Queensland University of Technology

Bachelor Of Engineering

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BEB802: Undergraduate Thesis (Project 2)

Undergraduate Thesis Progress Report

Feasibility of Low Voltage Direct Current Power Distribution

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FEASIBILITY STUDY OF LOW VOLTAGE DIRECT CURRENT POWER DISTRIBUTION

by
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Submitted for the degree of
Bachelor of Engineering &
Bachelor of Finance (IX28)

in the division of . . .

November & 2016.

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October 19, 2016

The Dean
School of Engineering
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Dear Professor Simmons,

In accordance with the requirements of the degree of Bachelor of Engineering / Bachelor of Finance (IX28) in the division of Computer Systems Engineering / Electrical and Electronic Engineering, I present the following thesis entitled Feasibility Study of Low Voltage Direct Current Power Distribution. This work was performed under the supervision of Associate Professor Geoffery Walker.

I declare that the work submitted in this thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at Queensland University of Technology or any other institution.

Yours sincerely,

DAVID PETRIE.

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Abhishek Bhasin and **Isaac Linett** from Q Electrical for their technical assistance and frequent questions.

Disa for her constant love and support through not only this project but my entire degree.

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Abstract

This design project aims to solve the issue of incorporating low voltage direct current (DC) power distribution systems to multi-residential and commercial buildings. Low voltage DC power is prevalent in telecommunications systems but has the possibility of being used for a variety of other applications to reduce electricity costs and improve efficiency. Due to the large costs involved in building power systems, the majority of this design project will be completed through software simulations and hand calculations. If these methods cannot be utilised, either physical testing or research will be completed as substitute. If successful, a more efficient and cheaper alternative to running simple electronics from AC mains will be created. This will allow for a portion of building's electricity demands to be self sufficient and not rely on the grid for continual supply.

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1 Introduction

In most Australian homes, power is consumed directly from the local distribution grid. All appliances are connected to one switchboard but can be separated over various circuits each with their own protective devices, usually circuit breakers. Generally, many modern Australian appliances will use Direct Current (DC) electricity but the outlets provide an Alternating Current (AC) source of 240 V at a frequency of 50 Hz. Each device therefore requires an converter that converts the AC source into the required constant DC voltage and current specific to that device.

This project will consider the feasibility of diverting a portion of power distribution from the standard 240 VAC sourced from the grid with an alternative solution. The considered option is utilising a low voltage direct current on a separate grid to power known low consumption devices such as lighting or electronics charging devices. An efficiency and financial analysis will be completed through hand calculations and software simulations.

This project will specifically focus on two aspects of this broader topic. These are whether alternative power generation systems will be utilised as well as whether the new possibilities for generation and distribution methods could be used in applications larger than residential homes. The additional locations for this application that will be analysed are apartment and commercial complexes. There will be a variety of design possibilities considered to find the optimal low voltage DC alternative implementation. To do this there will be a focus on cost, efficiency and usability comparisons of equivalent AC and DC systems.

2 Background & Literature Review

2.1 Introductory Statement

Due to my personal experience working as a trainee electrical engineer for an electrical contractor I have a stronger understanding of power systems in the construction industry than most students at my level. This project will be focusing on a designs and simulations to produce deliverables.

2.2 Literature Review

2.2.1 Existing Power Distribution Systems

Power systems consist of four major sections; generation, transmission, distribution and loads. AC electricity is generated in power plants and sent through high voltage transmission lines to substations and distributed to switchboards for use in residential, commercial and industrial areas [1]. In order to transport electricity over large distances (excess of 2km) without severe losses, very high voltage and low current is used [1]. This is voltage is lowered and current increased by a transformer at the substation and again at the residence. For electricity to reach the home and be utilised for devices there must be safety mechanisms installed to ensure damage is not done to the user or devices. The protective devices requiring consideration throughout this project will be fuses, circuit breakers and switchboards [2]. These devices are placed through the circuit to protect the more expensive equipment closer to the transformer and grid.

