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**NANYANG
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**Modeling, Analysis and Voltage Balancing for DC
Distribution Networks.**

CHEW SI HAO BENJAMIN

**SCHOOL OF ELECTRICAL & ELECTRONIC
ENGINEERING**

2019

**Modeling, Analysis and Voltage Balancing for DC
Distribution Networks.**

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University

in partial fulfillment of the requirement for the degree of

Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

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Authorship Attribution Statement

This thesis contains material from 1 paper published in the following peer-reviewed journal(s) where I was the first and/or corresponding author.

Part of Chapter 4 and Chapter 5 is published as Benjamin. Si. Hao. Chew, Yan. Xu, and Qiuwei. Wu, "Voltage Balancing for Bipolar DC Distribution Grids: A Power Flow Based Binary Integer Multi-Objective Optimization Approach," IEEE Transactions on Power Systems, vol. 34, no. 1, pp. 28-39, 2019.

The contributions of the co-authors are as follows:

- Assistant Professor Yan Xu provided the multi-objective optimization direction and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript was revised by Dr Qiuwei Wu.
- I designed the technical modeling study, performed and analyzed the multi-objective optimization simulation

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Title: Modeling, Analysis and Voltage Balancing for DC Distribution Networks.

Abstract

With the technological advancement in power electronics, DC LED lightings, distributed energy sources, DC energy storage systems, and the increasing use of end-user electronics, DC distribution system re-emerge as a potential system for energy savings such as in the case of DC LED lighting system for a built environment.

This dissertation examines the DC distribution power flow model using the iterative and nodal analysis based approach. The iterative based approach is used to evaluate the steady-state power losses and determine the system performances for variations of DC LED lighting system. The developed power flow model using nodal based analysis is then analyzed with variations in network operations such as grid islanding, grid-connected and single phase integration. With the developed power flow model, network optimization such as voltage balancing for multi-pole bipolar DC network is carried out. The power flow model established for this dissertation is validated and verified against an actual mock-up DC LED lighting system and a simulated system using Matlab Simulink.

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1 Introduction

1.1 Background

As societal concerns such as the depletion of energy sources and the increase in electrical energy demand from the use of electronics arises, there is a need to re-evaluate the use of energy in the power distribution system [1]. In addition, with the development of renewable energy sources, such as photovoltaic system and wind energy systems, the integration of such renewable energy systems has to be re-examined. One such approach is to look into the co-existence of AC and DC distribution system while taking advantage of each of the system characteristics. This is supported by the increasing use of end-user DC loads such as LED lighting and use of electronics [2]. When the DC distribution is used, the integration of home appliance is more energy efficient and cost effective [3]. The use of DC systems allows for a reduction in losses of about 2.5% [4], resulting in a smaller and more efficient use of power electronics [5]. Furthermore, higher extraction of energy is obtained when the maximum power tracking for distributed energy resources was placed nearer to the AC grid [6].

An overview of DC distribution system within the built environment is shown Figure 1 [7]. Two voltage levels are proposed to efficiently transport power to high and low power loads. This is to prevent the oversizing of distribution cables. One example that exhibits efficient DC distribution is a LED lighting system for a high rise building as LED lighting are predominantly DC loads [8]. The 48V DC LED lighting system allow for a simple and cost-effective distribution without the need for cables oversizing.

However, the use of extra-low voltage for efficient distribution is limited by its power and distribution distance. Furthermore, at extra-low voltage level ($<120\text{V DC}$), it is discussed that the use of voltage regulating converters may not improve the overall system efficiency [9]. While the loads can be distributed using the 380V DC distribution, such interfacing converters are not available readily off-the-shelf and the need for protection is a challenge in using voltage levels above 120V DC . As a result, such voltage drop phenomenon is predominantly found in lower voltage levels with a relatively higher current in the distribution system. The phenomenon of having a relatively higher current and a non-negligible voltage drop in the distribution system is

worthy of study due to an increase in the use of electrical energy while keeping the cost of cabling effective.

Figure 1-1: LVDC distribution system architecture for the built environment [7]

1.2 Motivation

As have introduced above, the phenomenon of voltage drop in the distribution system affects the use of energy from different energy sources. This phenomenon is shown when the ladder distribution architecture is used where the distributed energy resources and the grid interfacing converter is integrated at both ends of the distribution system in [10]. For different configurations and voltage design levels, the energy use between the two sources is different.

Unlike in AC distribution system, it is governed by a set of rules from the transmission system such that the voltage at point of common coupling is limited to within 5% of per unit value and the voltage drop at distribution level is limited to 3%. There is

currently no standard for DC distribution system while the main driving force is the efficient use of energy and cost-effective system design. As a result, there has yet to have much literature on the power flow modeling and analysis of DC distribution systems.

The basic steady-state analysis tool for any electrical network, power flow analysis, is essential to get the overall view of the system design and operation. It can then be applied to network optimization, component capacity optimization in the planning stage of the network. Power flow analysis can be embedded as a component in the energy management system of the network [11]. The steady state analysis tool is important to evaluate the steady-state power losses in the distribution network. One such system of interest with a focus towards efficiency study is the DC LED lighting system as introduced above.

The DC LED lighting is of interest due to its highest potential for energy savings from the use of DC distribution [12]. However, in the use of LED lighting, there are different configurations and use of DC LED lighting. The DC LED lighting can be powered up without the use of LED driver and still performs centralized dimming [13]. Other DC LED lighting design includes human-centric lighting with dimming function [14]. While such extra-low voltage DC LED lighting is energy efficient, it faces the problem of high voltage drop if the system power loss is not accounted for in the initial planning stage [15].

Furthermore, there are different DC distribution architectures and behavior, such as the DC unipolar, DC bipolar, the ladder architecture, grid isolated system and direct integration of energy storage systems. The system power losses of these architectural behaviors have to be accounted for in the planning of the LED lighting system. As a result, modifications to the conventional power flow equations have to be carried out in the modeling of the DC system to account for such architectural behaviors. Besides the different network operations, power flow modeling for single-phase DC source integration has to be accounted for to prevent under and overvoltage to the DC loads during DC network planning.

As there is no voltage regulation at the extra-low voltage level and there are different architectures of the LED lighting system, the efficiency study of the different architectures is compared with the different extra-low voltage DC LED lighting system.

Other static analysis includes the study of voltage balancing in the 2-phase DC bipolar network. While a bipolar distribution system is described to be energy efficient [16], in the case of asymmetrical distribution of loads in both distribution rails, there may be voltage imbalance between the loads. The study of voltage balancing is carried out using the static modeling of the distribution system.

The study of steady-state modeling for static analysis of DC distribution system will provide much insight towards future DC distribution design and planning such as component capacity and optimization planning. Using a DC LED lighting system as an example, it provides a case study sufficient to illustrate the effects of distributed voltage drop phenomenon at the distribution level. Furthermore, the static model provides the fundamental in DC power system design, planning and operation. The similar system modeling approach can be carried out for system dynamic analysis or small signal analysis. As such, the steady-state power flow modeling is an important component from the perspective of power system planning.

1.3 Proposed Solution

The need for steady-state power flow modeling of DC system has been discussed above. However, existing power flow modeling serves to analyze power flow at the transmission level using a single line diagram. At transmission level, power is transported using a 3 cable system without a return cable. Furthermore, due to the large cable size, the effects of resistance to the power flow modeling can be neglected which may not be true at the distribution level. At the distribution level, many kinds of literatures have looked into the effects of power losses due to relatively higher resistance to inductance ratio [17]. However, there is not much literature that examines power flow modeling for DC distribution system analysis.

As a result, the proposed solution to the problem of steady-state modeling for DC distribution system is to utilize the concept of nodal analysis of AC transmission system and model it for DC distribution system with relatively higher resistance to negligible inductance ratio. Two solution approaches are proposed to solve the problem. The aim of the first iterative approach is to provide a simple and fast analysis for the end-user radial distribution network. The aim for the second nodal based approach is to provide the following analysis: 1) To account for a generic power flow model for advanced power distribution architecture such as the ladder architecture; 2) To account

for the effects of single phase integration of DC sources; 3) To account for emerging system operation such as the grid islanding operation and 4) To perform and carry out other static analysis such as voltage balancing for the 2-phase bipolar DC network.

For both solutions, the single line nodal analysis is carried out on each of the DC distribution cables. For the first proposed solution, together with the use of circuit theorem and iterative approach, a backward algorithm is used to model the simple radial distribution network while the forward algorithm is to update the source voltage. As a result, a single source simple radial distribution network is modeled. It is fast, simple and intuitive which requires observable power flow. However, the disadvantage of such iterative based forward-backward algorithm is the inability to carry out advanced analysis and the need for observable power flow. It is not suitable for non-observable power flow such that the numbering of the “parent node” and “child node” arrangement is not easily constructed and iterative methods are not applicable [18]. One such example is the ladder architecture [19].

For the second proposed solution, the single line nodal analysis is combined to form a similar AC power flow representation of having Y-bus matrix. In the formulation, the sources and the loads matrices are separated for purpose of analysis. This is to account for the system behavior due to grid islanding and due to direct integration of DC energy storage systems. In the case of a single source bipolar DC network, voltage balancing for the 2-phase bipolar DC network is carried out using the power flow modeling.

Hence, the proposed solutions provide a simple, fast and comprehensive analysis that accounts for the system losses in different types of DC LED lighting system and different system behavior of DC systems in a building. Together with conventional and human-centric LED lighting system, the system performance of the LED lighting system can be compared. Furthermore, the DC LED lighting system can be used as a system representation for future DC distribution with non-negligible voltage drop phenomenon. The research will provide advance insights towards power system planning in the area of DC distribution architectures.

1.4 Objectives

Several objectives have been identified for the study of the proposed solution.

- Model and verify the backward-forward iterative approach and nodal-based power flow model approach using an actual highly resistive DC distribution system example of DC LED lighting system.
- Utilize the model to investigate distribution system power losses and power flow for the different topology of LED lighting and power distribution systems, including driver-driven and different driverless LED lighting system design [13], human-centric LED lighting [14], unipolar DC, bipolar DC [20], multi-source power distribution and grid isolated systems [10].
- Validate the nodal analysis based power flow model against different operations of the power system network, including grid isolated, grid-connected, single phase DC source integration and multi-pole bipolar DC architecture.
- Extend the power flow model to investigate on the steady state voltage balancing for bipolar DC networks using the DC LED lighting system as an example and compare with existing methodologies.

1.5 Publications

Related Journal Publications

- [1] **Benjamin S. H. Chew**, Y. Xu, and Q. Wu, "Voltage Balancing for Bipolar DC Distribution Grids: A Power Flow Based Binary Integer Multi-Objective Optimization Approach," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 28-39, 2019
- [2] **Benjamin S. H. Chew**, Yan Xu and King Jet Tseng, "An Iterative Approach for System Efficiency Analysis for DC LED Lighting System in High Rise Built Environment" In submission to *Energy and Buildings*, Elsevier
- [3] **Benjamin S. H. Chew** and Yan Xu, "A Modified Power Flow Model for Single-Source Bipolar DC Distribution Networks " In preparation for submission

Related Conference Publications

- [4] **S. H. Chew**, K. J. Tseng and Hoan Thong Nguyen, "An Energy Efficient 48Vdc Bipolar ELVDC LED Lighting System in a High-Rise Building." 11th IEEE International Conference on Power Electronics and Drive Systems (PEDS 2015), Sydney, Australia, 2015.
- [5] Edwin Chan, **S.H.Chew**, H.T.Nguyen, S.C.Chien, Y.L.Sum, B.H.Soong, K.J.Tseng, "Pilot Study of LVDC-Based LED Lighting System in Residential Buildings in Singapore." 28th Commission Internationale de l'Eclairage (28th CIE 2015), Manchester, UK, 2015.
- [6] **S.H.Chew**, K.J.Tseng, N.H.Ardiyanto, "Design and Comparative Analysis of a Driverless LED Lighting System and its Centralized Dimming Scheme in High-Rise Built Environment." International Conference on Building Energy Efficiency and Sustainable Technologies (ICBEST 2015), Singapore, 2015.
- [7] **S.H.Chew**, Edwin Chan, N.H.Ardiyanto, Y.L.Sum, S.C.Chien, B.H.Soong, K.J.Tseng, "Design Considerations for ELVDC Power Distribution System Integrated Directly with DC Energy Sources for LED Lighting in High-Rise Built Environment." 37th IEEE PELS International Telecommunications Energy Conference (INTELEC 2015), Namba, Osaka, Japan, 2015.

