DEVELOPMENT OF BOUNDARY CONDITIONS TO SELECT SUITABLE AC AND DC WIRING TOPOLOGY FOR FUTURE RESIDENTIAL HOUSES

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Abstract

Photovoltaic (PV) panels are installed on present-day residential houses which generate Direct Current (DC) power, and the energy is then stored in Battery Energy Storage Systems (BESS). DC power from the PV panels is usually converted into Alternating Current (AC) as the existing electrical power distribution is AC. Then the AC power is converted back into DC to energise the DC-based appliances.

DC-based appliances such as laptops, mobile phones, Tablets, Light Emitting Diode (LED) lamps, etc usage is exponentially increasing in the present market. This scenario opens the opportunity to directly utilise the DC electricity produced by PV panels without going through the conversion stages. Therefore, using DC wiring based residential houses, electrical energy losses will be reduced substantially by avoiding the conversion from DC power to AC and back to DC.

The low voltage DC concept is not new, but significant progress could not be achieved due to lack of tools and standards for DC power distribution. Some research has been reported in the literature to experimentally test and compare AC and DC wiring options. However, extensive accurate and precise experimental measurements are vital for establishing a sound theoretical basis, and this is difficult due to cost and time constraints.

House wiring simulation models were developed using standard cable impedance without consideration of ambient temperature, proximity and skin effect. Similarly, simplified converter circuits with oversized components were considered which is not practical. Moreover, there is no validated simulated model or tool reported in the literature to verify the simulation model results of AC and DC homes.

As reported in the literature, power losses in AC and DC cables have been compared using mathematical models. It is a significant contribution; however environmental and installation considerations were not considered to compare power losses. Furthermore, the mathematical comparison doesn't include the converter modelling to compare complete AC and DC wiring options. Power loss equations for different types of converters use different approaches, however, there is no validated mathematical model which has used a similar approach to estimate the losses of all types of converters along with the power losses in cables. Moreover, the cost factor is not covered in previous research work which does not include the installation cost along with the running cost of energy losses. Based on the previous research work, it is difficult for residential consumers to select the most efficient and cost-effective wiring topology from 230V AC, 12V DC, 24V DC and 48V DC.

Addressing the gaps in the literature, this PhD research developed a mathematical model for AC and DC wiring systems which includes the total power losses in cables and converters. This research is further supported by the validation of these models through experiments and simulations studies.

Finally, the boundary conditions are developed to select an efficient wiring topology among AC and DC systems for a house based on the operating conditions such as power rating of load, size and length of conductors. Using the developed boundary conditions, all residential houses with DC-based sources will have three wiring topology options AC, DC or mix.

The mathematical modelling is limited to the technical aspects therefore, three-bedroom and single bedroom house scenarios have been investigated from the cost-benefit perspective. The results show that the 48V DC or the hybrid wiring options would be the most suitable going forward based on this research. Since the most efficient and

cost-effective wiring option depends on the number of factors including the house design, living standard, these results would continue to evolve with the continuous changes in the technology of DC sources, DC loads and converters.

Keywords:

AC System, DC System, Converter losses, Cable Losses, DigSilent Programming Language, Efficient DC loads, Energy Efficiency, House Wiring, DigSilent/Power Factory Digital Simulation Model, Wiring Topologies, Climate Change

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List of Acronyms

AC	Alternating Current
AS/NZS	Australian Standard / New Zealand Standard
AUT	Auckland University of Technology
BLDC	Brushless Direct Current
BESS	Battery Energy Storage System
CB	Circuit Breaker
CoD	Coefficient of Determination
DC	Direct Current
DG	Distributed Generation
DPF	DigSilent Power Factory
DPL	DigSilent Programming Language
EPRI	Electric Power Research Institute
ES	Energy System
EWRB	Electrical Worker Registration Board
ENA	Electricity Network Association
EDB	Electricity Distribution Board
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronic Engineering
KESC	Karachi Electric Supply Company

LED	Light Emitting Diode
LVAC	Low Voltage AC
LVDC	Low Voltage DC
LV	Low Voltage
MPPT	Maximum Power Point Tracking
MATLAB	Matrix Laboratory
NEMA	National Electrical Manufacturers Association
PV	Photovoltaic
TPS	Tough Plastic Sheath
TV	Television
UPS	Uninterrupted Power Supply

List of Units

kWh	Kilowatt Hour
MWh	Megawatt Hour
MW	Megawatt
m	Metre
mm	Millimetre
TWh	Terawatt Hour
V	Volt

List of Symbols

α	Coefficient of linear expansion
$\cos \phi$	Power factor of the load
f	Frequency of AC supply from the grid
k_P	Proximity effect coefficient
k_S	Skin effect coefficient
L	Length of the cable
N_p	Total number of connected loads
N_l	Total number of wire length options
N_w	Total number of wire sizes
N_v	Total number of voltage levels
P	Power
ΔP_{ac}	Power losses in AC line
$\Delta P_{ac,3}$	Power losses in three-phase AC lines
ΔP_{dc}	Power losses in DC line
$P_{l,AC-DC}$	Power loss in an AC-DC converter at 25 ^oC temperature
$P_{l,DC-AC}$	Power loss in a DC-AC converter at 25 ^oC temperature
$P_{l,DC-DC}$	Power loss in a DC-DC converter at 25 ^oC temperature
$P_{l-t,AC-DC}$	Power loss in an AC-DC converter at ambient temperature
$P_{l-t,DC-AC}$	Power loss in a DC-AC converter at ambient temperature
$P_{l-t,DC-DC}$	Power loss in a DC-DC converter at ambient temperature

$P_{l,C}$	Power losses of a converter at 25 ℃ temperature
P_{T-AC}	Total power losses in AC wiring topology
$P_{l-t,c}$	Power losses of a converter at ambient temperature (T)
r_{20^0}	Conductor resistance per unit length at 20℃
R_{AC}	The AC resistance of the conductor
r_{AC}	The cable AC resistance per phase per unit length
R_{DC}	The DC resistance of the conductor
r_{DC}	DC resistance per unit length
T	Operating temperature of the conductor in ºC
t_f	Temperature factor of a converter
U_{ac}	RMS AC Phase voltage
V_{in}	Input voltage
X	Experimental Efficiency
Y	Mathematical Efficiency
Y_P	Proximity effect factor
Y_S	Skin effect factor

Attestation of Authorship

I **Junaid Ahmed Qureshi**, hereby declare that this submission is my own work and that to the best of my knowledge and belief, it contains no material previously published or written by another person or material which to a substantial extent has been submitted for the award of any other degree or diploma of a University or other institution of higher learning.

Signature

31^{st} Aug 2021

Chapter 1 Introduction

1.1 Significance of Research

In the existing AC based wiring topology of a residential house, DC power from photovoltaic panels or battery banks must be converted into AC. Most of the efficient electrical appliances internally work on DC, e.g., air conditioners, refrigerators, submersible pumps, universal motors, variable frequency drives, LED lamps, brushless DC (BLDC) fans, laptops, computers, TV, mobile phones, etc. These DC devices require conversion of the available AC power into DC. These DC-AC and AC-DC power conversion stages result in substantial energy losses.

It is well known that globally the amount of energy wasted is of the order of 1,000 TWh and most of these energy losses are due to the electrical power conversion from DC to AC and back (Pellis et al., 1997) ; (Vossos, 2011). Conversion losses in a typical home today run between 500 kWh to 1,000 kWh per year. Around 14% of power losses could be reduced by avoiding the conversion from AC to DC as summarised in Table 1.1 (Garbesi, 2012). This opens the opportunity to utilise the DC electricity produced by a Photovoltaic (PV) panel directly using DC power distribution.

Greenhouse gas emissions are one of the global concerns in the 21st century. New Zealand has also signed the Paris Agreement to move towards a zero-carbon future. Carbon emissions can be reduced through efficient and clean electricity generation, efficient electricity distribution and its utilisation. Therefore, better energy efficiency measures are needed due to environmental degradation and climate change.

The objective of this research is to contribute towards global significance by identifying the most efficient and cost-effective wiring option for residential houses.

1.2 Research Motivation, Assumptions

Emerging technologies are changing the way electricity is generated and used. This Section covers the motivation based on the increased penetration level of emerging technologies such as Distributed Energy Resources and efficient DC loads. The research work in this thesis is based on the following two assumptions.

1.2.1 Penetration of DC Loads

Many organisations such as Duke Energy, Lawrence Berkeley National Laboratory developed the DC models of AC loads. A comprehensive catalogue of DC appliances has been published by Lawrence Berkeley National Laboratory, University of California. According to this research, 33% of the total household load power demand could be reduced by using DC appliances with the existing AC grid as summarised in Table 1.1 (Garbesi, 2012). Netherland Energy Research Foundation found that 2,089 kWh per year could be conserved per household in the Netherland as a result of replacing AC loads with DC loads (Pellis et al., 1997).

Extensive research has been completed in manufacturing DC models of electrical appliances (D.Little, 2011; Söderström & Soorian, 2010). In (M. Amin, Y. Arafat, S. Lundberg, & S. Mangold, 2011), a combined DC refrigerator and stove has been designed. Similarly, in (Lucia Oscar, 2013), an induction heating cooktop has been designed to operate with DC power.

Table 1.1: Estimated energy savings by using DC as compared to AC (Garbesi, 2012)

Appliance	**(A) Energy savings from switching to DC- compatible run on AC**	**(B) Energy Savings from avoided AC-DC losses**
Lighting-Incandescent	73%	18%
Lighting-Reflector	71%	18%
Lighting-Torchiere	69%	18%
Refrigerators	53%	13%
Freezers	53%	13%
Dishwashers	51%	12%
Electric Water Heaters	50%	12%
Electric Space Heaters other than Heat Pumps	50%	12%
Spas	50%	12%
Central Air Conditioners	47%	11%
Electric Clothes Dryers	45%	11%
Room Air Conditioners	34%	11%
Furnace Fans and Boiler Circulation Pumps	30%	13%
Clothes Washers	30%	13%
Ceiling Fans	30%	13%
Electric Cooking Equipment	12%	12%
Lighting-Fluorescent	1%	18%
Home Audio	0%	21%
Personal Computers and Related	0%	20%
Rechargeable Electronics	0%	20%
DVDs/VCRs	0%	30%
Security Systems	0%	10%
Colour TVs and Set-Top Boxes	0%	15%
Coffee Makers	0%	13%
Electric Other	0%	13%
Microwave Ovens	0%	13%
Electric Heat Pumps	0%	12%
Geothermal Heat Pumps	0%	12%
Solar Water Heaters	0%	12%
Electric Heat Pumps	0%	12%
Geothermal Heat Pumps	0%	12%
Electric Secondary Space Heaters	0%	11%
Average savings (consumption weighted)	33%	14%

In research (Qureshi, Lie, Hasan, & Mujtaba, 2016), LED lamps have been taken as an example to further quantify the impacts of DC loads in Pakistan. As compared to the traditional AC lamps, the expected impact of LED lighting could result in a significant load reduction of 2,522.5MW which is equivalent to 10.5% of the total demand of Pakistan as of 2014. This demand reduction would be more meaningful for projected power demand. In another similar research work (Qureshi, Lie, & Hasan, 2016), the use of an efficient DC LED lighting scheme showed that the demand curves were significantly modified, and the peaks were removed. The improvements in similarity factors were estimated to be 43.45% in summer and 11% in winter. These results show that the DC load can be used as an energy management technique as well. With this drastic improvement in the similarity of curves and conservation of energy, the utility company can overcome the power demand with economic feasibility without needing to invest money in power generation, transmission and distribution networks.

1.2.2 Penetration of DC Sources

The dynamics and structure of power systems have changed dramatically in the last few decades. Distributed Generators (DGs) are now preferred to save the transmission and distribution power losses along with an increase in reliability in case of natural disaster. Various international organisations have considered DG, focusing on commercial buildings with the aim of zero energy buildings (Patterson, 2012). The increasing numbers of DG units, which generate DC power such as Photovoltaics (PVs) and household wind turbines, not only help the domestic consumers to reduce electricity bills but also provide a backup power supply in case of a power outage in the grid.

The Head Water company in New Zealand has installed the PV systems at Camp Glenorchy accommodation site, contributing towards a sustainable future. The trend of solar energy is extensively increasing due to the significant drop in the price of PV panels.

It is also evident from the growing number of solar power units installed by various organisations in New Zealand. Electricity Network Association (ENA) is actively working on the uptake of PVs which is evident from their Road Map. Electricity Development Boards (EDBs) in New Zealand are also getting ready for network transformation to maximise the benefits for their consumers as per their asset management plan. The International Energy Agency (IEA) has estimated that the solar energy share would be 11% of the global electricity generation (Blakers et al., 2009).

On the other hand, Battery Energy Storage Systems (BESS) have a significant role in distributed energy sources in the grid (C. A. Hill, 2012). Major applications of the BESS include an uninterruptible power supply (UPS), renewable energy systems, battery-powered devices and tools like mobile phones, laptops, drills, screwdrivers, etc. (Joseph & Shahidehpour, 2006). BESS applications would increase going forward due to the concept of pricing-based demand response by residential and commercial consumers.

In research (Qureshi, Lie, Gunawardane, Kularatna, & Qureshi, 2017), a residential house was operated in two different configurations, being AC source mode and DC source mode. The battery storage system was charged and discharged similarly in both configurations. The efficiency of the energy system can be increased by 6.39% in a residential house by replacing the AC source with a DC source.

1.2.3 Assumptions Regarding Future Residential Houses

Two assumptions have been made in this research work regarding future residential houses based on the expected penetration of DC loads and DC sources discussed in the previous Section. Results of this thesis would be useful for houses applying the following two assumptions.

1. Efficient DC loads would be used in future residential houses

It is evident from some of the existing research work presented in Section 1.1.1 that the demand for DC loads is increasing drastically. Therefore, it is assumed that the DC loads would replace the existing AC loads.

2. DC energy systems, e.g. Solar/PV would be used in future residential houses.

Some research work identifies the potential of the DC sources in future grids concerning the total energy conservation and the environmental focus as discussed in Section 1.1.2. The research work encourages the residential electricity users to move toward renewable energy DC sources for the BESS charging. Moreover, DC sources like PV based Energy Storage (ES) are used in the DG concept. Therefore, it is assumed that the DC sources would be used in future residential houses.

1.3 Scope and Structure of the Thesis

The scope of this PhD thesis is to compare the efficiency and cost of AC wiring topology with DC wiring topology for future residential houses where DC source and DC loads are used. The structure of this PhD thesis is outlined in Figure 1.1.

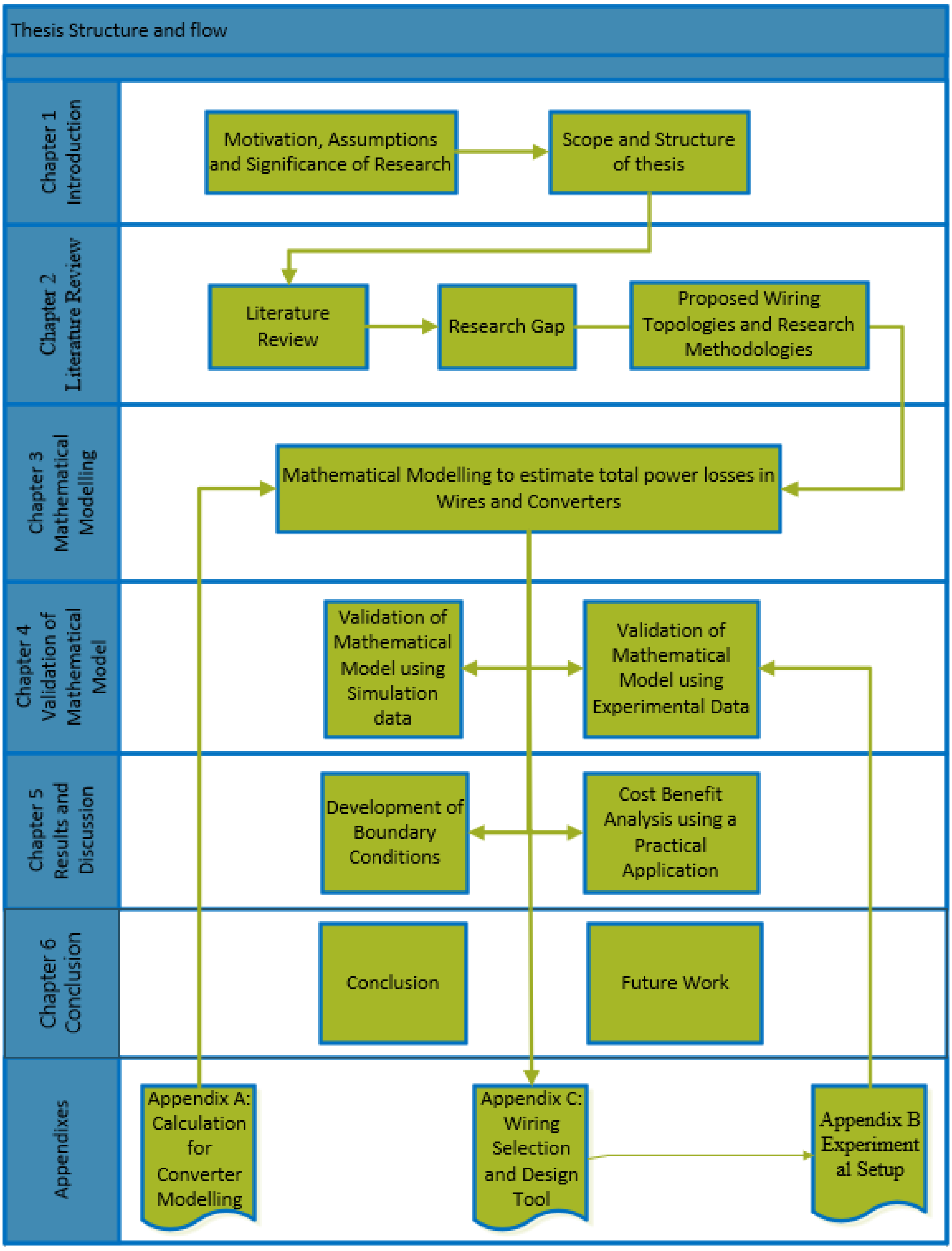

Figure 1.1: Research scope and Thesis Structure

Chapter 1 highlights the key motivation behind this research work along with the basis of assumptions regarding the penetration of DC loads and DC sources; these define the limitations of this research work when it comes to real-world application. This chapter also discusses the global significance and research flow along with the scope of this thesis.

Firstly, Chapter 2 covers the literature review and the contributions from previous research work to compare the AC and DC wiring topologies and their research methodologies such as through mathematical modelling, simulation and experimentation. Secondly, this chapter includes the development of AC and DC wiring topologies based on gaps in the literature, market trends and the assumptions made in Chapter 1. Finally, research questions are raised and methodologies designed to pursue this research.

Chapter 3 focuses on the mathematical modelling of the AC and DC wiring topologies proposed in Chapter 2. The objective of mathematical modelling is to estimate the total power losses in AC and DC wiring topologies which can help to compare the efficiency of wiring options.

Chapter 4 aims to validate the mathematical models using experimental and simulation studies. Experimental validation includes the installation of a solar energy system with AC and DC wiring options to determine the correlation between experimental and mathematical modelling. It also includes the system design as per New Zealand Standards along with experimental setup and measurements as per the requirements of the Electrical Worker Registration Board (EWRB). Simulation validation includes the development of Simulation models in DigSilent Power Factory software which is used by many Electrical Distribution Boards (EDBs) for network modelling and planning such as Aurora Energy.

Chapter 5 utilises the mathematical model to develop the boundary conditions for thousands of possible wiring cases which show the most efficient wiring options for various cable sizes, cable lengths and load power ratings. Overall trends are analysed from the boundary conditions to develop a general understanding. However, these boundary conditions do not include a cost-benefit analysis. Therefore, this research is applied to the typical residential houses to compare the efficiencies along with the cost.

Chapter 6 concludes this thesis followed by recommendations and future work. Some directions for policy and guidelines have been identified for New Zealand jurisdictions. It has also identified some more technical areas of research that will become necessary if DC wiring becomes predominant in the future.

Chapter 2 Literature Review of AC and DC Systems

The concept and comparison of AC and DC were first done by Edison and Tesla. AC was preferred due to the invention of the transformer. AC voltages are easily transformed so distribution losses are reduced by stepping up the voltage whereas DC cannot be transformed so the distance of distribution is reduced compared to AC. Tesla championed AC and Edison favoured DC. However, with power electronics it's easy to invert, transform and then rectify, or simply to change the DC voltage directly. This comparison has been revived again due to the developments in power electronics (Porter et al., 2014).

Many organisations including the American Institute of Architects, the U.S. Department of Energy and the Energy Efficient Buildings Hub focused on Low Voltage DC (LVDC) for new commercial buildings (Patterson, 2012). On the other hand, Penn State Centre for National Electrical Manufacturers Association (NEMA), Grid Star Centre and Electric Power Research Institute (EPRI) have started to focus on the conversion of existing buildings into DC (Patterson, 2012). The High Voltage DC (HVDC) concept is well established and has been implemented worldwide (Long & Nilsson, 2007). However, the LVDC area has a lot more potential to grow.

This Chapter aims to review the wiring topologies and research methodologies studied in the literature including case studies, simulation, experiments and mathematical modelling.

2.1 Review of AC and DC Wiring Topologies for Residential Houses

Various types of wiring topologies have been used to explore the feasibility of LVDC homes. These topologies have been customised over the last decade based on the research hypotheses, scenarios, technology development and emerging technologies as discussed in this Section.

2.1.1 Wiring Topologies with Hybrid (both AC and DC type) Loads

(D. Nilsson & A. Sannino, 2004), investigated generalised AC and DC wiring topologies in a residential house with the hybrid source and the hybrid load scenario as expressed by Figure 2.1 and Figure 2.2.

The research (D. Nilsson & A. Sannino, 2004) compares the efficiency of a 230V AC wiring system with a 325V DC wiring option and demonstrated the lower lines losses due to the lower current at 325V DC. This was a good point to build more understanding of wiring topologies, but the efficiency results are not valid as the internal AC-DC converter losses of loads in the AC wiring topology have been ignored. Moreover, the calculations rely on future technology developments and the results are based on reducing semiconductor losses by 50%.

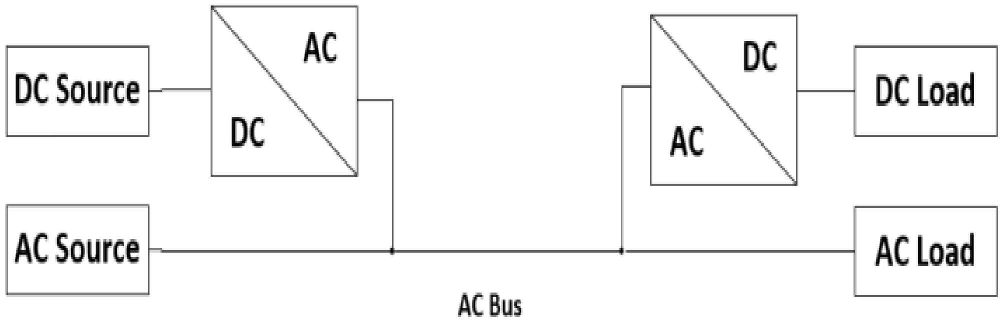

Figure 2.1: Proposed AC wiring topology 01 (D. Nilsson & A. Sannino, 2004)

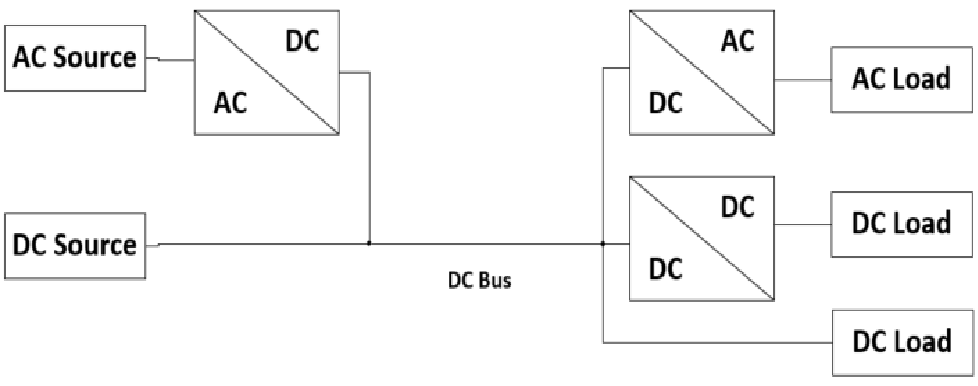

Figure 2.2: Proposed DC wiring topology 02 (D. Nilsson & A. Sannino, 2004)

Research (Amin, Arafat, Lundberg, & Mangold, 2011) compared the efficiency of a 230V AC wiring topology shown in Figure 2.3 with the LVDC wiring topology in Figure 2.4. On the other hand, there are few aspects to consider from this previous research (Amin et al., 2011). Firstly, power losses in AC and DC wiring topologies were not compared on similar grounds. Source and load combination were not similar in both wiring topologies, so the wiring efficiency comparison was not valid. Secondly, the AC source was proposed in DC wiring topology in Figure 2.4 but was not used as part of power loss calculations, therefore the source side AC-DC conversion losses have been ignored. This gives efficiency gains to the proposed DC wiring topology in Figure 2.3 as compared to the AC wiring option in Figure 2.4. Finally, wiring topologies in Figure 2.4 and Figure 2.4 were more focused on applications where the sensitive load is used.

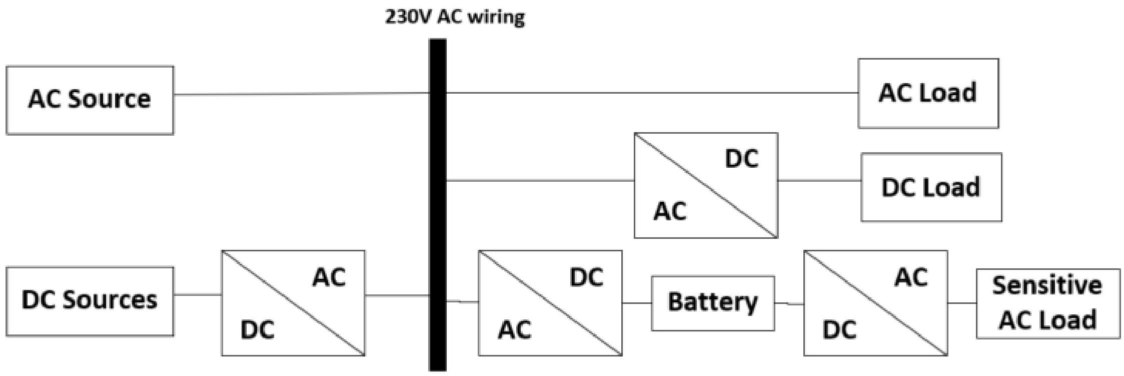

Figure 2.3: Proposed AC wiring topology 02 (Amin et al., 2011)

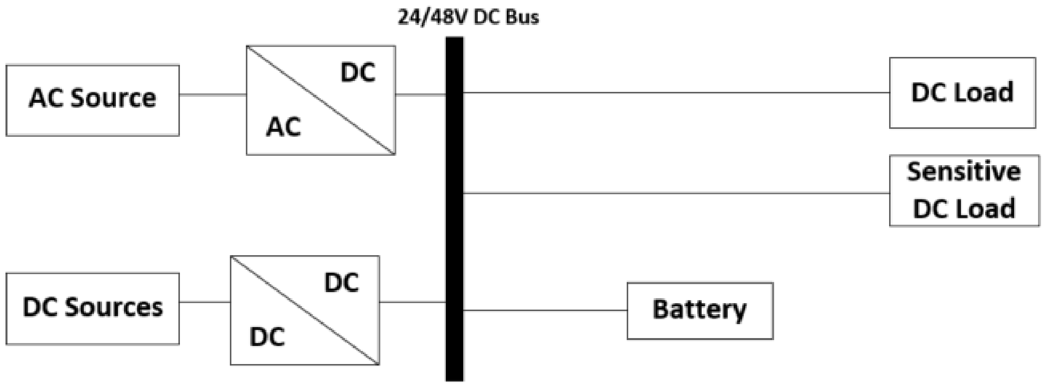

Figure 2.4: Proposed DC wiring topology 02 (Amin et al., 2011)

Another previous research (Seo et al., 2011) considered the existing AC grid options that feed LVDC load, AC heating and Variable Frequency Drive (VFD) motors such as heat pumps, refrigerators and the like as shown in Figure 2.5. This previous research proposed a 380V DC wiring topology where the main AC supply is converted into DC using an AC-DC converter to feed LVDC load, the DC heating and similar VFD motors as shown in Figure 2.6. In the DC wiring topology, the main AC-DC converter needed to operate at variable loading so a set of three converters was proposed in this Figure 2.6 to maximise the efficiency. Based on MATLAB simulations, the DC wiring topology was found to be 1.5% more efficient as compared to AC wiring. Moreover, this research proposed a DC distribution network so that the DC supply could be available directly to increase the efficiency up to 4.7%.

On the other hand, there are few aspects to consider from this previous research (Seo et al., 2011). Firstly, the power losses of AC wiring topology could be reduced by using one conversion to feed DC loads via an AC source rather than a two-stage conversion as proposed in Figure 2.5. However, based on the proposed topology, another stage was required to utilize the DC loads at various voltage levels. Secondly, the DC wiring topology in Figure 2.6 requires a control mechanism to utilise the set of three main AC-DC converters based on loading. Therefore, the minimal 1.5% increase in efficiency does not worth it due to the considerable increase in the cost and complexity of the circuit. Finally, the reliability of the proposed DC wiring system would be much less than the AC wiring topology due to the additional control circuit and main converters.

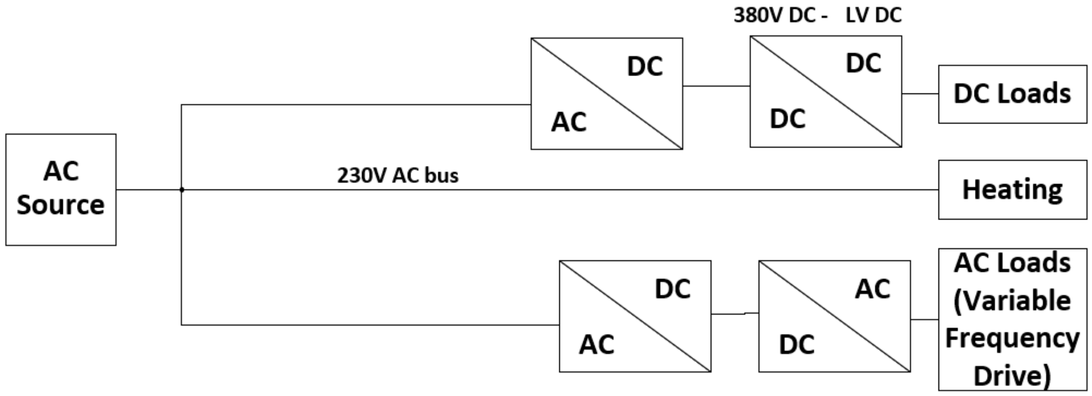

Figure 2.5: Proposed AC wiring topology 03 (Seo et al., 2011)

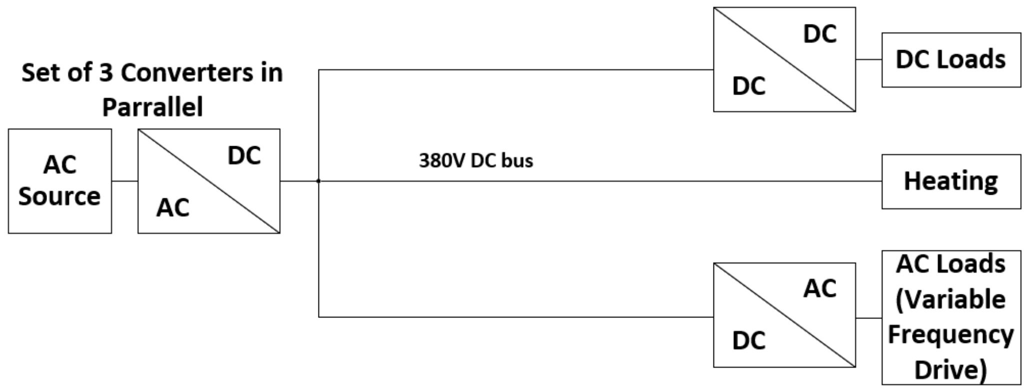

Figure 2.6: Proposed DC wiring topology 03 (Seo et al., 2011)

In research (Dastgeer & Gelani, 2017), an AC wiring topology was proposed for when the distribution network supply is 230V AC as shown in Figure 2.7 and, similarly, the DC wiring topology was proposed when the distribution network supply is 230V DC as shown in Figure 2.8. The reason is to compare both topologies at the same wiring voltage so that the line losses are almost the same for both topologies. AC wiring topology was found to be more efficient when there is no VSD based load. However, the DC wiring topology was found to be more efficient when the VSD based load contributes more than 9%.