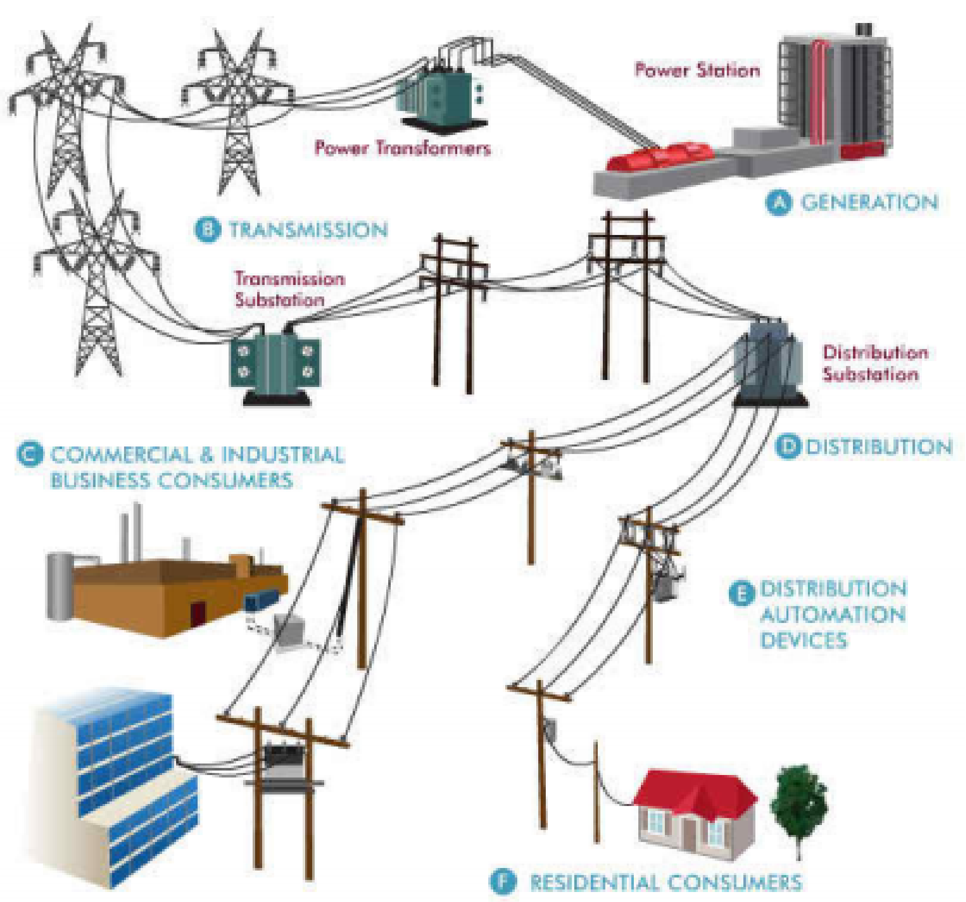

Figure 1: Current Power Distribution Methods [3]

2.2.2 Alternative Electricity Generation Solutions

In order to increase efficiency of power systems through utilising a low voltage DC sub-system, alternatives to drawing standard AC electricity from the grid must be considered. In Australia, a strong option for the generation alternative is photo-voltaic systems that are also known as solar panels. These systems will convert the sun's rays into electricity via a DC-DC converter and a DC-AC inverter and battery [4]. An important aspect is that the electricity is produced in DC and will require no inverter in a DC system.

2.2.3 Electrical Safety Mechanisms

2.2.4 Standards

Australian standards will be an integral part of this project. Without adhering to the rules and regulations put in place, the devised system will not be legally allowed to be installed. There are three standards that will be relevant to this report; AS3000, AS3008 and AS3015. The AS/NZS 3000 covers the standards realted to electrical installations or wiring rules within Australia and New Zealand [5]. These standards will be the main reference point however there are the additional publications of AS/NZS 3008 which are the regulations specifically related to electrical installations and cable specifications [6]. The final standards taken into consideration will be AS/NZS 3015 which specifically disctates the rules with regards to electrical installations of extra low voltage direct current power supplies and services earthing within public telecommunications [7].

