DESIGN AND DEVELOPMENT OF A LOW-VOLTAGE DC DOMESTIC POWER SUPPLY SYSTEM

By

CORNELIUS J VAN DER MERWE

Submitted in fulfilment of the requirements for the degree:

Master of Engineering (Electrical)

In the

Faculty of Engineering and Information Technology:
School of Electrical, Electronic and Computer Engineering

Central University of Technology, Free State

Bloemfontein

2018

Supervisor: **Dr. PT Manditereza** (PhD: Electrical Engineering)

Co-supervisor: **Prof. PE Hertzog** (D.Tech: Electrical Engineering)

DECLARATION

I, Cornelius Jacobus Van der Merwe, hereby declare that this research project which has been submitted to the Central University of Technology, Free State for the degree of Master of Engineering (Electrical), is my own independent work; complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State, and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Signature of student

Date: 2018-10-26

ACKNOWLEDGEMENTS

I would like to give sincere thanks to my supervisors, Dr. Patrick Manditereza and Prof. Pierre Hertzog, who were very supportive and helpful during my time of study. Their guidance and support does not go unnoticed. I would also like to thank Prof. Ivan Hofsajer from the University of the Witwatersrand, for his guidance on technical aspects of my research.

Finally, I would like to thank the Central University of Technology for granting me the opportunity to undertake this research.

ABSTRACT

Much effort is spent in regulating the power quality in alternating current power supplies for electronic devices. Many electronic devices, however, do not use alternating current, but rather direct current. The output of most small scale renewable energy systems are also direct current, so it can be connected to the loads more efficiently by eliminating the inverter stage. In a circuit with a number of rectification stages the conversion losses can add up to a significant amount. By reducing the number of conversion stages or possibly eliminating some of the stages the overall system could be more efficient. The purpose of this dissertation is to present the simulation design and results of a direct current distribution system, containing common household appliances connected to a direct current grid supply and a renewable energy source. A bottom-up design approach is used where a list of household appliances with their voltage needs is identified and the distribution voltage is then selected based on the voltage needs. The distribution system is modelled using Matlab and Simulink software.

Results show that common household loads can be supplied directly with direct current, from either a main direct current grid supply, or a renewable energy system with direct current output. This direct current distribution system is compared to two other systems: (1) Existing alternating current system and (2) Hybrid system (converting alternating current to direct current for distribution in the house). The three systems are compared to each other in terms of power efficiency and material cost. The existing alternating current system is shown to be the most efficient, with an average power efficiency of 87.85 %. The second most efficient system is the hybrid system with average power efficiency of 86.95 %, and the least efficient of the three is the direct current distribution system with 86.45 %. The main reason why the direct current system is less efficient is

because of the high input power of the microwave oven when connected to a direct current supply. The direct current system is more efficient than the alternating current system if the microwave oven load is taken out of both.

Future work will involve more detailed operational and transient state simulations of the loads in the direct current system. Another recommendation is to find a direct current design for supplying the microwave oven load that does not incur large losses. A final recommendation is to build a practical test set-up of the direct current system in order to analyse the practical aspects of a residential direct current distribution system.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

C_f	Filter capacitance [F]
C_{min}	Minimum capacitance [F]
C_o	Output capacitance [F]
$\cos\theta$	Power factor
D	Duty cycle
$\frac{d}{dt}$	A change with respect to change in time
f	Electrical frequency [Hz]
F_o	Cut-off frequency [Hz]
F_s	Switching frequency [Hz]
h_n	Harmonic of the n^{th} order
I_{in}	Input current [A]
I_{out}	Output current [A]
I_{rms}	Root mean square current [A]
L_f	Filter inductance [H]
L_{mb}	Magnetizing inductance [H]
M_i	Modulation index of a pulse generator
n	Transformer winding ratio
P_{in}	Input power of a circuit [W]
P_{out}	Output power of a circuit [W]
R_f	Filter resistance [Ω]
R_L	Load resistance [Ω]
t	Time
V_{in}	Input voltage of a circuit [Volts]

V_{out}	Output voltage of a circuit [Volts]
V_r	Ripple voltage of a waveform [Volts]
V_{rms}	Root mean square voltage [Volts]
η	Efficiency of a circuit [%]

LIST OF ABBREVIATIONS

AC	Alternating Current
CCM	Continuous Conduction Mode
CFL	Compact Fluorescent Light
CT	Current Transformer
DB	Distribution Board
DBR	Diode Bridge Rectifier
DC	Direct Current
DCM	Discontinuous Conduction Mode
DSM	Demand Side Management
ESLV	Extra Save Limit Voltage
FFT	Fast Fourier Transform
HV	High Voltage
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
LED	Light Emitted Diode
LV	Low Voltage
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MCCB	Moulded Case Circuit Breaker
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
PI	Proportional Integral

PQ	Power Quality
PV	Photo Voltaic
PWM	Pulse Width Modulation
R	South African Rand
RES	Renewable Energy System
RMS	Root Mean Square
SMPS	Switch Mode Power Supply
SPWM	Sinusoidal Pulse Width Modulation
THD	Total Harmonic Distortion
VDC	Voltage Doubler Circuit
VSI	Voltage Source Inverter

Word count: 29,325

Chapter 1
Introduction

1.1 Background

In the early days of electricity distribution, direct current (DC) voltages were used to transmit power in and around a building. For example, in Thomas Edison's Pearl Street Station, direct current generators were connected to loads at the same voltage level [1]. The generation, transmission and loads had to be of the same voltage because there was no way of changing DC voltage levels. Low DC voltages of around 100 V were used since that was a practical voltage for incandescent lamps, which was the primary electrical load at that time [2], [3]. Low-voltages also require less insulation for safe distribution in buildings [4]. The problem however with low-voltage distribution, especially in high power circuits, is the losses in the cables. The losses in a cable are proportional to the square of the current and the resistance of the cable. A higher system voltage would reduce the copper size to transmit a given quantity of power, and in Edison's time, no efficient method existed to change the voltage of DC power circuits. To keep losses to a practical level, the Edison DC system needed thick cables and local generators. Early DC generating plants needed to be within about 2 km of the farthest customer to avoid excessively large conductors [1]-[3].

Then in the late 1880s, there was a competition between direct current and alternating current, which was led by Thomas Edison and George Westinghouse, respectively [1]. This was commonly known as the "War of Currents" and the quarrelling was mainly about which is the best way to transport electric energy, with an AC system or a DC system. Eventually, it was concluded that AC is the better option for transmitting power. The reason for this decision was that power transformers made it possible to increase the voltage so that the current in the transmission and distribution lines could be decreased. By having minimal current flow, the size of conductors and distribution losses could be minimized which made the AC system more economical to distribute power over long distances. Since then, the traditional AC system has been the standard electricity distribution configuration for a long time, for both public electricity distribution and private residential distribution systems [5]. Figure 1.1 illustrates the basic principle of AC versus DC power distribution back then, given a low generation voltage output.

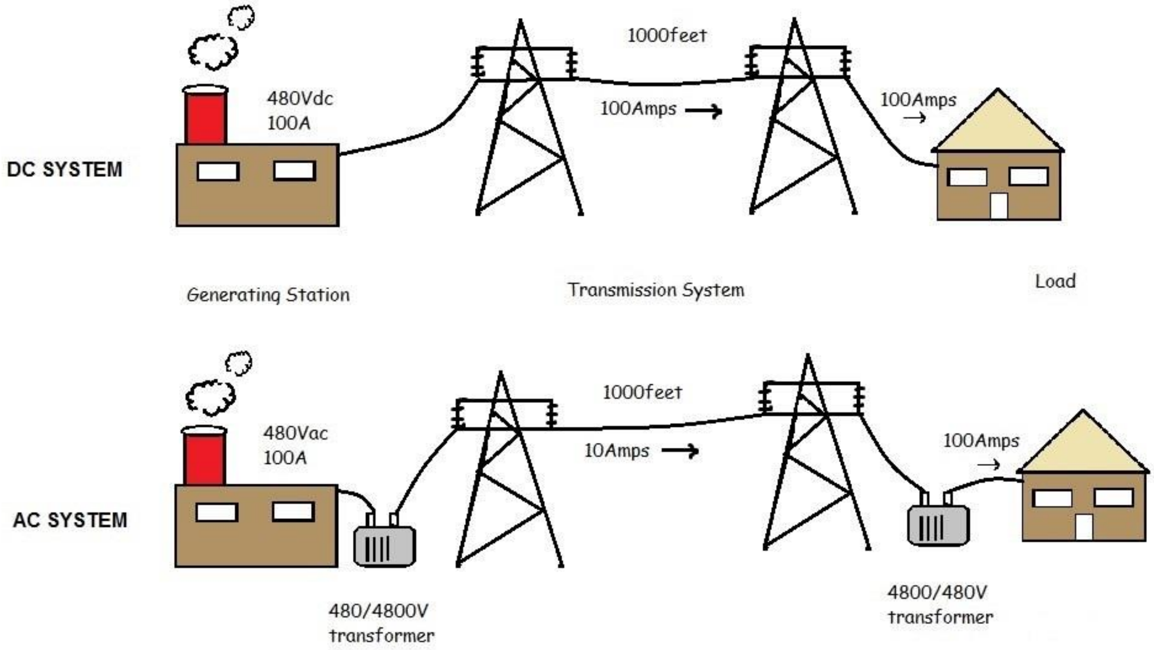


Figure 1.1: Principle of AC versus DC distribution [6]

In the figure, the power in the DC system is transmitted to the load at a low voltage over a considerable amount of distance. The low voltage is not sufficient enough to overcome the transmission losses in the conductor. In the AC system however, the generation voltage is stepped up to a much higher value so that the current flow in the system is minimal and transmission losses can be minimized.

The use of DC power then was not discouraged at all but was only used on a much smaller scale than AC and for specialized applications only, much like it is used today. Currently, DC systems can be found in special applications in industries where there are multiple sensitive DC loads to be supplied where voltage fluctuations cannot be tolerated [5], [6]. High voltage DC systems are used for transferring large amounts of power over very long distances because with DC distribution, there are reduced losses in the transmission process compared to the AC system [2], [8]. DC systems are also used for the control and protection of high voltage equipment in substations, telecommunication systems, electric vehicles (including trains) and shipboards.

Some researchers are currently busy investigating the traditional way of how we generate, transmit and distribute electrical energy, while others are constantly experimenting and developing new technologies. The main drives behind all this research and investigations are global concerns [9] such as climate change [9], environmental impacts such as pollution [3], and the population growth which puts more strain on the power grid, especially in developing countries such as South Africa. The generation of electrical energy through the burning of fossil fuels is one of the biggest contributors to air pollution in the world. In South Africa, around 93 % of the power produced by Eskom is from coal-fired power stations [10], so the country’s energy needs rely heavily on fossil fuels. It is however possible to lower emissions and minimize the carbon footprint caused by the burning of coal by looking at other forms of energy generation, or simply by using less electricity.

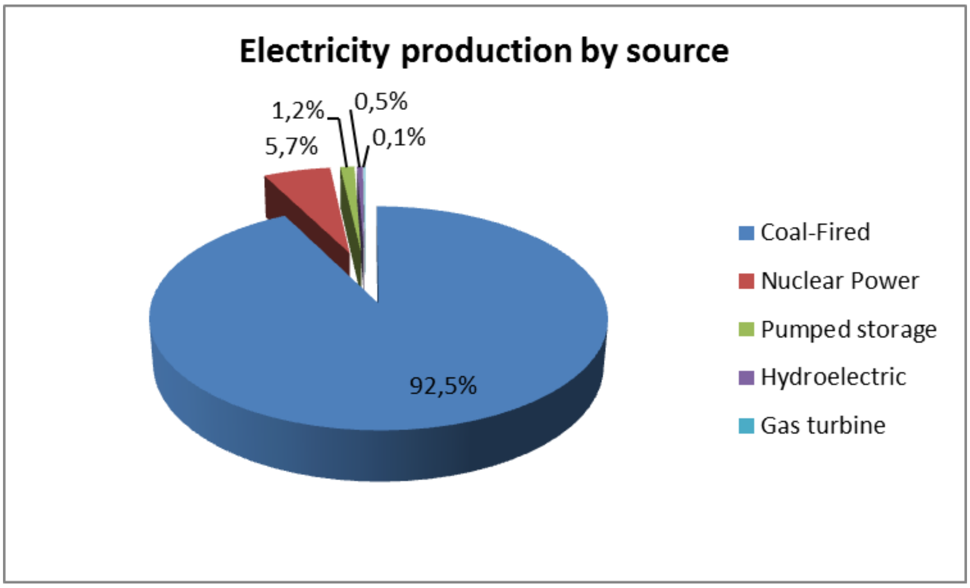


Figure 1.2: Electricity production by source in South Africa [11]

Figure 1.2 shows the electricity production by different sources in South Africa [11]. 93 % of all power is generated by coal-fired power stations, followed by nuclear power generation at 5.7 % and pumped storage schemes at 1.2 %. Power generation from renewable energy systems has very little impact on the electrical network in South Africa at present.

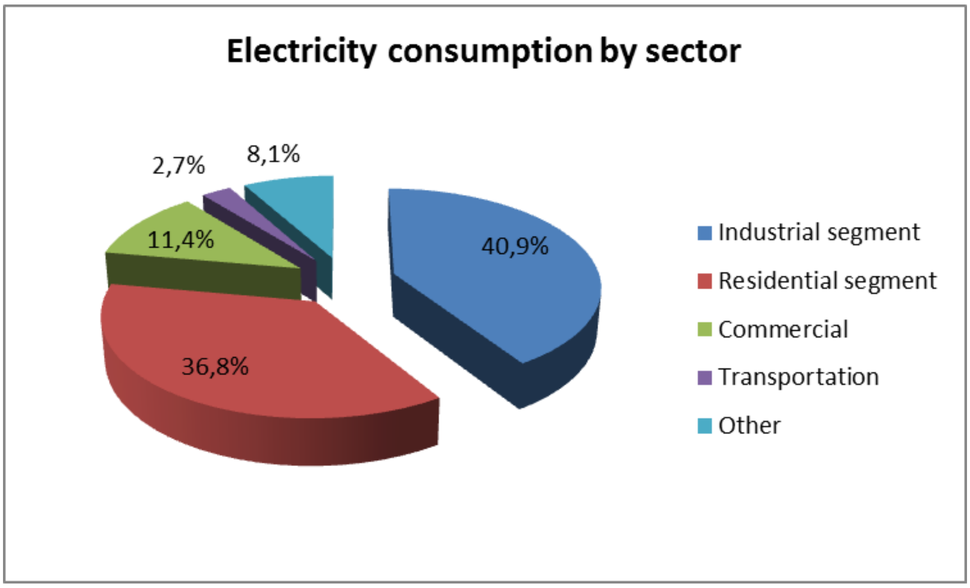


Figure 1.3: Electricity consumption by different sectors in South Africa [11]

Electricity consumption by different sectors in South Africa is illustrated in Figure 1.3. The largest segment taking its cut is the industrial sector with 40.9 %, followed by the residential sector with a 36.8 % contribution [11]. With the popularization of solar geysers and localised renewable energy systems, consumers can reduce their electricity consumption from the grid by a reasonable amount and ultimately reduce the energy demand of the residential sector.

1.2 Problem statement

Today, electronic appliances such as computers, televisions, entertainment systems and network equipment can be found in numbers in households and offices around the world. These devices are all designed to be connected to an AC outlet at a much higher voltage than what is needed and effort is expended in tightly regulating the AC power quality. However, none of these devices directly use the AC supply on the core components of the devices. Basically all electronic appliances operate internally at low DC voltages, mostly in the range of 12 V to 48 V and thus have built-in AC to DC conversion circuits. The conversion stages in the circuits cause power losses and these losses can add up to a significant amount when there are a lot of circuits in a distribution network [12]. However, these losses can be reduced if the number of conversions is decreased by using DC voltages directly [12]. The same applies for DC-based renewable energy systems and storage devices that are connected to a grid. These systems are usually connected to a network via DC-AC inverters which cause additional losses. The overall system efficiency can be improved by connecting these DC generators and storage devices directly to the DC-based loads, without the need for conversion.

This project will serve to explore whether it may be feasible to remove the AC-DC conversion out of the equipment and replace the domestic AC distribution with DC distribution that integrates renewable energy technologies, energy storage, and DC consumer equipment at the LVDC level.

1.3 Research questions

The research aims to answer the following questions:

1. Can all the appliances in a household be supplied directly with DC?
2. Does the renewable DC supply have to be inverted to AC?
3. At what DC voltage will the appliances be supplied?

1.4 Hypothesis

1. A wide range of household electrical appliances can work with AC as well as DC, however some equipment operate better and more efficiently using a DC supply.

2. Distributed generation incorporating renewable energy sources and storage devices can be more efficiently interconnected to consumer equipment at low-voltage DC (LVDC) compared to low-voltage AC (LVAC).

1.5 Objectives of the study

The objectives of this research are the following:

- To review the latest studies done on the various aspects of low-voltage DC distribution.
- To identify a list of common household appliances and define an appropriate DC voltage level(s) to supply these appliances.
- To build simulation models of the appliances, as well as a complete integrated DC house model using Matlab and Simulink.
- To design and build simulation models of the existing AC system and an AC/DC hybrid system for performance comparison.
- To see whether energy savings are possible by replacing the traditional AC system with a modernized DC system in a single family dwelling, and to see which system is more cost effective.

1.6 Research Methodology

In order to achieve the abovementioned objectives, the methodology is as follows:

Literature review: A thorough literature review is done in order to get familiar with low-voltage DC distribution concepts and applications. This helps to see where the LVDC system is at the moment and what can be taken from previous work and applied to this work. Progress of work involving DC systems in residential applications is reviewed as well as the methods used and results obtained from previous work.

Building a list of appliances and determining voltage level(s): A key part of this work is to identify a list of common household appliances and determining the optimal DC voltage to supply these devices with. All types of household appliances are considered for this work, which includes high-power and low-power devices.

Component modeling: The output power of all the appliances is used to design the circuit models with. Practical power use data of all the equipment is obtained and this input power value is then converted to an output power value using appliance circuit data. Matlab/Simulink software is used to do the modeling and simulations of the devices and the complete DC configuration. Matlab/Simulink software is used in this work because it is an extremely powerful and flexible tool that can be used to model basically any complex engineering system [13].

Performance and costing comparison: The existing AC system as found in all South African dwellings, as well as a combination of these two systems (AC/DC hybrid system) are designed and modelled. The AC system is designed with the same appliances that give the same output parameters as that in the DC system. The input of the appliances is designed to be connected to a 230 V AC supply. The hybrid system consists of a bulk grid-rectifier in order to provide a bulk DC supply to all the electronic loads in the system. In this hybrid system, all the high-power appliances are being supplied by 230 V AC. A material cost breakdown is also done on all three configurations in order to find a trade-off between the performance of each system and the material cost needed to install such a system. The trade-off decides which configuration is best.

1.7 Limitations of the study

The research is limited to the introduction of a LVDC distribution system to an average sized, medium income dwelling in South Africa. The study focuses mainly on the steady state operation (power efficiency) of a DC distributed house. External grid (outside the house) DC distribution and changes to the design of current electrical appliances will not be considered in this research. Other topics such as system optimization, smart control techniques and complex protection philosophies are also excluded.

1.8 Contribution to knowledge

The author of this research project provides the reader with the following:

- A review of relevant literatures based on various aspects of low-voltage DC systems. This enables researchers to identify gaps in the field and to focus on aspects that have little or no research background.
- A set of power converters for use in both DC and AC systems analysis and simulations. These converters can be used for relevant and/or further research.
- Complete Simulink models which can be used as templates for the study of different electrical distribution systems in current and future households.
- A technical efficiency comparison between DC and AC distribution systems for a house, as well as a material cost breakdown for each of the configurations.

1.9 Research output

Conference paper:

K. Van der Merwe, P.T. Manditereza and P.E. Hertzog, "*Design and Simulation of a Direct Current Distribution System*", Accepted for publication in Proceeding of the Southern African Universities Power Engineering Conference (SAUPEC) 2019, Bloemfontein, South Africa, 28-30 Jan. 2019).

1.10 Outline of the dissertation

Chapter 1 is an introduction to the dissertation. The chapter presents a historical background on electrical distribution systems, gives a problem statement, and outlines the research objectives. The research methodology, hypothesis and limitations of the study as well as the research outputs are given in this chapter.

Chapter 2 consists of a comprehensive literature review on various aspects of low-voltage DC distribution systems. The methodologies used and results obtained from similar work are discussed and brought into context of this research.

Chapter 3 presents the research design of the study and the approach taken. This is followed by the selection of the major research components. The last section in this chapter is an explanation of the other configurations which will be looked at in the study as well.

Chapter 4 is an extension of chapter 3. This chapter deals with the simulation design of all the system components and configurations. The individual circuits and components which ultimately form part of the complete DC system, are designed here and the operation of it explained in detail. These individual circuits are then all integrated into one complete system, where they will be simulated together. The same is done for the other configurations.

Chapter 5 presents the simulation results of the individual components and the complete configurations designed in the previous chapter. The outcome of the study is determined here and the results verify the validity and correctness of the designs. The efficiencies of the three systems are compared and a material cost breakdown is done regarding the material costs related to the implementation of each system.

Chapter 6 presents the conclusion in which the major findings from the research are identified and some recommendations are given for future research.

Chapter 2
Literature review

2.1 Introduction

In this chapter, a review is done on various studies conducted globally on the use of DC power in residential applications. The first part of the literature review gives an overview of the AC and DC systems and some influential issues are mentioned which sparked the interest in DC. The current progress of work involving DC in houses thus far is also discussed in great detail. The literature review also looks at various methodologies used by other researchers to compare the existing AC system to their proposed DC systems. This part of the literature review is important because it aids in making decisions on certain aspects of this work.

2.2 AC versus DC distribution for homes

Residential buildings today all use the AC power system for distribution in and around the house to supply all different kinds of household loads. The building gets its supply from the distribution grid at a standardized voltage of 230 V AC through a live and a neutral conductor and this is then connected to a distribution board where all the household circuits are connected to. All the appliances in the household are then supplied with the 230 V AC voltage, whether it is high powered kitchen appliances or low powered electronic appliances such as computers or cell phone chargers. So the mainstream household appliances available on the market today are all designed to be connected to an AC socket outlet, even electronic appliances which use DC voltages internally have an AC-DC converter stage at the input of the supply.

Researchers saw this as an opportunity for improvement on the current household electrical system, and so from this, various influential aspects then led to the re-examination of the use of DC in residential and commercial buildings [1]. These include:

- Renewable energy and storage systems
- Consumer electronics and lighting
- Reliability and power quality
- Intelligent control of DC-based power system components
- Electric vehicles
- Research in areas such as telecommunications and shipboard electrical systems

DC distribution systems however are not new and have been used in telecommunication systems, traction systems, and shipboards for quite some time now. A lot of past work has gone into these applications but not much has been done with regards to DC in residential buildings [14].

It has already been established by quite a few studies that the direct coupling of renewable energy and storage systems to a household grid account for better efficiency [15]-[17]. This is due to the fact that the output of the DC-based renewable energy source or battery does not have to be inverted back to AC for the grid and therefore the inversion stage can be eliminated, resulting in less system conversion losses between supply and load [18]. The same can be said for computers, lighting and other consumer electronics. By removing the rectification stage in a DC internal appliance and supplying the device directly with a low DC voltage will make the circuit more efficient [19]. Lighting circuits are also more efficient in a DC system than in an AC system [17]. Incandescent lamps are resistive loads and can be supplied with AC or DC. A vast majority of commonly used light bulbs can work with DC [12]. Fluorescent light bulbs are actually supplied by electronic ballasts which operate with DC [12]. Modern compact fluorescent light bulbs (CFL) and light emitting diode (LED) light bulbs can be either supplied by AC or DC and there are AC specific and DC specific CFL and LED products available on the market [20].

A DC distribution system makes the electrical supply to the loads more reliable, because it minimizes the number of power electronic converters necessary in the circuit [17], [21]. The DC system also caters better for an uninterruptible power supply (UPS) in the system and therefore makes the household circuit more reliable during unplanned outages [22]. Furthermore, the DC system has the ability to improve power quality in the circuit [22]. A DC supply makes for easier design practices and filtering in power electronic devices in order to increase harmonic power qualities [22].

Hammerstrom [22] also mentions the issue of voltage stability in both AC and DC systems. The advantage of an AC system is that the stable voltage can be controlled independently through the management of reactive power. In a DC system, voltage drops are direct consequences of real power flow in a conductor. However in a multi-converter system, different power electronic converters can be further loaded with more converter units and this can lead to system instability [23]. The reason for this is the integrated system of converters may have right half poles which will lead to system oscillations in the event of a small disturbance, even though the individual converters are designed for stable operation.

Another influential factor that sparked interest in household DC systems is plug-in hybrid electric vehicles (PHEVs) [18]. Electric vehicles are shown to be a big part of the household load in future and because it is a DC-based load, it is connected more efficiently to a DC system than to an AC system [18]. Naval and Oceanographic research has also greatly expanded the knowledge base of DC power systems regarding aspects such as equipment and the control of DC systems [22].

It is also important to look at the limits and benefits of a DC distribution system so that the knowledge gathered in previous works is applied and also complimented in this research.

There are a number of other technical advantages that DC distribution has over AC distribution. According to Woudstra [24], it is possible to transmit more power in a DC system than in an AC system, given the same cross section of cable. There are also no reactive power and power factor problems in DC systems [24]. The use of DC also has some limitations. According to Arafat [25], fault currents in DC systems are relatively higher than in AC systems due to the absence of limiting self-inductance. The interruption of current flow is also more complex in a DC system than it is in an AC system due to the absence of zero crossings in DC current [21], [25]. This then poses different safety requirements for DC applications in households [21]. Existing building codes and practices, locally and internationally, are specific to AC only and more work must be done in order to standardize the DC system [21], [24]. In a study done by Glasgo [21], it is also mentioned that DC circuits at the residential level rely on wiring and other hardware which are not currently manufactured at a scale needed to support broad adoption. Some studies also mention an increase in the capital cost of installations [21], [25].

2.3 Progress of work involving DC in houses

An important aspect of designing a specific electrical system is to look at the progress of work in the area. The DC voltage levels, arcing phenomenon and protection, and new DC-based appliance designs are all topics which are looked at in the research field and these are far from being concluded.

2.3.1 Determination of distribution voltages in residential DC systems

This has certainly been a main topic of discussion in many studies and the verdict is still out there. Various studies have used different approaches and reasons as to why they chose the values they did, but none of them agreed on the same distribution voltage level to be used in a residential DC system. According to Kinn [26], there is an international quest in the engineering community to find the magic number, which could be called the optimum DC voltage standard for use in data centers, offices and homes. From his low-voltage studies, he has seen that it is more complex and there are also too many variables in the system in order to define only one specific value. One of these variables is that there are trade-offs between the maximum length of cable and the amount of current that can be drawn through the cable which makes it difficult to define a single value for a system with different loads [26].

As for standards, there are no official standards on DC voltages for residential buildings and according to Rodriguez-Diaz, these are far from being finalized [27]. Kinn asks the question of how one chooses a value to create an official standard and will the standards emerge due to various market forces. The Emerge Alliance, which is an open industry with strong backing from world leaders in industry, has chosen 24 V DC for their DC system [26]. This is however only from a lighting and control systems point of view. In the United States, the regulatory authorities have stipulated that the voltage for DC lighting must not exceed 30 V [26]. This was the main criterion for the Emerge Alliance and other bodies using sub 30 V as their design benchmark.

It has been noticed that those who are producing working models and real DC powered homes (see section 2.3.5) are not only using extra-low DC voltages but are using higher voltages such as 360, 380 and 400 V DC as well. This is to supply the high-power appliances in a household [18], [26]. The designs with high DC voltages are for a developed world living standard where the goal is to reproduce the same comfort and usability of an ordinary AC powered house [26]. The same approach is taken in this work.

Webb [18] chose 24 V DC and 380 V DC in his design of a 380V/24 V DC-Microgrid for residential DC distribution. He used 380 V because the Emerge Alliance chose that as standard for data centers, and according to Webb, this will help standardize on equipment. 24 V DC was chosen as the low voltage component because DC voltage over 30 V is considered not safe and have specific insulation requirements. This decision was also based on decisions made by the Emerge Alliance. Vossos [15] chose 24 V DC and 380 V DC as well and for the same reasons Webb did. 24 V DC is an Emerge Alliance standard and 380 V DC is pending to be standardized [15]. According to Kinn, Intel is using 400 V DC in their systems and they see lower voltages such as 24 V DC and 48 V DC as having disadvantages.

The selection of the voltage level of a system is an important task in defining an LVDC system, because it affects further system planning such as component selection [28]. This work follows the above mentioned philosophy so that it makes the complete design of the DC system possible for further study. Panguloori [29] mentions some major factors influencing the selection of a DC electrical distribution voltage:

(a) Safety aspects: 12/24/48 V is recommended for battery based systems because these voltages fall in the category of extra safe limit voltage (ESLV). Low voltage systems are safer and less prone to arcing faults and are recommended for use in low powered systems with loads up to 1000W. 120 V is also accepted as a safe voltage level for humans by the International Electrotechnical Commission (IEC) [30].

(b) Unipolar/bipolar voltage systems: Panguloori mentions the use of bipolar distribution where three different voltages can be used, because it provides a variety of voltage levels in a system. A disadvantage of this system however, is that a load balancer is required at the input of the DC system. According to the standards Panguloori used in his study, the insulation voltage of residential wiring is rated for 450/750 V, so a bipolar 380 V DC system can be implemented without the change in cable specifications. This system then has 190 V and 380 V DC available for the connection of loads and supply, as opposed to the unipolar system with only one voltage level. Iyer [31] mentions that there is currently a bipolar 190 V DC system proposed for data centers but argues that it is too low compared to existing voltage standards and that a slightly higher voltage would be better compatible with either AC or DC loads.

