EFFICIENCY STUDY OF A HYBRID AC/DC HOUSE

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ABSTRACT

Efficiency Study of a Hybrid AC/DC House

Eunice Dominique Solomon Santiago

With the proliferation of residential-scale renewable energy sources and DC loads, it has become attractive to use residential DC electrical system that could offer benefits over the legacy residential AC electrical system. The Hybrid AC/DC house provides a sustainable alternative to preexisting residential electrical system by having both AC and DC buses. The DC bus facilitates the connection from DC sources to DC loads, whereas the AC bus interfaces AC sources to AC loads. The study develops the equations to calculate losses based on a model consisting of four main components: Multiple-Input Single-Output (MISO) converter, AC-DC converter, inverter, and DC-DC converter. Parameters such as AC and DC bus voltages, load consumption, and number of AC and DC branches were used to construct multiple scenarios and evaluate efficiency. Results of the study show that the Hybrid AC/DC house displays higher efficiencies than when the house has AC only sources with higher DC load consumption. Similarly, the Hybrid AC/DC house has better efficiency than when the house has DC only sources under higher AC load consumption. For the DC bus, results of the study further indicate that the higher DC voltage level yields better efficiency than those obtained from lower DC voltages.
I would like to thank my family and friends for everything that they do for me.

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Chapter 1: Introduction

As the world continues to develop technologically, energy consumption will continue to rise. According to the U.S. Energy Information Administration, the world energy consumption will increase by 50% between 2018 and 2050 [1]. Urbanization, increased access to electricity, and rising standards of living in developing countries contribute to most of the global increase in energy consumption [1]. Recent growth in electrification in the transportation sector has also added to the energy demand. With the irrefutable growth in energy consumption, energy supply consequently has to grow to meet the demand. Currently, the world still heavily relies on fossil fuels to supply energy as depicted in Figure 1-1. In 2021 for example, about 61% of electricity generation in the U.S. was from fossil fuels—coal, natural gas, petroleum, and other gases [2].

![Figure 1-1. Energy sources in the United States [3]](image-url)
Despite being a reliable source of energy since the Industrial Revolution, fossil fuels are not sustainable. This means fossil fuels are a finite source of energy that will deplete with continued use. Despite the limitations in supply, availability has not been the main concern with fossil fuels but rather the greenhouse gas emissions produced. According to United States Environmental Protection Agency, greenhouse gases trap heat and make the planet warmer [4]. Majority of the greenhouse gases come from burning fossil fuels for electricity, heat, and transportation [4]. Electricity generation, transmission, and distribution contribute 25% of the total U.S. greenhouse gas emissions [4]. The use of fossil fuels exacerbates the increase in global temperatures which leads to more energy consumption to regulate temperatures in buildings. This further yields a never-ending cycle of increasing energy consumption.

In addition to environmental consequences, reliance on fossil fuels proves to be disadvantageous with unstable gas prices and supply. There is an enormous amount of power given to countries that supply oil. This power can be used as a leverage to control gas prices by limiting global supply. Because of unsustainability, environmental effects, and instability issues with fossil fuels, there has been a push for increasing the use of renewable energy sources.

As defined by United Nations, renewable energy is “energy derived from natural sources that are replenished at a higher rate than they are consumed” [5]. In the United States, renewable energy sources account for 20% of electricity generation in 2021 [2]. This however does not include nuclear energy which contributes 19% of electricity generation [2]. The top three contributors in the renewable energy category are wind, hydropower, and solar [2]. With renewable energy, the majority of the problems
associated with fossil fuels such as sustainability, greenhouse gas emissions, and supply instability can be tackled. In addition, renewable energy provides diversification of energy sources and prevents the monopolization of the energy industry.

One way to help the widespread use of renewable energy sources is through their adoption in residential and building electrical systems. Today, residential homes and buildings predominantly operate with the legacy Alternate Current (AC) electrical distribution system. However, AC electrical system has been known to possess several major disadvantages. For example, the U.S. Energy Information Administration estimates around 5% of power losses in electricity distribution and transmission [6]. This may seem small at first but realizing that the U.S. generates about 4 trillion kWh/year, the 5% losses means that the U.S. loses around 200 billion kWh in AC transmission and distribution [2]. Another common issue with AC electricity is reliability. The growth in energy consumption as previously mentioned has also taken a toll on AC grids. This leads to frequent blackouts to relieve stress from the grid. With the addition of renewable energy sources such as solar panels, the AC grid can be relieved from the stress of increasing energy demand. Even when the AC system is integrated with renewable energy sources, which are mainly photovoltaics (PVs), the reduced overall system efficiency issue still remains especially due to the fact that PVs produce Direct Current (DC) power. More specifically, a DC-AC power converter also known as inverter is needed to operate the PVs with the AC house. Such a system may also require the use of transformers that further introduces additional 10% power loss through copper, hysteresis, and eddy currents [7]. Therefore, alternative solutions utilizing technologies that will enable more efficient use of renewable energy sources will be needed.
The increasing urgency to promote a sustainable solution to the previously explained energy consumption problem has brought about the idea of a net-zero energy building. A net-zero energy building is an infrastructure that produces as much energy as it consumes in a given time frame [8]. The building’s renewable energy system has to produce equal or more energy than it consumes to qualify as a net-zero energy building. In Massachusetts, the first state-owned net-zero energy building is the North Shore Community College [8]. The college building incorporates natural lighting, shade, and ventilation in its building design to reduce electricity consumption [8]. In addition, it utilizes a 50-well geothermal system and 340kW solar panels [8]. As a result, the college building not only reduces 4,000 metric tons of carbon emissions, but also saves roughly $3.5 million in electricity bills over the next 20 years [8].

Overall, the increasing energy consumption and demand are sustainability issues that could be potentially solved by enhancing electrical power systems and by significantly reducing the use of fossil fuels through the adoption of renewable energy sources. One way to improve the existing electrical system is by minimizing power losses that occur during the process of converting energy from the source to that required by the loads. One enabling technology that can achieve this goal is power electronics. With power electronics, techniques that offer AC to DC, AC to AC, DC to AC, and DC to DC energy conversion processes may be implemented to maximize the efficiency of an electrical system. To this end, complementing the existing AC electrical system with DC electrical system may provide the improved efficiency needed by the electrical power system to fulfill future energy demand [9].
Chapter 2: Background

Countries all over the world are investing in renewable energies because it provides long-term solutions to the aforementioned problems with fossil fuels [10]. This is great news since development of renewable energies sources will help provide energy both in urban and hard-to-reach areas. Moreover, added energy supply in rural areas creates opportunities for industrialization and better infrastructures. This will lead to job opportunities and avoid mass migration to urban environments [10]. However, as more renewable energy sources are deployed and integrated withing the existing power systems, energy conversion efficiencies become a concern. For example, PVs as the most widely used renewable energy source provide DC power. Therefore, when interfaced with the existing AC system they will need to be converted to AC first via an inverter before we can use them. Losses from the inverter are approximately between 23% to 28% [16].

The conversion process unfortunately does not end here especially in a residential electrical system. This is due to the fact that many residential loads such as LED lights, TVs, USB device chargers, electric stove, laptops internally require DC power. Hence, another stage of conversion from AC to DC must take place. Studies conclude that the losses accumulated by the conversion from DC to AC and back to DC are at least 10% [17]. As seen in Figure 2-1, the PV Array generates DC, and it has to be converted to AC in order to fit into the residential AC system. However, the house appliances that are plugged into AC converts it back to DC to power the control electronics inside. Even heavy AC loads, such as a refrigerator and washing machines, require conversions to DC
because of the use of control electronics. Avoiding these losses can save energy usage around 120-170 million Euros a year [17].

![Diagram of AC/DC conversion in a classic AC system distribution](image)

**Figure 2-1.** Conversion of AC/DC in a classic AC system distribution [17]

Besides the additional loss that an inverter will introduce when converting from DC to AC power, another undesirable trait of an inverter is that it uses electrolytic capacitors which shorten its lifespan [10]. Electrolytic capacitors are notorious for having a short lifespan that ranges from 5-8 years [10]. This means that the inverter will require frequent replacement and a power shutdown of the whole system [10]. Thus, the use of an inverter becomes laborious and costly in the long run. In contrast, if the DC to AC conversion can be bypassed, the straight DC-DC conversion process will not only reduce the energy consumption by 10-30%, but it will also decrease the cost by 15% due to fewer copper materials and components needed [17].

The changing landscape of energy sources requires the power system to adapt. Currently, the AC system is only 85% efficient when a PV array source is introduced
Whereas an all-DC system has 97% efficiency [17]. This is considering that all appliances use DC. In the FREEDM Systems Center study, four different house models were used to simulate the load profile [18]. The load profile includes High Power Base DC Load, Low Power Base DC Load, PV Generation, and EV Load Profile. The four house models are AC House, Retrofit DC, FREEDM Hybrid, and FREEDM DC [18]. The connections of the house models are shown in Figure 2-2. The SST is the solid-state transformer FREEDM Systems Center designed to provide a step-down function, reactive power compensation, voltage regulation, and DC link.

Figure 2-2. FREEDM house models simulation [18]

To further understand how each configuration affects the Net Present Value (NPV) which shows the cash flow of the investment [19], a cost benefit analysis tool was used to calculate annual electricity bills and cost of materials used. Table 2-1 displays the NPV of the four house models.
Results of the study depict that the FREEDM DC or the all-DC system provides a consistent positive NPV. On the other hand, an all-AC system produces the least NPV. The FREEDM hybrid still fares better than the AC but not as well as the DC. However, it is noted in the study that the FREEDM hybrid system still uses an AC/DC converter for the DC loads in the simulation [13]. The use of an AC/DC converter introduces power losses and worsen the efficiency of the hybrid system.

An implementation example of the all-DC design is the DC house prototypes at Universitas Padjadjaran in Indonesia and Technological Institute of the Philippines [10][11]. The initial design of the DC house consists of two renewable energy sources: 100-150W solar panels and 300W DC wind generator [12]. A multi-input DC-DC converter takes in different DC outputs from renewable energy sources and outputs a constant 48V DC [13]-[15]. The simplified layout of electrical connections is shown in Figure 2-3.

