Feasibility study of extra-low voltage DC implementation for LED lighting systems in building

Ardiyanto, Nurul Husna

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**FEASIBILITY STUDY OF EXTRA-LOW
VOLTAGE DC IMPLEMENTATION FOR LED
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NURUL HUSNA ARDIYANTO

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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Abstract

Total energy consumption in Singapore's household system is as huge as 6,560 GWh. Among this total energy consumption, the lighting system contributes to 20.9%. The common application of available LED system has a remarkable impact by reducing energy consumption. However, the DC/DC driver in the LED system contributes to system losses and has shorter lifetime than LED's. Therefore, in this study we proposed novel power distribution for LED lighting system. Compared to commonly available LED lighting system, our novel LED lighting system eliminated the DC/DC driver part. The systematic assessment of LED Lighting System driven by Extra Low Voltage Direct Current (ELVDC) topologies was conducted. Then, electrical characteristics of qualified LED lamps that meet Singapore regulations were applied to the calculation for ELVDC. In order to understand ELVDC feasibility in comparison with AC system for lighting application, we assessed the voltage drop across the cable, system power loss, total efficiency, safety and the potential economic savings. We found that LED lamp could replace CFL by producing 138 to 191 lux within tolerable voltage level with clear diffuser type. Furthermore, the feasible ELVDC topologies for LED Lighting system could achieve up to 92.22% efficiency in unipolar topology and 92.65% efficiency in bipolar topology. More importantly, it provided savings with respect to AC system up to 70.7%. Based on these results, we concluded that it is feasible to use driverless ELVDC topology for LED lighting system. Our results mainly impact on smart building development and may contribute to decrease global energy consumption.

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Chapter 1

1. Introduction

1.1 Background and Motivation

Global consumption of energy is continuously increasing due to the growth of population [1]. According to Singapore Energy Market Authority, the consumption of electricity for buildings and household use was 6,560 GWh or 15.7% of overall energy consumption in Singapore. In other hand, the energy consumption of lighting sector contributed to 20.9% of total household electricity consumption[2]. Since in 2015, more than 80% Singapore's resident population lived in flats provided by the Housing & Development Board (HDB), which is a public housing government and a lawful board under the Ministry of National Development of Singapore [3]. Most of Singapore's residents live in public housing provided by HDB, termed HDB flats. HDB flats buildings are high-rise buildings which has several blocks in an area. Each HDB flats blocks has common area intended to support social interaction. The common areas of HDB flats usually consist of corridors, staircases and a void deck. The void deck is usually located on ground floor which provide commodious space for communal activities such as bazaars, funerals and weddings. Several staircases also exists in a HDB flats block to accommodate people who live in high floor sections of the building. In each floor, corridors exist mainly to assist navigation to flat rooms. We proposed system that would be applied on HDB flats common area because it is always found in HDB flats and also the area that is mostly used by public. As it is dedicated for public, by considering HDB flats as a subject of research, it will yield more impact on the society. Reducing household's energy consumption, especially from HDB flats, is believed to have major impact on total energy saving. In addition, development of smart building that consumes electrical energy efficiently is substantial to be applied.

The concept of smart building has been proposed more than a decade ago [4] as the integration of efficient energy consumption and practicality. Smart building mainly manages AC system, lamp and IT loads in an integrated system to be dynamically changing as the needs. The advancement of LED lamp technology and the increasing

demand of IT technologies in the smart building promote improvement in the design of energy distribution in smart building. Smart building is designed to be more efficient and intelligent while using many appliances in building. In this strategy, smart building applies DC grid because it can improve the quality of power distribution, lower operating cost, and lower investment cost compared to AC system [5]. In DC grid system, voltage level is cascaded into 2 level grids. Firstly, 380 VDC grid is aimed for the power distribution network in building. Secondly, 24 VDC grid that is recognized as extra-low voltage DC (ELVDC) grid is aimed for lighting and Information Technology (IT) loads. For the lighting system, smart building applies dimmable solid state lamps (SSL) for lighting system, not only because dimmable SSL has been available in the market widely, but also using dimmable SSL may reduce energy consumption by 44.3% in lighting system [6]. However, AC distribution system needs additional interface device, such as rectifier, to supply these loads. In the other hand, DC distribution system may supply the load directly whenever the load voltage as required matches to the voltage of DC supply. Therefore in order to improve electrical system's efficiency, we compared AC distribution system to DC distribution system. Moreover, driverless system could extend the lifetime of the lighting system. It was because our system removed the need for driver which has shorter life time than SSL. In this study, we also designed our novel suitable power distribution topology to support the system. Our study mainly impacts on smart building development and may contribute to decrease global energy consumption.

1.2 Objectives

This thesis discusses about the processes of implementing Extra-Low Voltage DC distribution system for common area lighting, especially in HDB flats. There are two main goals of this research: to design lighting system for common area; to implement LED lighting system powered by ELVDC. The specific objectives of our study include:

1. To design lighting system for HDB flats' common area. A typical HDB flat's block has some area that is reserved for public activities. The activities could be for long time or temporary. Lighting design can be varied due to the period of the typical activity in the specific types of area. In this research, the most suitable and efficient lighting system for common area in HDB flats will be developed.

2. To design suitable Extra-Low Voltage DC distribution (ELVDC) system for the lighting system. Since LVDC was in the early stage as power distribution, ELVDC can be an alternative for power distribution system in building. Previously, ELVDC system has been mainly targeted for communication systems. Thus, the ELVDC topologies for power distribution system need to be studied, especially for lighting system application in this research.
3. To evaluate the feasibility of ELVDC system to retrofit existing AC system. Feasibility of ELVDC implementation will be decided according to electrical performance to meet requirements and economic analysis to understand the economic savings potential.

1.3 Organization of the thesis

This thesis consists of 6 chapters as follow:

Chapter 1: Introduction of master project. This chapter contains background and motivation, and objectives of the project.

Chapter 2: Literature review of lighting requirements, LED characteristics and LVDC micro-grid.

Chapter 3: Retrofitting Lighting System Design. This chapter describes the selection of lighting luminaries to replace existing luminaries, and also the characteristics of chosen luminaries.

Chapter 4: ELVDC Evaluation. This chapter explains the topology which can be applied to drive LED lighting system, and performance of LED Driving system, such as performance of AC System with single driver, Unipolar ELVDC system, and Bipolar ELVDC System which judged by the voltage drop, efficiency, harmonics, safety and economical savings of the system.

Chapter 5: Conclusion and Future Works.

Chapter 2

2. Literature Review

This research's purpose is to retrofit existing lighting system. To understand Singapore standard and code applied for lighting system in retrofitting target area then becomes essentials. Besides that, knowledge of LED characteristics is important because proposed replacement for existing lamp in this research was LED. Driving methods for LED were reviewed to gain knowledge of driver's components and schemes. DC power distribution were also reviewed to understand the DC system terminology and the retrofitting scheme from AC to DC system. Then, understanding of the driving method and retrofitting scheme that suitable for this research was expected to be achieved. In addition, some consideration in driving method for LED and DC system such as harmonic distortion and safety issues were reviewed. This literature review is divided into 5 sections. First section describes the fundamental to design lighting system in general. Then, the second section explains LED's characteristics. The third section explains LED Driving Technologies. Furthermore, the fourth section contains LVDC microgrid, and in the last section safety issues is discussed.

2.1 Lighting Requirements

Lighting system needs to be designed based on its purpose. There are two main purposes of lighting systems: to provide ambience and to support daily tasks. This may affect the choice of lighting design. For decorative purposes, lighting system should be designed by taking into account the colour production, shadow effect, and also the light distribution. However, generally, lighting system is used to provide visual comfort to support people in performing their daily tasks. A good lighting system design will allow users to perform tasks precisely, efficiently and also safely without leading to fatigue and discomfort [7, 8]. In order to reach that, Singapore makes guidelines for lighting designer to follow. The guidelines are listed on SS531 2006 which is divided into two parts. Guidelines for indoor lighting system design are mentioned in part 1, while guidelines for outdoor lighting system design are described in part 2. Because this thesis focuses on lighting system in building, this research will follow SS 531 2006 part 1 as guidance [9].

Lighting system design needs to consider the number of luminaries, illuminance level, colour rendering index, and also uniformity of the light distribution for the designed area. Moreover, different room type needs different requirements to fulfil. Staircase and corridor, based on SS531 2006, follow criteria as shown in Table 2-1. Table 2-1 shows that maintained lux for circulation area is 100 lux and for stairs are 150 lux. In this research the staircase is for circulation area. Thus, the minimum maintained illuminance level is adjusted to be 125 lux [10].

In lighting system design, there is Color Rendering Index (CRI) to indicate color accuracy of objects under certain light source. CRI value is from 0 to 100 that indicates the comparison between object's color under tested light source to object's color under natural light source (sunlight). The purpose of color rendering index is mainly to maintain the human visual comfort, to see color properly, for example human skin colour needs to be maintained to look normal. CRI value is important for the light source selection to comply lighting regulation. In Singapore Standard, CRI for building's common areas are 40. It means the color accuracy in those common areas is not significant. So that, light source color in this research can use cold to warm color with CRI level more than 40.

Table 2-1. Standard for Common Area Lighting System

Area	Maintained Illuminance Level (Lux)	Color Rendering Index
Circulation area and corridors	100	40
Stairs, escalators, and travelators	150	40

The required number of lamp can be calculated using equation (2.1) [11].

$$N = \frac{A \times E}{F \times n \times MF \times UF} \quad (2.1)$$

Where;

N : number of luminary

A : floor area to illuminate

- E : lux to be maintained
- F : initial lamp lumen
- n : number of lamp in a luminary
- MF : maintenance factor
- UF : utilization factor

In order to minimize the power consumption, minimum required number of luminary need to be achieved. As illustration, to minimize power consumption in a corridors area of $2.5 \times 2.5 \text{ m}^2$, the luminary is set to use one lamp. For staircase with maintenance factor and utilization factor 1, the number of luminary can be calculated below:

$$1 = \frac{6.25 \times 125}{F \times 1}$$

$$F = 781.25 \text{ lumens}$$

From the calculation above, for stated staircase which is designed to use single lamp, a lamp is needed to produce at least 781.25 lumens to meet the desired maintained lux value at 125 lux. Thus, the desired maintained lux value has higher than the minimum lux value required for corridors area at 100 lux.

2.2 Light Emitting Diode (LED) Characteristics for Lighting System

LED is a solid state device which is able to emit light when activated. LED has operating characteristics like zener diode with series resistance, as seen in Figure 2-3. It will operate after applied voltage on LED surpassing LED's forward voltage (V_f), and also has breakdown voltage which is the limit of the maximum voltage of the LED can handle when it is placed in the opposite polarity. [12]

LED works as luminary because of its ability to emit light. This emitted light is caused by photons production as the result of moving electron due to potential difference across P-N Junction [13]. A photon which produces light will be emitted when an electron loses energy and falls back into the valence band. The potential difference across P-N Junction also affects the wavelength of the light production. Thus, voltage difference across P-N Junction (voltage drop of LED) will produce different colour of LED. Red colour is at the lowest voltage drop, while blue colour requires highest voltage drop of P-N Junction as shown in Figure 2-1 [12]

Figure 2-1. Forward Voltage Drop vs Current

Figure 2-1 shows that LED has differential resistance characteristic. It means that current flowing through LED will change after forward voltage and following equation (2.2). Then, LED's (as shown in Figure 2-2) equivalent circuit will be identical with combination of series resistance and zener as shown in Figure 2-3. Following the equivalent circuit, Zener Diode with series resistance could be the replacement for LED as test subject when experiment to test LED driver performance being conducted.