2.2.5 Tariffs

Tariffs will be an important considerion with the feasibility of this project due to the possibilities of cost reduction. User expenses could theretically be reduced by implementing a system off the grid. Government policies have been put in place in order to prompt an increase in investment in renewable energy sources [8]. Users are able to sell their unused generated electricity back to the grid to reduce their overall electricity bills or possibly profit if consumption is low enough. In Queensland, according to the SolarChoice website a feed-in tariff of $0.06/kWh can be earned [9]. By not connecting the photo voltatic panels to the grid, this tariff can not be received however there is the possibility that it is more efficient and will produce less energy loss by storing in local batteries and running simple circuits rather than feeding the grid [10]. The consideration will be whether the cost reduction in electricity bill will be worth the investment in the equipment and future cost reduction.

2.2.6 Direct Current vs Alternating Current

A very broad and contextual understanding must be made about the differences between direct current and alternating current distribution systems. Compared with traditional AC designs, DC has the potential for large power supply capacity, smaller feeder loss, increased efficiency, more consistent power and more direct access to renewable energy solutions [11]. Alternating current is run to outlets at 240V, 50Hz and then devices are used to alter that source into whatever the device requires. Many household electronics such as computers, chargers, lighting and televisions operate internally at DC voltages meaning they each require either internal conversion circuitry or use a transformer between the powerpoint and device [12].

AC was originally depicted as the better choice for power distributions due to there being no method at the time for controlling DC electricity at the load causing large losses from the generator to device [13]. To remedy this, AC distribution was used due to efficienct transformers being developed to boost the voltage. AC remains the fundamental power type but DC is growing in popularity with improved converters and increased frequency of DC energy sources [13]. Utilising DC generation systems could also fulfill the power industry's obligation to increase the sustainability of their systems and be more environmentally conscious [14]. The required inverters to convert the AC supply into DC for electronics is reducing the efficiency (increasing voltage drop) of the overall system [13].

2.2.7 Direct Current & Alternating Current

A very broad and contextual understanding must be made about the differences between direct current and alternating current distribution systems. Compared with traditional AC designs, DC has the potential for large power supply capacity, smaller feeder loss, increased efficiency, more consistent power and more direct access to renewable energy solutions [11]. Alternating current is run to outlets and devices are used to change the source for the device. Many household electronics such as computers, chargers, lighting and televisions operate internally at DC voltages meaning they each require either internal conversion circuitry or use a transformer between the powerpoint and device [12]. Utilising DC generation systems could fulfill the power industry's obligation to increase the sustainability of their systems and be more environmentally conscious [14]. The required inverters to convert the AC supply into DC for electronics is reducing the efficiency of the overall system [13].

2.2.8 Low Voltage Direct Current

DC power is currently restricted to special applications such as telecommunications, electric vehciles and high-voltage direct current (HVDC) transmission [15]. Low-voltage DC power systems at 48V has been used fairly widely with telecommunications systems but is recently facing issues due to the high power requirements of computer system upgrades [15]. Studies have shown that the 48V system still remains more efficienct than a 270V DC or 200V AC but further investigation needs to be done into 230V and 325V through retrofitting existing low voltage AC installations [15]. Photo-voltatic generators are used frequently for these forms of power distribution systems as it can be powered directly or use simple DC to DC converters for different devices. Utilising a DC distribution system makes it easier to incorporate the local generation meaning not only could this be cheaper but if there are faults with the distribution grid, the separate micro-grid will be protected [14].

2.2.9 Converters and Inverters

Converters and inverters are electrical devices designed and constructed to convert current [16]. Converters are used to convert the voltage from AC to DC and inverters converter from DC to AC [16]. Inverters are used to convert the DC from solar panels to AC for transfer back into mains or to the necessary switchboard. An additional use for these is in Uninterrupted Power Supplies (UPS) where stored DC battery power [16]. There are three different types of converters and inverters;

Converters [16]

- Analog-to-digital converter (ADC): converts the input analog voltage to a digital value proportional to the magnitude of the voltage or current. An example of these would be a rotary encoder.
- Digital-to-analog converter (DAC): converts digital code to an analog signal. An example would be a computer sound card or digital music players.
- Digital-to-digial converter (DDC): converts one form of digital data to another.

