled as an average total load instead of individually. The daily usage of the loads will be the same for both the AC household and DC household models. Table 2.1 shows the appliances utilized in the household models, along with their respective power rating and daily usage.
Table 2.1: Appliances and their power rating and daily usage, taken from [5], [6], and [7]

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Power (W)</th>
<th>Estimated Hours Per Day On</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Conditioner (Summer)</td>
<td>5000</td>
<td>7</td>
</tr>
<tr>
<td>Washer</td>
<td>425</td>
<td>1</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>5000</td>
<td>1</td>
</tr>
<tr>
<td>Gas Furnance (Winter)</td>
<td>600</td>
<td>3</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>1800</td>
<td>1</td>
</tr>
<tr>
<td>Hair dryer</td>
<td>1538</td>
<td>0.25</td>
</tr>
<tr>
<td>Oven</td>
<td>1800</td>
<td>1.31</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>1500</td>
<td>0.17</td>
</tr>
<tr>
<td>Microwave</td>
<td>1100</td>
<td>0.083</td>
</tr>
<tr>
<td>Iron</td>
<td>1100</td>
<td>0.17</td>
</tr>
<tr>
<td>Toaster</td>
<td>1100</td>
<td>0.083</td>
</tr>
<tr>
<td>Water Heater</td>
<td>475</td>
<td>24</td>
</tr>
<tr>
<td>Cooking Range</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>LCD TVs</td>
<td>213</td>
<td>3</td>
</tr>
<tr>
<td>Refrigerator/Freezer</td>
<td>188</td>
<td>12</td>
</tr>
<tr>
<td>Video Game Player</td>
<td>195</td>
<td>2</td>
</tr>
<tr>
<td>Monitor</td>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>Desktop Computer</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td>Total Lighting (LED)</td>
<td>300</td>
<td>4.93</td>
</tr>
<tr>
<td>Mixer</td>
<td>100</td>
<td>0.02</td>
</tr>
<tr>
<td>Vacuum</td>
<td>650</td>
<td>0.29</td>
</tr>
<tr>
<td>Can Opener</td>
<td>100</td>
<td>0.01</td>
</tr>
<tr>
<td>Laptop</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>DVR w/ Cable Box</td>
<td>44</td>
<td>24</td>
</tr>
<tr>
<td>Cable Box</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>DVD Player</td>
<td>17</td>
<td>0.5</td>
</tr>
<tr>
<td>Alarm Clock</td>
<td>10</td>
<td>24</td>
</tr>
<tr>
<td>Wireless router</td>
<td>7</td>
<td>24</td>
</tr>
<tr>
<td>Cell Phone Charger</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>
2.3 The AC Household

2.3.1 The Modeled House

2.3.1.1 Loads’ Voltage Requirements

The AC household utilizes 240 V$_{\text{RMS}}$ and 120 V$_{\text{RMS}}$. High-powered loads utilize the 240 V$_{\text{AC}}$ to reduce the current requirement to power them to improve efficiency. The voltage requirements are provided by the manufacturer of the appliances. For this research, high power appliances will be utilizing 240 V$_{\text{AC}}$ and low power appliances will utilize 120 V$_{\text{AC}}$. Table 2.2 illustrates the voltage and current requirements of each selected load.
Table 2.2: Voltage and current requirements for appliances

<table>
<thead>
<tr>
<th>240 V AC Household</th>
<th>Total Power (W)</th>
<th>Individual Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>240 V Appliances</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Conditioner (Summer)</td>
<td>5000</td>
<td>20.83</td>
</tr>
<tr>
<td>Washer</td>
<td>425</td>
<td>1.77</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>5000</td>
<td>20.83</td>
</tr>
<tr>
<td>Gas Furnance (Winter)</td>
<td>600</td>
<td>2.50</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>1800</td>
<td>7.50</td>
</tr>
<tr>
<td>Oven</td>
<td>1800</td>
<td>7.50</td>
</tr>
<tr>
<td>Water Heater</td>
<td>475</td>
<td>1.98</td>
</tr>
<tr>
<td>Cooking Range</td>
<td>1000</td>
<td>4.17</td>
</tr>
<tr>
<td><strong>120 V Appliances</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hair dryer</td>
<td>1538</td>
<td>12.82</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>1500</td>
<td>12.50</td>
</tr>
<tr>
<td>Microwave</td>
<td>1100</td>
<td>9.17</td>
</tr>
<tr>
<td>Iron</td>
<td>1100</td>
<td>9.17</td>
</tr>
<tr>
<td>Refrigerator/Freezer</td>
<td>188</td>
<td>0.78</td>
</tr>
<tr>
<td>Toaster</td>
<td>1100</td>
<td>9.17</td>
</tr>
<tr>
<td>LCD TVs (3)</td>
<td>639</td>
<td>1.78</td>
</tr>
<tr>
<td>Video Game Player (2)</td>
<td>390</td>
<td>1.63</td>
</tr>
<tr>
<td>Monitor</td>
<td>150</td>
<td>1.25</td>
</tr>
<tr>
<td>Desktop Computer</td>
<td>120</td>
<td>1.00</td>
</tr>
<tr>
<td>Total Lighting (LED)</td>
<td>300</td>
<td>2.50</td>
</tr>
<tr>
<td>Mixer</td>
<td>100</td>
<td>0.83</td>
</tr>
<tr>
<td>Vacuum</td>
<td>650</td>
<td>5.42</td>
</tr>
<tr>
<td>Can Opender</td>
<td>100</td>
<td>0.83</td>
</tr>
<tr>
<td>Laptop (2)</td>
<td>100</td>
<td>0.42</td>
</tr>
<tr>
<td>DVR w/ Cable Box</td>
<td>44</td>
<td>0.37</td>
</tr>
<tr>
<td>Cable Box (2)</td>
<td>40</td>
<td>0.17</td>
</tr>
<tr>
<td>DVD Player (3)</td>
<td>51</td>
<td>0.14</td>
</tr>
<tr>
<td>Alarm Clock (2)</td>
<td>20</td>
<td>0.08</td>
</tr>
<tr>
<td>Wireless router</td>
<td>7</td>
<td>0.06</td>
</tr>
<tr>
<td>Cell Phone Charger (3)</td>
<td>12</td>
<td>0.03</td>
</tr>
</tbody>
</table>

2.3.1.2 Rectification and Conversion Losses

The AC household model will include power losses from both AC-DC and DC-AC conversions for appliances that operate on DC voltage. Since
most of the appliances connected in the household utilized DC voltage, the AC voltage has to be converted to DC at each point of use. There are different types of rectifiers available, with the most typical one used for DC power being the full-wave bridge rectifier. With the air conditioner, refrigerator, dryer, and washer, there are two-step conversions from AC-DC-AC, shown in Figures 2-1 and 2-2. There are more efficient topologies utilized today by manufacturers to maximize energy efficiency for DC powered appliances [8]. For this research, an efficiency of 92% will be used for loss due to conversion. Appliances that require a low DC voltage need a step-down transformer which contributes to losses [9]. The power loss due to conversions is shown in Table 2.3.

