DC Distribution Systems For Home Application

by

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B.E, R.V College of Engineering, 2013

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Applied Science

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Electrical and Computer Engineering)

The University of British Columbia
(Vancouver)

August 2015

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Abstract

Unprecedented expansion of native direct current (DC) powered equipment (computers and consumer electronics) has increased household DC electricity consumption over the past decade. Since power utilities deliver alternating current (AC) rather than DC, the conversion process (rectifier) used to supply DC loads is very inefficient. The research investigates the suitability of employing conventional AC wiring to distribute DC power to supply loads directly, in particular around outlet/switch arcing issues. The problem of arcing in DC system is very predominant and needs to be addressed to meet safety requirements while improving the efficiency of the system. In order to overcome the arcing issues, an alternative flat DC wiring system is proposed which offers improved transient electrical and thermal characteristics for household wiring. The flat wire solution employs the same raw materials and provides improvements in parasitic values associated with arcing while reducing thermal resistance. The proposed flat wire geometry is expected to achieve reduction of arcing and improve the overall efficiency of the distribution system.

Simulations of the two preliminary AC and DC systems are provided for typical domestic loads and switching events. These characteristics are verified by conducting similar tests on house wiring system prototype created in the lab. Furthermore, the switching behaviour is observed on loading the system through the outlet.
Preface

This research was done with the aim of using DC for homes while keeping the current architecture and design as far as possible. The study included comparing and testing the existing system with the proposed system.

The project was supported by Natural Sciences and Engineering Research Council of Canada (NSERC) under Grant CRDPJ 434659-12 & The Institute for Computing, Information and Cognitive Systems (ICICS) and Telus People & Planet Friendly Home (PPFH) Initiative at The University of British Columbia (UBC) throughout the term of research.

This work is based on research performed at the Electrical and Computer Engineering Department of the University of British Columbia by Shreya Iyer, under the joint supervision of Dr. William Dunford and Dr. Martin Ordonez.

A version of Chapters 1,3 and 4 have been published and presented at the IEEE Power and Energy Society General meeting (PESGM) 2015 [1].

Hardware design, assembly and testing of the DC home wiring set-up was done by Shreya Iyer under the guidance of Dr. Dunford and Dr. Ordonez.

As the first author of the above-mentioned publication and work, the author of this thesis developed the theoretical concepts and wrote the documents, receiving advice and technical guidance from supervisors Dr. William Dunford and Dr. Martin Ordonez. The author developed simulations and experimental set-up with help of Dr. Dunford, Dr. Ordonez and Dr. Ordonez’s research group.
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Glossary

UBC  University of British Columbia

NSERC  Natural Sciences and Engineering Research Council of Canada

PPFH  People & Planet Friendly Home

ICICS  The Institute for Computing, Information and Cognitive Systems

DC  Direct Current

AC  Alternating Current

PCB  Printed Circuit Board

HVDC  High Voltage Direct Current

EMF  Electromotive force

MCCB  Moulded case Circuit Breakers

AFCI  Arc Fault Circuit Interrupters

AWG  American Wire Gauge

IEC  International Electrical Code

RCD  Residual Current Device

XLPE  Cross-linked polyethylene

PVC  Polyvinyl Chloride
LV    Low Voltage
PSIM  Powersim
NEC   National Electrical Code
RMS   Root Mean Square
IEC   International Electrotechnical Commission
LCR   Inductance(L), Capacitance(C), Resistance(R)
Acknowledgments

I offer my enduring gratitude to the faculty, staff and my fellow students at UBC, who have inspired me to continue my work in this field. I owe particular thanks to my supervisor Dr. William Dunford and my Co-supervisor Dr. Martin Ordonez, whose penetrating questions taught me to think more deeply. They have helped me develop curiosity and made me more self-motivated. They have taught me to be organised and consistent with my work. Above all, they have kept constant faith in my work and encouraged me throughout the process.

This work was supported by PPFH initiative and I want to thank Dr. Panos Nasiopoulos and Dr. Mahsa Pourazad for accepting me as a student in this initiative.

I would also like to thank Ion Isbasescu, David Campos Gaona and Rafael Pena-Alzola for their help during my experiments. Special thanks to Mark Finniss for helping me out with all the materials and the tools required in the workshop. I couldn’t have done this without their help and support.

I also take this opportunity to thank my lab mates, Matin Rahmatian, Veronica Galvan and all other colleagues who have encouraged me and also guided me through some tough technical issues related to my research.

My heartfelt thanks to my friends and well wishers to keep me motivated throughout my research term.

Special thanks are owed to my parents and my sister, whose have supported me throughout my years of education, both morally and financially. They have always stood by me during my success and failure.
For my parents
Chapter 1

Introduction

1.1 Motivation

Direct Current (DC) distribution systems are becoming very popular nowadays and are being used for various applications. DC is largely used in telecommunication applications and certain renewable energy sources produce DC output. With the increasing number of alternative energy resources such as solar power coupled with batteries, there is abundant energy in the form of DC available.

DC as power source has been used in many devices, DC is also being used as a part of transmission in High Voltage Direct Current (HVDC) systems; but little is done to implement DC power as the primary source of power at the distribution level.

The main challenges while using DC in low voltage application such as homes, buildings and commercial applications is the compatibility with existing system and the costs involved in modification to suit the new system. Thus the primary aim of this work is:-

1. To evaluate the DC distribution systems for homes and check for compatibility in terms of power rating, load types and relevance to the existing system.

2. To propose a DC system configuration having better system characteristics, (i.e. switching transients, thermal properties) while maintaining the similar voltage and current ratings to the existing AC systems.
3. To modify the existing wiring systems by constructing a modified cable structure with line parameters such as to suit the system requirements and having the same current rating as that of the existing electrical wiring.

When implementing DC, defining a voltage standard for DC distribution becomes very important. For Telecom application, 48 V DC input is considered as a standard and is within safety limits. The same DC input voltage can be used for low voltage DC application but is not suitable for high power loads that are present in homes. The voltage standards of existing loads are 120 V or 240 V in North America, and 230 V in Europe. Currently, a $+/- 190V$ [3] is being proposed for data centers, is low compared to the existing voltage standards. A slightly higher voltage would be compatible with either Alternating Current (AC) or DC input. Establishing a voltage standard is an important step while implementing DC for residential applications. Some of the possible DC voltage standards are evaluated in[4] and [5].

1.2 Literature Review

1.2.1 History Of AC Power

It all began in the time of Edison, when he built a power station to light incandescent bulbs using DC power. The main drawback observed was that the power diminished with distance and it was concluded that the power houses must be near the source of electricity. This is mainly due to the losses in the cable or the losses in the resistance of the wire, popularly known as the losses due to $I^2R$.

Power delivered to the load (anything which uses power) is defined as the product of Amps and Volts, or $P=IV$. On the other hand, line losses (the energy lost in the transmission wires) are determined by the product of Amps squared times ohms (the resistance of the wire), or $I^2R$. The voltage plays no part in line losses.

With AC, then, the transformer (a low cost device that are only applicable to AC systems) stepped up the voltage (or down, depending on the ratio of the number of winding of input and output) to hundreds of thousands of Volts. Naturally, since output power must equal power input (minus losses), the AC current decreased in the same proportion[6].
Thus, super-high voltage and super-low current meant very low line losses irrespective of how far you needed to send it. Of course, very high voltage is dangerous for appliances, lights, and motors. With AC, however, once you get the power to the home, farm, or shop, a second transformer (on the utility pole) would step the voltage back down for use. The use of AC power continued until the demand for power became ever-increasing.

1.2.2 AC Versus DC

The current distribution system has been predominantly AC for a very long time. Considering DC systems to replace at least certain parts of the existing system would prove to be better with respect to many aspects. The most talked about advancement would be in the field of distributed generation and Micro-grids. The electric power systems has become increasingly distributed while trying to include more and more renewable energy resources. Clearly, some of the renewable resources such as Photo-Voltaic are inherently DC supplies and cannot be incorporated in the current system without power electronic interfaces.

The provision of energy storage is virtually non-existent in AC distribution systems but storage of DC energy in batteries is very practical. The DC distribution system will also minimize conversion losses incurred in the existing systems along the way [7].

In addition, DC offers greater capacity per power line, reducing the weight and size of power equipment throughout the grid and home, and can help to improve the reliability of power supplies as it is easier to control the voltage on DC lines. Thus the main benefits of DC based grids would be:

- Greater energy efficiency
- Higher power quality
- Smaller equipment
- Less complexity and lower costs

Though DC has more advantages over AC systems, some of the critical points that need to be addressed while using DC systems are the Voltage transformation,
Circuit breaker protection and Voltage stability. The voltage transformation in AC is possible with ease using transformers but similar function in DC systems can be quite complex while using DC converters[7].

The circuit breakers used in AC systems are more prominent and more developed in comparison to the existing technologies for DC systems. Some of the Trip Unit technologies used in DC circuit breakers are the Thermal-magnetic Moulded case Circuit Breakers (MCCB) and pneumatic-Magnetic MCCB. The usage of circuit breakers with electronic trip units is not possible for DC circuits since most of these use current transformers to sense currents[8].

The tripping time of the circuit varies in AC and DC systems. While interrupting a circuit, the inductance of the circuit stores energy that will expend itself through an electric arc during circuit switching or interruption. This is important mainly in DC circuits due to the absence of periodic zero voltage crossing, where a circuit breaker have higher probability of extinguishing a fault current arc. The key points that are necessary to extinguish an arc is to raise the voltage across the arc or by reducing the conductivity of the plasma region by decreasing temperature[8].

DC distribution clearly has lot of potential in terms of reliability and security of the system, energy efficiency and compatibility with multiple sources, load and demand side management. The use of DC microgrids (could be in any scale), and the practicality of such a system in today’s scenario where electronic loads are ever growing, can change the centralised generation and distribution of the power system to one that is more accommodating of the load and more flexible in terms of power generation.[9].

1.3 Existing Technologies

There has not been a lot of work done on implementing DC for homes. Some of the work done includes the development of a DC compatible plug by companies such as in reference[10], which addresses the issue of arcing. A magnetic circuit is used to spread the energy of the arc to enable extinguishing the arc easily. Additionally, apart from the commercial products, research has been done on reducing the transients by using effective snubber circuits across the plug and load side[11][12].