- [8] **S.H.Chew**, N.H.Ardiyanto, K.J.Tseng, "An Extra Low Voltage DC (ELVDC) Power Distribution for LED Lighting System." 37th IEEE PELS International Telecommunications Energy Conference (INTELEC 2015), Namba, Osaka, Japan, 2015.

Non-related Publications

- [9] Chien, S.-C., Sum, Y.L., Chan, Y.W.E, **Chew S. H.**, Soong, B.H., Tseng, K.J., (2015) "An integrated cyber-physical model towards high-performance lighting systems operation", CIE 2016, Melbourne, AU, 2016
- [10] **S.H.Chew** and K.J.Tseng, "A Line to Ground Fault Detection Technique for ELVDC Distribution System in Built Environment." 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG 2016), Vancouver, Canada, 2016.
- [11] Wei Feng, K.J Tseng, Li Kaiyuan, Yap Heng Goh, **Benjamin S. H. Chew**, "Harmonic Mitigation of Hybrid AC/DC Micro-grids with PMSG" 5th IET International Conference on Renewable Power Generation (RPG 2016), London, UK, 2016
- [12] **S.H. Chew** and Yan Xu, "Operational Analysis of Static Transfer Switch for Bipolar DC Network" Accepted for IEEE International Power Electronics Conference (ECCE Asia 2018), Niigata , Japan, 2018

Inventory Disclosure, Technical Disclosure, Technical Know-how

- [13] **S.H. Chew** and Yan Xu, 2017, "Static Transfer Switch Design For 2-Phase Bipolar DC Network" Submitted to NTUitive (TD/286/17)

1.6 Organization

Chapter 1 introduces the background, motivation, proposed solution, objectives and the organization of the research. The research revolves around the reasons and the need for power flow model and how the power flow model is used to investigate system efficiency and voltage balancing of a DC system using a DC LED lighting system as the case study.

Chapter 2 provides the literature review on the evolution of the DC distribution system and how the DC distribution system is proposed to be applied to the built environment. It also provides the literature review of power flow modeling methodology for AC systems, DC distribution modeling and the different methods of voltage balancing.

Chapter 3 presents the first modeling methodology of using the iterative approach. The approach is applied to a single source unipolar and bipolar power distribution system. The model is verified with an actual extra-low voltage DC LED lighting system. The system performances of the following different DC LED lighting systems, using the same luminaire requirements and design, are compared as follows: 1) Unipolar 24V and 48V DC, 2) Bipolar 48V DC, 3) Different topologies of driverless LED lighting system.

Chapter 4 presents the second modeling approach using the nodal based power flow modeling methodology. The approach models the sources and the loads matrices separately for the purpose of analysis. The model is verified with an actual extra-low voltage DC LED lighting system. The methodology is applied to unipolar DC, bipolar DC and multi-source power distribution network. The power flow model is then validated against different operations of the power system network, including grid isolated, grid-connected, single phase DC source integration and multi-pole bipolar DC architecture.

Chapter 5 extends the nodal based power flow for the bipolar DC network to investigate on voltage balancing and minimizing of voltage drop as an example of network optimization planning. In using the power flow based methodology, a binary load distribution model is proposed to distribute the different unipolar loads across the distribution system. A binary integer multi-objective optimization is used on the model to balance the voltage and minimize the system power loss across distribution system. The proposed model based optimization methodology is then compared with existing

iterative based methodologies and extended to a larger system for voltage balancing purposes. The proposed methodology of using power flow modeling has a higher degree of voltage balancing across the bipolar DC distribution system.

Chapter 6 summarizes and concludes the research.

Chapter 7 presents the future work that is associated with the power flow modeling methodology and the plausible research directions that can be extended from this research work.

2 Literature Review

In the last century, the centralized AC power system was an effective means for electricity generation and delivery. This is because the AC voltage can be easily stepped up using a transformer and AC power can be transported over long distances efficiently [21]. As technology advances and societal concerns increases over the years, there is a need to re-evaluate the power distribution system. Technological advances include the development of more efficient power electronic converters, the rise in the use of renewable energy generation and storage systems. Societal concerns include the depleting energy sources, the rise of global warming and the increase in demand for electrical energy from the increasing use of electronics [1]. One such approach is to look into the co-existence of AC and DC distribution system while taking advantage of each of the system characteristics. In the following work, direct current (DC) system is the main focus of the investigation.

2.1 Direct Current System

With the pressure due to societal concerns and technological advances, DC systems have been identified as the preferred power distribution system for some application use cases. These application use cases include efficient high power transmission, efficient and reliable use of power electronics in power system, efficient power distribution from distributed energy generation and efficient power utilization for passive and active DC loads.

2.1.1 Transmission System

The advantage in using DC systems is prominent in high voltage transmissions system. In [22], different transmission system, mainly HVAC and HVDC, are investigated and compared in terms of line losses. It was reported that in general, HVAC solution leads to the lowest losses for distances of up to 55–70 km, whereas for longer distances, HVDC solution has lower losses and is therefore preferable from the losses point of view. This is because the use of AC systems has higher losses incurred by the intrinsic reactive power circulation under heavy and light load conditions [23].

In a transmission system, due to the effect of large transmission line cable sizes, the line reactance is much larger than the resistance. As a result, the maximum power transfer capability of AC is reduced compared to that of DC when the resistance is only taken into consideration. Using DC, the maximum power transfer capability can be

increased by 10 times when comparing between AC and a bipolar DC system while it can be increased by 4 times when compared to a unipolar DC system [24]. Unlike AC systems, the interfacing converter and its converter losses determines the system efficiency of the HVDC transmission system [25]. In [26], it is reported that the converter losses are mainly due to the switching device and the freewheeling diodes, which consists of up to 75% of the majority of the converter losses. Thus, from the case study of the HVDC transmission system, the effects of system cable losses and converter losses are needed in the justification of using DC systems from the system efficiency point of view.

2.1.2 Telecommunication and Data Centers

Another use case for DC systems is in the applications to telecommunication and data centers. In telecommunication systems, the conventional 48V DC power supply system has been the standard for the past century [27]. This is because the telecommunication loads are DC power in nature and the 48V DC power supply system can be easily obtained from a utility power supply or an emergency generator using a rectifier. Furthermore, the operation and maintenance of 48V DC power supply system with the use of a reliable battery pack is simple and this increases the reliability of the power system in data center. High reliability is required due to the economic losses when a supply outage is experienced. At rack level, the use of 48V DC power system has the potential advantage of increased efficiency during light load due to proper management and sizing of the converters. This is done to achieve a highly efficient power system with high power density by reducing the amount of heat losses and increase the power distribution density in each server. The number of converters required to maintain the same level of redundancy is also reduced, which reduces initial procurement costs. Hence, the 48V DC system was universally used as the voltage level for the telecommunications systems applications.

In a typical data center, less than half of the power is used to compute the loads. The rest of power is lost through power conversion, distribution and for cooling. Furthermore, in the future, the cooling infrastructure required will exceed the cost of the purchase of the servers it can support [28]. There will be a significant change in the economics of data centers as servers hardware is no longer the primary cost driver. This is due to the increasing IT loads a data center can support. As a result, the cabling required is increased exponentially, which affects the cooling capability in a data

center. More air-conditioners have to be installed from a shortage of installation space due to increase in cabling size requirement and servers. To alleviate the needs of IT loads and cooling requirements, the recent trend in DC power systems for the data center is moving towards 'high voltage DC' at 380V DC [29].

A comparative study in terms of cabling size is carried out in [30] between 48V DC and 380V DC. The study concludes that the use of 380V DC is able to significantly reduce the wiring cost by more than 90% of the current installation. The savings in the wiring cost can also be translated to space savings in telecommunication centers. In terms of reliability, the 380V DC system has higher system availability over time when multiple UPSs without redundancy and distributed loads are considered. The study concludes that the DC distribution would hold a similar level of reliability as that of the typical ac system on a larger scale using a common redundancy index [31].

In terms of efficiency comparison, the centralized 380V DC distribution has the highest efficiency when the inverter (DC/AC conversion stage) in the UPS, the AC/DC converter in the power supply and the transformer in the power distribution are eliminated [32]. The use of 380V DC for distribution results in a slightly higher system level efficiency compared to the 48V DC distribution since the UPS does not have to be isolated. Furthermore, with the technological advancement of distributed energy sources such as fuel cells and solar power, the integration to 380V DC can be done easily and the energy from the renewable sources can be utilized efficiently [33].

To carry out further cost and space reduction in data centers, distributed microgrids are built to maximize the utilization of renewable energy by balancing out energy surpluses and shortages among different areas. The energy exchange system uses both AC and DC systems with the aim of reducing the capacity of energy storage system and creating a distributed autonomous energy society with the use of DC systems [34]. Within the data center itself, a multi-voltage output power supply (380V DC and -48V DC) is developed to allow for space savings as compared to individual legacy converters [35].

As a result, with cost and space savings as the main objectives, the shift towards 1) a community based autonomous energy has allowed for a reduction in size of distributed energy installations such as energy storage system, 2) the use of 380V DC distribution technology allows for higher system level reliability, higher energy utilization from

renewable energy sources and simple and cost-effective integration when compared to the conventional AC power system. This provides a compelling business case study for the adoption of 380V DC energy system for data centers [36].

2.1.3 Other DC Microgrid Use Cases and Features

The use of DC technology is then extended to within the built environment [37], between buildings [38], in industrial systems [39] and at utility level [40] by the IEC low voltage directive of below 1500V DC. Reference [7] displays the overview of DC voltage level across the urban settings at the distribution level. The US Department of Energy (DOE) has compared the advantages and disadvantage of AC against DC architectures for distribution in [41]. In reference [42], the development of DC technology standards has been briefly summarized. Reference [43] reports an open industry association, Emerge Alliance, which aims to lead the rapid adoption of safe DC power distribution in commercial buildings. Its occupied space standard defines a multifunctional low voltage DC power distribution infrastructure layer that interconnects the sources and the loads. In reference [44], it has outlaid a simple installation practice for DC networks within the built environment. However, one of the impediments against global adoption of DC systems is the lack of the standards from generation, transmission to distribution level. The standards are essential to convey the beneficial experiences of experts of DC systems to help improve the reliability and efficiency of such systems [45].

In the case of DC microgrid performance, reference [46] has reported that when maximum power tracking for distributed energy resources was placed nearer to the AC grid, it allows for higher extraction of energy from PV sources in DC microgrid. In integrating with energy storage systems, reference [47] demonstrates the direct integration of energy storage at 750V DC rated voltage for 1500V DC bipolar distribution system. It is designed to act as a backup power supply for 1 hour and the front end converter is capable of wide range of DC voltage control from 707V DC to 778V DC to charge the battery [48]. In terms of DC infrastructure, reference [49] reports the use of ring infrastructure for DC networks with the main concept of the power management not needing specific knowledge about the sources and loads connected to the DC bus. Reference [16] details one other emerging DC infrastructure, which is the bipolar DC infrastructure. A bipolar DC infrastructure is a 2-phase system

which has both poles out of phase with each other by 180 degrees which is similar to the AC counterpart at distribution end use level [50].