Figure 2-1: AC circuit for air conditioner

Figure 2-2: AC circuit for washer, dryer, and refrigerator

Standby power loss is also included in the AC household model. Standby loss occurs when household appliances are placed in standby mode.
or turned off, and the power used in standby can go up as high as 30 W [10].

Depending on the appliance and its usage (e.g. DVR and alarm clock remaining on at all times, devices being unplugged, or AC powered appliances), or lack of standby power usage information, not all appliances will have standby power associated with it. The standby power usage for certain appliances is shown in Table 2.3 [10], [11], and [12].
### 2.3.1.3 Wiring Selection

The American Wire Gauge (AWG) rating system is used to select the wiring. The AWG is a standard that is used to select wiring and is based on the cross-sectional area of a conductor. The AWG lists the maximum current...
rating allowed for a given cross-sectional area. The wire size selected for the AC household was 12 AWG.

Copper wiring is used in the household model due to its low resistivity of $1.68 \times 10^{-8} \, \Omega \cdot m^{-1}$. The household is designed with 30 m cables feeding from the power supply to each load, and with the voltage drop across the wires being less than 5%. To determine the voltage drop, the source voltage ($V_S$) and load voltage ($V_L$) are calculated in Equation 2-3. In this study, unity power factor is used for all loads since many of the modeled loads are operating with close to unity factor [9].

$$V_S = Z \times I + V_L \quad (2-3)$$

The complex resistance ($Z$) consists of the wire’s resistance ($R$) and inductance ($L$), and can be calculated using the following equation:

$$Z = R + j2\pi f L \quad (2-4)$$

PVC pipe is typically used in households to feed the phase and neutral wiring. Inside the PVC pipe, inductance is produced based on the distance between the phase and neutral wiring, and can vary at different positions in the pipe [9]. The inductance can be determined using the following equation:

$$L = 0.05 + 0.2\ln\frac{d}{r} \quad (2-5)$$

Where:

d: Separation between phase and neutral
r: Radius of wire
The inductance produced is insignificant to the overall resistance, thus it can be ignored for this research’s purposes, reducing Equation 2-3 and giving equation 2-6.

\[ V_S = R \times I + V_L \]  
(2-6)

The power loss \( (P_{\text{loss}}) \) in the wiring is calculated in Equation 2-7 and voltage drop \( (V_D) \) is calculated in Equation 2-8.

\[ P_{\text{loss}} = R \times I_{\text{ac}}^2 \]  
(2-7)

\[ V_D = \left(1 - \frac{V_L}{V_S}\right) \times 100\% \]  
(2-8)

The wiring selection of 12 AWG fulfills the requirement of maintaining a voltage drop of less than 5% for the 30 m desired length.

2.3.2 Energy Losses in the AC Home

The AC household has two areas of energy loss, “powered on” and “standby.” Powered on losses are energy losses from active appliances. Powered on loss is acquired by multiplying the various losses by the amount of time it is powered for the day. The standby loss is the power used by certain appliances when they are not powered on or in standby mode. Both forms of energy consumption are measured in kilowatt-hours (kWh).

The “powered on” loss consists of the power loss due to wiring resistance \( (P_{\text{wiring loss}}) \), and AC-DC and DC-AC conversions \( (P_{\text{conversion loss}}) \). The standby power loss \( (P_{\text{standby loss}}) \) is shown in Table 2.3 for the appliances data was acquired for. Figures 2-3 and 2-4 show the yearly losses calculated for
the loads in the AC model at 240 V and 120 V, respectively. The energy loss shown is the combined losses of the converters, wiring, and standby consumption. The combined energy loss was calculated using the power losses from above and time powered on ($t_{\text{Powered On}}$) and standby time ($t_{\text{Standby}}$) in Equation 2-9.

\[
\text{Energy Loss} = \frac{t_{\text{Powered On}} \times (P_{\text{conversion loss}} + P_{\text{wiring loss}} + P_{\text{standby loss}})}{1000} \times t_{\text{Standby}} \times 365 \text{ kWh/year (2-9)}
\]

![240 V Energy Loss](image)

Figure 2-3: Energy losses for 240 V loads
The total yearly energy loss for the AC model is calculated to be about 2443 kWh, illustrated above in Figure 2-5. Energy loss due to appliances
being powered on, or active, is calculated to be about 73% of the total yearly loss, or about 1771 kWh/year. The standby energy loss is calculated to be about 275 of the total yearly loss, or about 669 kWh/year.

2.4 The DC Household

2.4.1 The Advantages of the DC Home

2.4.1.1 Less Energy Conversion

Most electronics and appliances in the typical household require DC voltage to operate. By utilizing DC distribution, the need for rectification is eliminated for most devices, and so is power loss due to standby operation. DC distribution also provides more benefits for renewable energy integration by eliminating the need for inversion to convert the generated DC power to AC, and also allows integration of batteries into the DC micro-grid to store excess energy generated from renewable sources.

2.4.1.2 Renewable Energy Systems

The benefits of DC integrated with renewable energy are important because of the rising implementation of them into households and buildings. PV has proven to be a popular area in the residential sector for renewable energy growth, as shown in Figure 2-10 [13].
Figure 2-6: Renewable energy growth [13]

Though the chart above only goes up to 2010, the growth rate hasn’t stopped. In Q1 2012, PV capacity hit 506 MW [14]. With the large growth in renewable energy installations, maximizing efficiency by reducing power loss and maximizing storage becomes increasingly more important, improving the argument for the DC micro-grid. The energy efficiency is better with DC distribution with renewable energy generation, such as PV, due to the removal of an inverter to converter DC-AC since PV systems generate DC power. The only conversion left is DC-DC, which is required in both distribution topologies.
The DC household presents another advantage by reducing the conversions between the micro-grid and battery backup. Similar to renewable generation, battery backups benefit from DC by eliminating the need to convert DC-AC and AC-DC. DC homes implemented with battery backups will only require a DC-DC converter between the battery and micro-grid for charging and discharging of the battery. The DC household can also make use of home-to-grid, allowing for the household to generate power for the grid from the battery and renewable energy source with use of a bidirectional rectifier. The bidirectional rectifier is explored and simulated in chapter three.