An arc fault is an unintentional arcing condition in an electrical circuit, which
may lead to fire hazards in case of sustained arc formation. The causes of arc formation are mainly due to damaged wires, breakdown of electrical insulation, overheating of cables and wires. Having identified the main problem, arc fault detection is not very simple. The key problems while detecting an arc is the current absorption in many appliances that are used in homes, that tend to mask or attenuate the arcing characteristics[13]. These reasons may allow arcing to go undetected, which is very crucial when using an Arc Fault Circuit Interrupters (AFCI).

Since in AC systems the arc can reappear every half cycle, understanding the behaviour of DC systems with respect to the time taken for arc formation and the time to failure of the system becomes necessary.

With the advent of power electronics and modern control strategies, more and more number of loads use rectified AC mains supply. The growing number of loads not only affect the power quality but are vulnerable to power disturbances. As mentioned in [14], power disturbance not only affects the loads but also the operation of the power systems. For example, harmonics can create erroneous reading in meters, can affect operation of devices and also lead to heating of cables as well as produce eddy currents in transformers. A thorough study on the usability of alternative power distribution in residential and commercial buildings has been done in [15]. Various loads such as electronic appliances are on the rise and are compatible with DC supplies. Additionally the AC line voltage creates current distortion and complicates the construction when using rectifiers to supply these loads.

Feasibility analysis of DC distribution systems is done in [3], in which the losses in cables with respect to the voltage chosen (48V, 120V or 230V DC) is calculated to estimate the ideal voltage standard to be chosen in order to ensure minimum modification of existing cables and architecture. This analysis helps study the importance of choosing the right voltage standard for a new DC distribution system.

DC switching is another main area of concern. The ideal switching scenario would be when there is a physical disconnect between the source and the load [11]. But practically this is not the case. The current continues to flow to the load by ionizing the air around the switch resulting in the formation an arc. In the real case, the wiring and the load have inductive behaviour. There is energy stored in these
elements, which refuse to change instantaneously with the opening and closing of the switch. The only way to dissipate this energy is through the arc formed across the switch, causing power loss. In AC systems the arc would ideally quench in the nearest zero crossing of the current wave, but DC systems would need an external aid to duplicate this behaviour.

Typically, allowing an alternative path for the inductive energy would solve the problem. Adding a snubber circuit as demonstrated in the work in reference [11] and [12] would be useful. There can be many drawbacks when including such a circuit in terms of the charged capacitor which continues to hold some voltage. This is not very desirable in terms of safety in homes, while accessing the outlets for plugging and unplugging loads. In most cases using a bleeding resistance would serve the purpose, but it also depends on the discharging time of the capacitor. The charging constant must be comparable to the time taken to plug-in or plug-out the load [11][16].

1.4 Objectives

The primary objective of this research is to propose a new and improved distribution systems for homes with very little modification to the existing AC system.

As a consequence, some the secondary objectives would be:

1. Improving thermal and electrical properties of the wiring
2. Improving switching characteristics
3. Better integration of various energy sources
4. Cost effective solution to using DC power
5. Incorporating Power line communication

1.5 Organisation

This work has been organized as shown below.

- Chapter 2 describes the characteristics of DC distribution systems and includes the application of DC distribution for Low voltage application, i.e.
DC homes. It also compares the existing system with the new system in terms of the loads, protection & control methodologies. The drawbacks of DC as a power source has been dealt with in detail in this chapter as well.

- *Chapter 3* emphasises on the design aspects and explains the experimental work carried out. The theory and implementation of DC systems for homes application has been addressed in this chapter. The electrical and thermal model comparison of the line parameters when using DC or AC source is clearly indicated along with verification experimentally.

- *Chapter 4* enumerates the results thus obtained while conducting tests on a home wiring system while using AC supply. These results have been simultaneously compared by substituting the source to a DC supply. Finally, the same set of tests were carried out when a modified cable is used in the home wiring set-up when supplying DC. Some conclusions and analysis are drawn based on these tests.

- *Chapter 5* concludes the results and developments of the research and describes the future scope and extension to this work.
A typical home runs its loads through AC supply. Considering a DC form of energy will bring about many changes in the existing homes. However, a DC source is more advantageous over AC as described in the following sections.

Today, energy is available from multiple sources, like utility, Photo-Voltaic panels, wind turbines, possibly a small gas turbine. There will also be energy storage in the form of batteries and probably thermal storage. Certainly much of the electrical energy will be produced and used in DC form, so a DC wiring system is a logical way of connecting the sources and the loads.

Considering the various factors mentioned in Chapter 1, using DC in power distribution will help in moving towards a more green and efficient system.

2.1 Design Aspects

While considering the hardware required and distributing energy around the building, there are several aspects that need to be evaluated. DC systems have been not very popular because of the high cost of controlling and protecting them; the main problem being arcing while switching. In DC applications no natural zero crossing exits, hence quenching the arc can be challenging.

In a house, portable loads are mostly used wherein electrical plugs become
inevitable. The electrical plug and outlet is similar to a switch. It has to be designed properly for the safety of the users as well as the loads. The absence of zero crossing in DC systems makes developing a switch a challenge [10].

2.1.1 System Topology

Conventional AC grids have many stages of conversion. The various components are: generating station, power transformer, transmission and distribution lines and automation devices.

The AC generated voltage is stepped-up and stepped-down in various stages. Initially the AC voltage is stepped-up before being fed to the transmission lines, to reduce losses while transmission. The voltage is again stepped-down at the receiving end, i.e. at the transmission substation. The AC voltage is further reduced using the distribution transformer before being fed to various low-voltage consumers. Thus the AC systems are bulky and have high conversion losses.

The topology of some of the existing DC systems can be evaluated before implementing a 400 V DC Distribution system, e.g. a typical data center, telecom center. In a data center, the high voltage AC line is stepped down and then converted to DC, to be able to be paralleled with Battery-Backup systems. The DC is then converted to high-voltage AC for distribution within the building, then converted yet again to low voltage DC and then to voltages for other low voltage circuitry using DC-DC converters. This has 4 stages of voltage conversion.

In the case of telecom systems, there are two major stages of voltage conversion, but each of these stages are quite inefficient. Firstly the AC voltage is converted to 48 V DC and combined with the back-up batteries, which is also provided to the DC-DC converters that can supply the local low-voltage circuitry.

2.1.1.1 HVDC Distribution Systems

Looking into an HVDC distribution system, the number of conversion stages are similar to that of a telecom center, but there is a large improvement in the system reliability and conversion. The AC voltage is rectified to 380 V-DC (nominal) voltage, with a battery back-up operating at the same voltage. The DC voltage is then distributed to various low-voltage loads through DC-DC converters. This
The system can draw power from AC grid, the batteries and also be integrated with other renewable sources such as wind and solar depending on the power demand. The concept of HVDC and protection have been ventured into since a very long time. The Reference [17] talks about the principle and usability of the DC circuit breakers.

### 2.1.1.2 Choice of Voltage Standards

The choice of voltage and phase configuration determines the ease with which the current system can be modified to suit the DC system. The cost of conversion from an AC system as well as the compatibility to existing loads are important factors[11]. Sticking to the current voltage standards will reduce the cost of wiring, cost of conversion of voltages and enable working with existing loads.

A lot of research has been done on finding the optimum voltage standard for DC distribution, keeping in mind the voltage of distributed energy sources (which is smaller than the existing AC voltage standards). Choosing a high voltage can have issues relating to safety while choosing a low voltage can lead to major power loss in cables. Based on the two important criteria of ”Voltage Drop” and ”Power Loss”, the voltage standard and a suitable area of cross section of the cable has been evaluated in Reference [5].

### 2.1.2 Protection

A conventional AC circuitry has circuit breakers and fuses provided for the purpose of protection and isolation.

In a DC system, some protection is provided by the AC system circuitry that feeds it but additional protection circuit breakers and controls have to be provided for each DC sub-circuit. The main disadvantage when it comes to DC system is DC switching; AC current periodically passes through a zero crossing making it easier to extinguish arcs at current zero. Thus it becomes a costly and risky affair to install DC switches, circuit breakers and fuses which are difficult to design for very high voltages.

Apart from switching protection, protection from over current must also be explicitly provided for DC circuits due to the absence of current limiting transformer.
reactance as in case of AC circuits.

2.1.3 Types Of Loads

Most types of loads that exist in homes operate on existing voltage standards and are easily suitable to DC systems. The common types of loads are explained below.

2.1.3.1 Fluorescent Lighting

The use of fluorescent lights are known to be energy efficient when compared to conventional incandescent lights. The efficiency of fluorescent lights is increased further by using an electronic ballast. These ballasts basically improve the light output per watt of power. A typical electronic ballast has an inbuilt rectifier that rectifies the input AC voltage to DC and then it is converted to high frequency, which implies that usage of DC input would cut down the cost of the ballast while controlling harmonic distortion that would otherwise affect the power system [11].

The common phenomenon of ”flickering” of fluorescent lights is due to the oscillating nature of AC power. The high frequency ballast producing double AC line frequency components can be eliminated when DC input is used instead. The flicker is affected by the power quality, i.e. the continuity of power, variation of voltage magnitude, transients and harmonic content in AC power [11]. This will no more be an issue when dealing with DC.

2.1.3.2 Motor Load

Currently, the motor driven appliances contain an inbuilt inverter. The ability to control the motor based on the usage is provided by this inverter. Typically, a AC-to-DC converter is connected to a DC-to-AC converter to connect to the motor. The DC-to-AC converter helps in controlling the characteristics of the inverter. Thus to modify such loads to work with DC would be as easy as eliminating the AC-to-DC converter stage [10].

For instance; Various day to day household loads, like washing machines, that run on motors use a DC link that supply a stiff voltage to the variable frequency drive. The front end has a rectifier supplying the DC link giving a pulsed input current to the inverter. Using a DC source would eliminate the DC link filtering
and the need for a rectifier, although pulsed current will still be drawn from the
supply by the inverter. It will be interesting to study what would happen if the
inverter input capacitor were to be supplied directly from transmission line. There
would be a potential inrush current at the beginning and perhaps an inductor would
still be required at the input to draw a smooth current[10] [11] [18].