From this previous research (Dastgeer & Gelani, 2017), few aspects need to be considered such as (i) this research proposed 230V DC wiring in Figure 2.8 which requires the same safety protection as 380V DC but has more line losses compared to the proposed 380V DC wiring topology in Figure 2.6 (Seo et al., 2011); (ii) this research assumed replacement of the whole AC distribution network with a DC distribution network in future, but the present load remains hybrid. This assumption is not practical as the existing AC distribution network/grid will not change until, and unless, all existing AC loads in residential, commercial and industrial buildings as would be replaced with DC.

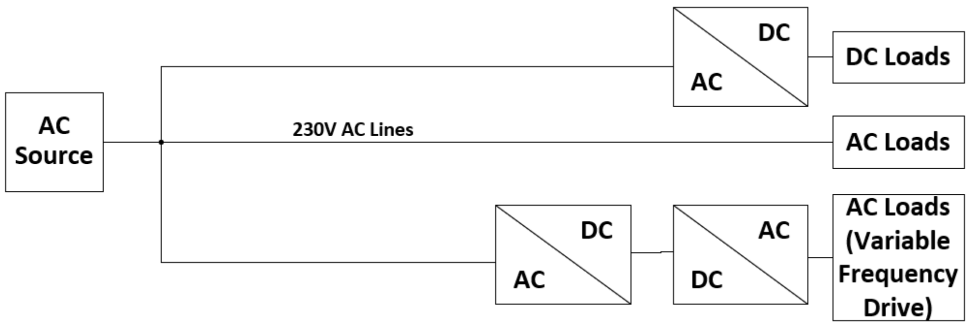

Figure 2.7: Proposed AC wiring topology 04 (Dastgeer & Gelani, 2017)

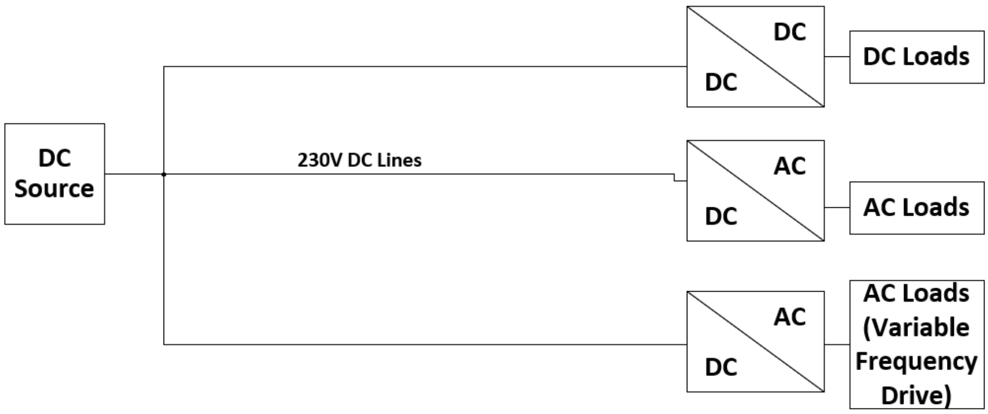

Figure 2.8: Proposed DC wiring topology 04 (Dastgeer & Gelani, 2017)

2.1.2 Wiring Topologies with DC loads

Another research paper (Rasheed, Khan, Gelani, & Dastgeer, 2019), used a similar approach to the topology in Figures 2.7 and 2.8 i.e. 230V AC source for AC wiring topology and 380V DC source for DC wiring topology as shown in Figures 2.9 and 2.10. However, the load type has been changed to entirely DC, based on future assumptions. This research employed MATLAB simulation methodology and concluded there was a 3.62% efficiency gain in the DC system compared to the AC system.

On the other hand, there are few aspects to consider from this previous research (Rasheed et al., 2019). The supply is not similar for both wiring topologies, so it does not compare the same scenario for both wiring options. Moreover, this research is limited to the comparison of 380V DC only and does not consider the low voltage DC wiring options which are mostly used in residential solar systems. Therefore, a DC-DC converter would be required to convert the LVDC source voltage to 380V DC.

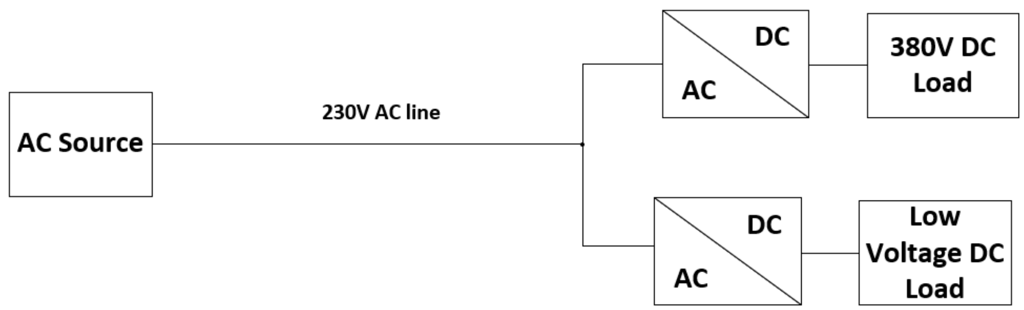

Figure 2.9: Proposed AC wiring topology 05 (Rasheed et al., 2019)

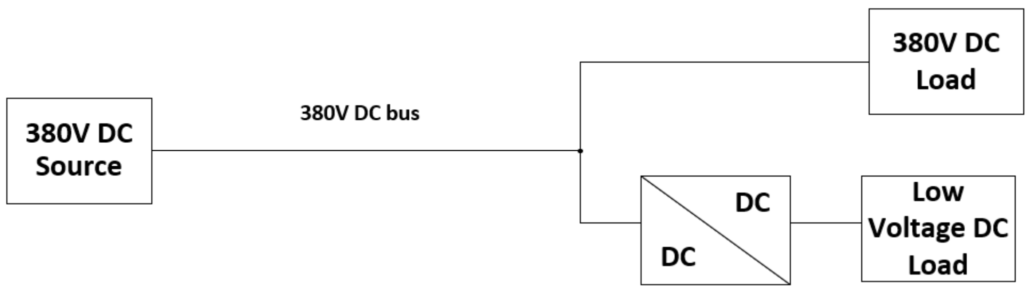

Figure 2.10: Proposed DC wiring topology 05 (Rasheed et al., 2019)

Another research (Gerber et al., 2017), compares 120V AC wiring topology with multi-voltage topology i.e. 380V DC and 48V DC wiring as shown in Figures 2.11 and 2.12. Load types and connections are similar to the previous topology shown in Figures 2.9 and 2.10 and a hybrid power source has been proposed which is similar for both cases. Simulation-based efficiency results concluded that the DC wiring topology can be up to 17% more efficient than AC wiring when enough DC power is available from a DC source such as PV panels.

On the other hand, there are few aspects to consider from this previous research (Gerber et al., 2017). Firstly, the building wiring lengths and loading data are unknown, so efficiency results from this case study are difficult to apply to actual applications. Secondly, the efficiency results from this research are not reliable as the components have been oversized by 400% which is neither practical nor cost-effective. Finally, in current residential houses, the DC power source directly charges battery banks at the LVDC bus; however, the proposed AC wiring topology adds two extra conversion steps to charge a battery from the DC source as shown in Figure 2.11. This additional conversion reduces the efficiency of AC wiring topology significantly and DC topology was found to be 17% more efficient. This research concluded that DC distribution is not economically justified without battery banks.

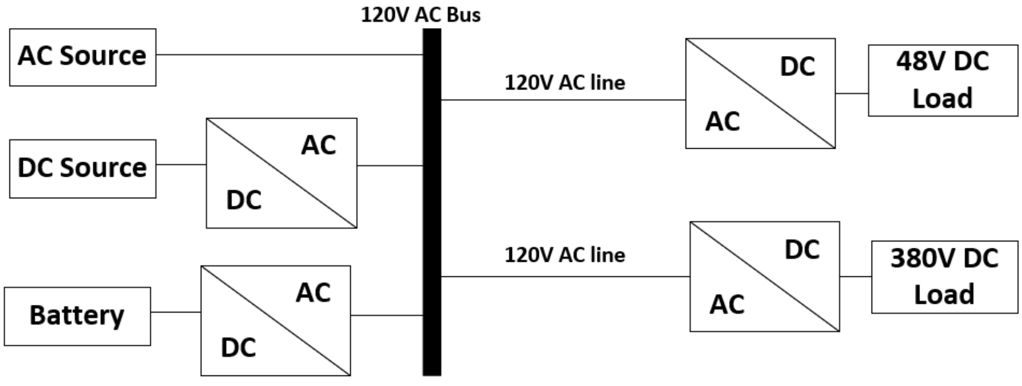

Figure 2.11: Proposed AC wiring topology 06 (Gerber et al., 2017)

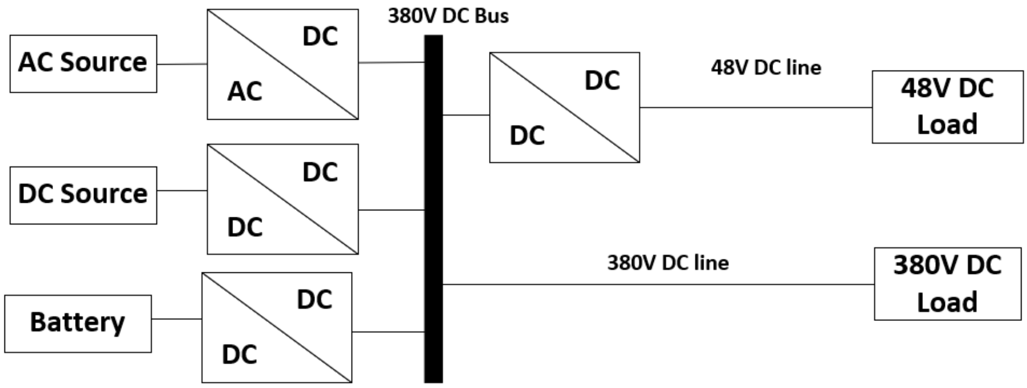

Figure 2.12: Proposed DC wiring topology 06 (Gerber et al., 2017)

Another research paper (Cvetkovic et al., 2012) is more focused on experimental validation of the 380V DC house model as shown in Figure 2.13. This wiring topology is similar to Figure 2.2 except the load type is based on DC loads only. Literature prior to this paper was based on simulations and case studies to compare AC wiring with DC wiring topologies but this experimental implementation was a contribution in terms of practical testing. However, this research does not compare DC wiring topology with AC wiring options. It is more about concept proofing of DC wiring options.

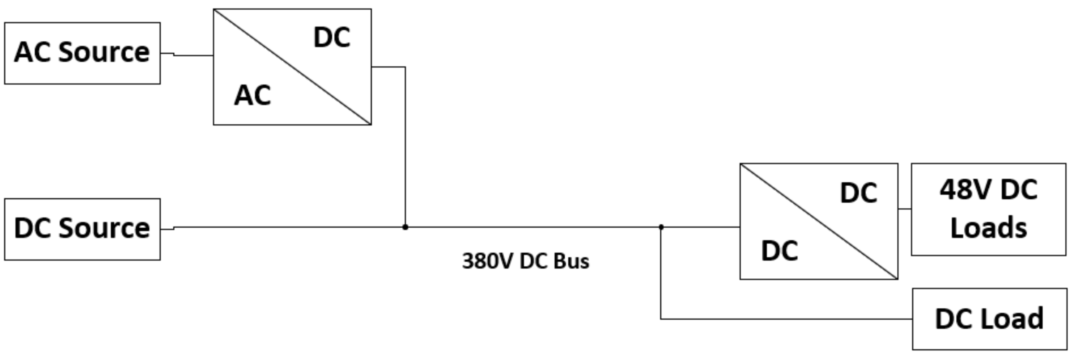

Figure 2.13: Proposed DC wiring topology 07 (Cvetkovic et al., 2012)

In other research (Jain, Vijay, Bhuvaneswari, & Singh, 2016) a 100W capacity solar system with a 13.6V DC wiring option for consumers not having access to grid electricity was proposed. The wiring topology in this research is also based on Figure 2.1. This research is focused on the design, simulation and concept proofing of 13.6V DC wiring topology rather than comparison to other wiring options.

2.1.3 Wiring Topologies with DC Sources and DC loads

Wiring topologies in recent research have not used any AC source and load which supports the assumptions made in Chapter 1. Wiring topology in another previous research (Cetin et al., 2010) has proposed multiple DC sources and DC loads with two DC line voltages to directly supply DC to 12V and 24V DC loads as shown in Figure 2.14. This previous research (Cetin et al., 2010) proposed an off-grid DC home concept using multiple DC sources connected to a single DC bus.

There are few aspects to consider from this previous research (Cetin et al., 2010). Firstly, it is more about experimental concept proofing with a cost estimation of DC sources, wiring topology and DC loads. Secondly, it does not consider the power loss estimation or comparisons to other wiring options. Thirdly, the length of wiring has been ignored and the DC voltage selection is based on the power rating of load. Finally, the efficiency of this wiring topology would vary based on the percentage loading on both DC-DC converters as each converter has been used to feed the group of DC loads.

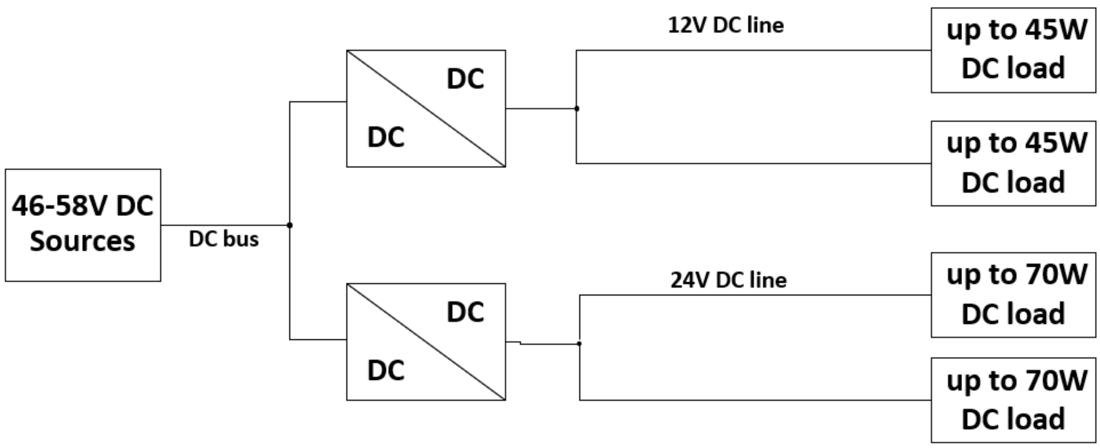

Figure 2.14: Proposed DC wiring topology 08 (Cetin et al., 2010)

DC wiring topology in other research (Rahman et al., 2019) has proposed to connect 48V DC solar output to DC loads directly as shown in Figure 2.15. Firstly, this research is focused on the design and cost of the DC system rather than from an efficiency perspective. Secondly, this research is limited to one DC wiring topology and does not compare the proposed topology with the AC wiring option. So, this work does not contribute to wiring topology comparison, however, it strongly supports the wiring topologies having DC sources and DC loads. Finally, it was assumed that the DC loads would be standardised at 48V DC which is not the case for all loads.

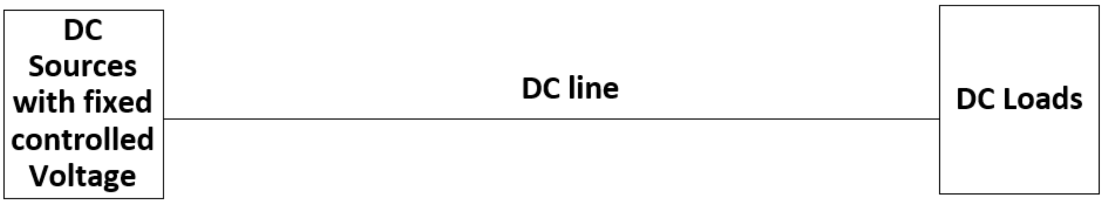

Figure 2.15: Proposed DC wiring topology 08 (Rahman et al., 2019, Moussa et al., 2019)

Recent research (Moussa, Ghorbal, & Slama-Belkhodja, 2019) is also based on Figure 2.15 which compares the DC bus voltages (12V, 24V, 48V, 60V and 100V DC) from an efficiency and cost perspective using a case study of a 1kW standalone DC home. The 60V and 100V DC wiring options were not recommended as DC loads were not available at this voltage level. 48V DC voltage was found to be a cost-benefit option. However, all DC loads do not operate at 48V DC, so a DC-DC converter should have been considered as part of the cost-benefit analysis. Moreover, this research does not compare the DC bus voltage with AC wiring options, and it is not supported by experiments and mathematical modelling.

In another recent research (Kamran et al., 2017) compares the 220V AC wiring system with a 308V DC wiring topology as shown in Figures 2.16 and 2.17. This research is focused on the transformation of existing AC loads which internally work on DC. This mainly includes the replacement of AC-DC conversion by DC-DC conversion so that all appliances operate on DC.

On the other hand, there are few aspects to consider from this previous research (Kamran et al., 2017). Firstly, the efficiency estimations of wiring topologies are limited to one case study and are based on the assumed overall efficiencies. Secondly, this research is not supported by any mathematical modelling or experiments. Thirdly, it does not include any low voltage DC options such as 12V DC, 24V DC and 48V DC. Finally, the existing AC lines can support up to 380V DC to minimize the losses and the reason for 308V selection was not clear in the research.

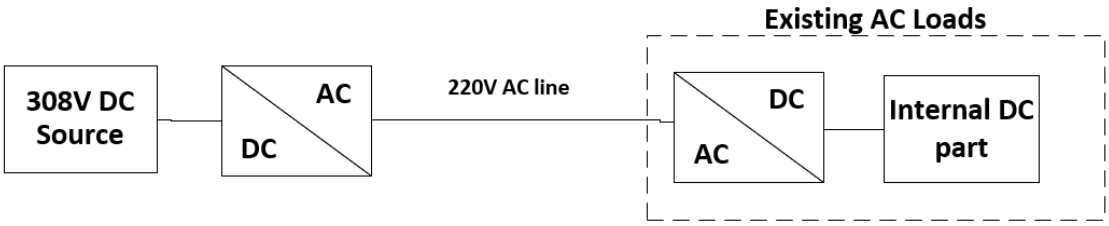

Figure 2.16: Proposed AC wiring topology 07 (Kamran et al., 2017)

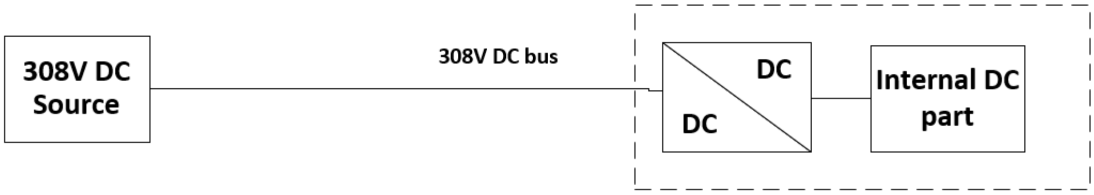

Figure 2.17: Proposed DC wiring topology 09 (Kamran et al., 2017)

2.2 Review of Research Methodologies

The majority of research papers have analysed wiring topologies with the help of simulation models, experiments and case studies. Table 2.2 outlines the research methodologies used in the literature discussed in Section 2.1. These methodologies have contributed well to concept proofing of DC wiring topologies and each of them gives a distinct idea of energy savings for house wiring cases only as explained in Table 2.1.

Table 2.1: Summary of Research Methodology

(Author name & Year)	**Simulation**	**Experiment**	**Case study**	**Mathematical Modelling**		**Cost Estimation**	
				Line	**Converters**	**DC Wiring Topology**	**AC wiring Topology**
(Daniel Nilsson & Ambra Sannino, 2004)			Yes	Yes	Yes		
(Cetin et al., 2010)		Yes	Yes			Yes	
(Seo et al., 2011)			Yes		Yes		
(Amin et al., 2011)			Yes	Yes		Yes	
(Cvetkovic et al., 2012)		Yes	Yes				
(Rani, Vignesh, Gunaki, & Jhunjhunwala, 2016)	Yes		Yes				
(Jain et al., 2016)	Yes		Yes				
(Thielemans, Di Zenobio, Touhafi, Lataire, & Steenhaut, 2017)		Yes	Yes				
(Gerber et al., 2017)	Yes		Yes			Yes	Yes
(Dastgeer & Gelani, 2017)			Yes				
(Kamran et al., 2017)			Yes				
(Rasheed et al., 2019)			Yes				
(Rahman et al., 2019)	Yes		Yes			Yes	
(Moussa et al., 2019)			Yes			Yes	

As discussed in Section 2.1, these research papers are limited to the case studies summarised in Table 2.1 However, there are thousands of possible wiring cases where power losses in AC and DC wiring topology vary drastically due to losses in power cables and converters. Therefore, a validated power loss estimation method is required to develop boundary condition charts that can help us to select the most efficient wiring option for the hundreds of possible cases/circuits in a residential house depending on the load power, cable size, cable length, wiring installation and operating conditions. So, the review of power loss estimation methods has been done in detail.

A few research papers (Amin et al., 2011; Daniel Nilsson & Ambra Sannino, 2004; Seo et al., 2011) have used the mathematical modelling approach to calculate the power losses in wiring topologies; however, only one research paper (Daniel Nilsson & Ambra Sannino, 2004) has modelled both line and converter power losses as summarised in Table 2.1. Moreover, these mathematical models of wiring topologies have not been validated by experimental or simulation studies.

2.2.1 Estimation Methods for Power losses in AC and DC lines

Research (Daniel Nilsson & Ambra Sannino, 2004) has used the fundamental power loss equation in AC and DC lines as expressed in Equations 2.1A and 2.2B.

$$\Delta P_{ac} = 2\mathrm{r}L * I_{ac}^2 \qquad (2.1A)$$

$$\Delta P_{dc} = 2\mathrm{r}L * I_{dc}^2 \qquad (2.1B)$$

where,

ΔP_{ac} = Power losses in AC line

ΔP_{dc} = Power losses in DC line

r = Resistance per unit length

L = Length of cable

I_{ac} = AC Current

I_{dc} = DC Current

This previous research (Daniel Nilsson & Ambra Sannino, 2004) has used cable datasheet resistance as a generalised resistance for both AC and DC lines. There are few aspects to consider from this previous research. Firstly, the installation conditions like the grouping factor of cable have also been ignored which can affect the AC resistance of cable depending on the number of cables in a group. Secondly, the operating conditions, e.g. skin effect were also ignored in the case of AC resistance. Finally, the effect of ambient temperature on both AC and DC resistances was not considered.

Another previous research (Amin et al., 2011) used a similar method to calculate the power losses in AC and DC lines as shown in Equations 2.1A and 2.1B. This research used Equation 2.2 to calculate the resistance of cable rather than using the resistance value from the cable datasheet.

$$\mathrm{R} = \rho \ \frac{l}{A} \tag{2.2}$$

where,

$\rho = 1.7 \ \times 10^{-8} \ \Omega/m$ is the resistivity for copper

l = length of cable

A = Area of the cable

There are few aspects to consider from this previous research (Amin et al., 2011). Firstly, the environmental temperature, to which the resistance of the cable is directly proportional, was not considered. Secondly as mentioned earlier, AC resistance can be more than DC resistance due to skin effects and proximity factors. Finally, this research has used a similar equation to calculate the AC and DC resistance of cable which can lead to inaccurate results during the comparison of power losses in AC and DC lines.

Therefore, this thesis has utilised the research work from literature and filled the knowledge gaps to precisely calculate the power losses in cables with the consideration of wiring installation and operating conditions.

2.2.2 Estimation Methods for Power losses in Converters using Overall Efficiency

Most of the previous research works outlined in Table 2.1 have used the overall efficiency of converters as summarised in Table 2.2 rather than using any mathematical equation. The efficiency of converters varies with the percentage loading and it is maximum at full load as shown in Figure 2.18 (Rasheed et al., 2019). Previous research studies have used the maximum efficiency with the assumption of full load operating conditions. However, oversized (rating) converters are used in a practical scenario to allow for the de-rating factors due to the input voltage and ambient temperature as shown in Figures 2.19 and 2.20 (MeanWell, 2019). This means a converter does not always operate at full load efficiency. Therefore, the use of the actual converter efficiency produces accurate results for comparing AC and DC wiring topologies.

Table 2.2: Efficiencies of converters in literature and experiments

References	Converter Efficiencies in %		
	AC-DC	**DC-AC**	**DC-DC**
(Cetin et al., 2010)			88.00
(Amin et al., 2011)	85.00		
(Rani et al., 2016)	93.00		93.80
(Thielemans et al., 2017)	85.2 -87.1		95.1 - 96.9
(Dastgeer & Gelani, 2017)	85-95	85-95	90-95
(Kamran et al., 2017)	85.00	85.00	85.00
(Rasheed et al., 2019)	86-90	88-97	89-98
(Moussa et al., 2019)			78.00

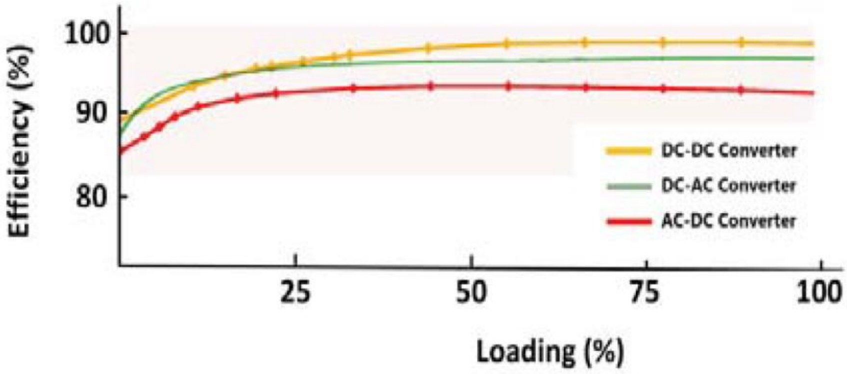

Figure 2.18: Converter Efficiency Vs % Loading (Rasheed et al., 2019)

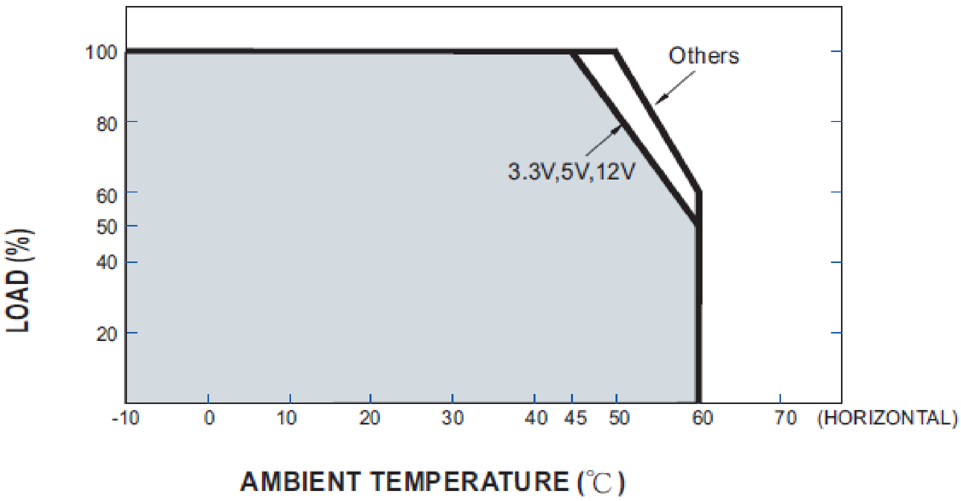

Figure 2.19 AC-DC converter de-rating curve based on ambient temperature(MeanWell, 2019)

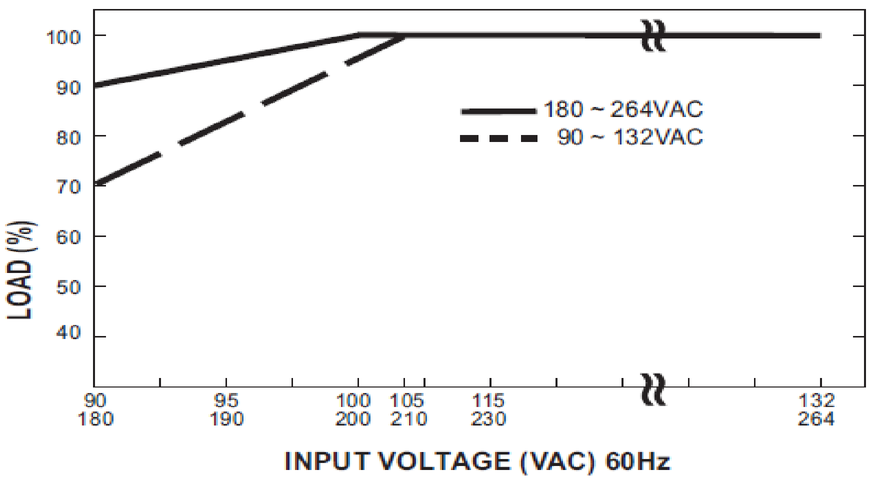

Figure 2.20 AC-DC converter de-rating curve based on input voltage (MeanWell, 2019)

2.2.3 Estimation Methods for Power losses in Converters using Mathematical Models

Relevant previous research works have been summarised in this Section that used mathematical models to estimate the power losses in converters. Previous research (Daniel Nilsson & Ambra Sannino, 2004) used AC-DC, DC-DC and DC-AC converters in wiring topologies but the mathematical equations were developed for AC-DC converters only. A voltage-source AC-DC converter based on an IGBT module was selected to estimate the power losses. The mathematical equations for conduction and switching losses were developed as expressed in Equations 2.3 and 2.4.

$$\Delta P_{cond} = \frac{2\sqrt{2}\,.\,V_{on}\,.I_{rms}}{\pi} + r_{on}\,.\,I_{rms}^{2} \tag{2.3}$$

$$\Delta P_{sw} = \frac{2\sqrt{2}}{\pi}.\frac{I_{rms}}{I_{nom}}.\left(E_{on} + E_{off}\right).f_{sw} + E_{RR}\,.f_{sw} \tag{2.4}$$

Where,

I_{rms} = The RMS value of the actual current through the IGBT

r_{on} = The on-state resistance of the IGBT

V_{on} = The on-state voltage drop

E_{on} = The energy losses during turn-on

E_{off} = The energy losses during turn-off

E_{RR} = The reverse recovery energy of IGBT

f_{sw} = Switching frequency

In the previous research (Daniel Nilsson & Ambra Sannino, 2004), the power loss calculation of the AC-DC converter is not accurate as the load current is partly carried by

IGBT and partly passed through the anti-parallel diode. Moreover, this model is limited to IGBT-based converters only and cannot be used for other types of switches such as MOSFET.