2.4.1.3 Standby Power Elimination

The DC household model provides an advantage over its AC counterpart by reducing standby power loss to a negligible amount. If the main power supplied is DC, there are no losses due to rectification between the micro-grid and loads, and negligible amount of loss due to standby [9]. Because of this, the standby losses are removed from the modeled loads for the DC home.

2.4.2 The DC Household Model

The DC micro-grid, illustrated in Figure 2-7, consists of two major components: the high-voltage (HV) and low-voltage (LV). The high-voltage component is established to be 380 V and the low-voltage component is
established to be 24 V. The external grid is expected to be the supplying the majority of energy to the household, which is a 240 V$_{AC}$ source. Rectifiers will convert the AC voltage to DC and enter through the HV component, and DC-DC converters will convert the 380 V to 24 V for the appliances that operate at 24V. The ratings of the rectifiers and converters will be dependent on the requirements of the household.

![Figure 2-7: DC household micro-grid](image)

The DC micro-grid can also be modified for utilization of renewable energy sources such as PV and wind turbines and provide generation for home-to-grid capabilities. Renewable energy systems methods of generation changes with the weather, making their power output random and unreliable.
for large power requirements of the modeled household. Due to the unreliable nature of renewable energy sources, they are not the primary source of generation. The modified micro-grid is shown in Figure 2-8.

Figure 2-8: Modified DC household micro-grid with generation capabilities

Renewable energy systems that are attached to the micro-grid are connected to highly efficient DC-DC converters due to them having d voltage levels. If renewable energy is utilized in the micro-grid, a battery should be attached as well in order to maximize energy usage by storing unused energy from renewable sources. The battery would also be connected through a highly efficient DC-DC converter to the micro-grid. The grid rectifier
implemented is a bidirectional rectifier and capable of inversion, allowing for the grid to receive power from the home.

2.4.2.1 Voltage Requirements for Loads

Similar to the AC model, high-powered loads would be designed to utilize the larger 380 V\(_{\text{DC}}\) to reduce the current requirement and maximize efficiency. These voltage requirements would be provided by the manufacturer of the appliances. For this research, high power usage appliances (e.g. air conditioning systems, microwaves, hair dryers, etc.) will connect to the 380 V bus and low power appliances (e.g. TVs, lighting, most refrigerators, most desktop computers, laptops, vacuum cleaners, etc.) will connect to the 24 V bus. Table 2.4 shows the voltage and current requirements of each selected load.
Table 2.4: Appliance voltage and current requirements for DC household

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Total Power (W)</th>
<th>Individual Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Power (380V)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Conditioner (Summer)</td>
<td>5000</td>
<td>13.16</td>
</tr>
<tr>
<td>Washer</td>
<td>425</td>
<td>1.12</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>5000</td>
<td>13.16</td>
</tr>
<tr>
<td>Gas Furnace (Winter)</td>
<td>600</td>
<td>1.58</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>1800</td>
<td>4.74</td>
</tr>
<tr>
<td>Hair dryer</td>
<td>1538</td>
<td>4.05</td>
</tr>
<tr>
<td>Oven</td>
<td>1800</td>
<td>4.74</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>1500</td>
<td>3.95</td>
</tr>
<tr>
<td>Microwave</td>
<td>1500</td>
<td>3.95</td>
</tr>
<tr>
<td>Iron</td>
<td>1100</td>
<td>2.89</td>
</tr>
<tr>
<td>Toaster</td>
<td>1100</td>
<td>2.89</td>
</tr>
<tr>
<td>Water Heater</td>
<td>475</td>
<td>1.25</td>
</tr>
<tr>
<td>Cooking Range</td>
<td>1000</td>
<td>2.63</td>
</tr>
<tr>
<td>Vacuum</td>
<td>650</td>
<td>1.71</td>
</tr>
<tr>
<td><strong>Low Power (24V)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCD TVs (3)</td>
<td>639</td>
<td>8.88</td>
</tr>
<tr>
<td>Refrigerator/Freezer</td>
<td>188</td>
<td>7.83</td>
</tr>
<tr>
<td>Video Game Player (2)</td>
<td>390</td>
<td>8.13</td>
</tr>
<tr>
<td>Monitor</td>
<td>150</td>
<td>6.25</td>
</tr>
<tr>
<td>Desktop Computer</td>
<td>120</td>
<td>5.00</td>
</tr>
<tr>
<td>Lighting (LED)</td>
<td>300</td>
<td>12.50</td>
</tr>
<tr>
<td>Mixer</td>
<td>100</td>
<td>4.17</td>
</tr>
<tr>
<td>Can Opender</td>
<td>100</td>
<td>4.17</td>
</tr>
<tr>
<td>Ceiling fan</td>
<td>75</td>
<td>3.13</td>
</tr>
<tr>
<td>Laptop (2)</td>
<td>100</td>
<td>2.08</td>
</tr>
<tr>
<td>DVR w/ Cable Box</td>
<td>44</td>
<td>1.83</td>
</tr>
<tr>
<td>Cable Box (2)</td>
<td>40</td>
<td>0.83</td>
</tr>
<tr>
<td>DVD Player (3)</td>
<td>51</td>
<td>0.71</td>
</tr>
<tr>
<td>Alarm Clock (2)</td>
<td>20</td>
<td>0.42</td>
</tr>
<tr>
<td>Wireless router</td>
<td>7</td>
<td>0.29</td>
</tr>
<tr>
<td>Cell Phone Charger (3)</td>
<td>12</td>
<td>0.17</td>
</tr>
</tbody>
</table>

2.4.2.2 Energy Losses for DC Home

The DC home will have three main components contributing to the overall energy loss:
• Rectification from the main power source (240 V\textsubscript{AC} Power Grid) to the Micro-Grid (380 V\textsubscript{DC}).

• DC-DC conversion of high voltage (380 V\textsubscript{DC}) to low voltage (24 V\textsubscript{DC}).