Figure 2-2. LED's Symbol

Figure 2-3. LED's Equivalent Circuit

The series resistance of LED is called Equivalent Series Resistance (ESR). ESR can be calculated by measuring the increasing voltage (dv) and divided by increasing current

(di) in the linear operating region of LED. This resistance value of ESR is differential resistance type, as its value constant following dv and di of LED operation value. The equation to calculate ESR is described in equation (2.2).

$$R = \frac{dv}{di} \Omega \quad (2.2)$$

In implementation, LED for lighting system has been studied in past years. It was able to produce high lumen, low power consumption and fast response to light up. There are many types of material to make LED. Each material has its own characteristics and operating performance. Gallium Arsenide (GaAs) could produce light with wavelength about 905nm. And also, it was the first material to produce LEDs by applying P-N Junction material. This LED emits red colour light.

The limitation of using LED was its narrow light production and decreasing life time due to operating temperature[14]. As shown in Figure 2-4 LED will get shorter life time when its temperature is higher. Then the T-junction temperature of LED must be maintained to be at slow operating temperature. Thus, typically LED needs driver to control current input by using current control driver.

Figure 2-4. LED's Lifetime Compared to Working Temperature (source:[14])

2.3 LED Driving methods

Typically LED driver for LED consists of AC/DC Converter (rectifier) if the source is AC supply, boost PFC Converter, and Half Bridge LLC Resonant Converter or DC/DC Converter[15, 16]. Besides that, LED Driver should employ Filter to reduce harmonics of the system. Constant current driver controls current flowing through LED lamp using feedback system in circuit. The strategies require switching system with controller which will need more passive device to couple the output as shown in Figure 2-5.

Some designs tried to simplify the drivers to reduce the passive components or replacing electrolytic capacitor in the circuit to improve efficiency and lifetime of the driver[17, 18]. Electrolytic capacitor was removed to improve driver's lifetime as it has 5000h which is much lower than LED's lifetime [17]. Moreover, electrolytic capacitor is better to use in lower temperature and current condition as shown in Figure 2-5 [19]. Figure 2-6 shows that with 105°C rated capacitor, if it was operated at 75°C and at rated current then the capacitor would have 8 times longer of lifetime.

Figure 2-5. Typical Technology for LED Driver

As the lumen output enhancement of LED lamp is related accordingly to the increase of current level of LED, the basic ideas to control LED lamp typically are controlling current flowing through LED modules. LED current's value depends on the voltage level and ESR value of LED. Thus, there are two ways to control LED lamp. They are passive control system and active control system.

Figure 2-6. Lifetime of Aluminium Electrolytic Capacitor[19]

Passive control system does not require any feedback to control current in a steady or constant level of LED lamp's current. It only needs to control current value to not surpassing tolerance of rated value of the current. Thus, in passive control system, it will only decide the value of ESR to restrict the value of expected current value to be in the rated range current level. LED driver which apply this method is called linear circuit, it is cost effective, but bulky in size[20].

Active control system will require feedback to adjust current output to be as close as possible to the desired value [21]. There are some techniques to control current value flowing through LED modules. They are constant voltage driver and constant current driver. The idea of constant voltage actually also expects LED lamp to have current level as required. It expects the LED modules to have same value of ESR. Then by controlling voltage level in related value, it will produce current level in rated value.

Designing LED Driver required consideration of understanding the LED characteristics, such as: ESR, colour production, and also the control technology used. The simplest design of LED driver is using external resistance as current limiter, as shown in Figure 2-7, to change the slope of LED's I-V curve characteristics. Thus by choosing the value of external resistor, LED could behave as expected in a situation which voltage level is decided. Then, the equation to choose value of external resistance will be limited by current rating of LED, and forward voltage rating of LED. The calculation followed equation (2.3) and equation (2.4).

Figure 2-7. External Reistor for LED

$$R_{total} = R_{EXT} + ESR \quad (2.3)$$

$$I_{LED} = \frac{V_{in}}{R_{total}} \quad (2.4)$$

For example, if current rating (I_{LED}) value of LED is designed to be 50mA, V_{LED} of 3.8V and operating power supply with voltage level (V_s) rating of 5V. Besides that, ESR of LED could be found by testing the LED modules for the particular LED. In the end, the value of external resistor can be chosen by following the nearest value from the calculation as follow.

$$R_{ext} = \frac{V_s - V_{LED}}{I_{LED}} \quad (2.5)$$

$$R_{EXT} = \frac{5 - 3.8}{50} = 24ohm$$

Then, by assuming the tolerance of voltage supply (V_s) by 10%, maximum and minimum value of current flowing through LED can be found using equation (2.5).

$$I_{min} = \frac{V_{Smin} - V_{LED}}{R_{EXT}} = 45mA$$

$$I_{min} = \frac{((100 - 10) \times 5) - 3.8mA}{24} = 45mA$$

$$I_{min} = \frac{V_{Smax} - V_{LED}}{R_{EXT}}$$

$$I_{max} = \frac{((100 + 10) \times 5) - 3.8}{24} = 55mA$$

As current maximum exceeded the rating, external resistance had to be modified to limit the current to be at rated current value as maximum value. Then, external resistor was chosen based on calculation below.

$$R_{EXT} = \frac{5.5 - 3.8}{50} = 34 \Omega$$

After modifying external resistor value, minimum and maximum current flowing through LED followed calculation below.

$$I_{min} = \frac{((100 - 10) \times 5) - 3.8}{34} = 20.59mA$$

$$I_{max} = \frac{((100 + 10) \times 5) - 3.8}{34} = 50mA$$

The most common method to drive LED lamp is using active control system. This method could operate LED lamp as designers want. As LED's brightness and lifetime are correlated to current value flowing through the modules, engineers designed LED driver focusing on the current value of the LED to set the brightness and also safety concern of LED. Thus, although there are some constant voltage drivers available in market, the most common drivers are constant current based technology. The design of current control for the driver followed Figure 2-8[22-25].

Figure 2-8. Typical LED Driving Method with Current Control System

2.4 Harmonics of Power Converter

Power Converter normally uses as the driver for Compact Fluorescent Lamp (CFL) modern lamp technology. Then, as LED popularity increasing, driver for LED also used to drive LED which compatible with ballast. People normally install LED for the more efficient device, but by installing with ballast it means that maximum efficiency of the system was not achieved. Besides that, the harmonic from the driver and ballast can cause the power loss.

Harmonics of the system is calculated by using Fast Fourier Transform. This method transforms time frame signal to frequency frame. The basic idea of using FFT is that one signal is composed by many waves with fundamental frequency and the multiplication of fundamental frequency with specific amplitude. Therefore, one signal will be modelled using Fast Fourier Transform equation, as stated in equation (2.6). [26, 27]

$$f(t) = F_0 + \sum_{h=1}^{\infty} F_h(t) \quad (2.6)$$

$$f(t) = \frac{1}{2}a_0 + \sum_{h=1}^{\infty} \{a_h(h\cos\omega t) + b_h(h\sin\omega t)\} \quad (2.7)$$

Where $F_0 = \frac{1}{2}a_0$ is the average value, and a_h and b_h is the magnitude of n harmonics following equation (2.8) and equation (2.9).

For
h=0,2,4... ∞

$$a_h = \frac{1}{\pi} \int_0^{2\pi} f(t) \cos(h\omega t) d\omega t \quad (2.8)$$

For
h=1,3,5,... ∞

$$b = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin(h\omega t) d\omega t \quad (2.9)$$

In DC system, especially for lighting system, loads are using DC voltage which requires AC/DC Converter. This converter could produce harmonics, as the harmonics level will be affected by the AC/DC current-modes. There are two modes in rectifying, Continuous-Current Modes (CCM) and Discontinuous-Current Mode (DCM).

Discontinuous-Current Modes happens when driver use too small inductance of inductor which will make the current wave form as shown in Figure 2-9.

Figure 2-9. DCM Current Supply Waveform in Rectifier (source: [28])

In Continuous-Current Modes (CCM), for full bridge diode will make typical current wave form as shown in Figure 2-10. It shows that the rectifier uses high inductance inductor is able to make constant current waveform in supply side.

If power supply used 220Vrms sinus wave input, with 50Hz frequency, and L is infinite. This rectifier will be in CCM, and then the harmonics component will be generated by 3, 5, 7, and odd harmonics. Then, THD of the system will be 44.5% as calculated below.

$$\text{For } h=3 \quad b_3 = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin(3\omega t) d\omega t$$

$$f(t) = 220\sqrt{2}\sin(100\pi t) d\omega t$$

$$b_3 = \frac{220\sqrt{2}}{3} \sin(300\pi t)$$

Then, the other odd harmonic component was calculated using equation (2.8) so that it produced Figure 2-11.

Total Harmonic Distortion (THD) of the system was calculated using equation (2.10).

$$THD = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1^2}} \quad (2.10)$$

Equation (2.10) tells that square of each current harmonic magnitude will be added to be compared to fundamental current. As only the odd harmonics appear on the system, THD of the rectifier with CCM was 44.5%. In this example as shown in Figure 2-11, only harmonic 3,5,7,9,11, and 13 appeared, then the calculation as follows;

h=3,5,
7,9 13

$$THD = \sqrt{\frac{\sum_{h=3}^{\infty} I_h^2}{I_1^2}}$$

$$THD = \sqrt{\frac{I_3^2 + I_5^2 + I_7^2 + I_9^2 + I_{11}^2 + I_{13}^2}{I_1^2}}$$

THD

$$= \sqrt{\frac{\left(\frac{1}{3}I_1\right)^2 + \left(\frac{1}{5}I_1\right)^2 + \left(\frac{1}{7}I_1\right)^2 + \left(\frac{1}{9}I_1\right)^2 + \left(\frac{1}{11}I_1\right)^2 + \left(\frac{1}{13}I_1\right)^2}{I_1^2}}$$

$$THD = 44.5\%$$

Figure 2-10. CCM Current Supply Waveform in Rectifier (source: [28])

Figure 2-11. Harmonic Component

There are some methods to eliminate harmonics component. As shown in Figure 2-11, the biggest magnitude of the harmonics is the 3rd harmonic, as the higher harmonic number will be less in magnitude. Thus, most methods will focus on the lower number harmonic to improve THD significantly.

There are passive and active methods to reduce THD. Passive method uses passive filter with inductor and capacitor. Active method uses Power Factor Corrector circuit with controlled switch [27]. Placement of Filter is shown in Figure 2-12. Choosing inductor and capacitor value need to consider the value of system frequency, load, and behaviour of the filter.

Figure 2-12. Boost Converter as Power Factor Corrector[29]

Figure 2-13. Current in Supply Side After Using PFC[27]

PFC Design is typically based on boost converter with C_{in} will be used to reduce ripple voltage output. Then, L_p is chosen to make CCM or DCM mode of current input in supply side. In ideal case, switching frequency will be set as infinite then L_p could be negligibly small [27]. Then PFC is operated by shaping the current in supply side to be as close as fundamental current as shown in Figure 2-13.

Where f_s is frequency of the switch, and then operation mode of boost converter will follow [30].

In CCM operation,

$$V_{out} = \frac{1}{1-d} V_{in} \quad (2.11)$$

With switching frequency f_s as describe in equation (2.12).

$$f_s = \frac{1}{t_{on} - t_{off}} \quad (2.12)$$

So that, during on and off period of the switch, t_{on} followed equation (2.13) and t_{off} followed equation (2.14)

$$t_{on} = \frac{L_p I_{rip}}{|v_s|} \quad (2.13)$$

$$t_{off} = \frac{L_d I_{rip}}{V_d - |v_s|} \quad (2.14)$$

Switching then followed equation (2.15).

$$f_s = \frac{(V_d - |v_s|)|v_s|}{L_p I_{rip} V_d} \quad (2.15)$$

Thus I ripple could be calculated using equation (2.16).

$$I_{rip} = \frac{(V_d - |v_s|)|v_s|}{f_s L_p V_d} \quad (2.16)$$

Where;

- V_d : output voltage of PFC (Boost Converter) (V)
- v_s : voltage input from supply (V)
- I_{rip} : ripple current in supply side (A)
- F_s : switching frequency for PFC (Hz)
- L_p : the inductor for PFC (H)

2.5 Low Voltage and Extra Low Voltage DC for Building

As DC power distribution system becomes more prospective over AC power distribution system, there have been some studies that show benefit of using DC system over AC system. The terms of High Voltage DC (HVDC), Low Voltage DC (LVDC), and Extra Low Voltage DC (ELVDC) has been stated in BS 7671 and IET Standard [31, 32]. As stated in the standard, the usage of HVDC, LVDC and ELVDC is shown in Table 2-2.