Inverters [16]

- Square wave inverter: built from a DC source with four switches and a load, it produces a square wave output. This is the cheapest device but produces the lowest quality power.
- Quasi wave or modified square wave inverters: the output waveform is square and therefore not sine which is required for pure AC sine waves. These waves have a step between the square waves which can aid in minimising noise or harmonics that can cause problems with electrical devices.
- True sine wave inverters: the most expensive form of inverter. These are not used actively due to the second option being more cost efficient.

2.2.10 LED Lighting

Improvements in LED lighting allow much less power to be used for the same amount of light. It is very possible to design and create an energy efficient LVDC grid powered LED lighitng system with additional automation aspects and energy storage [17]. Typical lighting systems that are used in a lot of commercial or residential buildings are flurescent systems that are powered directly from standard 230V AC due to the devices' high efficacy [17]. When comparing an AC flurescent system and a LVDC LED system, the LVDC gid system requires sigificantly less power conversion which increases the overall effiency [17]. The image below additionally compares how lower wattage and power consumption is now able to produce far more light (lumens). This is allow fewer a similar amount of lights per room but they draw far less power [18].

	Incandescent Bulb	CFL Bulb	LED Bulb
			
Wattage	40 W	9 W	7 W
Lumens	550 lumens	550 lumens	400 lumens
Lumens/Watt (Efficacy)	14 lm/W	61 lm/W	57 lm/W

Figure 2: Comparing Lighting Method's Efficiency [18]

2.2.11 Commercial and Industrial Power Systems

There are relatively large differences between home power systems and commercial. A home setting is fairly simple wih a transformer close to the house feeding the power into one switchboard that provides additional safety along with circuit breakers for the home circuits. In a commercial setting the loads are far higher and requires a stable connection [19]. For an apartment complex, shopping centre or business building for example, the supplies are usually separated into busses in order to identify separate requirements or areas. The requirements could be essential items (including emergency lifts, safety equipment or machines that cannot be stopped) or non-essentials (tenancies or general equipment). Additionally it can be used to separate the entire building's load over towers or zones to minimise faults. The figure below represents a single line diagram showing the two separate busses for a design.