• Wiring resistance

In order to power the DC home, the AC voltage from the grid has to be converted into DC. A PFC boost rectifier is utilized to convert 240 V\textsubscript{AC} to 380 V\textsubscript{DC}. This is a centralized component, so any device utilizing the HV component of the micro-grid will not require rectification at each point of use, allowing for maximum efficiency. Also by utilizing centralized rectification, the grid rectifiers are designed for higher load and capacity, which improves efficiency [15] as shown in Figure 2-9.
The DC household is modeled with centralized rectifiers. In this research, two topologies are investigated. For this chapter, a bridgeless PFC boost rectifier is utilized because of its high efficiency, even for low loads, as illustrated in Figure 2-10 by [16]. Multiple rectifiers will be utilized with intelligent management to ensure maximum efficiency even at very low loads, giving an efficiency of 97% [15]. Intelligent management will operate only the needed rectifiers depending on the power demanded by the household load, preventing all rectifiers from operating at once which would decrease overall efficiency.
There are a few electronics that require AC power in order to operate. The appliances that are modeled with requiring AC power are the air conditioner, washer, clothes dryer, and refrigerator [8]. These devices are modeled in Figure 2-11 with 95% power efficiency.

![Figure 2-10: Rectifier efficiency at various output power [16]](image)

The low voltage appliances will require a DC-DC converter to reduce the 380 V\textsubscript{DC} to 24 V\textsubscript{DC}. High efficiency DC-DC converters are designed and implemented in the household to ensure maximum efficiency instead of
relying on the manufacturers’ designs. The DC model will utilize Ćuk converters to step down the voltage. Since DC-DC converters typically have higher efficiency when compared to rectifiers, the converters will be modeled with an efficiency of 94% [9], [17]. The losses for all conversions are shown together in Table 2.5.
Table 2.5: DC household power losses

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Total Power (W)</th>
<th>ON Loss (Wh/day)</th>
<th>Total Loss (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Power (380V)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Conditioner (Summer)</td>
<td>5000</td>
<td>2995.12</td>
<td>546.61</td>
</tr>
<tr>
<td>Washer</td>
<td>425</td>
<td>34.20</td>
<td>12.48</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>5000</td>
<td>427.87</td>
<td>156.17</td>
</tr>
<tr>
<td>Gas Furnace (Winter)</td>
<td>600</td>
<td>55.20</td>
<td>20.15</td>
</tr>
<tr>
<td>Dishwaser</td>
<td>1800</td>
<td>57.61</td>
<td>21.03</td>
</tr>
<tr>
<td>Hair dryer</td>
<td>1538</td>
<td>12.19</td>
<td>4.45</td>
</tr>
<tr>
<td>Oven</td>
<td>1800</td>
<td>75.47</td>
<td>27.55</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>1500</td>
<td>8.08</td>
<td>2.95</td>
</tr>
<tr>
<td>Microwave</td>
<td>1500</td>
<td>3.94</td>
<td>1.44</td>
</tr>
<tr>
<td>Iron</td>
<td>1100</td>
<td>5.84</td>
<td>2.13</td>
</tr>
<tr>
<td>Toaster</td>
<td>1100</td>
<td>2.85</td>
<td>1.04</td>
</tr>
<tr>
<td>Water Heater</td>
<td>475</td>
<td>348.04</td>
<td>127.03</td>
</tr>
<tr>
<td>Cooking Range</td>
<td>1000</td>
<td>31.11</td>
<td>11.36</td>
</tr>
<tr>
<td>Vacuum</td>
<td>650</td>
<td>17.02</td>
<td>6.21</td>
</tr>
<tr>
<td><strong>Low Power (24V)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCD TVs (3)</td>
<td>639</td>
<td>215.06</td>
<td>78.50</td>
</tr>
<tr>
<td>Refridgerator/Freezer</td>
<td>188</td>
<td>360.02</td>
<td>131.41</td>
</tr>
<tr>
<td>Video Game Player (2)</td>
<td>390</td>
<td>86.04</td>
<td>31.41</td>
</tr>
<tr>
<td>Monitor</td>
<td>150</td>
<td>79.22</td>
<td>28.91</td>
</tr>
<tr>
<td>Desktop Computer</td>
<td>120</td>
<td>61.50</td>
<td>22.45</td>
</tr>
<tr>
<td>Lighting (LED)</td>
<td>300</td>
<td>179.33</td>
<td>65.45</td>
</tr>
<tr>
<td>Mixer</td>
<td>100</td>
<td>0.20</td>
<td>0.07</td>
</tr>
<tr>
<td>Can Opender</td>
<td>100</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Ceiling fan</td>
<td>75</td>
<td>36.68</td>
<td>13.39</td>
</tr>
<tr>
<td>Laptop (2)</td>
<td>100</td>
<td>46.30</td>
<td>16.90</td>
</tr>
<tr>
<td>DVR w/ Cable Box</td>
<td>44</td>
<td>99.88</td>
<td>36.46</td>
</tr>
<tr>
<td>Cable Box (2)</td>
<td>40</td>
<td>11.05</td>
<td>4.03</td>
</tr>
<tr>
<td>DVD Player (3)</td>
<td>51</td>
<td>2.34</td>
<td>0.85</td>
</tr>
<tr>
<td>Alarm Clock (2)</td>
<td>20</td>
<td>43.70</td>
<td>15.95</td>
</tr>
<tr>
<td>Wireless router</td>
<td>7</td>
<td>15.24</td>
<td>5.56</td>
</tr>
<tr>
<td>Cell Phone Charger (3)</td>
<td>12</td>
<td>8.68</td>
<td>3.17</td>
</tr>
</tbody>
</table>

Copper selected due to its low resistivity and the American Wire Gauge (AWG) rating system is used to select the wiring for the DC household, just like in the AC model. Using equations 2-6, 2-7, and 2-8, and knowing the voltage drop cannot exceed 5%, the wiring size selected are 8 AWG for the LV
bus and 12 AWG for HV bus, fulfilling the requirement of maintaining a voltage drop of less than 5% for the required distance of 30 m.

As stated earlier, since the appliances operate on DC voltage, the standby losses are negligible. Therefore, the DC household's model will see energy loss only when appliances are powered on, or active. The total energy loss will be calculated using Equation 2-10.

$$\text{Energy Loss} = \frac{t_{\text{on}} \times (P_{\text{conv loss}} + P_{\text{wiring loss}})}{1000} \times 365 \text{ kWh/year (2-10)}$$

The total loss for the high voltage (HV) and low voltage (LV) buses are shown in Figures 2-12 and 2-13, respectively.