(c) Compatibility: In terms of compatibility, if a 190 V DC system is used, then old wiring and a large number of appliances can be supplied without changing the power supplies or the cabling system. He advises that higher wattage loads should be supplied with 380 V DC to keep system losses and cable cost at minimum. Thinner conductors fit easily through wiring ducts so it will make hardware installation easier. Like other studies, he also mentions that low voltage off-grid applications are becoming popular and this means new designs of DC compatible appliances [29]. Makarabbi [32] mentions that all household loads are designed for 170 – 270 V and in his paper he uses 220 V DC to supply the appliances. He mentions that low DC voltages are not practical for devices which generate heat since they require a higher current rating and this increases the cable size and system losses. According to him, the 220 V DC is adaptable to almost all appliances and does not require any change in household wiring, except for the DC circuit breakers.

(d) Storage systems: A PV hybrid system is usually integrated with a battery bank to store excess energy when the load is low compared to the PV output, in other words, when the production of the PV energy is lower than the load. Storage is also used to cope with unreliable grid supplies. According to Panguloori, a 48 V battery bank is more efficient in terms of cell equalization and is safer than a high voltage such as 380 V DC.

(e) System efficiency and savings: In any distribution network, there are inverter and rectifier blocks and the efficiency of these blocks is a key part to determining the overall efficiency of the system. Panguloori compared the overall efficiency of a 230 V AC system to various DC systems with voltages ranging from 48 V, 110V, 230V and 380 V. He took the efficiency values from commercially available inverters and converters and observed that power distribution at 380 V DC increases system efficiency with a maximum efficiency improvement of 4 % over the 230 V AC circuit. This efficiency improvement is attributed to less conversion stages in the DC circuit and also fewer distribution losses due to the higher system voltage.

The above mentioned are some very important factors to look at when designing a DC system for optimal performance.

Rodriguez-Diaz [27] reviewed the latest findings of LVDC distribution systems for residential applications. He asks the question of whether the 380 V DC used in data and telecomm centers is really applicable for houses. Reason being the power consumption of a regular household is fairly lower than that of data centers therefore lower voltages can be used without increasing distribution losses, while increasing the safety limits. The study mentions that when supplying high power loads such as ovens and air conditioners, a 380 V DC system only shows an efficiency improvement of 0.3 % compared to a 120 V DC system.

In this work, an investigation is done on new DC voltage level(s). A bottom-up approach is used where it is first determined what voltage the specific appliance needs and a decision is then made based on this and a combination of other technical factors that come into play in a power system. The findings and recommendations from other studies are also taken into consideration.

2.3.2 Power quality standardization in the LVDC environment

Some work on power quality in DC networks was done by Magro [33]. In this paper, the definition of power quality indices for DC low voltage distribution networks is addressed. The author identified disturbances found in an AC network and then aimed to find an equivalent of that parameter in a DC network. Parameters such voltage fluctuations and flicker, voltage dips, harmonics and interharmonics, ripple, and voltage notches were looked at. According to Magro, a DC distribution network is a new network, for which there is a substantial lack of standards and guidelines concerning power quality (PQ) issues and acceptable levels of conducted disturbances. Magro states that for a DC distribution network, "harmonic" and "interharmonic" terms may be considered synonymous to "ripple", commonly used to indicate voltage fluctuations. The "harmonic" and "interharmonic" terms however, are frequency domain (or phasor) concepts, while "ripple" is a time domain concept. A ripple is defined as the variation of a quantity (voltage) about the steady state value during steady state electric system operation. So in essence, there are only power quality indices applicable to the voltage ripple parameter in a DC network, and not yet an official standard which can be used for residential DC systems.

2.3.3 Arcing in DC systems and wiring modifications

DC power poses different safety requirements in insulation and arc-quenching due to the nature of DC power [21]. Higher voltage DC wiring then requires specialized circuit breakers and protection [17]. In a DC system, as opposed to AC, there are no zero crossings in the current and voltage waveforms [25]. AC breakers interrupt the circuit and the arc caused by separating terminals is extinguished when the waveform passes through zero. Arcs in systems with voltages higher than 50 V can occur through loose wiring connection, damaged insulation or between a live wire and ground [17]. The DC system also has a typical problem of corrosion when in open air and this problem is larger in the DC system than in the AC system. Panguloori [29] states that low voltage DC systems are safer and less prone to arcing faults and that loads in a low voltage DC system should be limited so that arcing will not sustain. This then calls for the modification of existing systems to accommodate DC power [31]. To reduce arcing, transients in the line need to be reduced. This can be done by reducing the impedance in the line, and this in turn is done by reducing the inductance and increasing the capacitance of the cable [31].

Iyer [31] investigated the suitability of employing conventional AC wiring to distribute DC power to supply loads in a household directly, in particular to try and counter the arcing issues present in DC systems. An alternative flat DC wiring system is proposed which offers improved transient electrical and thermal characteristics for household wiring. This alternative is expected to reduce arcing and improve overall efficiency of the distribution system. Iyer showed that a flat wire has a higher power carrying capability as compared to regular cables due to a lower operating temperature. The inductance of the flat wire is much smaller and the capacitance is twice that of the regular wire with the same cross section [31]. In the study it is mentioned that the flat wire can be used to replace the existing wiring in both AC and DC systems because it has much better electrical and thermal capabilities [31].

2.3.4 New DC-based appliance designs

For quite some time now there has been a thriving niche market for DC only appliances [26]. These are usually gadgets on leisure craft, like boats and caravans [26]. According to Garbesi [20], there are two major new classes of DC products emerging for residential and commercial applications; one of which is DC electric appliances designed for operation with hybrid AC-DC power systems, and the other is electric vehicles and their charging stations. The current generation of DC appliances is not designed to be connected to a standard voltage [20]. These appliances also tend to be much smaller than the normal capacity range of mainstream AC appliances. According to Garbesi, the Emerge Alliance registered products such as fluorescent lighting, LED lighting and DC ceiling fans for connection to a DC system. These are however the only registered DC-based appliances or peripherals available on the market today that can be connected to a DC system without manual modifications. This work will not look into electric vehicles and their charging stations as household loads.

Vossos [15] mentions noticeable savings in his Direct-DC in residential buildings study where he lists the normal AC appliances and then calculates energy saving figures when replacing these appliances with DC equivalent ones. The core functions of the major household appliances (which is lighting, heating, cooling, mechanical work and computing) are given and mentions that all of these functions can be served by DC-compatible technologies with neutral or positive energy impact over the conventional technologies [15], [20]. He states that all major lighting technologies are either AC/DC indifferent or can be run with DC directly. Heating can be achieved by DC-indifferent resistance heating or by DC-favoring heat pump technology, while cooling can be achieved with DC fans [20]. Mechanical work can be performed by advanced brushless DC motors which are much more efficient than conventional AC induction motors [20]. Digital computing is DC-internal anyway and can benefit from a direct-DC supply. These savings are later discussed in section 2.4.1.

Japan’s New Energy and Industrial Technology Organization (NEDO) has modelled potential energy savings of direct-DC and engaged Panasonic in the assessment and development of DC appliance prototypes [20].

Amin [34] designed a combined refrigerator/stove unit which runs on 48 V DC. The system was simulated and a prototype was built in order to analyze the performance. The researcher mentioned that the unit has an overall efficiency increase compared to a standard stove and refrigerator because the thermal energy from the refrigerator is stored and later used for heating the stove. However, more research is recommended if the unit is to be made practical and more analysis is required to make the thermoelectric module more efficient and to make the unit cheaper [34].

2.3.5 Complete household DC installations

According to Rodriguez-Diaz [27], a demonstration facility was built in Fukuoka City in 2012. It is a hybrid AC-DC system with RES, an energy management system and loads. The AC system is fed from an inverter connected to the DC bus where it is used to supply all the AC loads. The DC bus is running at 380 V DC and connects all the components in the system [27]. In 2008, a microgrid was built in Tohoku Fukusi University in Sendai City [27]. The DC system of this microgrid is interconnected via a 400 V DC bus, connecting the generation system, battery storage unit and the loads. What is noteworthy about this installation is that it kept on operating autonomously even during the earthquake in the Tohoku area in 2011 [27]. According to Diaz, Philips Research has built an office lighting test bed in Eindhoven. It uses 380 V DC as well as 230/400 V AC for distributing power from the PV panels to the LED loads. The results of this study have shown that the efficiency of the LVDC system is 2 % higher than that of the AC counterpart system. These savings are linked to the reduction in conversion stages in the DC circuit and the overall power losses in the cables [27].

Another DC installation was built by the Samsung C&T Corporation in 2009. It is a 30 kW residential DC demonstration project with PV panels, wind power, fuel cells, battery storage and DC appliances [20]. The study claimed a modest 1.5 % - 3 % efficiency gain resulting from direct-DC.

Kinn [26] mentions academics that are also doing work in DC for residential applications. One of them is called Dushan Boroyevich from the Centre for Power Electronics systems at Virginia Polytechnic Institute and State University and he has designed a home using a 48 V DC and 380 V DC power supply. The other academic is called Professor Tsai-Fu Wu from the Department of Electrical Engineering, National Chung Cheng University in Taiwan. Professor Wu is overseeing a student accommodation complex which is an all DC system running at 360 V DC [26]. Due to the lack of available information, it is unclear what the outcomes and findings of these works are.

2.4 Efficiency analysis and comparison between AC and DC systems

This part of the literature review examines the previous methodologies used and the conclusions made by following these methodologies. The three most common approaches found for comparing AC systems to DC systems in residential applications were the following:

- Statistical analysis using load data and conversion efficiencies (also referred to as the top-down approach)
- Theoretical analysis and the use of simulation software
- Practical studies

2.4.1 Statistical analysis using load data and conversion efficiencies

The statistical approach is also commonly known as the top-down approach [26]. The methodology of this approach is to gather AC load data, obtain conversion efficiency values for power converters and then use these efficiency values together with the loading data to calculate energy savings for the DC system.

One of the studies that were looked at was a feasibility study of a DC electrical distribution system done by Park [35] in Korea. In this study, the efficiency of AC and DC supplies for common household appliances were analyzed. Annual power consumption figures were obtained for refrigerators, washing machines, air-conditioners, lighting and televisions and then these figures were re-calculated by eliminating unnecessary conversion stages in the supply circuit. Typical efficiency ratings for rectifiers, filters, inverters, motors etc. were used for the calculations. The study concluded that the configuration which consisted of a 310 V DC and a 48 V DC supply is more efficient and reported a savings figure of 7.2 %. This was the highest of all the configurations investigated. Liu [16] did similar research on the energy efficiency of DC distribution systems. Part of the work specifically looked at the calculation of energy efficiency in an office building. Power consumption figures of various office appliances were used to calculate losses and savings in both AC and DC systems. The study concluded that an office building supplied with DC can have an overall saving of about 14.9 %.

In Hammerstrom's [22] approach for the comparison of system conversion efficiencies in residences, four different scenarios for AC and DC systems was evaluated. The first two cases were the AC and DC systems supplied by the AC grid, and in the second two cases, both systems were supplied by fuel cells only. The study concluded that for the AC grid supply cases, the use of DC for residential distribution was predicted to be disadvantageous because of the inefficiency of the combined transformer-rectifier needed to convert bulk AC power to premise DC power. On the other hand, with the localized DC generation that feeds directly into the DC system, the conversion losses can be favourable for DC [22].

The study done by Vossos [15] claims significant savings in net-metered houses with PV systems in the United States. The researcher used PV system output and residential loading data for 14 different cities in the U.S. and modelled the net power drawn in a "direct-DC house" and a normal "AC house". The savings mentioned are achieved if the entire load in the DC house consists of DC-powered appliances and if the system incorporates battery storage. Figures like 5 % were calculated for houses without battery systems and 14 % for houses with battery systems. The study also mentions that further savings of about 33 % could be achieved by replacing existing internal appliance circuitry with more modern DC-based equipment.

Panguloori [29] also analyzed potential savings and compared the efficiency in AC and DC distribution systems with solar and without solar. He took the efficiency values of various converters and inverters from the commercially available market to compare AC and DC systems with different voltage levels. In the study, the existing 230 V AC system is compared to a 48 V DC, 110 V DC, 230 V DC and 380 V DC system and the results show that the 380 V DC system could have a 4 % efficiency improvement over the 230 V AC system. By introducing solar into the system, potential savings for the 380 V DC system increases to 6 % over that of the conventional 230 V AC system. This 6 % improvement in the 380 V DC system resulted in a 19 % reduction in solar capacity as well [29].

2.4.2 Theoretical analysis and the use of simulation software

Stockman [36] looked at the expected energy efficiency of 350 V DC households compared to 230 V AC households. A small network was simulated using AC and DC load models where the DC model is connected to the AC grid via an AC-DC converter. The study showed a potential gain of 1.35 % for the 350 V DC in-house installations over the present 230 V AC system. Another potential gain of 4.06 % was noted for the 350 V DC grid when both grids are equipped with complex loads and sources such as heat pumps, EVs and PV panels. The study also recorded a potential loss of 1.15 % for the DC system when the system used its own bi-directional AC-DC converter. Savings then went up to 7.53 % when “smartness” was added to the system in the form of adjusted load-profiles to match PV output. The results from the study concluded that adding complexity to the DC system enables it to outperform the conventional 230 V AC system.

Arafat [25] analyzed the feasibility of a low-voltage DC house by making use of a list of household appliances and their power ratings and then calculated the power consumption of these appliances with a 24 V DC, 48 V DC and 230 V AC supply. The total energy losses were also calculated for all three systems and the 230 V AC was found to have the least amount of total losses than the other low voltage DC systems. Arafat concluded that in a 48 V DC system with an optimized cable area, the cable cost will increase by 48 % compared to the cable cost of the 230 V AC systems. The 48 V DC system would be cheaper in the long run due to less energy consumption even though it will take a couple of years to achieve that saving [25].

At a later stage, Arafat published a paper on using 230 V/48 V AC-DC converters with a smart meter [37]. In this study, all appliances are being supplied with 48 V DC via converters except for the stove, which is supplied with 230 V AC. The purpose of the smart meter in the study is to theoretically analyze the consumption and to do housekeeping for efficient energy use. This later study found an energy consumption reduction for the low-voltage DC system of 1218.47 kWh per year but, the energy loss in the supply wire is 234.7 kWh per year. The net energy saving per year for the DC system however was calculated to be 983.77 kWh. This is compared to a similar system without a smart meter and DC appliances with rectifiers inside.

Webb [18] designed a 380 V/24 V DC micro-grid for residential DC distribution by making use of simulation software. Webb starts of by calculating the power consumption of household appliances in the range of 4 W to 5000 W using a 240 V AC, 380 V DC and a 24

V DC supply. Wiring losses, load losses, rectification losses and energy losses are calculated for the appliances in both systems in order to get accurate consumption values. The loss comparison between the AC system and the DC system showed that the DC system (380 V for high-power loads and 24 V for low-power loads) had a reduced power loss of 43 % compared to that of the AC system. This value was however just calculated theoretically. The main part of the research was to design the DC system in order to check the feasibility and operation. Webb used two different software for simulation namely, PSIM software and Matlab Simulink. The PSIM software was used to simulate the converters only, and Simulink was used to simulate both the converters, as well as the complete DC system. The results from the simulations showed that the 380 V/24 V DC micro-grid for the household is indeed possible and carries with it some advantages. The existing AC system was not simulated.

Another study including PV with a hybrid AC-DC system was done by Glasgo [21]. The aim was to see how much energy can be saved by using direct current circuits in homes in the United States. Simulations were done using appliance-level monitored loading data for 24 homes, along with conversion and inversion stage efficiencies for the DC appliances. The study reported low energy savings primarily due to non-coincident load profiles between solar PV generation and peak load times of the house. Vossos mentioned this non-coincidence in their study as well and highlights the importance of storage.

Gwon [38] did a simulation study where the efficiency of AC and DC load in a LVDC system was analyzed. He made use of EMPT software to model a sinusoidal pulse width modulated (SPWM) inverter, DC-DC buck converter, diode bridge rectifier and AC/DC load models. The simulation results showed that DC load is more efficient than AC load in a LVDC system due to the reduction in the number of power converters.

In a power consumption analysis simulation study done by Seo [39], power consumption data of a household containing high-penetration rate appliances are used to develop a simulation setup in Matlab Simulink for an AC and a DC system to compare their efficiencies. The appliances are categorized into three different groups, i.e. motor, heating and electric. The motor loads in the AC system is supplied with an inverter and converter combination, the heating loads are supplied directly with AC and the electric loads are supplied with a rectifier and a DC-DC converter. In the DC model, the motor loads were supplied with an inverter only, the heating loads directly with DC and the electric loads with a DC-DC converter only. To predict the effect of replacement of the conventional AC to a DC system, he uses the same structure for both systems. The AC system uses the conventional 230 V AC and the DC system implements a mixture of 24 V DC for the low power appliances and 400 V DC for high power appliances. Seo predicts an overall energy saving of 41.2 kWh per month with the DC system applied over the AC system.

Seo [9] did another simulation study and the key part of this study is the incorporation of system control algorithms. According to Seo, to achieve the maximum benefit from the DC distribution system, it is crucial to maximize the efficiency of the AC-DC converter. In this study, the control system manages the power flow through the converters because the converters operate more efficiently at higher loads [9]. The control algorithms were tested by simulating three converter modules connected in parallel, each rated at 3.3 kW, 220 V AC /380 V DC and it was found that the system is more efficient when running only one module at 30 % load, rather than running all three modules at 10 % load each. The energy efficiency for all three modules at 10 % load was found to be 78 % and the energy efficiency for one module at 30 % load was found to be 90 %.

In the same control algorithm study by Seo [9], four different distribution configurations where simulated as well. An AC only system, a hybrid system (AC and DC combined), a DC system with integrated power supply (AC-DC converter at the supply), and a supplier delivered DC system (DC supply from the grid). All AC circuits are 220 V and all DC circuits are 380 V with a 10 kW load (divided into motor, electric and heating loads) connected to each configuration. The DC systems included 3 of the AC-DC converter modules mentioned earlier, each at 3.3 kW. The supply delivered DC system was found to be most efficient. The results from the study show that a 4.7 % efficiency improvement is possible with DC distribution. None of the simulations included renewable energy sources or storage systems.

Dastgeer [23] compared AC and DC systems for residential areas with local DC based distributed generation using Matlab and EDSA Paladin DesignBase software. He used energy information administration data to divide household loads into three different categories which are; loads utilizing AC power, loads utilizing DC power and loads that can use both AC and DC. The relative percentage of these loads presented in a household are 52.6 %, 16 % and 31.4 %, respectively. The grid model he used for simulation is a medium voltage system where the building loads are being supplied from distribution transformers. The grid is supplied by a DC distributed generation system (fuel cell, PV or wind farm) which powers the entire load and the surplus power is sent back to the transmission grid. The building loads are supplied at 230 V AC in the AC system and the heating loads and induction motor loads are supplied directly from this AC while the DC based appliances use DC converters.

The exact same system is used in the DC model. The loads are identical with only the modification of the suitable power electronic converters where required. In the DC input supply system however, a converter is used instead of a transformer to supply the building loads at 325 V DC (peak value of 230 V AC r.m.s). Heating loads and DC based loads are supplied with DC but at different levels and the AC loads are supplied via DC-AC inverters. Different configurations for different voltage levels for the DC system are mentioned but the methodology of the study is to change as little as possible of the current system. In the comparison, he found that the DC system is slightly more efficient than the AC counterpart. Results showed a 87.8 % efficiency for the DC system and 85.3 % efficiency for the AC system. These values are attributed to no reactive currents in the DC system, no inversion stage for the DC supply input and the higher r.m.s voltage. These results are based on an important assumption which is the values used for efficiencies of the power electronic converters in the system. Dastgeer states that these values often tend to be too high to be achievable for practical and economic reasons and because of this, he developed a technique to determine the minimum required efficiency of converters in order to make the DC system practically comparable to the AC system [23].

This work uses the system simulation methodology as well. Individual appliances are modelled in Matlab/Simulink/SimPowerSystems software. Complete DC and AC household models are then built using these appliances and the configurations are analyzed and compared.

2.4.3 Practical studies

Panguloori [29] did a laboratory demonstration to investigate the system efficiency aspect of a 380 V DC grid. He built a test setup for an office application to power a 2 kW lighting load with solar power and the results show that over 7 % improvements in solar power path efficiency are possible in DC distribution over the standard AC distribution. Makarabbi [32] did a compatibility and performance study of home appliances in a DC home distribution system. He analyzed the operation of a mixer/grinder, induction cooker, and electronic loads by monitoring the circuit behavior when supplied with AC and DC. 220 V DC was used to supply the appliances with no or minor modification to the device. The appliances were tested so that they kept the same performance as when supplied with AC. The study concluded that if the appliances are supplied with DC, the system has decreased power loss in standby mode and that less conversion and inversion stages are necessary in the DC system. Makarabbi mentions that renewable energy sources can be utilized better by adopting a 220 V DC system to supply DC appliances [32].

2.5 Inadequacies of previous work

Overall, the data and statistics studies look at things from a more generalized point of view. There are basically three values that the statistical method is most interested in; the peak daily power, the amount of energy used in a year, and the efficiency values of power electronic devices available on the commercial market. However, layers of assumptions are made in the way the peak daily power and the amount of energy used in a year is obtained, and these assumed values are then transposed onto individual appliances in the DC system in order to make a comparison. Great emphasis is put on lumped and estimated values that are given by the manufactures or measured data. The use of statistics for these applications then becomes somewhat misleading and can lead to wrongful conclusions. This approach is also not technically detailed enough to make big claims and the more detailed operations of the circuits are not considered.

The studies that use only low DC voltages and where the high powered appliances in a household are also supplied with low DC voltages are not practical as there are some constraints and difficulties with such a system. In these cases, the high powered appliances can only be placed near the power source in order to minimize cable sizes or the appliances can be placed far away but with unnecessarily big cables to supply them. In some cases, the use of high powered appliances is avoided entirely.

Studies that take the top-down approach for selecting the voltage levels for their loads are also not looking into greater detail. It is better to look at the loads first and what voltage levels the loads require otherwise important factors are overlooked such as how much power the device actually use in reality. This can also lead to an over-design of the DC system where the use of extremely high voltages is not really necessary.

There are also studies that lump all the household loads into generalized groups or bulk loads and are not appliance specific. It is difficult to analyze the performance and efficiency of a household electrical system from an individual appliance point of view when all the appliances are lumped together. An important aspect to look at when designing a household grid with appliances is to look at the system behavior when high powered loads and low powered loads are connected on the same circuit. This is mainly from a switching point of view.

Chapter 3
Methodology and Approach

3.1 Introduction

In this chapter, the methodology and approach to the research problem is introduced and explained in detail. A complete overview of the research design is given, and is then followed by the selection of the major research components. The last section in this chapter is an explanation of other configurations which will be looked at in the study as well.

3.2 Research design

Today, electronic appliances comprise a large portion of the total appliance base in a household. Everything ranging from televisions, DVD players, computers and lighting (LED) are DC-internal loads, and operate at a low DC voltage. In the current electrical supply, these electronic loads needs to have a rectification stage and some filtering at the input in order to give the correct DC supply to the core internals of the device. Depending on the type of rectifier used and the relevant filter circuits, this process causes power conversion loss in the supply system, and the bigger the appliance power, the bigger the losses. This problem is especially noticeable with on-site small-scale renewable energy generation, where the output of the PV panels and/or batteries is DC that then needs to be inverted and connected to the AC network in the house. From this, several questions arise such as; can all the appliances in a household be supplied directly with DC? Does the renewable DC supply have to be inverted to AC? At what DC voltage will the appliances be supplied?

This study will focus on the electrical supply of a single-standing house of medium income level with common household appliances available on the market in South Africa. With the growing popularity of local large-scale DC-based microgrids, the supply to the house will be assumed to be a firm DC supply. As for the loads in the DC system, the approach will look at a wide range of common household appliances of all sizes and functionalities and see what type of electrical supply these appliances actually operate on. This method is known as the bottom-up approach where the appliances are first investigated and then a suitable supply is chosen based on the appliance needs. This is contrary to the top-down approach where the main focus is the supply voltage of the system, and all the loads are being designed to be connected to that specific supply voltage. By using local information such as that obtained from the smart living handbook [40], a list of “everyday use” household appliances is identified and their actual power usages are recorded.

An Efergy® energy consumption meter is used to get practical and realistic power use figures for the appliances and these values are then used in the study. The energy meter, however, measures the input power of the appliances connected to an AC supply, and it is desired to have knowledge of the output power of the appliance for further study. In order to get a value which more or less presents the output power of the device, efficiencies of the supply circuit components are obtained and the output power is calculated. Typical efficiency values of the supply circuit components from the study done by Park [19] are used. The calculated output powers do not have to be 100 % accurate, it is just to get an output figure to work with. A suitable supply voltage is then obtained and the value is based on the investigation done on the appliances internals. The appliances are then designed and modelled in a simulation environment. Matlab and Simulink software are used in this study as explained in the next section. Finally, all the appliance models are integrated into one complete DC circuit and simulated together. This DC system is also compared to other configurations such as an AC/DC hybrid system and the existing AC system in order to measure the performance of the DC system.

The study method chosen is reliable and valid because the appliance circuit models used in the simulation is designed theoretically using engineering principles. The results from a simulation study are usually very close to the practical real world scenario, especially in the engineering environment.

3.3 Research instruments

Matlab/Simulink/SimPowerSystems software is used for the modelling and simulations of the loads under different configurations. Matlab/Simulink software is used in this work because it is a very powerful tool that can be used to model basically any complex engineering system [13]. It has the ability to simulate circuits with advanced complexity and in numerous different ways. The software provides many basic components that can be used to build more complex models and configurations. It is also possible to create models for equipment that do not exist in the standard libraries of other simulation software.

An Efergy® energy consumption meter is used to obtain actual appliance power consumption data.

3.4 Selection of research components

The two major components of this study are the selection of appliances and the selection of a suitable DC supply voltage(s). These components form the basis for the rest of the study and will eventually influence the end results and the overall outcome of the study.

3.4.1 Appliances

A household mainly consists of various electronic devices, heating loads, lamps and appliances containing motors. According to the Census report of 2011, the most common household appliances used in South Africa today are cell phones, radios, computers, refrigerators, and televisions [41], [42]. These, along with other common household appliances available on the market are used to model the loads. The appliances chosen for the study are shown in Table 3-1. The input power was practically measured using an Efergy® energy consumption meter for smaller appliances, and a clamp-on CT with a multi-meter for the bigger appliances. The power was measured with the appliances connected to an AC supply.

Table 3-1: List of household appliances used in the study

Appliance	**Type of load**	**Input Power (W)**	**Voltage requirement (core parts)**
Television	Electronic	45	20 Vdc
Computer	Electronic	65	20 Vdc
DVD player	Electronic	11	12 Vdc
Refrigerator	Motor	165	230 Vac (variable frequency)
Microwave Oven	Electronic	850	5600 V DC
Vacuum cleaner	Motor	1200	± 230 V AC or DC
TV Decoder	Electronic	28	12 Vdc
Radio	Electronic	12	12 Vdc
Lights (LED)	Electronic	100 (total)	24 Vdc
Cell charger	Electronic	9	5 Vdc
Washing machine	Motor	345	230 Vac (variable frequency)
Geyser	Heating (resistive)	2600	± 230 V AC or DC
Stove	Heating (resistive)	3000	± 230 V AC or DC
Kettle	Heating (resistive)	1900	± 230 V AC or DC

The television, computer and other consumer electronic appliances are normal electronic loads that operate with a low DC voltage internally. A low DC voltage is obtained from the output of a switch-mode-power-supply (SMPS). These devices are therefore well suited for a direct-DC supply. LED lighting is used because it has higher efficacy levels than CFL lamps, especially at lower power levels [20], and can be supplied with DC directly. The light-emitted-diode is in essence a DC circuit component. The refrigerator and washing machine chosen for this study are based on the modern inverter technologies. In the supply circuit of the inverter-motor, the incoming 325 Vac (peak), 50 Hz supply is rectified to around 325 V DC and then inverted back to AC. The inverter supplies variable frequency AC to the motor and is then able to control the speed of the motor [43]. This circuit is called a voltage source inverter (VSI) or an AC/DC/AC (dc-link) converter and is shown in Figure 3.1. The refrigerator and washing machine also have peripheral circuitry such as controls and/or a small fan.

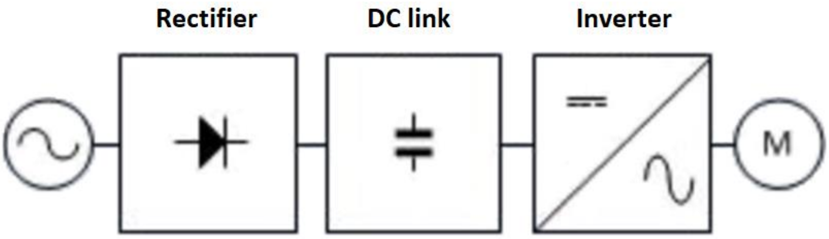


Figure 3.1: Voltage Source Inverter (VSI) for the supply of variable frequency drives

The microwave oven is a high-voltage load and consists of a magnetron tube, a small DC exhaust fan and a control circuit. The magnetron is supplied by a voltage-doubler circuit with an output voltage of 5600 V DC [44]. The high-power appliances chosen are the stove, geyser, kettle and vacuum cleaner. The stove, geyser and kettle are resistive loads and their core function is heating. Heating loads are purely resistive and can operate well on a DC voltage. The vacuum cleaner chosen for the study contains a universal motor and can be supplied with either AC or DC. A high-speed universal motor usually also has a small lagging power factor because it is an RL load. The high-power appliances, unlike the electronic and motor loads, do not contain any power conversion stages in their supply circuits.

Figure 3.2: Energy consumption meter used for plug-in appliances

Table 3-1 shows the input power of the appliances. In order to get approximate output power values to model the appliances with, the efficiency values of the relevant power converters in the devices had to be obtained. These values are based on the typical efficiency of the relevant power converters or rectifiers available on the market [19]. The Efficiency of a circuit containing multiple conversion stages can be given by

$$\eta_{\text{string}} = \eta_{\text{conv1}} \times \eta_{\text{conv2}} \times \eta_{\text{conv3}} \tag{3-1}$$

And with this, the ultimate output power can then be calculated using

$$P_{\text{out}} = P_{\text{in}} \times \eta_{\text{string}} \tag{3-2}$$

It is not that important to get the output power 100 % correct, the purpose of this is to get an approximate figure for the output power in order to model the appliances. The input power cannot be used to model the appliance because the input power in the simulation model will be too high and not realistic. Table 3-2 shows the typical efficiency values of the power conversion stages present in the appliances.