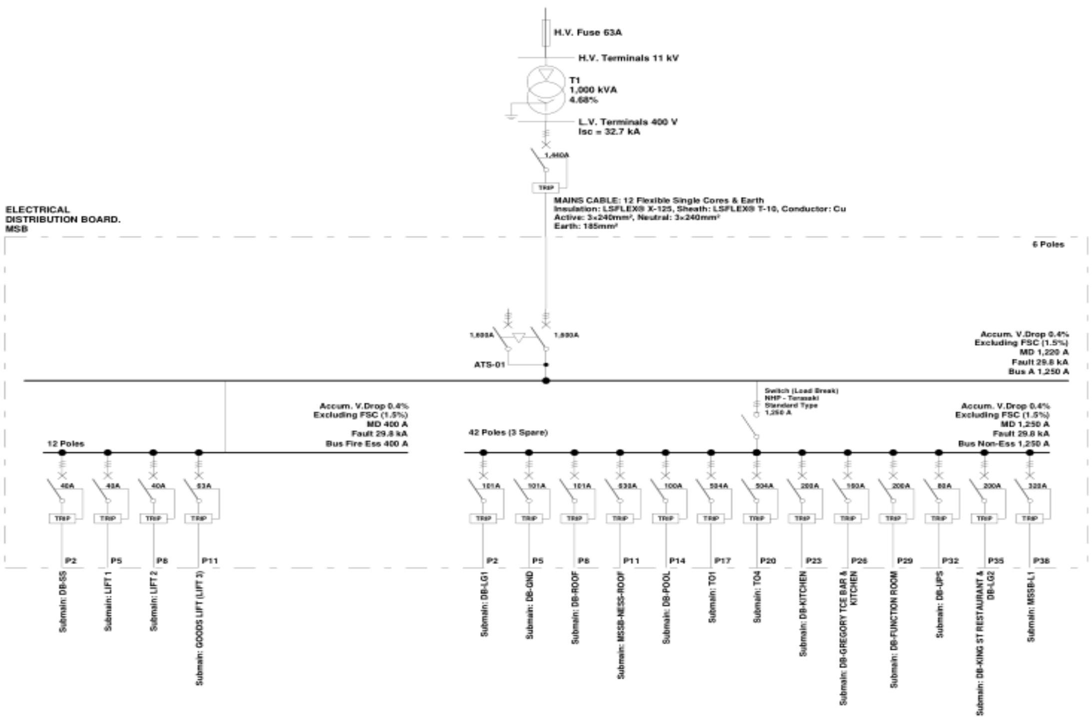

Figure 3: Hotel Single Line Diagram

2.2.12 Buck and Boost Converters

2.3 Prior Art

For a thorough research project to be completed, devices that have already been designed, tested and created must be research and analysed. With the popularity of DC power systems increasing in recent years, there have been an many more academics assessing the possibilities. Due to the predominately theoretical design nature of this report and similar aspects of previous papers, a significant focus was made on previous papers.

2.3.1 Previous Thesis: Extra-Low Voltage In-Home Power Distribution and Storage

Steven Donohue completed his undergraduate thesis under Geoffery Walker in 2014 [20]. This paper assessed various aspects of the similar topic question but specifically focussed on using low voltage DC electricity in homes to power lighting systems. He also considered battery storage solutions and devised that 48V was the best option for voltage levels for this application [20]. He finalised that a proposed installation model for low voltage distribution was uneconomical with current solar feed-in tariffs [20]. The final discussion of lighting application proved to be successful using LED lighting circuits in home. Donohue's project will be an asset to the completion of this thesis as the overall concept is very similar. It will be possible to make some assumptions and avoid investing time on smaller calculations due to Donohue's extensive research.

2.3.2 Previous Thesis: DC Supply In Buildings

From the University of Science and Technology in Norway, Aurora Bøhle Foss completed her master's thesis on encorporating DC supply into buildings with a larger focus on commercial buildings [21]. Her focus wasn't specifically to do with low voltage DC however it did incorporate some research and testing into the feasibility of these systems. her research found that the most important aspect of incorporating DC supplies into power systems is a highly efficient Voltage Source Converter (VSC). She discovered that if a load is requiring AC, it is more efficient to use an AC source. It has been found that higher power loads and cable lengths longer than 10 metres using 1.5mm^2 and 2.5mm^2 are impossible due to severe losses.

2.3.3 Micro-Inverters

A competitor to the system that will be designed throughout this thesis will be recent developments in micro-inverter technologies by Enphase [22]. These products are designed to be efficient, small and affordable to allow for the DC electricity generated by photo-voltaic cells to be converted to 240V 50Hz AC for the mains. A wide range of fittings are possible depending on the PV cells and switchboard distribution. They have a rated efficiency of 95.7% [22].

2.3.4 EP 0516025A3 Low Voltage DC to DC Converter

Due to this project being predominately simulation based and not specifically building an improved system, it will need to consider existing devices. As discussed, the largest hurdle will be ensuring that the devices maintain a high enough efficiency to allow DC systems to be viable. This patent represents the construction of a low voltage DC converter utilising MOSFETs [23]. The figure below shows the circuit diagram patented.

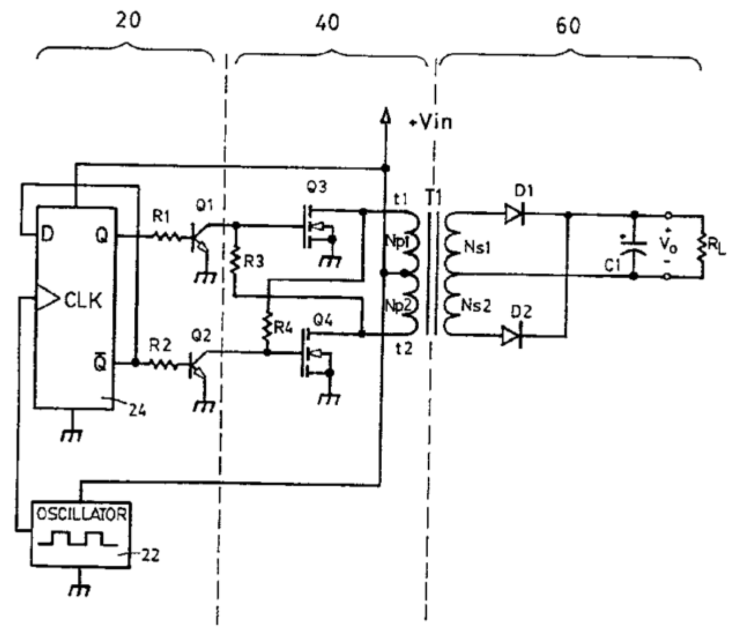

Figure 4: Low Voltage DC to DC Converter Design Patent [23]