Table 2-2. Voltage Level Range

Voltage Category	Voltage Range	
	AC System (V)	DC System (V)
High Voltage	>1000	>1500
Low Voltage	50-1000	120-1500
Extra Low Voltage	0-50	0-120

High Voltage DC was known to be used in transmission power system. Based on some studies it was start to be cost effective for long transmission system (i.e >600km), as

benefit of lower power loss and power flow controllability would be able to achieve, compared to DC system properties' (i.e conversion device) costs [33]. But with current technology, conversion device cost starts to be cheaper that increases feasibility of DC system implementation.

Low Voltage DC (LVDC) has been commonly used for telecommunication cabling system. Besides that, Power Line Cable (PLC) technology is operated in LVDC to be an important part of SMART grid. It can be used to deliver power while delivering signal for telecommunication. LVDC itself has many benefits compared to AC especially on investment cost of the cable by using bipolar system and improvement of the power quality of the system. Moreover, the implementation of Power over Ethernet (PoE) cable to deliver cable for devices has been well established. Therefore, this system is being the reference for the development of LVDC for power distribution[34].

In the past few years, LVDC as power distribution system has been studied. Cable performance employed in LVAC and LVDC system has been compared thoroughly. From the works done by Borioli *et. al* cable in DC system can carry more power compared to cable in AC system at the same voltage level. Using bipolar-3-wire system could save more energy, by reducing losses in a cable [35]. These could be some advantages of using DC system to deliver electricity.

Migration of LVAC to LVDC or even to lower voltage level as Extra Low Voltage DC (ELVDC) System has been regulated by IET. This standard has confirmed that migration from LVAC to LV and ELVDC is viable with some procedures considered. The procedures before migration include [31]:

1. Equipotential bonding and the main earth conductor should be exist and accurate;
2. Unsuitable loads for d.c. system need to be removed;
3. Existing conductors need to follow BS7671;
4. All installed protection measures need to be practicable;
5. Reviews and re-designs of the existing protection system need to be done to support d.c. power distribution system;
6. Converted wiring need to be tested with accordance to BS 7671.

In Section 7 of the standard, for the migration the existing conductor from the existing system (LVAC) was used. In unipolar system 2 conductors was used. In other case, 3 conductors will be used in bipolar system. And in both cases earthing cable should not be used as power cable. In radial topology, LVDC and ELVDC can be installed directly as seen in Figure 2-14. In other hand, in loop/ring topology, ring circuit interruption need to be placed as shown in Figure 2-15. In the end, wiring mechanism of these configurations will follow Figure 2-14 for radial topology and Figure for loop/ring topology[31].

Figure 2-14. LV/ELVDC Configuration for Radial Topology[31]

Figure 2-15. LV/ELVDC Configuration for Loop/Ring Topology[31]

DC distribution system will give advantages when renewable energy becomes the main resources of the system. Besides that, there are so many DC loads in our building, such as LED TV, Notebook, and smartphone nowadays. DC loads which are supplied by DC grid will have higher power consumption efficiency compare to AC loads. Besides that, increasing the number DC loads will add more losses in the AC system, because of rectifier power loss. It means that when more DC loads involved in our system, then the DC grid will be more beneficial [36].

Replacing CFL to LED has been done by some works. Chen *et al* replaced CFL using LED directly by attaching driver which can be used with ballast. This method will simplify the replacement of CFL. Besides that, using LED in this system consumes less electricity [37]. In our research, we tried to accomplish the simplicity of replacement from LVAC to LV/ELVDC using existing installation cable. The migration of LVAC to LV/ELVDC follows IET Standard which shown in Figure 2-16. From Figure 2-16, DC bus could be obtained. Then for power distribution from bus to load following Figure 2-16 will have characteristics as stated in [33] that shown in Table 2-3. ELVDC was installed as an effort to achieve higher electricity savings and improve conducted safety performance.

Figure 2-16. Migration of LVAC to LV/ELVDC Using Existing 4-Wire Conductors

2.6 Safety Issues in DC System

One of the considerations using Extra Low Voltage DC is the safety concern. As shown in Figure 2-17 and Figure 2-18, human will get different effect responding to AC and DC electric shock. AC electric shocks with low frequency (from 15-100Hz) are the most dangerous. It may cause Involuntary Muscular Contraction, and for the worst scenario it may cause ventricular fibrillation which interrupts heart pumping behaviour and leads to death [38].

Figure 2-17 shows that it is safe for human to get contact to wire which only able to conduct current less than 200mA for duration less than 10ms. This Safe Zone is described as zone AC-1, and for zone AC-2 is described as Clear Zone for the area between zone-1 and zone-2 which involuntary muscular contraction may occur but will not harm the victim. And for the last zone, human would be in very dangerous condition when more than 500mA AC current flowing through their body regardless of the duration. That condition is described as Very Dangerous Zone in AC-3 zone.

Compared to Figure 2-17, Figure 2-18 shows that DC Current effect on human is less than AC system. For example, in the same current 100mA, AC system with more than 300ms duration will be considered as very dangerous in AC-3, but in contrast, in DC system 100mA regardless the time it will be considered in clear zone.

Figure 2-17. Zones of AC Current Effects (Left Hand to Feet at 15-100Hz)[38]

Electric shock effect depends on the type of current (AC or DC), magnitude, time, and duration of the current flowing through body. Human body impedance will differ according to wet/dry condition of body part, current path, and also gender [39]. Human Body Impedance model were also explained in [38] as shown in Figure 2-19. In other case, body model also was observed in medical system. Human body model was represented as internal partial impedances (R_{ip}) which consisted of resistors and capacitors in parallel connection. In [40], human impedance would be higher corresponding to higher frequency of the current flowing through body. Besides, the impedance also depends on the type of body part, from the works in [40], muscle had lower impedance than fat.

Figure 2-18. Lumped Circuit for Human Body Model[38]

Figure 2-19 shows the effect of current path and current conducting body part would affect the total body impedance. For example, if someone touched a line wire with one hand and both feet on ground which able to conduct electric shock, then the total body impedance would be $R_{ip} + (R_{ip} // R_{ip})$ equals to $1.5R_{ip}$.

For safety purpose, worst case scenario was used for calculation. In [41], value of human body resistance was about $650k\Omega$. But, in [42] the measurement showed that the lowest possible resistance of human body is $500-1000\Omega$, when worst case happened such as wet condition without insulation (barefooted).

Figure 2-19. Zones of DC Current Effects (Left Hand to Feet at 15-100Hz)[38]

2.7. Summary

From the literature review, it is important to understand the lighting standard that applies to certain types of room where lighting design installed. We found that there are some important factors in designing lighting system, such as lumen output per lamp, color rendering index and illuminance level requirement. Moreover, LED characteristics including the I-V curve and lifetime aspect had been explained to provide the basic understanding as we used LED to replace CFL. It is also important to understand the driving methods that are commonly used as driver for LED lamp. Previous study mentioned that common LED driver used filter, rectifier, and DC/DC converter. According to these current evidences, we proposed a novel system that removes DC/DC converter because the voltage level still can be provided from DC grid. LVDC and ELVDC system were reviewed to understand the terminology and the potential benefit of DC grid application. In addition, study of safety issues in DC grid leads to understanding of potential benefit of using low level voltage DC grid.

Chapter 3

3. Retrofit of Lighting System

This chapter describes the selection of lighting luminaries to replace existing luminaries, and also the characteristics of chosen luminaries. The experiment was done to understand the basic need of providing a certain number of lumen as per the building standard and code. So that, experiment to test the compatibility of LED in replacing CFL and choosing the right type of diffuser was done. The selection of the luminary would be essential for this research to design light system for common area, as it affected electrical calculation for the next chapter which discusses about design suitable ELVDC. In general, lighting system in Singapore is required to follow the standard from SS531 2006. In this research, the lighting luminary was tested in recommended voltage range which is according to maximum voltage drop 4% tolerance and 6% tolerance [43].

3.1 LED Lamp Performance

Solid state lamp is already been well known as replacement for conventional lamp, such as lamp bulb and CFL. This research studied the characteristic of LED lamp and also the effect of LED module's shape. Basically, LED module is constructed by LEDs and resistors. This typical LED's strip circuit will be shown in Figure 3-1.

Figure 3-1. Typical Circuit of LED Strip

Figure 3-1 shows that inside LED strip there are some LEDs and also resistors that connected in series and parallel. This series connection is used to achieve LED's module voltage rating. In the case of GaN as the material to make LEDs module, it has 3.8V forward voltage. When 6 LEDs connected, it will have forward voltage. In order to get the best LED performance, some evaluations were done such as shape effect, and also diffuser effect. As reference for this experiment, LED strip was performed.

Figure 3-2. V-I Curves of LED Strip

Firstly, the V-I diagram for the LED as seen in Figure 3-2 represented the LED evaluation. Figure 3-2 also shows the forward voltage of this LED is 15V. This means that this LED could produce light for voltage level over 15V. Besides that, Figure 3-2 shows that LED lamp had linear relationship between voltage and current after 16V. Then, for the operation of this lamp over 17V, it could be approached using linear relationship as seen in equation (3.1).

$$I = 0.06V - 1 \quad (3.1)$$

$$R = \frac{100}{6} \left(1 + \frac{1}{I} \right) \quad (3.2)$$

From equation (3.1), it was known that the resistance value of LED strip while operating depends on the value of current flowing through it. Usually, in other typical circuit the relationship of voltage, current and resistance is only make one of them

constant by letting others changing. But, in this case, three of them were not constant which means LED Strips had differential resistance. This phenomenon made the calculation of the current flowing through LED strip would be based on voltage input following equation (3.1) and affecting resistance which follows equation (3.2).

Equation (3.2) shows that LED Strip has two components of resistance. First component was resistance that was independent to current. Second component was resistance that linearly decreased according to current value; it represented power consumed by LED to be used. Thus, the constant resistance for this LED strip was 16.67ohm. This value of constant resistance could be added to other resistance while connected in series for evaluation, for example cable resistance.

1. Shape effect evaluation

Light distribution of luminaries is one of the considerations for lighting design. In this section, different lighting shape was used to understand the effect of lamp shape. The evaluated shapes in this research are linear, parallel linear, and circular. In order to understand the effect comparably, the same lamp is used, but changing position of its component. It can be achieved by using cut-able LED strip.

Figure 3-3. Lighting Test Room

Firstly, this experiment was done in the room without other light source. The set up for the room is shown in Figure 3-3. Then, for the reference the linear shape was tested. The measurement of illuminance was done by using lux meter at 1m height and on floor. Figure 3-4 shows the result of LED Strip lumen test area.

Illuminance metering was done on 9 difference position. The size of each box is 60x60 cm². Then the result of measurement of illuminance on the floor is shown in the Table 3-1. After 20 lux people start to recognize other’s face. The result shows that LED strip can provide enough illuminance to recognize other’s face after 21.5V. Besides that, the uniformity of this LED strip was only 65%. LED’s uniformity result shows that LED strip produce direct lighting which could be the disadvantage of this lamp as glaring effect likely to occur. The shape of LED as strip also affected of higher illuminance level at position 6 than position 8. The difference of the level was 1.82lux on average.

Figure 3-4. Measurement Position

Table 3-1 shows that the lumen production on floor was not sufficient as there some parts of the area that has under 20lux of illuminance level. This result was measured on floor. Then, other experiment at 1m distance to floor was done to understand the difference light distribution on closer distance or at 1.5m distance from light source.