Table 3-2: Typical efficiencies of supply circuit components [19]

Device	**Proportion of load (%)**	**Supply stages**	**Typical string efficiency (%)**	**Calculated output power (W)**
Electronic devices	-	F → R → DC/dc[a,b]	83	33[f]
Compressor motor (Fridge)	75	F → R → I → M[c,d]	87	106
Evaporator Fan (Fridge)	12	None	-	6
Fridge controls	13	F → R → DC/dc	83	15.4
Motor (Washing M.)	80	F → R → I → M	87	238.9
Washing M. controls	20	F → R → DC/dc	83	50.7
Magnetron (Micro W.)	95	F → VD[e]	89	708
Micro W. Exhaust Fan + Controls	5	F → R → DC/dc	83	35.4

[a] F – Filter
[b] R – Rectifier
[c] I – Inverter
[d] M – Motor
[e] VD – Voltage Doubler
[f] Calculated output power of the television

3.4.2 System voltage

The other key aspect of the study is to find a suitable supply voltage for the DC system. The determination of voltage levels has already been discussed in detail in section 2.3.1 of the literature review, and the nature of both low-voltage and high-voltage systems are known.

Due to the nature of the high-power loads in the system, it will not be possible to use only a low-voltage such as 48 V. If this is the case, there will be very large currents present in the system with large heat and power losses in the cables. Considerably bigger cable sizes can be used but this will drive up the installation cost of the system. Looking at the RES supply, it would be ideal to supply the electronic loads in the system directly with the DC output from the RES system. For example, if the RES supply output is 48 V DC, then this can be delivered to the load directly without any conversion stages. This would have been possible if all the electronic devices operated on 48 V DC, however as can be seen in Table 3-1, the electronic devices do not all operate on the same voltage. The devices can be modified to all operate on 48 V DC, but the modification of appliances is not part of the scope of this study. This means that there needs to be a conversion stage between the supply and the device in order to get the device operating voltage and as mentioned earlier, this leads to inefficiency.

Another aspect regarding the RES supply voltage is the refrigerator load. The refrigerator forms part of the crucial loads which needs to be supplied by the RES when there is a loss of the main supply. The refrigerator operates on a 230 V AC supply and cannot be supplied with a low-voltage without a power supply conversion. There are DC-based refrigerators available on the market which is designed for low-voltage leisure applications but, for a DC-based refrigerator equivalent to the size of a normal household refrigerator, the difference in cost is quite significant [26].

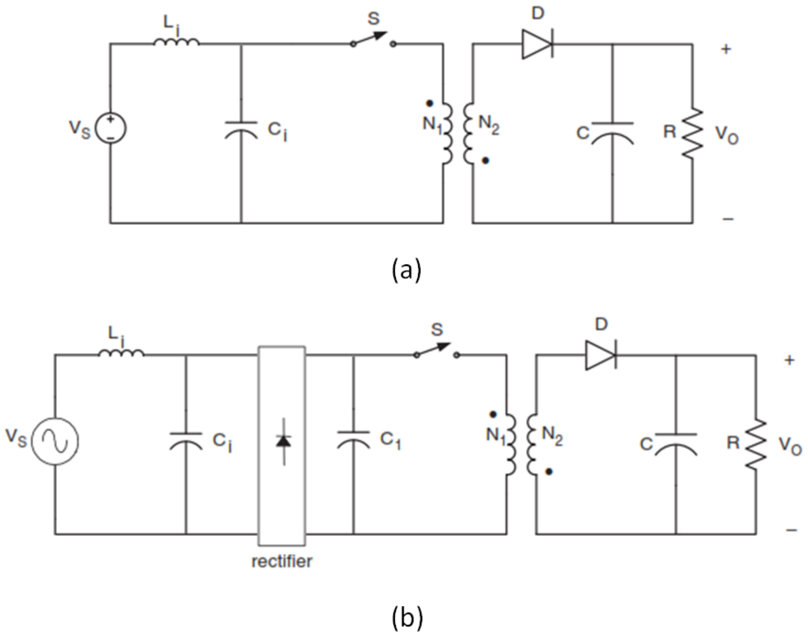
The motors used in the refrigerator and the washing machine are rated at 230 V rms. In an AC system, the motors are supplied by means of the VSI mentioned earlier. The DC-link in Figure 3.1 is at 325 V DC, and this is the voltage which is used for this study. The inverter-motors can be supplied directly, without having to replace the motors, and this also keeps to the rule of not modifying the core internals of the appliances. This high voltage is suitable for the high-power loads and is even better accommodating to the heating loads because there will be less current flowing in the conductors. The stove, kettle and geyser will be able to handle the slightly higher voltage. The only appliance which might have an issue with the higher voltage is the vacuum cleaner. The windings of the universal motor are rated at 230 V rms, however there are motors of the same size available with higher voltage ratings. There are DC vacuum cleaners available for household use but these are very expensive, and the universal type is still the most prevalent. For the electronic devices, the SMPS can be designed for a higher input voltage without affecting the load. There are many DC-DC converters available that can do this.

3.5 Configurations for comparison

The efficiency performance of this complete DC system will be compared to other configurations such as the existing AC system and an AC/DC hybrid system. The exact same appliances will be used in all three systems; the only difference will be in the supply input stages of the devices. Each system will have a main supply and a RES supply.

3.5.1 Existing AC system

The first configuration is the existing AC system as found in all residential installations in South Africa. This configuration will facilitate a direct-comparison between the AC and DC systems. The same appliances are used in the AC system, as in the DC system, however with rectification present in the electronic devices. For example, Figure 3.3 (a) shows a Flyback converter connected to a DC supply and (b) connection to an AC supply. This is done for all the equipment that requires AC-DC rectification, such as the electronic devices, control circuitry and voltage source inverters.



(a)

(b)

Figure 3.3: Flyback converter for (a) DC connection and (b) AC connection

3.5.2 AC/DC hybrid system

The hybrid system will be designed to be connected to an AC supply, like normal. In this system, all the appliances that contain conversion stages in their supply circuits are supplied with 325 V DC. These include all the electronic loads, refrigerator and washing machine. The high-power appliances such as the geyser, stove, kettle, vacuum cleaner and microwave oven are supplied with AC. In order to get a bulk DC supply from the AC grid; a grid-rectifier needs to be designed which can deliver the 325 V DC to the electronic loads.

Chapter 4
Simulation Design

4.1 Introduction

This chapter deals with the simulation design of all the system configurations which are investigated in this study. Every individual circuit component which ultimately forms part of the complete DC system is designed and its operation explained in detail. These individual circuit components are then integrated into a complete system. This is done for the three system configurations investigated in this study: (a) direct DC system, (b) existing AC system and (c) AC/DC hybrid system. Chapter 5 follows with in-depth analysis of the simulation results of the circuits designed in this chapter.

4.2 Design of system components

The design of system components forms the core part of this work. In this section, all the appliances with their main and peripheral components are designed, along with the renewable energy supply converter. These are all then incorporated into one circuit in order to simulate a complete household DC system. The complete DC system is designed with appropriate cable sizes and the setup is designed in such a way that individual appliances can be switched in and out of the circuit. The switching is done manually.

4.2.1 Appliance designs

4.2.1.1 Electronic loads

Flyback converters are used to model the electronic loads. The Flyback converter is a switched-mode-power-supply (SMPS) which can be utilised to supply common household electronic devices of 100 W or less [45]. There are many types of SMPS available but the Flyback converter is the most suitable because of fewer components in the design, as compared to similar isolated topologies such as the Cùk or the Zeta converter [45]. Figure 4.1 shows a basic circuit diagram of the Flyback converter.

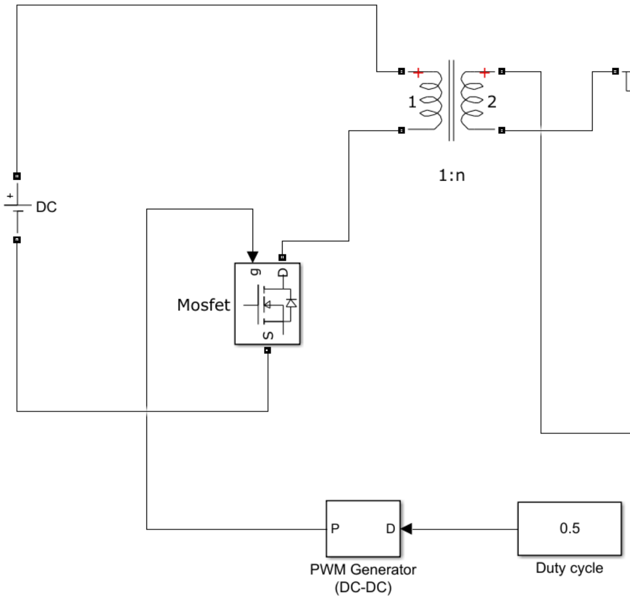


Figure 4.1: Basic Flyback converter

The Flyback converter is a practical isolated version of the buck-boost converter, where the inductor of the buck-boost converter has been replaced by a Flyback transformer. The source and the switch are connected is series with the primary of the transformer and the diode and RC output circuit are connected in series with the secondary of the transformer. The transformer contains the magnetizing inductance, L_{mb}, and the transformer has a turns ratio of $n = N_1/N_2$. When the switch is on, the current in the magnetizing inductor increases linearly. The diode is now off and there is no current flowing through the transformer windings. When the switch is off, the magnetizing inductor current is diverted into the transformer, the diode turns on, and the transformed magnetizing inductance current is supplied to the RC output (load). The DC voltage transfer function of the converter is given by

$$\mathrm{M_V} = \frac{\mathrm{V_O}}{\mathrm{V_S}} = \frac{D}{\mathrm{n}(1-D)} \tag{4-1}$$

The Flyback converter can be designed for operation in either discontinuous conduction mode (DCM) or continuous conduction mode (CCM). All the Flyback converters in this study are designed to operate in DCM. The value of the magnetizing inductance determines the boundary between DCM and CCM operation and is given by

$$\mathrm{L_{mb}} = \frac{\mathrm{n}^2(1-D)^2\mathrm{R}}{2f} \tag{4-2}$$

For the converter to operate in DCM, the chosen value of the magnetizing inductance should be less than the value obtained from Equation (4-2). This is called the critical inductance. The value of the filter capacitance at the output can be calculated using

$$C_{\min} = \frac{DV_O}{V_r R f} \tag{4-3}$$

The input current of the Flyback converter is not a smooth DC current such as that at the output. It has large current ripples in the waveform due to the switching action of the MOSFET and that makes it difficult to measure the value of the input current. There is then the need to filter out the current spikes using a low-pass LC filter, designed specifically for the converter. The filter is placed at the input of each of the Flyback converters in the study. Figure 4.2 shows the circuit diagram of the low-pass filter.

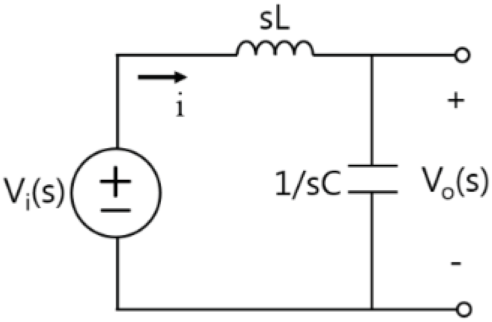


Figure 4.2: Low-pass LC filter circuit for input of converters

The filter components can be calculated using equation (4-4), where f_o is the cut-off frequency, which is chosen as 10 % of the switching frequency.

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{4-4}$$

Figure 4.3 shows the Flyback converter with the low-pass filter connected at the supply input. The switching of the converter and the regulation of the output voltage is done using the open-loop voltage control method. The duty cycle is adjusted manually until the correct output voltage is obtained. In this case, a constant block (with value of duty cycle) is put at the input of the PWM generator so that the duty cycle of the MOSFET can be adjusted by either increasing or decreasing the value in the constant block. Practical switch-mode-power-supplies make use of closed-loop voltage control, where there is a constant feedback loop between the supply voltage and the output voltage. However, for simplicity, the converters in this work are designed with open-loop control. The study will not look at load variation at the output or voltage disturbances at the input so open-loop control is sufficient.

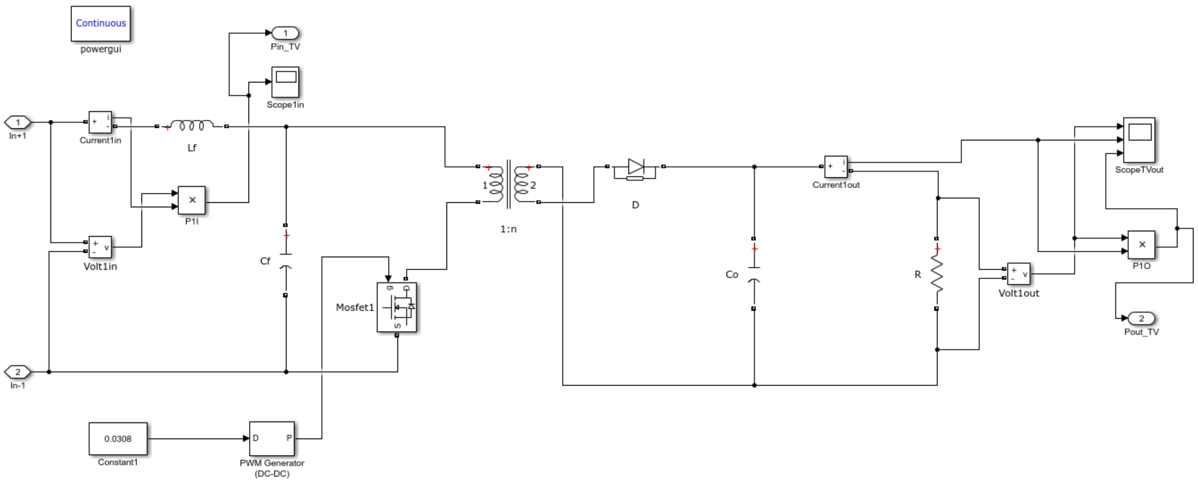


Figure 4.3: Flyback converter for electronic loads

It is also very important to check the efficiency of each of the designed converters, because that will determine the overall efficiency of the complete DC system. A Simulink wattmeter model (Figure 4.4) was created for this purpose. At both the input and output of the converter, the voltage and current is measured and sent to a product block where either the input power or output power is calculated. This simple wattmeter is however only used for the electronic loads, which are resistive. Built in Simulink power measurement tools are used in the systems where reactive power is present, such as in the inverter-motor loads.

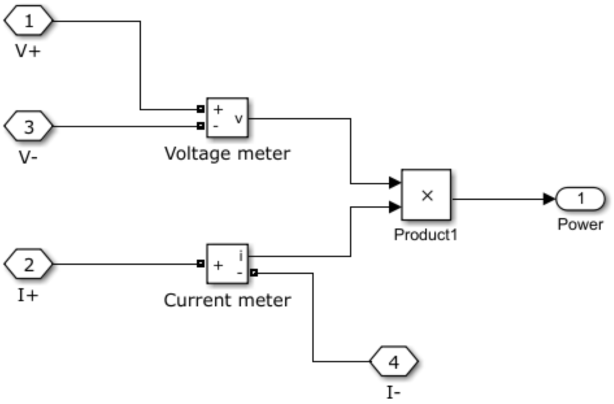


Figure 4.4: Wattmeter to measure input and output of converters

Table 4-1 shows the design parameters of a Flyback converter which is used to supply the television load. All the electronic loads in the study are modelledmodelled as Flyback converters. The converters are designed for different output power and voltage applications; it is only the input voltage to the converter that is the same in all cases.

Table 4-1: Design parameters of Flyback converter

Parameters	Design values
Input voltage (Vi)	325 V
Output voltage (Vo)	20 V
Output power (Po)	33 W
Transformer ratio (n)	0.5
Switching frequency (Fs)	45 kHz
Magnetizing inductance (Lmb)	31.2 µH
Output capacitance (Co)	291.31 µF
Load resistance (R)	12.12 Ω
Input inductance (Lf)	5 mH
Input capacitance (Cf)	0.25 µF

4.2.1.2 Refrigerator

A domestic refrigerator usually consists of three major parts, each with its own circuit. The largest component of the refrigerator is the compressor which is powered by an AC induction motor. The other two smaller parts are the evaporator fan and the control circuitry. The evaporator fan is also an AC motor but of much smaller power rating than the compressor motor. The controls are a small electronic load which controls the on and off switching cycles of the compressor and the evaporator fan. The compressor motor is supplied via a two-level SPWM sine wave inverter because the motor needs to have variable frequency control for adjusting the speed. In this study however, the speed control of the motor is irrelevant and the motor is modelled to run at full-load constant speed. Figure 4.6 shows the circuit diagram of the inverter with a RL load which represents the motor load.

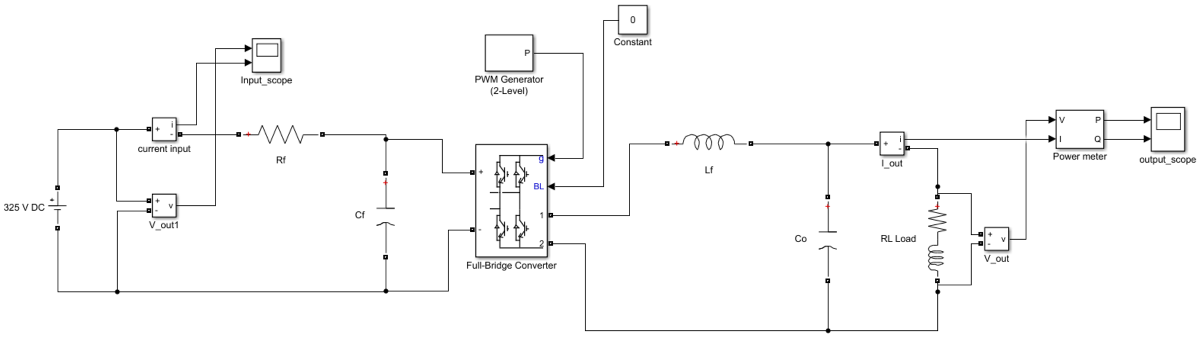


Figure 4.5: Inverter to supply the compressor motor

The principle of sinusoidal pulse width modulation is explained using Figure 4.6 and Figure 4.7.

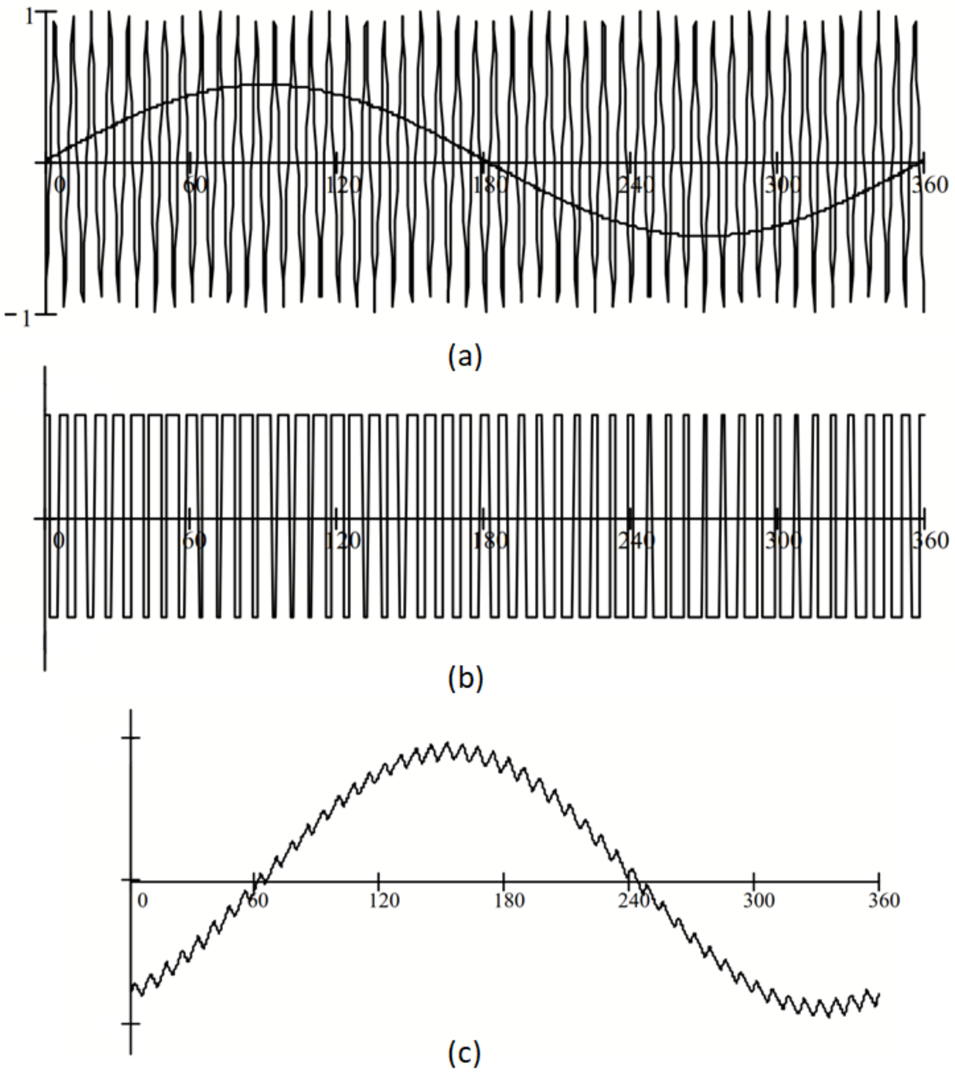


Figure 4.6: Principle of SPWM (a) with carrier and sine wave (b) output voltage (c) output current of inverter

In Figure 4.6 (a), the modulating signal is the sinusoidal waveform of amplitude f_m and the triangular carrier waveform of amplitude f_c and the ratio between these two is known as the modulation index, m, given by equation (4-5).

$$\mathrm{m} = \frac{f_c}{f_m} \tag{4-5}$$

The output voltage of the inverter contains large harmonics due to the switching of the inverter [46]. Figure 4.7 may be used to explain the output voltage waveform in more detail.

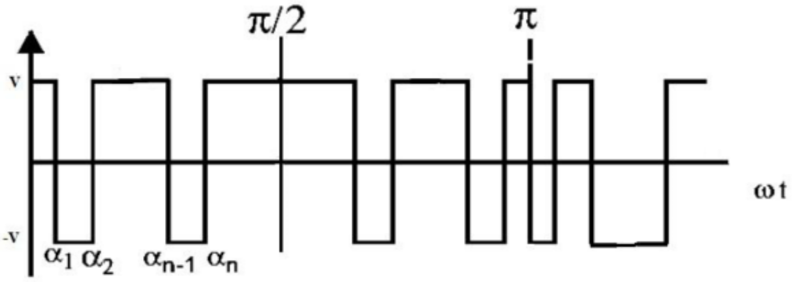


Figure 4.7: Two-level PWM waveform with odd and half-wave symmetry

In a two-level PWM inverter with a modulation index of 1, only odd harmonics are present [46]. Even harmonics are filtered out due to the half-wave symmetry of the waveform. So with a two-level inverter with odd and half-wave symmetries and *n* chops per quarter cycle as shown in Figure 4.7, the peak magnitude of harmonic components (h_k) which includes the fundamental frequency of 50 Hz is given by

$$h_1 = \left(4\frac{V}{\pi}\right)[1 - 2\cos \propto_1 + 2\cos \propto_2 - 2\cos \propto_3 \ldots 2\cos \propto_n] \tag{4-6}$$

$$h_3 = \left(4\frac{V}{3\pi}\right)[1 - 2\cos 3 \propto_1 + 2\cos 3 \propto_2 - 2\cos 3 \propto_3 \ldots 2\cos 3 \propto_n] \tag{4-7}$$

$$h_\mathrm{n} = \left(4\frac{V}{n\pi}\right)[1 - 2n\cos \propto_1 + 2n\cos \propto_2 - 2n\cos \propto_3 \ldots 2n\cos \propto_n] \tag{4-8}$$

Ultimately, the Fourier Cosine and Sine coefficients for a periodic waveform with period 2π is given by

$$a_0 = \frac{1}{2\pi}\int_0^{2\pi} f(\theta)d\theta \tag{4-9}$$

$$a_k = \frac{1}{\pi}\int_0^{2\pi} f(k\theta)\cos(k\theta)\,d\theta \tag{4-10}$$

$$b_k = \frac{1}{\pi}\int_0^{2\pi} f(k\theta)\sin(k\theta)\,d\theta \tag{4-11}$$

These harmonics can be eliminated by means of a method called selective harmonic elimination, where only selected harmonics are eliminated with the smallest number of switching [46]. This method however can be difficult to implement due to the nature of the load of the inverter. In this study, a low-pass filter is used to get rid of the harmonics in the output voltage.

The inverter is designed for a lagging power factor of 0.8 and an output power of 106 W. The load current is calculated using the relation between the rms voltage and apparent power, and is given by Equation (4-12). The load impedance is then calculated, and separate values for the resistance and inductance obtained

$$\mathrm{I_{rms}} = \frac{\mathrm{S}}{\mathrm{V_{rms}}} \tag{4-12}$$

The output LC filter components are calculated using equations (4-4) and (4-13). The impedance ratio of the filter components are calculated based on a small percentage of the load impedance, and this ratio is maintained when calculating the values of L and C.

$$\mathrm{Z} = \sqrt{\frac{\mathrm{L}}{\mathrm{C}}} \tag{4-13}$$

The input current of the inverter has very large current spike if a filter circuit is absent. A RC filter is designed for the input in order to smooth out the current ripple. The time the current takes to smooth out is basically the charging time constant of the RC circuit. A 1 ohm resistor is placed in series with the DC supply in order to create a charging voltage across the capacitor. The current then tends to take on the shape of the voltage, creating a smoother, measurable DC waveform. The size of the capacitor can be calculated using equation (4-14), where *i* is the current trough the capacitor and the change in voltage is the voltage ripple across the capacitor.

$$i = \mathrm{C}\frac{\mathrm{dV}}{\mathrm{dt}} \tag{4-14}$$

Finally, the efficiency of the inverter can be calculated using

$$\eta_{\mathrm{inverter}} = \frac{\mathrm{V_{rms}}\,\mathrm{I_{rms}}\cos\theta}{\mathrm{V_{dc}}\mathrm{I_{dc}}} \tag{4-15}$$

Table 4-2: Design parameters of the compressor motor

Parameters	Design values
Input voltage (Vi)	325 V
Output voltage (Vo)	230 V AC (rms)
Output power (Po)	106 W
Load resistance (Rl)	317.897 Ω
Load inductance (Ll)	758.92 mH
Power factor	0.8
Switching frequency	45 kHz
Load frequency	50 Hz
Input Filter resistance (Ri)	0.80287 Ω
Input Filter capacitance (Ci)	500 mF
Output Filter inductance (Lo)	5 mH
Output Filter capacitance (Co)	50 µF
Modulation index	1

The evaporator fan inverter is designed the same way as the compressor motor, only with a much smaller output power. It is necessary for the evaporator fan to be an AC motor as well, because it is crucial for the fan to be kept at a constant speed with no fluctuations. It is known that smaller low-power DC motors do not maintain a constant speed [47].

For the controls of the refrigerator, a buck converter is designed to step down the 325 V supply voltage to 24 V, which is the voltage the control circuitry is designed for. The buck converter has good output current characteristics and that makes it suitable to supply sensitive electronic loads [13]. The buck converter designed for the study is shown in Figure 4.8. The circuit consists of a DC input voltage source, a MOSFET, diode, filter inductor, filter capacitor and a load resistor.

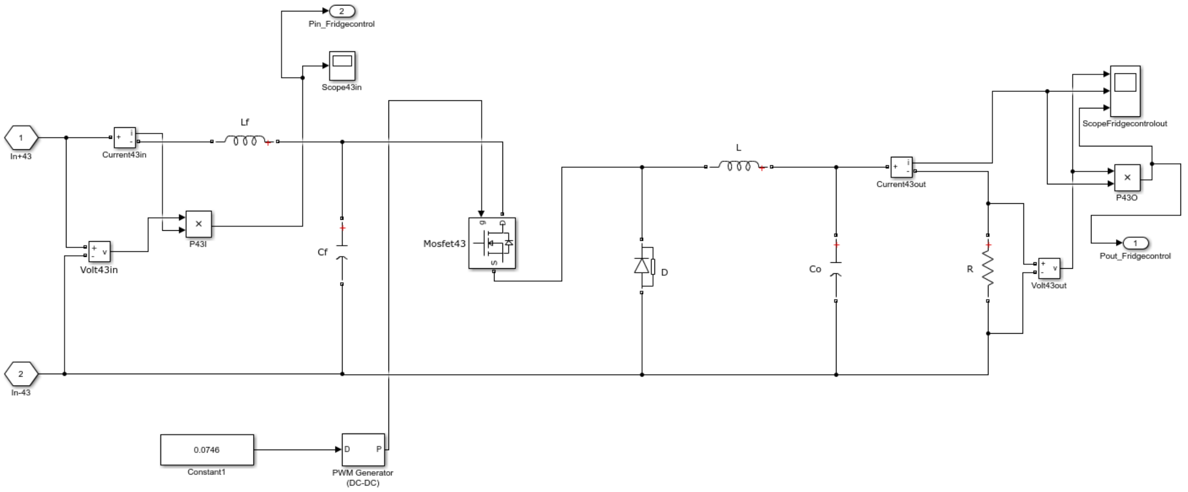


Figure 4.8: Buck converter supplying the control circuits of the refrigerator

The DC voltage transfer function, which is the ratio of the output voltage to the input voltage, is given by

$$M_V = \frac{V_O}{V_S} = D \qquad (4\text{-}16)$$

Unlike the Flyback converter, the Buck converter is designed to operate in CCM. The CCM is preferred for high efficiency and good utilization of semiconductor switches. For the Buck converter, the value of the filter inductance that determines the boundary between CCM and DCM is given by equation (4-17). The value of L_{mb} is chosen higher than the critical value given in the equation, in order to ensure the converter always operates in CCM.

$$L_{mb} = \frac{(1 - D)R}{2f} \qquad (4\text{-}17)$$

The current in the capacitor causes a small voltage ripple across the output voltage. To limit the peak-to-peak ripple voltage (V_r in equation) below a certain value, the filter capacitance is selected to be greater than

$$C_{min} = \frac{(1 - D)V_O}{8V_r L f^2} \qquad (4\text{-}18)$$

The Buck converter also has an input filter in order to smooth out the input current ripple. The control system used to give the gate signal to the switch is the open-loop control system, just like that of the Flyback converter. Table 4-3 shows the design parameters of the Buck converter for the supply of the refrigerator controls.