Figure 2-12: HV energy loss
The total yearly energy loss for the DC model is calculated to be about 1400 kWh. A comparison between the AC household and DC household is shown in Figure 2-14. Compared to the AC model, the power loss is reduced by close to 43% in the DC model, when factoring in standby loss. If standby loss was eliminated from the AC model, DC distribution would still reduce the power loss by almost 21%.
Figure 2-14: AC household vs. DC household energy loss comparison
Chapter 3

Design and Simulation

The grid rectifier and Ćuk converter will be designed and simulated for the DC household’s micro-grid. PSIM, from Powersim, Inc., will be utilized to design and model the converters. Powersim, Inc. is a leading company providing CAD software and consulting services for power electronics and motor control applications [18]. After designing working models in PSIM, they will be implemented into Simulink to simulate and analyze the converters at varying loads. Simulink is a very powerful simulation software that is part of MATLAB suite. Simulink utilizes a block diagram environment for simulation and design [19]. SimPowerSystems are the libraries and tools in Simulink that will be used for modeling the converter. SimPowerSystems is designed for simulating electrical power systems, allowing for development of control systems and testing system-level performance [20].

In order to create a working micro-grid, the converters have to be designed from the ground up. PSIM is used because it is fast, has great tools
for measuring power and energy, and SIMVIEW is a very powerful tool for viewing simulations results.

3.1 Grid Rectifier Topologies

In this chapter, there are two topologies investigated for the grid rectifier in the household, the single-phase boost PFC rectifier and interleaved full-bridge boost PFC rectifier. The single-phase boost rectifier is for rectification only, with no ability for reverse power-flow to send energy to the grid. The single-phase boost PFC rectifier is a high power factor rectifier which is obtained from a classical non-controlled bridge rectifier, with the addition of a transistor, diode, and inductor [2], shown in Figure 3-1. The rectifiers have PFC, or power factor correction, in order to improve the power factor and keep the current and voltage in phase. The use of the boost rectifier allows the AC voltage of 240 VRMS to be converted to 380 V_{DC}.

![Figure 3-1: Conventional single-phase boost rectifier circuit](image)
The boost rectifier controls the input current by changing the state of the transistor, T. When the transistor is in the “on state,” shown in Figure 3-2a, the supply is short circuited through the inductor (L). The diode avoids discharge of the filter capacitor through the transistor [2]. The behavior of the inductance current is given in Equation 3-1. Since absolute value of the source voltage ($v_s$) is greater than zero, the on state will cause an increase in the inductance current ($i_L$).

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{|v_s|}{L}$$

(3-1)

Looking at Figure 3-2b, when the transistor is in the “off state,” the inductor’s current flows through the diode, charging the capacitor [2]. The inductor current’s behavior is shown in Equation 3-2. During the off state, if
the absolute value of the source voltage is less than the output voltage, the inductor current decreases its instantaneous value \[2\].

\[
\frac{d_i}{dt} = \frac{v_i}{L} = \frac{|v_s| - v_o}{L}
\]  (3-2)

Since the output voltage (\(V_o\)) has to be greater than the input voltage, the transfer function (\(M_v\)) of a boost rectifier has to be at least 1, i.e. \(M_v \geq 1\). The transfer function can be calculated using the following equation:

\[
M_v \equiv \frac{V_o}{V_s} = \frac{1}{1-D}
\]  (3-3)

From Equation 3-3, the duty factor (\(D\)) can be determined:

\[
D = 1 - \frac{V_s}{V_o}
\]  (3-4)

The bidirectional interleaved full-bridge boost PFC rectifier (IFBR) \[22\] is a bidirectional rectifier that is capable of carrying out both rectification, AC-DC, and inversion, DC-AC. Just like the single-phase boost rectifier, IFBR features PFC to improve the power factor. IFBR offers a simple and efficient design that is very flexible. In this research, the IFBR designed for the micro-grid utilizes IGBT switches with anti-parallel diodes. The IGBT switches are assumed to be rated for a continuous 380 \(V_{DC}\) and 25 \(A_{RMS}\). The IGBTs will having switching losses which will contribute to the power loss seen in the rectifier.
When operating in “rectification mode” shown in Figure 3-3a, all three branches (A, B, and C) of the IFBR are controlled. A control system is used to control the states of the IGBTs. For simplicity, during the rectification mode, only the bottom three IGBTs are controlled while the upper IGBTs remain in an “off state” [23]. Initially, current flows through the boost inductors, following the bolded path shown in Figure 3-4a, with the positive-cycle path shown in red and the negative shown in blue. Once the inductors have stored enough current, the IGBTs are switched off and the voltage across the boost
inductors begin to rise to forward bias the anti-parallel diodes on Q1, Q3, and Q5 and current begins flowing, shown in Figure 3-4b, to charge filter capacitor.

![Diagram](image)

Figure 3-4: IFBR (a) inductor paths and (b) capacitor charging paths [23]

When the IFBR is switched to “generation mode,” the rectifier becomes an inverter as shown in Figure 3-3b. In this operation mode, the grid rectifier outputs 240 V\textsubscript{AC}. Q1, Q3, and Q6 are controlled to create the positive half-cycle and Q2, Q4, and Q5 are controlled to create the negative half-cycle.

The duty factor of IFBR is the same as the conventional single-phase boost rectifier, given by Equation 3-4. The inductor values can be calculated based on the maximum current ripple allowed. Utilizing Equations 3-1 and 3-4, the boost inductors can be determined based off the maximum ripple
current allowed in the rectifier, which is obtained from the following equation:

\[ \frac{di}{dt} = \frac{|v_s|}{L} \cdot D \]  

(3-5)

### 3.1.1 Control Systems

In order to regulate the output voltage in a household, a feedback control system is utilized to continuously modify the duty cycle in order to maintain a constant output voltage. The duty cycle is defined as the fraction of the period during which the switch is on [2]. In order to control the output voltage, the control system utilizes an error signal produced by the system based on present levels of the system compared with a defined reference. For the single-phase boost rectifier and IFBR in rectification mode, a sinusoidal pulse width modulation, or SPWM, controller is considered [2].