Table 3-1. Illuminance Level on Ground of LED Strip

No.	Voltage (V)	Current (A)	Position								
			1	2	3	4	5	6	7	8	9
1	20	0.21	16	20	19	26	27	33	28	29	36
2	20.5	0.24	18	24	20	28	29	36	28	33	42
3	21	0.26	19	24	22	33	29	40	30	35	45
4	21.5	0.29	21	28	24	35	34	43	33	37	47
5	22	0.32	23	31	26	36	35	46	37	40	53
6	22.5	0.35	24	36	27	37	37	46	38	43	54
7	23	0.38	26	38	32	38	41	51	40	43	59
8	23.5	0.41	28	38	35	43	40	55	43	44	62
9	24	0.44	29	40	34	47	41	54	46	50	65
10	24.5	0.47	33	41	36	49	44	60	47	50	68
11	25	0.5	34	42	37	49	47	62	47	52	71
12	25.5	0.53	35	46	48	52	49	63	48	55	73
13	26	0.56	33	41	35	44	49	65	49	56	76

The illuminance level at 1m is shown in Table 3-2. As the result in Table 3-1 shows that the light production of this LED strip was symmetrical, then for Table 3-2 shows the result for position 6 to 9, using the assumption that 6 with 2, 1, 3 and 5 with 7, and 4 with 8 had equal illuminance level.

Table 3-2. Illuminance Level at 1m of LED Strip

Voltage	Position			
	6	7	8	9
20	53	41	55	70
22	76	52	60	98
23	83	57	63	112
24	93	65	76	121
25	101	71	80	134
26	112	84	97	159

Table 3-2 shows that the illuminance level of the LED was higher than on floor. The ratio of the lumen could be more than twice. The uniformity at 1m was improved to be 73.5% compared to on floor measurement. The strip shape of LED caused higher illuminance level at position 6 than position 8. The difference of the illuminance level was 10.17lux on average.

Parallel shape and circular shape were tested by the same power supply at 24Vdc and using same LED. The LED was reformed to be 3 bars and positioned in parallel to each other as shown in Figure 3-5. The circular form was reconstructed to be in circular position with single bar in the centre as shown in Figure 3-5. The results of those experiments are shown in Table 4 to compare the effect of changing shape of LED.

Figure 3-5. LED Strip (left), Parallel LED (middle), and Circular LED (right)

Table 3-3 shows that the illuminance level of parallel form has wider range with the side area at point 8 had higher illuminance level, but the illuminance level at point 6 decreased as post effect of length reduction of the LED luminary. Besides that, the illuminance level under luminary just slightly decreased.

Table 3-3. Comparison of LED Performance for Different Shape

Voltage	Position			
	6	7	8	9
LED Strip	93	65	76	121
Parallel	84.4	70	96	118
Circular	95.2	74	92.2	112

Table 3-3 shows that circular shape has the balance illuminance level which point 6 and point 8 have similar illuminance level. In addition, circular shape

could increase illuminance level in the diagonal point 7. In the other hand, the illuminance level decreased as the effect of spreading the LED bars.

2. Diffuser Effect

In order to increase range of light distribution, diffuser can be an option besides changing LED's shape. Besides that, lamp cover will protect luminary from dust and water which can reduce the life time of luminary. LED lamp needs to have suitable optics to control light output [44]. In this experiment, solid colour and clear-matte diffusers were evaluated.

Figure 3-6. Solid Colour Lamp Cover

Solid Colour cover lamp was made by plastic with white solid colour as shown in Figure 3-6. This diffuser reduced glaring and caused the light distribution more even. The drawback of this diffuser was the reduction of illuminance level up to 50% which was too high.

Figure 3-7. Clear-Matte Cover

The other type of diffuser is clear-matte. This diffuser was made from glass and it had matte texture in some parts to diffuse the light. It had better performance to deliver the light, and also reduced glaring visually. This type of cover is shown in Figure 3-7.

Table 3-4. Diffuser Effect

Voltage	Position			
	6	7	8	9
Without diffuser	84.4	70	96	118
Solid colour	48	34	44	74
Clear-matte	74	64	80	108

In this experiment, the LED strip was shaped to parallel form to be fitted inside lamp cover/diffuser. Therefore, the LED parallel measurement result would be the reference for diffuser effect experiment. The result of this experiment is shown in Table 3-4.

3.2 Summary

Based on the experiment results shown in Chapter 3.1, LED with higher lumen production, strip shape and clear diffuser is selected to retrofit existing lamp in common area. Higher lumen production of the LED was achieved by selecting other LED lamp product which used different LED material. By selecting different material, LED could produce higher lumen at the same wattage. It means that the selected LED lamp, has higher efficacy (lumen/watt).

By using higher efficacy LED lamp, producing 162lux at 24V, a single lamp was able to meet the minimum illuminance level at 150lux. In contrast, using lower efficacy LED lamp, producing 121lux at 24V, two LED lamps were needed to meet the requirement. Thus, using higher efficacy lamp may lead to potential savings in the long run.

Figure 3-8. LED Lamp with 120deg Angle

Dimension of the area for lighting system determines lamp's shape option. As the form of stair case which will be retrofitted in this project was rectangular, thus LED

strip was the better as an option. Besides that, to protect LED luminary from dust and water the diffuser was chosen. This diffuser was able to make LED lamp produce 120° angle as shown in Figure 3-8. In the end the LED lamp had been tested to understand its characteristic. Its testing result is shown in Table 3-5. Table 3-5 shows that the illuminance level increased, but it has higher power consumption as shown from current value that increased.

Table 3-5. Higher Efficacy LED Lamp Performance

V	I	POSITION			
		6	7	8	9
23	0.26	100	74.5	97.5	138
23.5	0.3	108	83.5	108	152
24	0.33	121	95.5	117	162
24.5	0.36	125	103	128	178
25	0.4	133	107	133	191

From the V-I relationship of this LED lamp is shown in Figure 3-9. Figure 3-9 tells that current drawn by this LED lamp followed equation (3.3) and equation for resistance value of this lamp followed equation (3.4);

Figure 3-9. I-V Curve of Osram LED

$$I = 0.0681V - 1.3046 \quad (3.3)$$

$$V = 14.6843I + 1.3046 \quad (3.4)$$

Compared to previous LED strip, this LED lamp had lower internal resistance value and produced higher power consumption.

Chapter 4

4. ELVDC Evaluation

This study evaluated the feasibility of ELVDC system with LED lamp for retrofitting HDB flats' lighting system which used AC system topology with CFL. Feasibility of ELVDC implementation will be decided according to the electrical performance, such as: voltage drop, harmonic, safety, and efficiency. Based on the power savings of the system, pay-back period and Net Present Value (NPV) of the system can be calculated.

In this study, we compared ELVDC topologies to AC power distribution topology. The ELVDC topologies include Unipolar ELVDC and Bipolar ELVDC. Both topologies were chosen because AC system could be migrated to DC grid using both topologies following IET standard. As comparison, AC system with LED lamp was also evaluated in this chapter. These topologies were simulated in MATLAB to understand the voltage and current waveform in each load. Moreover, harmonic evaluation was done using MATLAB. Voltage drop, power loss and efficiency of the system was evaluated based on cable loss and lamp power consumption.

4.1 Topology of ELVDC Distribution System

Previous works done by Chen *et al.*[37] provided method to drive LED using existing ballast which concluded that LED could be used as replacement of CFL Lamp. There is also another works done by Tan *et al.* [6] explained the method to drive LED without ballast and using driver operated in DC system which claimed that the design could achieve 44.23% savings in user-preference-control mode. Then, this research studied the effect of using direct operation of LED as lighting system. Further explanation of the system used by conventional AC system driving CFL and LED is shown in Figure 4-1.

Figure 4-1 shows the typical topology for AC system to drive CFL. This system was not efficient as ballast consume some electricity. From this topology, Chen *et al.* replaced CFL to LED luminary with installed driver as shown in Figure 4-2. This system proved to be a simple way to retrofit CFL to LED, this system operated 20W LED to replace 36W CFL. In that time, their LED products produced 50lm/W [37].

The driver of the LED lamp would consume electricity. That was the drawback of the system.

Figure 4-1. Topology of AC system with CFL

Figure 4-2. Topology of AC system with LED Lamp

Then, Figure 4-3 shows the topology that Tan *et al.* studied about the driving method for LED using driver supplied by DC Grid, and without ballast. This method could reduce power consumption by 13.5% when without controlling scheme used. The controlling method of this system had the highest effect when daylight was involved to illuminate the room, then after operating user-preference method, the system achieved

44% savings [6]. Drawback of this system was the DC/DC driver efficiency and daylight dependant to reach highest savings.

Figure 4-3. Topology of DC System with DC/DC Driver for LED Lamp

The proposed topology as seen in Figure 4-4 will be evaluated in this research. This topology did not use driver in order to increase more power savings. The voltage drop from DC grid to lamp will contribute to the system loss. Therefore, it was one of the concerns in ELVDC system design.

Figure 4-4. Topology of Driverless DC System for LED Lamp

4.2 Voltage Drop Evaluation

Based on Singapore standard, the size of typical cable for residential building is 2.5sqmm size. This cable emulates the real case of HDB flats' condition. Thus,

retrofitting of HDB flats' electrical system could be evaluated. This cable has its own properties. Based on Singapore Standard it has typical internal resistance as much as 0.18ohm/m. Maximum voltage drop (V_{drop}) allowed is 4% tolerance and 6% tolerance (for lighting purposes). It means that for 230Vac system the voltage maximum voltage drop to the load is 9.2V. For ELVDC, there is still no regulation about voltage drop. Thus, applying the same regulation to ELVDC is the simplest way to evaluate ELVDC system in the beginning. This voltage drop is affected by the system cable dimension. Therefore, cable dimension of the system need to be measured.

Figure 4-5. Top View of Electrical Installation System

For calculation, wiring dimension in the typical HDB flats building staircase (e.g. staircase at Toa Payoh Block 423) is shown in Figure 4-5 and Figure 4-6. Figure 4-5 shows the existing condition of electrical installation. From top view it was clear that the cable length of the main trunk to distribute from one side trunk to another trunk was 6.5 m in the first floor. In addition, from the main trunk to load, there was 1.25 m branch cable (cable with green colour in Figure 4-5 and Figure 4-6). Then, each trunk went vertically up to 12 floors to deliver power. Since the electrical installation used 2 main trunks, then for each trunk was responsible to deliver 12 lamps each. Then Figure 4-5 shows that each floor was 2.5 m

height. The cable size and length affect internal resistance value. So it is important to understand the cable dimension. For technical analysis in the following sections would evaluate deeper using the dimension shown in Figure 4-5 and Figure 4-6.

Figure 4-6. Side View of Electrical installation System

1. Reconfiguration of the wiring

Initial evaluation is made by using one of rectifier product and also the cable specification as CP 5 listed. The information follows:

Rectifier:

Maximum power : 500W
 Input voltage : 220Vac
 Output voltage : 24Vdc
 Efficiency : 90%

Cable:

Size : 25mm²
 Internal resistance : 18mV/A per m (for Line and Neutreal Cable) or 9mV/A (per cable).

Figure 4-7. Reconfiguration of Existing Wiring System

By using the details of cable above and existing wire installation as seen in Figure 4-5 and Figure 4-6, this section will try to evaluate the effect of reconfiguration of wire installation. Figure 4-7 shows that reconfiguration of the system required wire connection to be inside of the main trunk uPVC. This reconfigured wiring would make two wires unused from trunk to load which able to reduce cable resistance from main trunk to load.

Figure 4-8. Reconfiguration Effect of Wiring System

For example, in the existing installation, each floor distance was 2.5m, and from main trunk to load was 1.25m. Thus total distance between loads to another load in a higher floor would be 5m with no distance from node (place for the cable connection) to load.

In contrast, total distance between loads to another load in a higher floor would be 2.5m. But, this configuration required cable from node to load with 1.25m in length. The significant benefit of this system happens when the main trunk (bus) handling accumulated loads current as shown in Figure 4-8 as illustration.