2.3.5 US 7435897B2 Apparatus and Method For Mounting Photovoltaic Power Generating Systems on Buildings

Miles Russell from Schott Solar, Inc based out of Massachusetts developed a new apparatus for mounting PV systems onto larger buildings [24]. It is not as technical but it discusses the benefits of utilising a specific mounting system for the largest energy production. The design is a simpler way of implementing the physical connection of panels to larger buildings. This patent does not consider the inverters or circuitry, it is purely for the attachment and orientation of panels.

3 Research Problems

The key problem that this research paper will be targeting is the feasibility of implementing a separate DC power distribution system for the specific purpose of powering LED lighting circuits and simple electronics. Additionally, the goal is to implement these systems into a commercial building and apartment setting within Australia. For a stronger understanding and case study, Brisbane city will be analysed due to the large amounts of sun and numerous high rises. Designs will be tested through physical devices where possible or software simulations otherwise. In order to answer this key question and complete the project, sub questions were separated and discussed.

1. Can direct current power be a suitable alternative to alternating current when efficiencies are compared?
2. Is 48V the most suitable option for this system?
3. Could a photo-voltaic system be implemented to power these circuits?
4. Will a separate circuit that powers the lighting be possible?
5. Could these proposed power distribution methods be implemented in commercial buildings?

4 Program and Design

4.1 Objectives

The objective of this research project is to attempt to answer the overall question of whether a low voltage DC power distribution system could be implemented to power low load devices such as lighting, simple electronics and charging devices. A secondary objective is to relate this project directly to renewable energy generation and in a commercial setting.

4.2 Methodology

In order to complete this task within a timely manner and ensure all aspects are thoroughly considered and discussed, a clear guideline of tasks musts be followed. Additionally, these tasks will need to specifically address the objectives that the research proposal addresses. As discussed in Section 3, there are five broad questions that are being addressed throughout the two semesters of this thesis. The methodology of the thesis is based around a combination of physical and theoretical testing. A reliance on previous research and design recommendations will be important [1]. Although research of DC systems has increased, this project will be focusing on an area that has not been sufficiently researched and analysed [25].

The five separate questions are related to the same solution. Initial stages of the project require extensive research on the possibilities and theories behind a purely DC system. Once a strong idea of the possibilities and previous papers were analysed a general analysis of whether or not 48V is the ideal voltage level is secondary. To do this, it will be predominately theoretical with voltage loss calculations over standard cable lengths. Additionally research will be used to back up findings. Software and research will be used to assess the options with solar panels and the best method of implementing them into the solution.

SMART goals will be used to measure the progress. This framework is based off having goals that are specific, measurable, attainable, realistic and timely. These goals are the milestones that are described. By doing so, tasks can be achieved and a regular logbook of activities maintained for process improvements. Spreadsheets and in-built software data storage will be used to record the findings. These findings will be analysed either through additional hand calculations or Matlab. The figure below shows the methodology behind technical design tasks.

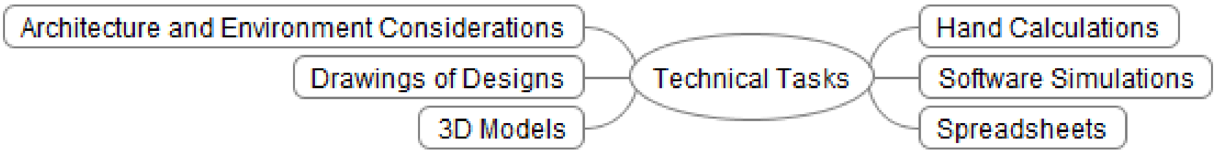

Figure 5: Considerations for a Technical Design Task

4.3 Research Plan

A majority of the project will be through simulations utilising Matlab, PowerCad5, Dialux4.12 and Homer. This is due to power systems electronics being expensive and large scale testing out of the financial scope of this project. Ideally, a full system would be built with Photo-Voltaic cells, battery, controller, DC-DC converters and connections to appliances, however finances will not allow this. Figure 4 below shows a basic PV DC system and the areas requiring consideration.