### Table 2-1. Net present value simulation results [18]

<table>
<thead>
<tr>
<th>Location</th>
<th>AC</th>
<th>Retrofit DC</th>
<th>FREEDM hybrid</th>
<th>FREEDM DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC-Wilmington</td>
<td>-$254</td>
<td>-$90</td>
<td>-$50</td>
<td>$1,258</td>
</tr>
<tr>
<td>FL-Orlando</td>
<td>-$103</td>
<td>-$43</td>
<td>$99</td>
<td>$1,232</td>
</tr>
<tr>
<td>GA-Columbus</td>
<td>$87</td>
<td>$122</td>
<td>$292</td>
<td>$1,377</td>
</tr>
<tr>
<td>LA-New Orleans</td>
<td>-$206</td>
<td>-$63</td>
<td>-$3</td>
<td>$1,255</td>
</tr>
<tr>
<td>TX-Austin</td>
<td>$16</td>
<td>$150</td>
<td>$220</td>
<td>$1,478</td>
</tr>
</tbody>
</table>
The DC bus feeds into 10 LED lights and 4 USB plugs [10]. Since not all DC loads are 48V DC, a DC-DC converter is needed to supply loads that are not 48V [10]. Since renewable energy production largely depends on the weather and climactic conditions, the main drawback of the system is having inconsistent generation of power. To resolve this issue, a battery system is put into place. The battery was sized to provide continuous power for 12hrs at 300W without any sources available [10].

Ideally, an all-DC system would be efficient, reliable, and economical in the long run. However, practically speaking, the current AC system will not be replaced anytime soon by a completely different power system. There are also heavy AC loads that will require large AC power. These factors will make it very challenging for the adoption of DC House as a future residential electrical system. Couple with also the fact that renewable energy source is intermittent for the most part, therefore, the hybrid AC/DC residential electrical system solution becomes appealing. With the hybrid AC/DC system, the inconsistencies of the renewable energy sources can be backed up with the AC grid while consumers can still buy regular AC appliances on the market [20].
NEST HiLo is a building in Dubendorf, Switzerland that supports a hybrid AC/DC network [21]. The building aims to investigate the transition to a 100% renewable energy society by combining renewable energy sources and optimized energy efficiency. In order to achieve an optimized energy efficiency, simulations were conducted to compare the performance of an AC-based power system and a DC-based power system. The two configurations shown in Figure 2-4 depict the block diagrams of the compared power systems.

![Diagram of AC coupled PV-LED lighting](image1)

![Diagram of DC coupled PV-LED lighting](image2)

**Figure 2-4.** Reference for AC system and DC system [22]
The simulation results show that for the AC coupled PV-LED lighting, efficiency reaches up to 82-86% while the DC coupled PV-LED lighting has an efficiency from 90-96% [22]. A DC microgrid reduces power conversion losses by approximately 20% without battery and 30% with battery [22]. The results further indicate that AC-DC conversions are 4-8% more efficient than DC-AC conversions. Since AC-DC conversions are more efficient, the DC coupled PV-LED lighting configuration in Figure 2-4 has a more optimized energy efficiency. The study concludes that DC configuration is beneficial for office and commercial buildings where most loads are DC [21]. The study also discovered that more losses are avoided when the installed PV power and battery capacity are increased as shown in Figure 2-5.

In another part of the world at Tagajo Campus of Tohoko Gakuin University, Japan, a hybrid microgrid was designed to prove the feasibility of the concept of AC and DC integration [23]. The design uses renewable energy sources such as solar and wind as a major energy source and a diesel generator as a backup [23]. The microgrid has a separate AC and DC bus unlike the previous examples. The main problem of the DC bus is stability because power fluctuates both at the source and load. Since renewable energy
sources are intermittent, the DC voltages supplied to the DC bus are inconsistent. Likewise, the use of DC loads varies and cause power fluctuations. To combat these problems, the hybrid microgrid used both a battery and EDLC (Electrical Double-layer Capacitor) to stabilize the DC bus voltage at a nominal of 135V [23]. AC stabilization is not a concern because the inverter stabilizes the AC output in islanding operation and the utility stabilizes AC input if the system is grid-connected [23]. The experimental system configuration is shown in Figure 2-6.

**Figure 2-6.** Experimental system block diagram [23]

**Figure 2-7.** Voltage profiles of DC and AC bus [23]
The simulation conducted in the study consists of renewable power fluctuation and incremental changes a controllable DC load (1050W ® 800 ® 600W ® 450W) [23]. The experimental results exemplify that both the DC and AC bus can withstand the change in DC loads and varying output of renewable energy sources. The results further demonstrate that the concept of a hybrid AC/DC electrical system is feasible and can be implemented in actuality.

To contribute to the advancement of hybrid AC/DC residential electrical system research, this thesis aims to conduct a study on the performance of a Hybrid AC/DC house when operated under various parameters. More specifically, the study will investigate the different combinations of DC voltages, AC voltages, number of DC branches, number of AC branches, and power in a hybrid AC/DC residential system. Each combination of the parameters will be simulated and analyzed with the focus on the efficiency and the cost of the system.
Chapter 3: Design Requirements

This project will model a hybrid AC/DC house and analyze the impact of various AC voltages, DC voltages, and wattages on the efficiency and cost of the system. This system operates on a primary goal of finding the most efficient and cost-effective combination.

Figure 3-1. Hybrid AC/DC Level 0 Block Diagram

The hybrid AC/DC house consists of two major inputs: AC and DC sources. Multiple AC and DC sources can be implemented into the system. A grid-tied hybrid AC/DC house will have an AC source regulated by a utility company. An off-grid hybrid AC/DC house has a generator to supply AC into the house. DC sources include multiple renewable energy sources such as PV, DC hydropower, and DC wind power. Other non-renewable DC sources include batteries. In Figure 3-1, the two major outputs of the system are AC and DC loads. Common AC loads are refrigerator, air conditioner, and washing machine, whereas LED lights, small house appliances, and electronics are the most common for DC loads.
When the hybrid AC/DC system is expanded, the two major inputs are specified as shown in Figure 3-2. The AC sources are the grid and a generator. On the other hand, the DC sources are separated into a renewable energy input (PV array) and a battery. The summing junction of the sources represent the option to add or remove sources. The DC sources have a direct path to supply power to small DC loads, and the same goes for AC sources and loads. There are AC/DC and DC/AC converters that bridge the AC and DC lines in case there is a need to supply from the other line.

**Figure 3-2. Hybrid AC/DC Level 1 Block Diagram**
Figure 3-3. Hybrid AC/DC Level 2 Block Diagram

With the level 2 block diagram, the path from the DC source to the DC load is illustrated. The PV array connects to a solar charger controller that outputs the optimal DC voltage to the Multiple Input Single Output (MISO) or the battery. Then, the outputs of the battery and the solar charger controller are connected to a MISO. The MISO selects one to output to the DC bus and supply power to small DC loads. The MISO is an optional component of the electrical system design. The AC line of the house will be either at 120V at 60Hz or 230V at 50Hz, which are the two most common combinations of AC voltage and frequency. As seen in Figure 3-3, for this study the DC line of the house ranges from 12-48V in increments of 12V. The total power consumption of the load examines 600-1500W in increments of 300W. As explained in Block Diagram Level 1, the design consists of an AC/DC and a DC/AC converter. The AC/DC converter acts as both a rectifier and a voltage regulator to properly convert the AC voltage to a DC voltage as well as maintain the DC voltage output to the load. The DC/AC converter is an inverter that meets the given voltage and wattage values of the simulation. The DC/DC converter denotes the DC voltage conversion that occurs between the DC line provided to
the house and the DC voltage required by the load. The dotted boxed area in Figure 3-3 is what will be focused on in the thesis. The focus will include the MISO, AC/DC converter, inverter, and DC/DC converter.

Certain assumptions must be made to simplify the development of the model for the proposed Hybrid House. The assumptions of the system are as follows:

- DC branches will have the same voltages.
- AC branches will have the same voltages.
- The total cable or wire length will be a fixed value divided into a total of 5 branches.

Example: Total wire length = 25m, 3 DC branches, 2 AC branches

\[
\text{DC wire length} = \frac{3}{5} (25 \text{ meters}) = 15\text{m}
\]

\[
\text{AC wire length} = \frac{2}{5} (25 \text{ meters}) = 10\text{m}
\]

- The loads will be running at full load conditions.
- The inverter and AC-DC converter cannot be turned on at the same time.
- Circuit breakers will trip when the current goes above current calculated per branch.
- Wires are copper material.

The technical specifications are summarized in Table 3-1.
**Table 3-1. Hybrid AC/DC House Technical Specifications**

<table>
<thead>
<tr>
<th>Engineering Specifications</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Voltages: 12V, 24V, 36V, 48V</td>
<td>Support common small DC loads</td>
</tr>
<tr>
<td>120VAC (60Hz), 230VAC (50Hz)</td>
<td>Power coming from the grid</td>
</tr>
<tr>
<td>600-1500W in increments of 300W</td>
<td>Initial power constraints to limit simulation count and test varying wattage values</td>
</tr>
<tr>
<td>AC/DC converter</td>
<td>Power from the AC line can support the DC line when the DC source(s) cannot supply power to the DC loads</td>
</tr>
<tr>
<td>DC/AC converter</td>
<td>DC sources act as backup power when blackouts or emergency power shutdowns occur</td>
</tr>
</tbody>
</table>

Ultimately, the goal of this thesis is to study the performance of a Hybrid AC/DC House when operating under varying permutations of DC voltages, AC voltages, and wattages. More specifically, the overall efficiency of the Hybrid House will be evaluated and compared to that of AC only and DC only operated houses.
Chapter 4: Design and Simulation

This chapter will discuss the individual blocks: MISO, AC/DC converter, inverter, and DC/DC converter. Furthermore, the equations and block diagrams of the different cases that could occur in the Hybrid House system will be covered in this chapter.

Since the simulation evaluates four wattages, there are three methods to consider when choosing the individual components’ wattage ratings. The first method is to buy a component that can handle all the wattages from 600-1500W. The second method is to choose a separate converter for each wattage. The third method is to place two or more converters in parallel to form the wattage requirements. For example, two 600W converters can be connected in parallel and create a 1200W converter. The third option is not an optimum solution because it is expensive, constitutes more power losses, and utilizes more space. Especially at lower loads, the efficiency of the converter decreases so the effect of having two or more converters in parallel would lead to more inefficiencies. The second option is also not practical because it will cost more to buy individual converters for different wattages. Therefore, the most practical method is getting a converter that can handle the 600-1500W requirements.
4.1 MISO

The MISO has multiple renewable energy inputs and outputs a single voltage in DC. The range of the DC output that will be examined is from 12-48V. The values that will be simulated are 12V, 24V, 36V, and 48V. The efficiency plots of MISO have the same trend of decreasing efficiencies at lower loads as the other converters.