As shown in Figure 4-8(b) cable in main trunk would handle the same accumulated current in a shorter distance cable. It means that the power loss of the cable could also be reduced. While power loss in cable of main trunk is stated in equation (4.3) and power loss in cable from node to load is stated in equation (4.4).

$$P_{cable\ loss} = I^2 \times Rcable \quad (4.1)$$

$$P_{cable\ loss} = P_{cable\ loss\ main\ trunk} + P_{cable\ loss\ node\ to\ load}$$

$$\begin{aligned} P_{cable\ loss\ main\ trunk} &= I_1^2 \times Rcable_{main\ trunk} + (I_1 + I_2)^2 \\ &\times Rcable_{main\ trunk} + (I_1 + I_2 + I_3)^2 \\ &\times Rcable_{main\ trunk} \\ P_{cable\ loss\ main\ trunk} &= (I_1 + (I_1 + I_2) + (I_1 + I_2 + I_3))^2 \\ &\times Rcable_{main\ trunk} \end{aligned} \quad (4.2)$$

For n number of loads we use equation (4.3), as follows

$$P_{cable\ loss\ main\ trunk} = \sum_{i=1}^n \left(\sum_{k=1}^i I_k \right)^2 \times Rcable_{main\ trunk} \quad (4.3)$$

$$\begin{aligned} P_{cable\ loss\ node\ to\ load} &= I_1^2 \times Rcable_{node\ to\ load} + I_2^2 \\ &\times Rcable_{node\ to\ load} + I_3^2 \times Rcable_{node\ to\ load} \end{aligned}$$

$$P_{cable\ loss\ node\ to\ load} = (I_1 + I_2 + I_3)^2 \times R_{cable\ node\ to\ load} \quad (4.4)$$

For n number of loads we use equation (4.5), as follows

$$P_{cable\ loss\ node\ to\ load} = \left(\sum_{i=1}^n I_i \right)^2 \times R_{cable\ node\ to\ load} \quad (4.5)$$

For example, if each load took 1A and R_{cable} is $18m\Omega/m$, then total power loss in existing system as seen in Figure 4-8 (a) would be 1260mW.

$$P_{cable\ loss} = (1 + (1 + 1)^2 + (1 + 1 + 1)^2) \times (5 \times 0.018) + 0$$

$$P_{cable\ loss} = 1260mW$$

In contrast, power cable of the reconfigured wiring system would be as stated in calculation below would be 697.5mW. From this example, by reconfiguration (as seen in Figure 4-8 (b)) power loss in the system by cable was reduced by 562.5mW or 44% less than existing configuration (as seen in Figure 4-8 (a)). Thus in the following simulation, configuration of the system followed proposed configuration as reconfigured wiring configuration.

$$P_{cable\ loss} = (1^2 + (1 + 1)^2 + (1 + 1 + 1)^2) \times (2.5 \times 0.018) + (1^2 + 1^2 + 1^2) \times (1.25 \times 0.018)$$

$$P_{cable\ loss} = 630mW + 67.5mW$$

$$P_{cable\ loss} = 697.5mW$$

2. 4% voltage drop regulation evaluation

Based on the information in sub-section 1 above, we tried to find the maximum cable length possible when drawing maximum power from rectifier. As the voltage reference of this system is 24Vdc (assumption made to be there was no Vdrop in the supply because of load effect). Then, Voutput was set to be 24V plus 4% tolerance in percentage (%), it will be 25.44V. The maximum Vdrop which follow equation (4.5) became only 1.92V.

$$Vd = I \times R \quad (4.5)$$

For single phase two wire system, the voltage drop was affected by 2 wires. Besides that, if we use the main voltage input to be within tolerance, then voltage level would be adjusted with the tolerance. Thus the voltage drop followed equation (4.6);

$$Vd = \frac{P_{out}}{V_{out}} \times R_{cable} \quad (4.6)$$

If internal resistance is proportional to the length of the cable, then the function of the maximum length of the cable for main trunk will follow equation (4.7):

$$l = Vd \times \frac{V_{out} \times (1 + tolerance)}{P_{out} \times R_{cable}} \quad (4.7)$$

$$l = 0.96 \times \frac{24}{500 \times 2 \times 0.009}$$

$$l = 2.56 \text{ m}$$

where

Vd	: voltage drop	(V)
I	: current flowing through the cable	(A)
R	: Resistance of the system	(Ω)
R _{cable}	: internal resistance of the cable	(Ω)
l	: length of the cable	(m)

Based on the evaluation, the maximum length of the cable for drawing 500W was only 5.32m. This evaluation shows that retrofitting building electrical system using one rectifier was not feasible to meet 4% voltage drop regulation as in the LVAC system regulation. With the assumption of the height of the typical height of common area room (corridor and staircase) was 2.5m. Thus, 2.56m was not feasible to be implemented as main trunk in real system.

3. 6% voltage regulation evaluation

Since there was still no voltage drop regulation in ELVDC system, and also the LED lamp was able to be driven when forward voltage was above 15V, this research tried to use 6% tolerance of the voltage following electrical installation guide based on IEC standard. Then, with 24Vdc as reference, thus the maximum voltage drop would be 1.44V.

$$l = Vd \times \frac{V_{out}}{P_{out} \times R_{cable}}$$
$$l = 1.44V \times \frac{24V}{500 W \times (2 \times 0.009\Omega/m)} = 3.84m$$

Using 6% regulation, the maximum length of the cable was proved to be increased to be as high as the ratio of the voltage drop tolerance, in this case 1.5 times. The assumption in this case was only single load that supplied using a cable. Thus, 3.84m would be the maximum distance for 500W load to the main supply.

4. Dividing loads evaluation

From the previous evaluation, drawing 500W using with typical cable in building as main trunk was not feasible. This research tried another approach to use the typical cable to supply smaller power consumption of the load. It means that the rectifier would not be operated at its maximum power rating. In this evaluation, the maximum loading for one main trunk was set to be 100W. Then, the maximum length of the main trunk for 100W, with 6% voltage drop regulation, would be 19.2m as seen in the calculation below.

$$l = Vd \times \frac{V_{out}}{P_{out} \times R_{Cable}}$$
$$l = 1.44V \times \frac{24V}{100 W \times (2 \times 0.009\Omega/m)} = 19.2m$$

This evaluation provided the proof that dividing loads or using smaller load power consumption may increase length. The maximum feasible length was

19.2m for the distance between total loads in single node at 100W. Thus, from the evaluation above, the feasible solution to implement ELVDC without changing the existing electrical installation was using 6% tolerance for voltage drop and using around 100W maximum loading for main supply cable.

4.3 Simulation for LED Lighting System Topologies

A. AC System with Individual LED Driver

The topology of the system is shown in Figure 4-9. Figure 4-9 shows that every LED would have dedicated AC/DC Driver. This AC/DC Driver was simulated and evaluated in this section.

Figure 4-9. Topology of AC System with Individual LED Driver

Before simulation of the system was done, verification of LED modelling was simulated using MATLAB to represent the actual LED used. The I-V curve of actual LED curve is shown in Figure 3-9 in Chapter 3.

Figure 4-10. Simulation Result of "Current Vs Time Characteristic of LED"

It will use configuration as seen in Figure 2-5. The configuration as seen in Figure 4-11 was used for each lamp, and then the harmonics effect of the lighting system would be accumulated. In this analysis, one driver for one lamp had been evaluated and simulated using MATLAB as shown in Figure 4-10.

For system using AC system, it requires AC/DC Converter for the lighting. Typically,

Figure 4-11. LED Driver for Each Lamp in AC System

In this simulation, LED Driver's design was using full-bridge diode with inductor and capacitor to reduce ripple output as Rectifier. The output voltage of rectifying of the system is shown in Figure 4-13. Figure 4-13 shows that out voltage from rectifier will be DC with 311V of voltage level. This model was able to represent ideal system of 220V AC supply to be rectified to DC out voltage with 0.02% voltage ripple or 0.063V.

Figure 4-12. Simulation of LED Driver for Each Lamp in MATLAB

This LED Driver model used rectifier configuration following [45]. Using Figure A-1, 2ohm series resistance (R_s) and 2μF capacitor (C_d) was placed. Besides that, the driver also used DC/DC Converter. The DC/DC Converter design used Cuk converter technology as seen in Figure 4-12. If the desired output voltage was 24 V with 0.5% ripple voltage, 0.5% ripple current at load and source (after rectifier part) side. with 50kHz for switching frequency, the parameter of duty cycle, inductance and capacitor follow [46] as seen in calculation below.

Duty cycle (D):

$$D = \frac{V_{dc}}{V_{dc} + V_s}$$

$$D = \frac{24}{24 + 220} = 0.098$$

Inductance:

L1 (inductance at source side)

$$L_1 = \frac{V_s(1 - D)}{\Delta I_{L_1} \times f_s}$$

$$L_1 = \frac{220(1 - 0.098)}{0.05 \times 50000} = 0.016172 \text{ H}$$

L2 (inductance at load side)

$$L_2 = \frac{V_{dc}(1 - D)}{\Delta I_{L_2} \times f_s}$$

$$L_2 = \frac{24(1 - 0.098)}{0.005 \times 50000} = 0.086592 \text{ H}$$

Figure 4-13. Rectified Wave in LED Driver Model

The output of Cuk converter was expected to be 24V with assumption of using ideal components. So that, there would be no current leakage in passive components and voltage drop in switches. From simulation, output voltage of diode is shown in Figure 4-14.

Figure 4-14. Output of Cuk Converter for LED Lamp

Figure 4-15. Output Current from Power Supply and Harmonics Level of the Current

Figure 4-14 shows that voltage output at load point is stable with 0.6 to 1 volt ripple or 2.5 to 4% voltage ripple. The current drawn by load also shows that LED model was behave accordingly as representation of the tested LED.

Without inductor filter and power factor corrector, this system produced THD of 119.32%. It was the result of DCM mode of current wave output in the AC power supply as seen in Figure 4-14. Thus, the approximate calculation of the THD as seen in Figure 4-15 can be done using equation (2.10), as follows :

$$THD = \sqrt{\frac{I_3^2 + I_5^2 + I_7^2 + I_9^2 + I_{11}^2 + I_{13}^2 + I_{15}^2 + I_{17}^2}{I_1^2}}$$

$$THD = \sqrt{\frac{0.85^2 + 0.63^2 + 0.2^2 + 0.1^2 + 0.1^2 + 0 + 0.05^2}{1^2}}$$

$$THD = \sqrt{\frac{0.7225 + 0.3969 + 0.16 + 0.04 + 0.01 + 0.01 + 0 + 0.0025}{1}} = 115.8\%$$

Figure 4-16. Filter at Supply Side

Design of PFC followed the guidance in[23, 27, 29, 30]. Filter was placed at supply side with 6.2k Ω of resistor, 10H of Inductor and 1 μ F of Capacitor. After using Filter, as seen in Figure 4-16, THD of the system was reduced to be 7.06% as seen in Figure 4-17. By reducing harmonic distortion value, the current waveform transformed to be similar to sinewave as shown in Figure 4-18.

Figure 4-17. Harmonic Component After Using Filter

Figure 4-18. Current Waveform in Supply Side after Placing Filter

A.1 Efficiency Analysis of AC System with Individual LED Driver

Simulation result of the system is shown in Figure 4-13. The Figure shows that load voltage level would be from 23.9V to 24.05V. By using individual driver, HDB flat block was able to be retrofitted by using one LED Driver for each Lamp, so there would be 24 drivers for 12-floor HDB flat's block. By using reconfigured wiring system configuration, evaluation of AC system with individual LED driver was conducted for different distance (height of the floors) and different power consumption of LED Lamp. Then, voltage level of each load will be shown in Figure 4-19.

As compared to AC system with CFL, 8W LED Lamp with individual driver would save more energy. The performance of LED lamp in AC system with individual driver is shown in Table A-2. Table A-2 shows that power consumption of the loads would be 192W.