SPWM method was chosen because it’s very robust and has low output voltage harmonic [2]. SPWM control system utilizes two feedback loops, a voltage outer loop and a current inner loop. The voltage loop takes the output voltage as a feedback signal and compares it to a reference voltage, and produces an error. The error is then sent to a PI controller to produce a stable output voltage under steady-state operation [2]. The error is then multiplied to the absolute value of the source voltage to create a reference current for the inner loop. The inner loop operates just like the outer loop, and compares the inductor current to reference current created from the outer loop to
produce an error, which is then sent to the PI controller and produces a waveform that is compared to a reference waveform to generate a firing pulse sequence, which is applied to the switches.

The PI controller consists of two components, proportional and integral. The proportional component takes the inputted signal and increases it by the proportional gain, $K_p$, specified. The integral component integrates the inputted signal with respect to time and multiplies it by integral gain, $K_i$. The two are then added together to create the output signal.

When in generation mode, the control system for IFBR is changed. SPWM is used in generation mode; however, the grid rectifier is operating as an inverter and has to output a sinusoidal voltage at a desired frequency. To achieve this, the output voltage is compared to a reference waveform to create an error signal. The error signal goes through a PI controller and the output is compared to a modulating signal, creating the signals to control the gates.

3.2 The DC-DC Converter

DC-DC converters are used to regulate and control output DC voltage in modern electronics. The DC-DC converter type investigated for this research was hard-switching PWM (pulse width modulated) converters. DC-DC converters have multiple topologies available for reducing voltage, which includes, but not limited to, the buck converter, forward converter, Ćuk converter, push-pull converter, and half/full-bridge converter. The topology
chosen for the DC household was the Ćuk converter because, unlike the buck topologies, Ćuk converters create a smooth current at both sides of the converter (thanks to the input and output inductors) while others have at least one side with pulsating current [2].

![Ćuk converter circuit](image)

Figure 3-5: Ćuk converter circuit

The Ćuk converter consists of a DC voltage source, input inductor ($L_1$), controllable switch, output inductor ($L_2$), diode (D), energy transfer capacitor ($C_1$), filter capacitor ($C_2$), and a resistive load. When the switch is in the “on” state, the diode is off and $C_1$ is discharged by the output inductor $L_2$. When the switch is in the “off” state, the diode conducts currents of both inductors and capacitor $C_1$ is charged by the inductor current of $L_1$.

The Ćuk converter is an inverting converter and the DC voltage transfer function of the Ćuk converter is given in the following equation:

$$M_v \equiv \frac{v_o}{v_s} = -\frac{D}{1-D} \quad (3-6)$$

The Ćuk converters used in the DC micro-grid operate in CCM, just like the boost rectifier. In order to maintain CCM, the input and output

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inductors have to be large enough to ensure their respective currents do not reach zero. The minimum inductance required to maintain CCM is called the “critical inductance,” \(L_{\text{crit}}\), which is given in Equations 3-7 and 3-8.

\[
L_{\text{crit}1} = \frac{(1-D)R}{2Df} \quad (3-7)
\]
\[
L_{\text{crit}2} = \frac{(1-D)R}{2f} \quad (3-8)
\]

The energy transfer capacitor, \(C_1\), can be calculated based on the maximum peak-to-peak ripple voltage, \(V_{r1}\), allowed.

\[
C_1 = \frac{DV_D}{V_{r1}Rf} \quad (3-9)
\]

3.2.1 Control System

In order to regulate the voltage under the varying load of the household, a control system must be implemented in each Ćuk converter just like the grid rectifier. The control system being used for the Ćuk converters is the voltage-mode control system. The voltage-mode control system works by creating an error from the reference voltage and output voltage, and feeding that through a PI controller to produce the error signal. The error signal is then compared with a sawtooth waveform at the desired switching frequency, producing the gate signals.

3.3 PSIM Simulation Design and Results

The topology chosen for simulation for the grid rectifier is the interleaved full-bridge boost PFC rectifier. By going with IFBR for the grid
rectifier, the DC households can utilize Home-to-Grid and generate power for the grid to maximize energy efficiency outside of the home and reduce energy costs.

3.3.1 **Bidirectional Interleaved Full-Bridge Boost Rectifier (IFBR)**

![PSIM schematic for bidirectional interleaved full-bridge boost rectifier](image)

Figure 3-6: PSIM schematic for bidirectional interleaved full-bridge boost rectifier

The IFBR grid rectifier is designed with six IGBTs with anti-parallel diodes with each leg connected to a pair. The IFBR includes two boost inductors and a filter capacitor. The inductors and capacitors are assumed to have a low equivalent series resistance (ESR). The capacitors are assumed to be optimized capacitors designed to reduce the ESR. An input line filter can modeled to help reduce high frequency harmonics. The grid rectifier will be simulated in two states, rectification and generation.
The grid rectifier that will be designed will have a maximum power rating 5 kW and a switching frequency of 25 kHz. The 5 kW rating was chosen because, as stated in Chapter 2, the household is designed to utilize multiple rectifiers to maximize energy efficiency across a wide range of loads. The switching frequency of 25 kHz is lower than what is normally used for PFC rectifiers and was chosen to reduce the power loss due to switching losses. The boost inductors’ size is determined by the maximum amount of input ripple current allowed, which can be obtained from Equation 3-5. The inductors for this design are sized at 1.9 mH for a maximum peak-to-peak ripple current limit of around 1 A, allowing for high power factor and efficiency.

The filter capacitor (C) for the grid rectifier is sized based off the desired ripple voltage seen at the output. The voltage ripple is dependent on the amount of current drawn through the load and the output ripple frequency of the rectifier. The filter capacitor can be determined using Equation 3-10. The size of the filter capacitor is calculated based off the worst-case scenario, which is when the rectifier is running at full power. Since the Ćuk converters are powered through the grid rectifiers, the voltage ripple has to be low enough to be filtered by them. The desired output voltage ripple for the designed grid rectifier is less than 5% of the output voltage.

\[ \frac{dV}{dt} = \frac{V_o}{RC} \]  

(3-10)
The grid rectifiers will have the feedback control systems described earlier connected to regulate the output voltage for both rectification and inversion. When the grid rectifier is in “rectification” mode, the control system shown in Figure 3-7 is used. The control system will have a reference voltage of 380 V\text{DC}, which will create the error voltage when the output voltage, \( V_O \), is subtracted from it. This error voltage is sent to the PI controller which outputs to the multiplication block. The PI controller’s output is multiplied with the absolute value of the source voltage (\(|v_s(t)|\)) to create the reference current. The inductor current is compared to the reference current, creating another error signal that is sent to a second PI controller. The second PI controller’s output is then compared with a modulating waveform, producing the control signal which is outputted to the IBGT gates.