Another research by (Seo et al., 2011) compared the AC and DC wiring topology using MATLAB simulation. A component-based power loss equation approach was used to calculate the total power losses in converters. MOSFET switch, diode and inductor power losses equations were taken from a power electronics fundamentals book (Ericson & Dragan, 2000). The conduction and capacitive losses in the switches were calculated using Equations 2.5 and 2.6. The conduction, capacitive and reverse recovery loss of diode was calculated using Equations 2.7, 2.8 and 2.9. The copper and core losses of inductors were calculated using Equations 2.10 and 2.11.

$$P_{switch\_cond} = \frac{V_o^2 . I_o^2}{V_{rms}^2} . \left(1 - \frac{8}{3\pi} \frac{\sqrt{2} . V_{rms}}{V_o}\right) . R_{ds\_on} \tag{2.5}$$

$$P_{switch\_cap} = \frac{1}{2} . C_{ds} . V_{ds}^2 . f_{sw} \tag{2.6}$$

$$P_{diode\_cond} = V_F . I_o \tag{2.7}$$

$$P_{diode\_cap} = \frac{1}{2} . C_{ds} . V_{ds}^2 . f_{sw} \tag{2.8}$$

$$P_{diode\_reverse} = Q_{rr} . V_{in} . f_{sw} \tag{2.9}$$

$$P_{copper\_loss} = R_l . i_{rms}^2 \tag{2.10}$$

$$P_{core\_loss} = P_{core} . \frac{f_{sw}}{f_o} \tag{2.11}$$

Firstly, these equations are quite useful but are not universally applicable to different types of converters. The equation needs to be adjusted in accordance with the converter schematics diagram.

Secondly, the capacitor power losses of converters were not considered in the total power estimations. The power losses of converters include capacitor charging loss, conduction loss, switching loss, and control circuit loss (Zhiguo, Fan, & Peng, 2005).

Thirdly, power electronics technology is focusing on more efficient converter topologies which needs specific consideration based on the component and algorithm. For example, research by (Fernando & Kularatna, 2015; Kularatna, 2015) proposed to use supercapacitors in converters and the standard equations do not apply for that topology.

Finally, the effect of ambient temperature has not been considered to estimate power losses of the converter's components. Changes in ambient temperature not only affect the converter capacity as considered above in Figure 2.19 but also affect the power losses.

This impact of ambient temperature on efficiency has not been considered in the previous research work (Itoh, Inoue, Ishigaki, Sugiyama, & Umeno, 2018; Rijanto et al., 2018; Yang et al., 2017). In 2017, Research (Hou, Li, Zhao, & Wang, 2017) showed the critical role of temperature-related losses and the power loss behaviour of each component with the change in temperature as shown in Figure 2.21.

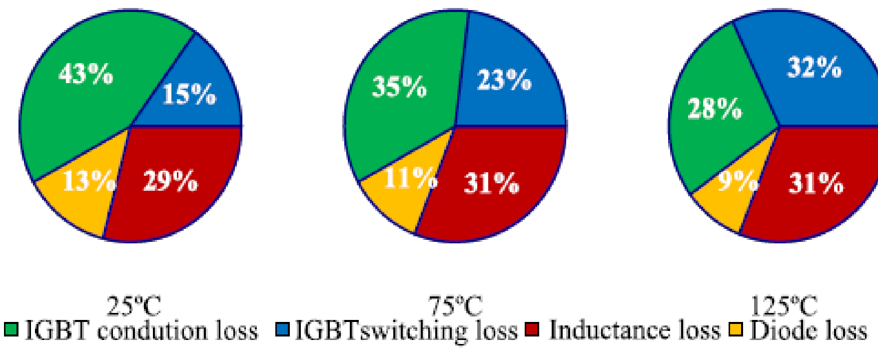

Figure 2.21: Power losses of converter components at different temperatures

This recent research (Hou et al., 2017) work has covered the effect of ambient temperature on power losses of basic DC-DC converter based on IGBT switches as shown in Figure 2.22. The power loss calculation is limited to basic proposed circuitry. However, converters available in the market have many additional blocks as shown in Figure 2.23. Although this previous research work **(**Hou et al., 2017**)** has considered the temperature effect, it has not considered the power losses in these additional circuits. Moreover, similar models need to be developed for all types (DC-DC, AC-DC, DC-AC) of converters available in the market with variable designs and topologies.

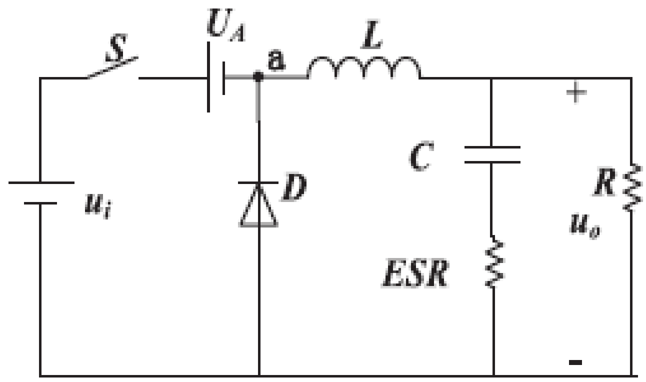

Figure 2.22: Basic DC-DC buck converter based on IGBT switches

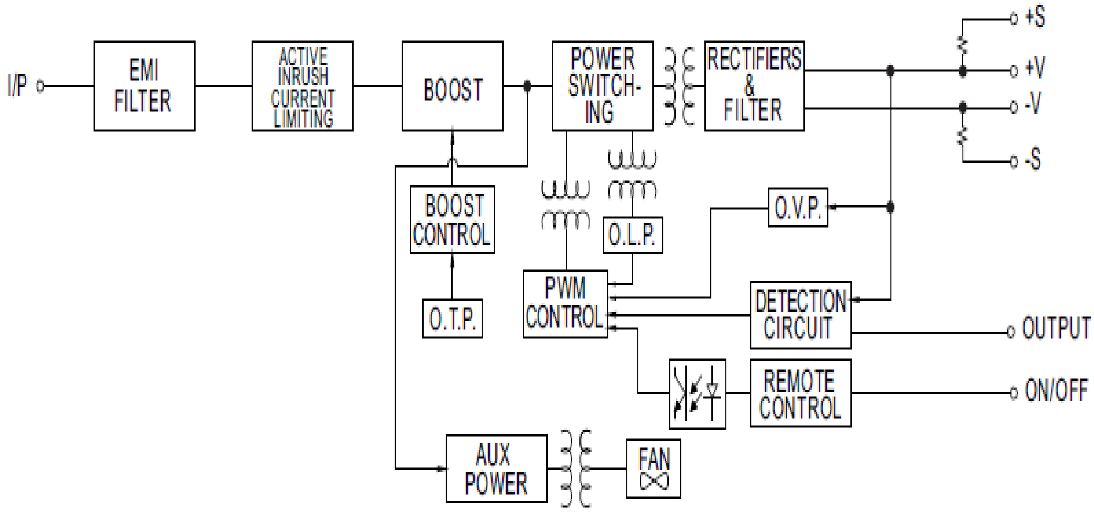

Figure 2.23: Block diagram of the DC-DC buck converter (MeanWell, 2019)

Converter equations are being developed based on the proposed converter designs and assumptions. For example, research (Sadigh, Dargahi, & Corzine, 2016) proposed the flying capacitor-based multicell converter and equations were derived for the specific proposed design only. Another recent research (Rijanto, Nugroho, & Dahono, 2018) simulated a proposed model with a full bridge resonant converter along with controller design incorporating the power losses of the controller as well. Another research (Yang et al., 2017), proposes a multi-level converter and considered this as one unit to simplify the analytical calculations. However, these proposed converter models are not available in the New Zealand market as very few of them have been commercialised. Therefore, it is difficult to source the actual converter to validate the AC and DC wiring topology models based on experiments.

2.3 Research Problems and Gaps Identified

There are two research gaps that have been identified based on the review of the existing literature.

2.3.1 Gaps in Mathematical Modelling

Firstly, the Mathematical modelling of cables has been done in literature to compare the power losses in AC and DC cables, however, the effects of ambient temperature, proximity and skin effect factor were not considered. Therefore, the research work in cable modelling needs to be extended to accurately estimate the power losses in AC and DC lines.

Secondly, Mathematical modelling of converters i.e. DC-DC, AC-DC and DC-AC have been discussed in Section 2.3. Each paper in the literature has focused on one converter design and proposed operating conditions such as the number of components, control circuit, switching frequency, switch type. Therefore, it is essential to develop the equations of DC-DC, AC-DC and AC converter using a similar methodology to accurately compare the AC and DC wiring topologies. On the other hand, converter technology is continuously improving therefore a robust and simple methodology is more important to incorporate future technologies irrespective of converter operation and technology.

Finally, there is no combined (cables and converters) validated mathematical model of AC and DC wiring topologies that can be used for power loss estimations and produce results very close to the actual experimental results.

2.3.2 Gaps in Analysis

Firstly, one case study of AC and DC wiring topologies has been analysed in each of the existing research papers. However, it has not been analysed for a wide range of load power ratings and conductor lengths and sizes. Therefore, there is a need to establish the Boundary Conditions to select the most efficient wiring topology for future homes.

Secondly, efficiency comparisons of AC and DC wiring topologies can help us select the most effective option, but the most efficient wiring topology may not be the most cost-effective option.

Thirdly, most of the existing research has focused on the cost of the DC system except for one (Gerber et al., 2017) as summarised in Table 2.2. That one research has compared a 230V AC wiring system with a 380V DC system. However, the proposed research in this PhD thesis is focused on the comparison of a 230V wiring system with low voltage DC wiring topologies at 12V, 24V and 48V DC as explained in Section 2.3.1.

Finally, the existing and new-build houses have not been analysed to consider the potential applications in New Zealand or other countries.

Chapter 3 Development of Wiring Topologies and its Mathematical Modelling

It is important to note that the wiring topologies are continuously changing due to changes in electricity use. The increasing use of DC sources and DC loads is the fundamental objective and motivation to re-consider the DC wiring options as compared to the well-established AC wiring infrastructure as discussed in Chapter 1. The AC and DC wiring topologies have been developed in this Chapter based on the assumptions made in Chapter 1. Then, the mathematical modelling is developed based on the gaps identified in the literature review as discussed in Chapter 2.

3.1 Development of Wiring Topologies

The wiring topologies in the literature have been reviewed along with the contribution and drawbacks (see Chapter 2). From the literature review (Chapter), the DC wiring options on various voltages were proposed such as 12V, 24V, 48V, 60V, 100V, 220V, 230V, 308V, 325V and 380V DC. However, none of the existing work is addressing the selection of DC source and wiring voltage which is the main key challenge of the study presented in this thesis.

DC appliances up to 99V with power rating less than 1,000W are classified as class 2.1a or class 2.1b depending on voltage. These classes are considered safe with little or no hazards as classified in Figure 3.1 (Moussa et al., 2019). The majority of DC appliances for residential applications are available at low voltage DC up to 50V such as 12V DC, 24V DC and 48V DC (Moussa et al., 2019).

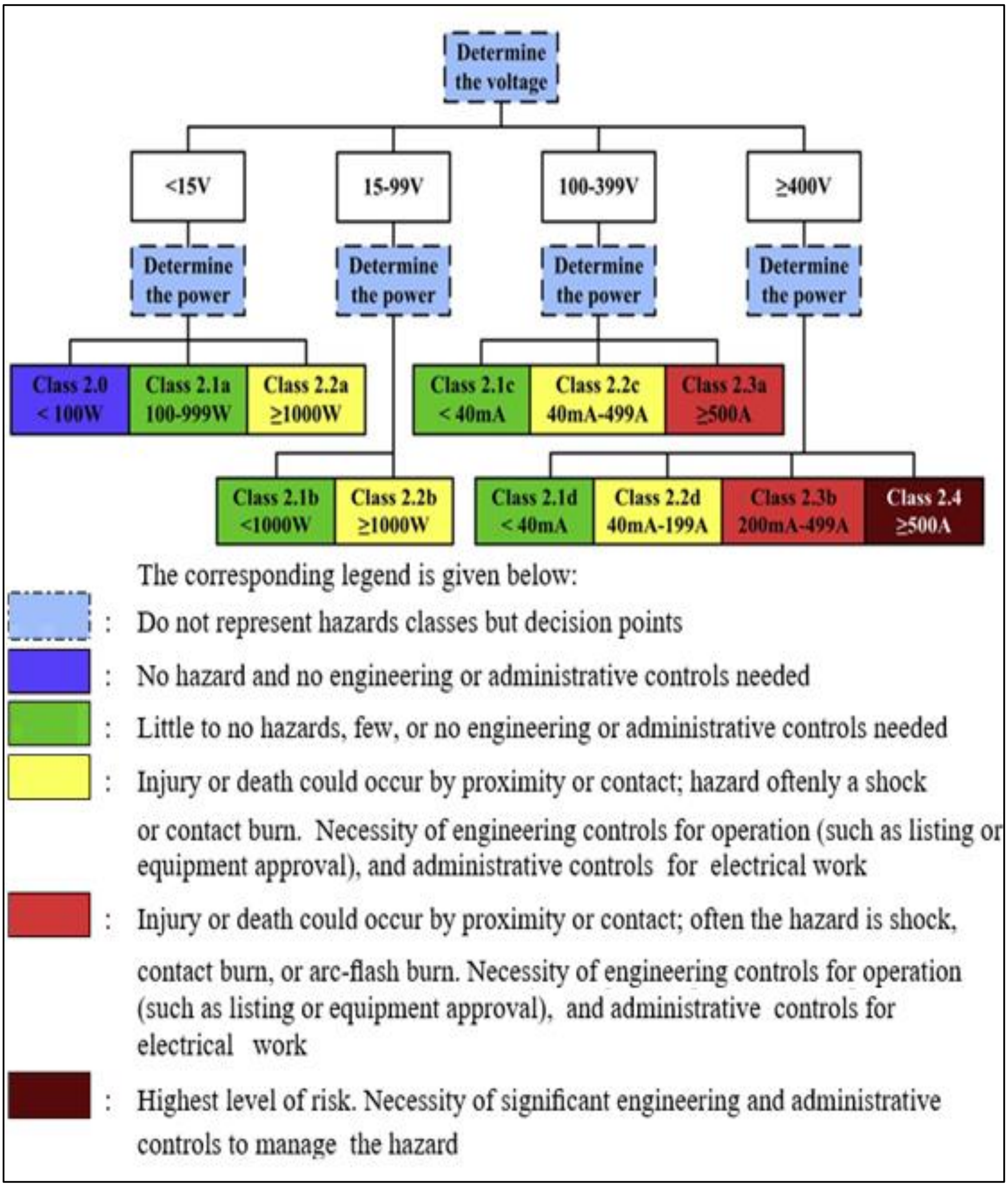

Figure 3.1 Classification matrix hazard class 2.x, DC (Moussa et al., 2019)

On the other hand, the terminal voltage of a household battery unit is 12V and the series combination of two batteries gives 24V terminal voltage, and similar, series combinations of three and four batteries give 36V and 48V respectively. Therefore, DC sources are available at different voltage levels ranging from 12V DC to 48V DC depending on the commonly used battery voltage level of distributed energy sources used at homes. This low voltage range is also aligned with the DC load voltage discussed in the previous Sub-section. In New Zealand, existing household energy systems are available at 12V DC, 24V DC and 48V DC only. 36V DC system is not commonly available in the local market.

Recent research work (Rahman et al., 2019, Moussa et al., 2019) already focused on the development of the DC wiring topologies at 12V, 24V and 48V DC to directly feed DC loads with DC sources as shown in Figure 2.15. However, a DC-DC converter is required for the majority of DC loads as they are available on various voltage ranges (Rodriguez-Diaz et al., 2016). Therefore, none of the previous research has compared the low voltage (12V, 24V and 48V) DC wiring topologies with 230V AC wiring topology with DC source and DC load feed via a DC-DC converter. This thesis aims to fill this key gap.

Based on these research requirements, a DC wiring topology as shown in Figure 3.2 is developed for the analysis. This allows the safe utilisation of DC systems in the local market at 12V, 24V and 48V. The AC wiring topology as shown in Figure 3.3 is developed to compare both topologies on similar grounds.

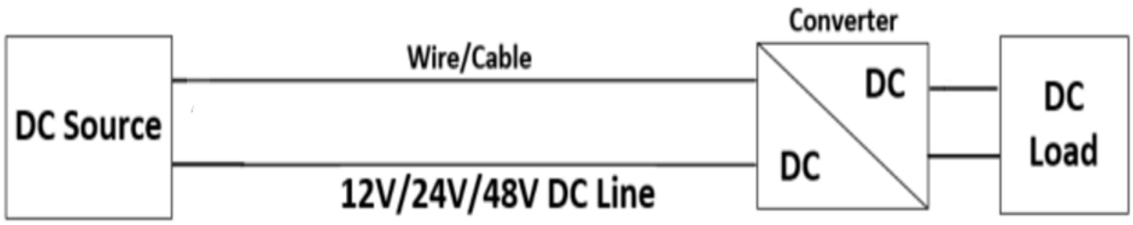

Figure 3.2: Proposed DC wiring topology in this thesis

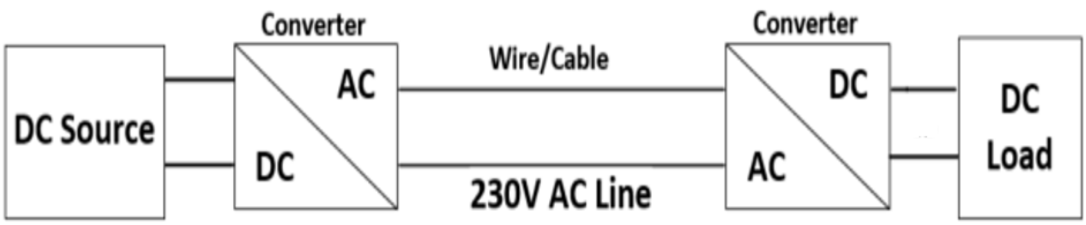

Figure 3.3: Proposed AC wiring topology in this thesis

This wiring topology can be used for various wire sizes depending on the power rating of load and voltage drop constraints. These proposed DC and AC wiring topologies in Figures 3.2 and 3.3 have not been analysed in previous research.

Since reliability is not the focus of this research, it is assumed that there will be no lack of DC power generation. Therefore, the proposed wiring topologies are valid for the homes which have enough DC power to supply throughout the year. This mainly fits well with off-grid systems. Moreover, the proposed topologies in this thesis will be equally useful for DC microgrids. However, it should be noted that there is a limitation of the proposed technique, the results will only be valid for the time when DC source is used.

3.2 Modelling of Power Losses in AC Wiring Topology

Figure 3.3 shows the proposed AC wiring topology for this thesis. DC power from a regulated DC source is converted to 230V AC using a DC-AC converter. AC power is transferred through house wiring, and it is converted back to DC using an AC-DC converter to feed the DC load. There are three parts of power losses in AC wiring topology. Firstly, DC power is converted to AC for power distribution which causes power losses in the DC-AC converter. Secondly, AC power is transferred through cables which causes line losses. Finally, AC power is converted back to DC to feed DC loads which causes power losses in the AC-DC converter. Therefore, total power losses in AC wiring topology can be represented by Equation (3.1).

$$P_{T-AC} = P_{l-t,DC-AC} + \Delta P_{ac} + P_{l-t,AC-DC} \tag{3.1}$$

where,

P_{T-AC} = Total power losses in AC wiring topology

$P_{l-t,DC-AC}$ = Power loss in a DC − AC converter

ΔP_{ac} = Power losses in AC line

$P_{l-t,AC-DC}$ = Power loss in an AC − DC converter

3.3 Modelling of Power Losses in DC Wiring Topology

Figure 3.2 shows the proposed DC wiring topology for this thesis. DC power from a regulated DC source is directly transferred to DC loads using the DC house wiring option. However, the various DC loads operate over different DC voltages. Therefore a DC-DC converter is used to convert the DC line voltage to match the requirements of DC load. In this case, total power losses will be the sum of power losses in DC wiring and DC-DC converter.

There are two parts of power losses in the DC wiring topology. Firstly, DC power is directly distributed through wiring which causes line losses. Secondly, the DC line voltage is converted to match the voltage requirements of DC loads which causes power losses in the DC to DC converter. The general equation for the DC wiring system can be represented by Equation (3.2).

$$P_{T-DC} = \Delta P_{dc} + P_{l-t,DC-DC} \tag{3.2}$$

P_{T-DC} = Total power losses in AC wiring topology

ΔP_{dc} = Power losses in DC line

$P_{l-t,DC-DC}$ = Power loss in a DC − DC converter depending on the voltage of DC wiring topology and DC load voltage

3.4 Modelling of Power Losses in the Lines/Cables

The losses in power cables depend on various factors such as environmental conditions, installation condition (number of cables in the group) and the nature of the current, i.e. AC or DC. These factors have been incorporated into power loss equations by using actual in-depth equations of AC and DC resistances.

3.4.1 Modelling of Power Losses in AC Lines

A single-phase AC system can be represented as shown in Figure 3.4. Therefore, this thesis has utilised the fundamental power loss equation derived from previous research (Pellis et al., 1997) but has used AC resistance rather than general resistance of the cable to consider the effect of ambient temperature, skin effect and proximity factor. The power losses in the single-phase AC lines can be calculated by using Equation 3.3.

$$\Delta P_{ac} = 2\, r_{AC} * L * \; I_{ac}^2 = 2. \frac{R_{AC}}{cos^2\varphi} . \frac{P^2}{U_{ac}^2} \tag{3.3}$$

where,

r_{AC} = AC Resistance per unit length

L = Length of cable

ΔP_{ac} - Power losses in AC line

R_{AC} − The AC resistance of the conductor

$Cos\ \phi$ - Power factor of the load

U_{ac} - RMS AC Phase voltage at the load terminal

P - Power consumption by Load

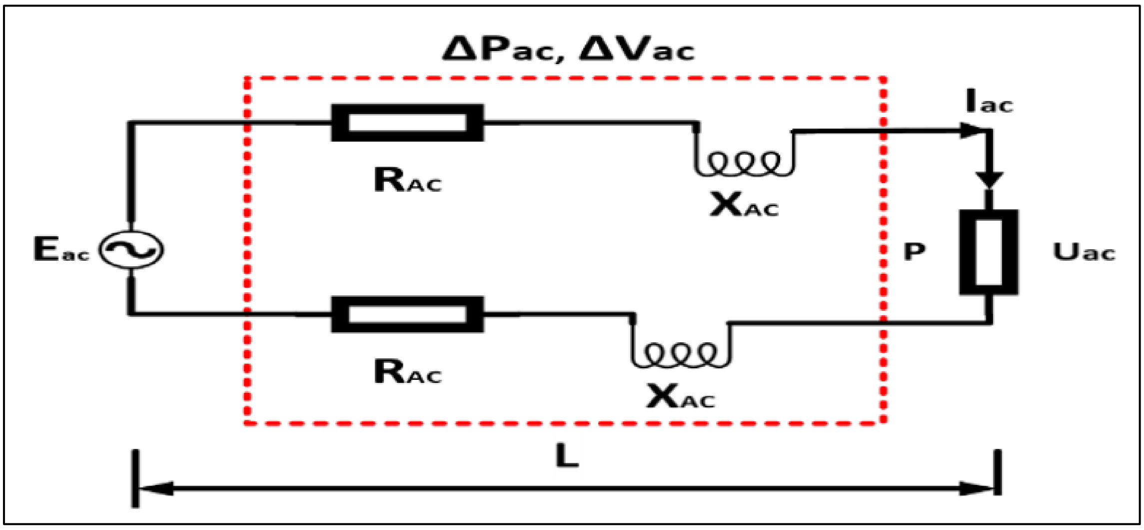

Figure 3.4: Parameters in the single-phase AC power distribution system

3.4.2 Modelling of Power Losses in DC Lines

The same load and cable have been analysed for DC power flow. Since the frequency of DC is zero, the reactance component is eliminated from the DC power distribution cables as shown in Figure 3.5. There are two cables, i.e. positive and negative therefore the power losses in the DC lines can be calculated by using Equation 3.4 (Pellis et al., 1997).

$$\Delta P_{dc} = 2.r_{DC}\, L\, I_{dc}^2 = 2.R_{DC}\frac{P^2}{U_{dc}^2} \tag{3.4}$$

where,

r_{DC} = DC Resistance per unit length

L = Length of conductor

ΔP_{dc} - Power losses in DC line

R_{DC} − The DC resistance of the conductor

U_{dc} - RMS AC Phase voltage at the load terminal

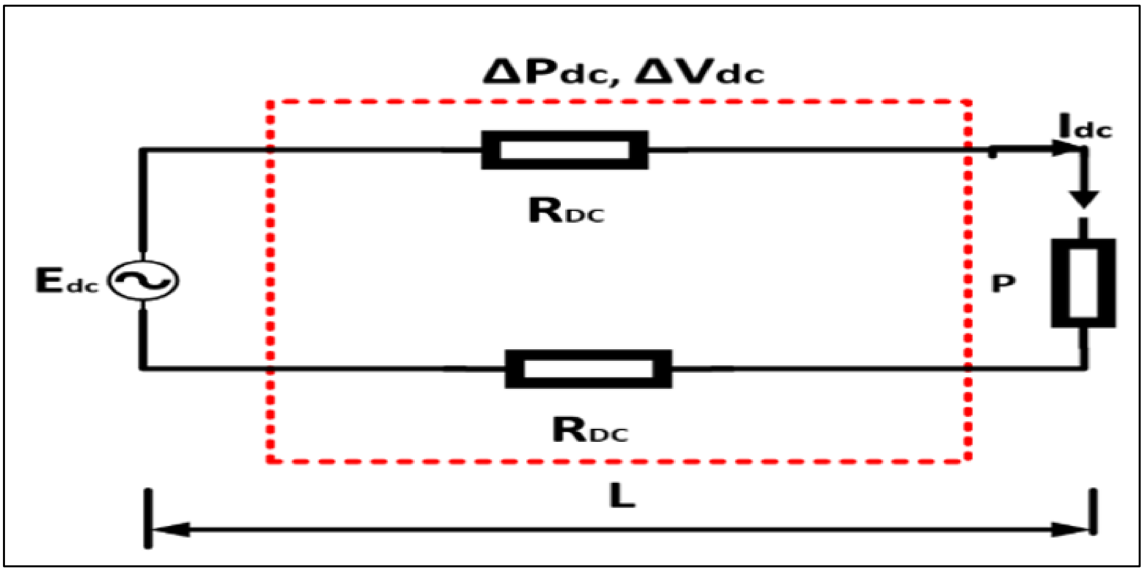

Figure 3.5: Parameters in DC power distribution system

3.4.3 Impact of Environmental and Installation Factors on AC and DC Resistance

AC and DC resistance concepts are well developed and Equations 3.5 through 3.11 in this Section are derived from the IEC standard (International Electrotechnical Commission, 2006). After considering environmental temperature, DC resistance can be calculated by using Equation 3.5.

$$r_{DC} = r_{20^0}[1 + \alpha(T - 20°\text{C})] \tag{3.5}$$

where,

r_{DC} − DC resistance per unit length of the conductor at temperature′T′

T− Operating temperature of the conductor in °C

r_{20^0} − Conductor resistance per unit length at 20°C

α − coefficient of linear expansion

The actual value of $\boldsymbol{\alpha}$ varies with respect to material and temperature. However, as per IEC 60287, 0.0039 gives good accuracy for both aluminium and copper conductors.

The total DC resistance can be calculated by using Equation 3.6 (International Electrotechnical Commission, 2006)

$$R_{DC} = r_{DC} \times L \qquad (3.6)$$

where,

R_{DC} − DC resistance of the line

L − Length of the cable

The AC resistance of the cable is increased due to the skin effect and proximity effect (Morgan, 2013). Based on these factors, the AC resistance of the conductor can be calculated by using Equation 3.7 (International Electrotechnical Commission, 2006).

$$R_{AC} = R_{DC}\,(1 + Y_S + Y_P) \qquad (3.7)$$

where,

R_{AC} − The AC resistance of the conductor

R_{DC} − The DC resistance of the conductor

Y_S − Skin effect factor

Y_P − Proximity effect factor

The skin effect factor can be calculated by using Equation 3.8 (International Electrotechnical Commission, 2006).

$$Y_S = \frac{X_S^4}{192+0.8\,X_S^4} \qquad (3.8)$$

Where the factor X_S can be calculated by using Equation 3.9 (International Electrotechnical Commission, 2006).

$$X_S = \sqrt{\frac{8\pi f}{R_{DC}} 10^{-7} k_S} \tag{3.9}$$

where,

f - Frequency of AC supply from the grid

$k_S -$ skin effect coefficient, which is based on the type of cables as summarised in Table 3.1.

Table 3.1: Skin effect and proximity effect coefficient Table (International Electrotechnical Commission, 2006)

Type		k_s	k_p
Copper	Round stranded or solid	1	1
	Round segmental	0.435	0.37
	Sector-shaped	1	1
Aluminium	Round stranded or solid	1	1
	Round 4 segment	0.28	0.37
	Round 5 segment	0.19	0.37
	Round 6 segment	0.12	0.37

The proximity effect factor Y_P is calculated by different mathematical models depending on the number of cores in the cable. For two core cables or two single-core cables, the proximity effect factor can be calculated by using Equation 3.10 (International Electrotechnical Commission, 2006).

$$Y_P = \frac{X_P^4}{192+0.8\, X_P^4} \left(\frac{d_c}{S}\right)^2 \times 2.9 \tag{3.10}$$

Where,

Xp factor can be calculated by using Equation 3.11 (International Electrotechnical Commission, 2006)

d_c = Diameter of conductor

S = Space between Conductors$X_p = \sqrt{\frac{8\pi f}{R_{DC}} 10^{-7} k_P}$ (3.11)

$k_P = s$kin effect coefficient, it is based on the type of cables as summarised in Table 3.1.

3.5 Modelling of Power Losses in a Converter

Power losses depend on the type of converter and its operating conditions. Complex power loss calculation equations which have been developed using different approaches for each type of converter are available in the literature. This PhD thesis is more focused on the comparison of AC and DC wiring topologies using the converters available in the New Zealand market; therefore, the target of this research is not the converter design.

For this research, converter modelling is based on the experimental data set of input and output parameters as shown in Figure 3.6. A converter has been considered as one system where power losses have been modelled as a function of the connected load. Power losses include no-load losses, switching losses and conduction losses. The converter has been analysed as one system to simplify the modelling approach. Therefore, this methodology is independent of the number of components in a converter, its schematic and its switch type such as MOSFET, IGBT etc.

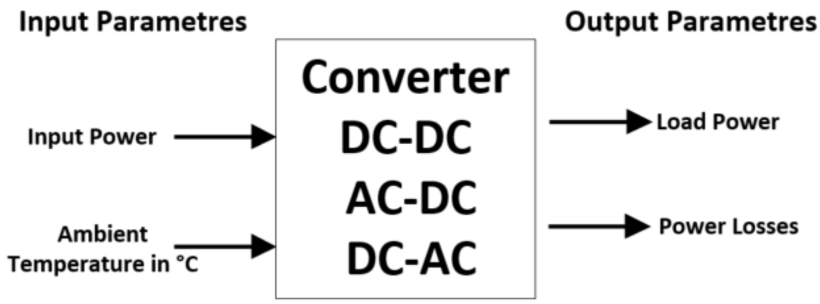

Figure 3.6: Block diagram for Converter Modelling

Since the power losses vary with the temperature change, a verified mathematical model is required which can cover different types of losses at ambient temperature as shown in Equation 3.12.

$$P_{l-t,c} = t_f \times P_{l,c} \tag{3.12}$$

where,

$P_{l-t,c} =$ Power losses of a converter at ambient temperature (T)

$t_f =$ Temperature factor of a converter

$P_{l,c} =$ Power losses of a converter at 25 ℃

3.5.1 Modelling of Temperature Factor

The purpose of the temperature factor of the converter is to consider the impact of ambient temperature on power losses. Converters consist of many components and the linear expansion coefficients for each type of material is different. Therefore, linear regression analysis can be used to calculate the temperature factor as represented in Equation 3.13. It covers the temperature coefficients of all components used in the converter at the ambient temperature.

$$t_f = (t_0 + t_1 T) \tag{3.13}$$

where,

t_0 & t_1 are the Temperature coefficients of converters

$T =$ Ambient Temperature

The coefficients t_1 *and* t_0 can be calculated using Linear Regression and Least Square Method as shown in Equations 3.14 and 3.15 respectively.

$$t_1 = \frac{\sum(T-\bar{T})(t_f-\overline{t_f})}{\sum(T-\bar{T})^2} \tag{3.14}$$

$$t_0 = \overline{t_f} - t_1\bar{T} \tag{3.15}$$

where,

T = Ambient temperature in °C

$\bar{T}$ = Mean of ambient temperature in °C

$\overline{t_f}$ = Mean of Temperature factor of a converter

An experimental data set of power losses at the range of ambient temperature was measured to calculate the temperature coefficients for a 12V input DC/DC converter as shown in Table 3.2. The P_l (Power losses observed at 25 °C) is 14.75W, however, the losses increase with the increase in ambient temperature. In Table 3.2, the temperature factor (t_f) has been calculated using Equation 3.12.