Figure 4-1. 48V MISO 600 Efficiency Plot [24]

Figure 4-2. 48V MISO 1800 Efficiency Plot [24]
Figures 4-1 and 4-2 show the efficiency plots of MISO that are rated at 600W and 1800W [24]. Both MISO600 and MISO1800 have at least an efficiency above 90% for any load percentage. At full load, MISO600 has a 96.5% efficiency and MISO1800 has a 96.4% efficiency [24]. The MISO specifications have an input voltage of 10-60V, 24V nominal, and average output voltage of 48V [24]. The same efficiency curve patterns would appear for different average output voltages as seen in figure 4-3 where a different MISO with an output of 12V generates almost the same curve shape and has an even higher efficiency of around 97% [25]. It can be assumed that from the range of 12V-48V, the efficiency curve will appear to be the same as the 12V and 48V efficiency curves. Therefore, for the simulation an efficiency of 96.4% will be used for the MISO when running at full load conditions since it is the lowest efficiency measurement of the MISO.

4.2 AC/DC Converter

The AC/DC converter in the Hybrid House system will work similar to a switched mode power supply. Figure 4-4 shows how a switched mode power supply works where
the main components are the rectifier, a high frequency converter such as a flyback converter, filter, and a feedback system such as a PWM controller.

![Switched Mode Power Supply](image)

**Figure 4-4.** Switched Mode Power Supply [26]

![Efficiency curve](image)

**Figure 4-5.** Efficiency curve for 5-kW AC-DC converter [27]

In figure 4-5, the efficiency curves are for a 5-kW isolated bidirectional ac-dc converter that has 220VAC input voltage and with 380VDC output voltage [27]. The chart is an example of what an ac-dc converter efficiency curve generally looks. The components of the 5-kW isolated bidirectional ac-dc converter offer the same efficiency curve as seen on the rectifier and CLLC resonant converter curves. The highest efficiency for the overall system is 95.6% at 2kW and 94.2% at 5kW (full load) [27].

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The AC/DC converter is connected to the AC sources such as to the grid and to the DC loads in the house. The AC/DC converter must meet the requirements of 600-1500W, output voltages of 12-48V, and AC voltages of both 120V (60Hz) and 230V (50Hz). FNP1800-48G can output either a 48V or 12V and handle both AC voltages. It has a nominal efficiency of 90% [28]. The FNP1800-48G does not have an efficiency curve in the datasheet. So, the average of the simulation from the 5-kW isolated bidirectional ac-dc converter and the FNP1800-48G will be utilized for the efficiency of the Hybrid House’s ac-dc converter. For the full load efficiency, the average of the two is 92.1%.

4.3 Inverter

In this electrical design, the inverter is connected to the MISO and the AC loads. Sandia National Laboratories modeled the power efficiencies of solar inverters and had field measurements of various solar inverters to compare the result of the model and the actual measurements [29]. The laboratory follows the guidelines of California Energy Commission (CEC) test protocol [29]. The CEC test protocol measures the power efficiency of the inverter at six different power levels —10%, 20%, 30%, 50%, 75%, and 100% of ac-power rating, as well as, at three different input voltage levels (V_{min}, V_{nom}, V_{max}) [29].
Figure 4-6 is an example of the field measurements recorded at Sandia National Laboratory using SWR-2500U inverter. The graph shows the inverter efficiency and relationship between ac-power and dc-power [29]. The test lasted for 13 days which included both clear and cloudy days and the graph shows over 4,000 field measurements [29]. The efficiency curve displays the same curve pattern as the other converters where a knee point shows at around 20% load conditions and efficiency stabilizes at higher load conditions. Sandia tested a multitude of inverters and have an inverter performance database in the inverter performance report [29]. For the simulation, the inverter requirement is to be able to handle 600-1500W of power. Also, there are two AC voltages to be considered 120V at 60Hz and 230V at 50Hz. It is assumed that the MISO will output a DC voltage to meet the inverter’s input DC voltage. The inverter chosen for the 120V at 60Hz is the FREEDOM X 2000 12V, manufactured by Xantrex. The FREEDOM X 2000 12V has a continuous output power of 2000W, has a DC input
nominal voltage of 12.0V, can be configured 50 or 60Hz, and has a >87.5% full load
efficiency [30]. Likewise, the inverter for 230V at 50Hz is the FREEDOM XC 2000
230V, also manufactured by Xantrex. The FREEDOM X 2000 230V has the same power
 specifications as the FREEDOM X 2000 12V [31]. The efficiency for the 230V is a 90%
at full load [31]. In the simulation, the efficiency for the inverter is set to 89% because
that is the average of the Sandia and Xantrex measurements at full load conditions.

4.4 DC/DC Converter

The DC/DC converter is the bridge from the DC bus line that will range from
12V-48V to the DC loads. The specific voltages of the loads are not required in the
simulation because the power consumption of the loads will be set, and the efficiency of
the DC/DC converter will be a known percentage. Therefore, input power from the
DC/DC converter can be calculated without knowing the specific voltages of the DC
loads. However, the typical DC loads values range from these values: 1.2, 1.5, 3, 3.3, 3.6,
5, 6, 10, 12, 15, 18, 18.5, 19, 20, 24, and 48 Volts [32]. Figure 4-7 shows the efficiency
curve of the DC/DC converter in buck mode when the input voltage is 48V and the
output voltage is 12V [33]. The graph comes from a bidirectional DC/DC converter that
will be used in the DC house battery management system [33]. According to the Bi-
Directional DC-DC Converter for the DC House Project paper, the efficiency is 86% at
full load in buck mode [33]. However, the LT8228 datasheet promises a 94% efficiency
[33]. As explained in the paper, the loads that were tested were running at a lower power
application than what the chip was designed for, which causes the lower efficiency
measurements [33]. The chips can handle a current output of 40A, while the design in the
paper only uses 8A of input current [33]. Figure 4-8 shows the boost mode efficiency curve of the DC/DC converter. In the boost mode, the input voltage is 12V and the output voltage is 48V [33]. The efficiency is around 84% at full load [33]. Likewise, the calculated efficiency is lower than the expected 93% efficiency from the datasheet and from the same reasons mentioned for the buck mode [33].

Figure 4-7. Buck Mode Efficiency Curve for DC/DC Converter [33]

Figure 4-8. Boost Mode Efficiency Curve for DC/DC Converter [33]
There is more research on improving the efficiency of bi-directional DC/DC converters. One research delves into increasing the efficiency of the converting using three techniques [34]. The first technique is using interleaved buck-boost converter for current sharing [34]. The second technique is coupling the inductors between phases to retain the efficiency of inductors [34]. Lastly, the third technique is using GaN devices [34]. GaN devices have high thermal conductivity, low resistance, low parasitic capacitance, and no intrinsic diode [34]. All these traits make GaN a more attractive choice than Silicon-based components because it allows for higher frequencies and lower losses from high currents [34]. As shown in figure 4-9, the efficiencies range from 96% to almost 98.5% with the three input voltages. The dc-dc converter is a 48V/12V bi-directional converter [34]. The experimental results displays that the converter reaches around a 97% efficiency in 2.4kW in buck mode [34]. Since the simulation requires for support of 600W-1500W, the GaN DC/DC converter has a more representative efficiency
than the low power application DC/DC converter. Therefore, an average of the efficiencies will be used for the DC/DC converter, which is 89% efficiency.

4.5 Design and Equations

4.5.1. Introduction

This section will cover the three cases that will be simulated, which are AC only sources, DC only sources, and the Hybrid system. Each system will be discussed and their equations to calculate power losses in the system.

![Diagram](image)

**Figure 4-10.** Hybrid system design electrical layout

The Hybrid House is modeled in the simulation as shown in figure 4-10. There are two sources: AC and DC sources. The AC loads are powered with either the AC source or the DC source with an inverter, or both. The DC loads are powered with either the DC source or the AC source with an AC-DC converter, or both. There should be five
branches in total. In figure 4-10, the diagram shows three branches of DC and two branches of AC. The different combinations of the number of AC and DC branches are shown in Table 4-1.

**Table 4-1. Different combinations of AC and DC branches**

<table>
<thead>
<tr>
<th>Number of DC branches</th>
<th>Number of AC branches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

In Table 4-1, 0 and 5 are not listed because they are already accounted for in the 0% and 100% load power consumption possibility in Table 4-4. As mentioned in chapter 3, the inverter and AC-DC converter cannot be both turned on; therefore, there are only three state possibilities for the switches connected to the inverter and AC-DC converter. The three states are shown in Table 4-2.
Table 4-2. State possibilities of the converters

<table>
<thead>
<tr>
<th>Inverter</th>
<th>AC-DC converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
</tr>
</tbody>
</table>

The wire resistances are modeled using a resistor, as well as the AC and DC loads connected to the electrical design. The AC and DC wiring losses are modeled using Equations 4-1 and 4-2 [35].

\[
P_{AC} = 2 \cdot r_{AC} \cdot L \cdot I_{AC}^2 = 2 \frac{R_{AC}}{\cos^2 \theta} \cdot \frac{P^2}{V_{AC}^2}
\]  

(4-1)

where,

\( P_{AC} = \) Power loss in AC line
\( r_{AC} = \) resistance/length in AC
\( L = \) length of wire
\( I_{AC} = \) AC current through wire
\( R_{AC} = \) AC resistance of the conductor
\( \cos \theta = \) Power factor of the load
\( V_{AC} = \) RMS AC Phase Voltage at the load terminal
\( P = \) Power consumption by load
and

\[ P_{DC} = 2 \cdot r_{DC} \cdot L \cdot I_{DC}^2 = 2 \cdot R_{DC} \cdot \frac{P^2}{V_{DC}^2} \]  \hspace{1cm} (4-2)

where,

- \( P_{DC} \) = Power loss in DC line
- \( r_{DC} \) = resistance/length in DC
- \( L \) = length of wire
- \( I_{DC} \) = DC current through wire
- \( R_{DC} \) = DC resistance of the conductor
- \( V_{DC} \) = RMS DC Phase Voltage at the load terminal
- \( P \) = Power consumption by load

The equations are based on the simple \( P = I^2R \) equation. The total power loss in the lines is multiplied by 2 to account for the traveling of current back to ground. However, for the Hybrid AC/DC House, the return current for the AC sources will cancel if the branches are even numbered, and if odd numbered, there is a wire power loss in the return path equivalent to the power loss in one of the AC branches. For the DC power loss, the return path is similar to the IEEE AC and DC wiring modeling efficiency paper equation 4-2 where the power loss was multiplied by 2. These equations were tested for accuracy using experimental results with 12V DC, 24V DC, 48V DC, and 230V AC [35]. The similarity between the simulation model and the experimental model is at least 98.61%, which means that the equations are an accurate representation of actual power loss in the lines [35]. The wire sizes are selected based on the National Electric Code (NEC)
guidelines. It is to be assumed that the wires are copper. Table 4-3 summarizes the requirements for the wire sizes.