Table 4-3: Design parameters of Buck converter

Parameters (Buck)	**Design values**
Input voltage (Vi)	325 V
Output voltage (Vo)	24 V
Output power (Po)	15.44 W
Load resistance (R)	37.313 Ω
Switching frequency (Fs)	45 kHz
Magnetizing inductance (Lmb)	0.39 mH
Output capacitance (Co)	16 µF
Input filter inductance (Lf)	5 mH
Input filter capacitance (Cf)	0.25 µF

The compressor motor, evaporator fan and control circuit are all combined to form one circuit under the refrigerator subsystem, as shown in Figure 4.9.

The input powers of the three components are added together to get one input power value and the same is done for the output power. This makes it easier to calculate the efficiency of the whole refrigerator circuit.

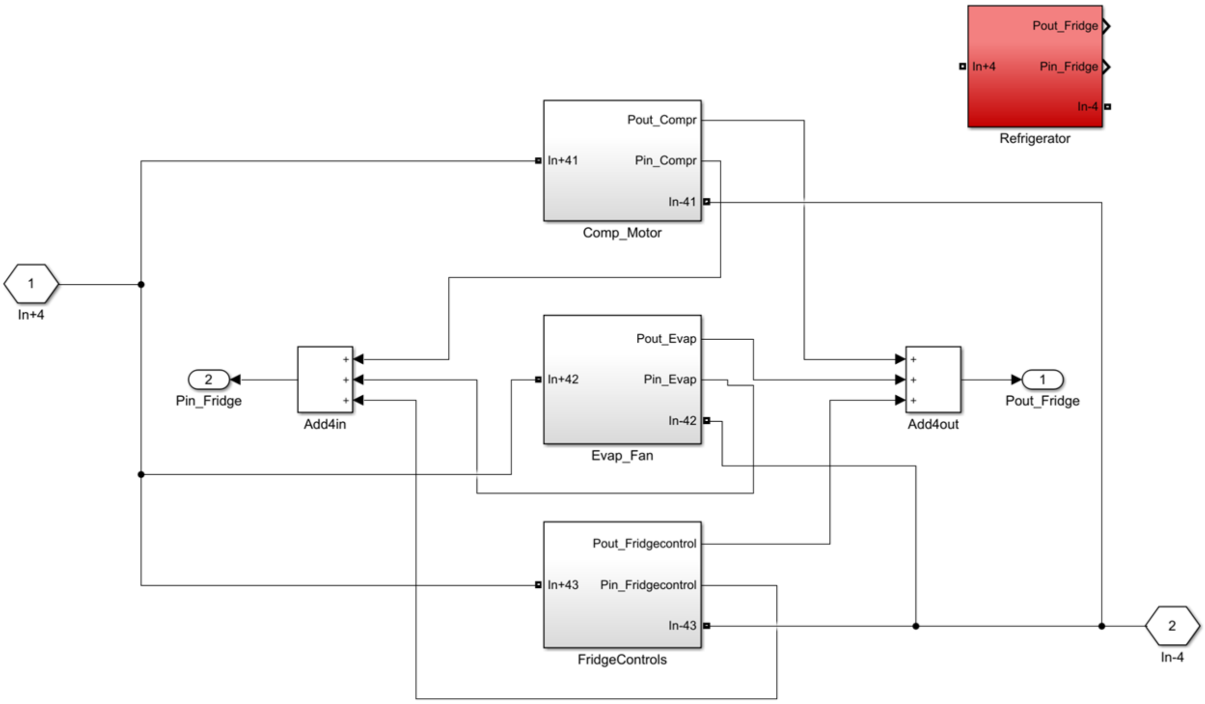


Figure 4.9: Combined refrigerator components

4.2.1.3 Washing Machine

The washing machine has more or less the same components as that of the refrigerator. The power rating of the motor in the washing machine is however slightly higher than that of the compressor motor in the refrigerator. The same inverter-motor load is designed for the washing machine, only with different circuit parameters. The design parameters for the AC induction motor load in the washing machine are shown in Table 4-4.

Table 4-4: Design parameters for washing machine inverter-motor

Parameters	Design values
Input voltage (Vi)	325 V
Output voltage (Vo)	230 V AC (rms)
Output power (Po)	299 W
Load resistance (Rl)	141.538 Ω
Load inductance (Ll)	337.898 mH
Power factor	0.8
Switching frequency	45 kHz
Load frequency	50 Hz
Input Filter resistance (Ri)	0.80287 Ω
Input Filter capacitance (Ci)	500 mF
Output Filter inductance (Lo)	5 mH
Output Filter capacitance (Co)	50 µF
Modulation index (Mi)	1

The controls of the washing machine are supplied by a Buck converter as well, just like the refrigerator. The Buck converter in this case is designed to provide an output power of 51 W at 24 V.

Table 4-5: Design parameters for buck (WM controls)

Parameters (Buck)	Design values
Input voltage (Vi)	325 V
Output voltage (Vo)	24 V
Output power (Po)	51 W
Load resistance (R)	11.294 Ω
Switching frequency (Fs)	45 kHz
Magnetizing inductance (Lmb)	0.12 mH
Output capacitance (Co)	48 µF
Input filter inductance (Lf)	5 mH
Input filter capacitance (Cf)	0.25 µF

Figure 4.10 shows the subsystem of the combined washing machine load components.

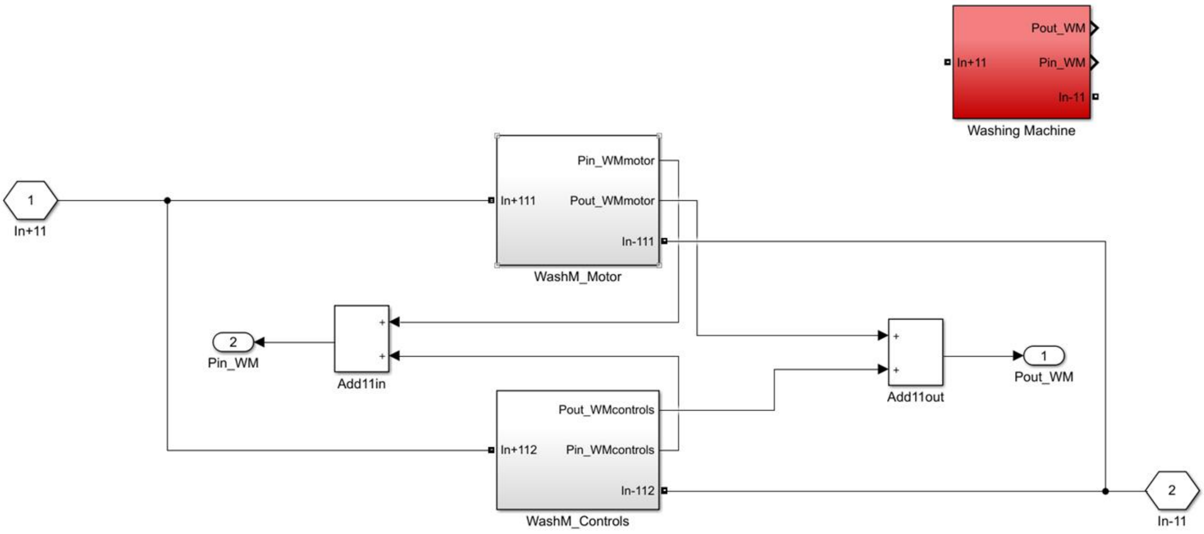


Figure 4.10: Combined load of the Washing Machine

4.2.1.4 Microwave Oven

The common microwave oven found in many households usually consists of three main parts; a cavity magnetron, an exhaust fan and the control circuitry. The cavity magnetron forms the main part of the microwave oven and contributes to about 95 % of the total appliance power consumption. In this study, the circuit of the low-power exhaust fan and the controls are combined as one load for simplicity. This combined load contributes to about 5 % of the total microwave oven load. The cavity magnetron is a high-powered vacuum tube that generates microwaves using the interaction of a stream of electrons with a magnetic field, while moving past a series of open metal cavities [48]. In the microwave oven, this high-power is supplied by a voltage doubler circuit. Figure 4.11 shows the voltage doubler circuit designed for this study. The circuit in this case has a DC input, as compared to the AC input normally associated with voltage doubler circuits.

The voltage doubler part of the circuit consists of two diodes, two capacitors, and an oscillating AC input voltage (in this case a PWM waveform with output filter). The diode-capacitor pump circuit gives a DC output voltage equal to the peak-to-peak value of the sinusoidal AC input. The output is double the peak voltage because the diodes and capacitors work together effectively to double the voltage. The output voltage can be written as $V_{out} = 2V_{in}$, the peak of the AC input voltage waveform. In this case, the transformer secondary winding is designed to give an output of 2800 V (peak) and the voltage doubler circuit then takes this value and converts it into 5600 V DC.

Voltage doubler circuits only tend to work well with a large resistance at the load and this is also the case in this study, because for the magnetron to give the correct output power, a 44 kΩ resistor is chosen. The circuit is also designed with an input filter to get rid of the switching harmonics caused by the inverter. Table 4-6 shows the design parameters of the voltage doubler circuit supplying the magnetron.

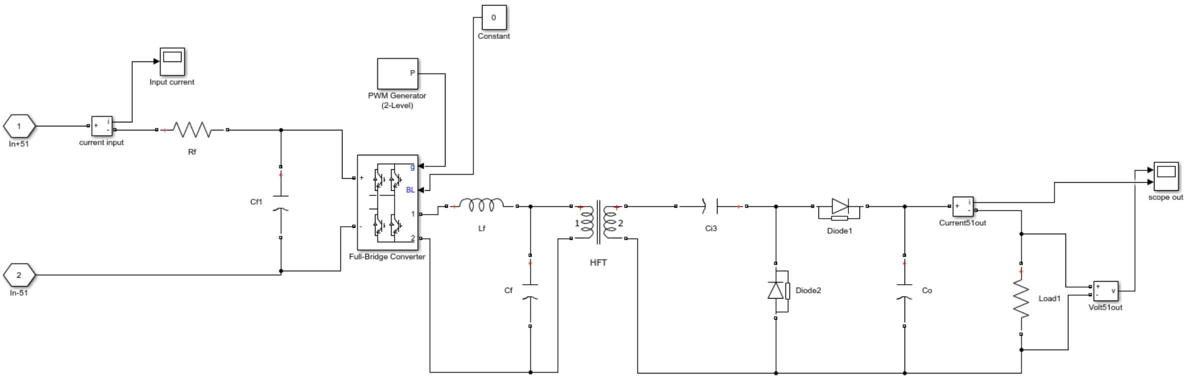


Figure 4.11: Voltage Doubler Circuit (VDC) for the supply of the magnetron in the microwave oven

Both the exhaust fan and the controls of the microwave operate at 24 V DC. A buck converter is designed to step down the DC supply voltage to the 24 Volts needed.

Table 4-6: Design parameters of the voltage doubler circuit

Parameters	**Design values**
Input voltage (Vi)	325 V
Output voltage (Vo)	5600 V
Output power (Po)	708 W
Load resistance (Rl)	44.29 kΩ
Output capacitances (Co1,Co2)	800 µF
Transformer power rating	1000 VA
Transformer winding ratio	1:10
Inverter output filter (Lf,Cf)	1.3 mH/3 µF
Input filter (Rfi,Cfi)	1 Ω/40 mF
Modulation index	1

The magnetron, along with the peripheral circuitry is combined into one circuit subsystem and is shown in Figure 4.12.

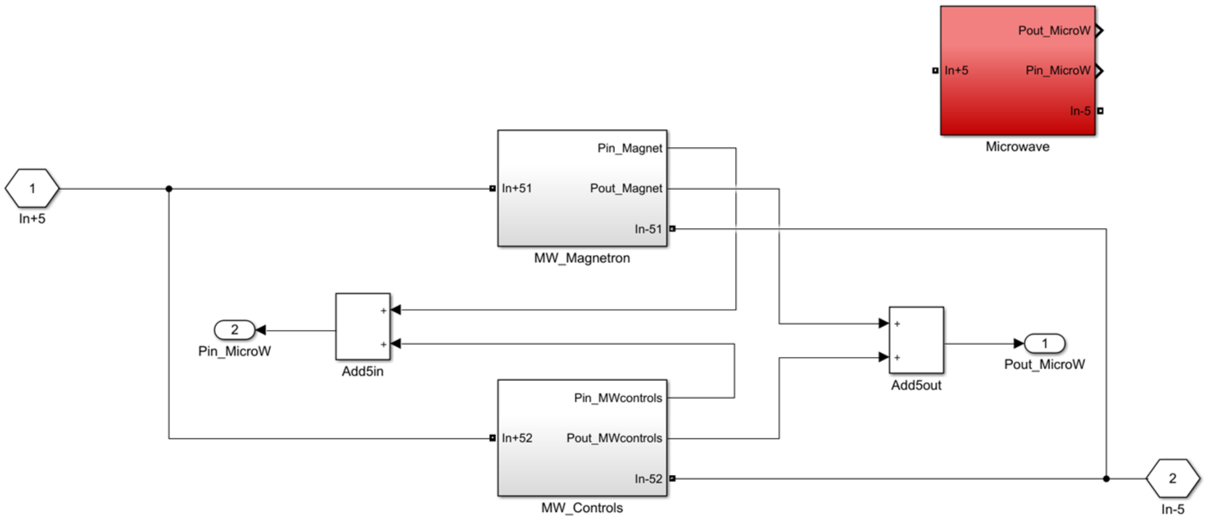


Figure 4.12: Combined microwave oven load

4.2.1.5 High-power loads

The high-power appliances such as the stove, geyser and kettle are modelled as pure resistive loads. These appliances do not contain any input supply circuit conversion stages and take the supply voltage as it is delivered. The core components of these appliances are heating elements which draw large currents. The core component of the vacuum cleaner is a high-speed universal motor which is essentially an RL load with a small power factor [49]. Table 4-7 shows the load characteristics of the high-power loads.

Table 4-7: Design parameters for high-power loads

Parameters	**Design values**			
	Stove	**Geyser**	**Kettle**	**Vacuum C.**
Input / Output voltage	325 V	325 V	325 V	325 V
Load Power	3000 W	2600 W	1900 W	1200 W
Load Current	9.23 A	8 A	5.85 A	3.69 A (pf = 0.94)

4.2.2 RES converter design

An isolated DC-DC step-up converter is used to represent the renewable energy supply converter. It is designed to supply the electronic loads and the refrigerator when the main supply is lost. This converter was chosen over the normal boost converter because the boost converter does not have a good output current characteristic [13]. The output of the RES is 48 V DC and this is then stepped up to 325 V DC because the refrigerator inverter operates at this voltage. The input voltage (output of RES supply) of 48 V was chosen because many battery connection configurations for household installations have an output of 48 V DC.

The 12 V solar panel batteries are arranged in series and parallel to get the needed ampere-hour ratings and the correct input supply voltage to the solar inverter. The RES converter designed for this study is shown in Figure 4.13. The circuit consists of an input RC filter, a DC-AC inverter, a high-frequency transformer, a diode bridge rectifier and a smoothing capacitor. The load resistor in the figure acts as the combined load of the RES loads.

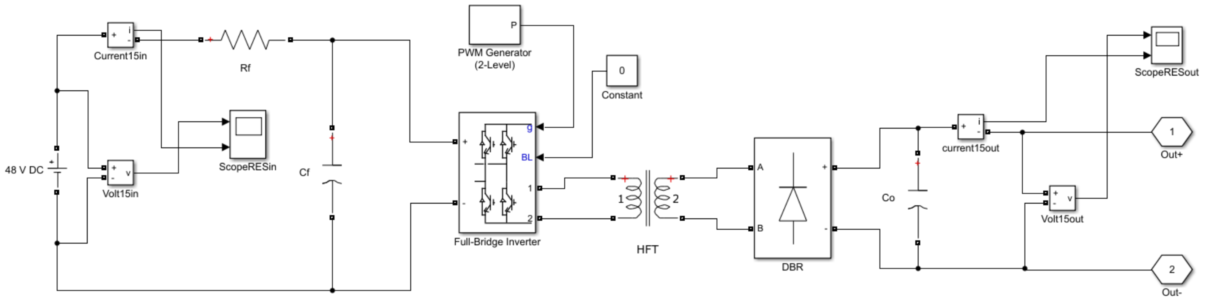


Figure 4.13: Full-Bridge Step-up DC-DC converter

In the circuit, the full-bridge inverter inverts the 48 V DC to 48 V AC and the high-frequency transformer then steps up the 48 V AC to 325 V AC. The high-frequency transformer is modelled as an ideal transformer and the voltage-to-winding ratio of an ideal transformer is given by

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \tag{4-19}$$

The diode bridge rectifier then converts the 325 V AC back to DC, and the DC voltage ripple is smoothed out using a smoothing capacitor across the output terminals of the rectifier. The size of the output smoothing capacitor is given as

$$C = \frac{V_{dc}}{2\, f\, R_L\, V_{RIP\,(p-p)}} \tag{4-20}$$

High-power-high-frequency transformers make this circuit topology possible and all the electronic loads as well as the refrigerator can be supplied from the on-site renewable energy supply. The converter is designed based on the sum of the input powers of the crucial loads, given in Table 4-8.

Table 4-8: Appliances supplied by RES system

Appliance	**Input power (W)**
Television	36.5
TV decoder	22.75
DVD player	9.5
PC (Laptop)	52
Radio	10.3
Cell charger	7.9
Lights (LED)	80
Refrigerator	145
Total input power	**364**

A small percentage of the total power being transmitted across a cable is lost due to cable resistance, and this in turn causes a small voltage drop [25]. This is called the wiring loss component of a circuit. The amount of power loss and the percentage voltage drop depends on the circuit parameters, cable size and cable distance. For a given cable resistance and current in a system, the power loss in the circuit is given by

$$P_{loss} = I^2R \tag{4-21}$$

The converter is then designed using the total input power of the crucial loads and a wiring loss component. The design parameters of the RES converter are shown in Table 4-9.

Table 4-9: Design parameters of the Full-Bridge Step-up DC-DC converter

Parameters	**Design values**
Input voltage (Vi)	48 V DC
Output voltage (Vo)	325 V DC
Output power (Po)	365 W
High-Frequency TRFR rating	500 VA
High-Frequency TRFR winding ratio	1:10
Input filter resistance (Rf)	1 Ω
Input filter capacitance (Cf)	1570 mF
Output capacitance (Co)	5.46 mF
Modulation index	1 (full-load)

4.2.3 The complete DC system

All the power converters and loads designed in the previous section are now incorporated into a single circuit, representing the total household electrical grid. The complete DC system layout is shown in Figure 4.14. The circuit has two supplies namely, main supply, which is the incoming 325 V DC from the micro-grid, and the RES supply, which is the on-site low-power renewable energy supply, stepped up to 325 V. In Figure 4.14, both supplies come into the main distribution board (DB) and connect to a common busbar at 325 V. On the outgoing of the DB, there are six wires going to the wall sockets and other single circuit appliances like the stove, geyser and lighting circuit. The appliances are divided up into the three supply sockets, namely branch 1, 2 and 3; where at each socket there is a combination of high-power and low-power appliances. The appliances are masked under the branch subsystems in Figure 4.14.

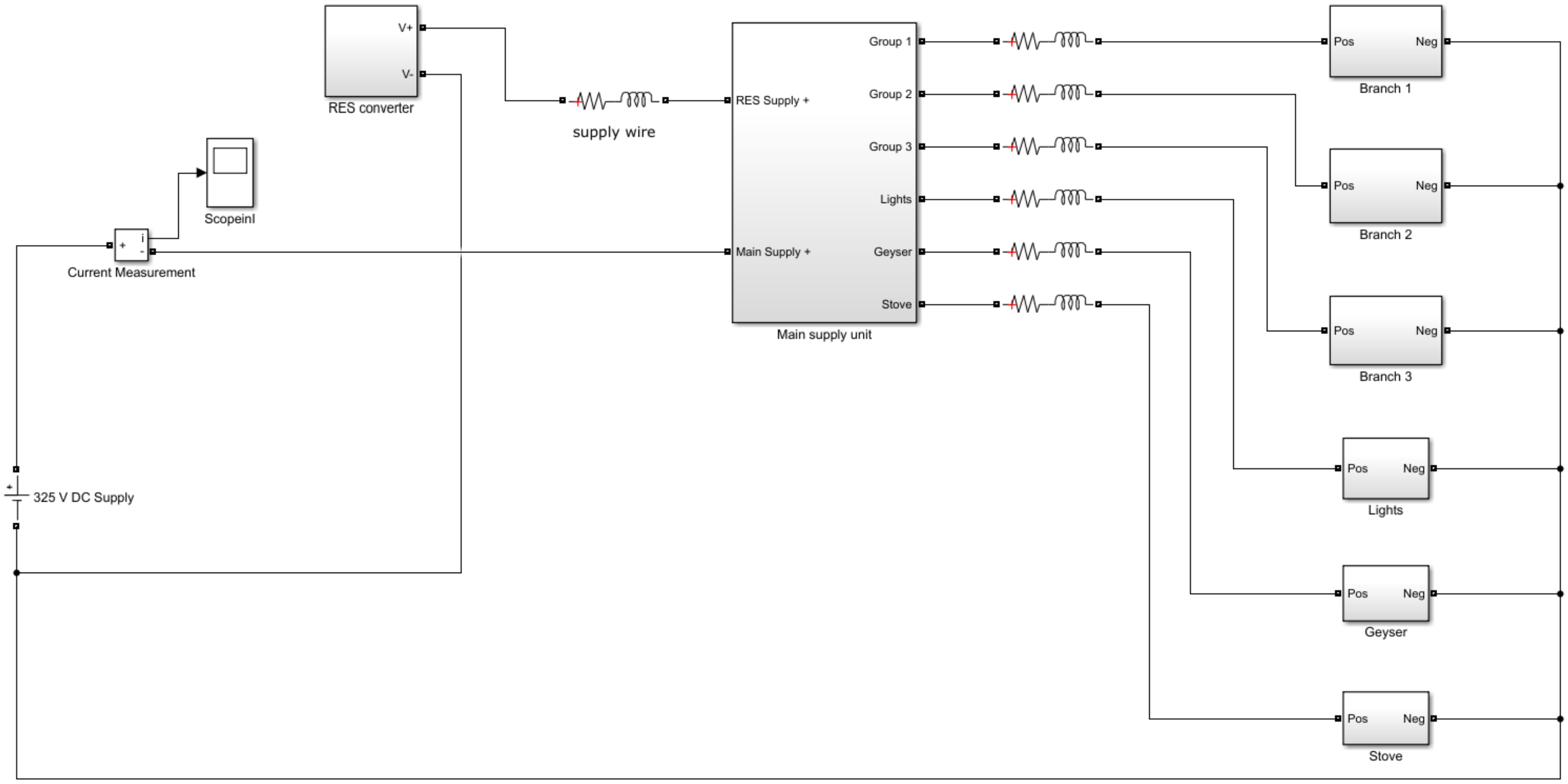


Figure 4.14: The complete DC system layout

Figure 4.15 shows the masked subsystem of the main distribution board. The positive of the main and RES supply comes in at the input ports and connects to a busbar. The outgoing circuits are then connected to the busbar and the supply goes to each one of the branches shown in Figure 4.14.

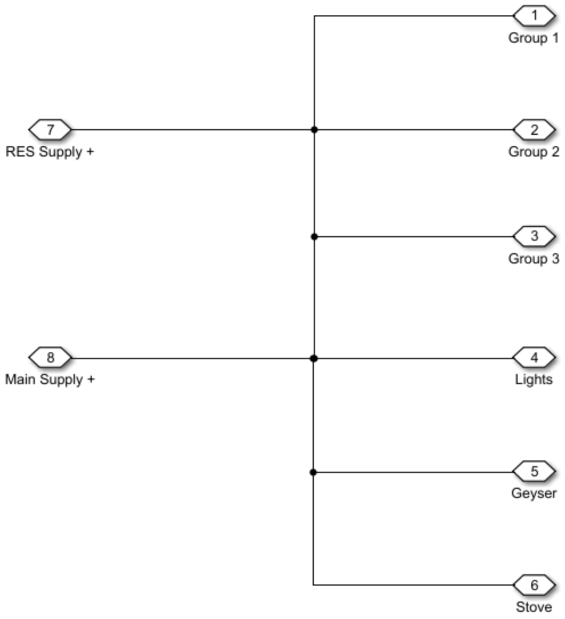


Figure 4.15: Subsystem of the main supply unit (DB)

It is also important to take into consideration the wire resistances and inductances of the cables when designing any electrical system. The standard wiring is used for the DC system as well because the aim is not to bring too much modification to the existing electrical infrastructure in the house. All the cables in the complete system in Figure 4.14 are made to be 30 meters long in order to simulate practical distances of supply to load. As mentioned in section 3.4.2, voltage drops in a 325 V system is not an issue and the power loss that is experienced in the cables does not affect the operation of the loads.

Table 4-10 shows the inductances and resistances of the cables used in the DC system. The cables are modelled with a small inductance because all cables have a natural internal inductance inherent in its design, although very small [50]. The motor loads will also push some reactive power into the DC system, which will circulate in the cables and to the supply. The effect if this will however not be seen because the inductive currents are significantly small.

Table 4-10: Inductance and resistance values for different core size cables [25]

Core size (mm^2)	Inductance (μH/m)	Resistance (Ω/m)
1.0	0.6224	0.0170
1.5	0.5757	0.0113
2.5	0.5170	0.0068
4.0	0.4595	0.0043
6.0	0.4070	0.0028
10	0.3354	0.0017

These values are used to calculate the wiring resistances and inductances of the cables over a 30 meter distance. The electrical characteristics of the different cable sizes are shown in Table 4-11.

Table 4-11: Electrical characteristics of different cable diameters at 30 m distance

	Load (W)	Current (A)	Cable size (mm^2)	Ampacity (A)	Inductance (H)	Resistance (Ω)
Branches	4000	12.31	2.5	17.5	0.5170	0.0068
Lights	100	0.308	1.5	13.5	0.5757	0.0113
RES supply	500	1.54	1.5	13.5	0.5757	0.0113
Stove	3000	9.23	4.0	25	0.4595	0.0043
Geyser	2600	8	4.0	25	0.4595	0.0043

The branch cable is connected to the input of the branch subsystems which contains the appliances. As mentioned earlier, each branch contains high-power and low-power appliances to evenly distribute the load in the system. Figure 4.16 shows one of the branch subsystems containing appliances. The on and off switching of appliances are done by routing a signal to the gate of the ideal switch. When the constant block value is set to 0, the switch is open, and if set to 1, the switch is closed.

The snubber resistances across the switches are disabled because if not, there will be small voltages and currents going through to the load when the switch is open, and this affects the power measurements in the system.

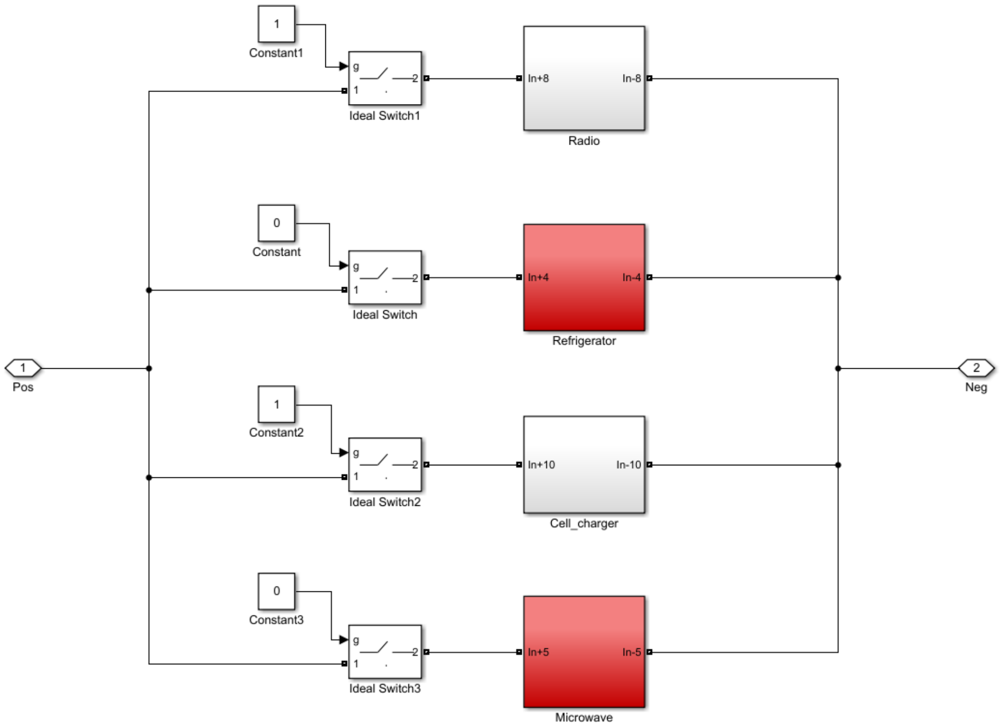


Figure 4.16: Subsystem of one of the appliance branches (branch 2)

The method used to calculate the total system efficiency is to measure the output power of all the individual appliances, add them up and then divide it by the total input power of the system. This takes into consideration the wire losses and the conversion losses inside the appliances. Equation (4-22) can be used to calculate the total system efficiency.

$$\eta_{\,total} = \frac{\sum P_{(out)appliances}}{P_{supply\ input}} \times 100 \qquad (4\text{-}22)$$

The design of the complete DC system is now complete. The simulation results of the power converters and the complete system are discussed in Chapter 5.