2.1.3.3 Electronic Loads
The common day-to-day electronic loads such as computers, television, mobile and
laptop chargers etc., mostly consume low DC voltage (about 3.3 V). There exists
an AC-to-DC converter fed to a DC-to-DC converter to step-up or step-down to the
necessary voltage levels to match the load requirements. Hence, these electronic
loads having a diode bridge supplying a high frequency inverter, can instead be
powered by DC too. But a similar issue with regard to the inverter input current
arises.

2.1.4 Other Advantages
The presence of transients in terms of harmonics (due to 60 Hz oscillation) can
cause interference with neighbouring communication lines. The power-line com-
munication can be interfaced more easily when using a DC input [11].

Another very common phenomenon of audible noise in fluorescent ballasts
and transformers that include magnetic components. This is due to the vibration of
metallic components at 60/120Hz due to the AC voltage oscillation. These heating
elements experience a "humming" noise with AC excitation due to the pulsating
forces between adjacent current carrying wires. No such problem exists in DC
systems.

There have been some health concerns due to the electric and magnetic fields
associated with AC transmission. The World Health Organisation gives statistics
on the magnitude of AC and DC magnetic field effect on human health [19]. These
statistics imply that there exists no such adverse effects on health when exposed to
static DC magnetic fields.
2.2 Transmission Lines

The effects of transmission lines affect the transfer of signal from the sending end to the receiving end. An experimental set-up similar to the panel for homes was fabricated to carry out tests to study switching behaviour of home distribution system. The set up conformed to all the rules as listed on the Canadian electrical code [20]. It was powered by the power supply i.e. 1φ 120V AC supply, which is the distribution level voltage standard in North America. The testing was aimed to provide important observations with regard to transmission line effects while using DC power over AC, and based on various load characteristics.

2.2.1 Transmission Line Effects

The transmission cable used in the experiment has a specific material and length that causes it to exhibit certain non-ideal characteristics. The material of the cable determines the velocity of propagation, but in addition to that, the cable behaves similar to a “transmission line” which brings in various other factors in the picture. Some of the effects that can be taken into account using the transmission line theory include the signal reflections and the associated reflection noise, cross-talk between closely spaced traces, simultaneous switching noise due to inductance in the power supply path connecting active drivers (this is of major concern especially when using DC source for reasons mentioned previously). In signal and systems terminology, these non-ideal effects are referred to as signal integrity, since the desired signal is corrupted by these effects as explained in the reference [21].

2.2.2 Transmission Line Parameters

The transmission line has various line parameters that can be determined from the physical properties, i.e. geometry and material, of the line. The propagation velocity can be calculated by considering the material properties, i.e. relative permittivity and permeability with respect to those of air. The dimensions of the line play no role in the velocity of an electrical signal. The relevant formulae are presented in Equation 2.1.

The other line characteristics involved are the characteristic impedance of the line. This is the intrinsic impedance offered by the line to the flow of signal. Unlike
the propagation velocity, the impedance depends on the geometry as well as the
material properties[21]. The calculations involved are mentioned in Equation 2.2 
& 2.3

During these reflections, there may be instances where the voltage at the load
may reach beyond the applied voltage due to positive reflection constant. The time
required to propagate also determines the time taken for the signal to reach steady
state which depends on the propagation constant. The line parameters are calcu-
lated by using the formulae below (Assuming zero resistance line). Propagation
Delay can be calculated as shown in Equation 2.4.

The Transmission line parameters appear as inductance, capacitance and re-
sistance. The propagation constant is used to describe this characteristic and is
shown in Equation 2.6. The resistance is offered by the geometry of the cable, as
mentioned before. But the inductance of the line is due to the current flowing in
the conductor. The flow of current induces a magnetic field which is varying sinu-
soidally with the voltage. Thus a varying magnetic field produces an Electromotive
force (EMF) which opposes the current flow in the line and appears as the inductive
effect on the line.

A conductance parameter arises in the line due to the leakage current that flows
from the conductor to the ground. In most cases, this is neglected. But there is a
potential difference between the phase conductors which gives rise to an electric
field. These lines act similar to the parallel plates of a capacitor. This arrangement
gives rise to the capacitance parameter of the transmission line.

2.2.3 Equations

The main line parameters of a transmission line are the velocity of propagation,
Characteristic impedance, Time Delay and the Propagation constant as explained
previously. The equations of the line parameters are listed below in detail[1]

**Velocity of propagation**

The velocity of propagation, also called wave propagation speed or velocity factor

\[ V = \sqrt{\frac{Z_0}{\mu_0 \varepsilon_0}} \]

where, \( L = \text{Inductance per unit length} \) & \( C = \text{Capacitance per unit length} \)

\( D = \text{Length of the cable} \) & \( R = \text{Resistance per unit length} \)

\( G = \text{Conductance per unit length} \) & \( w \) is the angular frequency defined as \( w = 2\pi f \), \( f = \text{frequency of signal} \), \( i \) is the imaginary unit

---

1 where, \( L = \text{Inductance per unit length} \) & \( C = \text{Capacitance per unit length} \)

\( D = \text{Length of the cable} \) & \( R = \text{Resistance per unit length} \)

\( G = \text{Conductance per unit length} \) & \( w \) is the angular frequency defined as \( w = 2\pi f \), \( f = \text{frequency of signal} \), \( i \) is the imaginary unit
of a transmission medium is the ratio of the speed at which a change of the electrical voltage on a copper wire passes through the medium, to the speed of light in a vacuum [22].

\[ v = \frac{1}{\sqrt{LC}} \text{m/s} \quad (2.1) \]

**Characteristic Impedance**

The characteristic impedance or surge impedance (usually written \( Z_o \)) of a uniform transmission line is the ratio of the amplitudes of voltage and current of a single wave propagating along the line; that is, a wave travelling in one direction in the absence of reflections in the other direction. The general expression for the characteristic impedance is [23]:

\[ Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \Omega \quad (2.2) \]

The terms are defined in the footnote defined at the end of this page. For a lossless line, \( R \) and \( G \) are both zero, thus the Equation 2.2 reduces to:

\[ Z_o = \sqrt{\frac{L}{C}} \Omega \quad (2.3) \]

**Propagation Delay**

Propagation delay, as it relates to transmission lines, is the length of time it takes for the signal to propagate through the conductor from one point to another [24].

\[ TD = \frac{D}{v} \text{sec} \quad (2.4) \]

**Propagation Constant**

\( \gamma \) is the propagation constant and is defined as the ratio of amplitude at the source of the wave to the amplitude at a certain distance (say \( x \)) such that [25]:

\[ \frac{A_o}{A_x} = e^{\gamma x} \quad (2.5) \]

\( \gamma \) is a complex quantity and has a real part \( \alpha \) and an imaginary part \( \beta \). The real part \( \alpha \) is called “attenuation constant” and the imaginary part \( \beta \) is called the “phase
constant \[^{[2]}\]

\[ \gamma = \alpha + i\beta = (R + i\omega L)(G + i\omega C) = \omega \sqrt{LC} \] (2.6)

### 2.2.4 Types Of Transmission Lines

Looking into the various types of transmission lines, there are the parallel plate type line, micro strips, regular two wires/ twin lead cables, coaxial cables. In the experiments, the types of cables used are the regular two wire type cables (house wiring cables). Some of the analysis done using a modified cable is similar to the parallel plate type cable. The types are shown in the book [21] and the two main types that are being used in this thesis has been reproduced with guidance from the book, in Figure 2.1.

\[ L = \mu \frac{D}{w} \]

\[ C = \varepsilon \frac{w}{D} \]

\[ L = \frac{\mu}{\pi} \cosh^{-1}\left(\frac{D}{2r}\right) \]

\[ C = \frac{\pi \varepsilon}{\cosh^{-1}\left(\frac{D}{2r}\right)} \]

**Figure 2.1:** Common Types of Cables

---

\[^{2}\]where, \( \gamma \) = Propagation constant, \( \alpha \) = attenuation constant & \( \beta \) = phase constant

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2.2.5 Termination Schemes

When a signal propagates along the transmission line, it causes a wave to start to travel down the transmission line. For a DC signal on the line, this would be a voltage or current wave. The amplitude of the wave is depicted by the line impedance of the line and the impedance at "input" or "generator" end and the "load" end. The difference in this impedance causes reflections of the waves back and forth.

If the line is unloaded, i.e. open circuited, the voltage would produce reflections while the current would be zero; while in case of a short circuit, the voltage would be zero but the current across the load would be non-zero. In each case, after a couple of reflections, the voltage and current approach their steady-state values. The reflections of the voltage and it’s propagation through the line is shown in figure 2.2. This figure was taken from a supplementary material prepared for a book as cited in Reference [2]. The cause of these reflections is when a finite

---

**Figure 2.2**: Transmission lines: (a) Short-circuited; (b) Open-circuited. Adapted from [2]
length transmission line in not terminated in its characteristic impedance. The extreme case would be when the far end is short-circuited. The explanation for the short circuit situation is demonstrated in figure a) in [2.2]. Initially, the source voltage (or the driver), views the line’s characteristic impedance and send across a voltage wave of \( V_{\text{src}}/2 \) (Refer figure [2.2]). As the wave propagates across the line and reaches the end at time \( T \), it views the short circuit. Thus to satisfy the kirchoff’s laws, a voltage wave propagates in the opposite direction, to cancel the original waveform. The far end will have the reflected original wave, and a short circuit is observed at time \( 2T \).

Another type of termination is the open-circuit, which is demonstrated in Figure b) in [2.2]. In the beginning, this case is similar to the short-circuit case explained previously. But when the wave hits the far end at time \( T \), the current has nowhere to go and hence a voltage of the same amplitude propagates back, adding to the original voltage. Twice the voltage \( V_{\text{src}}/2 \) is observed at the driver side at time \( 2T \). These reflections occur both at the near end as well as the far end of the line, if the source impedance (\( R_{\text{src}} \)) does not match the line impedance (\( Z_0 \)).