![PSIM schematic for grid rectifier’s control system](image)

Figure 3-7: PSIM schematic for grid rectifier’s control system

The signal from the control system controls only the bottom IGBTs (Q2, Q4, and Q6). Referring back to Figure 3-4, the upper IGBTs (Q1, Q3, and Q5) do not turn on during rectification and only the upper diodes are
operated. The bottom IGBTs are operated with the same signal since there is no issue with them operating during either the positive or negative cycles when their anti-parallel diode is forward biased.

The results of the grid rectifier are shown below in Figure 3-8. At a full load of 5kW, the output voltage is maintained at about 380 V with 120Hz ripple frequency and a ripple voltage of about 1.4%. The system has a power factor (PF) that is very close to 1, or unity power factor.

![Figure 3-8: PSIM grid rectifier waveforms, (violet) output voltage, (green) input voltage, and (blue) input current](image)

### 3.3.2 DC-DC Ćuk Converter

![Figure 3-9: PSIM schematic for isolated Ćuk converter](image)
The Ćuk converter designed utilizes a MOSFET and diode for the switching elements. The Ćuk converter is designed to handle up to 500 W. The 500 W rating was chosen because, as stated in Chapter Two, the household is designed to utilize multiple converters to maximize energy efficiency across a wide range of loads. The isolated Ćuk converter topology is used to assist with stepping down the voltage. The isolated Ćuk converter splits the capacitor and inserts a step transformer between them to step down the voltage, as seen in Figure 3-9. The proposed Ćuk converter will have a switching frequency of 75 kHz, a Schottky diode for low forward voltage drop and fast recovery, and a turn ratio \( n \) of 10. The turn ratio is the ratio of the transformer's primary to secondary windings. The equations to determine the components' size are slightly modified for the transformer and split energy capacitors. Just like the grid rectifier, the inductors and capacitors are assumed to have a low ESR. The transfer function and duty factor of the Ćuk converter is modified for the isolated Ćuk converter in Equations 3-11 and 3-12 to include the transformer's turn ratio.

\[
\begin{align*}
    n &> \frac{DV_S}{(1-D)V_o} \\
    D &= \frac{v_o}{v_s + \frac{1}{n}}
\end{align*}
\]

(3-11)  

(3-12)

The Ćuk converters have to be designed to have little current ripple at the output. Equations 3-13 and 3-14 illustrate the effect the inductor size has on the ripple current. The inductors also have to be sized greater than their
respective critical inductance to maintain CCM. The energy capacitor equation is modified for the isolated model, with Equation 3-15 and 3-16 created for both capacitors, $C_{1a}$ and $C_{1b}$.

\[
\frac{dl_1}{dt} = \frac{v_5}{2l_1} D \quad (3-13)
\]
\[
\frac{dl_2}{dt} = \frac{v_o}{2l_2} (1 - D) \quad (3-14)
\]
\[
\frac{dv_{C_{1a}}}{dt} = \frac{v_o}{2nRC_{1a}} D \quad (3-15)
\]
\[
\frac{dv_{C_{1b}}}{dt} = \frac{v_o}{2RC_{1b}} D \quad (3-16)
\]

The Ćuk converter will have the voltage-mode feedback control system shown in Figure 3-10 to regulate the output voltage for the LV component of the DC micro-grid. The control system creates an error signal from the reference voltage of 24 V$_{DC}$ and the output voltage. The error voltage is sent to the PI controller, and the output is then compared to a modulating waveform, producing the pulse signal which is outputted to the MOSFET switch. At full load (500 W), the output voltage of the maintained a ripple of less than 2%. The waveforms of the converter at full load are shown below in Figure 3-11.

Figure 3-10: PSIM schematic for Ćuk converter voltage-mode control system
Figure 3-11: PSIM waveforms for Ćuk converter. (Top) output voltage in red and current in blue, and (Bottom) source voltage in purple and current in green

3.4 Simulink Simulations and Efficiency

Figure 3-12: Simulink model of DC household micro-grid
The PSIM models are imported into Simulink using the SimPowerSystems library to simulate a working micro-grid with variable load. This is performed to ensure the viability of the system and to determine the efficiency of the individual converters and the overall micro-grid.

3.4.1 The Variable Load Block

Since the SimPowerSystems lacks a formal block for a varying resistive load, one had to be created in order to easily determine efficiency across a range of load values. To create a variable load block, this involves creating a “mask” in Simulink. The variable load block was created using fundamental equations for power electronics. The block is designed as a controlled current source, with the output current being determined by the current resistance value and voltage measurements. The resistance (R) is determined the output power desired (P) and the voltage level (V) of the micro-grid component, HV (380 V) or LV (24 V), that the load is connected to.
Using Equation 3-19, the load current \((I_L)\) demanded by the block can be determined and modeled in Figure 3-14.

\[
I = \frac{V}{R} \quad \text{(3-17)}
\]
\[
R = \frac{V^2}{P} \quad \text{(3-18)}
\]
\[
I_L = \frac{V_L}{V^2/P} \quad \text{(3-19)}
\]

Figure 3-14: Schematic for variable load block

### 3.4.2 The Grid Rectifier Simulink Model

The grid rectifier is model in Simulink with two operating modes, rectification and generation (inversion). While there are ways to automate the process of switching between the two modes, due to the complexity and increased simulation time, the modes are controlled manually for the purpose of this research. The rectification mode utilizes an AC voltage source to simulate the external grid. The load is modeled with two variable resistive load block for both high voltage and low voltage. The resistive load block
allows for basic operation of the rectifier when converting to DC voltage. The inverter mode is modeled with the battery providing DC power and a resistive load to simulate the external grid. The battery is modeled with a standard DC source, for simplicity and faster simulations.

The grid rectifier, shown in Figure 3-15, is a subsystem of the DC micro-grid. The circuit matches the model created in PSIM. The model consists of the spooling inductors and the filter capacitor. The IGBTs are modeled with the “Universal Bridge” block provided by Simulink, allowing for AC connections for each leg and DC connections. The block is controlled by the “Control System” mask created for simulation. The universal bridge requires six individual control inputs in order to operate.

Figure 3-15: Simulink schematic of grid rectifier
The grid rectifier subsystem contains two subsystems to allow for switching between generation and rectification, the AC and DC operation mode subsystems. The subsystems, shown in Figure 3-16, consist of ideal switches in order to switch between the modes. When G_Enable is “off,” the AC source and DC loads are connected, and the grid rectifier is in rectification mode. When G_Enable is “on,” the DC source and AC loads are switched connected, and the grid rectifier is in generation mode.