It is important to note, even though there are very high efficiencies for converters available, but they are very expensive. In practice, the majority of the end-users prefer affordable converters. Therefore, the affordable converters available in the market were used in this study to compare the wiring topologies.

Table 3.2 Power losses in 12V input DC-DC converter at different temperature

T (°C)	Pin (W)	Pout (W)	P_{l-t} (W)	t_f
15	64.608	50	14.61	0.9904
20	64.691	50	14.69	0.9960
25	64.750	50	14.75	1.0000
30	64.809	50	14.81	1.0040
35	64.893	50	14.89	1.0097

Table 3.3 below shows the summarised calculations to find the coefficient t_1 using Equation 3.14.

Table 3.3: Temperature coefficient calculations for 12V input DC-DC converter

T (°C)	t_f	$(T-\bar{T})$	$(t_f-\bar{t_f})$	$(T-\bar{T})(t_f-\bar{t_f})$	$(T-\bar{T})^2$
15	0.9904	-10	-0.00962	0.0962	100
20	0.996	-5	-0.00402	0.0201	25
25	1	0	0	0	0
30	1.004	5	0.00398	0.0199	25
35	1.0097	10	0.00968	0.0968	100

Using Equation (3.14), the calculated value coefficient t_1 = 0.000932.

The coefficient t_0 can be calculated by putting the value of the coefficient t_1 in Equation (3.15), and the calculated value coefficient t_0 = 0.97672

Using the values of t_1 & t_0 coefficients in Equation 3.11, the temperature factor equation can be developed for a 12V DC-DC converter as shown in Equation 3.16.

$$t_{f\ 12V\ DC/DC} = (0.97672 + 0.000932T) \qquad (3.16)$$

It is shown that the temperature factor has a direct relationship with ambient temperature and is higher at high ambient temperature as represented in Figure 3.7. On the other hand, power losses are directly proportional to the temperature factor which means the power losses would increase with the increase in temperature as observed in Table 3.2.

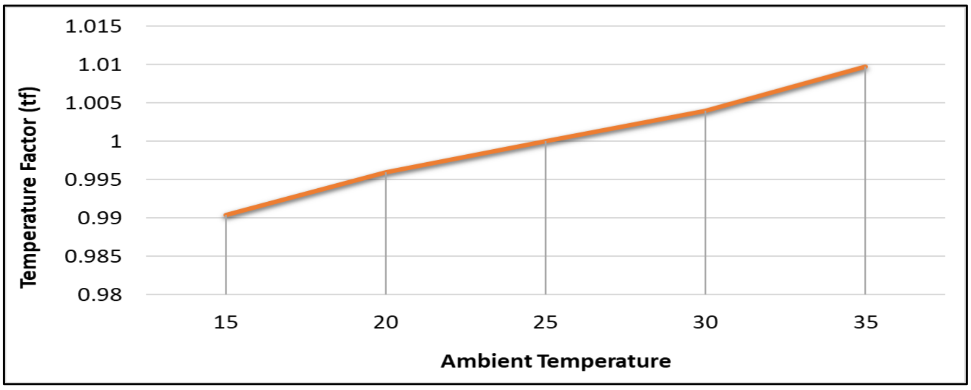

Figure 3.7 Temperature Factor (t_f) for 12V input DC-DC Converter

Similarly, to calculate the temperature coefficients of 24V input DC-DC, 48V input DC-DC, AC-DC and DC-AC, experimental data sets of power losses at a range of ambient temperatures were measured for each converter. Experimental data were analysed using linear regression analysis to calculate the coefficients t_1 and t_0. Finally, the temperature factor equation for each converter was explained in Appendix A.

3.5.2 Modelling of Converter Losses at Standard Ambient Temperature

The converter power losses at standard ambient temperature 25ºC can be calculated using the non-linear regression analysis as per Equation 3.17. The main aim is to cover different types of losses including no-load losses, switching losses and conduction losses.

$$P_{l,c} = (a + b\,P_o + c\,P_o^2) \tag{3.17}$$

where,

P_o = Power Output from a Converter at 25 ℃

a, b & c are the power loss coefficients of a converter

Here a, b and c are the coefficients to be determined using the non-linear regression analysis matrix based on the measurements and calculation as per equation 3.18. This equation can be solved using the Gaussian Elimination Method once the experimental data set of P_o & P_l is collected for each converter.

$$\begin{pmatrix} n & \sum P_o & \sum P_o^2 \\ \sum P_o & \sum P_o^2 & \sum P_o^3 \\ \sum P_o^2 & \sum P_o^3 & \sum P_o^4 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} \sum P_l \\ \sum P_l\, P_o \\ \sum P_l P_o^2 \end{pmatrix} \tag{3.18}$$

where, n = number of experimental samples

The connected load was incrementally increased to collect the experimental data set of P_o & P_l as shown in Table 3.4. The power losses are high due to the percentage loading as the efficiency of the converter change with the change in loading as expressed in Figure 2.18.

Table 3.4: Experimental data set of P_o & P_l for 12V input DC-DC converter

P_o – Pout (W)	P_l – Power Loss (W)
1	1.735
5	2.288
10	3.153
25	6.056
50	14.748

Table 3.5 shows the summarised calculations to find the coefficients *a*, *b* and *c* coefficients using regression analysis as per Equation 3.17.

Table 3.5: Power loss coefficients calculations for 12V input DC-DC converter

P_o	P_l	P_o^2	P_o^3	P_o^4	$P_l\,P_o$	$P_lP_o^2$
1.00	1.74	1.00	1.00	1.00	1.74	1.74
5.00	2.29	25.00	125.00	625.00	11.44	57.20
10.00	3.15	100.00	1000.00	10000.00	31.53	315.32
25.00	6.06	625.00	15625.00	390625.00	151.40	3784.90
50.00	14.75	2500.00	125000.00	6250000.00	737.41	36870.68
91.00	**27.98**	**3251.00**	**141751.00**	**6651251.00**	**933.52**	**41029.84**

Using the calculated data from Table 3.5, Equation (3.18) can be written as

$$\begin{pmatrix} 5 & 91 & 3251 \\ 91 & 3251 & 141751 \\ 3251 & 141751 & 6651251 \end{pmatrix}\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} 27.98 \\ 933.52 \\ 41029.84 \end{pmatrix}$$

Solving using the Gaussian elimination method, the equation can be written as

$$\begin{pmatrix} 1 & 18.2 & 650.2 \\ 0 & 1 & 51.78 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} 5.596 \\ 0.266 \\ 0.00332 \end{pmatrix}$$

And by using simple back-substitution, the *a*, *b* and *c* coefficients can be determined as follows:

$$c = 0.00332$$

$$b = 0.266 - (51.78 \text{ x } c) = 0.09409$$

$$a = 5.596 - (18.2 \text{ x } b) - (650.2 \text{ x } c) = 1.7248$$

Equation 3.19 is the mathematical equation of the 12V input DC-DC converter by substituting the calculated *a*, *b* and *c* coefficients into Equation 3.17.

$$P_{l,12v\ DC/DC} = 1.7248 + 0.09409\ P_o + 0.00332\ P_o^2 \tag{3.19}$$

where,

$P_{l,12v\ DC/DC}$ = The power losses in 12V input DC − DC Converter

3.5.3 Total Power Losses in Converters with Temperature Factor

Using Equation (3.12), the total power losses of a 12V input DC-DC converter with temperature effect ($\boldsymbol{P_{l-t,12v\ DC/DC}}$) can be expressed as in Equation 3.20.

$$P_{l-t,12v\ DC/DC} = (0.97672 + 0.000932T)(1.7248 + 0.09409\ P_o + 0.00332\ P_o^2) \tag{3.20}$$

Using the same methodology expressed in Section 3.4, the power losses have been modelled for 24V input DC-DC, 48V input DC-DC, AC-DC and DC-AC converters and the following relationships shown in Equations 3.21 to 3.24 were derived. The additional details along with the data sets and calculations of the remaining converters can be found in Appendix A.

$$P_{l-t,24v\ DC-DC} = (0.9847 + 0.000612T)\ (13.04 + 0.1049\ P_o + 0.000591\ P_o^2) \tag{3.21}$$

$$P_{l-t,48v\ DC-DC} = (0.9868 + 0.000532T)(16.8158 + 0.134087\ P_o + 0.00001624 P_o^2) \tag{3.22}$$

$$P_{l-t,DC-AC} = (0.92394 + 0.003028T)(7.0833 + 0.003134\ P_o + 0.000573 P_o^2) \tag{3.23}$$

$$P_{l-t,AC-DC} = (0.90875 + 0.00365T)(13.03315 + 0.133904\ P_o + 0.000124 P_o^2) \tag{3.24}$$

The development of the proposed mathematical model needs to include the power losses of the converters. Since converter technology is continuously improving, the best option today may not be the best option going forward. Therefore, the focus is more toward standardising a power loss estimation approach that can help us to compare AC wiring topology with DC wiring topologies for any new converter available in the market. The model can be reproduced by manufacturers, researchers and other stakeholders in future using a similar approach. For example, AUT Wiring Selection Tool as shown in Appendix C has been developed based on the proposed mathematical approach.

3.6 Concluding Remarks

The mathematical models of AC and DC wiring topologies have been developed in this Chapter. These models now need to be validated before using them for the development of boundary conditions and cost-benefit analysis. The next Chapter validates these models using two alternative methods.

Chapter 4 Validation of Mathematical Models

In this Chapter, the mathematical models derived in Chapter 3 are verified using experimental and simulation studies. Multiple verification methods have been used to validate the mathematical models developed in this research.

4.1 Experimental Setup

As assumed in Section 1.1.3, the future home would have DC-based distributed generation along with efficient DC loads. Figures 4.1 and 4.2 show the experimental setup and connections diagram based on the AC and DC wiring topologies proposed in Chapter 2.

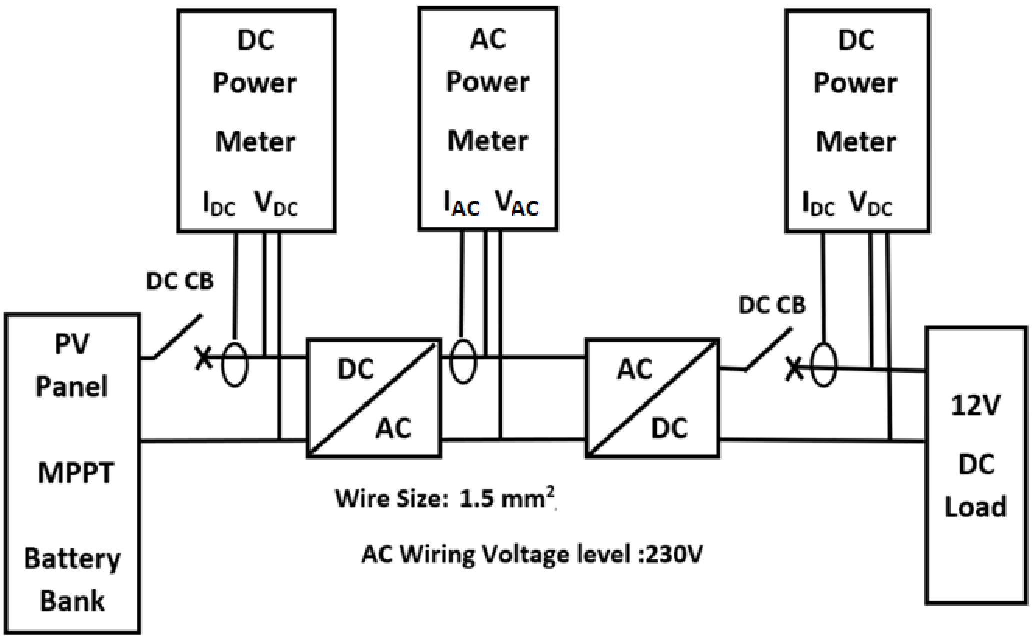

Figure 4.1: Experimental setup of proposed AC wiring topology

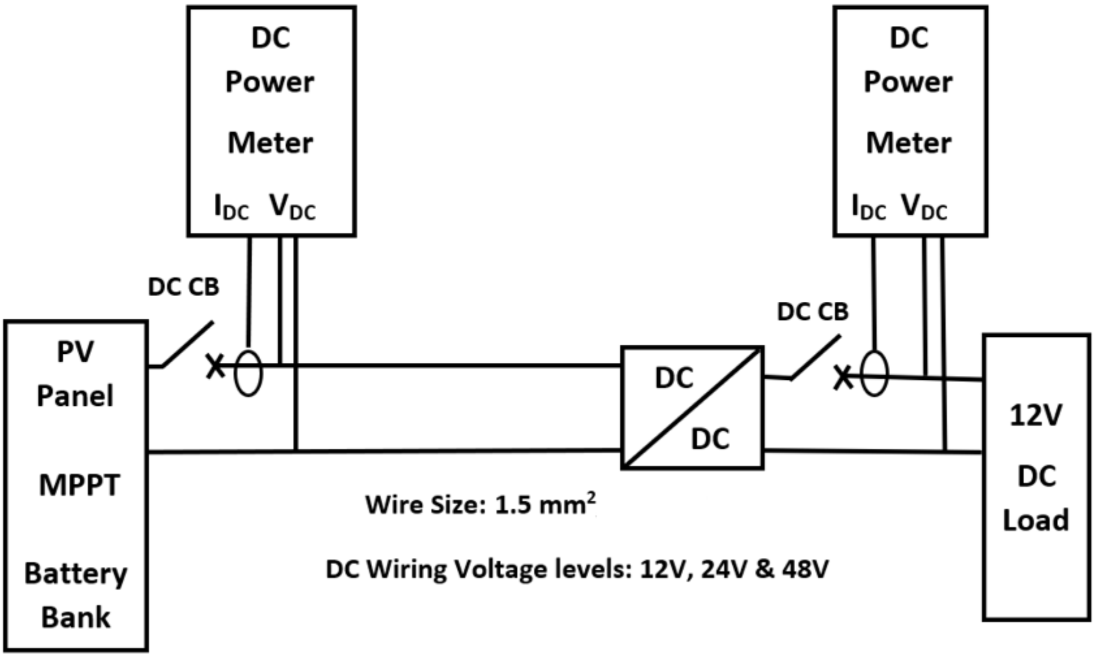

Figure 4.2: Experimental setup of proposed DC wiring topology

A solar PV energy system including a battery bank was installed at the research laboratory at AUT Centre for Energy and Power Engineering Research as shown in Figure 4.3. The design of this solar system was based on AS/NZS 4509.2:2010. Similar DC loads have been used to compare the efficiencies of all proposed AC and DC wiring topologies. The in-service safety inspection of electrical equipment including converters was carried out as per AS/NZS 3760:2010.

AC wiring topologies were based on AS/NZS 3000 and the low voltage DC wiring installation was carried out as per NZS 3015:2004. 3-core Tough Plastic Sheath (TPS) wire is used for domestic wiring in New Zealand and other countries. In New Zealand, 1mm^2 wire size is used for lighting circuits, 2.5mm^2 are used for power circuits. A medium-size conductor of 1.5 mm^2 has been used for experimentation due to time and cost constraints.

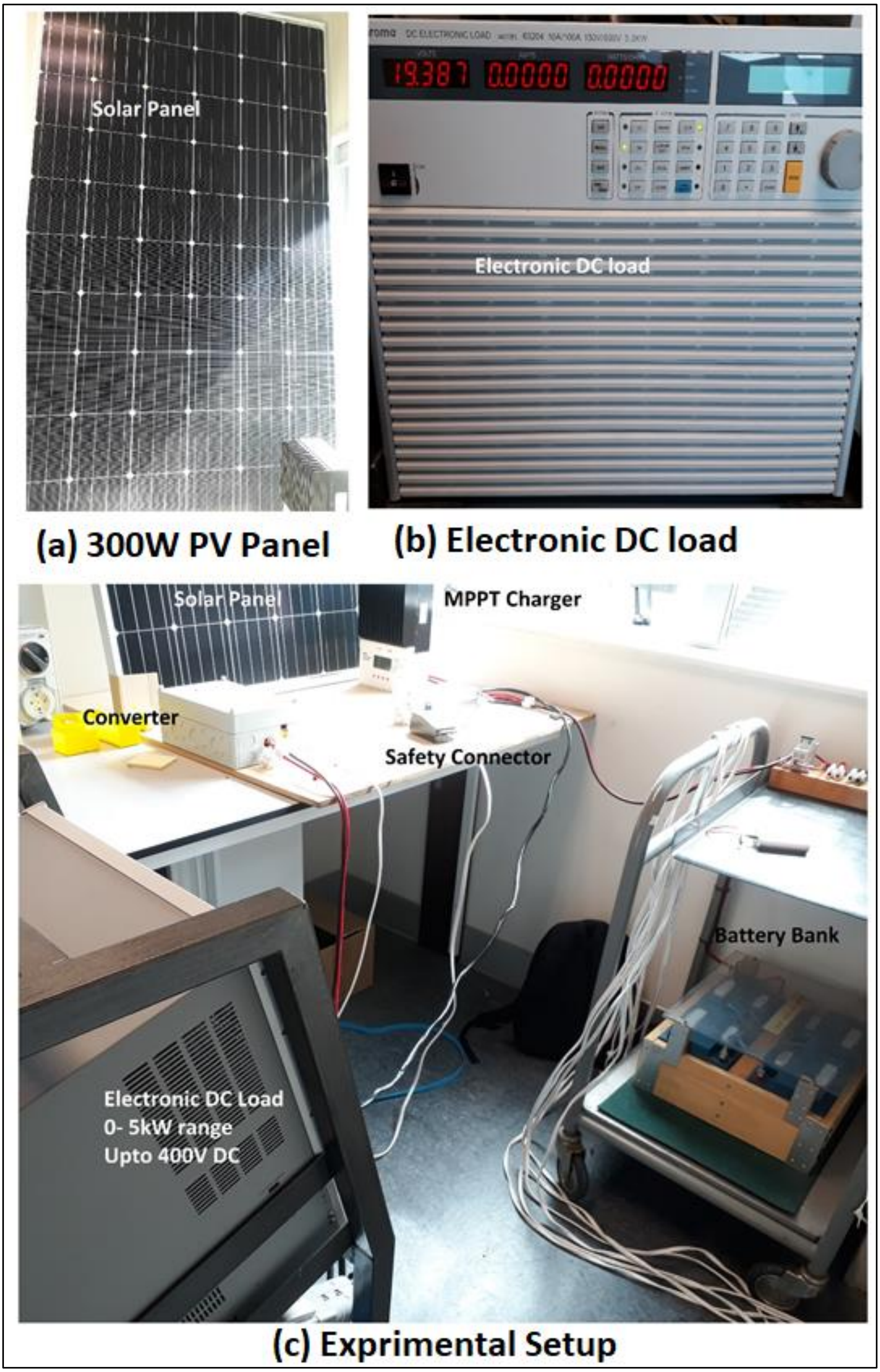

Figure 4.3: Experimental setup at AUT

4.1.1 Design

The electrical wiring topologies were designed as per New Zealand Standards which mainly include AS/NZS 3000 and AS/NZS 3008.1.2. Circuit Breaker (CB) ratings have been selected using AS/NZS 3000 as summarised in Table 4.1.

Table 4.1: Circuit Breaker Selection as per AS/NZS 3000

Wire size (mm^2)	**Ampacity (Ampere)**	**Circuit Breaker (CB) rating (Ampere)**
1	15	10
1.5	18	16
2.5	26	20

Experimental components along with specifications are summarised in Table 4.2. The output voltage of all converters is fixed at 12V to compare the efficiency on similar grounds. Datasheets of converters and charge controller can be found in Appendix B.

Table 4.2: Specifications of experimental components

S.No	**Component**	**Specification**	**Quantity**
1	DC/DC Converter	Vin = 9.2V - 18V DC Vout = 12VDC Power = 50.4W	1
2	DC/DC Converter	Vin = 19V - 72V DC Vout = 12VDC Power = 480W	1
3	AC/DC Converter	Vin = 230V AC Vout = 12VDC Power= 450W	1
4	DC/AC Converter	Vin = 12V DC Vout = 230V AC Power = 360W	1
5	MPPT Charge controller	Vin < 150V DC Vout = 12V DC, 24V DC, 48V DC Power = 800W	1
6	PV Panel	Maximum Vout = 32.38V Power = 270W	1
7	Battery	Voltage = 12V DC Capacity = 240 AH	4
8	Cable	TPS 1.5mm^2 ,2 Core + Earth	100 meters
9	DC Circuit Breaker	32A	2

Built-in converters are available for a few appliances such as laptop, TV, mobile phone etc. However, only converters currently available on the market were used in this research due to budget constraints.

GenCalc software developed by General Cable was used to design cables as per AS/NZS 3008.1.2 Standard (https://www.generalcable.com/eu/en/information-center/tools-applications/gc-app-low-voltage). House wiring and protection were designed as per AS/NZS 3000 Standard.

4.1.2 Measurements

Measurements were taken using Fluke calibrated measuring equipment including multimeters, clamp meters, and power loggers. Moreover, the readings were further verified using a shunt resistor and a multi-meter. Losses of the shunt resistance were also considered to obtain accurate readings.

The power rating of the load was changed from 5W to 175W at four various voltage levels. Measurements of 12V, 24V and 48V DC wiring topologies were taken as per Figures 4.1 and 4.2 as outlined in Section 4.3 (Tables 4.3 to 4.6). Measurements of 230V AC wiring topology with 1.5mm^2 wire were taken as shown in Figure 3.1 and the data are presented in Tables A.12.

4.2 Simulation Modelling

The simulation model can be used to measure the efficiency of house wiring cases similar to mathematical models. Various available simulation software packages were considered to select the most viable option based on accuracy, applications and integration with the New Zealand power system. In previous studies, all simulation studies have been conducted by MATLAB software developed by MathWorks (Seo et al., 2011) (Rasheed et al., 2019). However, DigSilent Power Factory (DPF) software is used in this research to develop the simulation model of AC and DC system systems based on the following key reasons.

- New Zealand Electrical Power system model is available DPF; therefore, the house wiring can be connected to the grid model in future to analyse the impacts of AC and DC in the New Zealand Power system.
- DPF is mainly used to simulate power distribution and transmission networks. However, it also contains a library to simulate house wiring systems.
- DPF has the option to use the programming scripts using DigSilent Programming Language (DPL) to run thousands of models within a few seconds. Moreover, it can export the measurements to Microsoft excel using DPL.

4.2.1 Modelling of AC and DC Wiring Topologies

230V AC line wiring topologies have been modelled with 1.5mm^2 wiring options as per the configuration in Figure 4.1. Figure 4.4 shows a general simulation model of 230V AC wiring topology.

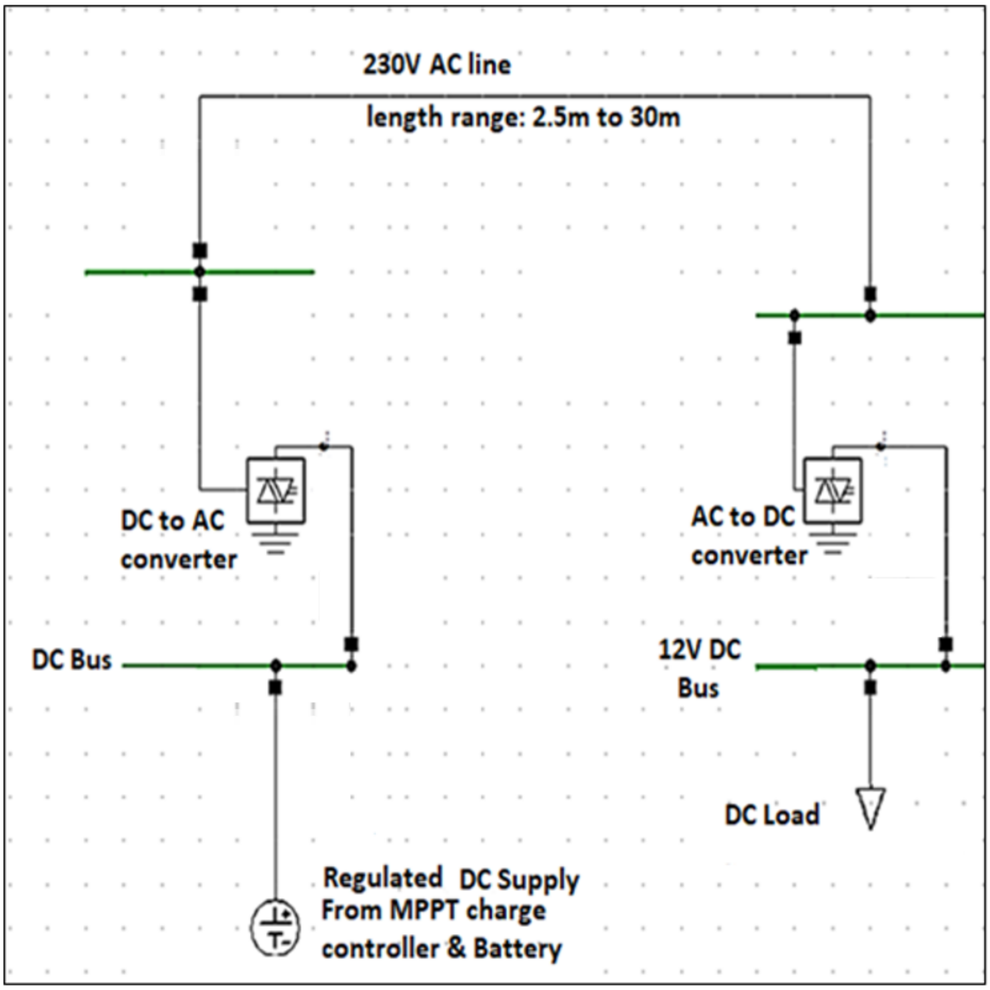

Figure 4.4: The Simulation model of proposed AC wiring topology

In the DC wiring option, the terminal voltage of all DC appliances is different therefore DC wiring topology has been simulated with a DC-DC converter as shown in Figure 4.2. The DC simulation model in Figure 4.5 has been developed with 1.5mm^2 wiring options for 12V, 24V and 48V DC wiring topologies. This model can be adjusted with respect to DC source voltage, line voltage, conductor size and length.

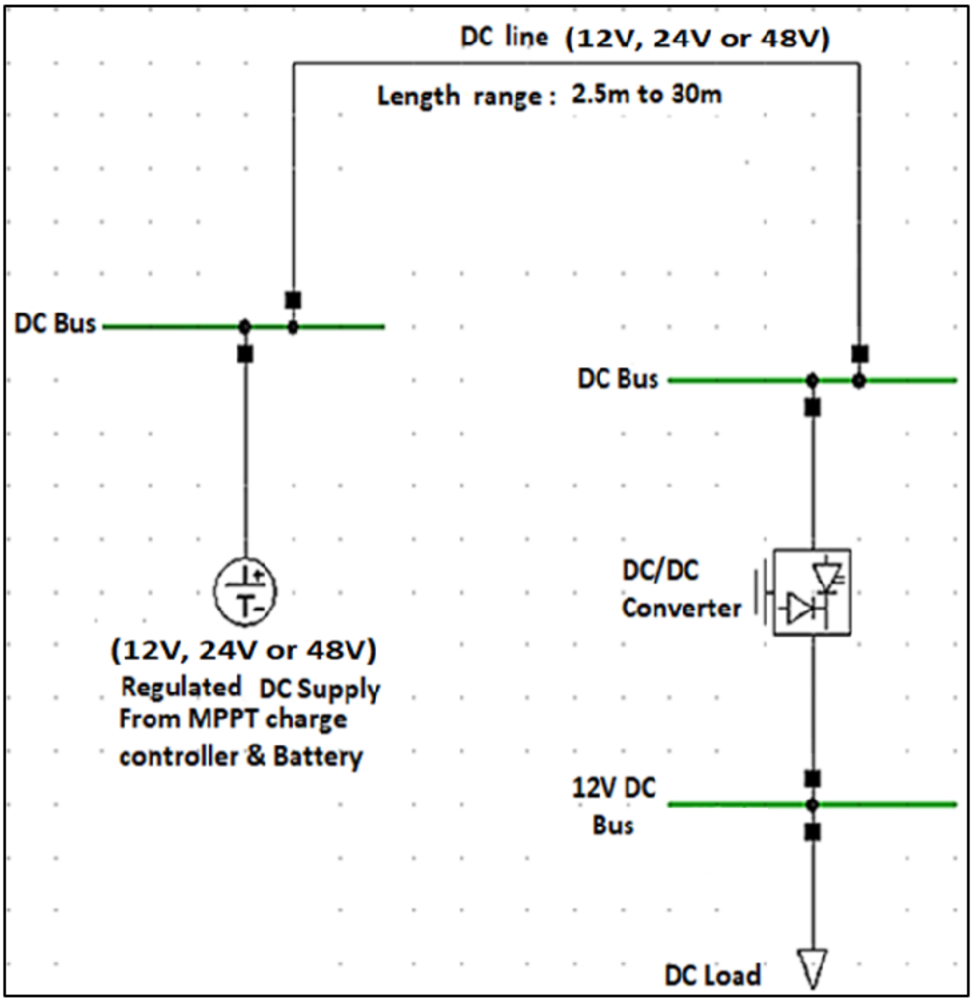

Figure 4.5: The Simulation model of proposed DC wiring topology

Scripts were written in DigSilent Programming Language (DPL) to run simulations as summarised using the flowchart shown in Figure 4.6. Mathematical scenarios cover from 5W to 175W with lengths from 2.5m to 30m. Simulation studies were conducted for the full range of load power and length irrespective of voltage drop constraints as per the flow chart of the DPL script. Using the VLOOKUP function in Microsoft Excel, the required cases data were filtered to align the data sets with experiments and mathematical models as outlined in Tables 4.3 to 4.6.