4.3 Design of other configurations

It is necessary to compare the performance of the designed DC system against other configurations in order to judge its feasibility. The first configuration is the existing AC system in residences, and the second is a hybrid AC/DC system, where all the electronic devices are being supplied with DC, and the high-power appliances with AC.

4.3.1 Existing 230 V AC system

The first configuration for comparison is the existing 230 V AC system, as found in most households across the world, including South Africa. The AC system is designed with the exact same appliances as in the DC system, and the layout is similar as well. However, the supply voltage in this case is AC, instead of DC. The other difference is that the appliances are now designed with an AC/DC input stage in order to get the correct supply voltage to the loads. The appliance designs for AC connection are described in the following section.

4.3.1.1 Appliance designs

4.3.1.1.1 Electronic loads

The Flyback converter designed in section 4.2.1.1 is used to power the same electronic devices in the AC system as well. The converters are designed to give the same output power. Table 4-12 shows the design parameters of the Flyback converter which supplies the television load in the AC system.

Table 4-12: Design parameters of Flyback converter in AC system

Parameters	Design values
Input voltage (Vi)	325 V DC[a]
Output voltage (Vo)	20 V
Output power (Po)	33 W
Transformer ratio (n)	0.5
Switching frequency (Fs)	45 kHz
Magnetizing inductance (Lmb)	31.2 µH
Output capacitance (Co)	291.31 µF
Load resistance (R)	12.12 Ω

[a.] After rectification

The only difference is that the converters now need a rectification stage at the supply input. This means that a rectifier has to be designed in order to rectify the AC grid voltage to the 325 V DC that the devices need. A general requirement for power converters connected to the AC system is that the power quality of the converter is to comply with a certain standard [51]. The reason for this is that the switching actions of power devices in a converter cause unwanted harmonic pollution in the AC waveform which supplies it, and therefore requires an intervention, usually in the form of a filter and/or a power factor correction circuit (PFC).

For this study, a single-phase PWM rectifier designed by a previous researcher [52] is used and the circuit diagram is shown in Figure 4.17. This rectifier provides power factor correction by means of current hysteresis control and this makes it possible to reduce the harmonic content and to measure the input power accurately. The operation of the circuit is explained below.

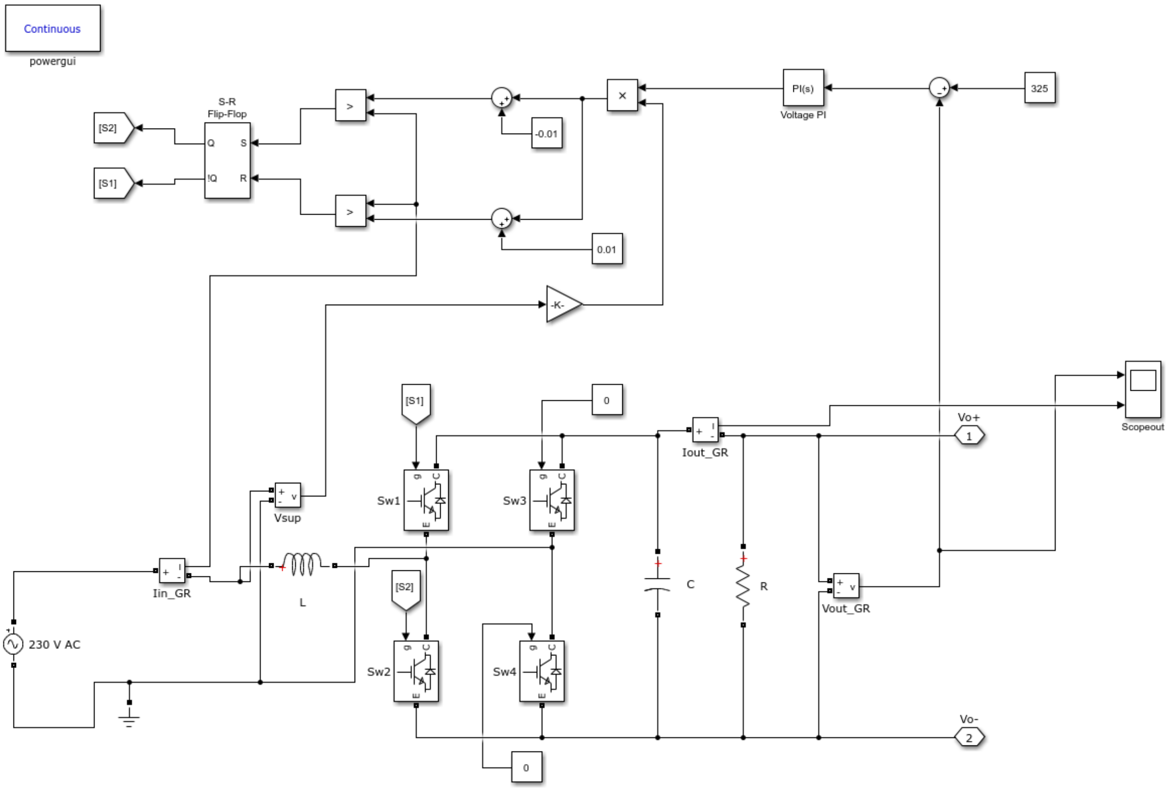


Figure 4.17: Single-phase PWM rectifier for AC grid rectification

The circuit in Figure 4.17 consists of four IGBT switches with anti-parallel diodes, an inductor at the input, filter capacitor and a load resistor which represents the load. The input inductor shapes the input current to a sinusoidal form and the filter capacitor reduces the ripple in the output voltage. When the rectifier is on, S1 and S2 are operated while only the diodes in S3 and S4 are conducting. The current flows through the inductor at the start of every sequence and once the inductor has stored enough energy, the IGBTs are switched off and the voltage across the inductor begins to rise. This causes the anti-parallel diodes in S3 and S4 to forward bias and current begins to flow to charge the capacitor. The IGBTs have switching losses which contribute to the power loss and overall efficiency of the rectifier.

When the switches are in the “on state”, the behaviour of the inductor current is described by

$$\frac{di_L}{dt} = \frac{\mathrm{V_L}}{\mathrm{L}} = \frac{\mathrm{V_S}}{\mathrm{L}} \tag{4-23}$$

And when the switches are in the “off state”, the behaviour of the inductor current is described by

$$\frac{di_L}{dt} = \frac{\mathrm{V_L}}{\mathrm{L}} = \frac{\mathrm{V_s} - \mathrm{V_o}}{\mathrm{L}} \tag{4-24}$$

The duty cycle of the rectifier is given by

$$\mathrm{D} = 1 - \frac{\mathrm{V_s}}{\mathrm{V_o}} \tag{4-25}$$

The input inductor can be calculated based on the maximum ripple allowed in the rectifier, which is obtained by

$$\frac{di_L}{dt} = \frac{\mathrm{V_s}}{\mathrm{L}} \times \mathrm{D} \tag{4-26}$$

The voltage ripple is dependent on the amount of current drawn by the load and the ripple frequency of the rectifier. The size of the filter capacitor is calculated based on the worst case scenario, which is when the rectifier is running at full power. The filter capacitor can be determined by a ratio of the output voltage and the RC load.

$$\frac{dV}{dt} = \frac{\mathrm{V_o}}{\mathrm{RC}} \tag{4-27}$$

PWM control is used to generate the pulses to the switches in the rectifier. The PWM control is used for three reasons: (a) to control the amplitude of the harmonics present on the input side, (b) to regulate the output voltage, and (c) to shape the input current to be sinusoidal and in phase with the supply voltage.

The PWM control compares the measured output voltage with the reference voltage and the error of this is sent to a PI controller to produce a stable output voltage. The output of the PI controller is then sent to the current controller which can either be a SPWM or a hysteresis controller. In this study, a hysteresis current controller is used. Figure 4.18 shows the hysteresis waveform and the control circuit to obtain hysteresis current control.

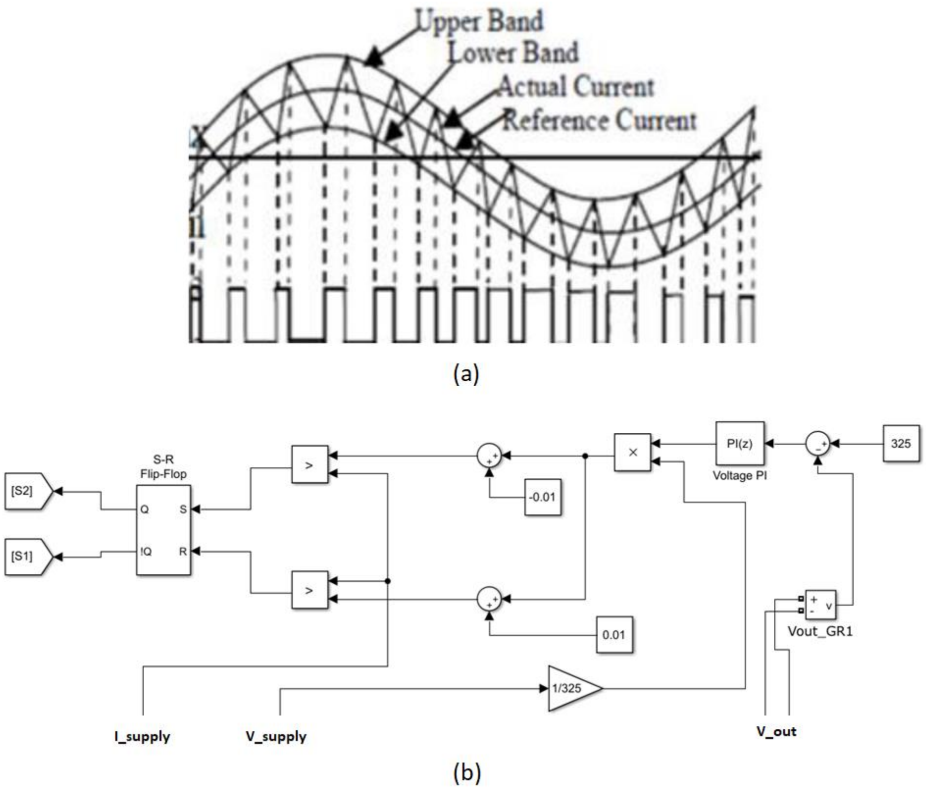


Figure 4.18: Control system of the rectifier (a) pulse generation by hysteresis control and (b) Simulink control system to obtain hysteresis control

In Figure 4.18 (b), the reference voltage is compared with the measured output voltage and the error is sent to the PI controller. The error voltage is multiplied with a sine template derived from the supply voltage and the output of that is the reference current. The actual input current is made to follow this reference current within a hysteresis band of 0.02 (upper and lower band shown in Figure 4.18 (a)). The PI controller is then tuned so that the circuit draws the required input current.

Table 4-13 shows the design parameters of the rectifier which supplies the Flyback converters in the AC system. The rectifier is designed using the input power of the Flyback converter as reference.

Table 4-13: Design parameters of the rectifier

Parameters	**Design values**
Input voltage (Vi)	230 V AC (rms)
Output voltage (Vo)	325 V DC
Output power (Po)	36.5 W
Input inductor (Li)	26.5 mH
Filter capacitor (Co)	75 µF

Figure 4.19 shows the Flyback converter with the PFC rectifier at the input.

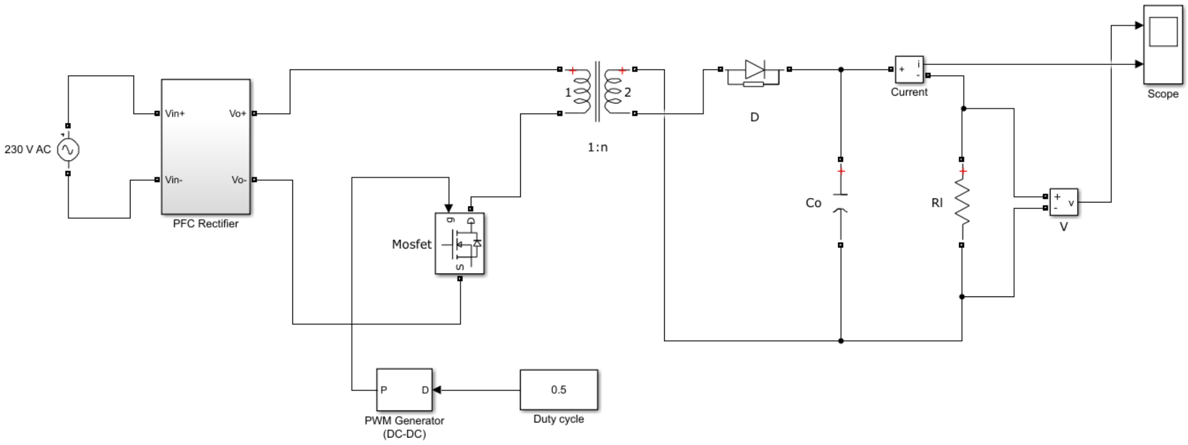


Figure 4.19: Flyback converter for AC supply

4.3.1.1.2 Refrigerator

For the combined refrigerator load, the inverter supplying the compressor motor unit and the buck converter supplying the refrigerator controls in section 4.2.1.2 are modified, but designed to give the same output power values. The design parameters of the converter are shown in Table 4-14. The inverter is designed with an AC input stage, which essentially makes it an AC/DC/AC (DC-link) converter as shown in Figure 4.20. The AC/DC input stage is designed with the same PFC rectifier as that in the Flyback converter.

Simulink power meters are placed at the input and output of the converter which measures active and reactive power at both ends.

Table 4-14: Design parameters of the AC/DC/AC converter

Parameters	Design values
Input voltage (Vi)	230 V AC (rms)
DC link capacitance (C_{link})	215 µF
Output voltage (Vo)	230 V AC (rms)[a]
Output power (Po)	106 W
Power factor	0.8
Switching frequency	45 kHz
Load frequency	50 Hz

[a] 230 V rms with variable frequency

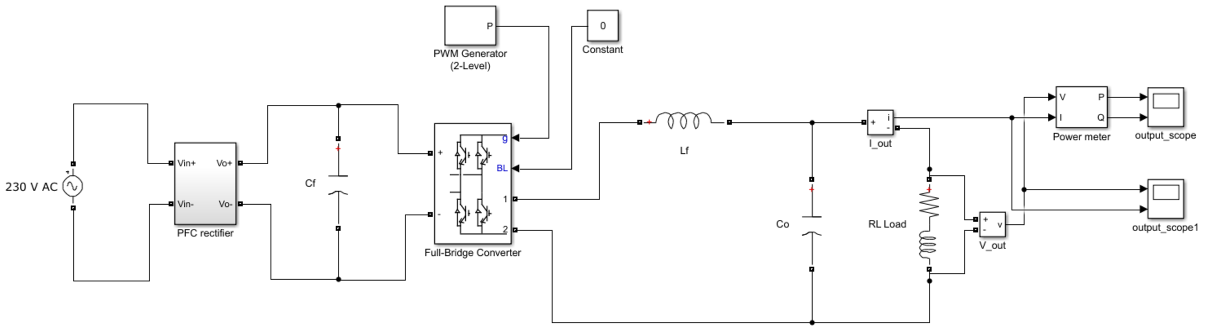


Figure 4.20: AC-DC-AC (dc-link) converter

The buck converter supplying the refrigerator controls is shown in Figure 4.21. In the circuit, the output of the rectifier supplies a smooth 325 V DC voltage to the input to the Buck converter. The Buck converter then steps down the 325 V to 24 V DC for the control circuitry, the same as in the DC system. The size of the components in the rectifier supplying the buck converter is different from that of the rectifier supplying the Flyback converters because of the difference in power ratings of the converters.

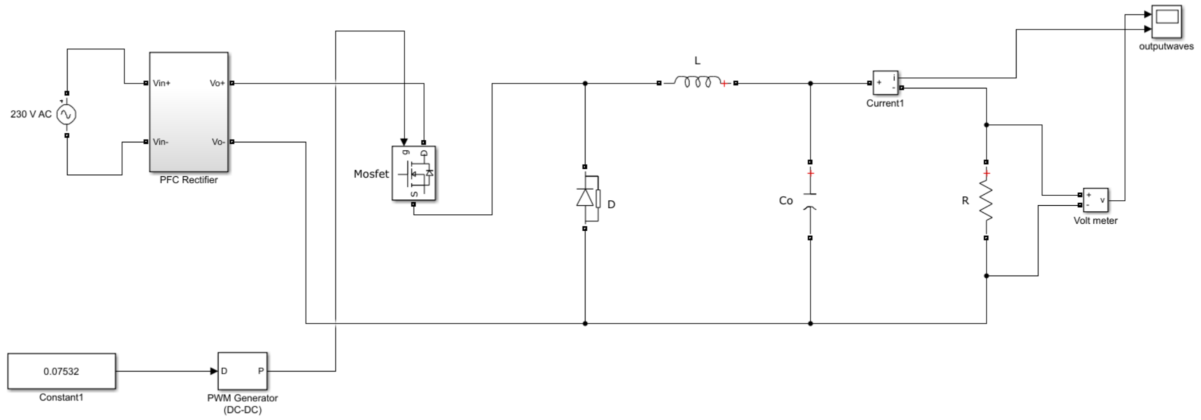


Figure 4.21: Buck converter connected to AC supply

The evaporator fan of the refrigerator is modelled as a small RL load, without any conversion stages. This fan only needs to provide a steady rotation (or constant speed) and does not need variable frequency to control the speed of the motor.

4.3.1.1.3 Washing Machine

Like in the DC system, the washing machine circuit takes the same shape as that of the refrigerator. The complete circuit consists of a main component, which is the motor, and the peripheral control circuitry. The motor is supplied by means of a DC-link converter and the controls are supplied by a buck converter, similar to the refrigerator. The inverter-motor and buck converter are designed to give the same output power values as the ones designed for the DC washing machine load in section 4.2.1.3.

The design parameters of the washing machine motor load in the AC system are given in Table 4-15.

Table 4-15: Design parameters of the AC/DC/AC converter for WM load

Parameters	Design values
Input voltage (Vi)	230 V AC (rms)
DC link capacitance (C_{link})	500 µF
Output voltage (Vo)	230 V AC (rms)[a]
Output power (Po)	238.6 W
Power factor	0.8
Switching frequency	45 kHz
Load frequency	50 Hz

[a] 230 V rms with variable frequency

4.3.1.1.4 Microwave Oven

Figure 4.22 shows the circuit diagram of the voltage doubler circuit which supplies the cavity magnetron in the AC system. The circuit gives the same output characteristics as the voltage doubler circuit in the DC system. The circuit connected to an AC supply does not require an inversion stage in order to step up the output voltage. The microwave oven controls and exhaust fan are supplied by a buck converter with an output voltage of 24 V.

The buck converter shown in Figure 4.21 is used.

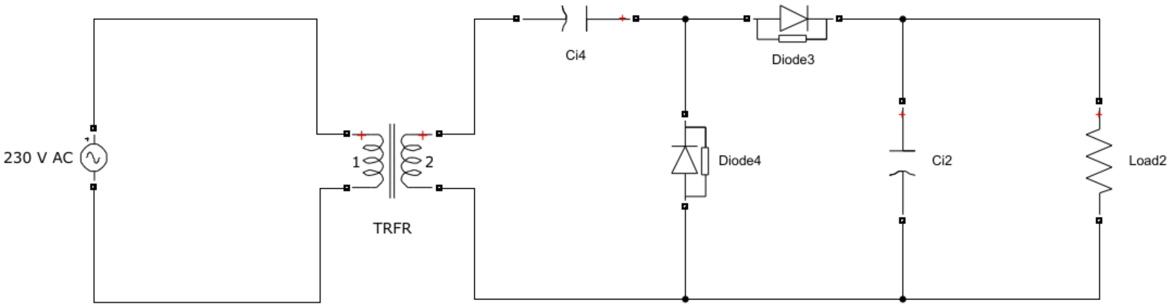


Figure 4.22: VDC to supply the magnetron of the microwave in the AC system

The design parameters of the voltage doubler circuit supplying the magnetron load in the AC system are shown in Table 4-16.

Table 4-16: Design parameters of the VDC in AC system

Parameters	**Design values**
Input voltage (Vi)	230 V AC (rms)
Output voltage (Vo)	5600 V
Output power (Po)	708 W
Load resistance (Rl)	44.29 kΩ
Output capacitances (Co1,Co2)	800 µF
Transformer power rating	1000 VA
Transformer winding ratio	1:10

4.3.1.1.5 High-power loads

The stove, geyser, kettle and vacuum cleaner are supplied directly with AC. These appliances have the same power ratings as those designed for the DC system. The heating loads like the stove, geyser and kettle are modelled as pure resistive circuits and the vacuum cleaner is modelled as a RL load with a power factor of 0.94. The design parameters of the loads are shown in Table 4-17. The circuit resistances and inductance values are calculated using 230 V rms.

Table 4-17: Design parameters for high-power loads in AC system

Parameters	**Design values**			
	Stove	**Geyser**	**Kettle**	**Vacuum C.**
Input / Output voltage	230 V	230 V	230 V	230 V
Load Power	3000 W	2600 W	1900 W	1200 W
Load Current	13 A	11.3 A	8.26 A	5.22 A (pf = 0.94)

4.3.1.2 RES converter design for AC connection

In an AC system, the DC output from the solar batteries or PV panels is inverted to AC so that the power produced by the RES system can be utilized by all the appliances. This is done with a DC-AC inverter with the DC input voltages usually ranging from 12-48 V, and output of 230 V rms. Figure 4.23 shows the circuit diagram of such an inverter. The input voltage in this case is 48 V, just like the RES converter in the DC system. The 48 V DC is inverted to 48 V AC and is then stepped up by a transformer to supply 230 V to the loads. The same crucial loads are supplied by the RES in the AC system, as in the DC system.

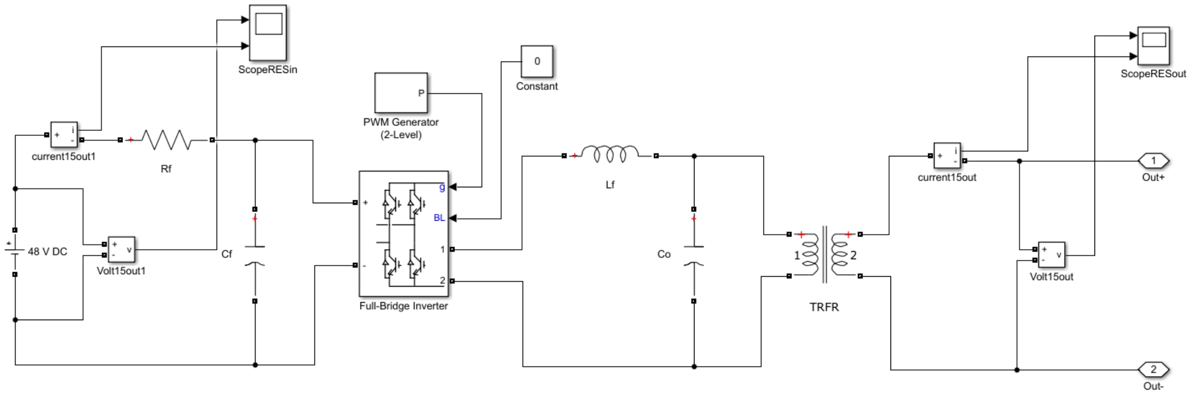


Figure 4.23: DC-AC inverter to supply crucial loads in the AC system

In Figure 4.23, the secondary side of the transformer provides a filtered 230 V rms supply to the crucial loads. The AC RES converter, like the DC RES converter, is designed using the total input power of the crucial loads along with a wiring loss component. The design parameters of the DC-AC inverter supplying the crucial loads are shown in Table 4-18.

Table 4-18: Design parameters of DC-AC inverter for RES supply conversion

Parameters	Design values
Input voltage (Vi)	48 V DC
Output voltage (Vo)	230 V AC
Output power (Po)	369 W
Transformer rating	500 VA
Transformer winding ratio	1:8.9
Input filter resistance (Rf)	1 Ω
Input filter capacitance (Cf)	18 mF
Inverter-output inductance (Lf)	2 mH
Inverter-output capacitance (Co)	30 µF
Modulation index	1

4.3.1.3 The complete AC system

The various AC components designed in the previous sections are combined into the complete AC system shown in Figure 4.24. The supply is directed to the appliances in the same way as that in the DC system, with the only difference being the supply voltage, which is now 230 V rms. The same cable sizes are used for the circuits as well. A power meter is placed at the supply input which measures the total power drawn from the AC supply.

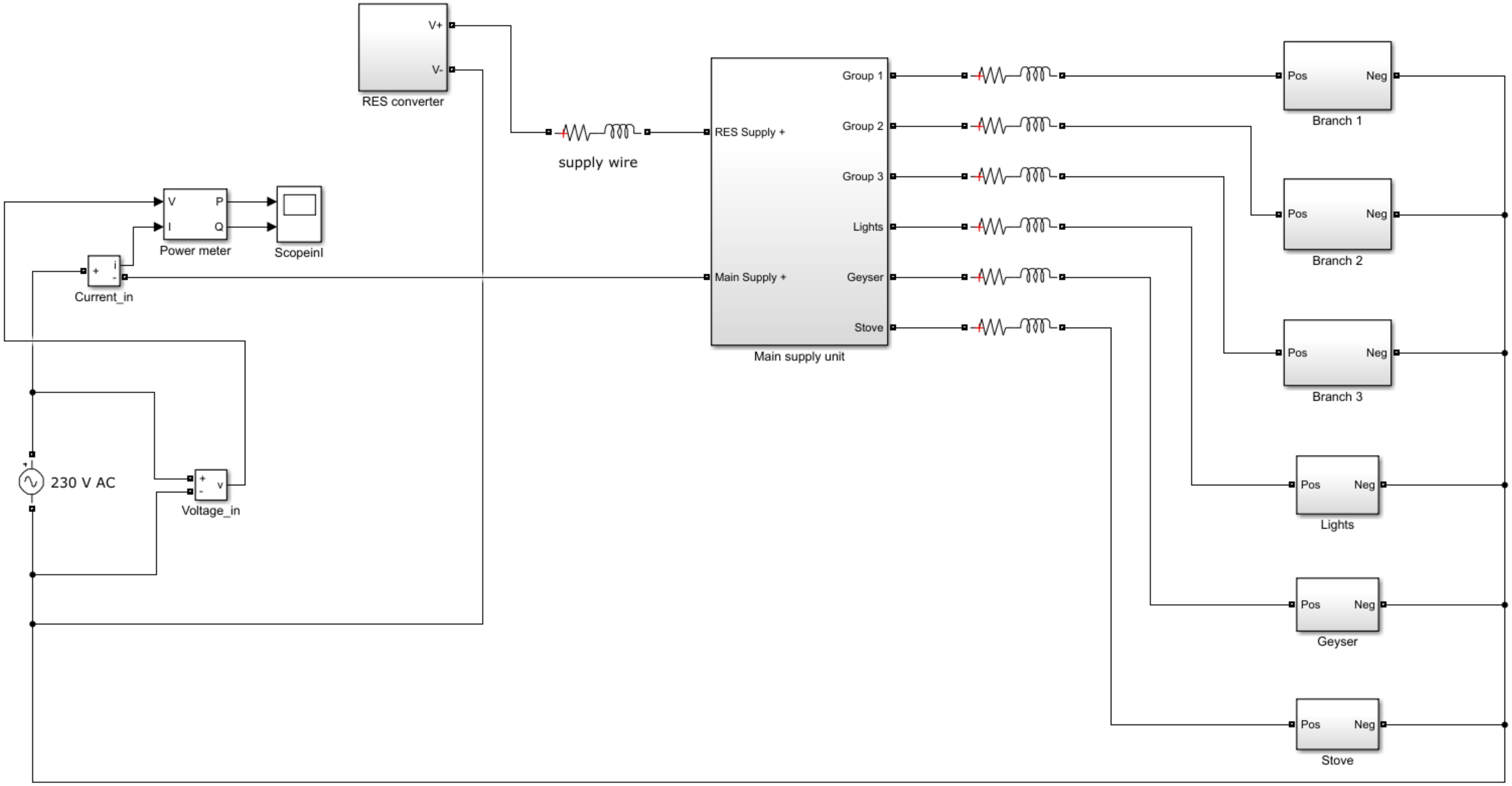


Figure 4.24: The complete AC system layout

4.3.2 The AC/DC hybrid system

The AC/DC hybrid system integrates the AC and the DC system design approaches. It builds on the premise that the supply to the house is the normal 230 V AC supply, like the existing AC system. However, the DC-based appliances which contain conversion stages in their supply circuits are supplied with 325 V DC directly. These include all the electronic loads, refrigerator and washing machine. The high-power appliances, including the microwave oven, are supplied directly with AC, without any conversion.

The single-phase PWM rectifier used for the AC appliances is modified and designed to provide a bulk-DC supply to the loads. The bulk rectifier is designed using the input power values of the electronic loads, refrigerator and washing machine, along with a wiring loss component. The design parameters of the bulk rectifier are shown in Table 4-19. The rectifier is designed to give an output power of 674 W at 325 V DC with 0.2 % ripple. The rectifier circuit uses IGBTs as switches for controlled power flow and the switches have a continuous current rating of 8 A.

Table 4-19: Design parameters of the single-phase PWM rectifier for grid-rectification

Parameters	Design values
Input voltage (Vi)	230 V AC (rms)
Output voltage (Vo)	325 V DC
Output power (Po)	674 W
Input inductor (Li)	10 mH
Filter capacitor (Co)	1350 µF
Cont. current rating of IGBTs	8 A

The layout of the AC/DC hybrid system is shown in Figure 4.25. The grid rectifier is supplied from the 230 V AC main, where the output of the rectifier then goes into the DC supply unit. The output of the RES supply goes into the DC supply unit as well, where it is connected to the common DC bus. The high-power AC loads are supplied separately from the DC system. The AC supply unit takes supply directly from the AC grid and distributes the power to the three branches. The high-power AC loads subsystem contains the kettle and the vacuum cleaner, which are supplied from the same socket. The input power of the main supply is measured at the AC supply input, before the grid-rectifier.