Similarly, direct integration of energy storage is applied for 24V DC LED lighting in the built environment at the extra-low voltage level. The system uses a ladder architecture which can be considered a multi-bus system that enhances the total efficiency of the system. In the case of shortage of power from the DC battery, the DC battery is isolated from the system. The DC battery is charged using the PV systems. Its design considerations are discussed in [10]. The DC multi-bus system is discussed in [51]. It allows for power flow exchanges between the DC buses by imposing local voltage deviations during the system design phase [52]. Loads are flexible in determining how they can select the desired bus for power as reported in [53] and [54]. The power can be also simultaneously supplied from multiple buses to enhance the total efficiency of the system. In the case of shortage of power or surplus of power, the buses can be automatically isolated from the system.

In terms of power management with the different energy sources, droop control design using distributed bus signaling between different DC energy sources is also reported and discussed in [55], [56]. Within each energy source, hierarchical control is used where the primary control is based on droop method, secondary control is based on the restoration of the deviations in droop control and the tertiary control is based on the power flow between the source and the distribution system. The details are shown in [57]. Within the droop control, one problem is that the power sharing capability is degraded if either the output impedance or the line impedance is unbalanced [58]. Such a phenomenon is more prominent in the distribution level and at built environment last-mile power distribution network because of the high resistance to inductance ratio [59], [60]. This problem is more prominent for low rise building with high penetration of distributed energy resources due to the resulting voltage drop in the purely resistive cable resistance when the DERs are integrated at the same DC bus with the grid [61]. Similarly, for high rise buildings, the voltage drop is non-negligible when a system is distributed with loads of significant current. The voltage drop phenomenon is due to the effect of distributed load currents and is independent of the load power or the distribution voltage [8].

A microgrid system integrates and manages distributed energy resources, energy storage systems, and is able to operate in both grid-connected and islanded modes [62], [63]. To understand the overall view of the system design and operation of the microgrid, power flow analysis is one of the approaches to provide a versatile tool for the steady-state analysis [64]. With the tool, it can be applied for DC microgrid planning and operation stages. It can also be used to investigate on system dynamic analysis, and small signal analysis, etc. Power flow analysis can be embedded in a program as an energy management system of the microgrid [17]. Other uses of power flow model is used as a tool to improve the voltage regulation performance and the accuracy of the power flow analysis by applying to the droop bus model [65].

2.1.4 DC Distribution System for the Built Environment

As a result, the move towards DC distribution for the residential or commercial buildings lies in the feasibility of 1) higher system efficiency, 2) cost-effectiveness and 3) a compromise of voltage safety and the other two factors [7].

The use of DC network allows for the reduction of power electronics which increases the system efficiency. However, the increase in system efficiency does not provide a strong justification for opting DC power distribution within the built environment. The justification comes when factors such as installation cost and life-cycle cost of the system are included for economic comparison, in particular for commercial buildings [3]. While PV can be integrated with the DC network, the savings from direct DC are not cost effective in the current market at the moment [66]. Other efforts of reducing energy are the use of smart DC sockets for supply and demand management using direct load control methodology [67].

Reference [68] provides an economic analysis with energy storage system designed for net-zero energy building. The use of DC energy storage systems is able to provide sufficient energy savings. However, due to the present high costs of storage devices, the investment is not yet cost-effective. With the fast reduction of investment costs that is projected for energy storage devices, the PV DC systems with energy storage systems are projected to be cost-effective before 2020. Reference [69] extends the economic analysis using discounted payback periods. It is discussed that the payback periods are shorter for the options with smaller sizes of PV or BESS units. When only solar PV units are used, the levelized cost of electricity is lower

To further reduce investment, reference [70] shows an efficient use of distributed energy resources through system design thinking. This is done in a way such that the photovoltaic system is used to charge the battery energy storage systems. For a rural application, the use of a DC network is cost effective compared to existing AC systems due to the use of simpler power electronics. Energy efficiency and simplicity are achieved with a minimal number of conversion stages and allows for easier control [71].

2.1.5 DC LED Lighting System

One use case for DC system that has been identified for the built environment is the LED lighting system. Research and developments in LED lighting, as shown in Fig. 2-1, have allowed for a substantial increase in the efficacy of LED lighting and a substantial decrease in the cost of LED lighting [72]. As a result, the use of LED lighting increases and the average LED power is lower compared to normal CFLs with the same lighting lumen requirements [73].

Figure 2-1: Research and development trends of LED lighting

With the emergence of DC network, the different ways to power LED luminaires are shown Fig. 2-2. In using extra-low DC voltage for distribution, the LED luminaires can be directly powered by the distribution voltage or through the use of a LED driver. In using higher voltage level such as 230V AC and 380V DC, the LED luminaire requires an interfacing power electronics converter.

Figure 2-2: Methods of powering LED luminaires

In integrating LEDs with distribution network of higher voltages, a step down converter is required to step down the interfacing voltage to the input voltage of the LED driver which is usually rated at 24V DC or 48V DC. The LED driver is used to regulate the output current to the LED. Alternatively, a current limiting resistor can be designed in the LED luminaire for the LED luminaire to be powered by the designed interfacing voltage.

The move toward DC-based LED lighting (380V DC or 24V DC) allows for the reduction of component size and a higher efficiency in the use of the interfacing converter. A case study, using a 380V DC distribution network in an office environment, has illustrated the above advantages in [5]. Another method of powering LEDs is to use extra-low voltages for distribution purposes. Combining with electrical system design knowledge, an extra-low voltage distributed LED lighting system is reported to be energy efficient [15]. From a retrofitting point of view, a 48V DC unipolar distribution system for a LED lighting system in the EDISON project has been reported in [74]. The lighting system was retrofitted from a single phase distribution system with TN-S grounding. The other unused circuit is used as wired communication for the dimming of the LED lights. Similarly, reference [20] proposes a 48V DC bipolar distribution lighting system which has both circuits powering up the LED lighting in a high rise building. Compared to a 24V DC or 48V DC unipolar distribution system, it is able to distribute more LED lightings with higher system efficiency. The main challenge of using an extra-low voltage for distribution purposes is its relatively non-negligible voltage drop with respect to the low distribution voltage.

In reference [9], it is discussed that while installation is simple, one of the challenges in system design is to keep system losses and voltage drop low. In reference [75], it has discussed that the voltage at the extra-low level for distribution is unable to distribute power for a grid with longer distances. This affects the functionality of the loads if the voltage drop is not accounted for during the design phase [13]. A ladder distribution system architecture, which is described in [19], is reported with energy storages powering on the other end of the radial distribution system as seen in [10]. The system design alleviates the voltage drop on the distribution cables and is a more energy efficient form of distribution.

However, the most energy conservation form of the lighting system is the human-centric lighting, as proposed in [14]. This is to say that the lighting system operates at full load in the presence of human activity and dimmed load in the absence of human activity. However, for such a case, the interfacing converter may suffer from a drop in converter efficiency as it is not operating at rated power [76]. In illustrating the effects of light loading during simulations and analysis, during dimmed loads, the efficiency of the interfacing converter decreases by 5% and the difference between an AC-DC and DC-DC converter is 5% [77].

The use of DC for distribution lowers the total unsubsidized capital costs by up to 20% in a PV-powered LED lighting systems if the production of LEDs follow DOE's cost and efficacy targets [12]. Another similar distribution method of powering the LEDs is the use of Power over Ethernet (PoE), at 48V DC rated. However, currently, there are no available test methods suitable for calculating energy from power measurements in PoE systems or similar DC circuits [78]. Furthermore, as the distribution voltage is low, the system power loss is non-negligible. Hence, to bridge the technical challenge, part of the research work looks into distribution network loss modeling for the system analysis of extra-low voltage DC LED lighting systems.

2.1.6 DC Systems Summary

From the above literature review, it can be seen that the implementation of DC systems emphasizes efficiency and cost savings as the main considerations. The design of DC systems also focuses on advanced infrastructures such as ladder [19] or ring infrastructure when the consideration the architecture of the installation is taken into account such as in the use case of shipboards power systems [79]. It is also observed

that power flow analysis is an essential tool to design and plan the operation of DC microgrids.

The implementation of DC systems is moving towards residential and commercial buildings. In particular, a direct DC system for low rise building with photovoltaic installation could reduce energy of up to 5% of the total load and 14% when energy storage is used [80]. Furthermore, as LEDs are DC loads, the use of DC circuits for grid-connected PV-powered LED lighting systems can lower the total capital costs up to 21% compared to the use of AC grid [12]. For commercial buildings, a bipolar 380V DC distribution is used for the distribution of commercial and high power loads [5].

A recent work shows that for buildings with large PV and battery capacity, they have more than 11% efficiency savings with the use of DC distribution. DC distribution has the most advantage in buildings with large solar capacity, large battery capacity, and high voltage distribution and is capable for a zero net energy (ZNE) building that can act as an islanded microgrid [81]. However, in periods of low renewable energy sources generation, it results in the loads powered by the grid rectifier. The grid rectifier artificially increases the losses of the overall dc distribution system, in comparison when the conventional AC distribution system is used and the grid rectifier is not required. In the case when the residential microgrid is isolated from the main grid and the loads are powered by the DC renewable energy sources, the overall DC distribution system has higher efficiency [82].

To summarize this sub-section, in providing an analytical analysis and bridge the technological advancement together, some of the objectives of the research work are as follows:

- Model the highly resistive DC distribution system in the built environment with considerations towards different electrical installation infrastructure using power flow modeling techniques.
- Apply the model to design different DC LED lighting systems at 24V or 48V DC level which is a good representation of the losses from the distributed load currents. The extra-low DC voltage LED lighting system is selected as it represents a balance between system efficiency from the selection of the DC voltage, the distribution load power and the safety from the DC voltage.

2.2 DC Network Power Flow Modeling

To carry out the power flow modeling for DC distribution network in the built environment, the literature review is carried out: 1) Power flow modeling, 2) DC bipolar network modeling and 3) Voltage balancing strategies.

2.2.1 Power Flow Modeling

Power flow analysis is the basic steady-state analysis tool for an electrical network. It is an essential tool to get the overall view of the system for the design and operation of microgrids which can then be applied to network optimization, component capacity optimization in the planning stage. It can be adopted for network reconfiguration and power control during real-time operation. The power flow model can be analyzed for power system security analysis and planned for protection coordination. Moreover, it can be used to study system dynamic analysis, and small signal analysis, etc. Power flow analysis is an important embedded tool for energy management in a microgrid [11].

Power flow analysis is first applied to transmission networks where the bulk of power is transported. Some methods of power flow analysis include: 1) A combination of backward current analysis, forward phase analysis and Newton Raphson for power flow solution [83]; 2) The use of implicit Z-bus method is adopted by using superposition principle for analysis such that at any one time, only a source is considered [84]; 3) Use of modified Gauss-Seidel method to solve a 3-phase coupled equation like a single phase equation using implicit Z-bus method to reduce computational time [85]; 4) Components are modeled using phase voltages, admittance and as current sources and the models are decoupled through compensation current injections whenever necessary [86]; 5) Use of sequence-components frame for single-phase power-flow to reduce the problem size and the computational burden as compared to the 3 phase-frame approach [83] and [87]; 6) Use of Newton-Raphson method for higher R/X ratios [88] and for positive sequence frame [89]; 7) Use of voltage dependent static load models and the forward and backward iterative methodology on nodal voltage using the Kirchoff's Law [90]; 8) Use of ladder network theory and basic electric circuit laws for observable power flow [91]; 9) Use of modified Newton method to replace the forming of Jacobian matrix, LU factorization and the use of forward/back substitution with back/forward sweeps on radial feeders with equivalent impedances [92]; 10) Use of multiport compensation technique and

basic formations of Kirchoff's laws to break weakly meshed network into smaller linear networks [93] and [94].

The use of iterative methods such as the forward-backward sweep methods are designed for radial distribution systems. The iterative method in [95] is popular due to its intuitive solution procedure. However, the solution methodology uses much sub-iteration on laterals and it requires complex procedures in numbering the radial distribution networks for algorithm execution. One main disadvantage of iterative algorithms is that the different component relationships are built by a direct observation method. This may result in the preparation being cumbersome and prone to errors like in reference [18].