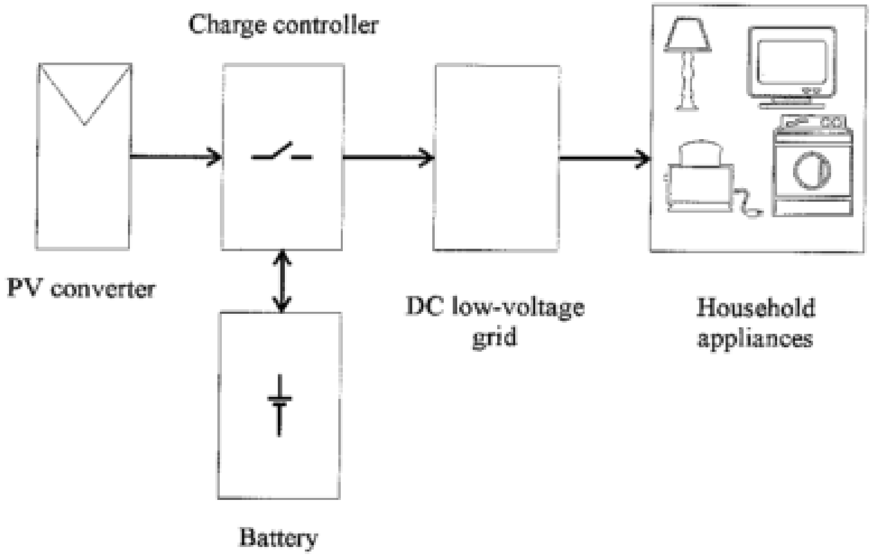

Figure 6: Initial Design Consideration for DC Home Power System [25]

The software will allow for data collection and spreadsheets used to track and assess. The benefit of using spreadsheets and Matlab is that formulas can be input and optimisation simulations run. If simulations are not being used and physical tests are required, a multimeter or computer interfaces will be utilised. If testing cannot be performed or simulated, additional research will be completed to find the closest solution possible. If this method needs to be done, it will explicitly stated in the final report that not all aspects could be physically tested.

4.4 Resources and Funding

The design and construction of this project would require a substantial amount of resources. Due to this, computer assisted design (CAD) programs will be used as the main design calculation feasibility analysis mechanism. The University facilitating this research project will allocate $50 for each student through purchase order applications. This value will be taken into consideration when designing possible testing mechanisms or models for the presentation.

4.5 Project Team

As previously stated, this project is being solely undertaken, however there are three students undertaking topics that are interrelated. In addition to my task focusing on low voltage DC systems in larger applications, the other two students are analysing sub issues in the same broad category. There will be discussions between the three students on relevant articles, journals and standards that each person finds.

4.6 Timeline

This project will be predominately based on two major resources; software availability and personal time. Software will be available at all times due to the University providing paid software packages and myself already having installed free ones. Personal time will be the major difficulty as it will be balanced between other University classes, part-time work, and personal responsibilities.

The tasks were be split into days and University weeks. It was ensured to include the holidays that University allows. This project does not simply end upon the completion of this semester. BEB801 is concluded on November 4th at the end of Week 14, however BEB802 is the subject allocation to complete the second half of this project. The task table will allocate SMART milestones. Additionally, the benefits of completing the subjects during this period is that there is the additional time from summer holidays to account for.

The table on the following page shows the milestones of this project. The University assigned submissions are represented as bold text. The four major deliverables for the first half of this project are the library assessment, project proposal, oral presentation and progress report. These four deliverables are what have outlined how the remaining tasks have been created and the time periods allowed for. Earlier due dates are set to allow for editing or possible difficulties to occur without major repercussions.