Table 4-3. Copper wire sizes and their current limits based on NEC standards [36]

<table>
<thead>
<tr>
<th>Copper Size</th>
<th>Current Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 AWG</td>
<td>7 A</td>
</tr>
<tr>
<td>16 AWG</td>
<td>10 A</td>
</tr>
<tr>
<td>14 AWG</td>
<td>15 A</td>
</tr>
<tr>
<td>12 AWG</td>
<td>20 A</td>
</tr>
<tr>
<td>10 AWG</td>
<td>30 A</td>
</tr>
</tbody>
</table>

The NEC specifies the current limit for each wire gauge and that the current through the conductor should not exceed the given limit [36]. The simulation will follow these guidelines to select the appropriate wire size. By selecting the appropriate wire size, AC and DC resistances of the wires can be calculated using Equations 4-3 and 4-6 [37][38].

\[
R_{AC} = \frac{\rho l}{A_{eff}} = \frac{\rho l}{\sqrt{\frac{\rho}{\pi f \mu_o \mu_r}}} \pi d
\]  

(4-3)

\[
A_{eff} = \delta \pi d
\]  

(4-4)

\[
\delta = \frac{\rho}{\sqrt{\pi f \mu_o \mu_r}}
\]  

(4-5)

\[
R_{DC} = \frac{\rho \frac{1}{\pi \left(\frac{d}{2}\right)^2}}
\]  

(4-6)
where,

\[ \rho = \text{resistivity of the conductor in } \Omega/m \]

\[ l = \text{length in meters} \]

\[ d = \text{diameter of the round conductor in meters} \]

\[ f = \text{frequency in Hz} \]

\[ \mu_r = \text{relative permeability} \]

\[ \mu_o = 4\pi \cdot 10^{-7} \text{ H/m (free space permeability)} \]

The next part will delve into the three cases and their equations. The three equations (4-7, 4-8, and 4-9) will be the same for all the cases.

\[
P_{DC-Load} = \left( \frac{DC \text{ Power Load Consumption } \%}{100} \right) P_{Total} \tag{4-7}
\]

\[
P_{AC-Load} = \left( \frac{AC \text{ Power Load Consumption } \%}{100} \right) P_{Total} \tag{4-8}
\]

\[
P_{IN-DC/DC} = \frac{P_{DC-Load}}{\eta_{DC/DC}} \tag{4-9}
\]

The DC and AC load power consumption percentages are defined according to the cases that are being simulated. The possible AC and DC power load consumption percentages are listed in Table 4-4. The total load power consumption needs to add up to 100\% because the loads are running at full load. The percentages are chosen to examine the effect on the efficiency of the different systems. For example, if the DC load power consumption is 80\% and the AC load power consumption is 20\%. With equations 5 and 6, at 600W, the DC loads are consuming 480W and AC loads are consuming 120W.
**Table 4-4.** Experimental power consumption percentages for AC and DC loads

<table>
<thead>
<tr>
<th>DC loads Power Consumption (%)</th>
<th>AC loads Power Consumption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

The $P_{IN-DC/DC}$ equation is based on the basic $\eta = \frac{P_{out}}{P_{in}}$ equation. The premise of finding the power loss of the system is assigning $P_{out}$ as the total load consumption and working backwards to calculate $P_{in}$ using the efficiency equation. Then, system loss can be found using $P_{in} - P_{out}$.
4.5.2. AC Only Sources

Figure 4-11. AC only sources system electrical layout diagram

The AC only sources system simulates the most common electrical design found in residential areas where the sole source of power in the house is the grid from a utility company. There is no inverter in the system due to the lack of DC sources. The only converters are the AC-DC and DC-DC converters so that AC power from the grid can power the DC loads. The equations for the AC only sources system are:

\[
P_{IN-AC/DC} = \frac{P_{IN-DC/DC} + P_{Wireloss\, DC}}{\eta_{AC/DC}} \tag{4-10}
\]

\[
P_{system\, loss} = P_{IN-AC/DC} + P_{AC-Load} + P_{Wireloss\, AC} - P_{Total} \tag{4-11}
\]
$P_{IN-AC/DC}$ is calculated by adding $P_{IN-DC/DC}$ and $P_{Wireless\ DC}$ and dividing by the efficiency of the AC/DC converter. The $P_{IN-DC/DC}$ is calculated from Equation 4-9 and the $P_{Wireless\ DC}$ is calculated using $I_{\text{calculated/branch}}^2 R_{DC}$ and multiplying it by the number of DC branches in the simulated system. The total power system loss for the AC only sources system is shown in Equation 4-11. The $P_{Total}$ is the sum of the $P_{AC\cdotLoad}$ and $P_{DC\cdotLoad}$.

4.5.3 DC Only Sources

![DC only sources system electrical layout diagram](image)

**Figure 4-12.** DC only sources system electrical layout diagram

The DC only sources system relies on DC sources alone to power AC and DC loads. Examples of DC sources are renewable energy sources such as solar panels and batteries. Depending on the percentage of power consumption of the loads, the inverter has to turn on to power AC loads from the DC sources. There is no AC-DC converter in the system because it is assumed that the DC sources can provide the power needs of the DC loads. The equation for this system is shown below:
\[ P_{IN-\text{inverter}} = \frac{P_{AC-\text{Load}} + P_{Wireloss \ AC}}{\eta_{\text{inverter}}} \]  

(4-12)

\[ P_{IN-MISO} = \frac{P_{IN-\text{inverter}} + P_{IN-DC/DC} + P_{Wireloss \ DC}}{\eta_{\text{MISO}}} \]  

(4-13)

\[ P_{system\ loss} = P_{IN-MISO} - P_{Total} \]  

(4-14)

The \( P_{\text{Wireloss \ AC}} \) and \( P_{\text{Wireloss \ DC}} \) are both calculated per branch then multiplied according to the number of AC and DC branches in the simulated system. The equations are generated based on the principle of the efficiency equations, where \( P_{out} \) and efficiency are known. \( P_{IN} \) is gathered by working backwards from knowing the total load consumption which is treated as \( P_{OUT} \). All the efficiencies of the blocks are known; therefore, \( P_{IN} \) can be derived. The system losses are found using the difference of \( P_{IN} - P_{OUT} \) as shown in Equation 4-14.
4.5.4 Hybrid

A. Hybrid Case 1

In this topology, both the inverter and AC-DC converter are turned off. The DC loads are receiving power solely from the DC sources; likewise, the AC loads are receiving their power from the AC sources. In the full hybrid case, there is no need for the converters to turn on because the sources meet the power demands of their respective loads. The equations for this case are listed below:

\[ P_{AC\ Loss} = P_{Wireless\ AC} \]  
\[ P_{DC\ Loss} = P_{IN-MISO} - P_{DC-Load} \]  
\[ P_{IN-MISO} = \frac{P_{IN-DC/DC} + P_{Wireless\ DC}}{\eta_{MISO}} \]  
\[ P_{System\ loss} = P_{AC\ Loss} + P_{DC\ Loss} \]
B. Hybrid Case 2

Figure 4-14. Hybrid AC/DC house: Case 2 (Inverter turned off and AC/DC converter turned on)

This case occurs when MISO reaches its power sourcing limits and DC loads still demand more power. So, AC grid supplies more and AC-DC converter turns on and inverter turns off. There are two possible cases before the Hybrid Case 2 occurs:

1. AC sources were supplying AC loads and DC sources were supplying DC loads.

2. DC was supplying both AC and DC loads and the inverter was turned on.

In this case, to simulate MISO power sourcing abilities need to be limited. For example, MISO can only supply 80% of what the DC load is demanding. In this simulation, percentage of limitation will be assigned. In future cases, this percentage can be varied.

This Hybrid case is the most likely scenario as renewables cannot supply sufficient power
for the system and the utility will have to provide the rest for the loads. The equations for this Hybrid case are listed below:

\[
P_{IN-AC/DC} = \frac{(P_{IN-DC/DC} + P_{Wireloss DC})(1 - \%_{max for MISO})}{\eta_{AC/DC}}
\]

\[
P_{IN-MISO} = \frac{(P_{IN-DC/DC} + P_{Wireloss DC})(\%_{max for MISO})}{\eta_{MISO}}
\]

\[
P_{IN-AC} = P_{IN-AC/DC} + P_{Wireloss AC} + P_{AC-Load}
\]

\[
P_{IN} = P_{IN-AC} + P_{IN-MISO}
\]

\[
P_{OUT} = P_{AC-Load} + P_{DC-Load}
\]

\[
P_{system loss} = P_{IN} - P_{OUT}
\]

C. Hybrid Case 3

**Figure 4-15.** Hybrid AC/DC house: Case 3 (Inverter turned on and AC/DC converter turned off)
In this Hybrid case, the AC sources somehow cannot supply enough power for both AC loads, so DC sources must provide the rest of the power to the AC loads. The inverter turns on and the AC-DC converter turns off. This case is not as likely as the Hybrid Case 2 because the AC source is more than likely a utility company. However, in the case of an AC generator, this is possible. There are two possible cases before the Hybrid Case 3 occurs:

1. The AC was supplying for both AC and DC loads.
2. The AC and DC sources were supplying AC and DC loads, respectively.

In simulation, like the Hybrid Case 2, there has to be a percentage limitation on what the AC sources can offer so that the inverter provides the rest. Likewise, this percentage has to be defined in the simulation. The equations for the Hybrid case 3 are shown below:

\[
P_{IN-AC} = (P_{Wireloss\ AC} + P_{AC-Load})(%_{\max\ for\ AC})
\]
\[
P_{IN-inverter} = \frac{(P_{AC-Load} + P_{Wireloss\ AC})(1 - %_{\max\ for\ AC})}{\eta_{inverter}}
\]
\[
P_{IN-MISO} = \eta_{MISO}
\]
\[
P_{IN} = P_{IN-AC} + P_{IN-MISO}
\]
\[
P_{OUT} = P_{AC-Load} + P_{DC-Load}
\]
\[
P_{system\ loss} = P_{IN} - P_{OUT}
\]

4.6 Simulation Count

To calculate the number of simulations in all the 5 cases, the number of changing variables is examined. The user-defined changing variables are the AC voltages, DC
voltages, overall power, number of AC and DC branches, and AC and DC load power consumption. There are two variations of AC voltages, 120V and 230V. There are four different DC voltages: 12V, 24V, 36V, and 48V. There are five AC and DC branches in total and this results into 4 combinations, excluding the extremes because it is accounted for in the extremes of load power consumption. The extremes are cases when there are only AC loads consuming power or when there are only DC loads consuming power. These are examined in the combination of load power consumption when either the AC or DC has 0% or 100% load consumption. The AC and DC branches possibilities are shown in Table 4-1. There are five combinations of load power consumption which are shown in Table 4-4. There are four cases of total power consumption: 600W, 900W, 1200W, and 1500W. The calculation of the overall possibilities is shown below:

$$4 \text{ cases } P_{\text{total}} \times 5 \text{ combinations of load power consumption } \times 4 \text{ combinations of number of branches } \times 4 \text{ DC voltages } \times 2 \text{ AC voltages} = 640 \text{ simulations}$$

The total individual simulations result to 640. The calculation is only for 1 case of power system design; therefore, for the 5 cases the number of simulations, the overall number is 3200 cases.