As distributed generation technology emerges, microgrids and active distribution system (ADS) change the centralized power system to a decentralized power system. The availability of accurate power-flow analysis is the first component of microgrid planning, operation, control, protection, and management of the ADS [96]. The conventional power-flow analysis methods, based on the system positive-sequence representation, that are widely used for large power transmission systems, are not directly applicable to microgrid [97]. It is because of the relatively high degree of power imbalance due to the presence of single-phase, two-phase loads and unbalanced three-phase loads [98]. It is also due to the single-phase and three-phase distributed generation and storage coupled together with different control strategies and operational modes [99], [100] and [101]. The presence of non-dispatchable DG units such as wind and photovoltaic power also plays a role in it [102]. Existing literature focuses on the steady-state modeling of electronically-coupled DER units and assumes only positive-sequence DER representation for power-flow analysis [103].

As distributed generation technology improves, the islanded microgrid can be formed at distribution level. As a result, a number of power flow analysis models are proposed to address the above-mentioned characteristics of distribution systems which include high R/X ratios, radial or weakly meshed topologies and a large number of branches and nodes.

A three-phase power flow model with the use of the forward-backward sweep is applied to distribution systems with a single AC power source. The method fails to be effective in distribution systems with several DGs or in islanded microgrids with

decentralized droop control [104]. The model is then improved by considering the operational limits and constraints of the DGs such as the maximum phase current and different operational strategies. However, the model fail to consider the operational behavior of islanded microgrids with decentralized droop control [105].

A three-phase power flow model is formulated as a set of nonlinear equations to adopt real characteristics of islanded microgrids and Newton-trust region technique is used to solve such equations. However, the technique is highly sensitive to the initial settings of problem variables [106]. Other analysis includes the use of evolutionary algorithms to examine the issue of initial values from the variables used. A Particle Swarm Optimization (PSO) is used to determine the droop parameters for optimizing the sharing of reactive power. However, the technique fails to calculate the sharing of active power among DGs [107]. Reference [108] discussed the use of genetic algorithm for power flow analysis model.

At distribution level, power flow methods, such as Newton-Raphson (NR) and Fast-Decoupled (FD), fail to solve power balance equations for distribution systems (DSs) due to the result divergence problem arising from the high value of R/X . To provide an effective ground for power flow analysis, distributed slack bus modeling has also been investigated in [96] and [104].

Current power flow analysis practices assume one DG with the highest capacity as a slack bus to operate like an infinite bus. Such an assumption might not also be economical for if the owner wishes to perform economic dispatch. Furthermore, voltage rise might occur in some buses when the DG is treated as slack bus and others as DGs with constant power. Therefore, considering merely one slack bus is not appropriate in an islanded mode [109].

One method proposed is to consider DG units based on droop operation where all DGs participate in voltage and frequency tuning of the microgrid. Such operation requires active power generation or local voltage of each DG to be pre-specified based on droop characteristic controllers. This involves a droop bus in addition to PV and PQ buses in the power flow analysis. Notably, in the case where MG operates in a grid-connected mode, a slack bus can be successfully considered [110].

Another issue associated with power flow analysis is the absence of a clear methodology to plan the reactive power. This is because the use of the Jacobian matrix for finding the power flow solution may diverge at distribution levels. Few studies have addressed these power flow analysis issues in islanded microgrids [111].

In this research work, the steady-state model of DC distribution system for DC power flow analysis is investigated. Existing literature works described DC power flow as the linearized version of the AC power flow. In reference [112], it discusses that the assumptions are not realistic. The voltage profile is not flat and may vary among busses, causing the voltage profile to be different from the assumption. The X/R ratio condition is not guaranteed high. The influence of the resistance increases with the decrease of voltage.

At the distribution level, the network losses have to be modeled and accounted for. In reference [113], it attempted to linearized the losses for practical optimal power flow. The network losses are modeled separately. In reference [114], it has identified that the line losses is one of the main source of errors in the linearized DC model. Hence, reference [115] improves the accuracy of the linearized DC model by restricting to only active line losses and incorporating to the algorithm.

The most common method is to use an AC solver to calculate the line losses and then add those losses to the loads in the linearized DC model. However, the assignment of losses to load points is arbitrary and could remove reasonable solutions from the DC power flow model. The solution also becomes inaccurate when line flow changes significantly. In reference [116], the losses are modeled without its flow direction. In reference [117], it concluded that DC power flow with loss compensation model accuracy is not satisfactory in most applications. For larger network, DC power flow with loss compensation has a better accuracy than the classical model. However, for smaller network, the performance is similar to that of the classical model. Reference [117] also illustrates that the loss compensated version may fail to deal with the heavy load condition or power systems with high R/X ratios. Recent literature examines the droop control aspect together with the power flow analysis for low voltage AC and DC Microgrids [17] and [118] while the power flow formulation is used for to aid in droop control of DC microgrids [119]. Recent literature also suggests that DC power flow has to be allocated for DC networks [120] and the constraints are discussed in [121].

Thus, in this section, the following can be summarised:

- Power flow analysis evolves from the conventional centralized transmission network to decentralized distribution microgrids then to islanded microgrids as distributed generation technologies advance.
- The use of DC power flow assumed from AC power flow may not be suitable for high R/X ratio distribution networks. The voltage profile is not flat and may vary among busses which can be a phenomenon in the built environment.
- Power flow analysis is reported to be used to aid in the decentralized droop control aspect for DC microgrids with multiple slack busses. There is a gap in steady-state analysis particularly for DC systems in the built environment with distribution networks of high R/X ratios.

2.2.2 DC Network Modeling

Existing literature on DC distribution system presents several methods of analyzing the systems. In particular, the unipolar DC distribution grid or DC bus is examined for stability analysis. A DC distribution bus containing only electric vehicles and photovoltaic module integrated with DC converters is investigated. The DC bus model is proposed to capture the steady-state and dynamic characteristics of the DC system for steady state and stability analysis. The model includes port capacitors of the converters, as well as the interconnection cables [122]. Extending from the DC bus system, a multiple source multiple load power system is investigated for stability analysis [123]. In reference [124], instead of a DC bus, it investigates on multi sources and loads at each node and with the effects of cable impedance. The mode, with an effort toward reduced modeling, looks into stability analysis of the DC distribution system. A DC power electronics cascaded system is then examined using the discrete time tool for stability analysis [125]. In the shipboard DC distribution, the impact of the cable and filter impedance is investigated using an average small signal model. The mathematical model is used for stability and power quality analysis at a lower computational cost [126].

The use of modeling allows for flexible and the ease of use for fast analysis of different systems without the need of rebuilding the model through a GUI or using iterative methodologies. Existing literature only considers unipolar configurations and they do not allow to be extended for advanced architecture such as the bipolar DC architecture

[16]. In [127], it addresses this issue by looking at the three-phase conductor in a bipolar DC distribution system. It proposes a model that uses state space approach and models the transient impact in a bipolar DC distribution. However, it has to be taken note that the model is valid when the lines are much shorter than the wavelength of the signals in the system. The bipolar DC distribution model includes individual multiple phase to ground conductors and its mutual interactions between phases. Together with the model, the symmetrical method of decomposing the DC distribution grid into a common mode and a differential mode as proposed in [128] is extended in [129]. The model provides a simplified analysis of balanced, unbalanced, and fault conditions of bipolar dc distribution systems through the use of the decomposition method.

Reference [130] looks into the load flow analysis of hybrid AC-DC systems. In doing, a new classification of DC buses is introduced. The generic set of load flow equations is derived based on different possible AC-DC system configurations and is applied onto the HVDC systems where there is a minimal number of distributed loads in the transmission systems compared to that of the distribution system. Besides, reference [131] examines the effects of network impedance in a train power system with the process of regenerative braking considered. It examines the voltage drop in the system due to system resistance and the voltage rise due to the system inductance resulted from regenerative breaking. Depending on the voltage level, the power flow between substations is revisited. The accuracy of the power flow results is reported to be higher when the power flow equation is considered together with the droop control and virtual impedance [17] and reference [132] report that single line modeling technique is not suitable to model the bipolar DC architecture directly.

Thus, in this section, the following can be concluded:

- Existing power flow modeling has to account for grid islanded effect and the impact of high R/X distribution network. The model has to be robust to account for multiple operations of distributed generation such as constant power or slack mode operation.
- The power flow model for DC distribution system has to be robust and extendable to model multi-pole DC distribution such as the bipolar DC system and the emerging technological advancement in DC distribution such as direct

integration of DC energy sources and asymmetrical integration of the DC energy sources.

2.3 DC Bipolar Voltage Balancing Strategies

In [133], it has compared the different DC distribution, mainly the unipolar, bipolar and homopolar DC distribution. In particular, comparing the homopolar and bipolar DC distribution, the disadvantage of earth return outweighs the advantage of reduced installation cost. Furthermore, in the 3-wire bipolar DC distribution system, it has the highest system efficiency and allows for the use of different voltage level for efficiency purposes. As with bipolar DC systems, there is a possibility of voltage imbalance. As a result of voltage imbalance, current will flow in the neutral conductor and back to the ground, depending on the different grounding systems. This is generally undesirable because this causes corrosion to the ground contact [129]. Hence, voltage balancing is required at multiple points where there is ground contact in the neutral cable.

Other reasons of voltage balancing from the AC system perspective include: 1) In power systems, the balancing of an unbalanced delta-connected load allows the compensation of an oscillating component that rides a dc value such that it can be supplied by the source [134]; 2) In 3 phase induction motors, unbalance input voltage can cause additional iron and copper losses, leading to temperature rises in the machines as well as torque vibrations which result in inefficient operation and loss of lifetime expectancy [135]. The use of voltage balancing index can extended to islanding detection in AC microgrid where the positive and negative sequence voltage is used as indices [136], [137].

Similarly, for voltage balancing in DC power electronics based system, it refers to the ratio of the positive and negative phase of the 2-phase bipolar DC system. The reasons for balancing DC voltage are as such: 1) To improve the system efficiency, 2) To reduce ground corrosion due to current flow in the neutral wire and 3) To use voltage balance indices for future investigations such as islanding detection.

Existing methods for managing voltage unbalance have been researched from the perspective of power electronics, mainly the voltage balancers which output a balanced reference voltage [138] and the current redistributor circuits which balances the input positive and negative poles distribution current to achieve a net zero balance of current in the neutral cable [139]. Different topologies of power electronics have been

researched such as the use of buck-boost converter [140] and a reduced component count voltage balancer design using the SEPIC-Cuk topology [141]. The effectiveness of voltage balancing placed at different locations has been studied in [142]. However, the power electronics based solution requires additional investment which is similar to the mitigation in AC systems using active filters. Furthermore, the use of additional power electronics for voltage balancing reduces the load efficiency which may reduce the overall system efficiency. While it is proposed in [9] to not regulate the system voltage and let the voltage drop across the system, the use of additional power electronics for voltage balancing requires additional investment.

Besides the power electronics perspective, other methods of managing voltage unbalance have been proposed from the power system planning and operation perspective. As the neutral wire current is the determining factor causing the voltage unbalance, [143], and [8] examine the problem of voltage balancing by reducing the current flow in the neutral wire for asymmetrical loading of the bipolar DC network or the use of system parameters such as interfacing voltage level or the total load power.

For the voltage balancing problem, the neutral wire current is investigated by using a linear backward forward sweep method. The system then redistributes the load using a static transfer load switch to reduce the absolute value of the current flow in the neutral cable. The proposed linear backward forward sweep method is applied to a small scale LVDC system and does not take into consideration the impact of the impedance between the two nodes [143].