The turning "on" and "off" of switch in a room connected to an incandescent bulb exhibits the reflection phenomenon as well. The movement of electrons along the wire is governed by the impedance mismatches along the cable. The resulting current is perturbed due to mismatches either at source or the load end, causing reflections. In the practical sense, these reflections usually last for a very short period of time (in nanoseconds) and hence can be ignored. But in certain cases, these reflections can cause significant amount of transients, causing power losses in forms such as heat dissipation.

The termination of the line is very crucial is depicting the reflections in the line. The correct termination scheme can eliminate the severe mismatches and this process of eliminating the reflections is known "Impedance matching". There are various effective transmission schemes, e.g. diode termination that gives flexibility while allowing to connect a load at the line end keeping the reflections minimum.

Terminating the line with a non-resistive load, or reactive terminations can have a different effect on the transient. In the real scenario, most line terminations contain some reactance, like shunt capacitance or series inductance[21].
2.3 DC Switching

One of the most important safety requirements while implementing DC system is the quenching of arc while switching and prevention of the re-striking of arc. The main reason for the formation of arc is due to the stored energy in the inductive element on both source and load end. There needs to be a way to either store or dissipate the \( \frac{1}{2}L_i^2 \) component of the inductive elements on both load and source sides.

Direct current presents a different problem than alternating current with regard to phenomena associated to the interruption of high value currents since arc extinction results to be particularly difficult. This problem is more prominent in DC systems since AC systems can normally quench the arc in the subsequent zero crossing of the current. This is due to the oscillatory nature of the AC voltage. Some of the stored energy in the inductive element gets dissipated in the arc and the rest can return to the source and the load. The ionization of the air could continue to next half cycle, but by this time the switch leads must be far enough to be able to re-strike. In the case of DC systems there exists the possibility of sustained arc because of the absence of natural zero-crossing of the current. Figure 2.3 shows the circuit elements in a typical DC circuit indicating the storage elements, source & load inductance. The steady-state equation of the circuit shown is described below.

\[
L \frac{di}{dt} = U - Ri - U_a \tag{2.7}
\]

To guarantee arc extinction, it is necessary that:

\[
\frac{di}{dt} < 0 \tag{2.8}
\]

Equation 2.8 implies that for the arc to be extinguished, the \( U_a \) (arc voltage) must be higher than the \( U \) (source voltage) such that equation 2.7 becomes negative. The extinction time of a direct current is proportional to the time constant of the circuit, \( \tau = \frac{L}{R} \) and also to the extinction constant. The extinction constant is a parameter that is dependent on the arc characteristic and the circuit supply voltage \([26]\).

\[3\] where \( U \) is the rated voltage, \( L_s \) is the source inductance, \( L \) is the load inductance, \( R \) is the resistance of the circuit & \( U_a \) is the arc voltage
Figure 2.3: DC Switching

The second sub-figure under figure 2.3 is a generic DC switch circuit with a decoupling capacitor $C_1$ which helps in closing of the switch and a flywheel diode $D_1$ across the $R - L$ load. The capacitor $C_2$ is pre-charged to the line voltage, thus at the instant of opening of the switch, the source voltage is impressed upon it, forcing the current across the switch to zero. The key element in the design is that for a given load or overload current the capacitor voltage must fall at a rate compared with the switch blade opening such that the switch voltage is always less then the ionization voltage of the air [11].
Chapter 3

Modelling And Design

According to the electrical installation guide [27]. Low-Voltage installations are usually governed by a number of regulatory and advisory texts. Based on these texts, the voltage ranges in North America have been defined based on the National Electrical Code (NEC)[1] voltage standards and recommendation. The common nominal voltages (three-phase four-wire or three-wire systems) are 230/400V or 380/660V in many countries like Europe[27][29]. The electrical Installation Guide is based on relevant International Electrotechnical Commission (IEC)[2] standards[20].

The power distribution utility connects Low Voltage (LV) neutral point to its MV/LV distribution transformer to earth. All LV installations must be protected by Residual Current Device (RCD) and all exposed conductive parts must be bonded together and connected to earth[27]. A residential wiring system usually includes a meter and in some cases an incoming supply differential circuit-breaker which include over-current trip.

---

1NEC, or NFPA 70, is a regionally adoptable standard for the safe installation of electrical wiring and equipment in the United States. It is part of the National Fire Codes series published by the National Fire Protection Association (NFPA), a private trade association [28].

2IEC is a non-profit, non-governmental international standards organization that prepares and publishes International Standards for all electrical, electronic and related technologies collectively known as "electro-technology" [30]
3.1 Electrical Model Of Transmission Line

The behaviour of a cable can be modelled as a transmission line. As explained in the previous sections, we can model a line using the per unit Capacitance and per unit Inductance. The line model is shown in Figure 3.1. The model shown was developed using Powersim (PSIM) software. Additional parameters of $R_{ser}$ and $R_{par}$ are taken into account for line losses. The line parameters are:

1. The series inductance that arises due to the emf produced by a varying magnetic field.
2. The shunt capacitance arising due to the voltage difference between the phase conductors.
3. Series resistance offered by the material and geometry of the line itself.
4. Shunt resistance or conductance developed by the leakage current that flows from the line to ground.

![Figure 3.1: Transmission Line Model](image)

The main problem that arises due to these parameters is arcing while switching (refer [2.3]). To reduce these effects, we need to minimise the transients in the line. This is done by reducing the impedance offered by the line. The main objective of modifying the existing wire would be to reduce the inductance of the wire and increase the capacitance, to effectively reduce the line impedance.

3.1.1 Equations

The equations used for this analysis are listed below. For the regular conductor with the circular cross-section the calculation of the capacitance of the 14AWG wire can
be calculated based on the equations described in Section 3.2.2. The dimensions and configuration is explained in Figure 3.2.

**Figure 3.2: Cable Cross-section**

### 3.1.1.1 Pair of Conductors with Circular Cross-section

The ordinary 14/2 cable used for home wiring is the NMD90 14/2 Romex cable with a specified insulation thickness as listed in Reference [31]. Wire types for North American wiring practices are defined by standards issued by Underwriters Laboratories, the Canadian Standards Association, the American Society for Testing and Materials, the National Electrical Manufacturers Association and the Insulated Cable Engineers Association. The common insulation type used is XHHW where XHHW stands for “XLPE (cross-linked polyethylene $\varepsilon_r = 2.25$ [32]) High Heat-resistant Water-resistant”. XHHW is a designation for a specific insulation material, temperature rating, and condition of use (suitable for wet locations) for electrical wire and cable [33][34][35].

The inductance of the pair of cables can be calculated as described in equation 3.1. It can be seen that the calculations are done for a 12AWG cable instead of the 14AWG. This is because of the inability to construct a flat cable with the same cross sectional area as the 14AWG, due to the unavailability of tapes of convenient dimensions. Though there are a variety of tapes of varied thickness and width, the one that had the exact match to the commonly used twin wire cables was the 12/2
cable. The calculations are provided in the appendix section to verify the above observation (refer Appendix:A.1). 3

The type of cable is the two wires/twin lead type of cable, where the conductors (live and neutral) are placed side by side with insulation around each conductor as well as a jacket around the whole assembly. The equations used are used from a reference book for transmission lines [21] [38].

\[ L = 4 \times 10^{-7} \cosh^{-1}\left(\frac{D}{2r}\right) H/m \]  \hspace{1cm} (3.1)

The capacitance of the pair of cables can be calculated from the equation [3.2]

\[ C = \frac{\pi \varepsilon}{\cosh^{-1}\left(\frac{D}{2r}\right)} F/m \]  \hspace{1cm} (3.2)

The dimensions of the cables are mentioned as used in the calculation later in the chapter.

3.1.1.2 Parallel Plate Type Conductors

Along similar lines, the line parameters of the parallel plate type or the modified flat type cable needs to be calculated. It is quite obvious that this type of design would increase the capacitance between the pair of cables, since they behave like the plates of a parallel-plate capacitor. Hence the equations would be similar to the capacitance equations for two parallel plates.

Clearly, the capacitance of the cables is much higher than the regular type of cables but the inductance might not be significantly lower. But the effect of increased capacitance and almost the same inductance might have a large influence on the transient characteristics of the cable.

To verify the above assumptions, the line parameters were calculated for a cable that is designed to have:

1. Equal cross-sectional area as that of the conventional cable: to ensure the same current rating as that of the regular cable.

---

3 where, \( r = \) radius of the conductor (12AWG wire of 0.08” mm)
\( D = \) distance between the conductors = 2.38 mm
\( \varepsilon = \varepsilon_0 \times \varepsilon_r = 8.85 \text{pF/m (Permittivity of Vacuum) } \times 2.25 \) (Relative permittivity of Polyethylene[32])
2. Same insulation thickness around the cable: to adhere to the insulation rules as stated in electrical guides such as References [31],[36] and [37].

3. Maximum width while maintaining the same area of cross section: to allow better electrical and thermal characteristics. Thus the cable can be made as thin as possible depending on the convenience of fabrication and also installation.

In our study we have considered a width suitable to be fabricated using available flat wire strips, while ensuring improvement in electrical and/or thermal characteristics. The equations for inductance and capacitance of the cables are listed below.

\[ L = \frac{\mu_0 \times D}{w} H/m \]  \hspace{1cm} (3.3)

\[ C = \frac{\varepsilon \times w}{D} F/m \]  \hspace{1cm} (3.4)

The dimensions of the cables are mentioned as used in the calculation later in the chapter.

3.1.2 Existing Wire Parameters

To study the wire parameters of a regular cable, the parameters were measured to analyse the magnitude of the line parameters. These parameters are quite insignificant over a short transmission distance, but in homes and other applications, the length of the cable is not negligible.