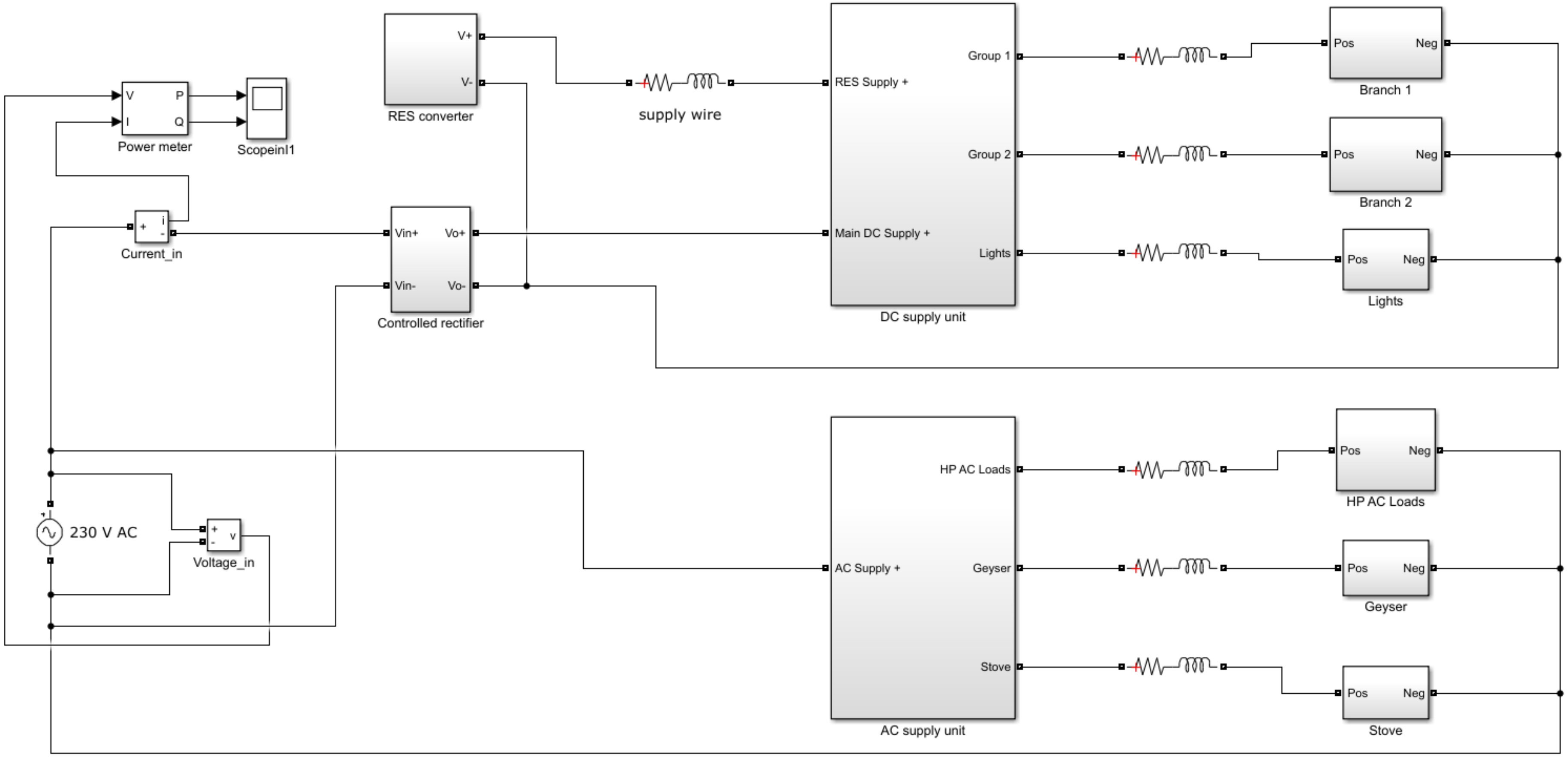


Figure 4.25: The complete AC/DC hybrid system layout

Chapter 5
Results and Discussion

5.1 Introduction

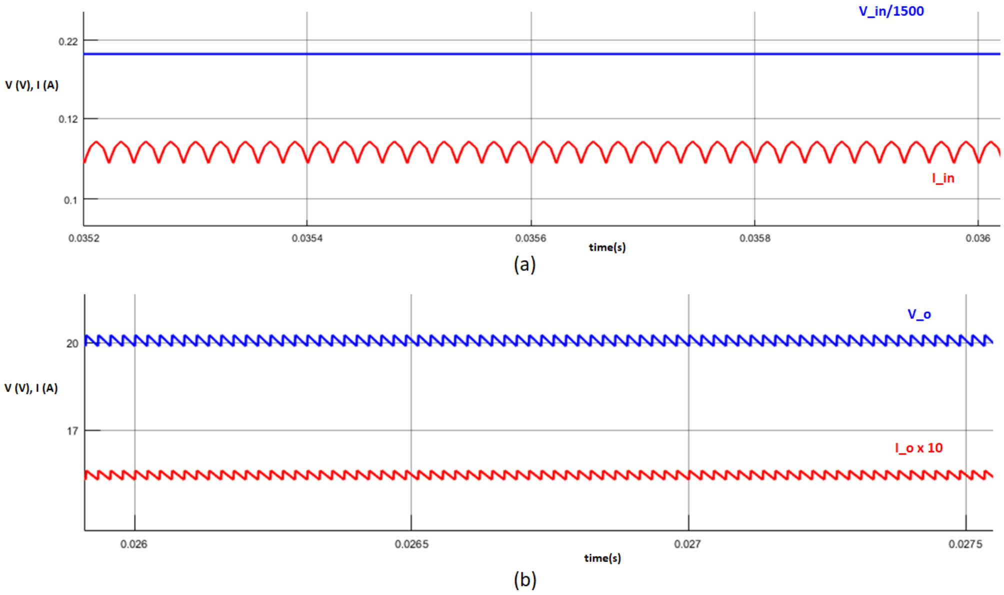
This chapter presents the simulation results of the circuit components and complete DC and AC distribution circuits designed in Chapter 4. The results presented in this chapter verify the validity and correctness of the designs. The efficiencies of the three distribution systems are compared. A material cost breakdown is also done on the installation and material costs related to the implementation of each system.

5.2 Simulation results of the DC system and components

5.2.1 Loads

5.2.1.1 Electronic loads

The waveforms of the Flyback converter designed in Figure 4.3 are shown in Figure 5.1. This specific converter was designed to supply the television load with an output power of 33 W. The electronic circuits inside the television operates at 20 V DC, and the Flyback converter supplies a smooth 20 V DC voltage with a ripple of 0.01%. The output current waveform follows the voltage waveform with a value of 1.65 A. The input power of the converter is found to be 36.5 W, and this gives an efficiency of 90 %. The converter has a response time of 8 ms. The response time is the time taken for the converter to reach steady-state condition from start-up. The input current has a very small ripple, which makes it easier to get an accurate mean value for the waveform.



(a)

(b)

Figure 5.1: Flyback converter (a) input and (b) output voltage and current waveforms

5.2.1.2 Refrigerator

The refrigerator components were simulated individually to verify the design values. The components were then connected together and the simulation repeated to get the total input and output power of the appliance (refrigerator). Figure 5.2 (a) and (b) show the input and output current and voltages (respectively) of the compressor motor inverter circuit of Figure 4.5. Both the input and output voltages are divided by a certain factor in order to allow the display of the voltage and current waveforms on the same scale. The output of the inverter is 325 V AC (peak) which the motor requires, and the current being drawn is at a lagging power factor of 0.8.

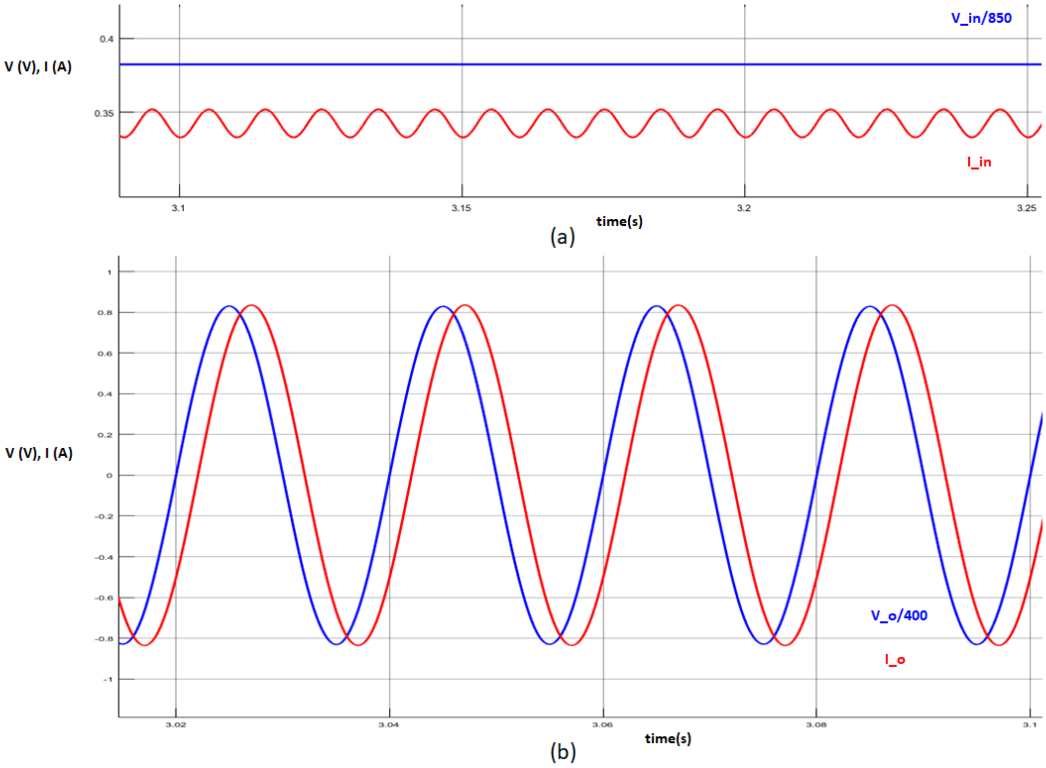


Figure 5.2: Compressor inverter-motor (a) input and (b) output waveforms

The input RC filter provides a smooth measurable current with minimum ripple at the input, as shown in Figure 5.2 (a). The inverter gives an active output power of 106 W with an input power 107 W. The simulation efficiency is calculated to be 99 %.

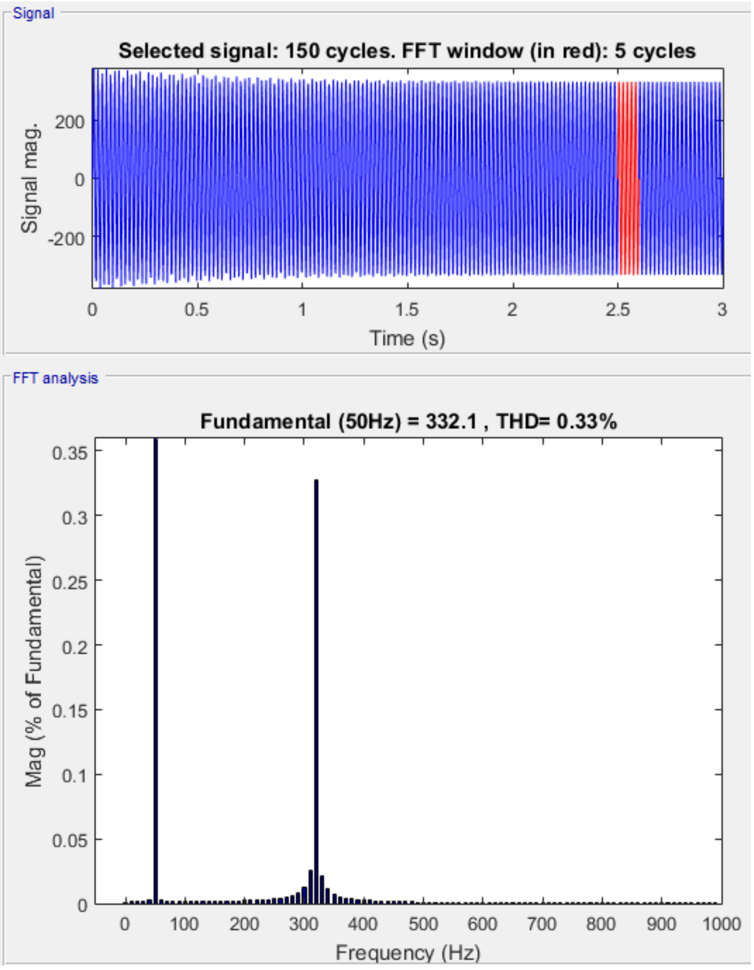
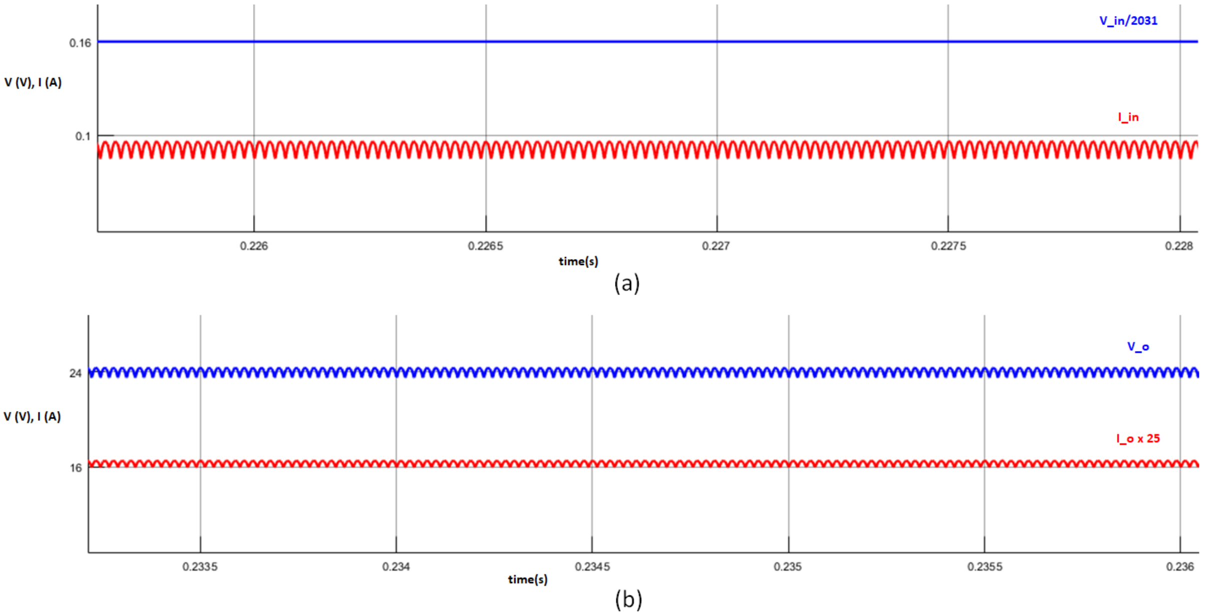


Figure 5.3: Frequency spectrum of the inverter output voltage

Simulink has a built in harmonic analysis toolbox (FFT) which can be used to display the total harmonic distortion of an AC waveform. Figure 5.3 shows an FFT analysis done on a selected range of cycles in the output voltage waveform of the inverter. The analysis is done on 5 cycles (highlighted in red) of the voltage waveform and the total harmonic distortion in the waveform is calculated to be 0.33 %. This is well below the limit of how much harmonic distortion is allowed in the supply voltage [53].

The supply given to the controls of the refrigerator is provided by the buck converter of Figure 4.8. The output voltage of the buck converter is 24 V and the simulation waveforms are shown in Figure 5.4. The buck converter has a small voltage overshoot in the start-up transient state, but only lasts for about 5 ms. The output voltage has a ripple of 0.01 %. The input current, like that of the Flyback converter is put through a low-pass filter in order to filter out the ripple and make it measurable. The input current of the buck converter is shown to have a ripple of 0.01 %. An efficiency of 50 % was obtained, which is quite low.

It was noted that the efficiency of the buck converter drops if the step-down voltage ratio becomes too big. For example, the converter has a higher efficiency if the step-down ratio is 2:1 (24V to 12V). The buck converter is not that efficient with a step-down ratio of 10:1 (240V to 24V).



(a)

(b)

Figure 5.4: Buck converter (a) input and (b) output waveforms

5.2.1.3 Washing Machine

The combined output power of the Washing machine load is shown in Figure 5.5. The washing machine load, as mentioned in the design process, consists of an inverter-motor and a control circuit. The two loads together gives an output power of 289 W at an input power of 308 W, giving a total circuit efficiency of 93.8 %.

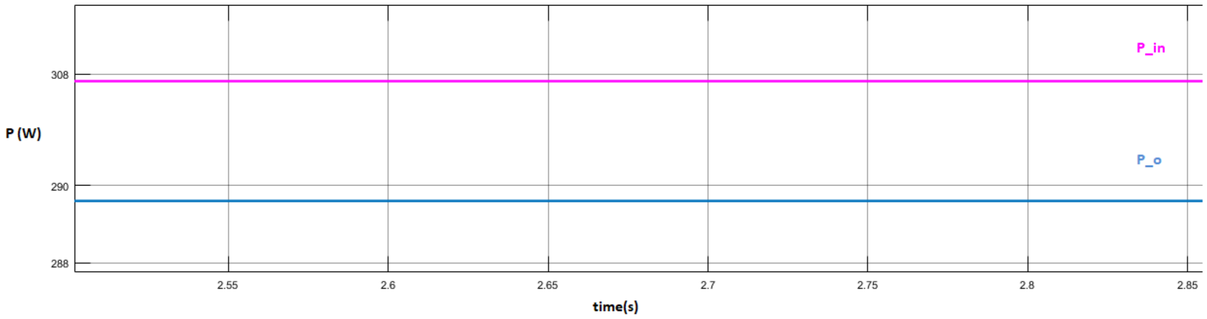


Figure 5.5: Input and output power waveform of the combined WM load

5.2.1.4 Microwave Oven

The circuit waveforms of the voltage doubler circuit designed in section 4.2.1.4 is shown in Figure 5.6 (a) and (b). The output of the voltage doubler circuit is 5600 V DC, created from the 2800 V AC at the high-frequency transformer secondary windings. The secondary voltage of the transformer had to be increased to 2942 V in order to get the 5600 V at the output. This is due to the voltage drop caused by the circuit components in the voltage doubler circuit.

The combination of the input RC filter and the output LC filter made the smooth input possible. The filtering circuits cause the converter to have a long response time; however, the input current ripple needs to be filtered in order to obtain a measurable waveform.

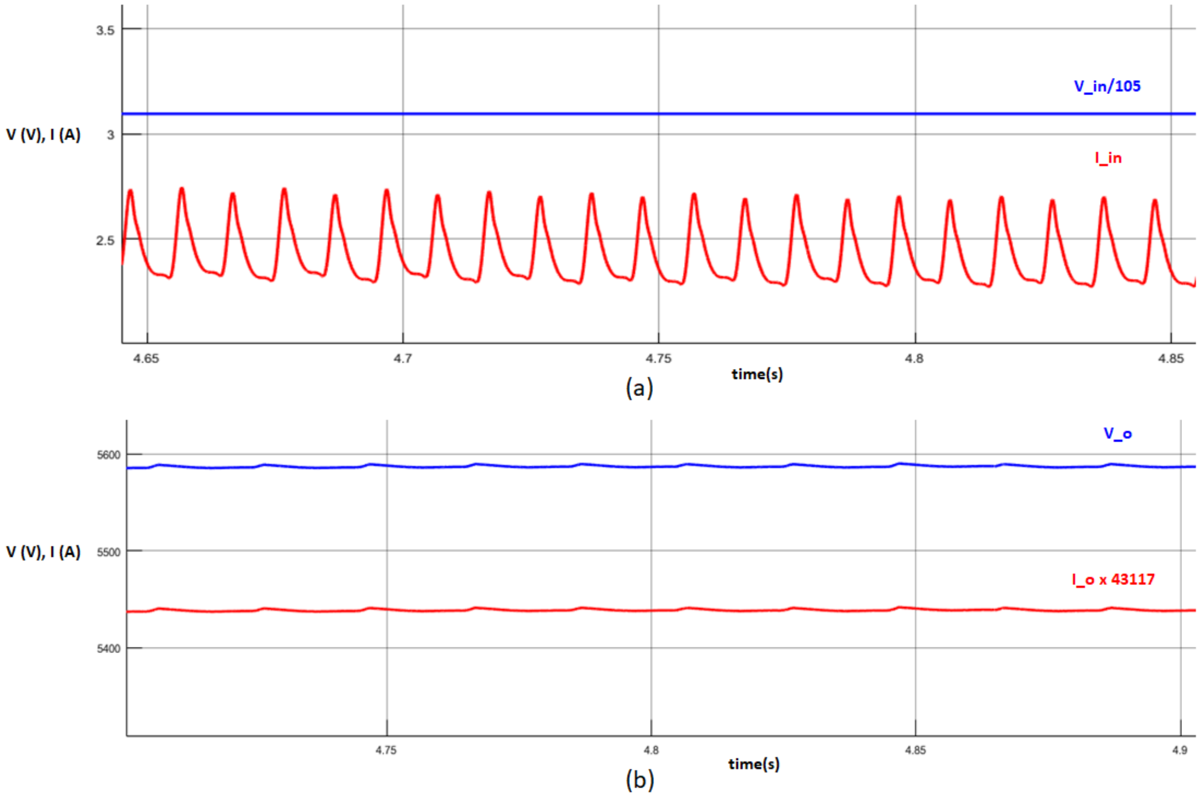


Figure 5.6: Voltage Doubler Circuit (a) input waveforms and (b) output waveforms

The input power measured for the voltage doubler circuit is 812.5 W and the output is 708 W. This gives a circuit efficiency of 87 %. It is worth noting that the filtering in the circuit causes a slow response time, and the converter only reaches steady-state at about 3.5 s. The power measurements are done only once the circuit has reached steady-state and once the charging time of the filtering circuit has reached its maximum.

The total microwave oven efficiency is calculated using the input and output power values of both the magnetron circuit and the control circuit. These values are given in Table 5-1, along with all the other appliances.

5.2.1.5 High-power loads

The high-power appliances were initially designed as controlled-current-sources (CCS) in Simulink, where the appliance current is created through a measurement of the supply voltage and the resistance value (resistance calculated using the load power and the square of the voltage). This caused a problem when all the components were simulated together in the complete system. The problem is when the high-power appliances are switched out, Simulink sees this as the CCS being open-circuited, and this is not allowed.

The CCS was then replaced with normal resistive and resistive-inductive loads, which gives the same current values. Figure 5.7 shows the kettle voltage and current connected to the DC supply. The other high-power appliances have similar output characteristics.

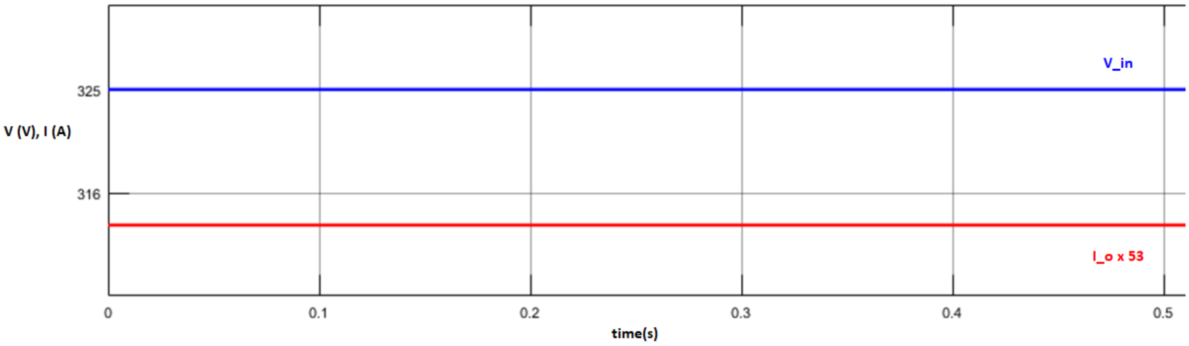


Figure 5.7: Voltage and current waveforms of the kettle connected to the DC supply

Table 5-1 shows the input and output power values of all the appliances, as well as the efficiency of each appliance. The inverter-motor loads such as the refrigerator compressor and the washing machine motor shows the highest efficiency of all the appliance circuit components. The least efficient components are the buck converters supplying the control circuitry in the refrigerator, microwave and washing machine.

It is noted that the buck converters designed for a higher output power has a better efficiency value than the ones designed for a lower output power. For example, the buck converter supplying the refrigerator controls is designed to give an output power of 15.44 W and the efficiency of the converter is 49 %, where the buck converter for the washing machine controls gives an efficiency of 75 %, with an output power of 51 W. The electronic loads all have efficiency values in the range of 83 – 91 %.

Table 5-1: Simulation results of the appliances and their components in DC system

Appliance	Input power (W)	Output power (W)	Efficiency (%)
Television	36.5	33	90.4
TV Decoder	22.75	20.6	90.5
DVD Player	9.5	8.1	85.3
Laptop	52	47.8	91.9
Radio	10.3	8.8	85.4
Cell charger	7.9	6.62	83.8
Fridge compressor motor	107.04	106	99.0
Fridge Evap. Fan	6.5	6	92.3
Fridge controls	31.5	15.44	49.0
Lights	80	73.5	91.9
Microwave magnetron	812.5	708	87.1
Microwave controls	47	35	74.5
Washing M. motor	239.81	238.6	99.5
Washing M. controls	68	51	75.0
Vacuum cleaner	1200	1200	-
Kettle	1900	1900	-
Geyser	2600	2600	-
Stove	3000	3000	-

The complete DC system results are given in the next section.

5.2.2 Complete DC system results

Figure 5.8 shows the input current of the main supply with all the appliances connected for the DC system of Figure 4.14. The total system current is measured at around 32.6 A with a ripple of 1 %, and when multiplied with the supply voltage of 325 V, gives a total input power of 10595 W. The current is only measured at around 3.5 seconds because this is when the complete system has reached steady-state operation. The current waveform does not give an accurate value when measured at a transient state.

The input power of the complete system is a combination of the input power of each appliance and the wire loss of each branch.

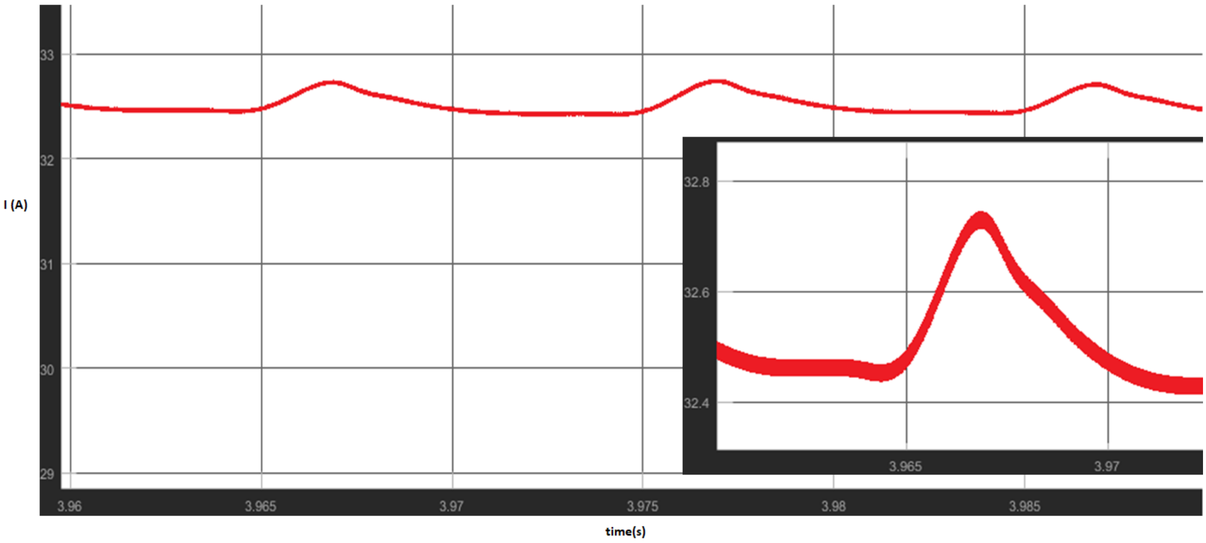


Figure 5.8: Input (supply) current of the main supply (full-load)

A disadvantage to simulating all the components in a complete system is the simulation time of the circuit. The simulation takes approximately 6 hours to run to completion. The reason for this is the simulation parameters such as the time settings, step size and the solver chosen for simulation. The solver chosen for this study is the ode23tb solver, which is a variable-step solver, used in systems with stiff differential equations. A test was done where the complete system was simulated in discrete mode using a fixed-step solver in order to decrease simulation time. However, this affects the operation of the components and makes the system inaccurate.

The resulting input and output waveforms of the full-bridge step-up DC-DC converter are shown in Figure 5.9. Figure 5.9 (a) shows the 48 V DC input voltage (blue) scaled down for display with the input current. The input current contains small ripples which make it difficult to obtain an accurate value therefore, a mean value is used. The value obtained for the input current of the converter is 9.75 A. This gives an input power of 467.9 W. Figure 5.9 (b) shows the output voltage (blue) and current (red) of the converter. The 325 V is scaled down to the same order as the current. The output current of the converter with all the crucial loads connected (full-load), is measured at 1.12 A. This gives an output power of 364 W and a total circuit efficiency of 78 %. The RES system has a response time of 0.4 seconds, and the efficiency of the system is measured after this time has elapsed. The compressor motor in the refrigerator takes around 0.4 seconds to reach steady-state operation, so the complete system can only be measured after this time.