The impact of network impedance is non-negligible when the distribution voltage is at an extra-low voltage level and the network is purely resistive. Therefore, voltage unbalance is a serious problem if system planning is not properly carried out. One example of such a network is a DC LED lighting system in [8]. The proposed method uses a linear backward forward sweep method on the voltage level of both distribution poles. The loads are distributed to the higher phase voltage using the backward sweep. Then, the forward sweep adjusts the distribution voltage. This takes into account the network impedance as the voltage drop is accounted for in the system.

The problem of voltage unbalance is also investigated by adjusting the interfacing DC voltage of the two DC distribution pole voltages. When the load receiving end voltage is out of the voltage balance range, a signal is sent to the interfacing converter to adjust

the output voltage such that the load is within the range of the voltage unbalance range [144]. Besides adjusting the interfacing voltage, another method is to redistribute the power consumption, using the energy storage systems (ESS) in EVs in [145], when the localized voltage is out of the voltage balance range. Reference [132] reports the use of locational marginal price to reduce congestions between either of the two-phase distribution iteratively. It also reports that the use of single line diagram is not suitable to model the bipolar DC network.

From the above-mentioned power system based methodologies, a linear analysis is conducted based on backward forward sweep of either the current or voltage drop in the neutral cable, and a localized voltage unbalance range and congestion reduction using locational marginal pricing are proposed. As an iterative algorithm, the forward-backward sweep consists of three steps, which are nodal current calculation, backward sweep to sum up line section current and forward sweep to update nodal voltage [94]. The direct iterative methods such as the forward-backward sweep methods are designed for simple radial distribution systems. The direct iterative method is popular due to its intuitive solution procedure [95]. However, one main disadvantage of iterative methods is that the relationships among components are built by a direct observation. If the network is large, the preparation can be difficult, as can be observed in [17], and prone to errors or when the observed network is non-observable such that the numbering of the “parent node” and “child node” arrangement is not easily constructed, iterative methods are not applicable [18].

Therefore, in this section, the following can be concluded:

- The existing iterative methods for voltage balancing are not suitable for larger scale non-observable DC systems such as multi-source network where the numbering of the “parent node” and “child node” arrangement is not easily constructed.
- The existing iterative methods for voltage balancing are based on absolute value of current flowing in the neutral wire or based on the voltage drop across the 2-phase bipolar DC distribution network. The methods do not consider the effects of voltage drop from the distribution of bipolar DC loads and the consideration of voltage balancing at the whole system level.

As a result, to provide insights toward the above 2 limitations, a DC LED lighting system is used as a case study to illustrate the effectiveness of different voltage balancing methodology in a highly resistive network. In this research work, a model based voltage balancing optimization methodology is explored to solve the problem of voltage unbalance for the 2-phase bipolar DC power system planning.

2.4 Summary

The following can be summarized as follows:

- The use of DC network allows for the reduction of power electronics which increases the system efficiency. However, the increase in system efficiency does not provide a strong justification for opting DC power distribution within the built environment. Other justification includes factors such as installation cost and life-cycle cost of the system for economic comparison, the need for higher reliability and the ease of integration as have seen in the data center use cases.
- One application use case at built environment last-mile power distribution is the LED lighting system. This is because LEDs are primarily DC loads. In using DC distribution for LED lighting, one of the technical challenges is the modeling of the distribution losses to justify the efficiency in the design and planning of the LED lighting system. Power flow modeling is identified as the main research interest to design and investigate the system design efficiency of different DC LED lighting systems, including extra-low voltage DC LED lighting system and human-centric lighting system. This is because power flow analysis, which is the basic steady state analysis tool for any electrical network, is essential to get the overall view of the system for the design and operation of LED lighting system.
- There is a gap towards a robust power flow model to account for the highly resistive DC distribution system in the built environment with different electrical installation infrastructure and operational mode such as single or multi-source, grid-connected, grid isolated networks and the multi-pole architecture such as the bipolar DC architecture.
- One other index of interest is the voltage balancing index in which it allows for efficient power system design and can be extended for further analysis such as fault identification.

- The existing iterative methods for voltage balancing are based on absolute value of current flowing in the neutral wire or based on the voltage drop across the 2-phase bipolar DC distribution network. The methods do not consider the effects of voltage drop from the distribution of bipolar DC loads and the consideration of voltage balancing at the whole system level. The power flow model is used to formulate a model based optimization methodology for voltage balancing and the performance is compared with existing iterative methodologies.

3 DC System Modeling using Iterative Approach

In the literature review, it is described that DC microgrid exhibits more advantages against AC microgrids [41], [146]. The rise of DC microgrid is due to technology advancement of power electronics, development of DC energy storage systems and DC LED lighting and the increasing penetration of distributed DC energy sources such as PV systems. Within the built environment, it is identified that LED lighting has the capacity for energy efficiency improvement using DC distribution.

In this chapter, it looks into the modeling of the DC system using the load ZIP model and forward-backward approach. In the approach, the network is modeled backward in an iterative manner using circuit theorem and then the distribution voltage is then adjusted in a forward manner. The use of forward-backward methodology is an iterative method and it requires intuitive power flow in the network [147], [148]. The modeling using forward-backward approach is verified using a mock-up single source DC LED lighting distribution system.

3.1 Introduction

3.1.1 LED Lighting

In the literature review, developments in LED lighting have allowed for a substantial increase in the efficacy of LED lighting and a substantial decrease in the cost of LED lighting. One energy conservation method for LED lighting is the use of human-centric lighting. Another method of powering up the LED lighting is to use the Power over Ethernet (PoE) infrastructure. However, it is discussed that there are no available test methods suitable for calculating energy efficiency from power measurements in PoE systems or similar DC circuits [78]. As a result, to bridge the technical gap, distribution loss is investigated from the use of forward-backward approach. While there are different applications for LED lighting, this chapter focuses on the low power LED lighting such as the provision of common space lighting in common corridors and dimmable LED lighting applications in the office environment. Such LED lighting system application is sufficient to model the DC power system at a distribution level with non-negligible voltage drop.

Besides the conventional method of using power electronics to power up the LED luminaire, one other method of powering the LED luminaires is to use a current

limiting resistor which limits the input current to the LED luminaire at 24V DC as shown in Fig. 3-1. In the driverless LED lighting system, the LED driver is replaced with the use of a current limiting resistor to limit the input current.

Figure 3-1: A driverless LED lighting diagram

3.2 Problem Description

One of the main challenges associated with the DC network at the distribution level is its non-negligible voltage drop due to the use of extra-low voltage as distribution voltage and the highly resistive distribution network. As a result, there is a need to model the distribution voltage drop across the distribution system to allow for the following:

- The investigation of different driverless DC LED lighting system performances without resulting in different brightness across the LED lighting system due to voltage drop.
- The investigation of DC LED lighting system using a DC unipolar and bipolar distribution system and to allow system comparative analysis in terms of system efficiency.

3.3 Mathematical Modeling

In a distribution network, there are different parameters affecting the performance of the system. The following subsections will proceed onto modeling the individual components, and then onto the distribution system. The distribution network has the following characteristics: 1) Only one DC power source is used; 2) The loads are

unidirectional; 3) The network is highly resistive; 4) There are no additional interfacing power converters for voltage regulation purposes; 5) The radial distribution network has observable power flow.

3.3.1 Cable Resistance Model

The factors affecting the DC resistance of a cable are described in [149]. As the main focus is towards DC distribution, the cable DC resistance used, represented by R , is the product of the resistance value of the standard cables used in IEC 60228 at 20°C, represented by r_{dc} , and the length of the cable used, represented by l . The cable resistance model can be expressed in (3-1).

$$R = r_{dc} * l \quad (3-1)$$

3.3.2 Current Ampacity of the Conductor Model

The current capacity of the current carrying conductor is the derated value of the current as defined in IEC 60364-5-52, represented by $I_{derated}$, is dependent on the following two factors. The current ampacity of the conductor model can be expressed in (3-2).

- 1) Ambient temperature of the current carrying conductor, represented by C_{temp}
- 2) Number of current carrying conductor in the conduit of the building, represented by $C_{circuit}$

$$I_{derated} = \frac{I_{conductor}}{C_{circuit} * C_{temp}} \quad (3-2)$$

3.3.3 Load Modeling

The LED luminaires can be powered by a LED driver [150] or the use of current limiting resistor. The LED driver behaves like a constant power load [151] and the load model can be modeled using the ZIP load model [152] and [153]. As the DC LED loads do not have reactive power, the load model follows the active power ZIP load model in [154] and can be defined as (3-3).

$$P = P_0(a_0 + a_1V + a_2V^2) \quad (3-3)$$

where a_0 , a_1 , a_2 and P_0 represent the values of the coefficients of the actual load composition and load study.

3.3.4 Node to Node Network Current Model

The DC LED lighting network consists of multiple DC LED lightings which are modeled as nodes in the distribution cables of the electrical network. The node to node network current model is dependent on lower network nodes and the nodal load current as shown in Fig. 3-2. It is expressed in (3-4).

$$I_{ij} = I_j + \sum_{i=j}^k (I_{ik}) \quad (3-4)$$

where I_{ij} , I_{jk} and I_j represent the node to node current between nodes (i,j) , (j,k) where $i < j < k$ and the load current at node j itself respectively.

Figure 3-2: Nodal current representation

3.3.5 Network Voltage Drop Model

The electrical distribution network of the built environment is highly resistive and together with the use of extra-low DC voltage (<50V DC) for distribution, the voltage drop is non-negligible. The voltage drop is expressed in (3-5).

$$Vd_{ij} = R_{ij} * I_{ij} \quad (3-5)$$

where Vd_{ij} , R_{ij} and I_{ij} represent the voltage drop, resistance and network current between nodes (i,j) respectively.

3.3.6 Network Power Loss Model

The use of DC LED lighting is due to efficient distribution. As a result, the power loss in the network cables has to be accounted for. The system network power loss is expressed as (3-6)

$$P_{sys,loss} = \sum_{\substack{x=(p,0,n) \\ i,j \in (0,N)}} I_{x,ij}^2 * R_{x,ij} \quad (3-6)$$

where $P_{sys,loss}$, $I_{x,ij}$ and $R_{x,ij}$ represent the system network power loss, resistance and network current between nodes (i,j) of either positive, neutral or negative rail respectively.

3.3.7 Driver Power Loss Model

To carry out a detailed analysis, the LED driver power loss has to be accounted for. As the LED driver outputs a constant power, the driver power loss model is expressed in (3-7).

$$P_{dri,loss} = \sum_{i=(1,N)} (V_i * I_i - P_{led}) \quad (3-7)$$

where $P_{dri,loss}$, V_i , I_i and P_{led} represent the total driver losses, the nodal voltage and current and the required LED lighting power respectively.

3.3.8 Resistor Power Loss Model

A DC LED lighting is also able to be powered without a LED driver by using a resistor to limit the input current to its required value as expressed in (3-8) to (3-11). The DC LED lighting with a current limiting resistor is shown in Fig. 3-1.

$$I_{led} = \frac{I_{in}}{n_{parallel}} \quad (3-8)$$

$$V_{led} * I_{led} = \frac{Lu_{min}}{n_{series} * n_{parallel} * \eta_e} \quad (3-9)$$

$$V_{in} = \frac{I_{in}}{n_{parallel}} * R_{limit} + n_{series} * V_{led} \quad (3-10)$$

$$P_{LED,CLR loss} = \sum \left(\frac{I_{in}}{n_{parallel}} * R_{limit} \right)^2 \quad (3-11)$$

where V_{led} , I_{led} and I_{in} represent the input voltage and current to each LED chipset and the input current to the DC LED lighting respectively. n_{series} and $n_{parallel}$ represent the number of LEDs in series and parallel in the LED array respectively. Lu_{min} , η_e , R_{limit} and $P_{LED,CLR loss}$ represent the minimum required lumen, the LED chipset efficacy, value of the current limiting resistor and the DC LED lighting resistor losses respectively.