The common wire gauge used for homes is 14 American Wire Gauge (AWG). The diameter of such a wire is around 1.62\text{mm} in diameter with a RW90 Cross-linked polyethylene (XLPE) insulation of 0.030\text{”} (0.76\text{mm}) thickness[36][37]. The dimensions are shown is Figure 3.2.

\[ \text{where,} \ w = \text{width of the conductor} (L \times w = \pi r^2) \]
\[ \text{Taken} \ w = 0.01\text{”}; \text{implied} \ L = 0.5\text{”} \]
\[ D = \text{distance between the conductors} = 0.09\text{”} (2w + 2 \times \text{insulation thickness of 0.03\text{”}}) \]
\[ \mu_0 = 0.4\pi \mu H/m \ (\text{Vacuum Permeability}) \]
\[ \varepsilon = \varepsilon_r \times \varepsilon_r = 8.85 \times 2.25 \ (\text{Permittivity of Vacuum}) \times 2.25 \ (\text{Relative permittivity of Polyethylene[32]}) \]

---

\[ 4 \text{where,} \ w = \text{width of the conductor} (L \times w = \pi r^2) \]
\[ \text{Taken} \ w = 0.01\text{”}; \text{implied} \ L = 0.5\text{”} \]
\[ D = \text{distance between the conductors} = 0.09\text{”} (2w + 2 \times \text{insulation thickness of 0.03\text{”}}) \]
\[ \mu_0 = 0.4\pi \mu H/m \ (\text{Vacuum Permeability}) \]
\[ \varepsilon = \varepsilon_r \times \varepsilon_r = 8.85 \times 2.25 \ (\text{Permittivity of Vacuum}) \times 2.25 \ (\text{Relative permittivity of Polyethylene[32]}) \]
3.1.3 Proposed Modification

When considering the flat wire configuration (laminated cable), it can be compared to that of a parallel plate capacitor; one plate being the live wire and the other being the neutral wire with a dielectric medium of the insulating material between them. Clearly, this creates a uniform high capacitance along the length of the transmission line reducing the inductive nature of the wires. Such a cable has a convenient geometry when being used to mount on flat surfaces like walls of a home.

The calculations for the electrical parameters rectangular cross sectional wire were done based on the equations for design of a micro-strip for Printed Circuit Board (PCB) (Printed Circuit Boards). The PCB have the similar problem of switching transients where the transmission line model displays wave characteristics. These boards have signal interference among neighbouring cables which are etched on the same plane. A similar characteristic can be adopted while modelling a flat cable wire, in which the conductor will be a copper sheet with the same insulation thickness (according to the NEC standards) for a 14AWG wire. The results are tabulated in Table 3.1 and Table 3.2.

<table>
<thead>
<tr>
<th>Table 3.1: Line parameters of Regular Cable (Refer 3.1.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line Parameters</strong></td>
</tr>
<tr>
<td>Formula</td>
</tr>
<tr>
<td>Calculated Value</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.2: Line parameters of Modified Cable (Refer 3.1.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line Parameters</strong></td>
</tr>
<tr>
<td>Formula</td>
</tr>
<tr>
<td>Calculated Value</td>
</tr>
</tbody>
</table>

3.1.4 Experimental Verification

A 50 feet long cable was used when fabricating the hardware set-up. This length of wire that was chosen accounted for the parasitic involved in a two-storied home.
With the aim of verifying the theoretical values for the line parameters, they were measured using an impedance meter, by conducting the open circuit and short circuit tests. Using the cable, the inductance and capacitance per meter length were derived. The results of the total inductance and capacitance are as tabulated in Table 3.3.

The per unit parameters can be calculated easily by dividing the total value thus obtained by the 50 ft (15.24 m) of wire which were verified to be matching to those obtained theoretically, as tabulated in the previous Tables 3.1 and Table 3.2. The calculation assumed a lossless line, but in real case there exists a series impedance and a conductance.

Table 3.3: Measured Parameters Of Regular Cable

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Circuit Test</td>
<td>$L_s$</td>
<td>0.41 $\mu$H/m</td>
</tr>
<tr>
<td></td>
<td>$R_s$</td>
<td>12.55 $m\Omega$ /m</td>
</tr>
<tr>
<td>Open Circuit Test</td>
<td>$C_p$</td>
<td>47.88 $pF$ /m</td>
</tr>
<tr>
<td></td>
<td>$R_p$</td>
<td>86.41 $M\Omega$ /m</td>
</tr>
</tbody>
</table>

Table 3.4: Measured Parameters Of Modified Cable

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Circuit Test</td>
<td>$L_s$</td>
<td>0.88 $\mu$H/m</td>
</tr>
<tr>
<td></td>
<td>$R_s$</td>
<td>37.07 $m\Omega$ /m</td>
</tr>
<tr>
<td>Open Circuit Test</td>
<td>$C_p$</td>
<td>82.78 $pF$ /m</td>
</tr>
<tr>
<td></td>
<td>$R_p$</td>
<td>84.23 $M\Omega$ /m</td>
</tr>
</tbody>
</table>

3.1.5 Summary

To summarize the values obtained for the line parameters using the well-known formulae and to verify with those obtained from the test results using the Inductance(L), Capacitance(C), Resistance(R) (LCR) meter for the cables, the data has been tabulated in Tables 3.5 & 3.6.

From the values summarized, it can be observed that there is an improvement in the line parameters of the modified cable, and has higher capacitance between the lines. This means that this modified line model is better in transmission of voltage along the line, resulting in improved transient characteristics (reduced reflection and peak overshoot) in the line. In other words, the line model now offers smaller
Table 3.5: Regular Cable Summary

<table>
<thead>
<tr>
<th>Line Parameters</th>
<th>Inductance</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>0.46µH/m</td>
<td>53.98pF/m</td>
</tr>
<tr>
<td>Measured</td>
<td>0.41µH/m</td>
<td>47.88pF/m</td>
</tr>
</tbody>
</table>

Table 3.6: Modified Cable Summary

<table>
<thead>
<tr>
<th>Line Parameters</th>
<th>Inductance</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>0.18µH/mm</td>
<td>110.62pF/m</td>
</tr>
<tr>
<td>Measured</td>
<td>0.88µH/m</td>
<td>82.77pF/m</td>
</tr>
</tbody>
</table>

line impedance when compared to the one with lower capacitance per unit length of cable.

Commenting on the error margin between the calculated and the theoretical values, it can be seen from Table 3.5 that the values are very close to each other. But when looking at Table 3.6, there’s quite a bit of variation in the measured and calculated values. The cause of error in the modified cable measurements could be either due to the mechanical construction or due to errors during measurement.

The flat cable was fabricated by placing the insulation layer by layer on the conductor strips such that the insulation layers were sandwiched between copper conductor plates.

1. While placing the layers of insulation and the copper tape, there could have been air bubbles in between the layers which modifies the medium in between the conductors.

2. Due to human error while placing the insulation, there could have been certain areas of the conductor that might have been exposed without any insulation.

3. The insulation coating around the flat copper strips was done using a double sided adhesive insulation tape. This is an acrylic adhesive of unknown relative permittivity \( \varepsilon_r \) and could be acting as an additional insulation jacket thus modifying the electrical properties of the cable.
3.2 Thermal Model

Thermal behaviour of the cables is attributed to the material of the cable components; the conductor, the dielectric and the sheath losses. The conductor is usually made of a single copper wire or many thin strands of copper twisted to form a strand of wire. The insulation jacket surrounds the conductor pair, generally with a ground copper wire running along the center. The insulation is made of Nylon or Polyvinyl Chloride (PVC).

The cable carrying current tend to dissipate power through heat. The insulation is designed to withstand a minimum temperature rise caused by these current carrying conductors. The ampacity of a 14 AWG (American Wire Gauge) wire is about 20 amps, in which some of the power is used in heating of the conductor. Ideally this heat, that causes temperature rise in the conductor, would be uniform throughout the copper material whereas the insulation would have a non-uniform heat flow depending on the proximity of the heat source. To summarize, the conductors are single point heat sources and the dielectric medium distributes heat along the length of the cable.

3.2.1 Thermal Model Design

The thermal model of a cable is as significant as the transmission line model. The thermal characteristics can be modelled as shown in Figure 3.3. A current carrying conductor emits power in the form of $I^2R$ loss, which is converted to the form of heat. The insulation is affected by the heat loss emitted by the conductors. The insulation as well as the geometry of the conductor can determine the efficiency of heat transferred into the environment.

The thermal model shown in the figure is for a two conductor model, with $J$ being the heat source, i.e. the current carrying conductors, and $Rth$ being the thermal resistance offered by the insulation material. $T_A$ is the ambient temperature and $T_1$ and $T_2$ are the temperatures at the two conductors.

3.2.2 Equations

The thermal resistance of the insulation (or conduit), made of PVC, has thermal resistance of $k = 0.51W/mK$. The thermal resistance is calculated as shown in
Ambient Temperature: $T_A = 20^\circ C$ (Refer Figure ??)

**Figure 3.3:** Thermal Equivalent Model

![Thermal Equivalent Model](image)

**Ambient Temperature:** $T_A = 20^\circ C$ (Refer Figure ??)

**Figure 3.3:** Thermal Equivalent Model

\[ R_{th} = \frac{L}{k \times A} \]  

(3.5)

where $k$ is the thermal conductivity of the insulator material, $L$ is the length of the flow of heat (i.e. Diameter of cross section in this case) and $A = 2\pi r^2 l$ ($l$ is the length of the cable) is the area of the curved surface. For the proposed flat cable, $L$ will be the breadth of the cross section of the conductor and $A = l \times b$ will be the area of the lateral side.

The electrical resistance of the cable is given by a similar formula shown in

\[ R_{th} = \frac{L}{k \times A} \]  

$^5$considering: $k = 0.51 W/mK$ (for Polyethylene insulation)
equation 3.6.

\[ R_e = \frac{\rho \times L}{A} \tag{3.6} \]

where \( \rho \) is the Electrical resistivity of the conductor material, \( l \) is the length of the cable, \( A \) is the area of cross section depending on the geometry of the cable.

The power loss in the cable can be equated to the temperature rise in the insulator due thermal resistance offered by it (refer equation 3.7).

\[ J = \frac{V^2}{R_e} \tag{3.7} \]

\[ T = T_A + (J \times R_{th}) \tag{3.8} \]

Using the above equations, the temperature of the conductor can be calculated as in equation 3.8. Below are the calculated results in table 3.7.

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Temperature((^\circ)C)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular cable</td>
<td></td>
<td>Modified cable</td>
</tr>
<tr>
<td>Live Conductor</td>
<td>21.80</td>
<td>21.80</td>
</tr>
<tr>
<td>Neutral Conductor</td>
<td>21.80</td>
<td>22.77</td>
</tr>
</tbody>
</table>

### 3.2.3 Verification Of Model

The Thermal behaviour of the two conductors was analysed using Elmer software package. Elmer is an open source modelling software and is very handy is carrying out simple thermal modelling for the purpose of research[39].