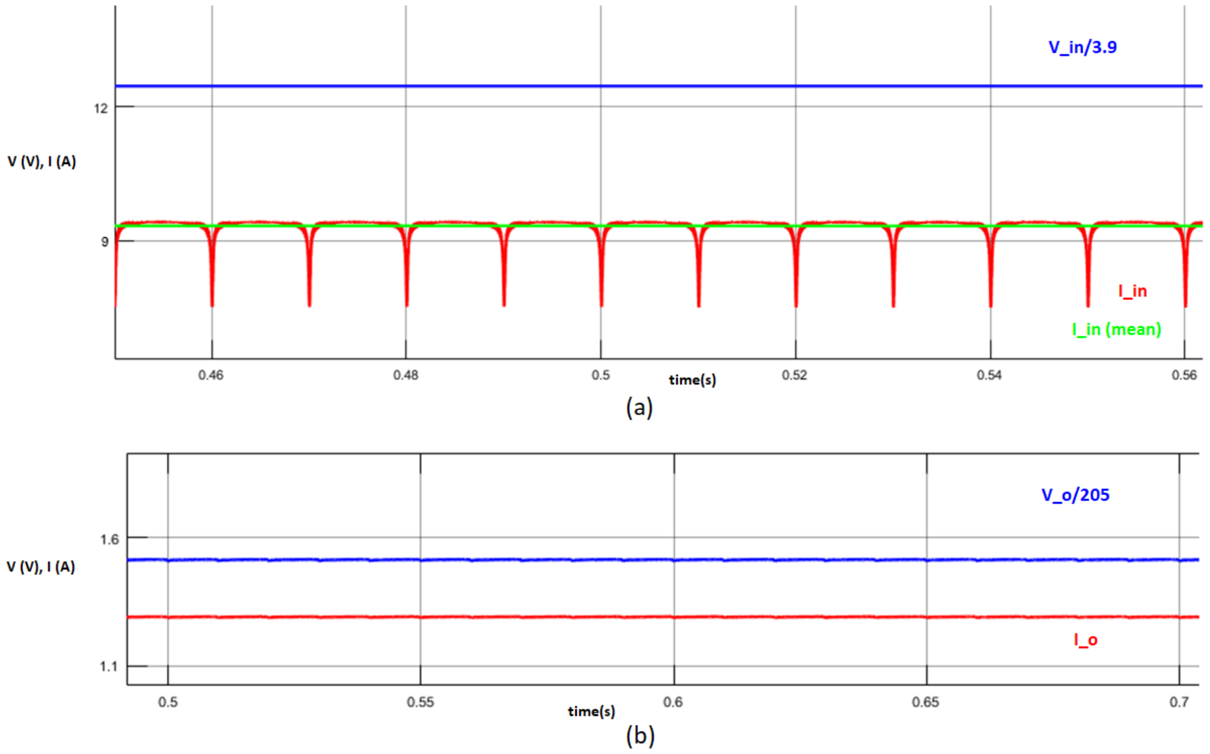


Figure 5.9: RES system (a) input and (b) output waveforms (full-load)

The RES system was simulated in decremented load steps of 10 %, starting from full-load to low-load, and the system maintained an efficiency of 78 % throughout. This is because the control system of the converter is open-loop voltage control, and the input-output of the converter was adjusted manually, in order to regulate the output voltage with variation in load. The converter thus has good load regulation (less than 1%).

Table 5-2 shows the simulation results of the complete DC system. With all the appliances connected to the main supply, the DC system gives an overall efficiency of 94.9 %, with a total power loss of 536.54 W. The RES system shows an efficiency of 78 % and total system loss of 110.85 W. The main supply efficiency is considerably higher than that of the RES supply because there is no input converter required.

Table 5-2: Simulation results of the complete DC system

	Input power (W)	**Output power (W)**	**Power loss (W)**	**System Efficiency (%)**
RES supply	467.9	364	103.9	78
Main supply	10595	10058.46	536.54	94.9

5.3 Simulation results of the other configurations

5.3.1 Existing 230 V AC system

5.3.1.1 Electronic Loads

The electronic devices in the AC system are also modelled as Flyback converters. However in the AC system, the Flyback converter has a PFC rectifier at the input, as discussed in section 4.3.1.1. Figure 5.10 shows the input (a) and output (b) waveform characteristics of the Flyback converter designed in Figure 4.19. The converter was designed to supply the television power of 33 W. The converter, like that used in the DC system, gives a smooth 20 V DC output to the load with minimum ripple. The input current contains some harmonics due to the switching elements in both the Flyback converter and the rectifier. These harmonics, though, do not influence the power measurements at the converter input and the power factor is actually improved by the circuit components inside the rectifier.

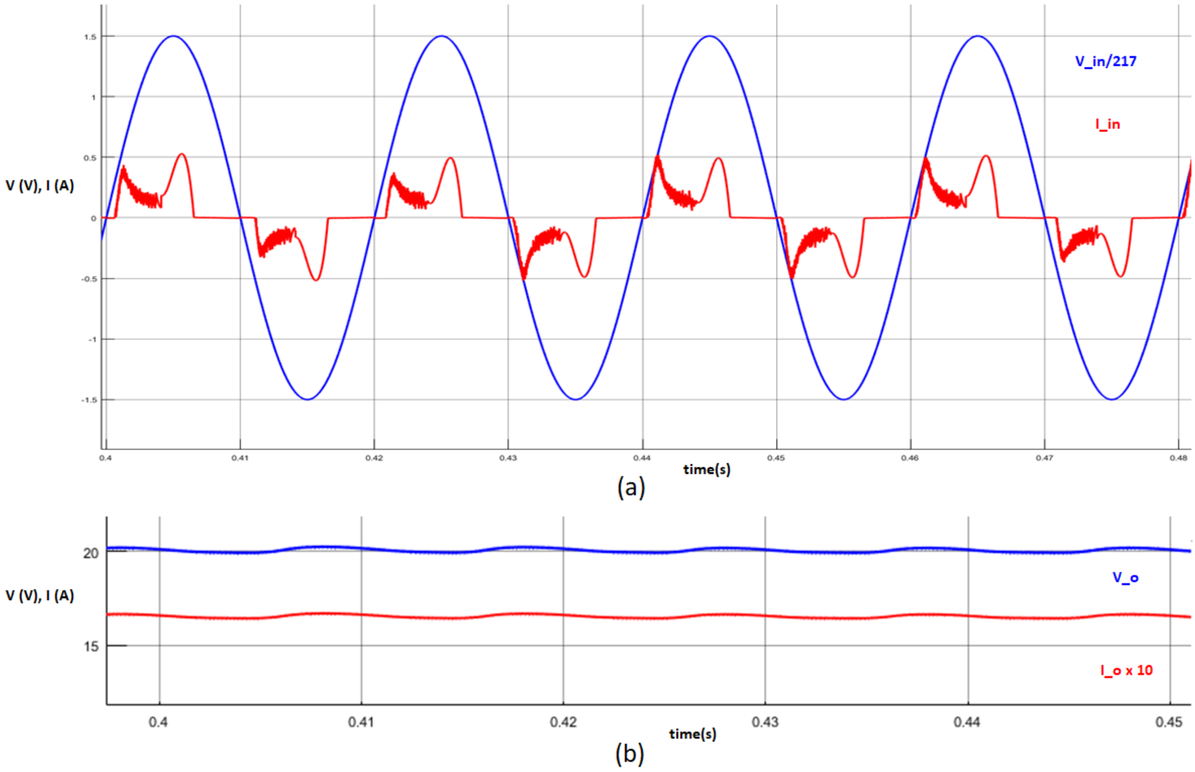


Figure 5.10: AC-connected Flyback converter (a) input and (b) output waveforms

The AC-input Flyback converter draws an input power of 36.9 W, giving a circuit efficiency of 89.5 %. This makes it 0.9 % less efficient than the DC-input Flyback. The hysteresis control in the rectifier makes the AC-DC rectification stage 99 % efficient. The AC-input Flyback converter has a response time of 20 ms.

5.3.1.2 Refrigerator

The individual circuits of the refrigerator were simulated separately in order to make sure the input and output characteristics are correct. The three circuits were then put together in one subsystem and simulated together. Figure 5.11 shows the input (a) and output (b) waveforms of the dc-link converter supplying the compressor motor. Without the input filter in the rectifier, the supply current has a large peak value, and when measured without the filter, the input power is quite large. The current waveform in Figure 5.11 (a) is put through the hysteresis controller and has a much smaller value. The dc-link converter gives the same 106 W output power as that of the inverter-motor in the DC system, however with a slightly higher input power of 107.29 W. The frequency spectrum of the output voltage waveform is the same as that of the inverter-motor in the DC system. The motor load has a lagging power factor of 0.8.

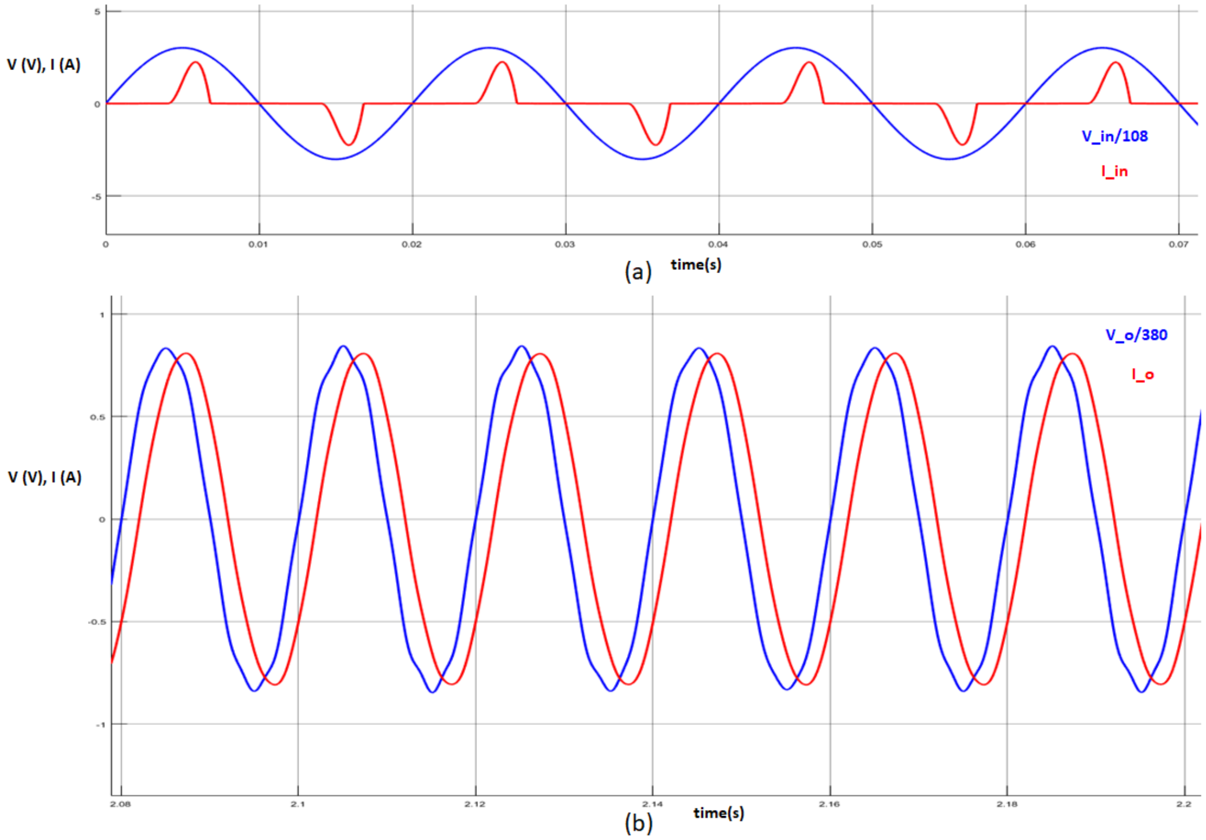
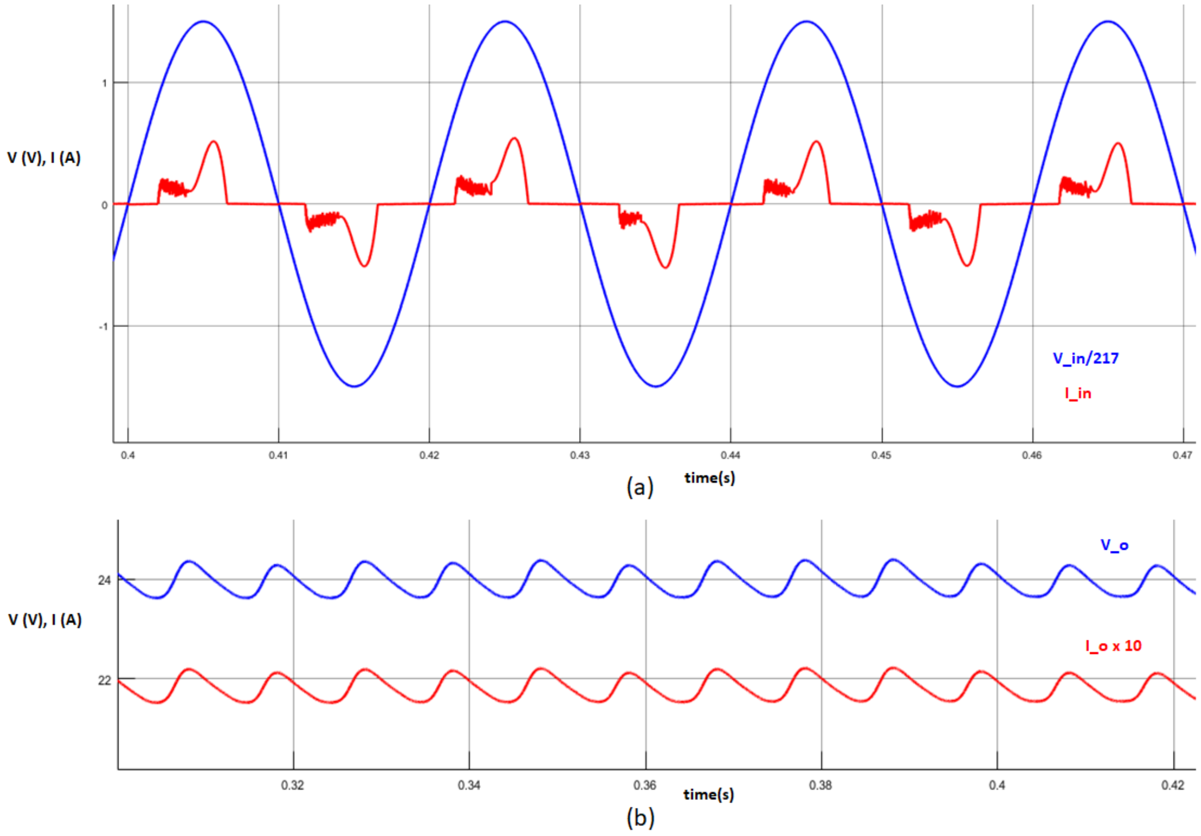


Figure 5.11: AC-DC-AC converter (a) input waveforms and (b) output waveforms

The supply to the evaporator fan in the AC system does not go through an inversion stage to create a stable, constant AC voltage to the load. It is supplied directly with AC, and draws a power of 6 W.

Figure 5.12 shows the input (a) and output (b) waveforms of the buck converter supplying the controls in the refrigerator load. The waveforms are the results obtained from the simulation of the circuit of Figure 4.21. The input current characteristics are similar to those of the

Flyback converter. The buck converter gives a 24 V DC output with a small ripple in both the voltage and current waveforms. The measured values for the input and output power are 33 W and 15.44 W, respectively. The efficiency of the AC-input buck converter is calculated to be 47 %. The same trend is picked up with the buck converters in the AC system, where the efficiency tends to go up with the increase in output power. The buck converters supplying the controls in the microwave oven and washing machine are more efficient than the low-power buck in the refrigerator.



(a)

(b)

Figure 5.12: AC-connected buck converter (a) input waveforms and (b) output waveforms

The refrigerator has a combined input power of 146.29 W and a combined output power of 127.44 W, giving a total appliance efficiency of 87 %. The combined refrigerator load in the DC system gives an efficiency of 88 %, making it 1 % more efficient.

5.3.1.3 Washing Machine

The combined input (purple) and output (blue) power waveforms of the washing machine load is shown in Figure 5.13. Like the washing machine load in the DC system, this load consists of an inverter-motor and a buck converter for the control circuitry. The inverter-motor and buck converters are both designed with a PFC rectifier at the input in order to connect to the AC supply. The combined input power of the WM load is 312.74 W and the combined output power is 289.6 W. This gives an appliance efficiency of 92.6 %.

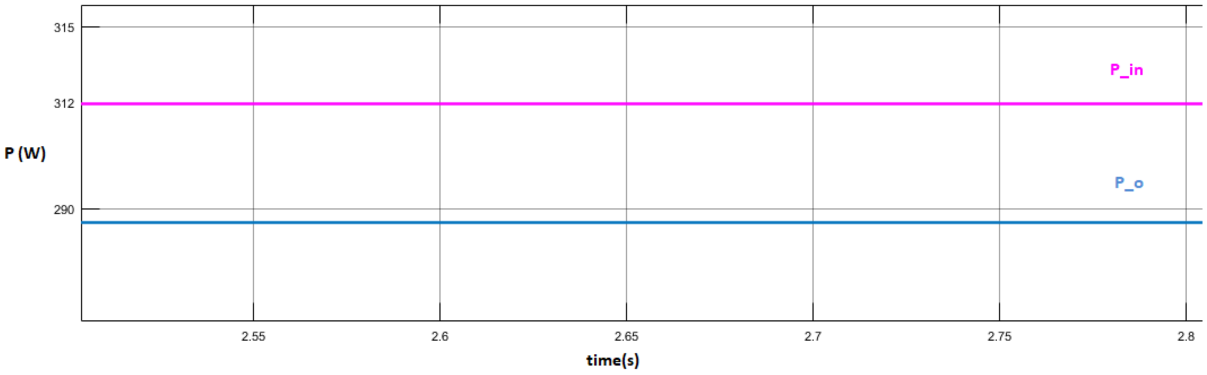


Figure 5.13: Combined input and output power of the WM load in AC system

5.3.1.4 Microwave Oven

The input (purple) and output (blue) power waveforms of the combined MW oven load are shown in Figure 5.14. When connected to the AC supply, the cavity magnetron gives the output power of 708 W, but with a much lower input power of 732 W. This is due to fewer components (inverter and filtering stages) in the supply circuit. The buck converter supplying the exhaust fan and control circuit however is 3 % less efficient than that in the DC MW. It was noted that the efficiency of the buck converter increased with an increase in output power. The buck converters in the DC system are slightly more efficient because there is now rectification stage at the supply input.

The combined input power of the appliance is 781.24 W and the output power is 743 W. These power values give a total appliance efficiency of 95.1 %.

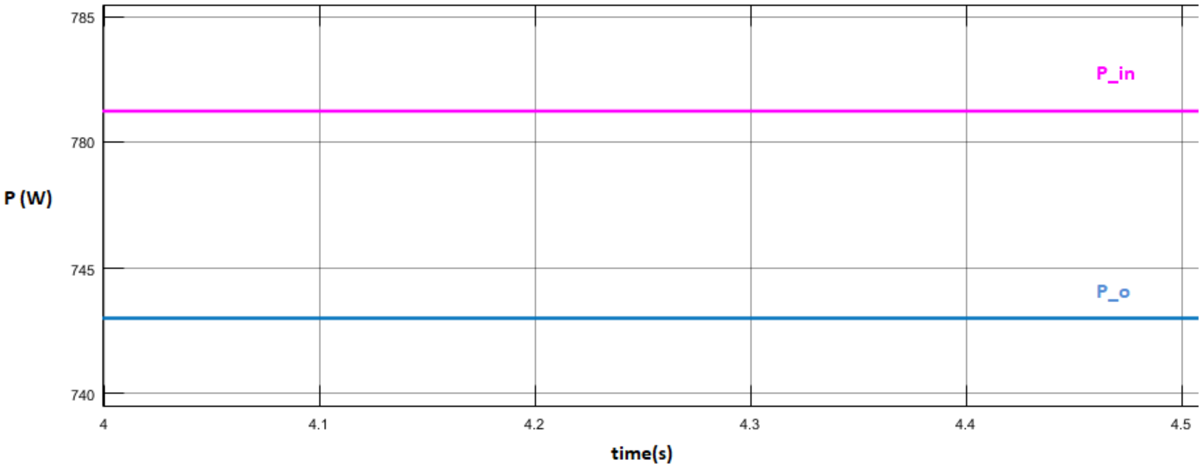


Figure 5.14: Input and output power of the combined MW load in AC system

5.3.1.5 High-power loads

Figure 5.15 shows the supply voltage (blue) and current (red) of the 1900 W kettle connected to the 230 V AC rms supply. The current has a peak value of 11.68 A and rms value of 8.26 A. Like in the DC system, the high-power appliances do not contain any power conversion stages in their supply circuits, and are supplied directly with AC.

The other high-power appliances connected to the AC supply have similar waveform characteristics.

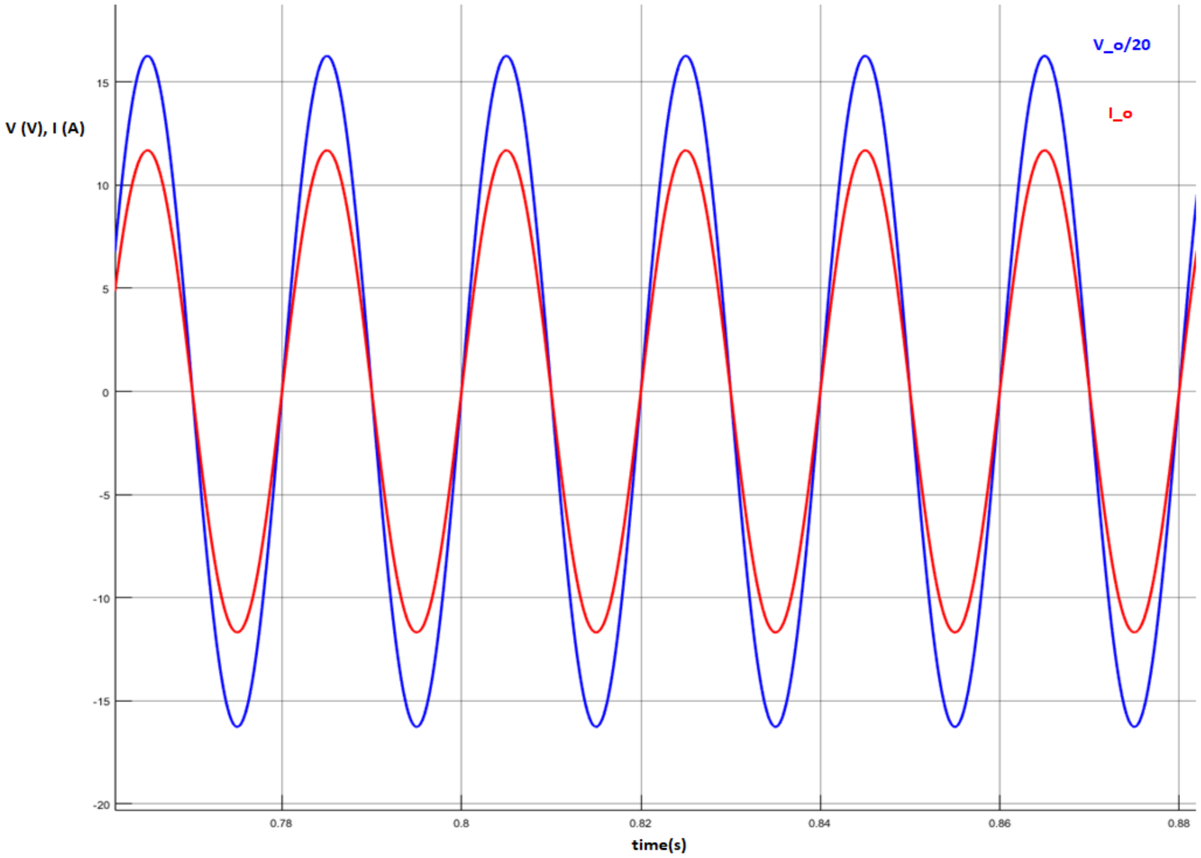


Figure 5.15: Output voltage (blue) and current (red) of the kettle connected to AC supply

Table 5-3 shows the simulation results of the appliances connected to the AC supply. The table contains the input and output power values of all the appliances, as well as the efficiency of each appliance.

The most efficient appliance components in the AC system are the washing machine motor and the refrigerator compressor, both at 99 %. The AC-input Flyback converters supplying the electronic loads all have an efficiency of 93 %. This differs from the electronic loads in the DC system. The reason for this is the current controller in the PFC rectifier keeps the input current characteristics the same for all the devices.

Table 5-3: Simulation results of the appliances and their components in AC system

Appliance	Input power (W)	Output power (W)	Efficiency (%)
Television	36.9	33	89.5
TV Decoder	23	20.6	89.6
DVD Player	9.6	8.1	84.4
Laptop	52.5	47.8	91
Radio	10.4	8.8	84.6
Cell charger	8	6.62	82.9
Fridge compressor motor	107.29	106	99
Fridge Evap. Fan	6	6	-
Fridge controls	33	15.44	47
Lights	80.8	73.5	90.9
Microwave magnetron	732	708	97
Microwave controls	49.24	35	71
Washing M. motor	241.5	238.6	99
Washing M. controls	71.24	51	72
Vacuum cleaner	1200	1200	-
Kettle	1900	1900	-
Geyser	2600	2600	-
Stove	3000	3000	-

5.3.2 Complete AC system results

The voltage and current waveforms measured at the main supply of the AC system are shown in Figure 5.16.

The power meter at the supply input measured an active power of 10522.62 W at full-load. The AC system has a power factor very close to 1 (0.996), which causes a small reactive power to flow in the supply. This is due to the resistive-inductive loads in the system and the small reactive currents flowing in the conductors. The complete AC system reaches steady state operation at around 0.7 seconds, where after this, the power measurements were taken.

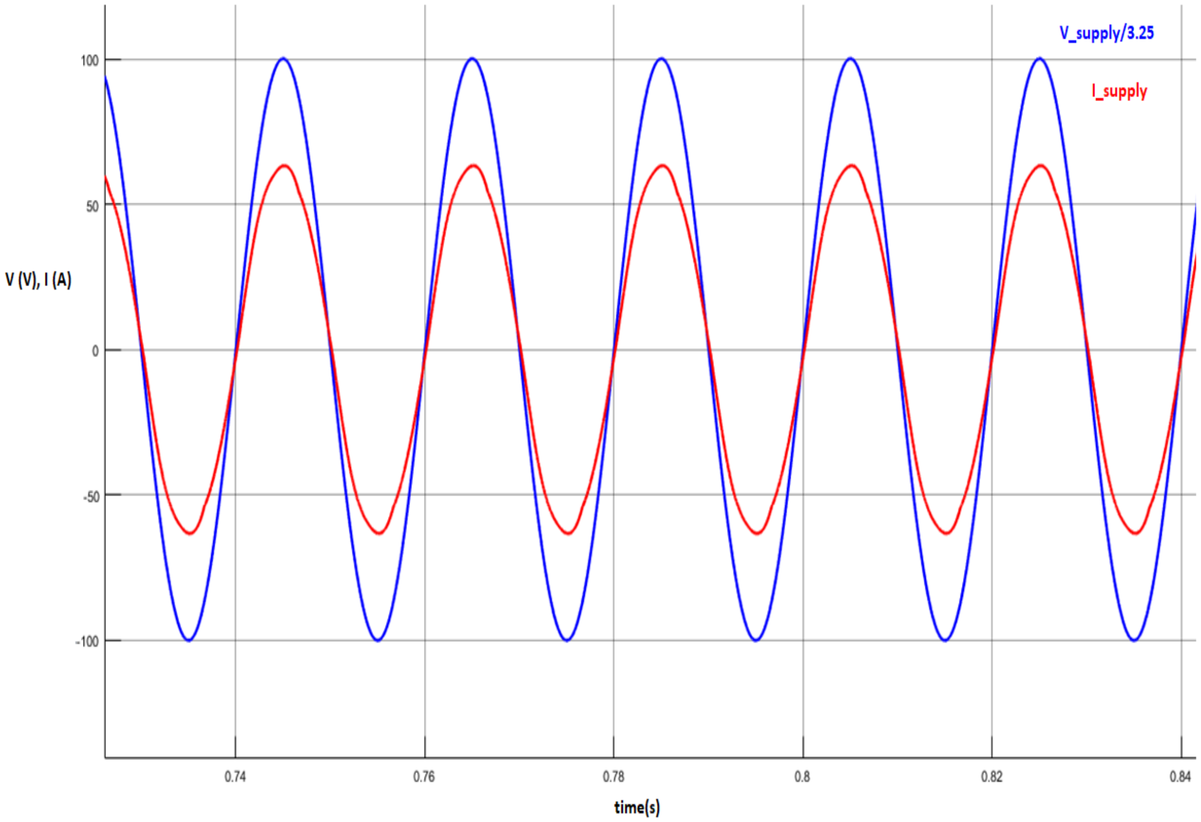


Figure 5.16: Waveforms of the AC system main supply

The resulting input and output waveforms of the DC-AC inverter are shown in Figure 5.17.

The value obtained for the input current of the converter is 9.61 A, which draws an input power of 461.25 W. The bottom part (b) shows the output voltage (blue) and current (red) of the converter. The output current of the converter with all the crucial loads connected (full-load), is measured at 1.6 A (rms). This gives an output power of 368 W and a total circuit efficiency of 80 %. The RES system has the same response time of 0.4 seconds, and the efficiency of the system is measured after this time has elapsed.