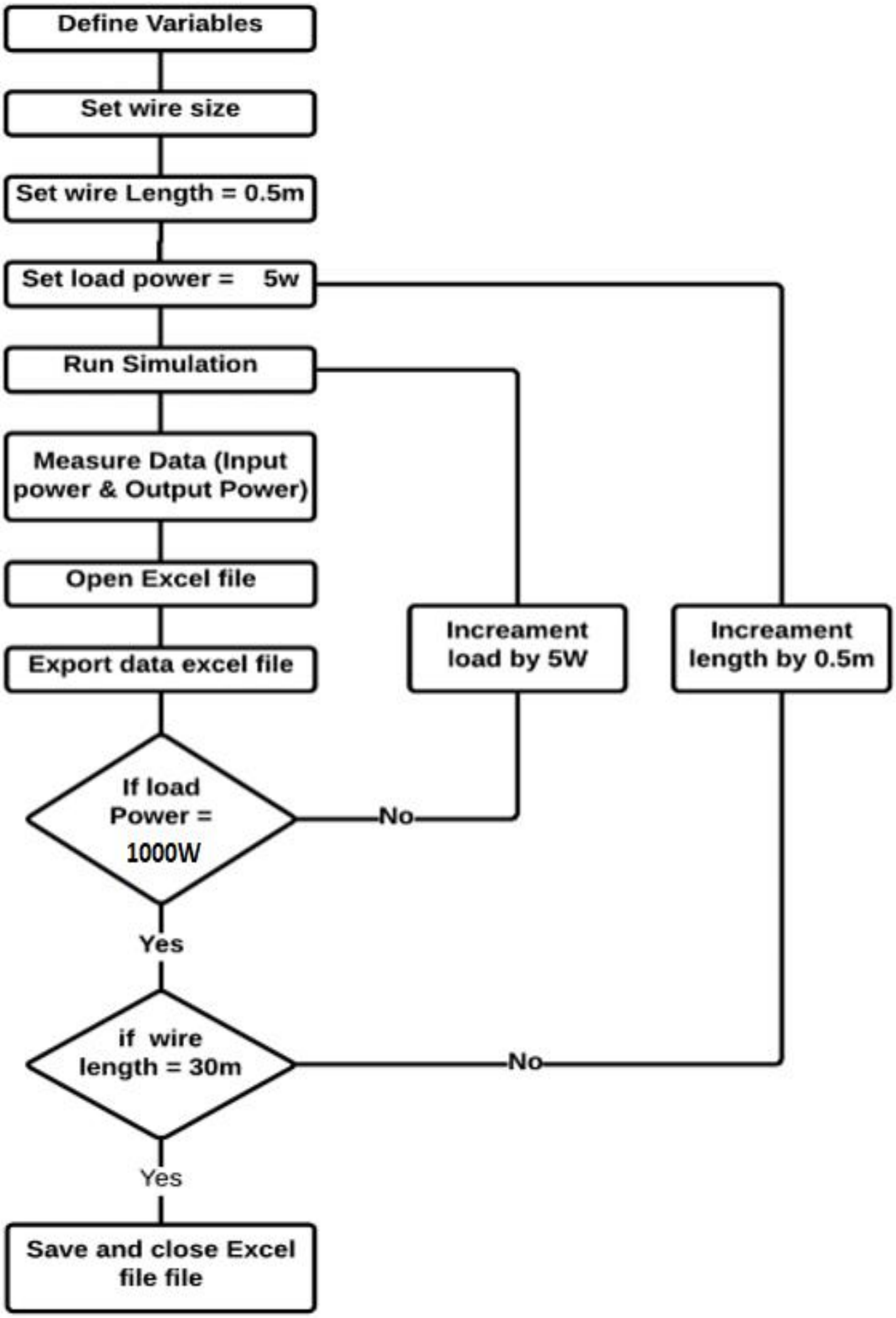

Figure 4.6: DigSilent Programming Language (DPL) script flow chart

4.3 Data Collection and Calculations

Experimental setup and simulation studies were conducted as per Figures 4.1 and 4.2. Equipment capability and design limitation such as current loading and voltage drop were considered for 1.5mm^2 wire size, therefore, this range has been slightly reduced in low voltage DC wiring topologies as shown in Tables 4.3 to 4.6. The 12V DC wiring topology is limited to 50W for the experimental verification due to the voltage drop constraints of 1.5mm^2 wire size. Similarly, 24V DC wiring testing was limited to 150W.

A total of 123 wiring cases have been taken for the validation purpose as outlined in Tables 4.3 to 4.6. Then the power losses and the input power of these wiring cases were estimated using the proposed mathematical models. Similar cases were repeated using the experiments and simulations as summarised in Tables 4.3 to 4.6.

Table 4.3: Validation Data collection for 12V DC Wiring Topology

Pout DC (W)	Length (m)	Mathematical Pin DC (W)	Experimental Pin DC (W)	Simulation Pin DC (W)
5	**2.5**	7.30	7.32	7.51
	5	7.32	7.39	7.51
	10	7.36	7.41	7.51
	20	7.45	7.43	7.61
	30	7.54	7.53	7.72
10	**2.5**	13.06	13.20	13.34
	5	13.13	13.30	13.44
	10	13.28	13.40	13.53
	20	13.56	13.72	13.71
25	**2.5**	31.55	31.47	31.71
	5	31.96	31.87	32.07
50	**2.5**	66.47	66.82	66.10

Table 4.4: Validation Data collection for 24V DC Wiring Topology

Pout DC (W)	Length (m)	Mathematical Pin DC (W)	Experimental Pin DC (W)	Simulation Pin DC (W)
5	**2.5**	18.62	18.72	19.35
	5	18.65	18.92	19.42
	10	18.73	19.12	19.48
	20	18.87	19.72	19.55
	30	19.02	20.18	19.68
10	**2.5**	24.21	24.17	25.94
	5	24.27	24.23	26.01
	10	24.40	24.57	26.09
	20	24.65	25.37	26.31
	30	24.89	26.03	26.54
25	**2.5**	41.21	40.59	41.69
	5	41.39	41.09	41.77
	10	41.75	41.49	42.08
	20	42.47	42.89	42.62
50	**2.5**	70.28	71.81	71.64
	5	70.80	72.81	72.00
	10	71.84	74.01	72.80
75	**2.5**	100.28	99.81	100.58
	5	101.33	101.41	101.41
	10	103.44	104.11	102.98
100	**2.5**	131.22	131.07	132.03
	5	133.01	133.57	133.40
125	**2.5**	163.13	163.66	163.00
	5	165.88	166.66	165.00
150	**2.5**	196.00	196.82	192.20
	5	199.94	201.78	195.00

Table 4.5: Validation Data collection for 48V DC Wiring Topology

Pout DC (W)	Length (m)	Mathematical Pin DC (W)	Experimental Pin DC (W)	Simulation Pin DC (W)
5	**2.5**	22.48	21.08	23.18
	5	22.49	21.24	23.19
	10	22.52	21.32	23.20
	20	22.57	21.45	23.26
	30	22.62	21.86	23.30
10	**2.5**	28.16	29.73	28.96
	5	28.18	29.76	28.97
	10	28.22	29.80	29.00
	20	28.30	30.00	29.08
	30	28.39	30.50	29.10
25	**2.5**	45.21	45.41	46.21
	5	45.26	45.53	46.30
	10	45.37	45.61	46.40
	20	45.58	45.87	46.50
	30	45.80	46.20	46.70
50	**2.5**	73.67	73.89	74.80
	5	73.82	74.04	74.90
	10	74.10	74.37	75.10
	20	74.68	74.64	75.60
	30	75.25	75.73	76.00
75	**2.5**	102.20	103.00	103.40
	5	102.48	103.20	103.60
	10	103.03	103.41	104.00
	20	104.13	104.62	104.80
	30	105.23	106.61	105.60
100	**2.5**	130.80	131.18	132.10
	5	131.25	131.74	132.40
	10	132.15	131.88	133.00
	20	133.95	134.07	134.30
	30	135.75	137.06	135.70
125	**2.5**	159.45	160.26	160.70
	5	160.12	161.02	161.20
	10	161.46	161.37	162.10
	20	164.13	164.79	164.10
150	**2.5**	188.17	188.42	189.40
	5	189.10	189.42	190.00
	10	190.96	190.67	191.40
	20	194.68	195.14	194.20
175	**2.5**	216.96	217.62	218.10
	5	218.19	218.54	219.00
	10	220.66	220.95	220.70
	20	225.59	226.98	224.50

Table 4.6: Validation Data collection for 230V AC Wiring Topology

Pout DC (W)	Length (m)	Mathematical Pin DC (W)	Experimental Pin DC (W)	Simulation Pin DC (W)
5	**2.5**	25.80	25.95	26.20
	5	25.80	25.98	26.20
	10	25.81	26.05	26.21
	20	25.83	26.10	26.23
	30	25.84	26.15	26.24
10	**2.5**	31.53	31.41	32.50
	5	31.53	31.42	32.50
	10	31.54	31.48	32.51
	20	31.56	31.51	32.52
	30	31.57	31.55	32.53
25	**2.5**	48.95	48.65	51.30
	5	48.96	48.69	51.40
	10	48.96	48.79	51.40
	20	48.97	48.85	51.40
	30	48.98	48.87	51.40
50	**2.5**	78.69	79.20	82.50
	5	78.69	79.27	82.50
	10	78.71	79.37	82.50
	20	78.74	79.40	82.60
	30	78.77	79.44	82.60
75	**2.5**	109.29	109.44	113.70
	5	109.31	109.58	113.70
	10	109.33	109.64	113.70
	20	109.39	109.69	113.80
	30	109.44	109.89	113.90
100	**2.5**	140.77	140.72	144.80
	5	140.79	140.83	144.90
	10	140.84	140.87	144.90
	20	140.93	141.13	145.10
	30	141.02	141.16	145.20
125	**2.5**	173.12	172.85	176.00
	5	173.16	173.09	176.10
	10	173.23	173.19	176.20
	20	173.37	173.35	176.40
	30	208.21	208.22	211.92
150	**2.5**	206.35	206.30	207.20
	5	206.40	206.52	207.30
	10	206.49	206.64	207.40
	20	206.69	206.83	207.70
175	**2.5**	240.44	240.62	238.40
	5	240.51	240.87	238.50
	10	240.65	241.09	238.70
	20	240.92	241.32	239.10

4.4 Validation

Graphical and statistical analysis methods have been used to validate the mathematical models.

4.4.1 Using Graphical Representation

Tables 4.3 to 4.6 outline the input power and output power for 123 cases as per mathematical modelling, experimental setup and simulation. The efficiencies of these methodologies have been calculated and verified using a graphical method.

Figures 4.6 to 4.9 show the comparison of mathematical efficiency estimation along with experimental and simulation efficiencies for 12V DC, 24V DC, 48V DC and 230V AC wiring topologies respectively. Figure 4.7 to Figure 4.10 show that the experimental and simulation efficiencies are close to the estimated efficiencies using the proposed mathematical models. The statistical tools are used in the next Section to validate the similarities.

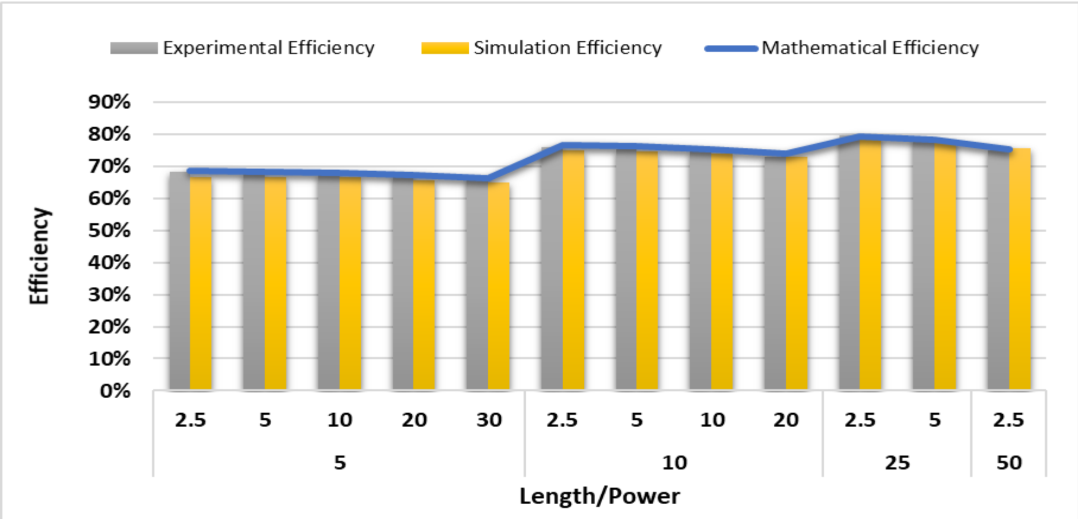

Figure 4.7: Validation charts for 12V DC wiring topology

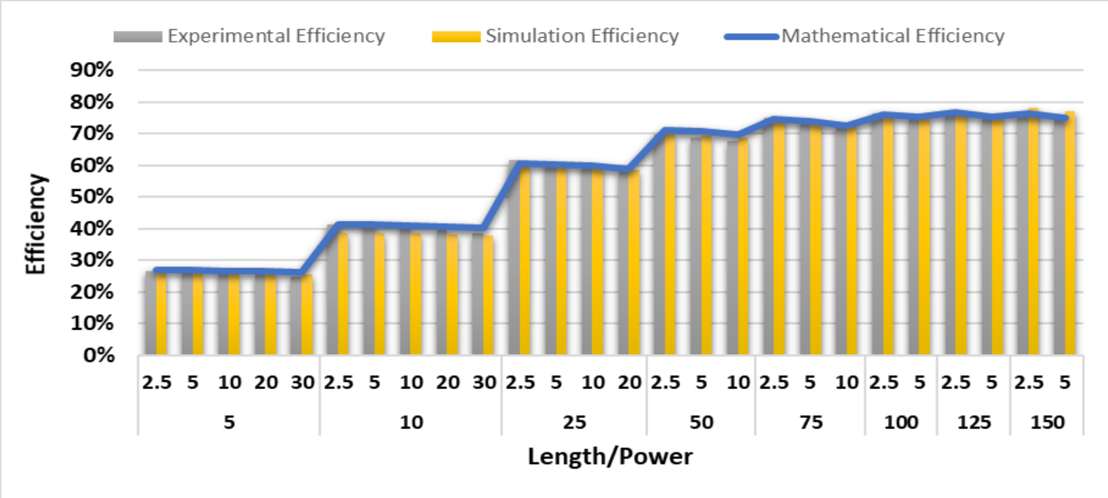

Figure 4.8: Validation charts for 24V DC wiring topology

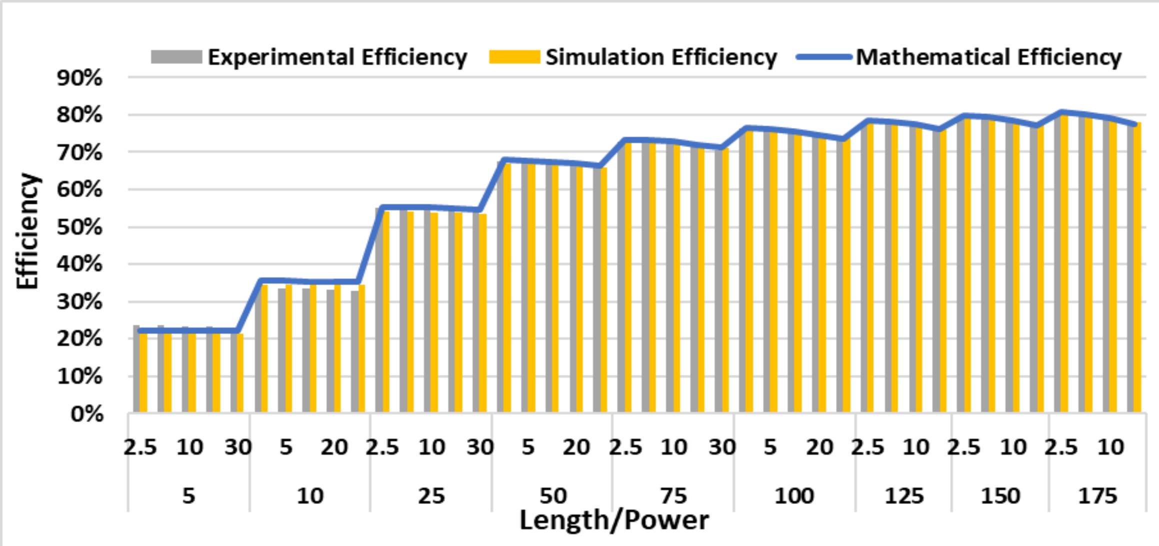

Figure 4.9: Validation charts for 48V DC wiring topology

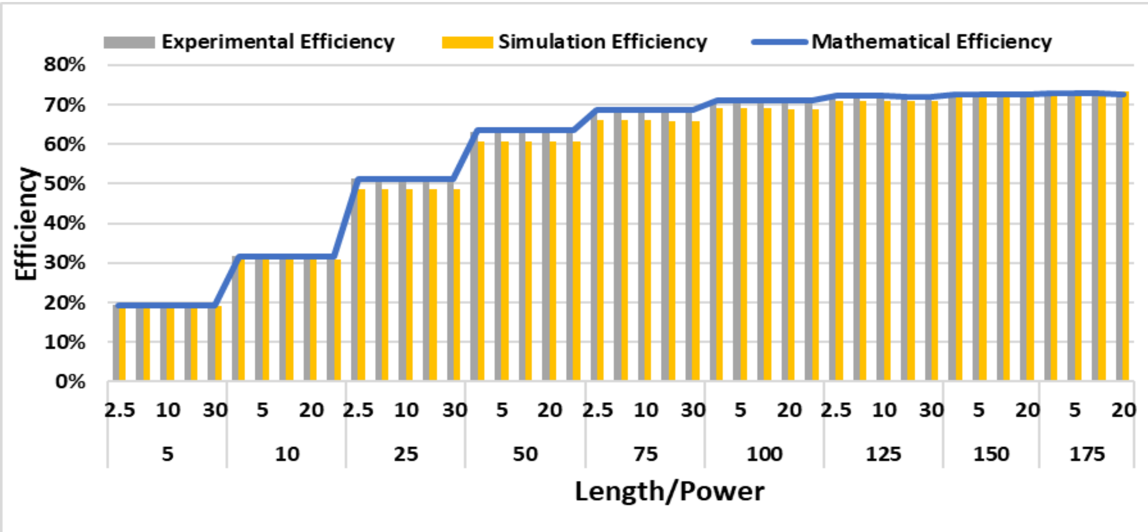

Figure 4.10: Validation charts for AC wiring topology

4.4.2 **Using Correlation Analysis**

Correlation analysis is a valid statistical tool to determine the similarity factor between two variables. In Equation 4.1, this tool has been used for correlation analysis of mathematically estimated efficiencies compared with experimental and simulation efficiencies. The coefficient of determination (r^2) in Equation 4.2 shows the similarity between the mathematical, experimental and simulation efficiencies for 12V DC, 24V DC, 48V DC and 230V AC wiring topologies as summarised in Table 4.7.

$$r = Correl(X, Y) = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}} \tag{4.1}$$

where,

X = Experimental Efficiency

Y = Mathematical Efficiency

$\bar{x}$ *and* $\bar{y}$ are the sample means of both variables

$$CoD = r^2 \tag{4.2}$$

Table 4.7: Similarity among mathematical, experimental and simulation methodologies

Wiring Topology	**Mathematical Model & Experiment Data**		**Mathematical Model & Simulation Data**		**Experiment data & Simulation**	
	Correlation Factor	**% Similarity**	**Correlation Factor**	**% Similarity**	**Correlation Factor**	**% Similarity**
12V DC	0.9955	99.11%	0.9930	98.61%	0.9940	98.81%
24V DC	0.9992	99.85%	0.9989	99.78%	0.9984	99.67%
48V DC	0.9992	99.83%	0.9999	99.97%	0.9992	99.84%
230V AC	0.9999	99.99%	0.9983	99.66%	0.9984	99.67%

The mathematical efficiencies are at least 98.61% similar to experimental and simulation studies as summarised in Table 4.7. These high similarity results validate the proposed mathematical models based on correlation analysis.

4.5 Concluding Remarks

Power losses comparisons of 123 cases using experimental and simulation studies have validated the mathematical model using both graphical and statistical methods. Thus, these validated mathematical models can be used for the analysis of AC and DC wiring topologies discussed in the next Chapter.

Chapter 5 Analysis and Results

One of the research objectives is to develop boundary condition charts that can help to select the most efficient wiring topology.

5.1 Boundary Conditions for Efficient House Wiring Topology

Boundary conditions should include the total number of wiring cases which depend on the power rating of load, length of the conductor, area of conductor and voltage level. Total wiring cases for each cable size can be calculated using Equation 5.1.

$$T_{WC} = N_p \times N_l \times N_w \tag{5.1}$$

Where,

N_p = Total number of connected loads (power in Watts)

N_l = Total number of cable length options in meters

N_w = Total number of cable sizes in mm^2, six cable sizes have been included in this thesis including 1 mm^2, 1.5 mm^2, 2.5 mm^2, 4 mm^2, 6 mm^2 and 10 mm^2

The total number of connected loads (N_p) depends on the range of load power and the step size between two connected loads as represented in Equation 5.2.

$$N_p = \frac{Maximum\ power\ of\ load\ to\ be\ connected}{Step\ size\ of\ load} \tag{5.2}$$

As discussed in Chapter 2, the maximum power of one connected load is limited to 1,000W.

The total number of wire length options (N_l) depends on the maximum length and step size between the wire sizes as shown in Equation 5.3.

$$N_l = \frac{Maximum\ wire\ length}{Step\ size\ of\ length} \tag{5.3}$$

From the total wiring cases calculated using Equation 5.1, few wiring cases did not comply with the ampacity and voltage drop requirements as per AS/NZS 3000. Therefore, the boundary condition chart was developed only for the wiring cases which did comply. The efficiencies of wiring cases were calculated for the proposed AC and DC wiring topologies at four voltage levels i.e. 230V AC, 12V DC, 24V DC and 48V. Finally, the efficiency of AC and DC wiring topologies was compared to develop the boundary condition charts for six conductor sizes from 1mm^2 to 10mm^2 as shown in Figures 5.1 to 5.6. Therefore, each boundary condition chart highlights the most efficient wiring system among the four voltage systems.

Length/ Power	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V
10	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V
25	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
50	12V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
75	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC
100	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC
125	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
150	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
175	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
200	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
250	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
300	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
350	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
400	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
450	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
500	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
550	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
600	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
650	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
700	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
750	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC

Figure 5.1: Efficient and acceptable wiring options for 1mm^2 cable size

In the boundary conditions chart,

12V	12V DC Wiring Topology is the most wiring efficient option
24V	24V DC Wiring Topology is the most wiring efficient option
48V	48V DC Wiring Topology is the most wiring efficient option
AC	230V AC Wiring Topology is the most wiring efficient option

It is easy to select the most efficient wiring topology for a residential house as these boundary condition charts are equally understandable for a technical and non-technical audience. Let's take an example of a 125W refrigerator that is connected to the main power board via 1 mm^2 wire size. In this case, the 48V DC wiring option would be the most efficient option up to the cable length of 17m above which AC wiring is recommended as shown in Figure 5.1. Another observation from Figure 5.1; 12V DC can only be used to feed a load up to 5W when the length is less than 25m; similarly, AC wiring topology is the most efficient option when a DC load of more than 500W is fed through a 1mm^2 cable size.

Length/ Power	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
10	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V
25	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V
50	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
75	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
100	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
125	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC
150	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC
175	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
200	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
250	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
300	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
350	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
400	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
450	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
500	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
550	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
600	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
650	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
700	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
750	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
800	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
850	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
900	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC

Figure 5.2: Efficient and acceptable wiring options for 1.5mm^2 cable size

1.5mm^2 cable is used for lighting circuits in New Zealand. The boundary condition chart for 1.5mm^2 in Figure 5.2 shows that 12V and 24V DC wiring topologies would be the most efficient option as the power rating of LED lamps is much less than 100W.

Length/ Power	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
10	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
25	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V
50	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V
75	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
100	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
125	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
150	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
175	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
200	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
250	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC
300	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC
350	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
400	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
450	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
500	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
550	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
600	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
650	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
700	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
750	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
800	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
850	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
900	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
950	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
1000	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC

Figure 5.3: Efficient and acceptable wiring options for 2.5mm^2 cable size

Three core 2.5mm^2 is commonly used in existing residential houses to feed power circuits as per AS/NZS 3000. The boundary condition chart for 2.5mm2 in Figure 5.3 shows that the 48V DC wiring option is limited to 900W load for wire lengths up to 7m. However, with 4mm^2, the boundary condition chart in Figure 5.6 shows that the 48V DC wiring option is recommended to feed a DC load up to 1,000W when the length is less than 11m.

Length/ Power	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
10	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
25	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V
50	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V
75	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V
100	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
125	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
150	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
175	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
200	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
250	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
300	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
350	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
400	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC
450	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC
500	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC
550	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
600	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
650	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
700	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
750	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
800	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
850	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
900	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
950	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
1000	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC

Figure 5.4: Efficient and acceptable wiring options for 4 mm^2 cable size

The boundary conditions charts show that the pattern is almost the same for all cable sizes as shown in Figures 5.1 to 5.6. The 12V DC wiring topology is efficient for shorter cable lengths and low power rating loads. Similarly, 24V and 48 have efficient bands in boundary conditions. The 24V band efficiency band has the thinnest band of all the options. The width of LVDC wiring topology has increased with the increase in conductor size. The AC wiring system is still the most efficient option for high power rating loads at longer wire lengths.

Length/ Power	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
10	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
25	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
50	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V
75	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V
100	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
125	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
150	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
175	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
200	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
250	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
300	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
350	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
400	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
450	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
500	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
550	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
600	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC
650	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC
700	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC
750	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC
800	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC
850	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
900	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
950	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
1000	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC

Figure 5.5: Efficient and acceptable wiring options for 6mm^2 cable size

Length/ Power	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
10	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
25	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
50	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V	12V
75	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V
100	24V	24V	24V	24V	24V	24V	24V	24V	24V	24V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
125	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
150	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
175	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
200	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
250	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
300	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
350	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
400	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
450	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
500	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
550	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
600	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
650	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
700	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
750	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
800	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
850	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
900	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V
950	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC
1000	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	48V	AC	AC

Figure 5.6: Efficient and acceptable wiring options for 10mm^2 cable size

Generally, the conductor size in existing houses is limited to 6 mm^2 but 10mm^2 has been included to consider the feasibility options in a future residential house. 10mm^2 boundary condition chart in Figure 5.6 shows that the DC wiring topology is the most efficient wiring option for most of the cases up to 1,000W DC loads with a maximum 28m cable length.

For the efficient wiring topology as per the boundary condition charts, the 3D chart in Figure 5.7 shows the expected power losses increased with the increase in load power rating and cable length. It is important to note that the power losses are quite significant for loads above 300W and the power losses increased non-linearly as shown in Figure 5.7. To further observe the power loss behaviour for the 4th dimension, the 3D charts were developed for cable sizes from 1mm^2 to 10mm^2 as shown in Figures 5.7 to 5.12. The power losses are reduced considerably with the increase in cable size. For example, Figure 5.12 shows the 3D chart for 10mm^2 cable size, and power losses at higher power rating loads at longer lengths are reduced significantly. Therefore, it is recommended to increase the cable size to feed the high power rating loads. However, the cost of larger cable sizes would be high as well. Therefore, it is important to view this from a cost-benefit viewpoint.

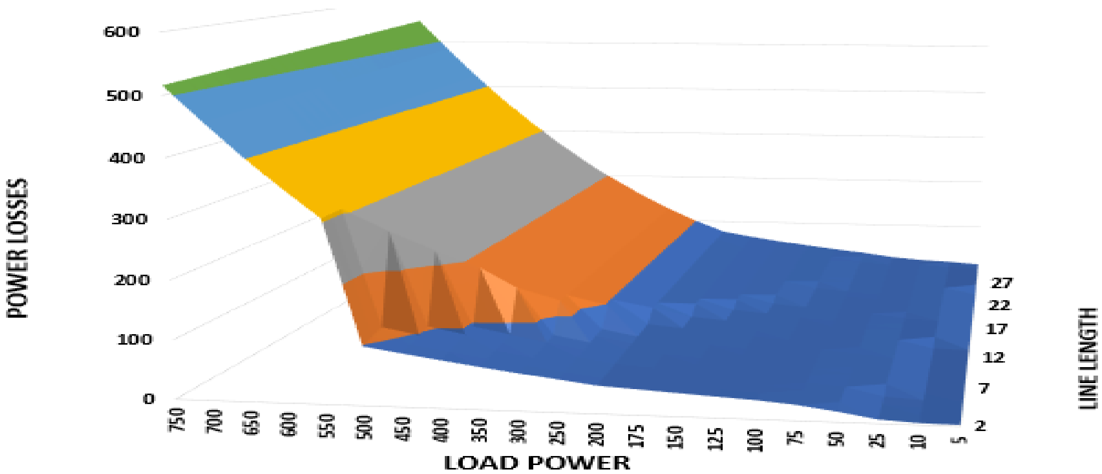

Figure 5.7: Power losses, wire length and load power chart for 1mm^2

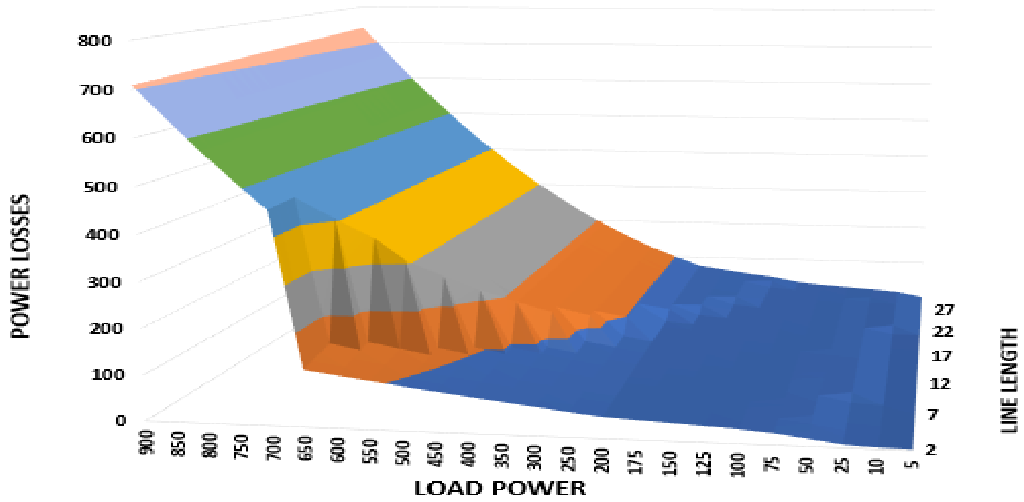

Figure 5.8: Power losses, wire length and load power chart for 1.5 mm^2

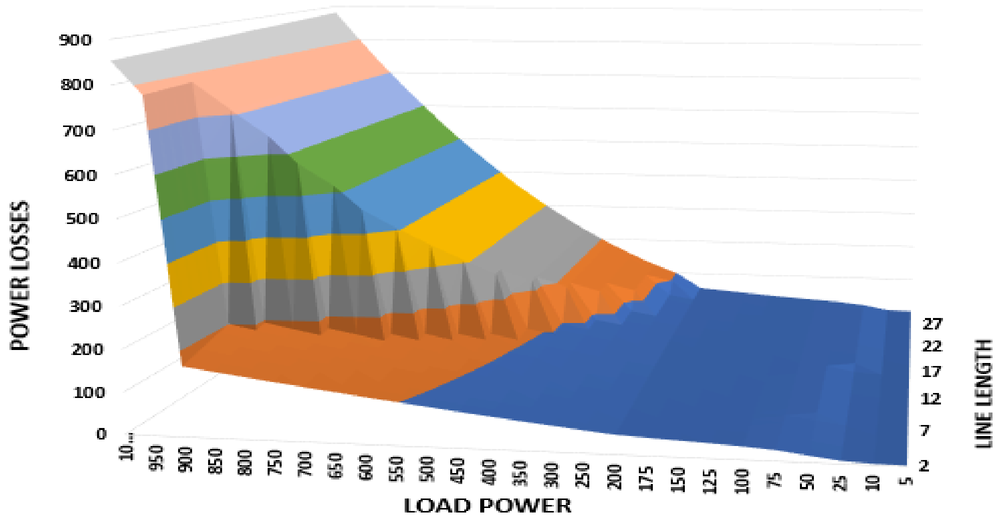

Figure 5.9: Power losses, wire length and load power chart for 2.5mm^2

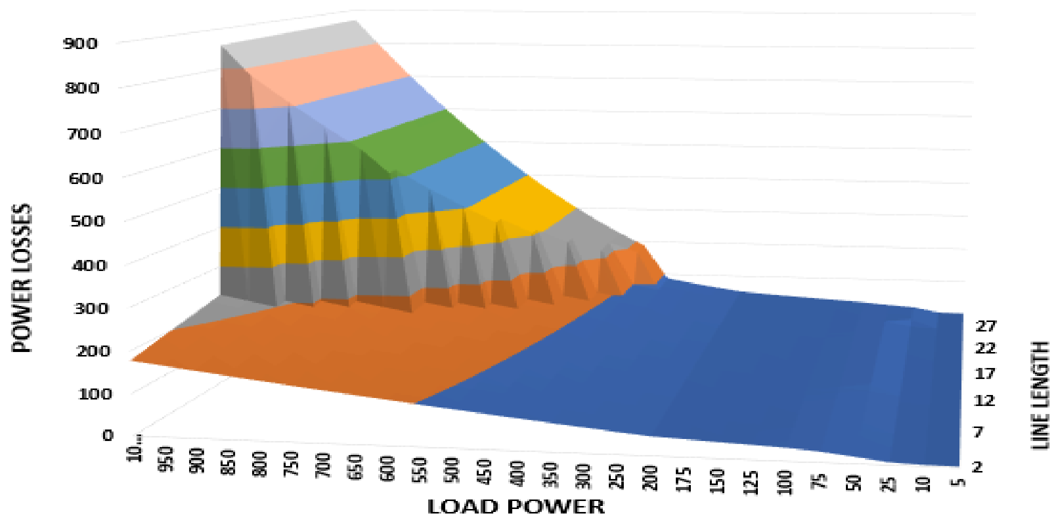

Figure 5.10: Power losses, wire length and load power chart for 4 mm^2

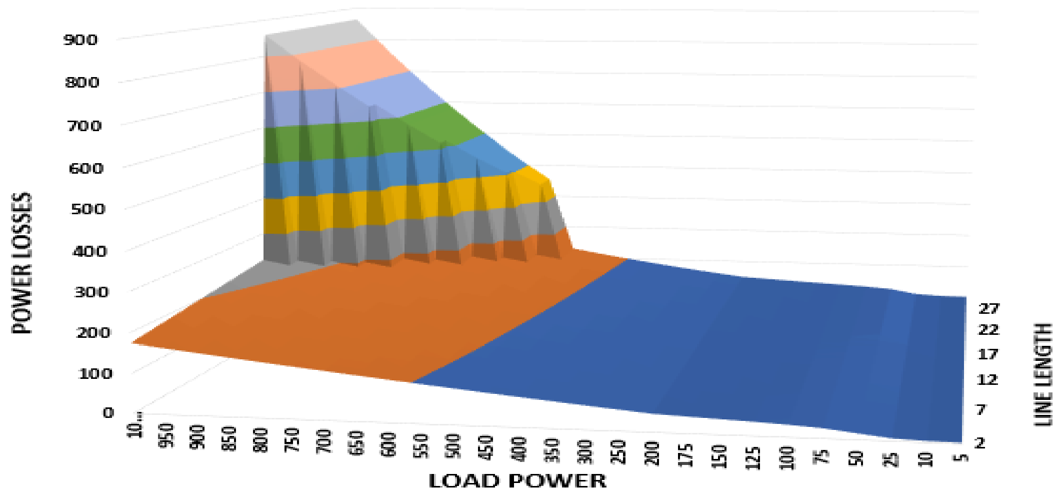

Figure 5.11: Power losses, wire length and load power chart for 6 mm^2

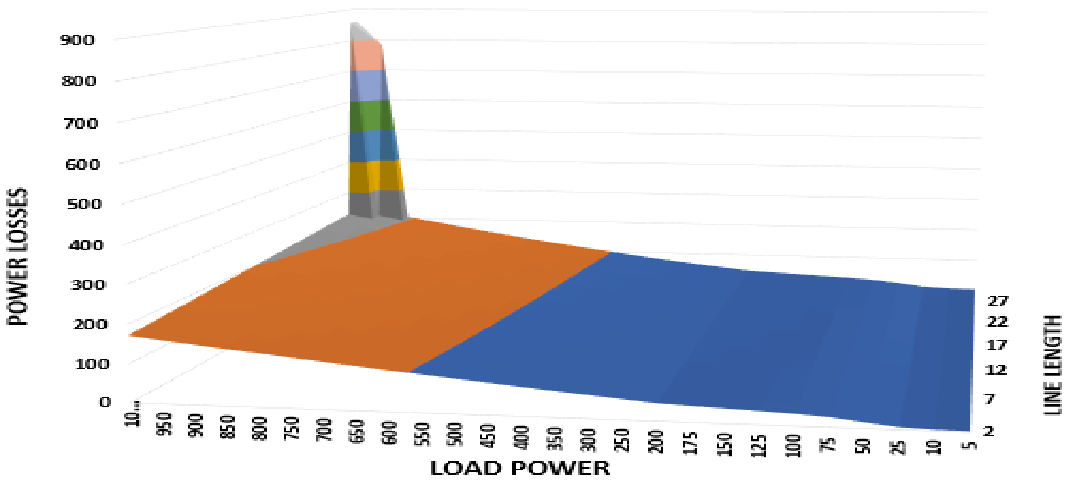

Figure 5.12: Power losses, wire length and load power chart for 10 mm^2

5.2 Analysis of Typical Houses in New Zealand

The boundary condition charts give a good understanding of individual loads from an efficiency point of view; however, the combination of load and cost impact is not considered. Most of the commercial decisions are based on cost-benefit analysis. Therefore, it is hard to quantify and recommend any one type of wiring topology for a combination of loads in a residential house. In-depth analysis of existing and new-build houses should be done to gain an understanding of the combination of loads. Therefore, an example of the typical three-bedroom house has been discussed to make recommendations based on cost-benefit analysis. The analysis has been extended for a single bedroom house/unit due to the growing concept of tiny houses in cities like Auckland, Wellington and Queenstown where the land prices are very high.