The temperature distribution was modelled based on the resistivity of the copper in the conductor and the thermal resistance of the PVC (Poly-vinyl Chloride) insulation.

Figure ?? is the cross section of the flat cable such the conductors are placed above each other. The sub-figure (a) is the cross section of the regular cable where

\[^6\text{considering}: \rho = 1.68 \times 10^{-8} \text{ (for copper conductor)}\]

\[^7\text{Ambient Temperature: } T_A = 20^\circ \text{C}\]
the conductors are placed side by side. The ground wire runs in between the live and the neutral wire.

The maximum temperature of the cables shows improvement in the model. Additionally, the heat distribution in the flat cable is much more efficient owing to the larger surface area.

Figure 3.4: Thermal Model of Cross-section of Cable

3.3 Hardware Set-up

Power is distributed to residences and cottages through overhead wires or underground cables. The service supplied is a three-wire service consisting of two live conductors and a neutral wire. Three-wire service provides 120 V, 120/240 Volts and 240 Volts capabilities. In North America, individual residences and small commercial buildings will usually have three-wire single-phase distribution, often with only one customer per distribution transformer. Standard frequencies of single-phase power systems are either 50 or 60 Hz. Single phase is commonly divided
in half to create split-phase electric power for household appliances and lighting. Since all the voltages in a 1φ phase supply vary in unison, a revolving electric field cannot be produced unlike the 3φ voltage supply. Thus motor loads are not self starting and a single phase motor would require an additional circuitry for starting.

3.3.1 Materials Required

The standard way of measuring the thickness of a wire is AWG. It indicates the thickness of the wire only (not including the insulation).

The wiring of homes generally use Multi-conductor cables. These are basically cables consisting of two or more conductors. The general house wiring would have two insulated conductors, for the live and the neutral, and one bare copper conductor for the grounding. Such a cable is referred to as the “14/2 with ground cable”, since the cables are 14 AWG thick conductor pair.

The commonly used wire sizes for wiring in homes are 14, 12, 10, and 8 AWG conductors. Thickness of the conductors determines the current rating of the cables, and is decided based on the amperage required for a particular circuit, which is determined by the connecting load in case of home applications. For eg: A 14 AWG wire can be used for 15 Amp circuits such as supply loads like receptacles and switches.

A higher amperage would mean a thicker cross sectional area and lower AWG; for example, a 12AWG wire is used for 20A circuits and so on. Thus the current rating of a cable is known as the Ampacity and is defined by the NEC as the maximum amount of electrical current a conductor or device can carry before sustaining immediate or progressive deterioration.

The switches used in the wiring uses a single pole switch that is used to control a light or an outlet from one location only. Other types of switches used are the three-way switches and the four way switches based on the number of control points.

The house wiring requires the installation of receptacles (outlets) and must be of good quality in areas where there is usage of outlets constantly.
3.3.2 Implementation

Based on the 2012 Residential Wiring guide and the North American Electrical codes, the wiring of a panel of a home wiring set-up was modelled as shown in figure 3.5. The set up shown was done using the regular 14 AWG wiring. A modified flat type cable was designed to carry out tests for similar conditions. The flat cable was insulated and tested using DC signal to analyse the transient characteristics of the cable, the results of which are shown in Chapter 4. The modified cable and the measurement and test set-up are shown clearly in figure 3.6.

The input plug was given either an AC/DC signal using the 120V power supply/Laboratory DC power supply. The house set-up included one mechanical switch and one plug outlet to observe the transient response under various conditions.

The mechanical switch is the standard switch used for homes and buildings. The switching action while constant turn-off or turn-on action over time can cause damage to the properties of the mechanical contact. These switches seem to have an inbuilt snubber circuit to prevent switching at peak voltages (oscillating AC signal).

The outlet is a double pole plug with two loading points. Some loads are mechanically pulled out or plugged in without the use of switches which affect the health of the plug. The transient while switching or plugging are the main areas of

![House Wiring Set-up](image)

**Figure 3.5: House Wiring Set-up**
study in the following chapter.

The wiring used in the set-up (as shown in §3.5) clearly shows the excess length of cable used that is wound in a coil. This extra length was used to take into account the length of a typical home wiring. A maximum length of about 50 feet (i.e., 15.23 m) was used to model an electrical design close to reality.

The distribution box used is typical of a home wiring, from where multiple parallel circuits are made. A main circuit breaker is installed in the module to power the whole house circuitry. In addition to which, there needs to be inserted a secondary circuit breaker for controlling each parallel circuit mainly to isolate the circuit under emergency, to enable normal operation of other circuits.

3.4 Analysis

Based on the results tabulated and displayed above, it can be clearly seen that:

1. The inductance of the rectangular cross section wire is much smaller than that of the existing wire. The capacitance of the rectangular cross section
wire is much larger than that of the existing wire.

2. Thermal characteristics of the flat cable is better for the same current carrying conductor with the same thickness insulation as seen in the regular cable. The configuration of the conductors in the modified cable (placed one above the other) has a better temperature distribution when compared to the regular cable configuration (placed side by side).

3. The regular conductor model is shown to experience higher temperature gradient and sudden changes in temperature. Thus, to transfer the same amount of current, a thinner copper conductor would be sufficient in case of the modified cable structure. This also improves cost of the construction of the cable.

4. Also mechanically, the flat cable would be more convenient to clamp down and will have more contact area with the clamping surface making it neater while wiring.

5. The capacitance and the thermal characteristics can be further improved making thinner conductors, having wider geometry. The more the area of the plates, higher will be the capacitance in addition to having better heat dissipation. But making the conductors very flat, can make them more fragile and susceptible to damage.
Chapter 4

Experimental Results

The switching characteristic at the load outlet and at the switch were studied to analyse the effect of the cable parasitic at the load end. When applying an AC supply, the instant at which the load is unplugged is very crucial. At the peak of AC voltage, the switching transients are more pronounced due to the high voltage that is impressed across the open switch. To be able to analyse the high instantaneous voltage across the switch, a number of tests were carried out to study the behaviour of the transmission line (cable).

The primary aim of the tests were to study the existing switching transients in the current wiring architecture and to bring about improvement with the modified cable. Various tests were conducted on the cables with DC supply to study the switching behaviour of the cables. A low-voltage DC about (40V) was given to the system instead of the AC supply itself. It was interesting to see the ringing and the oscillations due to the line inductance and capacitance. There could be additional reasons to the ringing effect; like the mechanical characteristics of the switch itself. Voltage at the load (plug outlet) is expected to be same as the input square wave varying between 0 and 40V. On the other hand the voltage across the switch must be zero since the circuit is switched on. Since there is no load connected to the outlet, there will be no current drawn at the output.
4.1 Tests On Regular Cable

The primary focus being on the transient characteristics of the house wiring, various tests were conducted to study the behaviour of the house wiring while switching and under loading conditions. The following are the tests that were carried out.

To observe the transients that occurs while switching, the transmission line reflections in the output voltage and the input current, series of tests for both AC supply voltage and low voltage DC supply were conducted. The results are shown in the following sections.

4.1.1 Open Circuit AC Tests

The general test set-up for AC test is as shown in Figure 4.1. Depending on whether the load is being plugged in or out or an open circuit test is being performed, the corresponding switch would be engaged. For example; an open circuit test will not involve the study of load switching, hence switch $S_2$ (Refer Figure 4.1) will be permanently in a closed position. The switch $S_1$ would be the one that’s being turned on and off. In case of the home set-up, the switch $S_1$ is the circuit breaker provided in the distribution box itself and switch $S_2$ is the mechanical switch installed to control the supply to the outlet.

![Figure 4.1: Open-circuit Test Model](image)

Beginning with the steady state performance of the test set-up, the set-up is plugged into the AC supply. The results of the tests are shown in Figure 4.3 and the switch condition for the same is indicated in Figure 4.2.
To observe the switching characteristics, the switch $S1$ is turned on and off to study the peak voltage and the time taken for the oscillations to die out. The first test is done to view the switching behaviour while turning on the switch $S1$, the switching condition for which is shown in Figure 4.4, followed by similar tests to observe the turn-off characteristics. The open circuit test of a long transmission line is expected to provide the same voltage drop at the outlet as that supplied at the source end. The absence of load would produce no current at the output. Though there’s no
current drawn, the switching action causes reflections in the form of oscillations in the current as well; refer figure 4.5 & figure 4.6. It is observed that the Root Mean Square (RMS) value of the peak to peak voltage i.e. $2 \times V_{ac} \times \sqrt{2} = 360V$ and the current is 0A.

The transients observed in Figure 4.6 can be due to more than one factors. The most obvious reason is the transmission line behaviour of the cable, but this could also arise because of the source impedance offered by the AC source (the single phase power supply). The mechanical ”switch bouncing” effect can also contribute to the
transients observed. Thus we cannot fully isolate the cause of the transients due to the multiple factors involved in this case.

The high frequency transients also arise the possibility of an additional inbuilt circuitry in the switch that forces turn-off at zero voltage, forcing the current to zero very quickly. In the following tests it was also observed that the turn-off always happened at zero voltage, strengthening the previous assumption of the presence of an inbuilt snubber circuit.

The same set of experiments were carried out, but this time while the switching off switch $S_1$, the switch condition for which is indicated in Figure 4.7. The results are followed in Figures 4.8 & 4.9. As the switch is turned off quickly (mechanical switch installed in the home set-up), the transients were captured in the normal mode of the oscilloscope. As expected from the transmission line characteristics, there’s a sudden step-down in the voltage which creates transients in the current flowing through the line. The voltage must rise to $2 \times V_{p-p}$. But during the tests as observed in 4.8 and 4.9, the switching never happens at the peak voltage; it is assumed that the switch has an inbuilt snubber (refer [40] & [41]) circuit to turn on/tturn off at zero voltage only.
4.1.2 Open Circuit DC Tests

The test set-up for the DC open circuit test is as shown in Figure 4.10. Since a square wave input is applied as a source, the mechanical switching action is not required. The switching condition is shown Figure 4.11. Here the source side switching is done using square pulse, which eliminates the factors concerning the mechanical nature of the switch. Hence the transients observed can be safely assumed to be mainly due to the transmission line characteristics. The results follow in Figures 4.12 & 4.13.
Figure 4.9: Open-circuit Current(CH1) & Voltage(CH2) Transient Waveform While Switching (Turn-off) Tested On Regular Cable

The simulation results using the same cable model created for the AC tests are used and the result is as indicated in Figure 4.14.