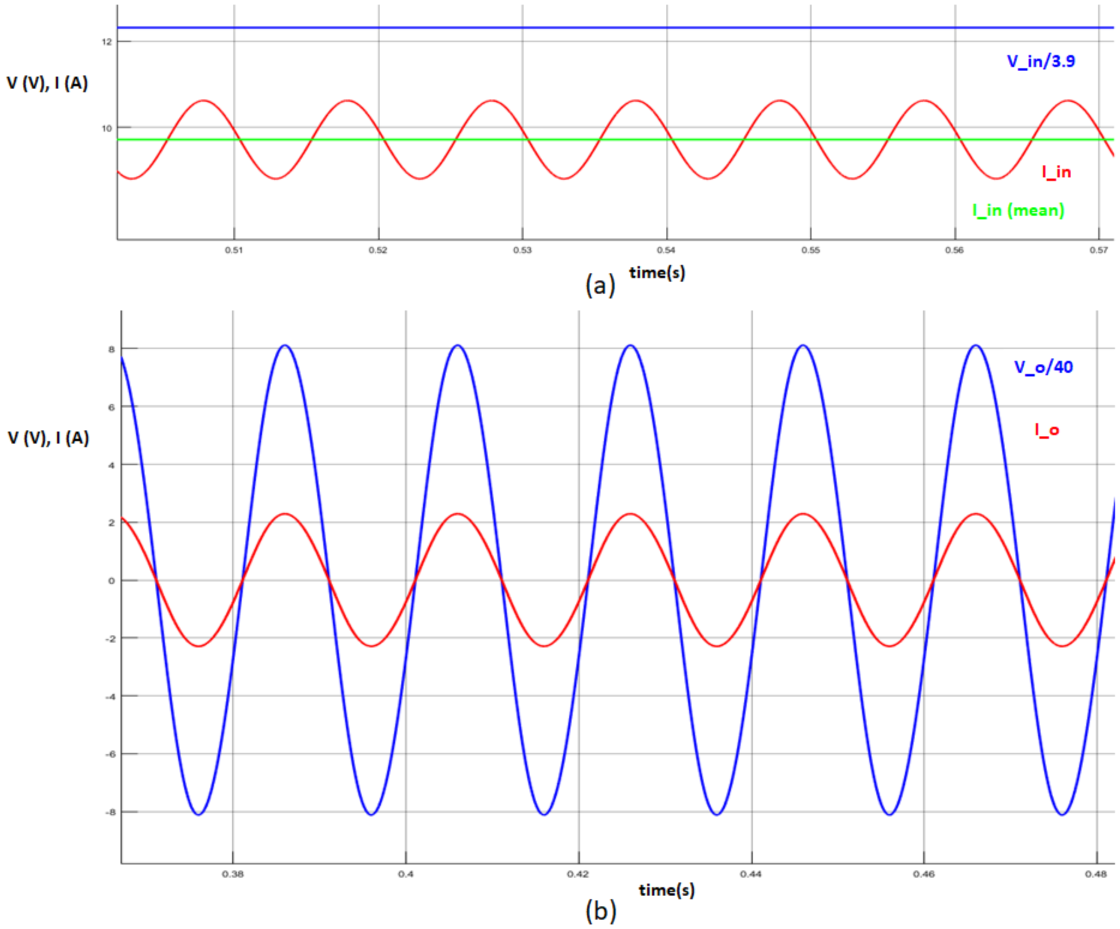


Figure 5.17: AC RES (a) input and (b) output waveforms (full-load)

In the AC RES system, the actual output power of 368 W corresponds well with the designed value, which is also 368 W. The RES system was also simulated in decremented load steps of 10 %, starting from full-load to low-load, and the system maintained an efficiency of 80 % throughout, because of the open-loop manual regulation.

Table 5-4 shows the simulation results of the complete AC system. With all the appliances connected to the main supply, the AC system gives an overall efficiency of 95.7 %, with a total power loss of 464.2 W. The RES system shows an efficiency of 80 % throughout and a total system loss of 92.85 W at full-load.

Table 5-4: Simulation results of the complete AC system

	Input power (W)	**Output power (W)**	**Power loss (W)**	**System Efficiency (%)**
RES supply	461.25	368	92.85	80
Main supply	10522.62	10058.46	464.16	95.7

5.3.3 AC/DC Hybrid system

5.3.3.1 AC-grid rectifier

Figure 5.18 shows the input (a) and output (b) waveforms of the bulk rectifier. With all the DC-based loads connected at the output of the rectifier, the output current is measured at 2.074 A. This gives a full-load output power of 674 W, which is the same as the designed value. The output of the rectifier gives the 325 V DC with minimum ripple to all the appliances connected at the output. The input current is measured at 3.349 A (rms) and this gives a total input power of 770.3 W. The bulk rectifier has a calculated efficiency of 87.5 %, and operates at unity power factor.

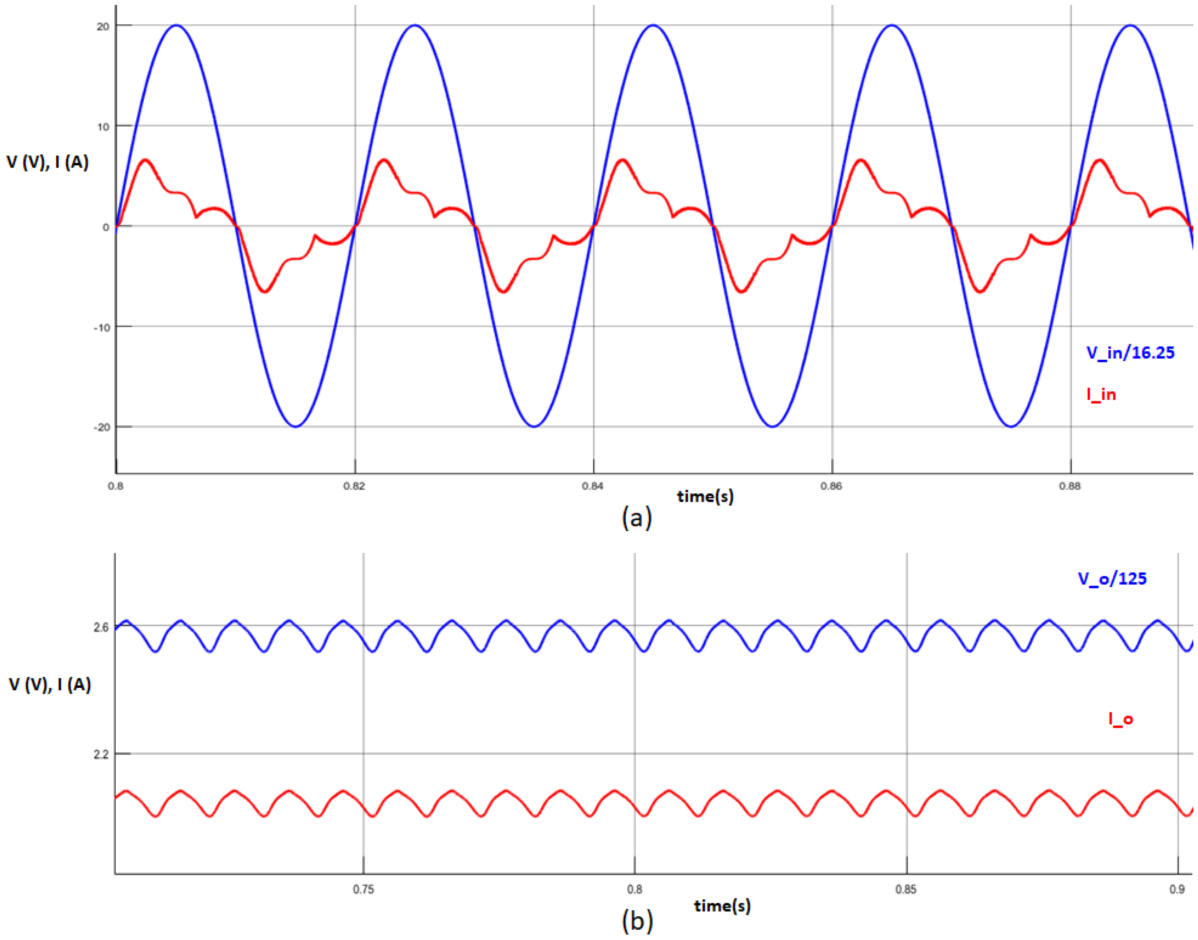


Figure 5.18: Single-phase PWM rectifier (a) input and (b) output voltage and current waveforms

A FFT analysis was done on 5 cycles of the input current of the rectifier, and the total harmonic distortion in the current waveform is 40.66 %. Figure 5.19 shows the frequency spectrum of the harmonic content in the input current waveform. The 5 cycles are highlighted in red in the top part of the figure. This work does not look at the power quality in AC systems or to improve the power quality in existing AC systems. The AC waveforms are only required to be in a suitable form that can be measured accurately.

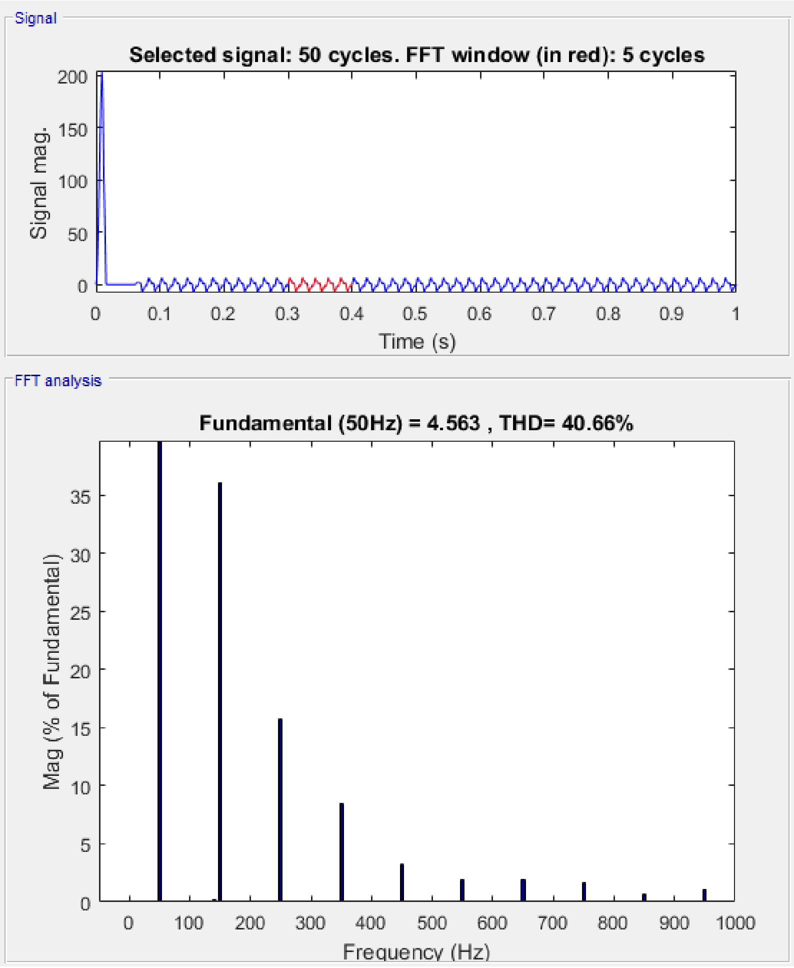


Figure 5.19: Frequency spectrum of the input current of the rectifier

5.3.3.2 Complete AC/DC hybrid system results

As mentioned in section 4.3.2, the hybrid system is a combination of the DC and AC systems. The electronic loads are all supplied via the bulk grid rectifier and the high power appliances are supplied by AC from the grid. Figure 5.20 shows the waveforms of the input voltage and current.

The uneven and rippled sinusoidal input current of the rectifier is merged with the supply current of the complete system. Most of the current drawn in the system is that of the high-power loads, which is a pure sine wave shape, and the uneven rectifier current has only a small effect on the waveform. The power meter at the supply input measured an active power of 10493 W at full-load. The combined output power of the system is 10058.46 W, giving a main supply system efficiency of 95.9 %. The complete system also has a near unity power factor of 0.996. The hybrid system, like the AC system, reaches steady state condition at around 0.7 seconds.

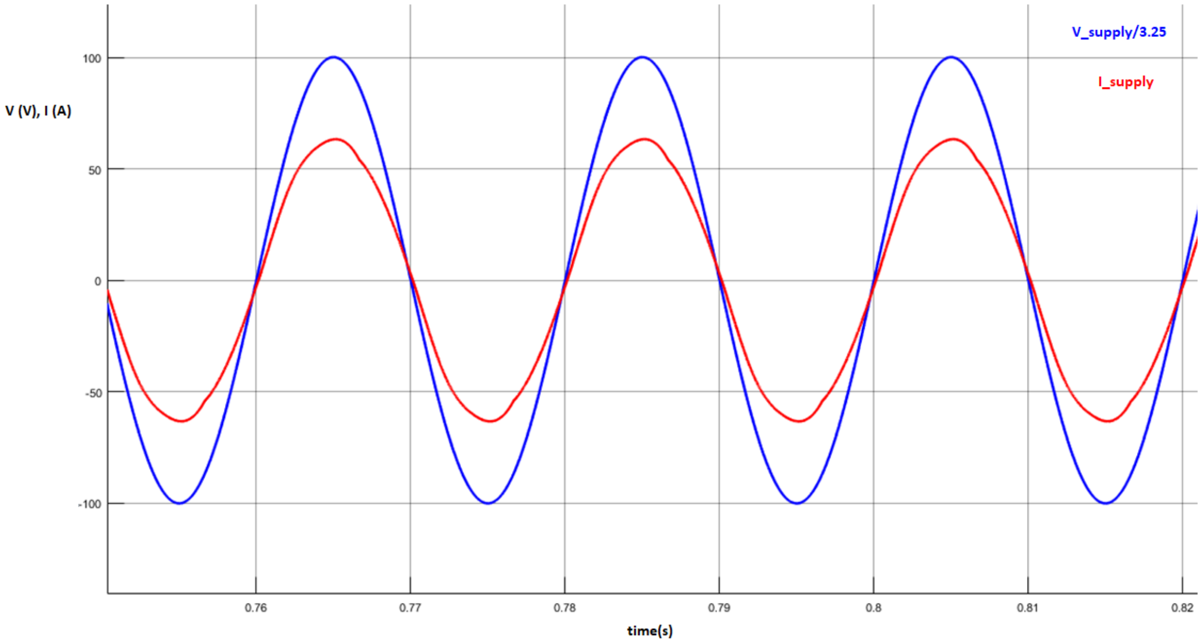


Figure 5.20: Input (supply) voltage and current of the complete hybrid system

The RES system in this configuration is the same as in the DC system. The same loads in Table 5-1 are being supplied by the same RES converter. Table 5-5 shows the simulation results of the complete hybrid system. With all the appliances connected to the main supply, the hybrid system gives an overall efficiency of 95.9 %, with a total power loss of 434.5 W. The RES system shows efficiency of 78 % throughout and a total system loss of 103.9 W at full-load, like in the DC system.

Table 5-5: Simulation results of the complete AC/DC hybrid system

	Input power (W)	**Output power (W)**	**Power loss (W)**	**System Efficiency (%)**
RES supply	467.9	364	103.9	78
Main supply	10493	10058.46	434.54	95.9

5.4 Performance comparison of configurations

This section gives a summary of the simulation results of the three configurations. Figure 5.21 shows the main and RES supply efficiencies of the three configurations. The results show that the AC/DC hybrid system has the highest main supply efficiency. The AC system follows with an efficiency of 95.7 %, only 0.2 % less than that of the hybrid system. The DC system main supply is the least efficient of the three, with a value of 94.9 %. There is only a difference of 0.8 % between the AC system and the DC system main supply efficiencies, making these two systems comparable. The main reason for the DC system being less efficient is because of the amount of input power drawn by the microwave oven when connected to a DC supply. In the DC system, the VDC supplying the cavity magnetron in the microwave oven requires an inverter in order to step up the voltage to the high frequency transformer. It is this high-power inversion stage which causes the large power loss in the supply circuit of the microwave oven, and ultimately, the DC system. Other studies in the literature review have not attempted the simulation of the microwave oven connected to a DC supply, and do not discuss this possible problem with DC distribution.

The hybrid system and the DC system make use of the same RES converter, so the RES supply efficiency of these two configurations is the same. The DC-AC inverter used as the RES converter in the AC system is 2 % more efficient than the full-bridge step-up DC-DC converter used in the DC and hybrid systems. This is the reason why the AC RES system shows better efficiency.

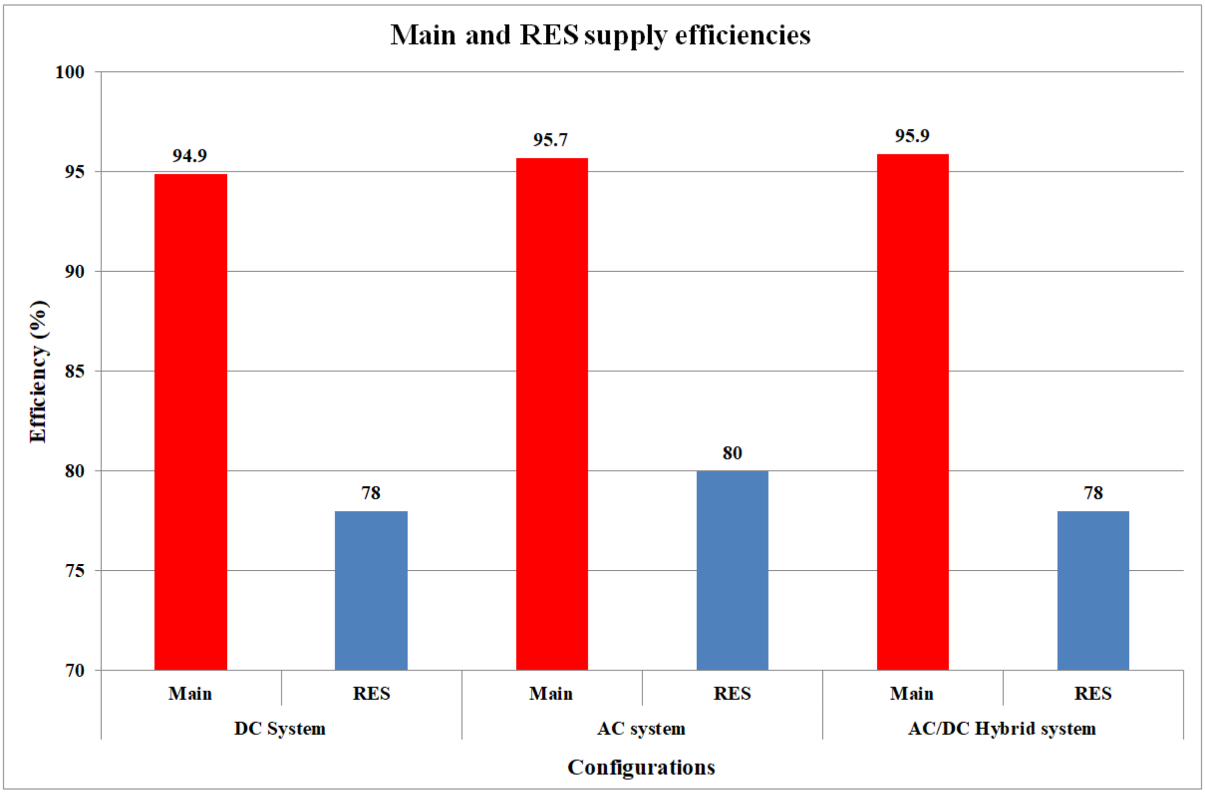


Figure 5.21: Main and RES supply efficiency comparison graph

An overall comparison of the parameters obtained from the simulations is done in Table 5-6. The full-load output power of the three configurations is the same. This is because the loads are all designed to give the same output power in all the systems, no matter the input. When comparing the main supplies, the DC system has the most system losses at 536 W, 72 W more than that in the AC system. This power loss is attributed to the microwave oven in the DC system. The RES in the AC system also gives slightly less losses than that in the DC and hybrid systems.

Table 5-6: Performance overview of the supply configurations

	DC system	**AC system**	**Hybrid system**
System output power (W)	10059	10059	10059
System input power (W)	10595	10522	10493
Full-load losses (W)	536.34	464.2	434.54
Main supply efficiency (%)	94.9	95.7	95.9
RES output power (W)	364	368	364
RES input power (W)	467.9	461.3	467.9
RES Full-load losses (W)	103.9	92.85	103.9
RES supply efficiency (%)	78	80	78
Average efficiency (%)[a]	86.45	87.85	86.95

[a]. average value of Main and RES efficiencies

Overall, the AC system is shown to be the most efficient of all the three, considering a combination of the main and RES supplies. This is only by a small margin. A low-voltage DC system can be much more efficient than the existing AC system, given two factors. Firstly, all the appliances in the system must be low-voltage appliances, which operate at the same voltage level, for example 48 V DC. Secondly, there must be no conversion stage between the output of the renewable energy source and the input to the loads. Some of the work that was looked at in the literature review did do studies using only low-voltage appliances however, these low-power DC systems were designed for off-grid purposes and for the electrification of rural areas.

5.5 Material Cost Breakdown

It is important to look at how much a DC system would cost, and to compare this cost to that of the existing AC system and the AC/DC hybrid system. In this section, a material cost breakdown is done on the equipment and hardware needed for each of the configurations. Hardware such as converters, wires, plug sockets, switches, and filter components are taken into consideration in order to see which configuration needs the largest capital investment. These costing figures are used to determine whether the system is worth the cost in a cost-performance tradeoff comparison. The appliances in the three systems do not form part of the costing; however, the rectification and filter stages of the appliances in the AC system are added to the total system cost of the AC system.

Table 5-7 shows the cost breakdown of the hardware needed for the DC system. Installation and labour costs are not considered, because these costs vary quite often and to a large extent in some cases.

Electrical hardware and equipment designed for DC applications are more expensive than the AC counterparts, mainly due to the different design and also the availability of the equipment. This is especially true for the DC circuit breakers (DC MCCB). The same cable sizes are used in the DC system so that the existing infrastructure does not have to be modified or replaced, and also to make a fair comparison between the DC system and the existing AC system.

Table 5-7: Costing for DC system

Item	p/p unit	Quantity	Cost
RES converter	R 1 250.00	1	R 1 250.00
63 A MCCB (2 pole)	R 545.00	1	R 545.00
20 A MCCB	R 350.00	4	R 1 400.00
10 A MCCB	R 250.00	2	R 500.00
30 A MCCB	R 400.00	1	R 400.00
Distribution board (empty)	R 200.00	1	R 200.00
Earth Leakage Protection	R 400.00	1	R 400.00
Wiring – 1.5 mm^2 [a]	R 590.00	0.6	R 354.00
Wiring – 2.5 mm^2	R 950.00	0.9	R 855.00
Wiring – 4.0 mm^2	R 1 404.00	0.6	R 842.40
Wall plugs	R 250.00	6	R 1 500.00
Isolators	R 185.00	2	R 370.00
Light switches	R 100.00	8	R 800.00
Total cost			**R 9 416.40**

[a.] 1 unit of wire = 100 meter roll

The cost breakdown of the hardware needed for the AC system is shown in Table 5-8. Similar numbers and type of equipment are used in the AC system as in the DC system. The only difference is the cost of the equipment. The AC MCCBs are considerably cheaper than the DC ones and are also more readily available. The RES converter in the AC system, which is a DC-AC inverter, is more expensive than the RES converter used in the DC system. The reason for this is that the components in the DC system RES converter (high-frequency design) are smaller than those in the AC system RES converter.

The rectification stages are not that expensive, compared to the other hardware in the system. The rectification stage consists of a diode bridge rectifier and a low-pass filter, and there are 13 needed in total.

Table 5-8: Costing for AC system

Item	p/p unit	Quantity	Cost
Rectification stage	R 12.00	13	R 156.00
RES converter	R 1 990.00	1	R 1 990.00
63 A MCCB (2 pole)	R 250.00	1	R 250.00
20 A MCCB	R 70.00	4	R 280.00
10 A MCCB	R 60.00	2	R 120.00
30 A MCCB	R 100.00	1	R 100.00
Distribution board (empty)	R 200.00	1	R 200.00
Earth Leakage Protection	R 350.00	1	R 350.00
Wiring – 1.5 mm^2 [a]	R 590.00	0.6	R 354.00
Wiring – 2.5 mm^2	R 950.00	0.9	R 855.00
Wiring – 4.0 mm^2	R 1 404.00	0.6	R 842.40
Wall plugs	R 150.00	6	R 900.00
Isolators	R 185.00	2	R 370.00
Light switches	R 75.00	8	R 600.00
Total cost			**R 7 367.40**

[a] 1 unit of wire = 100 meter roll

Table 5-9 shows the cost breakdown of the hardware needed for the AC/DC hybrid system. This is the most expensive of the three configurations, and by a large margin. There are two main reasons for this. The first is that the hybrid system requires a bulk grid-rectifier to rectify the incoming AC grid supply to a smooth DC voltage for the electronic loads, and this is an added cost.

The second reason is that the hybrid system uses hardware from both the AC and the DC systems. The DC hardware is shown to be more expensive, especially the circuit breakers with high current interrupting ability.

The hybrid system also needs two main circuit breakers (one for AC and another for DC), two sets of earth leakage protection, and two separate distribution boards.

Table 5-9: Costing for AC/DC hybrid system

Item	p/p unit	Quantity	Cost
Grid rectifier	R 2 100.00	1	R 2 100.00
RES converter	R 1 250.00	1	R 1 250.00
32 A MCCB (2 pole-DC)	R 400.00	1	R 545.00
10 A MCCB (DC)	R 250.00	4	R 500.00
63 A MCCB (2 pole-AC)	R 250.00	1	R 250.00
30 A MCCB (AC)	R 100.00	1	R 100.00
20 A MCCB (AC)	R 70.00	2	R 140.00
Distribution board (empty)	R 200.00	2	R 400.00
Earth Leakage Protection (DC)	R 400.00	1	R 400.00
Earth Leakage Protection (AC)	R 350.00	1	R 350.00
Wiring – 1.5 mm^{2} [a]	R 590.00	0.6	R 354.00
Wiring – 2.5 mm^{2}	R 950.00	0.9	R 855.00
Wiring – 4.0 mm^{2}	R 1 404.00	0.6	R 842.40
Wall plugs (AC)	R 150.00	2	R 300.00
Wall plugs (DC)	R 250.00	4	R 1 000.00
Isolators	R 185.00	2	R 370.00
Light switches	R 100.00	8	R 800.00
Total cost			**R 10 911.40**

[a.] 1 unit of wire = 100 meter roll

The AC/DC hybrid system is the most expensive, with a total hardware cost of R 10 911.40. This is followed by the DC system, with a total cost of R 9 416.40. The least expensive configuration is the AC system, with a total cost of R 7 367.40. By looking at the performance of these three configurations in section 5.4, and the hardware cost of each one, the logical conclusion would be that the AC system is the better option at this stage.

Chapter 6
Conclusions and Recommendations for Future Work

6.1 Conclusions

This work aimed to see whether it is possible to supply common household appliances directly with DC, instead of rectifying the AC grid voltage to DC first. The study was built on the premise that the supply to the house is a firm DC supply, provided by a nearby DC microgrid. Another aim was to see if on-site-small-scale renewable energy systems such as battery banks and small PV installations can be connected to the household grid without the need for inversion. The performance of this DC system was then compared to other supply configurations, such as the existing AC system, and an AC/DC hybrid system. These configurations were compared in terms of their efficiencies and power losses in both the main supply and the RES supply modes. A cost breakdown of the material required for each system was also done in order to find a trade-off between the performance and the cost of each system.

The bottom-up approach was used in this study, where the aim is to look at the load needs first, instead of selecting a supply to which all the loads have to conform to. A list of common household appliances available on the market in South Africa was used as the basis for the supply voltage selection, device modelling and simulation designs. Matlab and Simulink/SimPowerSystems software was used to simulate all the circuits and configurations. Results show that it is possible to supply a wide range of household appliances directly with DC. This, in turn, means that it is possible to remove the rectification stages in existing electronic devices and motor-driven appliances with inverter technologies. The complete DC system with all the appliances connected (full-load operation) to a firm DC supply, gives an efficiency of 94.9 %. The RES system, with the crucial loads connected to the on-site 48 V DC supply gives a constant efficiency of 78 %.

The appliances designed for the AC system are shown to be more or less just as efficient as the appliances in the DC system. This is reflected in the power measurements in the complete AC system as well. The complete AC system with all the appliances connected to a 230 V AC supply, gives an efficiency of 95.7 %, which is 0.8 % more efficient than the DC system. The DC-AC inverter used as the RES converter in the AC system has a constant efficiency of 80 %, making it 2 % more efficient than the DC RES system. The total AC system then is slightly more efficient, and is also the cheapest to install. The hybrid system has a main supply efficiency of 95.9 %, which is 0.2 % more efficient than the AC system. The hybrid system also has the highest material cost of the three configurations investigated.

The main reason why the DC system is less efficient is because of the high input power of the microwave oven, when connected to a DC supply. If the microwave oven is taken out of the equation, the DC system is more efficient than the AC system.

The Simulink software used for this work is extremely powerful and advantageous. It allows controllability of its components, where the logic and control functions can easily be designed and interfaced with the electrical components of the circuit. The software provided everything that was needed to fulfil the research requirements. A downside however is the simulation time of the complete system. The complete system simulation time is extremely long but, is needed in order to get accurate results.

6.2 Future work

Future works and recommendations are to model wider range household loads and to model these loads in full-detailed operation. Another recommendation is to physically modify the supply input stages of the appliances and to investigate the practical aspects when connecting these appliances to a 325 V DC supply. A practical test-bed setup can also be built, with all the appliances connected to a main DC supply and a renewable energy source. Interaction between supply and load can also be investigated by implementing advanced microgrid control systems such as smart grid control, coupled with some sort of demand-side-management (DSM) system. Another recommendation is to find a DC design solution for supplying the microwave oven that does not incur large power losses.

The Simulink models created in this study for the complete configurations can be used as templates by other researchers. The models can be used to simulate fault conditions on the network and to add control devices like circuit breakers and/or fuses. Transient states and circuit breaker coordination can be modelled into the templates as well. Another useful study would be to simulate multiple DC houses, and to integrate various generation sources (AC and DC based) into the network. This will however pose its own challenges, especially regarding simulation times and equipment not included in the libraries of whichever software is used.

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