The recommended wiring topology would change based on the circumstances such as house design, living style, size of the house, converter technology etc. Therefore, the cost-benefit analysis in this research can only be taken as a case study.

5.2.1 Input Matrix

An input matrix was used to analyse the typical residential houses from both technical and financial standpoints. This input matrix can be classified into two types of parameters: installation and operating parameters.

Installation Parameters

The first major input is the power rating of load and cable length. That is used to estimate the line current and cable size in mm^2. Table 5.1 shows the DC resistance of each wire size which is required to estimate the line losses. This is also used for design check including the ampacity of cable and voltage drop as per AS/NZS 3000.

Table 5.1: Specifications and cost of cables

Cable size (mm^2)	V_d factor at Max 45 Degree	Ampacity (A)	Cost per meter	DC Resistance (Ohms)/km
1	40.3	13	0.89	18.1
1.5	25.9	16	0.10	12.1
2.5	14.1	23	1.54	7.41
4	8.77	31	2.45	4.61
6	5.86	40	3.84	3.08
10	3.49	54	6.02	1.83
16	2.19	72	9.43	1.15

One conduit normally carries more than one wire to feed multiple loads. Due to multiple cables in a conduit, the AC resistance of cables is increased due to the proximity factor; this is already accounted for in the mathematical modelling. However, the current carrying capacity of the cable is also reduced for AC power flow as per the grouping factor in Table 5.2.

Table 5.2: Cable de-rating factor based on grouping

No of cables	Group factor
1	1
2	0.88
3	0.8
4	0.75
5	0.71
6	0.69

Operating Parameters

Power loss calculations are based on the mathematical modelling at 24 ^{o}C ambient temperature which is aligned with the average temperature throughout New Zealand (Service, 2020)

The demand factor is used to calculate the maximum demand for the house as expressed in Equation 5.4. The utilisation factor helps to estimate the average utilisation time of electrical loads as expressed in Equation 5.5. These factors have been considered in this research to estimate the average energy usage of a house over 5 years. The demand factor has been considered as 0.4 along with the utilisation factor of 0.25 based on the observation and typical use of the house used for this research. (Jignesh.Parmar, 2020).

$$D_F = \frac{\text{Maximum demand of a system}}{\text{Total connected load to the system}} \tag{5.4}$$

$$U_F = \frac{\text{The time that equipment is in use}}{\text{The total time that it could be in use}} \tag{5.5}$$

where,

$D_F =$ Demand Factor

$U_F =$ Utilization Factor

5.2.2 Results Matrix to Compare Wiring Topologies

Recommendation for AC or DC wiring topology will be based on a results Matrix which will be represented by **PEC** which means (**P**ossible cases, overall **E**fficiency and **C**ost). This section outlines the four results along with their estimation method.

Possible Circuits/Cases

Wiring topologies can only be compared for the possible circuits. Possible means that the proposed wiring topology can feed the load and it also complies with New Zealand standards, regulations and legislation such as voltage drop limit of 5%. The percentage of the possible circuit has been can be calculated using Equation 5.6.

$$\% \; of \; Possible \; Cirucits = \frac{n_p}{n_T} \times 100 \tag{5.6}$$

where,

$n_p = Number \; of \; possible \; circuits/cases$

$n_T = Number \; of \; Total \; circuits/cases$

Overall Efficiency

Firstly, the power losses of individual cases are calculated using the mathematical models developed in Chapter 3. The overall efficiency percentage is calculated using Equation 5.7. This efficiency will be based on the possible circuits/cases only.

$$Overall \; Effieincy =$$

$$\frac{\sum_{i \to 1}^{n_p} Power \; losses \; in \; Possible \; circuits}{\sum_{i \to 1}^{n_p} Power \; losses \; in \; possible \; circuits + \sum_{i \to 1}^{n_p} load \; Power \; of \; possible \; circuits} \times 100 \tag{5.7}$$

Initial Cost per Watt at the time of installation (Material)

For the proposed DC and AC wiring topologies in Figures 3.2 and 3.3, the initial "Cost per Watt at installation time" can be estimated from Equations 5.8 and 5.9. The costs of cables and converters have been summarised in Tables 5.1 and 5.3. This cost is limited to the material cost only as it is difficult to estimate the installation cost due to various factors such as market competition, region, property type and location.

$$C_{DC\_\text{Initial}} = \frac{C_{Cable} + C_{DC-DC}}{\sum Power\ of\ Possible\ cases\ in\ Watts} \tag{5.8}$$

$$C_{AC\_\text{Initial}} = \frac{C_{DC-AC} + C_{Cable} + C_{AC-DC}}{\sum Power\ of\ Possible\ cases\ in\ Watts} \tag{5.9}$$

where,

$C_{DC\_\text{Initial}} = Initial\ cost\ of\ DC\ wiring\ topology$

$C_{AC\_\text{Initial}} = Initial\ cost\ of\ AC\ wiring\ topology$

$C_{Cable} = Cost\ of\ cable$

$C_{DC-DC} = Cost\ of\ DC\ to\ DC\ converter$

$C_{DC-AC} = Cost\ of\ DC\ to\ AC\ converter$

$C_{AC-DC} = Cost\ of\ AC\ to\ DC\ converter$

Table 5.3: Market cost of converters (MeanWell, 2019)

S. No	**Converter Type**	**50W**	**200W**	**500W**	**1000W**
1	12V input DC/DC	56	112		
2	24V input DC/DC	78	156	260	390
3	48V input DC/DC	82	164	274	411
4	DC to AC	92	148	185	241
5	AC to DC	67	107	134	175

Cost Per Watt over 5 Years

The objective of this parameter is to consider the short term and long term cost impact in terms of percentage that can help to make better decisions. This is the sum of installation cost and the cost of energy losses in 5 years as expressed using Equation 5.10.

$$C_{5\,years} = C_{\text{Initial}} + E_{loss} * E_{rate} \tag{5.10}$$

where,

$C_{5\,years} = Five\ years\ Per\ Watt\ cost\ of\ Wiring\ Topology$

$C_{\text{Initial}} = Initial\ cost\ of\ wiring\ topology$

$E_{loss} = Total\ Energy\ lost\ in\ 5\ years\ (KWh)$

$E_{rate} = Energy\ rate\ per\ KWh$

The energy loss over five years can be calculated

$E_{loss} = U_F \times D_F \times P_{loss}$ x (5*365*24)

Where,

$U_F = Utilization\ factor$

$D_F = Demand\ factor$

$P_{loss} = Power\ loss\ in\ Wiring\ Topology$ (Watts)

The electricity rate slightly varies from city to city depending on the line charges by transmission and distribution companies. The Wellington city energy rate of 29 cents/kWh has been used for cost calculation of power losses over 5 years to calculate the feasibility (Ministry of Business, 2020).

Faults, repairs, maintenance, and replacement costs have not been considered in the cost-benefit analysis. The frequency of faults along with converter life span needs to be estimated or calculated which is beyond the scope of the thesis. Therefore, without losing much of generality, the cost-benefit analysis of this research is limited to 5 years only.

Development of Tool to Calculate Results Matrix

The cost-benefit analysis involves power loss calculations, development of boundary condition charts, wire design check and cost estimation. This analysis needs to be repeated for any minor change in input conditions such as the ambient temperature, load power rating, cable size or length or even the number of loads.

Therefore, the AUT Wiring Selection Software has been developed to save calculation and analysis time. It is based on the proposed mathematical models and the costs of equipment and energy. This tool takes inputs such as load, cable size, cable length, ambient temperature, grouping factor, utilisation factor, energy rate and the number of years over which cost-benefit analysis is conducted. This tool also checks the compliance of wiring topology with AS/NZS 3000 and AS/NZS 3015. The user interface and detailed features of the AUT wiring Selection Software are explained in Appendix D.

5.2.3 Analysis of a Typical Three Bedroom House

The three-bedroom house has been analysed with three scenarios. Firstly, the existing house with existing wiring scenario where the cable length and cable size cannot be changed. Secondly, an existing three-bedroom house with new wiring where the cable length cannot be changed due to the wiring structure of the existing house, but cable size can be changed in the case of new wiring. Finally, a new build three-bedroom house where cable length and size can be optimised.

Existing Three Bedroom House with Existing Wiring

The load and wiring data for an existing three-bedroom house is summarised in Table 5.4.

Table 5.4: Data of existing three-bedroom house with existing wiring

Location	Appliance	Load Power Rating (Watts)	Existing Wire Length (m)	Wire Size in Existing AC (mm^2)	Number of Circuits in Conduit
Kitchen	Microwave oven	800	20	2.5	6
	Electric Cooker	500	20	2.5	6
	Coffee maker / Electric Kettle/blender	990	20	2.5	6
	Refrigerator	125	20	2.5	6
	Dishwasher	500	20	2.5	6
	LED Lamp	7	20	1.5	6
Lounge	LED TV	90	15	2.5	5
	LED Lamp	7	15	1.5	5
	LED Lamp	7	15	1.5	5
	Heat Pump	900	10	4	5
	Cell phone charger	5	15	2.5	5
Bathroom	LED Lamp	7	15	1.5	3
	Fan Heater	500	15	2.5	3
	Fan or equivalent	25	15	2.5	3
Laundry and others	Washing machine	500	25	2.5	3
	Vacuum cleaner	300	25	2.5	3
	Iron	1000	25	2.5	3
Bedroom 1	LED Lamp	7	10	1.5	4
	Cell phone charger	5	10	2.5	4
	Laptop	50	10	2.5	4
	Fan or equivalent	25	10	2.5	4
Bedroom 2	LED Lamp	7	25	1.5	3
	Cell phone charger	5	25	2.5	3
	Fan or equivalent	25	25	2.5	3
Bedroom 3	LED Lamp	7	35	1.5	4
	Cell phone charger	5	35	2.5	4
	Fan or equivalent	25	35	2.5	4
	Fan Heater	500	35	2.5	4

PEC results were calculated for the minimum wire design as in Subsections 5.2.1 and 5.2.2. The overall efficiency in Table 5.5 is only limited to the possible circuits and loads as per Equation 5.7. It is clear from the summary of Table 5.5 that the 12V DC wiring system has the maximum overall efficiency of 73.1% and this is due to the line losses at low voltage DC. The 12V DC wiring option can only be used for 42.9% of loads due to design limitations.

Similarly, the 48V DC wiring topology has an overall efficiency of 70.29% which is better than the AC wiring option, but it can only be used to replace two-thirds of the circuits. Therefore, it is not possible to replace this existing house wiring system with a DC-only option as summarised in Table 5.5. On the other hand, the existing AC wiring system can be used for all circuits, but the overall efficiency of the AC wiring option is only 58.43% due to the power losses in double conversions. It means the hybrid wiring option gives better overall efficiency as compared to the AC wiring option for all circuits. The hybrid wiring option is the mixture of 12V DC, 24V DC, 48V DC and 230V AC wiring topologies as per boundary conditions as outlined in Table 5.6.

Table 5.5: Output Parameters for the existing three-bedroom house with existing wiring

Result Parameters	**Hybrid System**	**12V DC System**	**24V DC System**	**48V DC System**	**230 AC System**
Possible circuits	28	12	17	19	28
Connected load (Watts)	6924	112	309	1334	6924
% Ratio of Possible circuits with total	100.00%	42.86%	60.71%	67.86%	100.00%
% Ratio of Connected load with total	100.00%	1.62%	4.46%	19.27%	100.00%
Overall efficiency	62.52%	73.10%	52.85%	70.29%	58.43%
% Cost in 5 years	23.9%	100.0%	87.3%	31.9%	28.5%

In terms of cost comparison, the hybrid system is the most cost-effective option with system cost of 23.9% (see Table 5.5). Therefore, hybrid wiring is becoming very common in sustainable and green buildings due to the efficiency perspectives to save the environment as witnessed for Camp Glenorchy Eco Retreat which is connected to Aurora Energy Network (Headwaters, 2018).

Table 5.6: Hybrid option for a three-bedroom existing house with existing wiring

Appliance	**Load Power Rating (Watts)**	**Existing Wire Length (m)**	**Wire Size in Existing AC (mm2)**	**Hybrid Option**
Microwave oven	800	20	2.5	AC 230V
Electric Pressure Cooker	500	20	2.5	AC 230V
Coffee maker / Electric Kettle/Juicer blender	990	20	2.5	AC 230V
Refrigerator	125	20	2.5	48V DC
Dishwasher	500	20	2.5	AC 230V
LED Lamp	7	20	1.5	12V DC
LED TV	90	15	2.5	48V DC
LED Lamp	7	15	1.5	12V DC
LED Lamp	7	15	1.5	12V DC
Heat Pump	900	10	4	48V DC
Cell phone charger	5	15	2.5	12V DC
LED Lamp	7	15	1.5	12V DC
Fan Heater	500	15	2.5	AC 230V
Fan or equivalent	25	15	2.5	12V DC
Washing machine	500	25	2.5	AC 230V
Vacuum cleaner	300	25	2.5	AC 230V
Iron	1000	25	2.5	AC 230V
LED Lamp	7	10	1.5	12V DC
Cell phone charger	5	10	2.5	12V DC
Laptop	50	10	2.5	24V DC
Fan or equivalent	25	10	2.5	12V DC
LED Lamp	7	25	1.5	12V DC
Cell phone charger	5	25	2.5	12V DC
Fan or equivalent	25	25	2.5	24V DC
LED Lamp	7	35	1.5	24V DC
Cell phone charger	5	35	2.5	12V DC
Fan or equivalent	25	35	2.5	24V DC
Fan Heater	500	35	2.5	AC 230V

Existing Three Bedroom House with New Wiring

Based on the existing wire size and design, there is no DC-only option available in an existing three-bedroom house. Now the wiring of the existing house has been designed to consider the possibilities of DC-only wiring option as summarised in Table 5.7. The maximum possible wire size is 10 mm^2 due to the limitations of installation conditions.

Table 5.7: New Wiring design for an existing three-bedroom house

Appliance	Load Power Rating	Wire Size (mm^2)			
		12V DC	24V DC	48V DC	230V AC
Microwave oven	800			6	1
Electric Pressure Cooker	500			4	1
Coffee maker / Electric Kettle/Juicer blender	990			10	1
Refrigerator	125		4	1.5	1
Dishwasher	500			4	1
LED Lamp	7	1.5	1	1	1
LED TV	90	10	2.5	1	1
LED Lamp	7	1	1	1	1
LED Lamp	7	1	1	1	1
Heat Pump	900			4	1
Cell phone charger	5	1	1	1	1
LED Lamp	7	1	1	1	1
Fan Heater	500	0		4	1
Fan or other similar equivalent	25	2.5	1	1	1
Washing machine	500			6	1
Vacuum cleaner	300			4	1
Iron	1000				1
LED Lamp	7	1	1	1	1
Cell phone charger	5	1	1	1	1
Laptop	50	4	1	1	1
Fan or other similar equivalent	25	2.5	1	1	1
LED Lamp	7	1.5	1	1	1
Cell phone charger	5	1.5	1	1	1
Fan or other similar equivalent	25	4	1.5	1	1
LED Lamp	7	2.5	1.5	1	1
Cell phone charger	5	1.5	1	1	1
Fan or other similar equivalent	25	6	2.5	1	1
Fan Heater	500			10	1

PEC results were calculated for the minimum wire design as in Sections 5.2.1 and 5.2.2. The PEC results changed due to the replacement of the existing wiring. Wiring cost has been reduced when designed based on minimum possible size and this change is quite significant for some wiring cases. The possible number of cases has been increased in each category; for example, 48V DC wiring options can be used for 96.43% of circuits as summarised in Table 5.8.

It is clear from the PEC results that the 48V DC system has the maximum possible efficiency of 78.74% with the minimum cost of 25.9% over 5 years. 48V DC wiring topology cannot be used for all cases which means we either need to remove remaining load cases or use hybrid wiring options. Therefore, the hybrid would still be the most suitable option for the existing house with new wiring. The hybrid wiring options are a mixture of 12V DC, 24V DC, 48V DC and 230V AC wiring topologies as per boundary conditions as outlined in Table 5.9. These results are based on one typical house and would change on a case by case basis. The AUT Wiring Selection Software can be used to evaluate other cases.

Table 5.8: Output parameters an existing three-bedroom house with new Wiring

Result Parameters	**Hybrid System**	**12V DC System**	**24V DC System**	**48V DC System**	**230 AC System**
Possible circuits	27	17	18	27	28
Connected load (Watts)	5924	309	434	5924	6924
% Ratio of Possible circuits with total	100.00%	60.71%	64.29%	96.43%	100.00%
% Ratio of Connected load with total	100.00%	4.46%	6.27%	85.56%	100.00%
Overall efficiency	80.01%	71.86%	57.14%	78.74%	57.79%
% Cost in 5 years	26.8%	95.8%	100.0%	25.9%	40.9%

Table 5.9: Hybrid option for a three-bedroom existing house with new wiring

Appliance	Load Power Rating (Watts)	Existing Wire Length (m)	Wire Size in Existing AC (mm2)	Hybrid Option
Microwave oven	800	20	6	48V DC
Electric Pressure Cooker	500	20	4	48V DC
Coffee maker / Electric Kettle/Juicer blender	990	20	10	48V DC
Refrigerator	125	20	1.5	48V DC
Dishwasher	500	20	4	48V DC
LED Lamp	7	20	1	24V DC
LED TV	90	15	1	48V DC
LED Lamp	7	15	1	12V DC
LED Lamp	7	15	1	12V DC
Heat Pump	900	10	4	48V DC
Cell phone charger	5	15	1	12V DC
LED Lamp	7	15	1	12V DC
Fan Heater	500	15	4	48V DC
Fan or equivalent	25	15	1	24V DC
Washing machine	500	25	6	48V DC
Vacuum cleaner	300	25	4	48V DC
Iron	1000	25	1.5	230V AC
LED Lamp	7	10	1	12V DC
Cell phone charger	5	10	1	12V DC
Laptop	50	10	1	24V DC
Fan or equivalent	25	10	1	24V DC
LED Lamp	7	25	1	24V DC
Cell phone charger	5	25	1	24V DC
Fan or equivalent	25	25	1	48V DC
LED Lamp	7	35	1	48V DC
Cell phone charger	5	35	1	24V DC
Fan or equivalent	25	35	1	48V DC
Fan Heater	500	35	10	48V DC

Analysis of a Typical New-build Three-bedroom House

The design of a new-build house is focused on sustainable energy practices. The converter losses are less in low voltage DC wiring; however, the line losses are significant for high power loads. High power consumption appliances are generally used in kitchen and laundry. Therefore, the main power board should be installed close to these areas to reduce line lengths as shown in the power and length data for a new-build house in Table 5.10.

Table 5.10: Data of new-build three-bedroom house

Location	Appliance	Load Power Rating (Watts)	Wire Length (m)	Wire Size (mm^2)	Number of Circuits in Conduit
Kitchen	Microwave oven	800	8	4	6
	Electric Pressure Cooker	500	8	2.5	6
	Coffee maker / Electric Kettle/Juicer blender	990	8	6	6
	Refrigerator	125	8	2.5	6
	Dishwasher	500	8	2.5	6
	LED Lamp	7	8	1.5	6
Lounge	LED TV	90	13	2.5	5
	LED Lamp	7	13	1.5	5
	LED Lamp	7	13	1.5	5
	Heat Pump	900	13	6	5
	Cell phone charger	5	13	2.5	5
Bathroom	LED Lamp	7	20	1.5	3
	Fan Heater	500	20	4	3
	Fan or equivalent	25	20	2.5	3
Laundry and others	Washing machine	500	15	4	3
	Vacuum cleaner	300	15	2.5	3
	Iron	1000	15	6	3
Bedroom 1	LED Lamp	7	25	1.5	4
	Cell phone charger	5	25	2.5	4
	Laptop	50	25	2.5	4
	Fan or equivalent	25	25	2.5	4
Bedroom 2	LED Lamp	7	30	1.5	3
	Cell phone charger	5	30	2.5	3
	Fan or equivalent	25	30	2.5	3
Bedroom 3	LED Lamp	7	20	1.5	4
	Cell phone charger	5	20	2.5	4
	Fan or equivalent	25	20	2.5	4
	Fan Heater	500	20	4	4

In case of the new build three-bedroom house, PEC results in Table 5.11 show that the 48V DC system can be used for all circuits with an overall efficiency of 79.73% which is maximum as compared to other individual wiring topologies. On the other hand, the overall efficiency of the hybrid wiring option is 81.32%. The hybrid wiring options is the mixture of DC and AC wiring topologies as per boundary conditions as outlined in Table 12. The hybrid efficiency is around 2% more efficient than the 48V DC wiring option as summarised in Table 5.11. However, the cost of the 48V DC system is only NZD 0.72/W which is around 6% less compared to hybrid and other systems. This cost impact is quite considerable and the 48V DC option remains cost-effective in the longer run e.g. for 5 years as shown in Table 5.6.

Table 5.11: Output parameters for a new-build three-bedroom house

Result Parameters	**Hybrid System**	**12V DC System**	**24V DC System**	**48V DC System**	**230 AC System**
Possible circuits	28	10	18	28	28
Connected load (Watts)	6924	62	434	6924	6924
% Ratio of Possible circuits with total	100.00%	35.71%	64.29%	100.00%	100.00%
% Ratio of Connected load with total	100.00%	0.90%	6.27%	100.00%	100.00%
Overall efficiency	81.32%	70.14%	57.72%	79.73%	58.72%
% Cost in 5 years	11.0%	100.0%	47.2%	10.7%	19.2%

Table 5.12: Hybrid option for a three-bedroom new-build house

Appliance	Load Power Rating (Watts)	Existing Wire Length (m)	Wire Size in Existing (mm2)	Hybrid Option
Microwave oven	800	8	4	48V DC
Electric Pressure Cooker	500	8	2.5	48V DC
Coffee maker / Electric Kettle/Juicer blender	990	8	6	48V DC
Refrigerator	125	8	2.5	48V DC
Dishwasher	500	8	2.5	48V DC
LED Lamp	7	8	1.5	24V DC
LED TV	90	13	2.5	48V DC
LED Lamp	7	13	1.5	12V DC
LED Lamp	7	13	1.5	12V DC
Heat Pump	900	13	6	48V DC
Cell phone charger	5	13	2.5	12V DC
LED Lamp	7	20	1.5	12V DC
Fan Heater	500	20	4	48V DC
Fan or equivalent	25	20	2.5	24V DC
Washing machine	500	15	4	48V DC
Vacuum cleaner	300	15	2.5	48V DC
Iron	1000	15	6	
LED Lamp	7	25	1.5	12V DC
Cell phone charger	5	25	2.5	12V DC
Laptop	50	25	2.5	24V DC
Fan or equivalent	25	25	2.5	24V DC
LED Lamp	7	30	1.5	24V DC
Cell phone charger	5	30	2.5	24V DC
Fan or equivalent	25	30	2.5	48V DC
LED Lamp	7	20	1.5	48V DC
Cell phone charger	5	20	2.5	24V DC
Fan or equivalent	25	20	2.5	48V DC
Fan Heater	500	20	4	48V DC

Summary and Recommendations for a Typical Three Bedroom House

The hybrid wiring option is suitable for an existing three-bedroom house with existing or new wiring as these buildings were not designed from an energy efficiency perspective and many of the heavy loads are quite far from the point of supply. The efficiency can be increased by nearly 18% by replacing the existing wiring with new wiring along with the cost recovery in the long run as summarised in Table 5.18. Therefore, it is recommended to change the wire sizes to achieve better efficiency and cost benefits in an existing three-bedroom house. This recommendation may not be valid for all three-bedroom houses and other sizes as it depends on the design of the existing house and this needs to be checked with the AUT Wiring Selection software.

If the new build three-bedroom house is designed with energy efficiency perspectives, then the efficiency for the hybrid wiring would be maximum as per option 1 shown in Table 5.18, Although, the efficiency of 48V DC wiring topology is slightly lower than for the hybrid case, it would be the cost-effective solution going forward with 98.1% cost over 5 years as compared to the hybrid option. This cost difference is not the only driving factor to select between the hybrid and the 48V DC wiring option, so other factors need to be considered such as wiring complexities and installation viewpoint. Therefore, it is recommended to use the 48V DC wiring option because that would be simple and easy to install and maintain.

Table 5.13: Analytical summary of a three-bedroom house

Parameter	**Existing three bedroom House**		**New Build house**	
	Existing Wire size	**Designed Wire size**	**Option 1**	**Option 2**
Most efficient wiring topology	Hybrid	Hybrid	Hybrid	48V DC
Efficiency	62.52%	80.01%	81.32%	79.73%
% Cost in 5 years	100.0%	77.7%	100.0%	98.1%

5.2.4 Analysis of a Typical One Bedroom or Tiny House

The analysis has been extended to a tiny house with existing and new wiring.

Existing One Bedroom House with Existing Wiring

The kitchen and laundry appliances are almost similar however the total number of circuits and the wiring length are reduced in a tiny house as shown in Table 5.14. Based on the PEC results for an existing one-bedroom house with the existing wiring in Table 5.16, the 48V DC option gives the maximum efficiency of 78.86%, however, it can only be used for 84% of the circuits. Therefore, the hybrid wiring option is suitable for this tiny house as per the combination outlined in Table 5.15. The overall efficiency of the hybrid wiring option is less than the 48V DC wiring option. However, the cost-benefit analysis shows the cost of hybrid wiring would be less than the 48V DC wiring only option over 5 years as summarised in Table 5.16.

Table 5.14: Data of existing one-bedroom house with existing wiring

Location	Appliance	Load Power Rating (Watts)	Existing Wire Length (m)	Wire Size in Existing AC (mm^2)	Number of Circuits in Conduit
Kitchen	Microwave oven	800	8	2.5	6
	Electric Pressure Cooker	500	8	2.5	6
	Coffee maker / Electric Kettle/Juicer blender	990	8	2.5	6
	Refrigerator	125	8	2.5	6
	Dishwasher	500	8	2.5	6
	LED Lamp	7	8	1.5	6
Lounge	LED TV	90	10	2.5	4
	LED Lamp	7	10	1.5	4
	Heat Pump	900	10	4	4
	Cell phone charger	5	10	2.5	4
Bathroom	LED Lamp	7	10	1.5	2
	Fan or equivalent	25	10	2.5	2
Laundry and others	Washing machine	500	8	2.5	3
	Vacuum cleaner	300	12	2.5	3
	Iron	1000	8	2.5	3
Bedroom 1	LED Lamp	7	25	1.5	4
	Cell phone charger	5	25	2.5	4
	Laptop	50	25	2.5	4
	Fan or equivalent	25	25	2.5	4

Table 5.15: Hybrid option for an existing tiny house with existing wiring

Location	Appliance	Load Power Rating (Watts)	Existing Wire Length (m)	Wire Size (mm2)	Hybrid Option
Kitchen	Microwave oven	800	8	2.5	AC 230V
	Electric Pressure Cooker	500	8	2.5	48V DC
	Coffee maker / Electric Kettle/Juicer blender	990	8	2.5	AC 230V
	Refrigerator	125	8	2.5	48V DC
	Dishwasher	500	8	2.5	48V DC
	LED Lamp	7	8	1.5	12V DC
Lounge	LED TV	90	10	2.5	48V DC
	LED Lamp	7	10	1.5	12V DC
	Heat Pump	900	10	4	48V DC
	Cell phone charger	5	10	2.5	12V DC
Bathroom	LED Lamp	7	10	1.5	12V DC
	Fan or equivalent	25	10	2.5	12V DC
Laundry and others	Washing machine	500	8	2.5	48V DC
	Vacuum cleaner	300	12	2.5	48V DC
	Iron	1000	8	2.5	AC 230V
Bedroom 1	LED Lamp	7	25	1.5	12V DC
	Cell phone charger	5	25	2.5	12V DC
	Laptop	50	25	2.5	24V DC
	Fan or equivalent	25	25	2.5	24V DC

Table 5.16: Output Parameters for an existing one-bedroom house with existing wiring

Result Parameters	Hybrid System	12V DC System	24V DC System	48V DC System	230 AC System
Possible circuits	19	7	11	16	19
Connected load (Watts)	5843	63	353	3053	5843
% Ratio of Possible circuits with total	100.00%	36.84%	57.89%	84.21%	100.00%
% Ratio of Connected load with total	100.00%	1.08%	6.04%	52.25%	100.00%
Overall efficiency	66.14%	73.34%	62.50%	78.86%	58.21%
% Cost in 5 years	16.9%	100.0%	59.5%	17.0%	22.9%

Existing One Bedroom House with New Wiring

The wiring of the existing house has been designed with new wire sizes as outlined in Table 5.17. The main aim is to consider the impact on efficiency, cost and possible circuits in each category.