Similarly, the transients during turn-off (or step-down of square pulse input) is as indicated in Figure 4.15.

The verification of the above results obtained during the experiments are done using the PSIM model and is as shown in Figure 4.16. Looking at the simulation
results in both the cases i.e. 4.14 and 4.16 a good agreement between the simulation and the test results can be observed. The line model created on PSIM did not incorporate the mechanical nature of the switch or even the arc model, which would have been necessary when using a DC source and a mechanical switch to study the transients. For the DC test, the source is replaced by a DC supply, using the square wave input from a signal generator. The purpose of using a square waveform is to observe the step response. The switching happens at the source end, i.e. $S_1$ is used in figure 4.10. A low voltage DC supply is used to observe the behaviour, based on which similar conclusions can be drawn for higher DC systems (220V) compatible.
Figure 4.13: Output Voltage (Ch2) & Input Voltage (Ch3) Transient Waveform
With Step-up Input Voltage Applied On Regular Cable

Figure 4.14: Verification Of Transients During Step-up Voltage Using PSIM
For Regular Cable
Figure 4.15: Output Voltage (Ch2) & Input Voltage (Ch3) Transient Waveform With Step-down Input Voltage Applied On Regular Cable

Figure 4.16: Verification Of Transients During Step-down Voltage Using PSIM For Regular Cable
for house supply.

The interference of source impedance can be neglected since DC supply is given as input from a signal generator. But in the real case scenario, the input voltage must be bridged using a high impedance, i.e. using a large capacitor at the source end. As mentioned previously, we also eliminate the mechanical nature of the switch from contributing to the transients observed.

As observed in figure [4.12] the output follows the input voltage. The voltage at the load end lags the source end by a small phase angle. The inductive nature of the transmission line is verified by this phenomenon.

The time delay is measured in the waveform observed in the oscilloscope as demonstrated in figure [4.17]. Similarly the frequency of oscillations in the step response are also verified as shown in figure [4.18].

The transient response can be observed in figure [4.13] and figure [4.15]. It is clear that the output peak to peak voltage jumps to $2 \times V_{p-p} = 2 \times 31.8V$ as expected from the transmission line model explained in Section [3.1].

4.1.3 Waveform Properties and Measurements

![Figure 4.17: Time Delay Calculation Using Cursors In Oscilloscope](image)

The time delay in transmission of time period $T$ is calculated from the wave-
form as observed in Figure 4.17. The time delay was observed to be 140 ns. The calculation of the line parameters are listed in Table 4.1. The line parameters for the new and modified, which is expected to have much lower characteristic impedance, is tabulated in Table 4.2 is shown later in the section.

Table 4.1: Transmission Line Parameters Calculation For Regular Cable (Refer Section 3.2.2)

<table>
<thead>
<tr>
<th>Velocity of propagation</th>
<th>Characteristic Impedance</th>
<th>Time Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v = \frac{1}{\sqrt{LC}} )</td>
<td>( Z_o = \sqrt{\frac{L}{C}} )</td>
<td>( TD = \frac{D}{v} )</td>
</tr>
<tr>
<td>( v = 2.01 \times 10^8 m/s )</td>
<td>( Z_o = 92.38\Omega )</td>
<td>( TD = 75.77\text{ns} )</td>
</tr>
</tbody>
</table>

Figure 4.18: Frequency Calculation Using Cursors In Oscilloscope

The time period for two cycles as observed from the waveform in Figure 4.18 was about 1.52\( \mu s \). Thus the frequency is given by \( 1/2T \). According to observation from the waveform; the frequency is given by:

\[
 f_w = \frac{1}{2 \times T} = \frac{1}{2 \times 1.52\mu s} = 6.58 MHz
\]  

\( ^1 \) \( L = 4.60 \times 10^{-7} H/m \) & \( C = 5.39 \times 10^{-11} F/m \)  
\( D = 50 ft \) & \( R = 0 \Omega \) (considering lossless line)
According to theoretical calculation, the time period $T$ is given by:

$$f_{th} = \frac{D}{v} = \frac{2.01 \times 10^8 m/s}{50 ft} = \frac{2.01 \times 10^8 m/s}{15.24 m} = 13.19 MHz$$ (4.2)

The time period $T$ as observed from Figure 4.17 are of the same order and can be verified by the above calculations.

The line parameters of a the laminated cable is tabulated in table 4.2. We can compare the parameters and see an reduction in the line characteristic impedance by more than 50%. The waveform comparing the two types of cables are shown in the following sections.

**Table 4.2: Transmission Line Parameters Calculation For Modified Cable**
(Refer Section 3.2.2)

<table>
<thead>
<tr>
<th>Velocity of propagation</th>
<th>Characteristic Impedance</th>
<th>Time Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v = \frac{1}{\sqrt{LC}}$</td>
<td>$Z_0 = \sqrt{\frac{L}{C}}$</td>
<td>$TD = \frac{D}{v}$</td>
</tr>
<tr>
<td>$v = 2.24 \times 10^8 m/s$</td>
<td>$Z_0 = 40.34 \Omega$</td>
<td>$TD = 68.03 ns$</td>
</tr>
</tbody>
</table>

4.2 Tests On Modified Cable

The fabrication of the flat cable, demonstrated in chapter 3, has better electrical properties when compared to the existing type of wiring as verified in the theoretical calculations. However it is yet to be verified experimentally, if the proposed cable is worth investing in.

For this reason, the flat cable was fabricated using copper tapes of desired thickness and width (Refer Appendix A.1) based on the area of cross section of the existing type of cables. The cable was then subjected to DC (one copper tape is ”$+$ve” electrode and the other being ”$-$ve” electrode), to observe the behaviour. Although, it should be noted that the cable measurement and construction was done using readily available parts, i.e. the copper tapes ($50' \times 0.5'' \times 0.01''$) and PVC insulation with double sided adhesive($50' \times 1'' \times 0.03''$). The aim was to be

\[2L = 1.80 \times 10^{-7} H/m & C = 11.06 \times 10^{-11} F/m \]
\[D = 50 ft & R = 0 \Omega \text{ (considering lossless line)} \]
able to get the best possible substitute for an existing circular cross-section cable using the flat type cable.

The step response of the modified cable and the corresponding regular, circular-cross section cable were to be compared to draw final conclusions. The test set-up for the DC open circuit test is as shown in Figure 4.19. The waveform for the flat

cable is verified using the test set up illustrated. The transients while switching are observed to compare with that obtained when using the regular cable. The switch condition is shown in Figure 4.20 and the subsequent waveform in Figure 4.21.

To verify the results obtained, a PSIM model of transmission line was modeled

similar to that done in the section 4.1.1 and 4.1.2. The line parameters of the per unit length segments would be different in case of the modified cable as measured and verified in 3.1.4. The simulation results are illustrated in Figure 4.22.
**Figure 4.21:** Step Response. Input Step (Ch1), Regular Cable (Ch2) & Modified Cable (Ch3)

a) Comparison of Step response of regular 12 AWG cable and corresponding modified cable

b) Overlapping Step response of regular 12 AWG cable and corresponding modified cable
The peak over shoots captured when comparing the transients of a regular ca-

Figure 4.22: Step Response Obtained Using PSIM

ble with that of the modified (flat cable) are as shown in Figure 4.23. The peak
overshoot (peak to peak) value of the modified cable is about 10V lower than the
regular cable. Although the experimental results did not reach the expected lev-

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Figure 4.23: Peak Overshoot. Input Step(Ch1), Regular Cable(Ch2) & Modified Cable (Ch3)
els of improvement as predicted from the simulation results, there’s an observed improvement in characteristics.

Comparing the results obtained on PSIM with those captured on the oscilloscope, the results are similar in showing the reduced transients when using the modified cable, however the improvement in performance is far more pronounced while studying the simulation results shown in Figure 4.22. From the simulation waveforms, there is a reduction in the peak overshoot by a large margin. This change in the observation can be attributed to the following; difference in material of insulation, non uniform insulation and/or trapped air bubbles, change in material properties from the extra adhesive layers, errors while construction of cable or mechanical punctures while coiling the long cable.

Commenting on the “transient time”, it is clear from the test results that the time taken in both the cases (Regular Cable and Modified Cable) is similar which is in contrast to the observations from the results obtained on PSIM. There is a large improvement in transient time in the simulation results. This discrepancy can be attributed to the switch bouncing effect of the switch. The transient time is dependent on the mechanical bouncing, which is similar in both cases as we use the same mechanical switch in both of the circuits.

4.3 Load tests

![Test Circuit For Load Tests](image)

**Figure 4.24:** Test Circuit For Load Tests

To compare the results further, some load tests were performed with common loads i.e the resistive loads commonly seen in household loads like the toasters, and the inductive load which represents most household loads. The "switching-on"
and "switching-off" characteristics of the various kinds of loads are demonstrated below. The test set up is shown in the figure 4.24.

4.3.1 Resistive Load

The transmission lines were terminated with a pure resistance of 9.1Ω. The load was switched on and off using a regular 15A mechanical switch and the transients were to be noted. The mechanical switch had its own constraints in terms of the "switch bouncing" effects and the transition time to disconnect or connect the load. Figure 4.27 shows the transient voltage and current at the load end while using the two types of cables. The characteristics are almost similar in both these cases. The test case is illustrated in figure 4.25. The PSIM results for the same test case is shown in figure 4.28. On the other hand, the "switching-off" condition for the same load shown in figure 4.29 shows some improvement. It can be observed that the peak to peak value of the voltage is about 180V using the regular cable, but

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Figure 4.27: Load Characteristics (Resistive Load) During ’Switch-on’ State. Load Current (Ch2), Load Voltage Of Regular Cable (Ch1) & Load Voltage Of Modified Cable (Ch4)
Figure 4.28: Load Characteristics (Resistive Load) During 'Switch-on' State
Obtained Using PSIM
the voltage is about 100V when using the flat cable. There is a improvement and reduction in peak to peak voltage by about 44%. The time taken for the current to rise is almost similar and is more than the time frame shown in the figure.