Figure 4-19. Load Voltage Level in AC with Individual LED Driver

The efficiency in this system depended on the cable voltage drop and driver's efficiency. Then, the calculation of voltage drop followed equation (4.8);

$$\eta = \frac{P_{out}}{P_{in}}$$

$$\eta = \frac{\sum(V_l \times I_l)}{P_{loads} + P_{loss}} \quad (4.8)$$

In AC system as seen in Figure 2-5, LED Driver used AC/DC Conversion stage and DC/DC Conversion stage with typical efficiency of AC/DC Driver was 93-97% and DC/DC converter was 94%. Thus, typical power conversion loss would be combination of AC/DC conversion efficiency and DC/DC conversion efficiency. With best scenario of this system, AC/DC Driver with efficiency of 97% and DC/DC conversion efficiency of 94% would make the LED driver efficiency reaches 91.18%.

In this experiment, by using 24 loads of each trunk to supply 12 floors, the total power out would be 192 W. Using 91.18% total driver efficiency, and cable power loss between power consumed by LED lamp could be transformed to 210.57W. So that the total efficiency would be 91.03% as follow;

$$\eta = \frac{192}{\frac{192}{0.97 \times 0.94} + 0.002 + 0.338}$$

$$\eta = 91.03\%$$

A.2. Safety Analysis in of AC System with Individual LED Driver

Safety analysis was conduct by using worst case assumption. The assumption was using lowest human body resistance (in wet condition). Besides that the electric shock occurred in the nearest place to power supply.

Figure 4-20. Electric Shock in AC System with Individual LED Driver

In this section, there were two schemes for victim to touch wire. Scheme A was the best position as only one hand touching the wire and one foot on ground. Scheme B would be the worst case scenario as body part touched line wire with both hand and both feet on ground. This scheme is illustrated in Figure 4-20. The detail of fault current and total human body resistance is shown in Table 4-2.

With the scheme as seen in Figure 4-20, the victim will be affected by 220Vac flowing through his/her body. The body resistance follows calculation as seen in Table 4-1.

Table 4-1. Fault Current for AC System with Individual Driver

Scheme	Equivalent Human Body Resistance	R _{body} (Ω)	I _{fault} (A)	Max duration (ms)
A	$body = R_{ip} + R_{ip} = 2R_{ip}$	1000	0.22	220
B	$R_{body} = (R_{ip} // R_{ip}) + (R_{ip} // R_{ip})$ $= R_{ip}R$	500	0.44	32

With R_{ip} equals to 500Ω , the current flowing through would be $0.44A$ with frequency of $50Hz$. Figure 4-21 shows that maximum duration for current flowing through in the body was $32ms$. It shows that after $32ms$ it would be categorized as very dangerous zone which people might get ventricular fibrillation, so that quick response switch to open circuit was needed. Thus, the circuit breaker for this system should operate to make open circuit in below $32ms$.

Figure 4-21. Fault Current on Human Body Effect in AC System

B. Unipolar System with 24Vdc Power Supply

The topology of the system was using flyback converter as driver with $24V$ output voltage. Then, this topology was evaluated to understand the harmonics level and maximum loads in a branch. The design is shown in Figure 4-22.

Based on section 4.1., ELVDC of this system used 6% voltage drop regulation. By using DC system in steady state as assumption, the reactive component of the cable will not affect the system's voltage drop. Then only resistive part of the system will contribute to voltage drop. From Chapter 3, LED lamp has the similar character to resistor. The equivalent circuit for the system is shown in Figure 4-23.

Figure 4-22. Unipolar 24V Driverless Topology

For the analysis the main trunk and branches was distinguished to have different value of resistance. The resistances of the main trunk were labelled y and the resistances of branches are labelled as x . Then, current flowing through circuit would have specific value depending on load voltage level. Then the voltage drop in the last load of the system relationship will follow equation (4.9), equation (4.10) and equation (4.11) below.

$$Vd = I \times R$$

$$Vd = IR_{y1} + (I - I_1)R_{y2} + (I - I_1 - I_2)R_{y3} + \dots + (I - I_1 - I_2 - \dots - I_{n-1})R_{y(n)} + I_l R_{xn} \quad (4.9)$$

$$Vd = IR_{y1} + (I_2 + I_3 + \dots + I_n)R_{y2} + (I_3 + I_4 + \dots + I_n)R_{y3} + \dots + I_n R_{y(n)} + I_l R_{xn} \quad (4.10)$$

$$Vd = \sum_{i=1}^n R_{yi} \left(\sum_{k=i}^n I_k \right) + I_l R_{xn} \quad (4.11)$$

Where;

- V_d : Voltage drop
 I : Total current of the system
 I_l : Current in the load
 R_y : Resistance in main trunk
 R_x : Resistance in branch
 N : the number of branches

Figure 4-23. Equivalent Circuit of ELVDC

In fact that the cable resistances are proportional to its length and constant (based on CP 5, it is 0.018Ω). Besides that, the length of cable within floors and each branch to main trunk were same. The function of the voltage drop would follow.

$$Vd = 2 \times 0.009 \left(\sum_{i=1}^n l_{yi} \left(\sum_{k=i}^n I_k \right) + I_l l_{xn} \right) \quad (4.12)$$

Where;

l_y : length of cable between node that related to resistance in main trunk

l_x : length of cable in branches of each load

Moreover, in this research, cable length between one floor to another floor was assumed to be the same. So that, R1, R2 until Rn would have the same value. Current flowing through each load (I_l) was recognized as I_1, I_2 until I_n . Resistance internal of the branch cable was added to resistance of LED lamp as stated in equation (4.12). Then, LED lamp could be treated as load on main trunk as shown in Figure 4-24.

Figure 4-24. LED Circuit Treated as Load on Main Trunk

By using equation (3.4) as the value of internal resistance of LED lamp, total resistance of the cable and LED lamp followed equation (4.13). And then, the load model would be using equation (4.15).

$$R = R_{cab} + R_{led} \quad (4.13)$$

$$R = (2 \times 1.5 \times 0.009) + \left(\frac{1}{0.0681} \left(1 + \frac{1.3046}{I} \right) \right)$$

$$R = \frac{1}{0.0681} \left(\left(1 + \frac{2 \times 1.5 \times 0.009}{\frac{1}{0.0681}} \right) + \frac{1.3046}{I} \right)$$

$$R = 1.0018387 + \frac{1.3046}{I} \quad (4.14)$$

$$I = 0.06785V - 1.29982 \quad (4.15)$$

Where;

Rcab : internal resistance of the cable (Ω)

Rled : internal resistance value of LED Lamp (Ω)

The topology of the system was using flyback converter with 24V output voltage level. Then, this voltage would be connected to LED lamps using diode and capacitor as shown in Figure 4-25.

Figure 4-25. Unipolar ELVDC Using Flyback Converter

Simulation result of the system is shown in Figure 4-26. The Figure shows that all loads reached 22.6V at minimum and 23.9V at maximum load voltage level. It shows that it was above the minimum requirement voltage level (6% or 22.56V). Figure 4-26 shows that load in the first floor 1A had the highest voltage level, as the result of the

shortest distance between load to the power supply. And also, 8B had the lowest voltage level as the longest distance between load to power supply. After 16 loads, voltage drop in the last load had violated the limit. Thus, after floor 8B, another AC/DC Converter was operated. After operating additional AC/DC Converter, the voltage of each load followed the curve shown in Figure 4-26.

Figure 4-26 shows that the voltage drop of the system was not linear. Decreasing of the voltage level in loads reduced the current drawn by the loads, and then it made the voltage drop of the system in nodes not linear. From this curve, the maximum number of loading for single AC/DC Converter was 16 lamps which are still able to meet the voltage drop requirement (up to floor 8B). Moreover, for the remaining loads, another AC/DC Converter was required to drive the remaining loads in each case as seen in Figure 4-26.

Figure 4-26. Voltage Drop Evaluation of Unipolar System

Besides that, by using reconfigured wiring system configuration, evaluation of Unipolar ELVDC system was also conducted with different distance (height of the floors) and different power consumption of LED Lamp (for case which might happen in other building design). Then the best scenario of Figure 4-25, 8W LED lamp with 2.5m height between floors, was used for further analysis.

B.1. Efficiency Evaluation of Unipolar ELVDC

Figure 4-27. Load Voltage Level in Unipolar System

Simulation result of the system is shown in Figure 4-26. The Figure shows that all loads reached 22.6V at minimum and 23.9V at maximum load voltage level. It shows that it was above the minimum requirement voltage level (6% or 22.56V). Figure 4-26 shows load in the first floor 1A will have highest voltage level as it will be the nearest load to the power supply, and 8B will have the lowest voltage level as the furthest load to power supply. Table A-3 shows the voltage level and power consumption for each load in the system. It shows that lowest voltage level is 22.654V at load 8B.

In this experiment, by using 24 loads of each trunk to supply 12 floors, the total power out was 158.73W. In other hand, total power supplied was 101.28W. The details of the current of each load and the voltage drop is shown in Table A.3. Thus the efficiency is calculated as follow;

$$\eta = \frac{158.733}{158.733 + 0.09 + 4.703}$$

$$\eta = 97.069\%$$

This efficiency value was very high as the effect of not considering driver efficiency value. In ELVDC the AC/DC Converter typically has 93-97% efficiency and DC/DC Converter has 93-98%. Then, in this analysis, total highest converter efficiency would be 95.06%. Thus, using 95% total Converter efficiency, this unipolar topology design will achieve **92.216%** of efficiency.

B.2 Safety Issues Analysis of the Unipolar Topology

Safety analysis in this section used the assumption and parameter in the section A.2 with worst case assumption. The different aspects in this scheme were DC system operation and lower voltage level.

In unipolar system there were 2 schemes of fault current conducted through victim as shown in Figure 4-28. These schemes are same similar to the schemes in section A.2. Then, by using the same method as mentioned in A.2, this system would have fault current value stated in Table 4-3.

Figure 4-28. Electric Shock in Unipolar ELVDC System with Scheme A and B.

By using 24V, current flowing through body would significantly become lower, as in this system, maximum fault current would be 0.048A which would never be in the dangerous zone. Fault current flowing through the victim for both schemes would not be in very dangerous zone, instead it would only be in Clear Zone which make victim

may feel involuntary muscle effect after 500ms in scheme B, and after 1.8s for scheme A as shown in Figure 4-29.

Table 4-2. Electric Shock Performance in Unipolar ELVDC-24V

Scheme	Equivalent Human Body Resistance	R_{body} (Ω)	I_{fault} (A)	Duration maximum before Clear Zone (ms)
A	$R_{body} = R_{ip} + R_{ip} = 2R_{ip}$	1000	0.024	1800
B	$R_{body} = (R_{ip} // R_{ip}) + (R_{ip} // R_{ip}) = R_{ip}$	500	0.048	500

Figure 4-29. Fault Current on Human Body Effect in Unipolar DC System

C. Bipolar System with Two-24Vdc on One-Neutral

This topology was used to reduce losses by eliminating ground current. This topology is shown in Figure 4-30. By using bipolar mode, one cable of ground would be used by two branches.

Figure 4-30. Bipolar Topology for Driving LED Lamps

The topology of the system was using flyback converter with 48V output voltage level. Then, this flyback converter's output was divided to drive two branches of LED lamps using diode and capacitor as shown in Figure 4-31.

Figure 4-31. Bipolar System Using Flyback Converter and Diode Clamping

C.1. Efficiency Evaluation of Bipolar ELVDC

Simulation result of the system is shown in Figure 4-31. The Figure shows that all loads reached 22.6V at minimum and 23.9V at maximum load voltage level. It shows that it was above the minimum requirement voltage level (6% or 22.56V). Figure 4-32 shows load in the first floor 1A would get the highest voltage level as the effect of shortest distance from load to the power supply. Then, load at 15B would get the lowest voltage level as the effect of longest distance from load to power supply. With

15 loads of each branch, this bipolar topology was able to retrofit HDB flat's blocks with one power supply.

Figure 4-32. Load Voltage Level in Bipolar System

The advantage of using bipolar topology is getting nearly zero current value in the ground cable. It is because of the current subtraction from branch A and branch B. With unbalance load, as the topology require different cable in each branch, it still produced small current in ground cable. The current wave was shifted about -0.4mA means that branch B consumed more power than branch A. The current produced by the system is shown in Figure 4-33.