The PEC results for a tiny house with the designed wiring for wiring topologies have been summarised in Table 5.18. It is clear from the results that the 48V DC options are not only the most efficient wiring option for this tiny house but also the most cost-effective option.

Table 5.17: Wiring design for an existing one-bedroom house

Appliance	Load Power Rating	Wire Size (mm^2)			
		12V DC	24V DC	48V DC	230V AC
Microwave oven	800	0	0	2.5	1
Electric Pressure Cooker	500	0	10	2.5	1
Coffee maker / Electric Kettle/Juicer blender	990	0	0	4	1
Refrigerator	125	10	2.5	1	1
Dishwasher	500	0	10	2.5	1
LED Lamp	7	1	1	1	1
LED TV	90	10	2.5	1	1
LED Lamp	7	1	1	1	1
Heat Pump	900	0	0	4	1
Cell phone charger	5	1	1	1	1
LED Lamp	7	1	1	1	1
Fan or equivalent	25	2.5	1	1	1
Washing machine	500	0	10	2.5	1
Vacuum cleaner	300	0	6	1.5	1
Iron	1000	0	0	4	1
LED Lamp	7	1.5	1	1	1
Cell phone charger	5	1.5	1	1	1
Laptop	50	10	2.5	1	1
Fan or equivalent	25	4	1.5	1	1

Table 5.18: Output parameters based on design cable size existing three-bedroom house

Result Parameters	**12V DC System**	**24V DC System**	**48V DC System**	**230 AC System**
Possible circuits	11	15	19	19
Connected load (Watts)	353	2153	5843	5843
% Ratio of Possible circuits with total	57.89%	78.95%	100.00%	100.00%
% Ratio of Connected load with total	6.04%	36.85%	100.00%	100.00%
Overall efficiency	68.48%	67.21%	80.33%	57.93%
% Cost in 5 years	100.0%	52.5%	28.3%	51.6%

Summary and Recommendation for One Bedroom/Tiny House

Based on the PEC results matrix of one-bedroom house, the hybrid wiring option can be used with existing cable sizes, but it is recommended to replace the existing wiring with new design cable sizes as per the 48V DC wiring topology option to increase the efficiency by around 14% as summarised in Table 5.19.

The initial cost of new wiring is higher compared to the utilisation of existing cables, but it is a cost-effective option for a five-year cost-benefit analysis. Table 5.19 shows that 25.6% of the cost can be saved by installing the new cables designed as per 48V DC line voltage. Based on the results, it is recommended that the wiring should be redesigned and replaced in an existing tiny or single bedroom house.

Table 5.19: Analytical summary of one-bedroom/ tiny house

Parameter	Existing Wire size	Designed Wire size
Most efficient wiring topology	Hybrid	48V DC
Efficiency	66.14%	80.33%
% Cost in 5 years' time	100.0%	74.4%

New-build three-bedroom house design aims to reduce the cable lengths for high power rating DC loads. Since the size of the tiny house is already small and cable lengths are already short so there will not be a significant change in the cable lengths. Therefore, the new-build tiny house has not been analysed.

5.3 Analysis of a House with Standard Voltage DC Loads

Analysis of residential houses in this thesis can help to select the efficient and cost-effective option. However, there would still be significant power losses due to the non-standardised voltage requirements of DC loads. The DC-DC converter is used in the DC wiring option as DC loads operate on various DC voltages. If all DC appliances can operate at the same voltage, then the requirement and of the DC-DC converter can be eliminated as shown in Figure 5.13.

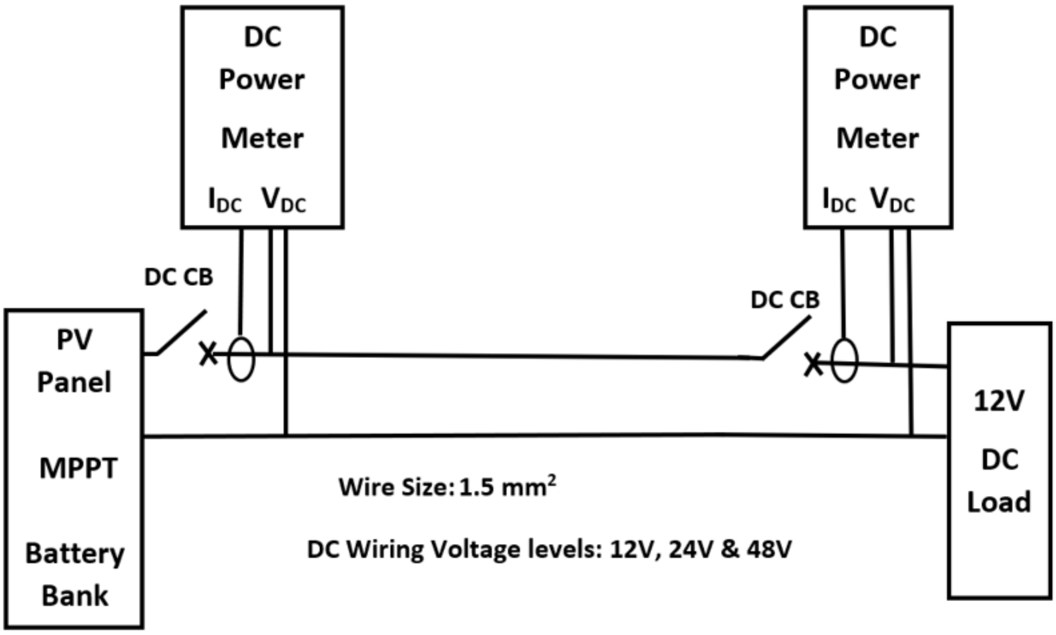

Figure 5.13: DC Wiring Topology with Standardized DC load Voltage

5.3.1 Experimental Testing

Initially, this scenario was experimentally tested with a 1.5mm^2 wire size. Each voltage level had power limit based on the design requirements therefore efficiency is not available for those cases in Table 5.20. It is apparent from the experiments that the efficiency of 48V DC wiring is much better than the AC wiring system as shown in Table 6.1. Therefore, this research recommends standardising the DC appliances at 48V DC.

Table 5.20: Experimental efficiencies of wiring topologies without DC/DC converter in DC wiring topologies

Load (W)	Wire length (m)	Efficiency of 230V AC Wiring	Efficiency of DC Wiring Topologies without DC-DC Converter			Efficient Topology
			48V DC	24V DC	12V DC	
5	2.5	19.16%	99.98%	99.40%	98.16%	48V DC
	5	19.19%	99.95%	99.05%	97.58%	48V DC
	10	19.12%	99.86%	98.56%	95.40%	48V DC
	20	19.27%	99.74%	97.50%	94.78%	48V DC
	30	19.24%	99.62%	96.40%	95.10%	48V DC
10	2.5	31.70%	99.80%	99.14%	97.20%	48V DC
	5	31.70%	99.74%	98.80%	96.56%	48V DC
	10	31.83%	99.26%	98.12%	93.73%	48V DC
	20	31.77%	99.12%	96.90%	92.03%	48V DC
	30	31.83%	98.96%	95.68%		48V DC
25	2.5	51.15%	99.75%	98.90%	96.45%	48V DC
	5	51.38%	99.60%	98.10%	95.55%	48V DC
	10	51.23%	99.10%	97.92%	93.25%	48V DC
	20	51.18%	99.02%	96.55%		48V DC
	30	51.23%	98.80%	95.21%		48V DC
50	2.5	62.98%	99.70%	98.51%	96.09%	48V DC
	5	63.13%	99.52%	97.78%	94.02%	48V DC
	10	63.00%	99.01%	97.50%		48V DC
	20	62.94%	98.98%	94.92%		48V DC
	30	63.00%	98.49%			48V DC
75	2.5	68.38%	99.66%	98.47%		48V DC
	5	68.41%	99.45%	97.40%		48V DC
	10	68.53%	98.90%	97.26%		48V DC
	20	68.25%	98.25%			48V DC
	30	68.40%	97.72%			48V DC
100	2.5	70.99%	99.60%	98.19%		48V DC
	5	71.01%	98.82%	96.94%		48V DC
	10	71.06%	98.75%	95.00%		48V DC
	20	70.86%	97.87%			48V DC
	30	70.84%	96.66%			48V DC
125	2.5	72.17%	99.52%	97.91%		48V DC
	5	72.22%	98.80%	96.41%		48V DC
	10	72.32%	98.60%			48V DC
	20	72.04%	97.27%			48V DC
	30	72.11%	96.05%			48V DC
150	2.5	72.59%	99.37%	97.29%		48V DC
	5	72.71%	98.63%	95.94%		48V DC
	10	72.63%	98.22%			48V DC
	20	72.59%	96.58%			48V DC
175	2.5	72.59%	99.28%			48V DC
	5	72.73%	98.64%			48V DC
	10	72.65%	97.78%			48V DC
	20	72.52%	96.02%			48V DC

5.3.2 Cost-Benefit Analysis

Now the existing three-bedroom house with the new wiring case has been analysed to quantify the impacts of DC appliance voltage standardisation as summarised in Table 5.21. With this assumption, the efficiency of the 48V DC wiring system can be increased up to 96.70%, whereas it was only 80.01% with non-standardised voltage DC loads. Moreover, the cost has been reduced significantly. Reliability would be increased due to less chance of converter failure. Therefore, it is recommended that the standardisation of DC loads need to be considered by policymakers and international bodies.

Table 5.21: Three bedroom house with new wiring and standard input DC loads

Result Parameters	Hybrid System	12V DC System	24V DC System	48V DC System	230 AC System
Possible circuits	27	10	15	27	27
Connected load (Watts)	5924	62	194	5924	5924
% Ratio of Possible circuits with total	100.00%	37.04%	55.56%	100.00%	100.00%
% Ratio of Connected load with total	100.00%	1.05%	3.27%	100.00%	100.00%
Overall efficiency	96.70%	97.19%	97.91%	96.70%	59.61%
% Cost in 5 years	11.5%	9.4%	5.2%	2.6%	100.0%

5.3.3 Challenges for DC Appliance Manufacturers

International standard organisations need to work together to standardise the residential DC loads at one voltage level. Standardisation of DC load voltage would a global challenge for DC appliance manufacturers. This challenge does not only require research recommendations but also requires international influence as this decision would affect a lot of companies from the commercial point of view.

Chapter 6 Conclusion, Recommendations and Future Work

The objective of this research is to significantly contribute towards global energy saving by identifying the most efficient and cost-effective wiring option for residential houses and they as summarised in the following sections.

6.1 AC and DC Wiring Topologies

In DC Wiring Topologies, DC sources have been connected to DC loads via a 12V, 24V or 48V DC line. A DC-DC converter was used with DC loads as DC appliances operate on different voltage levels. In AC Wiring Topology, similar DC sources and DC loads were connected via 230V AC line using DC-AC and AC-DC converters. These practical topologies have been evaluated in this PhD to fill the gaps in the literature.

However, this research is limited to the house where DC loads' power rating is up to 1,000W only. Moreover, this research assumed that the DC source would have enough power to feed the DC loads throughout the day. This research would be useful for off-grid houses. However, if the house is connected to the AC grid for the backup power option then these PEC results will not be valid for that duration. Moreover, this research is limited to DC loads only.

6.2 Mathematical Modelling

Mathematical models of proposed AC and DC wiring topologies have been developed to accurately estimate the power losses in both wiring topologies. The modelling of power cables has been done using the fundamental power loss equations along with the consideration of installation and environmental factors such as temperature, proximity factor, skin effect, grouping factor and ambient temperature. Converter modelling in the literature was either available for a basic design or new converter technologies. However, the schematic diagram of converters available in the market is slightly different to this which can limit the results to a particular converter technology. In this thesis, converter models have been developed using the data collected in laboratory tests considering the effect of ambient temperature and validated by experimental and simulation studies. Moreover, the mathematical models have been validated by experimental and simulation studies.

6.3 Boundary Conditions

Using the mathematical models, 230V AC wiring topology has been compared with LVDC wiring topologies at 12V DC, 24V DC and 48V voltage levels. Boundary condition charts were developed for DC appliances up to 1,000W with six cable sizes from 1mm^2 to 10mm^2. These boundary conditions were developed at the ambient temperature of 24 ^{o}C, therefore, the actual temperature should be used in the AUT Wiring Selection software to update the boundary conditions.

It can be concluded that each wiring topology has its efficiency band depending on the load power rating, cable size and length. 48V DC has the widest band compared to other topologies and it can be used to feed DC loads up to 1,000W when the cable length is less than 28m. This lower length can be achieved in new sustainable house designs by placing the heavy appliances near the point of supply. Power losses are quite high in case of heavy loads at longer lengths and these power losses are reduced considerably with the increase in cable size as shown in Chapter 5.

One particular wiring topology cannot be recommended based on these boundary conditions as each is better than others depending on the wiring case i.e. load power, cable size and length. However, it can be concluded that if the cable size is increased to select the most efficient wiring topology, then DC wiring topology can be used for most of the wiring cases as shown in Figure 5.6.

6.4 Recommendation Based on Analysis of Typical Houses

The results have been extended to include the cost-benefit analysis of a typical three-bedroom and single bedroom house. Based on the PEC results for an existing three-bedroom house, the hybrid wiring option was found to be the most cost-effective option with existing wiring and new wiring options. Similarly, based on the PEC results for an existing single bedroom house, 48V DC wiring topology was found to be the most cost-effective option when the existing wiring is replaced with new wiring. The 48V DC wiring topology is recommended in the case of new build houses. New-build houses should be designed as per sustainable practices to reduce the cable length between the point of supply and heavy DC appliances. Heavy appliances are mainly in the kitchen and laundry so these two locations can be located close to each other and the main power board.

The PEC results for three-bedroom and one-bedroom should be considered to build some understanding of cost-benefit analysis only as these PEC results will change with the change input matrix such as the number of loads, cable lengths, ambient temperature, utilisation factor, demand factor and grouping factor. The AUT wiring selection software can be used to generate the PEC results for customised input matrices. Thus, the methodology is more important than the actual results and this is a continuous improvement process in technology and cost.

Similarly, the home analysis in Chapter 5 is based on a single load connected to the circuit however the home configuration may have more than one load connected to a similar circuit. To use this research work, the group of loads connected to a single circuit should be treated as one load.

6.5 Recommendation Based on New Zealand's Residential Sector

Residential sectors in New Zealand consumes around 12,971 GWh per annum which is the combination of both island energy consumption reported by the Electricity Authority for the period from 1st Jan 2019 to 31st Dec 2019 as summarised in Table 6.1. The accuracy of this data is quite high as it covers around 95% residential sector.

Table 6.1: Annual Energy Consumption in Residential sector of New Zealand (Electricity Authority, 2019)

Region	Average consumption (kWh)	Est. total consumption (GWh)	Coverage %
North Island	6763	9237.926	95.11
South Island	7882	3733.572	94.74

Based on the examples of typical houses, the PEC results show that the existing AC wiring needs to be replaced with recommended 48V DC or hybrid wiring option as the efficiency of recommended topologies is around 21% more compared to the existing AC wiring topology. If half of the residential sector can move toward efficient wiring topologies in future, then around 1,362 GWh per annum energy can be conserved which can help residential consumers to save NZD 395 Million each year. New Zealand has signed Paris Agreement and this energy conservation would help New Zealand towards a zero-carbon future.

The most efficient wiring option may not be used in future residential houses as the investors are more concerned about the initial cost of the house than the low running cost. First home buyers have limited resources therefore budget houses are another option in New Zealand. Latitude homes builder's website shows that a similar budget house can be NZD 30,000 cheaper than a good quality house. However, currently, house prices do not reflect the energy star rating of a property which means the builders or house owners will not benefit from savings should the property be sold within a short period.

This research shows potential energy savings in future, On the other hand, Electricity demand in the residential sector is going to increase due to the increased penetration trend of Electric Vehicles in New Zealand. The existing transmission and distribution infrastructure of New Zealand would be upgraded to meet the growing demand which would be an additional cost to domestic consumers in terms of line charges. Energy savings as a result of this research can be used to meet the growing needs of electricity which can save electricity network upgrade costs in some parts of New Zealand. This is hard to quantify how much in each region as this depends on the uptake ratio of PV and EV.

The Energy Efficiency and Conservation Authority (EECA) New Zealand is already working to improve the efficiency of New Zealand homes. EECA can consider the future developments in house wiring options to improve the energy policies that can help in achieving the expected benefits out of emerging technologies.

6.6 Future Work

This research work can be extended in future to following the following aspects.

6.6.1 Applications Aspect

The application of this research has been focused on residential houses in New Zealand but can be extended to other applications such as commercial buildings, industrial plants, factories, ships, boats, motor homes etc. Moreover, it can be extended to compare the low voltage DC (LVDC) wiring topology with 110V AC wiring topology, which is used in many countries such as America and the Middle East.

6.6.2 Power Quality Aspects

A cluster of DC loads would have a significant impact on the power quality of the electricity grid. Electricity Distribution Boards (EDBs) need to prepare their networks for additional non-linear loads as DC houses would have a partial connection to the grid. In the existing AC home wiring configuration, few loads are supplied through a single circuit. This depends on home size, load power rating, conductor length and the number of loads in one house area such as kitchen, laundry or room. The home AC and DC wiring configurations need to be developed for safe and efficient power flow.

6.6.3 Safety Aspect

In this thesis, the experimental system was aligned with New Zealand standards, however, the fire safety aspect has not been covered. A solar system may become a potential source of fire if an electrical failure occurs. Fire incidents have increased with the increase in solar system installations. New South Wales, Australia fire and rescue team reported 30 fires in the last quarter of 2020 (https://theconversation.com/solar-panel-fire-season-is-all-year-round-and-its-getting-more-intense-in-australia-150751). Most of the fires were caused by components other than the actual photovoltaic (PV) panel.

PV panels are now getting cheaper and cheaper but need more regulations to ensure fire safety. Therefore, system design, passive DC side grounding and protection are important aspects that affect system design, considering the risk of fire. Further research work in this area will lead to solar technology and industry-standard improvements to minimise fire risk.

References

Amin, M., Arafat, Y., Lundberg, S., & Mangold, S. (2011). *Low voltage DC distribution system compared with 230 V AC.* Paper presented at the IEEE Electrical Power and Energy Conference (EPEC), 2011.

Blakers, A., Wright, P., Gazzoni, D., Hestnes, A., Kituyi, E., & Kretzschmar, J. (2009). Research and development on renewable energies. *A global report on photovoltaic and wind energy, ISPRE*.

C. A. Hill, M. C. S., D. Chen,J. Gonzalez,W. M. Grady. (2012). Battery energy storage for enabling integration of distributed solar power generation. *IEEE Transactions on Smart Grid, 3*(2), 850-857. doi: 10.1109/TSG.2012.2190113

Cetin, E., Yilanci, A., Ozturk, H. K., Colak, M., Kasikci, I., & Iplikci, S. (2010). A micro-DC power distribution system for a residential application energized by photovoltaic–wind/fuel cell hybrid energy systems. *Energy and Buildings, 42*(8), 1344-1352.

Cvetkovic, I., Dong, D., Zhang, W., Jiang, L., Boroyevich, D., Lee, F. C., & Mattavelli, P. (2012). *A testbed for experimental validation of a low-voltage DC nanogrid for buildings.* Paper presented at the 15th International Power Electronics and Motion Control Conference (EPE/PEMC), 2012

D.Little, A. (2011). DC appliances prototypes by Japan’s New Energy and Industrial Technology Organization (NEDO) [Press release]

Dastgeer, F., & Gelani, H. E. (2017). A Comparative analysis of system efficiency for AC and DC residential power distribution paradigms. *Energy and Buildings, 138*, 648-654.

Ericson, R. W., & Dragan, M. (2000). Fundamental Of Power Electronics Second Edition. *Kluwer Academic Publishers*.

Fernando, J., & Kularatna, N. (2015, 7-10 June 2015). *Supercapacitors for distributed energy storage in DC microgrids and loads.* Paper presented at the IEEE First International Conference on DC Microgrids (ICDCM), 2015

Garbesi, K. (2012). Catalog of DC appliances and power systems.

Gerber, D. L., Vossos, V., Feng, W., Khandekar, A., Marnay, C., & Nordman, B. (2017). *A simulation based comparison of AC and DC power distribution networks in buildings.* Paper presented at the 2017 IEEE Second International Conference on DC Microgrids (ICDCM).

Headwaters, T. (2018). Camp Glenorchy Eco Retreat. from https://www.theheadwaters.co.nz/about-us/

Hou, Y., Li, H., Zhao, L., & Wang, Y. (2017). Temperature-related power loss modeling for buck converter. *IEICE Electronics Express, 14*(6), 20170004-20170004.

International Electrotechnical Commission. (2006). IEC 60287-1-1:2006 Electric Cables—Calculation of the Current Rating. *International Electrotechnical Commission: Geneva, Switzerland*.

Itoh, K., Inoue, S., Ishigaki, M., Sugiyama, T., & Umeno, T. (2018). Power loss estimation for three-port DC/DC converter for 12-V/48-V dual-voltage hybrid electric vehicle subsystem. *IEEJ Transactions on Electrical and Electronic Engineering, 13*(7), 1060-1070.

Jain, A., Vijay, M. D., Bhuvaneswari, G., & Singh, B. (2016). *Design and simulation of a solar powered DC home with grid and battery back-up.* Paper presented at the 2016 IEEE 7th Power India International Conference (PIICON).

Jignesh.Parmar. (2020). Demand Factor-Diversity Factor-Utilization Factor-Load Factor. from https://electricalnotes.wordpress.com/2011/10/31/demand-factor-diversity-factor-utilization-factor-load-factor/

Joseph, A., & Shahidehpour, M. (2006, 0-0 0). *Battery storage systems in electric power systems*. Paper presented at the IEEE Power Engineering Society General Meeting.

Kamran, M., Bilal, M., & Mudassar, M. (2017). DC home appliances for DC distribution system. *Mehran University Research Journal of Engineering and Technology, 36*(4), 10.

Kularatna, N. (2015). *Supercapacitor Assisted Low Dropout Regulators (SCALDO) for high efficiency DC-DC converters for DC microgrid applications.* Paper presented at the IEEE First International Conference on DC Microgrids (ICDCM), 2015.

Long, W., & Nilsson, S. (2007). HVDC transmission: yesterday and today. *IEEE Power and Energy Magazine*, *5*(2), 22-31. doi: 10.1109/MPAE.2007.329175

Lucia Oscar, C. I., Boroyevich Dushan,Mattavelli Paolo,Lee Fred C,. (2013). *Design of household appliances for a Dc-based nanogrid system: An induction heating cooktop study case.* Paper presented at the Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2013

M. Amin, Y. Arafat, S. Lundberg, & S. Mangold. (2011, 3-5 Oct. 2011). *An efficient appliance for low voltage DC house.* Paper presented at the IEEE Electrical Power and Energy Conference (EPEC), 2011.

MeanWell. (2019). Converters. from https://nz.element14.com/

Ministry of Business, i. a. E. (2020). Domestic electricity prices in New Zealand towns and cities. from https://figure.nz/chart/Kx2boXoRyZYpLWBb

Morgan, V. T. (2013). The Current Distribution, Resistance and Internal Inductance of Linear Power System Conductors—A Review of Explicit Equations. *Power Delivery, IEEE Transactions on, 28*(3), 1252-1262. doi: 10.1109/TPWRD.2012.2213617

Moussa, S., Ghorbal, M. J.-B., & Slama-Belkhodja, I. (2019). Bus voltage level choice for standalone residential DC nanogrid. *Sustainable Cities and Society, 46*, 101431.

Electricity (Safety) Regulations 2010 (2010).

Nilsson, D., & Sannino, A. (2004, 10-10 June 2004). *Efficiency analysis of low- and medium- voltage DC distribution systems.* Paper presented at the Power Engineering Society General Meeting, 2004. IEEE.

Nilsson, D., & Sannino, A. (2004). *Efficiency analysis of low-and medium-voltage DC distribution systems.* Paper presented at the IEEE Power Engineering Society General Meeting, 2004.

Patterson, B. T. (2012). Dc, come home: Dc microgrids and the birth of the" enernet". *Power and Energy Magazine, IEEE, 10*(6), 60-69.

Pellis, Jan, RIJT, V. D., NM, OTTERDIJK, V., KHTJ, I., . . . DRINGH. (1997). *The DC low-voltage house*: Netherlands Energy Research Foundation ECN.

Porter, Foster, S., Denkenberger, Dave Mercier, Catherine May-Ostendorp, & Peter, E. (2014). Reviving the War of Currents: Opportunities to Save Energy with DC Distribution in Commercial Buildings.

Qureshi, J. A., Lie, T. T., Gunawardane, K., Kularatna, N., & Qureshi, W. A. (2017). *AC Source vs DC Source: Charging Efficiency in Battery Storage Systems for Residential Houses* Paper presented at the IEEE PES Innovative Smart Grid Technologies Auckland, New Zealand.

Qureshi, J. A., Lie, T. T., & Hasan, R. (2016). *LED Lighting as Energy Management Tool through Correlation Analysis of Daily Electricity Demand and Supply Curve*. Paper presented at the IEEE ICSET 2016, Honoi.

Qureshi, J. A., Lie, T. T., Hasan, R., & Mujtaba, T. (2016). *Impact of Efficient DC loads: LED Lighting as Equivalent to Large Power Generation Plant.* Paper presented at the IEEE Southern Power Electronics Confrence, Auckland, New Zealand.

Rahman, F. A., James, R., Jose, S., Ahmed, S., Mohammed, M. A., & Kunju, K. B. (2019). *Solar DC Homes: Energy for All.* Paper presented at the TENCON 2019-2019 IEEE Region 10 Conference (TENCON).

Rani, P., Vignesh, D., Gunaki, S., & Jhunjhunwala, A. (2016). *Design of converters for leveraging 48V DC power line at homes/offices.* Paper presented at the 2016 First International Conference on Sustainable Green Buildings and Communities (SGBC).

Rasheed, A., Khan, S., Gelani, H. E., & Dastgeer, F. (2019). *AC vs. DC Home: An Efficiency Comparison.* Paper presented at the 2019 International Symposium on Recent Advances in Electrical Engineering (RAEE).

Rijanto, E., Nugroho, A., & Dahono, P. A. (2018). *A Dynamical Model of Full Bridge LLC Resonant Converter Which Incorporates Power Loss Coefficients for Controller Design.* Paper presented at the 2018 International Conference on Sustainable Energy Engineering and Application (ICSEEA).

Rodriguez-Diaz, E., Chen, F., Vasquez, J. C., Guerrero, J. M., Burgos, R., & Boroyevich, D. (2016). Voltage-Level Selection of Future Two-Level LVdc Distribution Grids: A Compromise Between Grid Compatibiliy, Safety, and Efficiency. *IEEE Electrification Magazine, 4*(2), 20-28. doi: 10.1109/MELE.2016.2543979

Sadigh, A. K., Dargahi, V., & Corzine, K. (2016). Analytical determination of conduction power loss and investigation of switching power loss for modified flying capacitor multicell converters. *IET Power Electronics, 9*(2), 175-187. https://digital-library.theiet.org/content/journals/10.1049/iet-pel.2015.0369

Seo, G.-S., Baek, J., Choi, K., Bae, H., & Cho, B. (2011). *Modeling and analysis of DC distribution systems.* Paper presented at the 8th International Conference on Power Electronics-ECCE Asia.

Service, M. (2020). Seasons in New Zealand. from https://www.metservice.com/

Söderström, G., & Soorian, N. (2010). Appliances in a low-voltage DC house-Low-power solutions in the kitchen area.

SolarKing. (2019). The Ultimate NZ Off-grid Guide. from https://solarking.co.nz/off-grid-free-ebook-download/

Thielemans, S., Di Zenobio, D., Touhafi, A., Lataire, P., & Steenhaut, K. (2017). DC grids for smart LED-based lighting: The EDISON solution. *Energies, 10*(10), 1454.

Vossos, E. (2011). Optimizing energy savings from" Direct-DC" in US residential buildings.

Yang, L., Li, Y., Li, Z., Wang, P., Xu, S., & Gou, R. (2017). A simplified analytical calculation model of average power loss for modular multilevel converter. *IEEE Transactions on Industrial Electronics, 66*(3), 2313-2322.

Zhiguo, P., Fan, Z., & Peng, F. Z. (2005, 6-10 March 2005). *Power losses and efficiency analysis of multilevel dc-dc converters.* Paper presented at the Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE.

Appendix A: Data and Calculations for Converter Modelling

A.1 Modelling of 24V Input DC/DC Converter

A.1.1 Temperature Factor Equation

Experimental data set of power losses at different ambient temperatures were collected to calculate the temperature equation coefficients for a 24V input DC-DC converter as shown in Table A.1.

Table A. 1: Power losses in 24V input DC-DC converter at different temperature

T (°C)	Pin (W)	Pout (W)	P_{l-t} (W)	t_f
15	71.124	50	21.12	0.9938
20	71.195	50	21.19	0.9971
25	71.256	50	21.26	1.0000
30	71.317	50	21.32	1.0029
35	71.388	50	21.39	1.0062

Using section 3.4.1 methodology, a temperature factor equation can be developed for a 24V DC-DC converter as shown in Equation A.1.

$$t_{f\ 24V\ DC-DC} = (0.000612 + 0.9847\,T) \qquad (A.1)$$

A.1.2 Power Loss Equation

Experimental data set of P_o & P_l were collected to calculate the power losses equation coefficients for the 24V DC/DC converter. The connected load was incrementally increased to observe the power losses as shown in Table A.2. The power losses are high due to the percentage loading as efficiency of the converter change with the change in loading as expressed in Figure 2.18.

Table A. 2: Experimental data set of P_o & P_l for 24V input DC-DC converter

Pout (W)	Power Loss (W)
5	13.583
10	14.072
25	15.549
50	21.253
75	23.472
100	28.871
125	35.682
150	42.324
175	49.387

Using section 3.4.2 methodology, the power losses equation of 24V DC-DC converter at standard ambient temperature has been developed as shown in Equation A.2.

$$P_{l-\,24v\,DC/DC} = 13.04 + 0.1049\,P_o + 0.000591\,P_o^2 \qquad \text{(A.2)}$$

where,

$$P_{l-\,24v\,DC-DC} = The\ power\ losses\ in\ 24V\ inout\ DC - DC\ Converter$$

Using section 3.4.3 methodology, the total power loss of 24V input DC/DC converter with temperature effect ($\boldsymbol{P_{l-t,24v\,DC-DC}}$) can be developed as shown in Equation (A.3).

$$P_{l-t,24v\,DC-DC} = (0.000612 + \ 0.9847\,T)(13.04 + 0.1049\,P_o + 0.000591\,P_o^2) \qquad \text{(A.3)}$$

A.2 Modelling of 48V Input DC/DC Converter

A.2.1 Temperature Factor Equation

Experimental data set of power losses at different ambient temperatures were collected to calculate the Temperature equation coefficients for a 48V input DC-DC converter as summarized in Table A.3.

Table A. 3: Power losses in 48V input DC-DC converter at different temperature

$\boldsymbol{T}$ (℃)	Pin (W)	Pout (W)	$\boldsymbol{P_{l-t}}$ (W)	$\boldsymbol{t_f}$
15	73.389	50	23.39	0.9950
20	73.443	50	23.44	0.9972
25	73.508	50	23.51	1.0000
30	73.573	50	23.57	1.0028
35	73.638	50	23.64	1.0055

Using section 3.4.1 methodology, the temperature factor equation can be developed for a 48V DC-DC converter using equation A.4.

$$t_{f\ 48V\ DC-DC} = (0.000532 + 0.9868\,T) \quad \text{(A.4)}$$

A.2.2 Power Loss Equation

Experimental data set of P_o & P_l were collected to calculate the power losses equation coefficients for the 48V DC/DC converter. The connected load was incrementally increased to observe the power losses as shown in Table A.4. The power losses are high due to the percentage loading as the efficiency of the converter change with the change in loading as expressed in Figure 2.18.