To summarize Chapter 4, there are three parts to this chapter The first part delves into the four component blocks in the systems, which are the MISO, AC/DC converter, inverter, and DC/DC converter. Each component has its own efficiency curve and since part of the assumption in the simulation is that the loads are running at full load, the efficiencies for these components are defined as one value. The efficiency values used in the simulation for these converters are chosen using the averages of efficiency values found on the different efficiency curves and real-world components. The second part of
Chapter 4 explains the three different cases of electrical design for the house, which are AC only sources house, DC only sources house, and the Hybrid AC/DC house. Under the Hybrid AC/DC house case, there are three subcases for this main case. In total, there are five different cases for electrical design for the house. Alongside enumerating the five different cases, the power loss equations for each case are also listed. The last part of Chapter 4 calculated the total number of iterations that will be examined in the simulation. The total number resulted to 3,200 cases, which means that there will be 3,200 power loss calculations in the simulation.

Chapter 5: Simulation Results and Analysis

The simulation software of choice is MATLAB. The simulations consist of equations of power loss for the five different house cases: AC only sources, DC only sources, Hybrid Case 1, Hybrid Case 2, and Hybrid Case 3. The simulations are varying permutations of the changing variables in the five house cases. The varying variables are the AC voltages, DC voltages, load power consumptions, number of AC and DC branches, and total load power consumption. The sum of these combinations results in a total of 3,200 cases. This means there will be 3,200 power loss numbers for the individual cases.

The code resulted into five 32x20 matrices that contain the power losses for the different cases. The matrix is divided as shown in Figure 5-1, where the rows are separated with the AC voltages and DC voltages.
The first 16 rows are 120VAC and the next 16 rows are 230VAC. The first 4 rows are 12VDC, the second 4 rows are 24VDC, the third 4 rows are 36VDC, and fourth 4 rows are 48VDC. The pattern repeats for 230VAC.

For the columns, the first 5 columns are cases with 1 AC branch and 4 DC branches. The second 5 columns are 2 AC branches and 3 DC branches. The third 5 columns are 3 AC branches and 2 DC branches. The fourth 5 columns are 4 AC branches and 1 DC branch. The 4x5 matrix, highlighted in orange, has a set DC voltage, AC voltage, and the numbers of AC and DC branches. Within the set 4x5 matrix, the rows represent 600W, 900W, 1200W, and 1500W. The columns are the AC and DC percent load consumptions. The columns are divided according to these combinations of AC and DC percent load consumptions: 0%/100%, 20%/80%, 50%/50%, 80%/20%, 100%/0% as shown in Figure 5-1.

These variables are defined in the initial part of the code: total load power consumption, AC voltages, DC voltages, %AC and %DC load power consumptions, wire
length, frequency, power factor, maximum percentage power contribution for MISO and AC sources, efficiency values, and number of AC and DC branches. The next part of the code calculates the current of the branches. The current of the branches dictates the wire gauge based on the NEC chart discussed in the previous chapter. By finding the appropriate wire gauge for the current branches, the AC and DC resistances of the wires are found. Using Equation 4-1 and 4-2, the wire power losses are calculated. The power losses for AC only sources, DC only sources, Hybrid Case 1, Hybrid Case 2, and Hybrid Case 3 are tabulated into their own 32x20 matrices as shown in Figure 5-1. The efficiency was calculated by dividing output power by input power. Five efficiency tables are generated from the power loss tables as shown from Figure 5-2 to 5-6. The code is listed in Appendix A.

<table>
<thead>
<tr>
<th>AC ONLY SOURCES</th>
<th>1/4</th>
<th>3/4</th>
<th>2/3</th>
<th>3/2</th>
<th>4/1</th>
<th>Total Load Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>120VAC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600W</td>
</tr>
<tr>
<td>120VDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600W</td>
</tr>
<tr>
<td>60VDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>300W</td>
</tr>
<tr>
<td>48VDC</td>
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<td></td>
<td>240W</td>
</tr>
<tr>
<td>24VDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120W</td>
</tr>
<tr>
<td>12VDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60W</td>
</tr>
<tr>
<td>4VDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15W</td>
</tr>
</tbody>
</table>

Figure 5-2. AC only sources efficiency values
Figure 5-3. DC only sources efficiency values

Figure 5-4. Hybrid Case 1 efficiency values
Figure 5-5. Hybrid Case 2 efficiency values

<table>
<thead>
<tr>
<th>Hybrid Case 2</th>
<th>ACG/WDC Branches</th>
<th>Total Load Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>12VDC</td>
<td>4.07 0.88 0.88 1.00</td>
</tr>
<tr>
<td></td>
<td>3/3</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
<tr>
<td></td>
<td>4/1</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
<tr>
<td>Hybrid Case 3</td>
<td>ACG/WDC Branches</td>
<td>Total Load Consumption</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>1/2</td>
<td>12VDC</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
<tr>
<td></td>
<td>3/3</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
<tr>
<td></td>
<td>4/1</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
</tbody>
</table>

Figure 5-6. Hybrid Case 3 efficiency values

<table>
<thead>
<tr>
<th>Hybrid Case 3</th>
<th>ACG/WDC Branches</th>
<th>Total Load Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>12VDC</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
<tr>
<td></td>
<td>3/3</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
<tr>
<td></td>
<td>4/1</td>
<td>0.84 0.88 0.88 1.00</td>
</tr>
</tbody>
</table>

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There are five main changing variables that will be conducted for this study: AC voltages, DC voltages, total power load consumption, number of AC and DC branches, and DC and AC load power consumption.

Changing variables:

AC voltages: 120 VAC, 230 VAC
DC voltages: 12V, 24V, 36V, 48V
Total Power Load Consumption: 600W, 900W, 1200W, 1500W
Number of AC branches/number of DC branches: 1/4, 2/3, 3/2, 4/1
DC Load/AC Load Percent Power Consumption: [0%/100%, 20%/80%, 50%/50%, 20%/80%, 100%/0%]

To examine the effect of each changing variable, the variables that are not tested have to remain constant. Figures 5-7 to 5-11 show the results of the calculations.
Figure 5-7. AC Only Sources Efficiency Plot for different AC branches. (Top Left) 1 AC branch, (Top Right) 2 AC branches, (Bottom Left) 3 AC branches, and (Bottom Right) 4 AC branches.
**Figure 5-8.** DC Only Sources Efficiency Plot for 1 AC branch (left) and 4 AC branches (right).

**Figure 5-9.** Hybrid Case 1 Efficiency Plot for 1 AC branch (left) and 4 AC branches (right).
Figure 5-10. Hybrid Case 2 Efficiency Plot for 1 AC branch (left) and 4 AC branches (right).

Figure 5-11. Hybrid Case 3 Efficiency Plot for 1 AC branch (left) and 4 AC branches (right).

Figure 5-7 shows the efficiency plot of AC only sources in a range of DC voltages at 12V, 24V, 36V, and 48V. The points come from the column of 20% AC load consumption and rows of 120VAC of Figure 5-1. In Figure 5-7, the AC branches range
from 1 to 4. The minimum and maximum efficiency values are shown for each DC voltage in the bar graphs. As the number of AC branches increase, the average efficiencies increase. The efficiencies also slightly increase as the DC voltages increase. The efficiencies increase when there are more AC branches because the higher voltage associated with AC compared to DC yields lower current requirement per given load wattage. This in turn produces less conduction loss on the AC branch. More AC branches also mean less DC branches in the system. This would result in a lower number of DC-DC converters in parallel which would increase the overall efficiency of the system.

The four-color bars represent the total power load consumptions at 600W, 900W, 1200W, and 1500W. The amount of power that the loads are consuming does not seem to be affected by the change in DC voltages and AC branches. The other cases show the same patterns and the complete bar graphs are listed in Appendix B. For Figures 5-8, 5-9, 5-10, and 5-11, the left plots depict 1 AC branch, and the right plots show 4 AC branches. Both plots show the minimum and maximum number of AC branches in each electrical house design case. The same trends can be seen for the DC only sources and the Hybrid cases as in the AC only sources cases. The efficiencies increase with an increase in DC voltage and number of AC branches. This can be attributed to the AC voltage being a lot higher than the DC voltage; thus, the current would be smaller in the wire which would mean lower power loss in the AC wires. Even though, in AC wires there are skin effect, capacitive, and inductive losses, those are not enough to combat the losses from the lower voltage in DC especially with the low frequency of 50 or 60 Hz. The results of the graphs also show that the more DC branches result in a lower overall efficiency in the system.
This could be due to the fact that with more DC branches, there are more DC-DC converters in parallel which would lower the efficiency of the branches.