Figure 4-33. Current Flowing Through Ground Cable

Figure 4-34. Voltage Drop Evaluation of Bipolar Topology

Besides that, by using reconfigured wiring system, evaluation of Bipolar ELVDC system was conducted using different distance (height of the floors) and different power consumption of LED Lamp (for case which might happen in other building design). Figure 4-34 shows that only Bipolar topology with 8W LED Lamp for each load and 2.5m distance between floors used 1 AC/DC Driver. For other cases, each case used additional driver whenever voltage drop violate 6% regulation. Then the best scenario as seen in Figure 4-34, 8W LED lamp with 2.5m height between floors, was used for further analysis.

As the result of nullifying ground current, power losses in cable was reduced as the power cable losses will come from the line cable. Then, voltage drop in the cable also reduced so that it made the system could drive up to 15 LED Lamps in a branch. Power Consumption of the system is shown in Table A-4.

Figure 4-34 shows that voltage drop of bipolar topology was lower than using unipolar topology which shown in Figure 4-26. It made bipolar system's load used less number of AC/DC Converter (especially in case 15W each LED Lamp and 5m distance), but the system drew more power as the current load increased as the result of higher load voltage level. Even though the load current increased, power loss of this system was

lower than power loss of unipolar topology. Based on the result in Table A.3 and Table A.4, the difference of the power loss was 0.693W.

In this research, by using 24 loads of each trunk to supply 12 floors, the total power out was 161.523W. In other hand, total power supplied was 165.623W. The details of the current of each load and the voltage drop is shown in Table A.4. Thus, the efficiency was calculated as follow;

$$\eta = \frac{161.523}{161.523 + 0.087 + 4.013}$$

$$\eta = 97.52\%$$

This efficiency value was very high as the effect of not considering driver efficiency value. In ELVDC the AC/DC Converter typically has 93-97% efficiency and DC/DC Converter has 93-98%. Then in this analysis total highest converter efficiency would be 95.06%. Thus, using 95% total Converter efficiency, this unipolar topology design would achieve **92.64%** of efficiency.

C.2 Safety Issues Analysis of the Bipolar Topology

Safety analysis in this section followed the assumption and parameter in the section A.2 by using worst case assumption. Besides that it also used the graph for DC system similar with section B.2 except it had bipolar system as shown in Figure 4-35.

Figure 4-35. Electric Shock in Unipolar ELVDC System with Scheme A , B and C

In Bipolar system there is another scheme that unavailable in unipolar. It is fault with both hand touched both line. So that the voltage level applied to victim will be doubled, but as the current path makes both hand in series connection, the resistance becomes doubled.

Figure 4-36. Fault Current on Human Body Effect in Unipolar DC System

Table 4-3. Electric Shock Performance in Bipolar ELVDC-24V

Scheme	Equivalent Human Body Resistance	R_{body} (Ω)	I_{fault} (A)	Duration maximum before Clear Zone (ms)
A	$R_{body} = R_{ip} + R_{ip} = 2R_{ip}$	1000	0.024	1800
B	$R_{body} = (R_{ip} // R_{ip}) + (R_{ip} // R_{ip}) = R_{ip}$	500	0.048	500
C	$R_{body} = R_{ip} + R_{ip} = 2R_{ip}$	1000	0.048	500

By using -24V,0, +24V, these three schemes shown in Figure 4-35 were analysed. The analysis result then presented in Table 4-4 which shows that maximum fault current would be 0.048A. It was the same to unipolar fault current magnitude. Fault current flowing through the victim for both schemes

would not be in very dangerous zone, instead it would only be in Clear Zone which made victim may feel involuntary muscle effect during scheme B and C after 500ms, and for scheme A after 1.8s as presented in Figure 4-36.

Using assumption of CFL of AC system consumed 22W per lamp, and by using the same parameter of cable type and length, AC system would consume 558.26W including 2.47W power loss as presented in Table A.1. Then, compared to LED lamp system, LED lamp would save more power which shown in Table 4-4, using system without driver, so that 70.7% power savings is achievable. A comparison between AC system with CFL, AC system using LED (works done by Chen *et al*) and LED with dimming function (done by Tan *et al*) are shown in Table 4-5. Table 4-5 shows that proposed system could achieve the highest savings compared to other method. However, this system lacks of dimming control function which were not able to adapt with daylight. In conclusion, this system was suitable for replacing lighting which operates in night time.

Table 4-4. Lamp's Performane Comparison

LIGHTING TYPE	Life time (hours)	Dimming	Saving w.r.t LVAC CFL
AC System with CFL	15000	Complex	-
DC System with LED	50000	Simple	44.23%
AC System with LED	50000	Simple	63.74%
Unipolar DC System with LED	50000	Not available for individual dimming	70.71%
Bipolar DC System with LED	50000	Not available for individual dimming	70.33%

4.4 Economic Savings Evaluation

As comparison, savings of the evaluated system was compared to the existing AC system with 22W CFL Lamp. If the system was using CFL lamp, power consumption of the each load was kept constant at 22W, then the power loss is shown in Table A-1.

In this section, savings calculation of the evaluated systems was using an assumption price of which the following year's price would be similar to the electricity price in 2014. Electricity price in 2014 was 25.28cents per kWh [48].

For each staircase, this system's savings for an hour could reach 394.74W per hour with unipolar DC ELVDC System. Then, the savings could be translated to 9.98cents per hour. If this system operated for 12 hour (from 18.30 pm to 6.30 am) then it would save up to 119.75cents in a day. Assuming for a year usage, each staircase could save the energy bills up to 437.01\$. Using the same calculation method, LED with individual driver could save 394\$/year, and bipolar system could save 434.76\$/year.

For the calculation purposes, this research used the evaluated LED lamp cost 45\$/lamp, AC/DC driver cost 50\$ and the assumed installation fee of 200\$ per staircase. By using simple pay-back period in equation (4.16), payback period for LED using individual driver would be 4 years.

$$\text{pay back period} = \frac{\text{Initial costs}}{\text{Savings per year}} \quad (4.16)$$

$$\text{pay back period} = \frac{24 \times 45 + 24 \times 12.57 + 200}{394}$$

$$\text{pay back period} = 4 \text{ years}$$

With the life time of LED lamp could be up to 50000 hours. By using only 12hours in a day, then this system could be used for about 12 years. Where I, the interest rate of banks, was 0.31% [48]. Then the present value was calculated using equation (4.17).

$$P_n = \frac{F}{(1 + i)^n} \quad (4.17)$$

$$P_{12} = \frac{394}{(1 + 0.0031)^{12}}$$

$$P_{12} = 379.63 \$$$

For the present value, it followed Present Value Function as stated in equation (4.18).

$$PV = A \frac{(1 + i)^k - 1}{i} \quad (4.18)$$

Where A is annual cash flow, i is the interest rate and n is the life time of this system. So that, the equivalent present value was

$$PV = 394 \frac{(1 + 0.0031)^{12} - 1}{0.0031}$$

$$PV = 4809.45\$$$

Subsequently, the Net Present Value (NPV) at 12th year of this system, which followed equation (4.19), would be equal to;

$$NPV = PV - initial\ cost \quad (4.19)$$

$$NPV = 4809.45\$ - 1581.68\$ = 3227.77\$$$

For NPV calculation, as a comparison, LVAC using CFL was compared to ELVDC using LED lamp. The assumption of CFL lamp's life time was 15000hours or about 4years with price of 10\$/lamp. However, ELVDC using LED lamp could sustain up to 12 years with price of 45\$/lamp. Then, the comparison between them would be up to 12years, using discount rate of 0.31%, the effective period would be adjusted to 11.76years.

$$PVF = \frac{(1 + i)^k - 1}{i(1 + i)^k} \quad (4.20)$$

$$PVF = \frac{(1 + 0.0031)^{12} - 1}{0.0031(1 + 0.0031)^{12}}$$

$$PVF = 11.76\ years$$

Table 4-5. Payback Period for Different Lighting Topologies

Topology	Install- ation fee (\$)	n	Driver Cost (\$)	Lamp Price (\$)	Total Invest- ment Cost (\$)	Powe r Savin g (W)	Saving /day (¢)	Saving / year (\$)	Pay- back Perio d
AC with individual	200	24	12.57	45	1581.68	355.8	107.9	394	4.01

driver									
Unipolar ELVDC	200	2	30	45	1340	394.7	119.7	437.1	3.07
Bipolar ELVDC	200	1	30	45	1310	392.6	119.1	434.8	3.01

The AC system with CFL's annual electricity consumption was 618.14\$/year. If this system was the retrofitted system, then this system's initial cost would be zero. Then for ELVDC with LED lamp system would there be initial cost, but replacement after 4 years would be necessary. The initial cost for AC system with individual driver was 1381.68\$. So, the present values (P) of their system annual costs followed;

$$P(AC_{CFL}) = 2 \times 10 \times 24 + 11.76 \times 618.14 = 7749.33\$$$

$$P(AC_{LED}) = 200 + 30 \times 24 + 11.76 \times 224.14 = 3555.89\$$$

ELVDC using LED lamp was better than LVAC with CFL lamp with Net Present Value (NPV) of 4193.44\$ as calculated below.

$$NPV = 7749.33 - 3555.89 = 4193.44\$$$

It means that ELVDC using LED lamp was 4193.44\$ more efficient than LVAC.

Table 4-6. NPV Calculation for Different Lighting Topologies

Topology	Total Investment Cost (\$)	cost/year (\$)	Present Value or P (\$)	Net Present Value ($P_{AC} - P_{system}$) (\$)
AC System with CFL	480	618	7749.38	-
AC with individual driver	1581.68	224	4217.60	3531.78
Unipolar ELVDC	1340	181	3469.33	4280.05
Bipolar ELVDC	1310	183	3466.64	4282.73

With n is the number of driver in the system, then using the same calculation using equation (4.16), payback period for both Unipolar and Bipolar ELVDC system was presented in Table 4-6. For Unipolar and Bipolar ELVDC System used the same price scheme with AC System with individual driver. By using 11.76 years of PVF and simple pay-back period in equation (4.16) to equation (4.20), Table 4-7 was generated to show NPV for each the systems.

4.4. Summary

Retrofitting LVAC system to ELVDC system was challenging. Some factors must be put in consideration, such as the feasibility of loading, feasibility of not violating voltage drop regulation, and reduce energy consumption. In this research, ELVDC was feasible to replace LVAC in lighting system case with some limitation. Main supply of ELVDC needed to be positioned as close as possible to loads to maintain the voltage. In the case of 100W loading, 18.9m will be the maximum distance. Besides that, maximum loading would be restricted. Moreover, using suitable rectifier might give more benefit with regard to rectifier efficiency, because the performance of rectifier with low loading might not reach the maximum rectifier efficiency.

Table 4-7. Summary of Topology Comparison for LED Lighting System

Topology	Cable Power Loss (W)	η (%)	Worst Case for Safety	Lamp Price (\$)	Pay-back Period	Saving w.r.t AC system	Saving/day (¢)
AC with individual driver	2.5	91.03	Very Dangerous	45	4.01	63.74%	107.9
Unipolar ELVDC	4.7	92.22	Clear Zone	45	3.07	70.71%	119.7
Bipolar ELVDC	4.1	92.65	Clear Zone	45	3.01	70.33%	119.1

From simulation harmonic of rectifier could be reduced by using passive filter in supply side. By choosing high capacitor value, small voltage ripple could be achieved

and as the loads of the system was LED Lamp output current followed the waveform of output voltage of flyback converter. Thus, main harmonic source was the AC/DC driver itself.

According to efficiency evaluation, the highest efficiency of the system was achieved by AC system with individual driver for LED. This topology had only 2.5W cable power loss, meanwhile Unipolar ELVDC topology had 4.7W cable power loss, and then Bipolar topology had 4.1W cable power loss. It shows that AC system with higher voltage level than DC voltage may gain benefit of smaller cable power loss.