The assessed deliverables for Semester 2 are similar to the first. The major difference predicted is that the task should be very well understood by the beginning of semester. By having this advantage as well as the additional time during summer break, it allows for a very strong foundation for the final design. This is why the non-assessed milestones are predominately finalisation throughout the entire semester. The summer break will be utilised to reduce the required work during the University period.

Milestone	Deadline
Project Definition	Week 3
Library Assessment	**Week 4**
Initial Research Phase	Week 6
Project Proposal	**Week 7**
Initial Design Phase	Week 9
Initial Prototype Design Finalised	Week 11
3D Modelling for Presentation	Week 12
Written Report	**Week 13**
Initial Oral Presentation	**Week 14**
Implement Feedback From Report	Summer Break
Complete Research Shortcomings	Summer Break
Complete Further Technical Calculations	Summer Break
Initial Finance Analysis	Week 2
Design Simulations	Week 6
Progress Report	**Week 7**
Finalised Design	Week 10
Finalised Simulations & 3D Modelling	Week 11
Finalised Financial Analysis	Week 12
Final Report	**Week 13**
Final Presentation	**Week 14**

Table 1: Major Milestones of Project

4.7 Current Design Consideration

The milestone for having the initial prototype design is not until week 9 however the research completed and discussions with Geoffery has allows a beginning concept for what could be a feasible design. The main design constraints are cable lengths need to be short, the power generation should be with photo-voltaic systems and due to load constraints, many micro-grids should be used. To do this, with tall and thin buildings it would be possible to use PV cells instead of shading or window awnings to generate electricity. Each floor has their own cells and generates electricity to power their lighting and simple electronics or USB wall charging ports.

Utilising Steven Donohue's findings of 48V being the perfect voltage level for these forms of systems, the intial plan is to utilise this level [20]. The cables being run would follow Australian building standards at 2mm^2 2 core and earth and would easily provide the necessary current carrying capacity. These cables would feed to separate, dedicated switchboards for a purely DC supply and then through to LEDs where a highly efficiency

DC-DC converter needs to be found or designed. Each floor would therefore have it's own switchboard to power an area between $50m^2$ and $100m^2$ although further calculations are required to check this. An office space is approximately $9m^2$ requiring only 4 LEDs to provide necessary lux levels meaning the load for lighting should not exceed 40 watts and at 48V that's only 0.83A. With multiple rooms such as this, the design should be feasible with further simulations.

5 Discussion

The following section will go into technical detail of the five questions that this project will analyse. Due to the fact this is a progress report and not the final, there are not solutions to all answers however mechanisms put in place so that the solutions can be found. If a question has not been solved, it will be outlined how the solution will be found over the remaining semester.

5.1 Is 48V the Optimal Voltage Level?

5.2 Can Photo-Voltatic Systems Be Used Effectively for this Application?

5.3 What Lighting Options Are Optimal?

5.4 Structural Design and Safety Mechanisms to Minimise Cable Losses

5.5 Can Direct Current Be Used as an Alternative to Alternating Current for Commercial Lighting Systems?

6 Future Work & Conclusion

The project being undertaken plans to design and confirm the feasibility of a DC power distribution for commercial buildings to power low load electronics such as lighting and simple devices with a group of photo-voltaic cells. The completion of this task will require extensive research, time, calculations and computer simulations. Milestones that have been set meet the SMART criteria which will allow for tracking and maintaining progress throughout the project. The initial research phase has been completed and designs will begin to be theorised and soon tested following the timeline.

Computer simulations are the main design solution due to the large costs involved in commercial power system implementation. By simulating designs and providing visual aids through 3D rendered images, the presentation will be show not only calculation data but designs implemented on a visual model. In the event that an experimental test can be financially and physically completed and it would benefit the task, it will be done.

Overall it is expected that this research project will be completed with a feasible design. If it is found that no solution will be suitable, a strong justification and possible future areas of discussion will be brought forward. November 2016 will have a preliminary design along with justification for the feasibility so that a presentation can be made and successful progress shown. By ensuring that this stage is reached, valuable feedback will be provided via the project supervisor and academic team behind the course.

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