![Graph showing efficiency changes](image)

**Figure 5-12.** DC Load Consumption Efficiency Plot at 1500W, 120VAC, 12V, and 3 DC branches

Figure 5-12 shows the efficiency when the DC load consumption is increased. Each color of the bars represents each house case. As the DC load percent consumption is increased, the efficiencies become lower. At 0% DC load consumption, the AC only sources case is the most efficient while the least efficient is the DC only sources house. It makes sense that with no DC loads or all AC load consumption, the most efficient design is an only AC source because no conversion is needed to supply power to the loads. On the other hand, at 100% DC load consumption, the most efficient is the DC only sources case and the least efficient is the AC only sources case. With having all DC loads, it is the
most efficient to have a DC only source electrical system because at 0%, no conversion is needed to supply from DC source to DC load. From 0% to 100% DC load consumption, the Hybrid case 1 continues to top the efficiency values followed by the Hybrid Case 2 and Case 3. The same graph is generated with 230VAC, 600W, 900W, and 1200W. The graphs all show the same trends and patterns as shown in Appendix C.

The next set of graphs examine the difference in efficiency values with different AC voltages. The variables that remain constant are 900W, 24VDC, and 3 DC branches, while the percent load consumption changes. Figure 5-13 displays the efficiency values of 120VAC and 230 VAC at 50% AC load consumption and 50% DC load consumption. Figure 5-14 shows the efficiency values of 120VAC and 230 VAC at 20% AC load consumption and 80% DC load consumption.

![Bar chart showing efficiency values for different AC voltages and load consumptions.]

**Figure 5-13.** 120VAC and 230VAC Comparison at 50% AC Load Consumption / 50% DC Load Consumption
Both Figures 5-13 and 5-14 demonstrate that the efficiency values decrease as the AC load consumption decreases. In 50% AC load consumption, the efficiency values are at around 80% while in 20% AC load consumption, the efficiency values decrease to around 74%. The two bar graphs are around the same height. This signifies that there is no significant difference in efficiency values in different AC voltages. The efficiencies are approximately the same because the wire gauges are calculated based on the calculated current per branch. Since 230VAC is a higher voltage than 120VAC, the calculated current per branch is smaller which results in thinner wires and larger resistance. In turn, the 230 VAC system will have similar loss to that of the 120 VAC system. The five
combinations of load consumptions are included in Appendix D. All combinations show the same trend where the efficiencies for 120VAC and 230VAC are the same.

![Efficiency plots](image)

**Figure 5-15.** AC only sources efficiency plot for 1200W and 120VAC with different numbers of DC branches

The 3D efficiency plot shows the relationship of DC voltages and percent AC load consumption. The four plots in Figure 5-15 are the efficiency plots when the DC branches increase in an AC only system. When the DC voltage and % AC load consumption decrease, there is a larger dip in efficiency. Lower AC load consumption percentage means a higher DC load consumption percentage. More DC load consumption
places a heavier weight on the importance of DC voltages. Lower DC voltages constitute higher current per branch and larger wire power losses. Therefore, lower DC voltages lead to lower efficiency values.

![Figure 5-16. DC only sources efficiency plot for 1200W and 120VAC with minimum and maximum number of DC branches](image)

In the DC only system, the efficiencies are approximately the same when the number of DC branch is 1. Compared to the AC only sources system, the DC only system’s efficiencies with 1 DC branch have a smaller difference when DC voltages and % AC load consumption vary. There is no significance difference in the efficiency values because the case only has 1 DC branch. As the DC voltage level changes, the wire gauge varies. The change in gauge causes a different resistance and leads to the around the same efficiency as the other DC voltage levels. When the number of DC branches are at maximum, the efficiency values decline at lower DC voltages and % AC load consumption, similar to the AC only sources system. The reason for this is the same as in the AC only system. More DC load consumption has a heavier weight on the DC voltages and produces lower efficiency values.
Figure 5-17. Hybrid Case 1 efficiency plot for 1200W and 120VAC with different numbers of DC branches
Figure 5-18. Hybrid Case 2 efficiency plot for 1200W and 120VAC with minimum and maximum number of DC branches

Figure 5-19. Hybrid Case 3 efficiency plot for 1200W and 120VAC with minimum and maximum number of DC branches

In Hybrid Case 1, the efficiency values for 1 DC branch are at similar levels to each other even if the DC voltage and % AC load consumption change. Like the other cases, the efficiency values decrease when DC branches increase and the DC voltage decrease. The Hybrid cases follow the same trend seen in the AC and DC only sources system while having high efficiency values across all simulations. Figure 5-18 and Figure 5-19 show that both Hybrid Cases 2 and 3 maintain the same pattern that is seen for all
cases. At higher number of DC branches, the efficiency values go down at lower DC voltages and % AC load consumption because the system is basically running at only DC loads which means that the low DC voltage has a bigger impact on the power loss of the system.
Figure 5-20. Efficiency plots for 230VAC at 4 DC branches and 1200W

Figure 5-20 depicts the same plot in all the electrical design system with the AC system operating at 230VAC. Changing the AC voltage produces no significant...
difference in efficiency as summarized by the plots above. This is again due to the calculation of the wire gauges at a higher AC voltage as explained earlier. Each case still shows the dip in efficiency at lower voltages and percent AC load consumption at 4 DC branches. With the same number of DC branches, the efficiency values are approximately the same for all cases, which means that for the same combination of branches, voltages, and load consumption, the electrical design in the system does not seem to have a large effect on efficiency.
Chapter 6: Conclusion

The aim of this study is to examine the power loss or efficiency of the Hybrid AC/DC House under different DC voltages, AC voltages, number of AC and DC branches, and power levels. In addition to the Hybrid AC/DC House, AC only sources and DC only sources systems were also examined in terms of efficiency and under the same variable permutations.

To study the power losses and efficiency of the Hybrid AC/DC House, AC only sources, and DC only source, the electrical design of the house was constructed. Using block diagrams, four component blocks were taken into consideration in the system, which are the MISO, AC/DC converter, inverter, and DC/DC converter. Then, the efficiency curves for all the blocks were researched and the average of the efficiencies at full load were utilized for the calculations. The Hybrid AC/DC House was further investigated into 3 cases: Hybrid Case 1, Hybrid Case 2, and Hybrid Case 3. These were all possibilities considered that can occur in the Hybrid AC/DC House case. The cases stem from the assumption that the AC/DC converter and inverter cannot be turned on at the same time. Hybrid Case 1 is when the inverter and AC/DC converter are turned off. Hybrid Case 2 is when the inverter is off and AC/DC converter is on. Hybrid Case 3 is when inverter is on, and AC/DC converter is off. Thus, in total, there are five cases where efficiency is examined.

The initial challenge of this study is finding relevant literatures on Hybrid AC/DC House. Most prior research on implementing renewable energy is geared towards DC only houses instead of Hybrid AC/DC houses. Another challenge in conducting this
thesis relates to reducing the number of simulations to analyze to limit the scope of the study while still being able to obtain some meaningful results. With this constraint, the number of AC and DC branches had to be limited to 5 branches and the number of DC voltage levels is four. The maximum contributions for Hybrid Case 2 and 3 are also set to 80% in order to control the number of cases to analyze. Another challenge was finding a suitable way to present the results since the study involves loss and efficiency calculations employing several interdependent variables. The bar graphs worked well since data can be represented in discrete values instead of continuous.

The study demonstrated multiple results. One of the results showed that the increase in number of AC branches, increased the efficiencies of the system. There was also a slight increase when the DC voltage level was increased. When there are lower AC branches and higher number of DC branches, more DC/DC converter are in parallel which causes the overall efficiency to decrease. Also, the high AC voltage produces less power loss than the low DC voltage which results to higher efficiency values. When changing the percent of DC load consumption, the Hybrid cases’ efficiency values were the highest or one of the highest among the five cases examined. The only scenarios when Hybrid did not come on top were during the extreme percentages of DC load consumption. At 0% DC load consumption, the AC only sources had the highest efficiency values and the lowest was the DC only sources. The results were valid because no DC loads means that all loads are AC, and no conversion is needed from the AC sources. The DC only sources would have to convert all the power from DC to the AC loads which would yield the lowest efficiency value. At 100% DC load consumption, the result is the opposite where the DC only sources had the lowest efficiency value, whereas
the AC only sources had the highest efficiency value. Moreover, it is further examined that as the percent AC load consumption decreases, the more the DC voltage level matters. The 3D bar graphs showed a decrease in efficiency values when the DC voltage level is 12V (low) and % AC load consumption is at 0% (low). Lastly, for all changing values, it was demonstrated that there was no significant difference between 120VAC and 230VAC in efficiency values under the same conditions in the study.

Further work may be conducted based on this study. One area that will be the most valuable continuation of the study is finding and optimizing the cost of the system. This may involve investigation of the costs of the system under different scenarios. Costs such as wire gauges, converters, and power losses should be considered in future evaluations. Other follow up study could incorporate more complexity to the variables used in the simulations. The efficiency values can be replaced by equations representing the efficiency curves of the converters. Therefore, the cases can be evaluated not only at full load, but also at different load conditions. Various power factors can also be used for the data to examine the changes it has on the efficiency values. Variables such as DC voltage levels, maximum contributions of AC sources and MISO, can all be changed to study the effect in efficiency values.