3.3.9 Node Current Convention

There are two main types of DC architecture that can be used to distribute DC LED lighting, mainly a unipolar DC architecture and a bipolar DC architecture [16]. A bipolar DC architecture is a type of multi-pole DC architecture [133]. The analysis can be extended other forms multi-pole DC architecture. Mathematically, it is expressed in (3-12) to (3-14) for the bipolar DC architecture. For unipolar DC architecture

representation, the bipolar load currents and the neutral cable representation are not applicable. The load current conventions are depicted in Fig. 3-3.

$$I_{i,+} = (I_{i,b} + I_{i,p}) \quad (3-12)$$

$$I_{i,0} = (I_{i,n} - I_{i,p}) \quad (3-13)$$

$$I_{i,-} = -(I_{i,b} + I_{i,n}) \quad (3-14)$$

where $I_{i,+}$, $I_{i,0}$ and $I_{i,-}$ represents nodal current of positive, neutral and negative cable at node (i) respectively. $I_{i,b}$, $I_{i,p}$ and $I_{i,n}$ represents the load current distributed across the bipolar, positive rail and negative rail respectively.

Figure 3-3: Node current convention for different DC loads

3.4 Forward-Backward Modeling Approach

Forward-backward iterative approach is chosen for its simplicity of implementation with its intuitive solution procedure and the applicability to a radial lighting distribution system [155]. Furthermore, the iterative approach has an advantage of easy modification with design objectives such as voltage balancing using voltage-based distribution with consideration of non-negligible voltage drop [8] or through minimizing the absolute neutral current value [143].

3.4.1 Iterative Approach

In applying the forward-backward iterative approach, the system nodes have to be labeled. A node is created on the distribution cable where a DC load is distributed, respective of distributing across unipolar DC or bipolar DC rail. The numbering of the nodes is taken such that DC source node is numbered as 0 while the remaining load nodes are numbered in increasing order with respect to the distance from the DC source. It has to be noted that in a radial distribution network, the relationship between the parent node and child node is intuitive and the network has only one DC source.

The backward forward iterative approach has 3 main steps. Firstly, a 'backward' sweep is carried out to model the relationship between the nodes, starting from node n and back to node 0, using (3-1) to (3-5) together with current convention (3-12) to (3-14). This is carried out by setting the last node voltage to be the initial distribution voltage of 24V DC or 48V DC in this case study. After completing the backward sweep, a 'forward' sweep is carried out by adjusting the last load node to the ending criterion by reflecting the first node 0 voltage to the DC distribution voltage. Last of all, a design framework or objective is set and the forward-backward process is iterated until the objective is achieved. The iterative approach flowchart, as described, is shown in Fig. 3-4.

Figure 3-4: Forward-backward iterative flowchart

3.4.2 Driverless DC LED Lighting System Design

A driverless DC LED lighting system is a system design that takes a compromise between system efficiency and the additional cost of LED drivers. With different lighting applications, a driverless DC LED lighting system has the ability of a

centralized dimming function by adjusting the DC voltage of the DC source [13]. Unlike a driver driven DC LED lighting, the input current to a driverless DC LED lighting is determined by the value of the current limiting resistor. As a result, the compromise in system efficiency is due to the availability of resistor value for current limiting purposes. The design of the driverless DC LED lighting system framework is shown in the objective part of the iterative approach flowchart in Fig. 3-4.

3.4.3 DC LED Lighting System Performance

The motivation for DC LED lighting is due to its system efficiency. In determining the system efficiency, the various possible causes for losses are modeled in (3-6) to (3-11). The losses are required to evaluate the performance of the DC LED lighting system with a high level of confidence which is determined after the DC LED lighting system is designed. The evaluation of the lighting system efficiency is shown in the objective part of the iterative approach flow chart in Fig. 3-4.

3.5 Simulation and Experimental Results

Different detailed simulations are carried out for a DC LED lighting case study using extra-low voltage for distribution purposes, mainly a) 24V DC unipolar, b) 48V DC unipolar and c) 48V DC bipolar. The simulations are carried out on variations of DC LED lighting system such as the use of a LED driver or the use of a current limiting resistor. The simulations are carried out using the forward-backward modeling iterative approach. System functional analysis using the index of system efficiency is then briefly carried out

3.5.1 Case Study System Mock-Up

The case study is the stairwell lighting high rise building as shown in Fig 3-5. It can be described as a low power LED lighting system for illumination purpose with an option for dimming function. A mock-up of the actual 11-storey stairwell lighting system is set up in the lab using a DC driver driven LED lighting as shown in Fig 3-6 and Fig. 3-7. The network parameters are shown in Table 3-1.

Figure 3-5: High-rise building lighting stairwell case study

Table 3-1: DC electrical network parameters

	Parameters	Values
Electrical Network Properties	Cable Size	14 AWG
	Line Resistance	0.0074Ω/m
	Length between Lighting Node	5m
	Length between converter and first LED lighting	5m
	Derated Factor	0.8
LED Lighting Properties	Driver Efficiency for 24Vdc system:	96%
	Driver Efficiency for 48Vdc system:	94%
	LED load power	6.7W

Figure 3-6: Retrofit for a) unipolar 24V DC, b) unipolar 48VDC, c) bipolar 48V DC network

Figure 3-7: A a) Unipolar 24V DC and b) Bipolar 48V DC LED lighting system mockup.

3.5.2 DC LED lighting load model

The DC LED lighting can be powered using a LED driver or to use a resistor for current limiting purposes. The actual DC LED lighting uses OSRAM DURIS S5 LEDs of array 7 series by 6 parallel with a total power of 6.7W and an input current of 0.350A to the luminaire. It can be powered using a DC LED driver such as the RECOM RCD-24 or RCD-48 DC driver. The same array is also used to design the LED lighting with different values of current limiting resistor for current limiting purposes.

Fig. 3-8 shows the I-V characteristics curve of OSRAM LED Chip LCW JDSI.EC chipset. The rated voltage and current values of the LED chipset based on the datasheet are estimated to be 2.8V DC and 0.55mA respectively. The resistor value is estimated

based on (3-8) to (3-10) using the following values: $Lu_{min} = 700$, $n_{series} = 7$, $n_{parallel} = 6$, $V_{led}^* = 2.8\text{V DC}$ and $I_{led} = 0.55\text{mA}$.

Figure 3-8: I-V characteristics curve of OSRAM LED Chip LCW JDSI.EC

Table 3-2: Resistor values for different input voltage range

Input Voltage Range (V)	LED Luminaire Resistor Value (Ω)
23.5 – 24.0	66
23.0 – 23.5	54
22.5 – 23.0	48
22.0 – 22.5	40
21.5 – 22.0	26
21.0 – 21.5	15

As the resistor values are selected due to manufacturer limitations and the corresponding linearized load model parameters for simulation are shown in Table 3-2. For each of the voltage range, the design of the current limiting resistor is such that the input current is limited to the range of 0.350A to 0.400A. The load model used to model the DC LED lighting is the active power polynomial ZIP load model in (3-3). It can be reduced to (3-15) such that it is a voltage-dependent load as described in [156].

$$I = \frac{P}{V} = P_0 \left(\frac{a_0}{V} + a_1 + a_2 V \right) \quad (3-15)$$

Table 3-3: Simulation load parameter using empirical measurements

Power (W)	P_0	a_0	a_1	a_2
21 (B)	3	0	-0.0036	0.3256
7 (B)	1	0	-0.0036	0.3256
21 (U)	3	0	-0.012004	0.586634
17.5 (U)	2.5	0	-0.012004	0.586634
14 (U)	2	0	-0.012004	0.586634
10.5 (U)	1.5	0	-0.012004	0.586634
7 (U)	1	0	-0.012004	0.586634
66 OHMS	1	0	0.0690	- 1.2489
54 OHMS	1	0	0.0778	- 1.4015
48 OHMS	1	0	0.0868	- 1.5750
40 OHMS	1	0	0.0967	- 1.7428
26 OHMS	1	0	0.1325	- 2.3986
15 OHMS	1	0	0.1540	- 2.7757

The corresponding values of P_0 , a_0 , a_1 and a_2 for the different DC LED lighting loads are shown in Table 3-3 above. The values calculated are based on the empirical measurement of the different DC LED lighting loads. Fig. 3-9 shows a DC LED lighting luminaire powered by a DC LED driver while Fig.3-10 to Fig. 3-12 show the empirical measurement of the load model of a 24V DC, 48V DC and driverless DC LED lighting luminaire.

Figure 3-9: Actual DC LED lighting luminaire

Figure 3-10: Plot of 24V DC LED lighting load model

Figure 3-11: Plot of 48V DC LED lighting load model

Figure 3-12: Plot of different driverless and driver 24V DC LED lighting load model

3.5.3 24V DC Unipolar DC LED lighting with driver

The iterative approach is validated against a mock-up and a simulated lighting system. The first validation is against the 11-node mock-up lighting system using a 24V DC unipolar DC architecture. The lighting unipolar DC distribution system is shown in Fig. 3-13. The nodal voltage validation is shown in Fig. 3-14. The mockup uses the same electrical network and mocks up the operating conditions of that in the actual setting. The simulation uses the forward-backward modeling with the 24V DC LED lighting with driver load model.

Fig. 3-14 shows the voltage level across the nodes for the mockup 24V DC unipolar electrical system and compares it with the simulation. It can be observed that the distribution system voltage drop is consistent with the actual system mockup. It can also be observed that for some of the nodes, the simulated voltage is higher than the measured voltage. The error can be due to 1) the errors encountered in the approximated linear load model used, 2) the temperature conditions of the mockup system may not be constant at 30 degrees, consequently, this affects the derating factor of the current capacity of the cables and 3) the errors are relatively magnified due to the use of extra-low voltage for distribution.

Figure 3-13: A 24V Unipolar DC LED Lighting Distribution System

Figure 3-14: Comparison of nodal voltages for 24V unipolar DC system

3.5.4 48V DC Bipolar DC LED lighting with driver

Similarly, to verify the proposed mathematical modeling for a bipolar DC network, a mockup 48V bipolar DC LED lighting system is set up in the laboratory. The mockup uses the same electrical network and simulates the operating conditions of that in the actual setting. In the bipolar DC architectures, the loads are distributed alternately between the two rails with the last load at the positive rail. In the bipolar DC distribution, the LED lightings are distributed using the 24V DC rail. There is no consideration of bipolar DC loads. The simulation uses the forward-backward modeling with the DC LED lighting load model and the modeling of the current flow of the shared cable. The mock-up electrical system diagram is shown in Fig. 3-15.

Fig. 3-16 shows the voltage level across the nodes for the mockup 48Vdc bipolar electrical system and compares it with the simulation. Similarly, it can be observed that the relative shape of the distribution system voltage drop is consistent with the actual system mockup and the reasons in the modeling errors are the same as that of the DC LED lighting unipolar mockup.

Figure 3-15: A 48 Unipolar DC LED Lighting Distribution System

Figure 3-16: Comparison of nodal voltages for 48V bipolar DC system

As have observed in the above mock-up voltage verification against the iterative approach, the next validation is against a Matlab Simulink of 15-node system with consideration of non-negligible voltage drop effects due to DC bipolar loads. The 15-node network is shown in Fig. 3-17 with the nodal voltage comparison as shown in Fig. 9.

Figure 3-17: 15-node simulated lighting distribution system

Figure 3-18: Plot of the nodal voltage of the iterative approach for 15-node simulated system

3.5.5 24V DC Standard Resistor LED Lighting System

From the above two results comparison, the mathematical modeling is successful in modeling the voltage values of the of the unipolar and bipolar DC network distribution system. Consequently, the driverless DC LED lighting system simulation is explored to determine the functional capability of the lighting system by driving the LED luminaires without the LED driver. It has to be taken into account that if the input voltage is too low, the LED luminaire is unable to deliver the minimum lighting power.