![Simulink schematic of operation mode subsystems](image)

Figure 3-16: Simulink schematic of operation mode subsystems, (a) AC and (b) DC

The gates of the universal bridge are controlled by the “Control System” mask which outputs six control signals (one for each gate). The control system is broken into two separate subsystems, one for controlling rectification and one for controlling inversion. G_Enable controls which controller is used and is illustrated in Figure 3-17a. When G_Enable is “on,” the inverter controller is active, and when G_Enable is “off,” the rectifier controller is active. The rectifier control system (Figure 3-17b) utilizes the
same topology designed in the PSIM model. In the Simulink model, the universal block requires six signals, one for each IGBT. Since the universal block only has one input, the individual signals are combined into a single vector output.

Figure 3-17: Simulink schematic of (a) control system mask, (b) rectifier controller, and (c) inverter controller
The control system for IFBR’s generation is different from the one used for rectification and is shown in Figure 3-17c. It will compare the AC output voltage with a reference sine waveform of 60 Hz and an amplitude of 240 V\textsubscript{rms}. The error signal is sent through the PI controller and the output is compared to a modulating waveform for the positive half-cycle, and an inversion of the PI controller’s output is compared to modulating waveform for the negative half-cycle. The signals are then outputted to the IGBT gates. The generation function of the grid rectifier is simulated through Simulink and the output is in Figure 3-18.

![Figure 3-18: Grid rectifier “generation mode” output](image)

3.4.3 DC-DC Converter Simulink Model

The DC-DC isolated Ćuk converter and its control system are modeled into Simulink using the PSIM schematic. The primary voltage source for the
Ćuk converter is the grid rectifier versus a DC voltage source utilized in PSIM; however, a switch is implemented so the Ćuk converter is able to utilize the “battery source” as a secondary option for simulation purposes. The Ćuk converter is modeled as a subsystem shown in Figure 3-19.

![Figure 3-19: Simulink schematic of Ćuk converter](image)

The control system is designed the same as the PSIM model. The Simulink model is designed as a mask, just like the rectifier’s model, allowing easy modification of the PI controller’s gains, frequency, and reference voltage.
3.4.4 System Efficiency

Using PSIM, the rectifier and converter were individually tested to determine efficiency at full loads. The results are shown in Figure 3-21, (a) grid rectifier and (b) Ćuk converter. The grid rectifier’s efficiency averaged around 98.4% at 5 kW and the Ćuk converter’s efficiency averaged around 98.4% at 500 W. The micro-grid is tested for efficiency at full load of 5kW in Simulink, which outputted an efficiency of about 97% with the HV loads utilizing 4.5kW and the LV loads demanding the remaining 500W.
Figure 3-21: Full load efficiency results of (top) grid rectifier, (middle) Ćuk converter, (bottom) micro-grid
Simulink was used to measure the efficiency across a load range by utilizing the variable load block. A load profile, representing a range from 10% to 100% of the maximum loads, was attached to the variable load blocks. The final micro-grid efficiency results are shown below in Figure 3-22.

![Efficiency curve for micro-grid](image)

**Figure 3-22: Efficiency curve for micro-grid**

The efficiency curve shows that the efficiency of the micro-grid increases as the load on the system increases. The efficiency of the system when first simulated was approximately 91%, with the main problem being the Ćuk converter. This was rectified by replacing the voltage-mode control system with the double-loop feedback system used by the grid rectifier. The modified control system allowed the micro-grid to achieve an efficiency of 96.98%.
Chapter 4

Conclusions and Future Research Work

4.1 Conclusions

The electric grid is approaching the point where the increasing energy demand is going to require major changes to either improve the electric grid to handle the higher demand, or reducing the demand on the grid itself. The latter has been employed over the past decade through the utilization of renewable energy generation, alternative fuels, and intelligent regulation (Smart Grid).

This research investigates and demonstrates the viability of DC as an alternative for distribution within households. This thesis evaluated DC distribution that can support a wide range of loads that would be otherwise limited if a low power distribution system was used. The utilization of a DC micro-grid with both 380 V$_{DC}$ distribution and 24 V$_{DC}$ distribution allows for support of a wide range of appliances to be compatible with a variety of home sizes and lifestyles.
The AC and DC households, respective loads, were outlined and modeled, and then tested. The loads modeled were those found in a typical middle-class, American household; however, the DC distribution system is expandable and can be modified to support households with larger or smaller energy demands. The DC household reduced the losses seen in the AC household from rectification and conversions, and significantly reduced the standby loss through the elimination of power supplies for AC-DC conversion in appliances.

The DC micro-grid was designed and simulated in both PSIM and Simulink. The topology of the grid rectifier and DC-DC converter were discussed in detail. The grid rectifier chosen was the interleaved full-bridge PFC boost rectifier. This was chosen primarily for the bidirectional support and near unity power factor. The topology chosen for the DC-DC converter was the isolated Ćuk converter, which was selected because it provides good continuous current at the output. The models of the converters were created and simulated in PSIM for easier design and faster simulation, and were then imported into Simulink. Simulink was utilized for simulating and verifying the generation capabilities of the grid rectifier, obtaining the efficiency of the IFBR and Ćuk converter, and simulating the DC micro-grid across a load range to obtain its efficiency. The results obtained from the
simulations verified the micro-grid is capable of obtaining the desired energy efficiency of DC household. Both the comparison of the AC and DC household models showing that the DC household reduces energy loss by nearly 43% and the high efficiency obtained from the DC micro-grid that was simulated present DC distribution as a more efficient alternative to the current AC distribution in residential households.

4.2 Future Research Directions

Future research of the proposed DC household would include the following areas:

- Simulink could be used to model a scalable system to simulate and test the power demand at levels that exceed that of the grid rectifier through the use of intelligent management of multiple rectifiers.
- Implementation of a battery model and its DC-DC converter for further testing into the DC household’s generation capabilities and efficiency, along with automating the switching of rectification and generation modes [24].

This thesis can also be used as a template for home automation and demand-side management (DSM), allowing for migration of energy demand
from high demand periods to off-peak periods, and improving energy efficiency and conservation through control and automation of appliances [25].
References


DISTRIBUTION SYSTEM FOR HYBRID RENEWABLE ENERGY SYSTEMS," 2010.