Table A. 4: Experimental data set of P_o & P_l for 48V input DC-DC converter

Pout (W)	**Power Loss (W)**
5	15.840
10	19.597
25	20.211
50	23.511
75	27.380
100	30.485
125	34.090
150	36.813
175	40.759
200	44.363
225	47.926
250	51.180
275	54.548
300	58.351
325	62.558

Using the Regression Analysis and Gaussian Elimination Method like section 3.4.2, the mathematical equation of the 48V DC-DC converter can be developed as shown in Equation A.5.

$$P_{l-\ 48v\ DC/DC} = 16.81583 + 0.134087\,P_o + 0.00001624 P_o^2 \quad \textit{(A.5)}$$

where,

$$P_{l,48v\,DC-DC} = The\ power\ losses\ in\ 48V\ input\ DC\ to\ DC\ Converter$$

Using section 3.4.3 methodology, the total power loss of 48V input DC-DC converter with temperature effect $(\boldsymbol{P_{l-t,48v\,DC-DC}})$ can be developed as shown in Equation (A.6).

$$\mathrm{P_{l-t,48v\,DC-DC}} = (0.000532 + 0.9868\ \mathrm{T})(16.8158 + 0.134087\ \mathrm{P_o} + 0.00001624\mathrm{P_o^2}) \quad (A.6)$$

A.3 Modelling of DC to AC Converter

A.3.1 Temperature Factor Equation

Experimental data set of power losses at different ambient temperatures were collected to calculate the temperature equation coefficients for a DC-AC converter as summarized in Table A.5.

Table A. 5: Power losses in DC to AC converter at different temperature

$\boldsymbol{T}$ (℃)	**Pin (W)**	**Pout (W)**	$\boldsymbol{P_{l-t}}$ **(W)**	$\boldsymbol{t_f}$
15	55.928	50	5.93	0.9692
20	56.022	50	6.02	0.9846
25	56.117	50	6.12	1.0000
30	56.205	50	6.21	1.0144
35	56.300	50	6.30	1.0300

Using section 3.4.1 methodology, a temperature factor equation can be developed for a DC-AC Converter as shown in Equation A.7.

$$t_{f\,DC-AC} = (0.003028 + 0.92394\,T) \quad \text{(A.7)}$$

A.3.2 Power Loss Equation

Experimental data set of P_o & P_l were collected to calculate the power losses equation coefficients for the DC-AC converter. The connected load was incrementally increased to observe the power losses as shown in Table A.6. The power losses are high due to the percentage loading as the efficiency of the converter change with the change in loading as expressed in Figure 2.18.

Table A. 6: Experimental data set of P_o & P_l for DC-AC converter

Pout (W)	Power Loss (W)
5	7.312
10	7.039
25	7.463
50	8.634
75	10.537
100	12.972
125	16.674
150	20.479
175	25.079

Using the Regression Analysis and Gaussian Elimination Method like section 3.4.2, the power losses equation of the DC-AC converter at standard ambient temperature has been developed as shown in Equation A.8.

$$P_{l,DC-AC} = 7.0833 + 0.003134\, P_o + 0.000573 P_o^2 \quad \text{(A.8)}$$

where,

$$P_{l,DC-AC} = The\ power\ losses\ in\ AC\ to\ DC\ Converter$$

Using section 3.4.3 methodology, the total power loss of DC-AC converter with temperature effect ($\boldsymbol{P_{l-t,DC-AC}}$) can be developed using Equation A.9.

$$P_{l-t,DC-AC} = (0.003028 + 0.92394\, T)(7.0833 + 0.003134\, P_o + 0.000573 P_o^2) \quad \text{(A.9)}$$

A.4 Modelling of AC to DC Converter

A.4.1 Temperature Factor Equation

Experimental data set of power losses at different ambient temperatures were collected to calculate the temperature equation coefficients for an AC-DC converter as summarized in Table A.7.

Table A. 7: Power losses in AC-DC converter at different temperature

T (℃)	Pin (W)	Pout (W)	P_{l-t} (W)	t_f
15	69.813	50	19.81	0.9636
20	70.185	50	20.19	0.9817
25	70.562	50	20.56	1.0000
30	70.932	50	20.93	1.0180
35	71.317	50	21.32	1.0367

Using section 3.4.1 methodology, the temperature factor equation can be developed for an AC-DC Converter as shown in Equation A.10.

$$t_{f\ AC-DC} = (0.00365 + 0.90875\,T) \tag{A.10}$$

A.4.2 Power Loss Equation

Experimental data set of P_o & P_l were collected to calculate the power losses equation coefficients for an AC-DC converter. The connected load was incrementally increased to observe the power losses as shown in Table A.8. The power losses are high due to the percentage loading as the efficiency of the converter change with the change in loading as expressed in Figure 2.18.

Table A. 8: Experimental data set of P_o & P_l for AC-DC converter

Pout (W)	Power Loss (W)
5	13.634
10	14.371
25	16.189
50	20.564
75	23.907
100	27.747
125	31.175
150	35.818
175	40.540

Using the Regression Analysis and Gaussian Elimination Method like section 3.4.2, the power losses equation of AC to DC converter at standard ambient temperature has been developed as shown in Equation A.11.

$$P_{l,AC-DC} = 13.03315 + 0.133904\, P_o + 0.000124 P_o^2 \qquad \text{(A.11)}$$

Where,

$$P_{l,AC-DC} = The\ power\ losses\ in\ AC\ to\ DC\ Converter$$

Using section 3.4.3 methodology, the total power loss of an AC-DC converter with temperature effect ($\boldsymbol{P_{l-t,AC-DC}}$) can be developed as shown in Equation A.12.

$$P_{l-t,AC-DC} = (0.00365 + 0.90875\, T)(13.03315 + 0.133904\, P_o + 0.000124 P_o^2) \qquad \text{(A.12)}$$

Appendix B: Experimental Setup

B.1 Testing and Safety Aspects

Installation was carried out as per the regulations of the Electrical Worker Registration Board (EWRB) New Zealand. Class 1 devices have an insulated power cable with an outer metallic body. However, class 2 devices use insulated power cables and their outer body is also insulated. As per the Electrical Safety Regulations in New Zealand, all class 1 devices with three-pin 230V AC plugs are converted into double insulated class 2 devices for installation (New Zealand Legislation, 2010). AC electrical installation was tested as per AS/NZS 3017. Following tests were performed before starting the experimental measurements.

- Resistance test of main earthing conductor
- Insulation resistance test of the complete installation
- Polarity test of consumer mains
- Polarity test of sub mains incorporating an earthing conductor
- Polarity test of single pole switch using an ohmmeter
- Measurement of an individual circuit earth fault loop impedance
- Operation of Residual Current Device (RCDs)
- Measurement of resistance of the earth electrode

B.2 Converter Data Sheets

SRNE Solar Charge Controller 60AMP - MPPT with Auto voltage Detect

Technical Specifications

Operating Voltage	: 12V/24V/36V/48V (Automatic Detection)
Max Input Voltage of PV Panel	: < 150V
No-load loss	: 0.7W~1.5W
Max Solar Power Input	: 800W (12V) / 1600W (24V) / 2400W (36V) / 3200W (48V)
Stand by self consumption	: <20mA
Charge current	: 60A
Transfer efficiency	: > 98%
MPPT tracing efficiency	: > 99%
Over voltage protection	: 16V~17V ; * nV
Limit charge voltage	: 15.5V~16V ; * nV
Equalizing charge voltage	: 15.0~15.5V ; * nV (25°C)
Equalizing charge interval	: 3 ~ 30 days
Bulk charge voltage	: 14.0V ~ 15.0V; * nV (25°C)
Bulk charge return voltage	: 12.3V ~ 14.0V : * nV (25°C)
Float charge voltage	: 13.2V ~ 14.0V ; * nV (25°C)
Over discharge voltage	: 9.7V ~ 11.8V ; * nV
Temperature compensation	: -4.0mV / °C / 2V
Over temperature protection	: Yes
Light-operated open voltage	: 5V
Light-operated close voltage	: 6V
Light operated delay time	: 5min
Device address	: 1 ~ 16
FITTING AND CONSTRUCTION	
IP Rating	: IP32
Max wiring dimension	: 25mm^2
Working temperature	: -35°C ~ ?°C
Dimensions	: 286.7 x 170 x 128mm

Figure A. 1: MPPT charger technical specifications

MODEL		SE-450-3.3	SE-450-5	SE-450-12	SE-450-15	SE-450-24	SE-450-36	SE-450-48
OUTPUT	DC VOLTAGE	3.3V	5V	12V	15V	24V	36V	48V
	RATED CURRENT	75A	75A	37.5A	30A	18.8A	12.5A	9.4A
	CURRENT RANGE	0 ~ 75A	0 ~ 75A	0 ~ 37.5A	0 ~ 30A	0 ~ 18.8A	0 ~ 12.5A	0 ~ 9.4A
	RATED POWER	247.5W	375W	450W	450W	451.2W	450W	451.2W
	RIPPLE & NOISE (max.) Note.2	200mVp-p	200mVp-p	200mVp-p	200mVp-p	200mVp-p	200mVp-p	200mVp-p
	VOLTAGE ADJ. RANGE	2.97 ~ 3.63V	4.5 ~ 5.5V	10.8 ~ 13.5V	13.5 ~ 16.5V	21.6 ~ 28.5V	32.4 ~ 39.6V	43.2 ~ 52.8V
	VOLTAGE TOLERANCE Note.3	±3.0%	±3.0%	±1.0%	±1.0%	±1.5%	±1.0%	±1.0%
	LINE REGULATION	±0.5%	±0.5%	±0.3%	±0.3%	±0.2%	±0.2%	±0.2%
	LOAD REGULATION	±2.0%	±2.0%	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%
	SETUP, RISE TIME	1500ms, 50ms/230VAC 1500ms, 50ms/115VAC at full load						
	HOLD UP TIME (Typ.)	16ms/230VAC 12ms/115VAC at full load						
INPUT	VOLTAGE RANGE	90 ~ 132VAC / 180 ~ 264VAC selected by SW 254 ~ 370VDC						
	FREQUENCY RANGE	47 ~ 63Hz						
	EFFICIENCY (Typ.)	74%	78%	83%	84%	86%	86%	88%
	AC CURRENT (Typ.)	10A/115VAC 6A/230VAC						
	INRUSH CURRENT (Typ.)	35A/115VAC 55A/230VAC						
	LEAKAGE CURRENT	<2.5mA / 240VAC						
PROTECTION	OVERLOAD	105 ~ 150% rated output power						
		Protection type : Shut down o/p voltage, re-power on to recovery						
	OVER VOLTAGE	3.8 ~ 4.6V	5.75 ~ 6.75V	13.8 ~ 16.2V	18 ~ 21V	32 ~ 36V	45 ~ 52V	57.6 ~ 67.2V
		Protection type : Shut down o/p voltage, re-power on to recovery						
	OVER TEMPERATURE	Shut down o/p voltage, recovers automatically after temperature goes down						
ENVIRONMENT	WORKING TEMP.	-10 ~ +60℃ (Refer to "Derating Curve")						
	WORKING HUMIDITY	20 ~ 90% RH non-condensing						
	STORAGE TEMP., HUMIDITY	-40 ~ +85℃,10 ~ 95% RH						
	TEMP. COEFFICIENT	±0.05%/℃ (0 ~ 50℃)						
	VIBRATION	10 ~ 500Hz, 2G 10min./1cycle, 60min. each along X, Y, Z axes						
SAFETY	SAFETY STANDARDS	UL60950-1 approved						
	WITHSTAND VOLTAGE	I/P-O/P:3KVAC I/P-FG:2KVAC O/P-FG:0.5KVAC						
	ISOLATION RESISTANCE	I/P-O/P, I/P-FG, O/P-FG:100M Ohms / 500VDC / 25℃/ 70% RH						
OTHERS	MTBF	200K hrs min. MIL-HDBK-217F (25℃)						
	DIMENSION	225*124*50mm (L*W*H)						
	PACKING	1.25Kg;12PCS/16Kg/1CUFT						

NOTE

1. All parameters NOT specially mentioned are measured at 230VAC input, rated load and 25℃ of ambient temperature.
2. Ripple & noise are measured at 20MHz of bandwidth by using a 12" twisted pair-wire terminated with a 0.1uf & 47uf parallel capacitor.
3. Tolerance : includes set up tolerance, line regulation and load regulation.

■ Features :

•AC input active surge current limiting
•AC input range selected by switch
•Protections: Short circuit / Overload / Over voltage / Over temperature
•Forced air cooling by built-in DC ball bearing fan
•Built-in remote sense function
•LED indicator for power on
•UL approved
•2 years warranty

Figure A. 2: AC to DC converter technical specifications

MODEL:		MI5700	MI5702	MI5703	MI5704	MI5706	MI5708	MI5710
OUTPUT	Continuous output	180W	360W		800W	1100W	1500W	2000W
	Surge	360W	720W		1600W	2200W	3000W	4000W
	Voltage	AC230V						
	Frequency	50Hz						
	Waveform	Pure Sine Wave(THD<3%)						
	Regulation (Typ.)	Vrms <±3%						
	USB Output (Typ.)	DC 5V ± 5% 500mA						
INPUT	Battery Voltage	12V		24V	12V			
	DC Current (Typ.)	20A	40A	20A	80A	120A	160A	220A
	Low Battery Alarm	10.6±0.2V		21.2±0.3V	10.6±0.2V			
	Low Battery Protection	10±0.2V		20±0.3V	10±0.2V			
	High Battery Protection	15±0.2V		30±0.3V	15±0.2V			
	No Load Current	0.35A	0.4A	0.2A	0.5A	0.75A	0.85A	0.95A
	Stand-by Current	0.08A	0.1A	0.05A	0.15A	0.18A	0.2A	0.2A
	Efficiency (Typ.)	89%	90%	92%	91%	91%	91%	91%
Protection		High Temperature ; Short-Circuit ; Over Load ; Input Voltage						
Load Control	Load 95~100%	Alarm but remain working						
	Load 105%	Alarm then after 1 minute shut down						
	Load 120%	Alarm then after 5 seconds shut down						
Operating temperature range		-20℃ ~ 40℃						
Operation Humidity		20 ~ 90% RH						
Storage Temp Humidity		-30℃ ~ 70℃, 10~90% RH						
Intelligent Design Heat Auto Control		Fans slow speeding up 38℃±3,Fans start speeding up:42℃±3						
		High Temperature Shut Down : 65℃±3, Restart Output: 56℃±3						
Indicator		Inverter : Green LED / Over Load : Red LED / Over Temperature : Yellow LED						
Others	Soft Start-up	Soft Started Function						
	Remote Controller	NO			YE			
Mechanical	D*W*H(mm)	186x117x57	230x118x57		295x165x57	364x180x74	350x230x74	450x230x74
	Weight(kg)	0.85kg	1.05kg		1.9kg	3.6kg	4.2kg	5.5kg
Note		Efficency test done at approx 75% load, with 13V input for 12V model, 26V input for 24V model						

Figure A. 3: DC to AC converter technical specifications

MODEL		SD-50A-5	SD-50B-5	SD-50C-5	SD-50A-12	SD-50B-12	SD-50C-12	SD-50A-24	SD-50B-24
OUTPUT	DC VOLTAGE	5V			12V			24V	
	RATED CURRENT	10A			4.2A			2.1A	
	CURRENT RANGE	0 ~ 10A			0 ~ 4.2A			0 ~ 2.1A	
	RATED POWER	50W			50.4W			50.4W	
	RIPPLE & NOISE (max.) Note.2	100mVp-p			120mVp-p			150mVp-p	
	VOLTAGE ADJ. RANGE	4.5 ~ 5.5VDC			11 ~ 16VDC			23 ~ 30VDC	
	VOLTAGE TOLERANCE Note.3	±2.0%			±1.0%			±1.0%	
	LINE REGULATION	±0.5%			±0.3%			±0.2%	
	LOAD REGULATION	±0.5%			±0.3%			±0.2%	
	SETUP, RISE, HOLD UP TIME	2.5s, 50ms, ------ at full load							
INPUT	VOLTAGE RANGE	A:9.2 ~ 18VDC B:19 ~ 36VDC C:36 ~ 72VDC							
	EFFICIENCY (Typ.)	70%	73%	76%	72%	75%	78%	74%	80%
	DC CURRENT	7A/12V	3A/24V	1.5A/48V	7A/12V	3A/24V	1.5A/48V	7A/12V	3A/24V
PROTECTION	OVERLOAD	105 ~ 150% rated output power							
		Protection type : Hiccup mode, recovers automatically after fault condition is removed							
	OVER VOLTAGE	5.75 ~ 6.75V/10% load			16.8 ~ 20V/10% load			31.5 ~ 37.5V/10% load	
		Protection type : Hiccup mode, recovers automatically after fault condition is removed							
ENVIRONMENT	WORKING TEMP.	-10 ~ +60℃ (Refer to "Derating Curve")							
	WORKING HUMIDITY	20 ~ 90% RH non-condensing							
	STORAGE TEMP., HUMIDITY	-20 ~ +85℃, 10 ~ 95% RH							
	TEMP. COEFFICIENT	±0.03%/℃ (0 ~ 50℃)							
	VIBRATION	10 ~ 500Hz, 2G 10min./1cycle, 60min. each along X, Y, Z axes							
SAFETY & EMC (Note 4)	SAFETY STANDARDS	Design refer to LVD							
	WITHSTAND VOLTAGE	I/P-O/P:1.5KVAC I/P-FG:2KVAC O/P-FG:0.5KVAC							
	ISOLATION RESISTANCE	I/P-O/P, I/P-FG, O/P-FG:100M Ohms / 500VDC / 25℃/ 70% RH							
	EMC EMISSION	Compliance to EN55022 (CISPR22) Class B							
	EMC IMMUNITY	Compliance to EN61000-4-2,3,4,6,8, EN55024, heavy industry level, criteria A							
OTHERS	MTBF	365.6K hrs min.(SD-50A) 357.5K hrs min.(SD-50B) 368.5K Hrs min.(SD-50C) MIL-HDBK-217F (25℃)							
	DIMENSION	159*97*38mm (L*W*H)							
	PACKING	0.48Kg; 24pcs/12.7Kg/0.75CUFT							

NOTE

1. All parameters NOT specially mentioned are measured at 12,24,48VDC input, rated load and 25℃ of ambient temperature.
2. Ripple & noise are measured at 20MHz of bandwidth by using a 12" twisted pair-wire terminated with a 0.1uf & 47uf parallel capacitor.
3. Tolerance : includes set up tolerance, line regulation and load regulation.
4. The power supply is considered a component which will be installed into a final equipment. All the EMC tests are been executed by mounting the unit on a 360mm*360mm metal plate with 1mm of thickness. The final equipment must be re-confirmed that it still meets EMC directives. For guidance on how to perform these EMC tests, please refer to "EMI testing of component power supplies." (as available on http://www.meanwell.com)

■ Features :

·2:1 wide input range
·Protections: Short circuit / Overload / Over voltage
·1500VAC I/O isolation
·Built-in EMI filter, low ripple noise
·100% full load burn-in test
·Fixed switching frequency at 83KHz
·Low cost
·High reliability
·2 years warranty

Figure A. 4: DC to DC (12V input) converter technical specifications

MODEL		SD-500L-12	SD-500L-24	SD-500L-48	SD-500H-12	SD-500H-24	
OUTPUT	DC VOLTAGE	12V	24V	48V	12V	24V	
	RATED CURRENT	40A	21A	10.5A	40A	21A	
	CURRENT RANGE	0 ~ 40A	0 ~ 21A	0 ~ 10.5A	0 ~ 40A	0 ~ 21A	
	RATED POWER	480W	504W	504W	480W	504W	
	RIPPLE & NOISE (max.) Note.2	150mVp-p	150mVp-p	150mVp-p	150mVp-p	150mVp-p	
	VOLTAGE ADJ. RANGE	11 ~ 15V	23 ~ 30V	46 ~ 60V	11 ~ 15V	23 ~ 30V	
	VOLTAGE TOLERANCE Note.3	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%	
	LINE REGULATION	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	
	LOAD REGULATION	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	
	SETUP, RISE TIME	500ms, 50ms at full load					
INPUT	VOLTAGE RANGE Note.5	19 ~ 72VDC			72 ~ 144VDC		
	EFFICIENCY (Typ.)	86%	88%	89%	87%	89%	
	DC CURRENT (Typ.)	24.2A/19VDC 24.8A/24VDC 12A/48VDC			8A/72VDC 6A/96VDC		
	CURRENT (AT NO LOAD)	Max. 0.2A/48VDC			Max. 0.1A/96VDC		
	INRUSH CURRENT (Typ.)	60A/48VDC			60A/96VDC		
PROTECTION	OVERLOAD	105 ~ 125% rated output power					
		Protection type : Constant current limiting, shut down o/p voltage after about 5 sec., re-power on to recover					
	OVER VOLTAGE	16 ~ 19V	30.8 ~ 35.2V	62 ~ 68V	16 ~ 19V	30.8 ~ 35.2V	
		Protection type : Shut down o/p voltage, re-power on to recover					
	OVER TEMPERATURE	Shut down o/p voltage, recovers automatically after temperature goes down					
FUNCTION	REMOTE ON/OFF CONTROL	Please refer to function manual					
	OUTPUT OK SIGNAL	Open collector signal low when PSU turns on, max. sink current :10mA					
ENVIRONMENT	WORKING TEMP.	-20 ~ +60℃ (Refer to "Derating Curve")					
	WORKING HUMIDITY	20 ~ 90% RH non-condensing					
	STORAGE TEMP., HUMIDITY	-40 ~ +85℃, 10 ~ 95% RH					
	TEMP. COEFFICIENT	±0.02%/℃ (0 ~ 50℃)					
	VIBRATION	10 ~ 500Hz, 2G 10min./1cycle, 60min. each along X, Y, Z axes					
SAFETY & EMC (Note 4)	SAFETY STANDARDS	IEC60950-1 CB approved by TUV					
	WITHSTAND VOLTAGE	I/P-O/P:2KVAC I/P-FG:2KVAC O/P-FG:0.5KVAC					
	ISOLATION RESISTANCE	I/P-O/P, I/P-FG, O/P-FG:100M Ohms / 500VDC / 25℃/ 70% RH					
	EMC EMISSION	Compliance to EN55022 (CISPR22) Class B					
	EMC IMMUNITY	Compliance to EN61000-4-2,3,4,6,8, light industry level, criteria A					
OTHERS	MTBF	196.3K hrs min. MIL-HDBK-217F (25℃)					
	DIMENSION	215*115*50mm (L*W*H)					
	PACKING	1.15Kg; 12pcs/14.8Kg/0.92CUFT					

NOTE

1 All parameters NOT specially mentioned are measured at 48, 96VDC input, rated load and 25℃ of ambient temperature.
2 Ripple & noise are measured at 20MHz of bandwidth by using a 12" twisted pair-wire terminated with a 0.1uf & 47uf parallel capacitor.
3 Tolerance : includes set up tolerance, line regulation and load regulation.
4 The power supply is considered a component which will be installed into a final equipment. All the EMC tests are been executed by mounting the unit on a 360mm*360mm metal plate with 1mm of thickness. The final equipment must be re-confirmed that it still meets EMC directives. For guidance on how to perform these EMC tests, please refer to "EMI testing of component power supplies." (as available on http://www.meanwell.com)
5 Derating may be needed under low input voltages. Please check the derating curve for more details.

■ Features :
·DC input active surge current limiting
·Wide 4:1-2:1 DC input range (24V: 19-72VDC, 96V:72-144VDC)
·Protections: Short circuit / Overload / Over voltage / Over temperature / Input polarity(by fuse)
·2000VAC I/O Isolation
·Forced air cooling by built-in DC fan with fan speed control function
·Output OK Signal
·Built-in remote ON-OFF control
·Built-in remote sense function
·3 years warranty

Figure A. 5: DC to DC (24V & 48V input) converter technical specifications

Appendix C: Development of Tool/Software

This tool can be used to design the AC and DC wiring systems based on the input parameters of supply and house wiring requirements. Figure A.6 shows the main page of Wiring System Selection Software which has the options to enter the installation conditions such as ambient temperature and grouping factor, AC voltage and frequency. This tool can be used with a 110V AC wiring system as well so it is equally useful for the American system. Operational requirements such as diversity factor, utilization factor, the energy cost have been used for the calculations of power loading, annual energy usage.

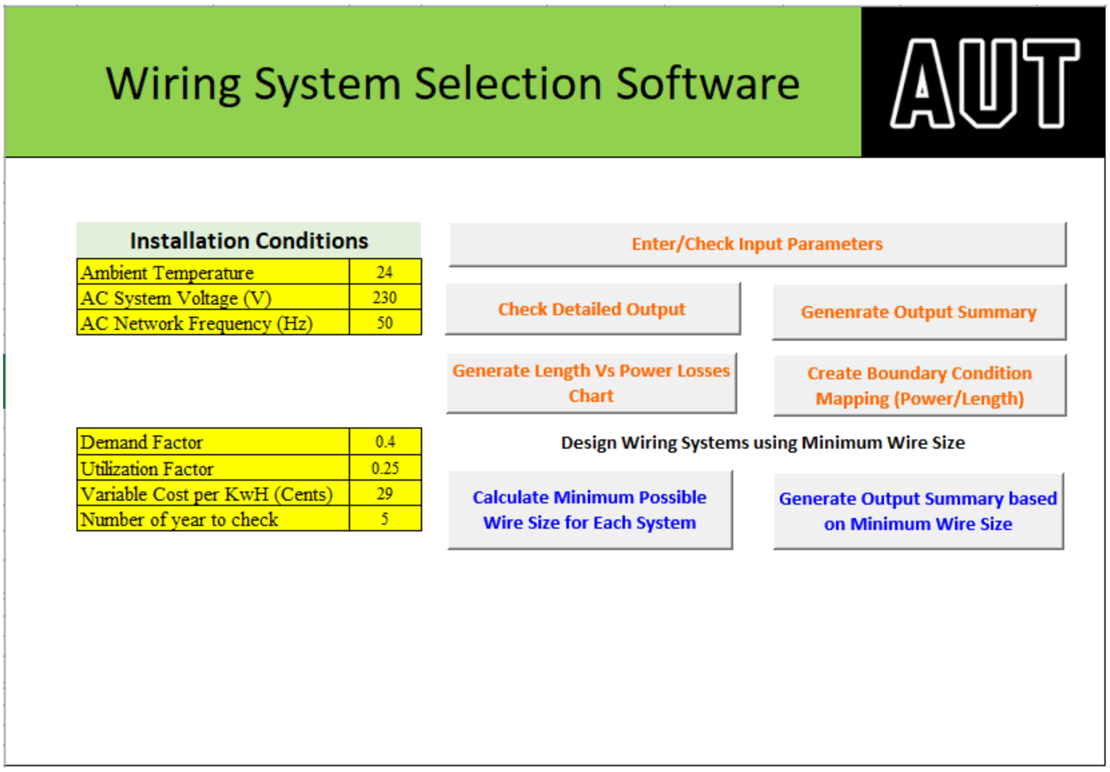

Figure A. 6: Main page of Wiring System Selection Tool

C.1 Input Parameters and Library

The house wiring requirements can be entered by clicking the "Enter/check input parameter as shown in figure A.6. At this stage, the tool is limited to 5000 loads and it can be extended for large commercial and industrial buildings. The installation details such as load power rating, length, wire size and the number of circuits in each conduit can be entered as per the snapshot shown in Figure A.7.

The library includes different types of wires and converters which can be selected based on the available options in the local market. Default converters are selected initially but the converter selection can be customized using the library. New converters can be added using the plugin issued by manufacturers once this tool is released commercially.

Back to Main Page | Detailed input | Show Recommended System | Return to Basic Input fields

Number of Loads with Lengths					DC Wiring System			AC Wiring System	
S.No	Load Power (Watts)	Line Length (m)	Conductor Size (mm2)	Number of circuits in group	12V input DC to DC Converter	24V input DC to DC Converter	48V input DC to DC Converter	DC to AC Converter	AC to DC Converter
1	800	8	4	6	12V DC converter 02	24V DC converter 04	48V DC converter 04	DC to AC converter 04	AC to DC converter 04
2	500	8	2.5	6	12V DC converter 02	24V DC converter 03	48V DC converter 03	DC to AC converter 03	AC to DC converter 03
3	990	8	6	6	12V DC converter 02	24V DC converter 04	48V DC converter 04	DC to AC converter 04	AC to DC converter 04
4	125	8	2.5	6	12V DC converter 02	24V DC converter 02	48V DC converter 02	DC to AC converter 02	AC to DC converter 02
5	500	8	2.5	6	12V DC converter 02	24V DC converter 03	48V DC converter 03	DC to AC converter 03	AC to DC converter 03
6	7	8	1.5	6	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
7	90	13	2.5	5	12V DC converter 02	24V DC converter 02	48V DC converter 02	DC to AC converter 02	AC to DC converter 02
8	7	13	1.5	5	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
9	7	13	1.5	5	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
10	900	13	6	5	12V DC converter 02	24V DC converter 04	48V DC converter 04	DC to AC converter 04	AC to DC converter 04
11	5	13	2.5	5	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
12	7	20	1.5	3	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
13	500	20	4	3	12V DC converter 02	24V DC converter 03	48V DC converter 03	DC to AC converter 03	AC to DC converter 03
14	25	20	2.5	3	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
15	500	15	4	3	12V DC converter 02	24V DC converter 03	48V DC converter 03	DC to AC converter 03	AC to DC converter 03
16	300	15	2.5	3	12V DC converter 02	24V DC converter 03	48V DC converter 03	DC to AC converter 03	AC to DC converter 03
17	1000	15	6	3	12V DC converter 02	24V DC converter 04	48V DC converter 04	DC to AC converter 04	AC to DC converter 04
18	7	25	1.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
19	5	25	2.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
20	50	25	2.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
21	25	25	2.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
22	7	30	1.5	3	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
23	5	30	2.5	3	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
24	25	30	2.5	3	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
25	7	20	1.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
26	5	20	2.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01
27	25	20	2.5	4	12V DC converter 01	24V DC converter 01	48V DC converter 01	DC to AC converter 01	AC to DC converter 01

Figure A. 7: Input Parameter Window in AUT Wiring Selection Tool

C.2 Output Reports

This tool generates multiple types of reports including detailed analysis to compare the efficiency and cost of wiring options. The most efficient wiring option is recommended based on the input parameter. The summarised report function of this tool has been used in Chapter 5 for the boundary conditions charts and cost-benefit analysis. This tool is also capable of designing the minimum wire size for each wiring topology as shown in Figure A.8.

Back to Main Page Input Load Requirements			Minimum Required cable size for Wiring Systems (mm2)			
S.No	Load Power (Watts)	Line Length (m)	12V DC	24V DC	48V DC	230 AC System
1	800	8	Constraint	Constraint	2.5	1
2	500	8	Constraint	10	2.5	1
3	990	8	Constraint	Constraint	4	1
4	125	8	10	2.5	1	1
5	500	8	Constraint	10	2.5	1
6	7	8	1	1	1	1
7	90	13	10	2.5	1	1
8	7	13	1	1	1	1
9	7	13	1	1	1	1
10	900	13	Constraint	Constraint	6	1
11	5	13	1	1	1	1
12	7	20	1.5	1	1	1
13	500	20	Constraint	Constraint	4	1
14	25	20	4	1.5	1	1
15	500	15	Constraint	Constraint	4	1
16	300	15	Constraint	10	2.5	1
17	1000	15	Constraint	Constraint	6	1
18	7	25	1.5	1	1	1
19	5	25	1.5	1	1	1
20	50	25	10	2.5	1	1
21	25	25	4	1.5	1	1
22	7	30	2.5	1	1	1
23	5	30	1.5	1	1	1
24	25	30	6	2.5	1	1
25	7	20	1.5	1	1	1
26	5	20	1	1	1	1
27	25	20	4	1.5	1	1

Figure A. 8: Wiring Design for AC and DC Wiring topologies