In other hand, AC system with higher voltage level might cause very dangerous consequences for people as discussed above. For ELVDC, both system Unipolar and Bipolar did not injure people with serious damage. The maximum effect would be only involuntary muscle in a much longer period than AC system.

From economic analysis, ELVDC using LED lamp was proven to have better performance compared to LVAC using CFL lamp system. According to Table 4-7 bipolar topology gave the highest savings in a 12-year run. Moreover, the retrofiting strategy reduced the complexity of installation process and costs. Table 4-8 was presented to summarize the research in Chapter 4.

Chapter 5

5. Conclusion and Future Work

5.1 Conclusion

Based on the efforts, we conclude that ELVDC with LED lamp for lighting system could achieve higher energy efficiency, longer system lifetime and ease of integration with common LVAC infrastructure in buildings. Thus, retrofitting existing electrical system to ELVDC becomes a more feasible solution for cost effectiveness.

The selected LED lamp had high efficacy and 120° angle of light distribution. This lamp consumed 7.92 watts at rated voltage and produced high illuminance level at task area level. The design with cover could protect LED lamp from external disturbances that could reduce lamp's life time. The equivalent of internal resistance of this lamp was function of current. This approach simplified the system's voltage drop calculation by adding cable resistance with lamp's internal resistance. Voltage drop of the system was a non-linear function for the whole system depending on the number of loads.

Main supply of ELVDC system required to be placed as close as possible to loads to reduce cable loss. The load current was accumulated through the main trunk, so that node to node voltage drop between main supply to the first load was the highest cable voltage drop. Because of retrofitting purpose, changing the cable to bigger size was anticipated; therefore, reducing the length of cable would be the best possible solution.

By using LED lamp, 63.74-70.7% savings was achievable. However, driverless ELVDC did not provide individual dimming control function which could not adapt to daylight condition. In conclusion, this system would be suitable for replacing lighting which operates in night time.

By doing economic analysis, this retrofitting CFL lamp to LED lamp was considered to be prospective project. This project required less than 4 years for the pay-back period while using ELVDC System. Besides that, the ELVDC system's Net Present

Value shows that ELVDC system would give more savings of 4282.73\$ in 12 years, compared to LVAC with CFL lamp.

The feature of low voltage level in ELVDC gave more benefits in terms of safety without compromising cable power loss. When the voltage level of AC system was high enough, it may make people to get ventricular fibrillation which may lead to death. In contrast, by using ELVDC system people would not be in a danger with worst possible scenario would only put people in clear zone. It means that ELVDC could be promising solution to reduce energy in lighting sector for building with additional benefit of safety reason.

5.2 Recommendations for Future Work

The implementation of ELVDC in this work focuses on migration of LVAC to ELVDC for lighting system application. Moreover, the implementation of ELVDC was aimed to retrofit lighting system specifically in common area without using any dimming control. In order to get more understanding of ELVDC implementation in building lighting system, more efforts are needed, including:

1. Investigated lamp in this work was aimed to meet the minimum requirements with least power consumption. Therefore, in other applications, another lamp types may be applied. Thus the equation (3.3) needs to be reconsidered accordingly following the lamp characteristics.
2. It is known that dimming control may give more savings in lighting system. Therefore, the centralized dimming control for ELVDC topologies design needs to be investigated in the future.
3. Renewable energy resources have been understood to give more advantages when integrated in DC system. Hence, integration of renewable energy resources with ELVDC for building lighting system needs to be researched.

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APENDIX

Simulation result for LED Lighting System :

1. AC System with CFL Lamp

Table A. 1. Power Consumption of CFL Lighting System Using AC System

Floor	Voltage Node (V)	V load (V)	Load Current (A)	Voltage drop Node (V)	Power Loss Node to Loads (W)	Power Loss Node to Node (W)	Power Loss Node to Loads (W)
1A	220.000	219.997	0.10526	0.003	22.000	0.0003	0.00030
1B	219.997	219.994	0.10526	0.009	22.000	0.0003	0.00199
2A	219.988	219.985	0.10527	0.014	22.000	0.0003	0.00449
2B	219.973	219.971	0.10528	0.019	22.000	0.0003	0.00798
3A	219.955	219.952	0.10528	0.024	22.000	0.0003	0.01247
3B	219.931	219.928	0.10530	0.028	22.000	0.0003	0.01795s
4A	219.902	219.900	0.10531	0.033	22.000	0.0003	0.02444
4B	219.869	219.866	0.10533	0.038	22.000	0.0003	0.03193
5A	219.831	219.829	0.10534	0.043	22.000	0.0003	0.04041
5B	219.789	219.786	0.10536	0.047	22.000	0.0003	0.04990
6A	219.741	219.738	0.10539	0.052	22.000	0.0003	0.06038
6B	219.689	219.686	0.10541	0.057	22.000	0.0003	0.07187
7A	219.632	219.629	0.10544	0.062	22.000	0.0003	0.08437
7B	219.571	219.568	0.10547	0.066	22.000	0.0003	0.09786
8A	219.504	219.501	0.10550	0.071	22.000	0.0003	0.11237
8B	219.433	219.430	0.10554	0.076	22.000	0.0003	0.12788
9A	219.357	219.355	0.10557	0.081	22.000	0.0003	0.14440
9B	219.277	219.274	0.10561	0.085	22.000	0.0003	0.16192

10A	219.191	219.189	0.10565	0.090	22.000	0.0003	0.18046
10B	219.101	219.098	0.10569	0.095	22.000	0.0003	0.20002
11A	219.006	219.004	0.10574	0.100	22.000	0.0003	0.22058
11B	218.907	218.904	0.10579	0.104	22.000	0.0003	0.24217
12A	218.802	218.800	0.10584	0.109	22.000	0.0003	0.26477
12B	218.693	218.690	0.10589	0.114	22.000	0.0003	0.28839
				TOTAL	528	0.0072	2.44929

2. AC System with LED Lamp

Table A. 2. Power Consumption of AC System with LED Driver

Floor	Voltage Node (V)	V load (V)	Load Current (A)	Voltage drop Node (V)	Power Loss Node to Loads (W)	Power Loss Node to Node (W)	Power Loss Node to Loads (W)
1A	220.000	219.997	0.040	0.042	8.000	0.00007	0.00030
1B	219.957	219.956	0.040	0.040	8.000	0.00007	0.00199
2A	219.917	219.916	0.040	0.038	8.000	0.00007	0.00449
2B	219.879	219.877	0.040	0.036	8.000	0.00007	0.00798
3A	219.843	219.841	0.040	0.035	8.000	0.00007	0.01247
3B	219.808	219.806	0.040	0.033	8.000	0.00007	0.01795s
4A	219.776	219.774	0.040	0.031	8.000	0.00007	0.02444
4B	219.745	219.743	0.040	0.029	8.000	0.00007	0.03193
5A	219.716	219.714	0.040	0.027	8.000	0.00007	0.04041
5B	219.688	219.686	0.040	0.025	8.000	0.00007	0.04990
6A	219.663	219.661	0.040	0.024	8.000	0.00007	0.06038
6B	219.639	219.637	0.040	0.022	8.000	0.00007	0.07187
7A	219.617	219.616	0.040	0.020	8.000	0.00007	0.08437

7B	219.597	219.596	0.040	0.018	8.000	0.00007	0.09786
8A	219.579	219.577	0.040	0.016	8.000	0.00007	0.11237
8B	219.563	219.561	0.040	0.015	8.000	0.00007	0.12788
9A	219.548	219.546	0.040	0.013	8.000	0.00007	0.14440
9B	219.536	219.534	0.040	0.011	8.000	0.00007	0.16192
10A	219.525	219.523	0.040	0.009	8.000	0.00007	0.18046
10B	219.516	219.514	0.040	0.007	8.000	0.00007	0.20002
11A	219.508	219.506	0.040	0.005	8.000	0.00007	0.22058
11B	219.503	219.501	0.040	0.007	8.000	0.00007	0.24217
12A	219.496	219.492	0.040	0.000	8.000	0.00007	0.26477
12B	219.496	219.491	0.040	0.042	8.000	0.00009	0.28839
				TOTAL	192	0.002	0.338

3. Unipolar ELVDC

Table A. 3. Power Consumption of LED Lighting System in Unipolar ELVDC

Floor	Voltage Node (V)	V load (V)	Current (A)	Power for each loads (W)	Power Loss Node to Loads (W)	Power Loss Node to Node (W)
1A	24.000	23.991	0.329	7.882	0.767	0.767
1B	23.821	23.807	0.316	7.534	0.651	0.651
2A	23.657	23.643	0.305	7.218	0.549	0.549
2B	23.506	23.493	0.295	6.933	0.459	0.459
3A	23.369	23.356	0.286	6.675	0.379	0.379
3B	23.245	23.232	0.277	6.443	0.309	0.309
4A	23.133	23.121	0.270	6.237	0.248	0.248
4B	23.033	23.021	0.263	6.054	0.195	0.195
5A	22.945	22.934	0.257	5.894	0.149	0.149

5B	22.869	22.858	0.252	5.756	0.110	0.110
6A	22.804	22.793	0.247	5.639	0.078	0.078
6B	22.750	22.739	0.244	5.543	0.051	0.051
7A	22.707	22.696	0.241	5.467	0.031	0.031
7B	22.675	22.664	0.239	5.409	0.015	0.015
8A	22.654	22.643	0.237	5.372	0.000	0.000
8B	22.654	22.637	0.237	5.364	0.000	0.000
9A	24.000	23.985	0.329	7.880	0.244	0.244
9B	23.902	23.888	0.322	7.690	0.180	0.180
10A	23.819	23.805	0.316	7.529	0.127	0.127
10B	23.750	23.736	0.312	7.397	0.084	0.084
11A	23.695	23.681	0.308	7.291	0.050	0.050
11B	23.654	23.640	0.305	7.213	0.025	0.025
12A	23.627	23.161	0.303	7.161	0.004	0.000
12B	23.627	23.035	0.303	7.150	0.007	0.000
TOTAL				158.733	0.090	4.703

4. Bipolar ELVDC

Table A. 4. Power Consumption of LED Lighting System in Bipolar ELVDC

Floor	Voltage Node (V)	V load (V)	Current (A)	Power for each loads (W)	Power Loss Node to Loads (W)	Power Loss Node to Node (W)
1A	24.000	24.000	0.329	7.886	0.000	0.501
1B	23.847	23.833	0.318	7.584	0.005	0.470
2A	23.857	23.843	0.319	7.603	0.005	0.409
2B	23.709	23.695	0.309	7.317	0.004	0.383
3A	23.728	23.714	0.310	7.355	0.004	0.328

3B	23.584	23.571	0.300	7.080	0.004	0.308
4A	23.614	23.600	0.302	7.136	0.004	0.258
4B	23.473	23.460	0.293	6.870	0.004	0.242
5A	23.512	23.499	0.296	6.944	0.004	0.197
5B	23.375	23.362	0.286	6.686	0.004	0.185
6A	23.425	23.412	0.290	6.779	0.004	0.146
6B	23.290	23.277	0.280	6.527	0.004	0.137
7A	23.350	23.337	0.284	6.639	0.004	0.103
7B	23.218	23.205	0.275	6.393	0.003	0.097
8A	23.288	23.275	0.280	6.523	0.004	0.068
8B	23.158	23.145	0.271	6.282	0.003	0.064
9A	23.239	23.226	0.277	6.432	0.003	0.040
9B	23.110	23.098	0.268	6.194	0.003	0.038
10A	23.202	23.189	0.274	6.364	0.003	0.020
10B	23.074	23.062	0.266	6.129	0.003	0.019
11A	23.177	23.165	0.273	6.318	0.003	0.000
11B	23.050	23.038	0.264	6.086	0.003	0.000
12A	23.177	23.161	0.273	6.316	0.004	0.000
12B	23.050	23.035	0.264	6.083	0.004	0.000
TOTAL				161.523	0.087	4.013

Figure A-1. Estimated Capacitor and Series Resistance Value for Certain Load Resistance and Ripple Voltage Value [45]