Figure 4.29: Load Characteristics (Resistive Load) During ’Switch-off’ State. Load Current(Ch2), Load Voltage Of Regular Cable(Ch1)& Load Voltage Of Modified Cable(Ch4)
4.3.2 Inductive Load

Along similar lines, an inductive load, i.e. an $R - L$ load was used to load the lines. The inductive termination of the transmission line represents most loads since most loads exhibit inductive characteristics.

To verify the above results, PSIM results are as shown below in figure 4.31. The switching action was captured using a inductance coil of 3$mH$ in series with a resistance of 9.1$\Omega$. Figure 4.30 shows the "Turn-on" behaviour while measuring the load end voltage and current. Clearly, there is not much improvement in the peak to peak voltage or the transient time. The test case is illustrated in figure 4.26.

As in the case of the purely resistive load, there is a reduction in the peak to peak voltage in the case of "switching-off" the $R - L$ load. The recorded peak to peak values show reduction from 160$V$ in the case of regular cable to about 130$V$ in the case of the laminated cable. There is an improvement of about 19% in terms of the reduction of the voltage. The switching-off characteristics are shown in figure 4.32.

The "switch-off" characteristic on PSIM using either kind of loads showed no transient behaviour. Since the PSIM model did not incorporate the mechanical characteristic of the switch or the arc characteristics, the switching off characteristic was observed to be that of an ideal switch.
Figure 4.30: Load Characteristics (Inductive Load, i.e. $R - L$) During 'Switch-on’ State. Load Current(Ch2), Load Voltage Of Regular Cable(Ch1)& Load Voltage Of Modified Cable(Ch4)
Figure 4.31: Load Characteristics (Inductive Load, i.e. $R - L$) During 'Switch-on' State obtained using PSIM
Figure 4.32: Load Characteristics (Inductive Load, i.e. R-L) During ‘Switch-off’ State. Load Current(Ch2), Load Voltage Of Regular Cable(Ch1)& Load Voltage Of Modified Cable(Ch4)
4.4 Analysis

The difference in the observed waveform and the simulation can mainly be attributed to the mechanical nature of the switch that was used in the hardware set-up. Thus in some cases, there was no significant improvement seen in the test results when compared to the simulation results. The mechanical switch model was not considered while simulating the transmission line parameters. The primary focus of this research being on reducing the line parameters, the 'switch bouncing' effects involved with the mechanical switch was not taken into account. As the components of the switch settle into their new position, they mechanically bounce, causing the underlying circuit to be opened and closed several times. This non-ideal behaviour of the switch causes multiple electrical transitions each time the state of the switch is changed.

Additionally the error margin between the expected and the actual results can also be influenced by the difference in the properties of material used while fabricating the laminated cable. Since the cable was constructed manually for a length of about 50 ft, there is scope for a lot of imperfections and non-uniformity between the layers of the cable.

A lot of work has been done on representation of DC arc in the form of various mathematical equations have been done to study its characteristics. Incorporating the arc model to simulate the real case scenario would perhaps help in understanding the arcing behaviour in DC switches more accurately.

The mechanical characteristics of the switch or the arc equations in the simulation model is complex and shifts the focus of this research. Our main objective is bring about practical improvement in DC switching.
Chapter 5

Conclusions

5.1 Summary

This thesis investigated the properties and characteristics of the wiring in the current residential wiring. A new and modified wiring was proposed with the aim of improving both electrical and thermal characteristics, especially useful for DC power distribution systems in residential application.

The proposed flat-wire system ensured minimal modification to the existing load and power configuration, while having better switching characteristics—which is one of the main concerns while implementing DC as power supply.

Over a period of time the arcing affects the lifetime of the switch and calls for replacement more often. Improving the cable to address this issue not only improves the lifetime of the switch but also is a long-term solution in the wiring of homes.

In most other scenarios, DC power is more user-friendly and more suitable for homes. The compatibility of loads with DC power supply was studied before carrying out various tests to prove improved electrical characteristics of the proposed wiring system.

A DC homes wall set-up was fabricated to do these tests. Additionally, the flat wire cable of about 15 meters in length was laid with insulation, manually, to be able to compare the proposed wiring system with the regular existing wiring system.
A thermal analysis was also carried out using a software called Elmer to observe any improvements in this field. Subsequently, all these tests were verified with simulation by modelling a transmission line model in PSIM with the measured line parameters of each type of system.

After conducting innumerable tests and running simulations, the modified cable thus proposed has the following benefits:-

1. Improved electrical properties: Line parameters of the cable are better than the regular cable parameters, contributing to better electrical properties.

2. Better switching characteristics: Large margin of improvement in the peak overshoot as well the transient time implying lesser risk due to arcing in terms of faster arc quenching properties.

3. Efficient and convenient mechanical structure: Flat architecture would be more convenient to install and can be mounted in a neat fashion.

4. Possible reduction in cost of manufacturing: Same amount of copper used in the modified cable can be rated for higher current. Thus the cost of copper required for the same current rating would be lesser in the modified-flat type cable than the regular type of cable.

Having proven and stated the above conclusion, the main objective of this modification was to improve the switching characteristics. The main question that comes to mind is if there still is requirement of using a snubber across the switch, or if substituting with the modified cable is sufficient to observe much improvement.

The main concern would be the problems related to the practical fabrication of these cables and implementing them in a large scale. There needs to be thorough analysis in terms of the effort versus improvement in efficiency in comparison to the exiting, conventional cables.

5.2 Future Work

There is still scope for improvement and advancement to this work. A lot of research is already being done in this field. In terms of carrying forward this partic-
ular work, the final objective of this research would be the fabrication of a professional flat-cable set-up to replace the house wiring. Also to be considered would be to match the safety standards specified for home application. Since DC switching has a lot of stored energy, plugging in and out of loads can be dangerous and can pose severe electrical hazards. To prevent this each DC outlet must be coupled to a DC switch which must be turned off before being able to manipulate with the load. The design of this outlet-switch arrangement would be similar to the system implemented in various countries where each plug has a designated on/off switch. The usage of a plug lock system to prevent unplugging when the power is on is another possible way of avoiding electric shocks.

Designing of the DC arc characteristics in the simulation study cases would also help in understanding the effect of change in line parameters on the arc behaviour and the time taken to quench the arc. Additionally, considering the effects on the output characteristics due to the mechanical switch properties like the switch bouncing effect, turn-on and turn-off times, can be of interest. Alternatively, it will be interesting to notice the change in characteristics if the switch were perhaps replaced with an electronic switch with better turn-on and turn-off times as well as reduced switch bouncing effects. This will help in understanding the detrimental effects in switching characteristics due to the mechanical switch.

Future work would also involve fabrication of wiring components like plugs to be readily installed in home distribution system while incorporating the solution to arcing while plugging in and out of the loads. Having done this, another major step would be to conduct cost analysis to check for feasibility of installing and modifying the existing system and to ensure that this modification is worth the investment.

If DC distribution systems for homes becomes successful, there would be considerable reduction in the power consumption of the loads, since the power rating of individual loads can be lowered with DC [42]. In addition to the other obvious beneficial outcomes by using DC power, overcoming the main drawback of DC power today (DC switching) will help in the promotion of a new distribution system altogether.
Bibliography


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Appendix A

Theory

A.1 Verification of the Cross-sectional Area

The dimensions of the chosen flat cable for tests are Width (W)=0.5” and thickness (L)=0.01”. The area of cross section of such a cable:

\[ A = L \times W = 0.5 \times 0.01 = 0.005\text{inch}^2 \]  

\hspace{1cm} (A.1)
A regular cable of equal cross-section was chosen.

\[ A = \frac{\pi D^2}{4} = 0.005\text{inch}^2 \]  
\[ (A.2) \]

\[ D = 0.08\text{inches} \]  
\[ (A.3) \]

Hence D=0.08” is calculated to be a 12 AWG wire.

### A.2 Line parameters and PSIM Line Model

**Table A.1:** Line Parameters of Regular Cable in PSIM Model

<table>
<thead>
<tr>
<th>Specification</th>
<th>( L )</th>
<th>( C )</th>
<th>( R_s )</th>
<th>( R_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per unit length values</td>
<td>0.46( \mu H/m )</td>
<td>53.98( pF/m )</td>
<td>12.55( m\Omega/m )</td>
<td>86.41( M\Omega/m )</td>
</tr>
<tr>
<td>Per Segment values</td>
<td>0.35( \mu H/m )</td>
<td>41.16( pF/m )</td>
<td>9.57( m\Omega/m )</td>
<td>65.88( M\Omega/m )</td>
</tr>
</tbody>
</table>

**Table A.2:** Line Parameters of Modified Cable in PSIM Model

<table>
<thead>
<tr>
<th>Specification</th>
<th>( L )</th>
<th>( C )</th>
<th>( R_s )</th>
<th>( R_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per unit length values</td>
<td>0.176( \mu H/m )</td>
<td>110.62( pF/m )</td>
<td>37.07( m\Omega/m )</td>
<td>84.23( M\Omega/m )</td>
</tr>
<tr>
<td>Per Segment values</td>
<td>0.13( \mu H/m )</td>
<td>84.35( pF/m )</td>
<td>28.26( m\Omega/m )</td>
<td>64.23( M\Omega/m )</td>
</tr>
</tbody>
</table>

The PSIM model was created using the line parameters calculated and verified by measurements using the LCR meter. Using the distributed line model, 20 segments were created to model the line. It was observed that increasing the number of segments beyond this did not have significant change in the output waveform.

The line parameters obtained during the experiments were per unit length values (i.e per metre). To obtain the values of the each of the 20 segment parameters, the per unit length metre is multiplied by the total length and is thus divided into twenty equal parts.

The per unit length values and the per segment values are as shown below in Tables A.1 & A.2. The per segment value is calculated by simply multiplying the per meter values by a factor of \( \frac{15.23m(50ft)}{20} \).