In the simulation, a standard LED luminaire with 54 ohms resistor for current limiting purposes is used for all 11 nodes. The nodal voltage (blue) and the corresponding nodal current (red) are shown in Fig. 3-19. It can be seen that the current through each node is inconsistent. As the current through the LED luminaires determines the brightness of the LED lighting, inconsistent input node current implies that there is inconsistent brightness across the different floors. The effect of brightness inconsistency is significant for the larger electrical system because the voltage drop across the first and last node is significant and this reduces the input current to the LED luminaire of the first and load node. As a result, while the use of driverless LED luminaire helps to save up on the LED driver cost, there is an issue with brightness inconsistency due to non-

negligible voltage drop. One alternative is to adjust the current limiting resistor values of the LED luminaries so that the input current to the LED luminaires is within a desirable range.

Figure 3-19: Plot of the nodal voltage and current for a driverless standard LED lighting system

3.5.6 24V DC Non-Standard Resistor LED Lighting System

The issue of brightness inconsistency due to non-negligible voltage drop can be mitigated by adjusting the current limiting resistor values of the LED luminaries. However, selecting the right resistor values is a challenge as the node voltages are unknown and the pool of resistors available is limited. As a result, there is a need to model the nodal voltage in a DC distribution system. For nodes with a lower input voltage due to voltage drop, a smaller resistor is used while for nodes with a larger input voltage a larger resistor is used to maintain the input current to the LED luminaire at the desirable range.

To determine the resistor values, the forward-backward iterative approach is modified as shown in Fig. 3-20. The design principle is such that in the first iteration, a constant current load model is used for the modeling to obtain the nodal voltages. Then, starting from the last node to the first node, the load model of each node is replaced from a pool of available driverless LED load model. The process is repeated until the current at each node is within a desirable range.

Two driverless LED lighting systems using different distribution rated voltage, mainly 24V DC and 22V DC, are simulated. The simulations have shown that the input current does not exceed 0.450A and does not fall below 0.350A with the modified design iterative approach. The simulations have successfully shown that the LED lighting

system is able to carry out its function when the distribution voltage is rated at 22V DC. The list of available driverless LED luminaires is given in Table 3-2 and the distribution of driverless LED lighting for the two simulations is given in Table 3-4.

Figure 3-20: Modified forward-backward iterative approach flowchart

Figure 3-21: Plot of the nodal voltage and current for non-standard 24V DC lighting system

Figure 3-22: Plot of the nodal voltage and current for non-standard 22V DC lighting system

Table 3-4: Distribution of resistor values for driverless non-standard LED lighting systems

LED Lighting Node	1	2	3	4	5	6	7	8	9	10	11
Resistor Value (Ω) (24VDC)	66	66	66	48	48	48	48	48	40	40	40
Resistor Value (Ω) (22VDC)	48	40	40	26	26	26	26	26	15	15	15

3.5.7 48V DC Unipolar DC LED lighting with driver

Another efficient system design philosophy is to use a higher distribution voltage to reduce the voltage drop. This is because with the similar power, the current in the distributions system is lower, resulting in negligible voltage drop. However, using a 48V DC rated LED driver to drive a LED luminaire designed to be powered using a 24V DC rated LED driver, the LED lighting experiences a drop in driver efficiency. The comparison of driver efficiency powering a 24V DC rated LED luminaire is shown in Fig. 3-23. The decrease in driver efficiency is one of the determining factors

for a lower system level efficiency when compared to the use of bipolar 48V DC architecture for distribution. The comparison of the simulation results is carried out in the next section.

Figure 3-23: Comparison of driver efficiency of a) 24V DC Driver and b) 48V DC Driver

3.5.8 Driverless LED Lighting System Performance Comparison

The value of the resistor is determined by the input DC voltage to the DC LED lighting, as shown in (3-8) to (3-10). Due to non-negligible voltage drop across the distribution system, the selection of the resistor value is dependent on the design frameworks. Hence, different design frameworks are explored in this paper using the fast simulation and intuitive analysis advantage in the forward-backward iterative approach. The different design frameworks are as follows:

- 1) Use of rated 24V DC distribution voltage and standard driverless DC LED lighting
- 2) Use of rated 24V DC distribution voltage and non-standard driverless DC LED lighting to be determined at each node iteratively
- 3) Use of non-rated 24V DC distribution voltage and non-standard driverless DC LED lighting to be determined at each node iteratively
- 4) Use of rated 24V DC distribution voltage and constant current load model to determine current limiting resistor
- 5) Use of non-rated 24V DC distribution voltage and constant current load model to determine current limiting resistor

Case 1) represents the base case and is used to illustrate that the design is unable to deliver the minimum lighting power requirement due to the effects of voltage drop. Case 2) and Case 3) illustrate the framework when the driverless DC LED lighting is designed based on the availability of DC LED lighting while Case 4) and Case 5) illustrates the framework when the optimal current limiting resistor is determined to

deliver the minimal lighting power and to minimize the power loss due to current limiting resistor. The load model is obtained from OSRAM DURIS E5 datasheet and is assumed to be linear at the following two points at ($V_f=2.9V$, $I=50mA$) and ($V_f=3.1V$, $I=100mA$). Fig. 3-24 shows the nodal currents of the frameworks in Case 1) to Case 5) using the 11-node system case study.

Figure 3-24: Plot of nodal currents using the different driverless design frameworks

3.5.9 DC LED Lighting System Performance Comparison

Besides the 5 driverless DC LED lighting system, additional 3 other DC LED lighting system are compared as follows: Case 6) 24V unipolar DC driver based LED lighting system; Case 7) 48V unipolar DC driver based LED lighting system and Case 8) 48V bipolar DC driver based LED lighting system. Case 6) to Case 8) evaluates the DC LED lighting system performance against the different types of DC architectures.

Two system performance simulations are carried out. The simulations compare the different power losses of all 8 cases and the system efficiency using the 11-node actual LED lighting case study as shown in Fig. 3-25 and Fig. 3-26 respectively.

Figure 3-25: Comparison of power distribution for the 8 cases

Figure 3-26: Comparison of system efficiency for the 8 cases

The next simulation compares the system efficiency of the DC architectures against increasing number of DC LED lighting distributed using the same stairwell lighting. The system efficiency plot is shown in Fig. 3-27. Using a 17-node LED lighting system as the comparison study, Fig. 3-28 shows the breakdown of the lighting power, driver and cable losses using the three DC distribution system.

Figure 3-27: System efficiency simulation for DC systems with increasing loads

Figure 3-28: Distribution system architecture performance comparison chart

3.6 Results Discussion

The comparison between the different distribution system architectures and LED lighting architectures is similar to US Department of Energy report on commercially marketed Power over Ethernet (PoE) connected lighting systems. The system performance comparison compares the two design factors, mainly 1) the net lighting power used and 2) the efficiency of the system design. According to the above system performance simulations, Fig. 3-24 to Fig. 3-28, the following conclusions can be drawn

- 1) Using standard 24V DC LED lighting results in un-even lighting power output at each node for a highly resistive distribution network. This can be seen in Fig. 3-24 that for nodes 9 to 11, the input current to the LED lighting is below the minimal value of 0.35A.
- 2) Comparing the efficiency of driverless DC LED lighting system in Fig. 3-26, it is seen that the design framework affects the system efficiency. In comparing Cases 2 and 3 against Cases 4 and 5, it can be seen the reduced system efficiency in Cases 2 and 3 is due to the over-provision of the LED lighting power which is due to the availability of the LED lighting, as shown in Fig. 3-25. The over-provision of lighting power also causes higher power losses due to the current limiting resistor which further reduces the overall system efficiency.
- 3) Comparing Case 4 and Case 5, it can be seen that while a higher distribution voltage allows for more capacity for voltage drop, it does not translates to higher

system efficiency in Fig. 3-25. This is because the system efficiency is also affected by the higher resistive power losses in the current limiting resistor in the LED lighting in Fig. 3-26.

- 4) Comparing a driver-based system and a driverless system, a driver based system has a slightly higher efficiency compared to the optimal system design (Case 5) in Fig. 3-26. This is due to the provision of the minimal lighting power which is regulated by the LED driver. However, a driver-based system requires an additional LED driver which requires more cost justification compared to a near-optimal design driverless LED lighting system due to availability of LED lighting.
- 5) Comparing the DC architectures, it can be shown that the system efficiency is a compromise between network cable and LED driver power losses in Fig. 3-26. In distributing a lower rated voltage LED lighting using a higher rated LED driver, it can be seen that the system efficiency for low number of distributed loads is higher in the unipolar 24V DC architecture compared to the unipolar 48V DC in Fig. 3-27. This is due to the higher LED driver efficiency. However, for a higher number of distributed loads, the higher DC voltage system architecture has higher system efficiency because the effects of cables power losses outweigh the gain in driver efficiency in the lower DC voltage system architecture.
- 6) For higher number of loads, it can be seen that a bipolar DC architecture has a higher system efficiency compared to the unipolar DC architecture in Fig. 3-27. This is because in using the bipolar DC architecture, the lower voltage rated loads are distributed by a higher voltage rated LED driver. Furthermore, in the bipolar DC architecture, due to the opposite current flow in the neutral cable, it results in a lower net current flow and it results in a lower net power loss in the neutral distribution cable. Hence, the use of bipolar DC architecture has higher efficiency because of the use of higher efficient rated LED driver and a lower net current flow in the neutral distribution cable.
- 7) In Fig. 3-28, without accounting for the driver losses and only accounting for the system cable losses, it can be seen that the system efficiency of a unipolar 48V DC LED lighting (96.8%) is comparable to that of a bipolar 48V DC (96.7%). However, when comparing against the net energy consumed, the unipolar 48V DC architecture consumes more energy than that of a bipolar 48V DC LED lighting system although the system efficiency is comparable. This is because of net higher driver losses in the LED lighting system. Consequently, the use of total power

utilization, which is inclusive of distribution and driver losses, is a better system design metric compared to system efficiency for accurate energy reporting.

- 8) In determining system efficiency, the different loss components have to be clearly distinguished for accurate system comparison. It can be shown in Fig. 3-28 that a 48V bipolar DC distribution architecture has the highest system efficiency out of the other 2 when the associated losses are accounted for. This is due to reduced cable losses in the neutral distribution cable and a higher driver efficiency in using the rated DC voltage to power up the same rated DC voltage load.

Hence, for different lighting applications or requirements, such as the need for centralized dimming or personalized individual dimming, a driverless DC LED lighting system can be a better solution application due to the absence in the need of a LED driver. Furthermore, depending on the power level of the LED lighting load, a higher distribution voltage may not necessarily result in higher system efficiency. This is because the loss in LED driver efficiency is higher due to a higher ratio between the input voltage and output load voltage. Last of all, depending on the availability of the electrical network, a bipolar DC architecture design is able to capture the advantage of higher load efficiency by distributing the loads using the rated voltage and lower cable losses due to the opposite directional flow of current in the in the neutral cable. The bipolar DC architecture has both the advantage of higher driver efficiency and lower cable losses.

3.7 Concluding Remarks

The modeling of the DC unipolar and bipolar network of using the forward-backward iterative approach is carried out successfully using a DC LED lighting system as a case study. In the iterative approach, the DC network requires observable power flow so that the relations of the current and voltage between the loads can be established by direct observation. The modeling of the network requires accurate load modeling and the modeling of the shared distribution cable of the bipolar DC network. The successful modeling of the DC network allows for performance and lighting analysis of the DC LED lighting system architectures.

Using the DC LED lighting system as a case study, the analysis of the different system and LED lighting architectures can be concluded as follows:

- A bipolar network has the capacity for a more efficient system distribution design because of the reduced voltage drop caused by the shared distribution line and the ability to distribute the loads using its rated voltage which results in a higher driver efficiency.
- In comparing electrical system architecture performances, the net power of the functional system is the better design metric for energy conservation compared to system efficiency. The efficiency of the system has to account for the losses due to the driver for DC LED lighting systems.
- A unipolar 24V DC network is more efficient than a unipolar 48V DC network for small distribution networks because the cable losses experienced in a unipolar 24V DC does not outweigh the driver losses in a unipolar 48V DC network, assuming the same loads are distributed.
- For lighting applications without the need of individual lighting dimming due to LED driver, a driverless LED lighting system is able to provide a cost-effective option for lighting system design. In such a case, the design of the system has to reduce the value of the overall current limiting resistor by reducing the distribution voltage without compromising on system functionality. It has also been shown that different design approaches for driverless DC LED lighting has varying system performances.