In conclusion, this study provides a foundational framework for the feasibility study of a Hybrid AC/DC House. With the results of losses and efficiency have been completed as presented in this report, future extension of the study can be performed to involve other aspects such as additional parameters, operating conditions, and costs of the Hybrid AC/DC House.
REFERENCES


[7]. Taufik, Introduction to Power Electronics. Lulu Publishing Inc., 2021


APPENDICES

A. MATLAB Code

%% Section 1: Defining variables
% Constants
mu0 = 4*pi*10^(-7); % air permeability
muR = 0.999994; % Copper relative permeability
Cu_res = 1.77*10^(-8); % Copper resistivity in Ohm-meter

% Define these variables
P_load = [600, 900, 1200, 1500]; % 600, 900, 1200, 1500W
AC_voltage = [120, 230]; %120V,230V
DC_voltage = [12, 24, 36, 48]; %12,24,36,48V
Percent_AC_load = [0, 0.20, 0.50, 0.80, 1]; %0-1
Percent_DC_load = [1, 0.80, 0.50, 0.20, 0]; %0-1
wire_length = 50; % meters
freq = [60, 50]; % hertz
pf = 0.97; % utility normal power factor
max_miso = 0.80; % max percentage contribution of miso
max_AC = 0.80; % max percentage contribution of AC sources

% efficiency values
n_dc_dc = .89;
n_ac_dc = .921;
inverter = .89;
miso = .964;

% AC branches + DC branches = total branches
num_AC_branches = [1,2,3,4];
um_DC_branches = [4,3,2,1];
total_branches = length(num_AC_branches)+1;

%% Section 2: For loops calculation
mat_P_AC_load = [Percent_AC_load; Percent_AC_load;Percent_AC_load;Percent_AC_load];
for i = 1:length(P_load)
    mat_P_AC_load(i,:) = mat_P_AC_load(i,:).*P_load(i);
end
mat_P_DC_load = fliplr(mat_P_AC_load);

mat_P_AC_total = [mat_P_DC_load./AC_voltage(1);mat_P_DC_load./AC_voltage(2)];
mat_Pin_dc_dc = mat_P_DC_load./n_dc_dc;
mat_I_DC_total = [mat_Pin_dc_dc./DC_voltage(1);mat_Pin_dc_dc./DC_voltage(2);mat_Pin_dc_dc./DC_voltage(3);mat_Pin_dc_dc./DC_voltage(4)];

mat_I_AC_per_branch = [mat_I_AC_total./num_AC_branches(1) mat_I_AC_total./num_AC_branches(2) mat_I_AC_total./num_AC_branches(3) mat_I_AC_total./num_AC_branches(4)];
mat_I_DC_per_branch = [mat_I_DC_total./num_DC_branches(1) mat_I_DC_total./num_DC_branches(2) mat_I_DC_total./num_DC_branches(3) mat_I_DC_total./num_DC_branches(4)];

mat_AC_gauge = mat_I_AC_per_branch;
mat_DC_gauge = mat_I_DC_per_branch;
momat_d_AC = mat_I_AC_per_branch;
momat_d_DC = mat_I_DC_per_branch;

% Assigns the right gauge and diameter for AC and DC
for i = 1:numel(mat_I_AC_per_branch)
    AC_param = calculateGauge(mat_I_AC_per_branch(i)); % returns -> [AWG, diameter in m]
    mat_AC_gauge(i) = AC_param(1); % returns -> AWG
    mat_d_AC(i) = AC_param(2); % returns -> diameter in m
end

for i = 1:numel(mat_I_DC_per_branch)
    DC_param = calculateGauge(mat_I_DC_per_branch(i)); % returns -> [AWG, diameter in m]
    mat_DC_gauge(i) = DC_param(1); % returns -> AWG
    mat_d_DC(i) = DC_param(2); % returns -> diameter in m
end

arr_AC_length= (num_AC_branches./total_branches).* wire_length;
arr_DC_length= (num_DC_branches./total_branches).* wire_length;

% Finding the resistance of wires in AC
mat_R_AC = mat_d_AC;
size_AC = size(mat_d_AC); % returns -> [row, col]
row_AC = size_AC(1);
col_AC = size AC(2);

for i = 1 : row_AC
    for j = 1 : col_AC
        % Setting AC frequency
        if i <= 4
            freq_element = freq(1); % first 4 rows is 120V so freq should be 60Hz
        else
            freq_element = freq(2); % second 4 rows is 230V so freq should be 50Hz
        end
        % Setting the right AC length
        if j<=5
            AC_length_element = arr_AC_length(1);
        elseif j<=10
            AC_length_element = arr_AC_length(2);
        elseif j<=15
            AC_length_element = arr_AC_length(3);
        elseif j<=20
            AC_length_element = arr_AC_length(4);
        end
        mat_R_AC(i,j) = (Cu_res*AC_length_element)/(sqrt(Cu_res/(pi*freq_element*mu0*muR))*pi*mat_d_AC(i,j));
    end
end

% Finding the resistance of wires in DC
mat_R_DC = mat_d_DC;
size_DC = size(mat_d_DC); % returns -> [row, col]
row_DC = size_DC(1);
col_DC = size_DC(2);

for i = 1 : row_DC
for j = 1: col_DC
    % Setting the right DC length
    if j<=5
        DC_length_element = arr_DC_length(1);
    elseif j<=10
        DC_length_element = arr_DC_length(2);
    elseif j<=15
        DC_length_element = arr_DC_length(3);
    elseif j<=20
        DC_length_element = arr_DC_length(4);
    end
    mat_R_DC(i,j) = (Cu_res*DC_length_element)/(pi*(mat_d_DC(i,j)/2)^2);
end

%% Calculating Wireloss
% AC wireloss
mat_P_AC_wireloss1 = mat_R_AC; % set size
for i = 1:4:5
    if i == 1
        AC_voltage_element = AC_voltage(1);
    else
        AC_voltage_element = AC_voltage(2);
    end
    AC_branches_counter = 1;
    for j = 1:5:16
        mat_P_AC_wireloss1(i:i+3,j:j+4) = (mat_R_AC(i:i+3,j:j+4).*(pF^2)).*(mat_P_AC_load./AC_branches_counter).^2./(AC_voltage_element^2);
        AC_branches_counter = AC_branches_counter + 1;
    end
end
mat_P_AC_wireloss = mat_P_AC_wireloss1;
for i = 1:length(num_AC_branches)
    if num_AC_branches(i) == 1 || num_AC_branches(i) == 3
        mat_P_AC_wireloss(:,x:x+4) = (num_AC_branches(i)+1).*mat_P_AC_wireloss(:,x:x+4);
    else
        mat_P_AC_wireloss(:,x:x+4) = num_AC_branches(i).*mat_P_AC_wireloss(:,x:x+4);
        x = x+5;
    end
end

% DC wireloss
mat_P_DC_wireloss1 = (mat_I_DC_per_branch.^2).*mat_R_DC;
mat_P_DC_wireloss = mat_P_DC_wireloss1;
for i = 1:length(num_DC_branches)
    mat_P_DC_wireloss(:,x:x+4) = 2.*(num_DC_branches(i)).*mat_P_DC_wireloss(:,x:x+4);
    x = x+5;
end

%% AC only sources - Power Loss
% Find Pin_AC_DC
mat_Pin_AC_DC = mat_P_DC_wireloss; % set size
for i = 1:4:13
   for j = 1:5:16
      mat_Pin_AC_DC(i:i+3,j:j+4) = (mat_Pin_de_dc + mat_P_DC_wireloss(i+3,j+4))./n_ac_dc;
   end
end

% Finding AC Power System Loss

% 1st Part - Pin_AC_DC + P_AC_load
mat_P_AC_only_systemloss = mat_Pin_AC_DC; % set size
for i = 1:4:13
   for j = 1:5:16
      mat_P_AC_only_systemloss(i+3,j+4) = (mat_Pin_AC_DC(i+3,j+4) + mat_P_AC_load);
   end
end

% 2nd Part - Pin_AC_DC + P_AC_load + P_AC_Wireloss

mat_P_AC_only_loss1 = mat_P_AC_only_systemloss;
mat_P_AC_only_loss2 = mat_P_AC_only_systemloss;
i = 1;
for j = 1:4:13
   mat_P_AC_only_loss1(j+3,:) = mat_P_AC_wireloss(i+3,:) + mat_P_AC_only_loss1(j+3,:); % 120V
end
i = 5;
for j = 1:4:13
   mat_P_AC_only_loss2(j+3,:) = mat_P_AC_wireloss(i+3,:) + mat_P_AC_only_loss2(j+3,:); % 230V
end
mat_P_AC_only_systemloss = [mat_P_AC_only_loss1; mat_P_AC_only_loss2];

% 3rd Part - (Pin_AC_DC + P_AC_load + P_AC_Wireloss) - P_load
mat_P_load = mat_P_AC_load + mat_P_DC_load;
for i = 1:4:29
   for j = 1:5:16
      mat_P_AC_only_systemloss(i+3,j+4) = (mat_P_AC_only_systemloss(i+3,j+4) - mat_P_load);
   end
end

% Efficiency
mat_P_AC_only_efficiency = mat_P_AC_only_systemloss; % set size
for i = 1:4:29
   for j = 1:5:16
      mat_P_AC_only_efficiency(i+3,j+4) = mat_P_load./(mat_P_AC_only_systemloss(i+3,j+4) + mat_P_load);
   end
end

% DC only sources - Power Loss

% Pin_inverter
mat_Pin_inverter = mat_P_AC_wireloss; % set size
for i = 1:4:5
   for j = 1:5:16
      mat_Pin_inverter(i+3,j+4) = (mat_P_AC_wireloss(i+3,j+4) + mat_P_AC_load)./n_inverter;
   end
end

% Pin_miso
% 1st Part - P_DC_wireloss + Pin_dc_dc
mat_Pin_miso = mat_P_DC_wireloss; % set size (16x20)
for i = 1:4:13
    for j = 1:5:16
        mat_Pin_miso(i:i+3,j:j+4) = mat_P_DC_wireloss(i:i+3,j:j+4) + mat_Pin_dc_dc;
    end
end

% 2nd Part - P_DC_wireloss + Pin_dc_dc + Pin_inverter (32x20)
mat_Pin_miso1 = mat_Pin_miso;
mat_Pin_miso2 = mat_Pin_miso;
i = 1;
for j = 1:4:13
    mat_Pin_miso1(j:j+3,:) = mat_Pin_inverter(i:i+3,:) + mat_Pin_miso1(j:j+3,:); % 120V
end
i = 5;
for j = 1:4:13
    mat_Pin_miso2(j:j+3,:) = mat.Pin_inverter(i:i+3,:) + mat.Pin_miso2(j:j+3,:); % 230V
end
mat_Pin_miso = [mat_Pin_miso1; mat_Pin_miso2];
mat_Pin_miso = mat_Pin_miso./n_miso;

% Pin_miso - Pload
mat_P_DC_only_systemloss = mat_Pin_miso; % set size (32 x 20)
for i = 1:4:29
    for j = 1:5:16
        mat_P_DC_only_systemloss(i:i+3,j:j+4) = mat_Pin_miso(i:i+3,j:j+4) - mat_P_load;
    end
end

% Efficiency
mat_P_DC_only_efficiency = mat_P_DC_only_systemloss;
for i = 1:4:29
    for j = 1:5:16
        mat_P_DC_only_efficiency(i:i+3,j:j+4) = mat_P_load/(mat_P_DC_only_systemloss(i:i+3,j:j+4) + mat_P_load);
    end
end

% Case 1: Inverter off/ AC-DC off
% P_AC_loss same as P_AC_wireloss
% Pin_miso
mat_Pin_miso = mat_P_DC_wireloss; % set size (16x20)
for i = 1:4:13
    for j = 1:5:16
        mat_Pin_miso(i:i+3,j:j+4) = mat_P_DC_wireloss(i:i+3,j:j+4) + mat_Pin_dc_dc;
    end
end
mat_Pin_miso = mat_Pin_miso./n_miso;

% P_DC_loss
mat_P_DC_loss = mat_Pin_miso; % set size (16 x 20)
for i = 1:4:13
    for j = 1:5:16

mat_P_DC_loss(i:i+3,j:j+4) = mat_P_miso(i:i+3,j:j+4) · mat_P_DC_load;
end
end

% P_Hybrid1_systemloss = P_AC_loss + P_DC_loss
mat_P_Hybrid1_systemloss1 = mat_P_DC_loss;
i = 1;
for j = 1:4:13
    mat_P_Hybrid1_systemloss1(j:j+3,:) = mat_P_AC_wireloss(i:i+3,:) +
    mat_P_Hybrid1_systemloss1(j:j+3,:);  % 120V
end
i = 5;
for j = 1:4:13
    mat_P_Hybrid1_systemloss2(j:j+3,:) = mat_P_AC_wireloss(i:i+3,:) +
    mat_P_Hybrid1_systemloss2(j:j+3,:);  % 230V
end
mat_P_Hybrid1_systemloss = [mat_P_Hybrid1_systemloss1; mat_P_Hybrid1_systemloss2];

% Efficiency
mat_P_Hybrid1_efficiency = mat_P_Hybrid1_systemloss;
for i = 1:4:29
    for j = 1:5:16
        mat_P_Hybrid1_efficiency(i:i+3,j:j+4) = mat_P_load./(mat_P_Hybrid1_systemloss(i:i+3,j:j+4) +
        mat_P_load);
    end
end

% Case 2: Inverter on/ AC-DC off

% Pin_AC_DC
mat_Pin_AC_DC = mat_P_DC_wireloss;  % set size (16x20)
for i = 1:4:13
    for j = 1:5:16
        mat_Pin_AC_DC(i:i+3,j:j+4) = mat_P_DC_wireloss(i:i+3,j:j+4) + mat_Pin_dc_dc;
    end
end
mat_Pin_AC_DC = mat_Pin_AC_DC.*(1-max_miso);
mat_Pin_AC_DC = mat_Pin_AC_DC./n_ac_dc;

% Pin_miso
mat_Pin_miso = mat_P_DC_wireloss;  % set size (16x20)
for i = 1:4:13
    for j = 1:5:16
        mat_Pin_miso(i:i+3,j:j+4) = mat_P_DC_wireloss(i:i+3,j:j+4) + mat_Pin_dc_dc;
    end
end
mat_Pin_miso = mat_Pin_miso.*(max_miso);
mat_Pin_miso = mat_Pin_miso./n_miso;

% P_Hybrid2_systemloss
% 1st part: Pin_AC_DC + Pin_miso
mat_P_Hybrid2_systemloss = mat_Pin_AC_DC + mat_Pin_miso;
% 2nd part: Pin_AC_DC + Pin_miso + P_AC_wireloss
mat_P_Hybrid2_systemloss1 = mat_P_Hybrid2_systemloss;
mat_P_Hybrid2_systemloss2 = mat_P_Hybrid2_systemloss;
i = 1;
for j = 1:4:13
    mat_P_Hybrid2_systemloss1(j:j+3,:) = mat_P_AC_wireloss(i:i+3,:) +
    mat_P_Hybrid2_systemloss1(j:j+3,:); % 120V
end
i = 5;
for j = 1:4:13
    mat_P_Hybrid2_systemloss2(j:j+3,:) = mat_P_AC_wireloss(i:i+3,:) +
    mat_P_Hybrid2_systemloss2(j:j+3,:); % 230V
end
mat_P_Hybrid2_systemloss = [mat_P_Hybrid2_systemloss1; mat_P_Hybrid2_systemloss2];

% 3rd part: -P_DC_load
for i = 1:4:29
    for j = 1:5:16
        mat_P_Hybrid2_systemloss(i:i+3,j:j+4) = mat_P_Hybrid2_systemloss(i:i+3,j:j+4) - mat_P_DC_load;
    end
end

% Efficiency
mat_P_Hybrid2_efficiency = mat_P_Hybrid2_systemloss;
for i = 1:4:29
    for j = 1:5:16
        mat_P_Hybrid2_efficiency(i:i+3,j:j+4) = mat_P_load./(mat_P_Hybrid2_systemloss(i:i+3,j:j+4) +
        mat_P_load);
    end
end

% Case 3: Inverter off/ AC-DC on

% Pin_AC
mat_Pin_AC = mat_P_AC_wireloss; % set size
for i = 1:4:5
    for j = 1:5:16
        mat_Pin_AC(i:i+3,j:j+4) = (mat_P_AC_wireloss(i:i+3,j:j+4) + mat_P_AC_load).*max_AC;
    end
end

% Pin_inverter
mat_Pin_inverter = mat_P_AC_wireloss; % set size
for i = 1:4:5
    for j = 1:5:16
        mat_Pin_inverter(i:i+3,j:j+4) = (mat_P_AC_wireloss(i:i+3,j:j+4) + mat_P_AC_load).*(1-max_AC);
    end
end
mat_Pin_inverter = mat_Pin_inverter./n_inverter;

% Pin_miso

% 1st Part - P_DC_wireloss + Pin_dc_dc
mat_Pin_miso = mat_P_DC_wireloss; % set size (16x20)
for i = 1:4:13
    for j = 1:5:16
mat_Pin_miso1 = mat_Pin_miso;
mat_Pin_miso2 = mat_Pin_miso;
i = 1;
for j = 1:4:13
    mat.Pin_miso1(j:j+3,:) = mat.Pin_inverter(i:i+3,:) + mat.Pin_miso1(j:j+3,:); % 120V
end
i = 5;
for j = 1:4:13
    mat.Pin_miso2(j:j+3,:) = mat.Pin_inverter(i:i+3,:) + mat.Pin_miso2(j:j+3,:); % 230V
end
mat.Pin_miso = [mat.Pin_miso1; mat.Pin_miso2];
mat.Pin_miso = mat.Pin_miso./n_miso;

% Pin = Pin_AC + Pin_miso;
% Pout: mat_Pout = mat_P_load;
% P_Hybrid3_systemloss = Pin - Pout
mat.P_Hybrid3_systemloss = mat.Pin; % set size (32 x 20)
for i = 1:4:29
    for j = 1:5:16
        mat.P_Hybrid3_systemloss(i:i+3,j:j+4) = mat.P_Hybrid3_systemloss(i:i+3,j:j+4) - mat.P_load;
end
end

% Efficiency
mat.P_Hybrid3_efficiency = mat.P_Hybrid3_systemloss;
for i = 1:4:29
    for j = 1:5:16
        mat.P_Hybrid3_efficiency(i:i+3,j:j+4) = mat.P_load./(mat.P_Hybrid3_systemloss(i:i+3,j:j+4) + mat.P_load);
end
end

function gauge = calculateGauge(current)
    if current < 7
        gauge = [18, .001024];
    elseif current < 10
        gauge = [16, .001291];
elseif current < 20
gauge = [14, .001628];
elseif current < 25
  gauge = [12, .002053];
elseif current < 30
  gauge = [10, .002588];
elseif current < 40
  gauge = [8, .003264];
elseif current < 55
  gauge = [6, .004115];
elseif current < 70
  gauge = [4, .005189];
elseif current < 85
  gauge = [3, 0.05827];
elseif current < 95
  gauge = [2, .006543];
elseif current < 110
  gauge = [1, .007348];
elseif current < 125
  gauge = [110, .008252];
elseif current < 145
  gauge = [210, .009266];
elseif current < 165
  gauge = [310, .010404];
elseif current < 195
  gauge = [410, .011648];
else
  error("exceeding current limit")
end
end
B. Graphs: Changing the number of AC and DC branches

AC ONLY SOURCES
DC ONLY SOURCES
Hybrid Case 1
Hybrid Case 2
Hybrid Case 3

Hybrid Case 3: Efficiency Plot at 120Vac, 1 AC branch, 25% AC Load

Hybrid Case 3: Efficiency Plot at 120Vac, 2 AC branches, 25% AC Load

Hybrid Case 3: Efficiency Plot at 120Vac, 3 AC branches, 25% AC Load

Hybrid Case 3: Efficiency Plot at 120Vac, 4 AC branches, 25% AC Load
C. Graphs: Changing the number of AC and DC % Load Consumptions

120VAC in 600-1500W
230VAC

Changing AC load Consumption: 1500W, 230Vac, 48V, 2 AC branches

Changing DC load Consumption: 1500W, 230Vac, 48V, 3 DC branches
D. Graphs: AC voltages comparison

50% AC Load / 50% DC Load

![Different AC Voltages: 900W, 24Vdc, 3 DC branches, 50% AC Load Consumption](image)
20% AC Load / 80% DC Load
80% AC Load / 20% DC Load

\[
\begin{array}{cccccc}
\text{AC only} & \text{DC only} & \text{Hybrid Case 1} & \text{Hybrid Case 2} & \text{Hybrid Case 3} \\
0.92 & 0.83 & 0.94 & 0.93 & 0.91 \\
0.93 & 0.83 & 0.94 & 0.93 & 0.91 \\
\end{array}
\]
E. Graphs: Efficiency vs. % AC Load Consumption vs. DC Voltage Level (1200W, 120Vac)

AC Only Sources
DC Only Sources

DC Only Sources: Efficiency Plot at 1200W, 120Vac, 1 DC branch

DC Only Sources: Efficiency Plot at 1200W, 120Vac, 2 DC branches

DC Only Sources: Efficiency Plot at 1200W, 120Vac, 3 DC branches

DC Only Sources: Efficiency Plot at 1200W, 120Vac, 4 DC branches
Hybrid Case 1

Hybrid Case 1: Efficiency Plot at 1200W, 125Vac, 1 DC branch

Hybrid Case 1: Efficiency Plot at 1200W, 125Vac, 2 DC branches

Hybrid Case 1: Efficiency Plot at 1200W, 125Vac, 3 DC branches

Hybrid Case 1: Efficiency Plot at 1200W, 125Vac, 4 DC branches
Hybrid Case 2
Hybrid Case 3
F. Graphs: Efficiency vs. % AC Load Consumption vs. DC Voltage Level (1200W, 230Vac)

AC Only Sources
DC Only Sources
Hybrid Case 1
Hybrid Case 2
Hybrid Case 3
230VAC at 4 Branches