The modeling and fundamental efficiency and voltage drop analysis is successfully carried out because the DC network is observable such that power flow can be established using direct observation. In the case when the DC network is not observable such as the direct integration of DC energy sources and the need of power quality analysis such as voltage balancing, a more robust DC network modeling is needed, which is explained in Chapter 4 and 5 using nodal analysis.

4 DC System Modeling using Nodal Analysis Approach

4.1 Introduction

The modeling of the DC system with a single source using the forward-backward iterative approach is discussed in Chapter 3. However, the use of forward-backward iterative approach requires observable power flow such that the node to node relationship can be modeled directly and iteratively to form a network model [147], [148]. If the network is large, the preparation can be difficult, as can be observed in [17], and prone to errors [18]. Also, the approach will not be effective when the network is not observable such that the numbering of the “parent node” and “child node” arrangement is not easily constructed and power flow analysis is required to be carried out. One example of an unobservable DC network is a multi-source network with the direct integration of DC energy source and another rectified power source from the main grid. With a decrease in the state of charge from the energy storage systems, the power flow from the two power sources changes.

In this chapter, a steady state power flow model for DC network is proposed to model such unobservable DC network. The model uses nodal analysis on each of the distribution cable and formulates the power flow model, which is similar to the conventional AC power flow model. Then, using the proposed model, power flow analysis is carried out on different variations of the network operation such as grid isolated and grid-connected operations. The model is also verified using a mock-up DC LED lighting system. Unlike the transmission system which requires power measurements at each of the bus, the proposed model uses voltage measurements of the DC energy sources and is also able to be integrated with emerging technological advances such as direct connection and disconnection of DC energy sources.

4.2 Problem Description

As a basic steady-state analysis tool, power flow analysis is essential to get the overall view of the system in the design and operation of DC power systems so that network optimization can be carried out in the planning stage [64]. Conventionally, power flow analysis is model using by nodal voltage analysis of the P and V buses in DC system [148]. However, such features are distinct in power transmission systems and conventional methods for power flow analysis are becoming no longer suitable at distribution level [17]. Specific to the distribution system in a built environment which

has multiple slack buses, one limitation is the presence of voltage-only measurements such as the direct integration of DC energy sources [8]. Another technological advance is such that the DC network may experience grid islanded operational mode due to the direct integration of DC energy sources [10]. As a result, with the above distribution network characteristics, the power flow model has to be robust to account for 1) voltage-only measurement of the DC energy sources, 2) grid islanded operation and the effects of connection and disconnection of DC energy sources. Hence, there is a need to model the power flow in the distribution system to allow for the following:

- To accurately model and investigate the power flow analysis in variations of DC network operations such as different grid operation modes such as grid isolated and grid-connected and single phase integration of DC power sources in multi-pole DC networks such as bipolar DC network.

4.3 Mathematical Modeling

There are different subsystems that form a distribution network which requires modeling. The following subsections will model the DC distribution network with the following subsystems: 1) Grid interfacing converter; 2) Direct integration of DC energy storage system; 3) Bipolar DC architecture; 4) Load model; 5) Modified bipolar DC architecture with single phase DC source integration. The approach for modeling uses nodal analysis on each node with emphasis towards the steady-state model.

4.3.1 Converters System Modeling

DC distribution systems are primarily power electronics based power systems. The interfacing converters have two operating modes, mainly the unidirectional mode when power is sourced out from the power converters and the bidirectional mode where the power can be absorbed by the power converters. In the power sinking mode, the power converter is modeled as a steady state load model drawing power from the network. Its impact towards power flow modeling is trivial and will not be investigated.

In the research work, it is also assumed that the converter DC link voltage is always higher than the DC distribution network voltage during the unidirectional mode such that no back power flow happens due to power electronics topology design. The steady-state model of a unidirectional power converter is shown in Fig. 4-1. Mathematically, it can be expressed as (4-1).

Figure 4-1: Unidirectional converter steady-state model

$$V_{DC,sys} = \begin{cases} NI, & \text{for } V_{DC,grid} < V_{DC,sys} \\ V_{DC,grid}, & \text{for } V_{DC,grid} > V_{DC,sys} \end{cases} \quad (4-1)$$

Where $V_{DC,sys}$ and $V_{DC,grid}$ represents the system network and grid voltage respectively. NI describes that the grid voltage source has no impact and is not applicable towards the modeling of the power flow.

4.3.2 DC Energy Storage Systems Modeling

A unique characteristic of DC network at distribution level is that the DC network can be powered by directly integrating the DC energy storage systems (DC ESS). Fig. 4-2 shows the steady-state model of the DC energy storage systems for grid applications. The model distinguishes itself from converters system model such that it can act as a load or a source, depending on the interfacing voltage. The DC ESS disconnects itself when the DC ESS state of charge drops below a percentage level. Mathematically, it can be expressed as (4-2).

Figure 4-2: DC energy storage system steady-state model

$$V_{DC,sys} = \begin{cases} NI, & \text{for } V_{DC,ESS} < V_{DC,ESS SOC X\%} \\ V_{DC,ESS}, & \text{for } V_{DC,ESS SOC X\%} < V_{DC,ESS} < V_{DC,ESS SOC 100\%} \end{cases} \quad (4-2)$$

Where $V_{DC,sys}$ and $V_{DC,ESS}$ represents the network and DC ESS voltage respectively. NI describes that the grid voltage source has no impact and not applicable towards the

modeling of the power flow. $V_{DC,ESS SOC X\%}$ describes the voltage of the DC ESS at below X% state of charge and it requires it to be disconnected from the system. $V_{DC,ESS SOC 100\%}$ represents the voltage of the DC ESS at 100% state of charge.

4.3.3 DC Network Power Flow Modeling

A bipolar DC network is a three-wire network with the neutral line used for distribution purposes. It is able to distribute bipolar and unipolar loads. The bipolar DC loads are distributed by phase voltages which are out of phase by 180 degrees with reference to the neutral line [50] while the unipolar loads is distributed by either the positive or negative pole distribution system.

The bipolar DC network established as the base case has the following characteristics: 1) Both positive and negative rail power sources are integrated at every source node; 2) The bipolar and unipolar loads are unidirectional; 3) The network is highly resistive; 4) There are no additional interfacing power converters for voltage regulation purposes.

As have discussed in Chapter 3, each of the three distribution cables, i.e. the live, neutral and the return cable, carries different current flow representations. In the subsequent modeling, the similar convention is used such that the direction of load current flowing out of the node of each distribution cable is positive. Similar to the modeling of a unipolar DC network power flow, a network node is created on the distribution cable when a DC load is distributed across either two of the three distribution cables.

The labeling of the network nodes is divided into two components, mainly the source and load nodes. The nodes are indexed from '0' to 'n' to 'm'. The voltage node of the grid interfacing converter corresponds to the “slack” node. It is indexed as node '0' ($i = 0$). The corresponding 'n' number of nodes is the load nodes in running order with node '1' the closest to the interfacing converter. The remaining 'n + 1' to 'm' number of nodes is the remaining source nodes. The conductance between node index i and j , g_{ij} , remains the same representation.

In a bipolar DC network, a node is created when a DC source is integrated or a DC load is distributed across either of the unipolar or the bipolar distribution pole. As a bipolar DC network consists of three distribution cables, the bipolar DC network is decomposed and nodal analysis is carried out for each of the distribution cables. As

such, $G_{+/N/-(i,j)}$ represents the cable conductance of positive, neutral and negative pole cables between the node i and j respectively. $V_{+/N/-(i)}$ represents the voltage node of positive, neutral and negative pole at node i while $I_{+/N/-(i)}$ represents the output current at node i , respectively. Using the convention of positive reference current direction as out of the system node, the positive pole load draws current from the positive pole node and returns via the neutral pole node, the negative pole load draws current from the neutral pole node and returns via the negative pole node and the bipolar load draws current from the positive pole node and returns via the negative pole node. $I_{p/n/b(i)}$ represents the positive, negative and bipolar pole distribution load current at network node i . Combining the above descriptions, Fig. 4-3 shows the representation of the voltage, current, cable conductance and load currents between the network nodes of a two-node system.

Figure 4-3: A two-node simplified system diagram example

For the nodal analysis on each single line modeling, without the loss of generality, (4-3) to (4-5) are used to model the relationship between the bipolar and unipolar load currents in linear algebraic form with the two-phase bipolar DC network.

$$I_+ = I_p + I_b = G_+ V_+ \quad (4-3)$$

$$I_N = I_n - I_p = G_N V_N \quad (4-4)$$

$$I_- = -I_n - I_b = G_- V_- \quad (4-5)$$

where $\mathbf{I}_{p/n/b}$ and $\mathbf{V}_{p/n/b}$ represent the current and voltage vectors of positive, negative and bipolar load in the bipolar DC system, respectively. $\mathbf{I}_{+/N/-}$ and $\mathbf{V}_{+/N/-}$ represent the current and voltage vectors of the network nodes in the bipolar DC system, respectively. $\mathbf{G}_{+/N/-}$ represents the conductance matrix with the conventional representation in a positive, neutral and negative distribution cable, respectively

As the measurement of a positive, negative rail and bipolar rail voltage is taken as the difference between the positive and neutral pole, neutral and negative pole, and positive and negative pole node respectively. Taking the vector difference of (4-3) and (4-4), (4-4) and (4-5) and (4-3) and (4-5), the generic DC voltage vector for positive, negative and bipolar pole distribution can be modeled as $\mathbf{V}_{p/n/b}$. The distribution of bipolar loads is a form of splitting single phase voltages which are 180 degrees out of phase with reference to the neutral line and no current flows in the neutral cable. Furthermore, as the electrical network consists of multicore cables, the cable conductance for all the three cables between node i and j is the same, i.e., $\mathbf{G} = \mathbf{G}_{+/N/-}$. As such, the power flow model for a two-phase bipolar DC network, analogous to power flow for AC networks, can be expressed as (4-6) to (4-8).

$$\mathbf{G}_+ \mathbf{V}_+ - \mathbf{G}_N \mathbf{V}_N = \mathbf{G} \mathbf{V}_+ - \mathbf{G} \mathbf{V}_N = \mathbf{G} \mathbf{V}_p \quad (4-6)$$

$$\mathbf{G}_N \mathbf{V}_N - \mathbf{G}_- \mathbf{V}_- = \mathbf{G} \mathbf{V}_N - \mathbf{G} \mathbf{V}_- = \mathbf{G} \mathbf{V}_n \quad (4-7)$$

$$\mathbf{G}_+ \mathbf{V}_+ - \mathbf{G}_- \mathbf{V}_- = \mathbf{G} \mathbf{V}_+ - \mathbf{G} \mathbf{V}_- = \mathbf{G} \mathbf{V}_b \quad (4-8)$$

Combining the nodal voltage and current modeling together, the power flow model for a bipolar DC distribution network can be established as expressed in linear algebra as shown in (4-9).

$$\begin{bmatrix} 2\mathbf{I} & -\mathbf{I} & \mathbf{I} \\ -\mathbf{I} & 2\mathbf{I} & \mathbf{I} \\ \mathbf{I} & \mathbf{I} & 2\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix} = \begin{bmatrix} \mathbf{G} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{G} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G} \end{bmatrix} \begin{bmatrix} \mathbf{V}_p \\ \mathbf{V}_n \\ \mathbf{V}_b \end{bmatrix} \quad (4-9)$$

where $\mathbf{I}$ is the identity matrix. $\mathbf{I}_{p/n/b}$ and $\mathbf{V}_{p/n/b}$ represent the current and voltage vectors of positive, negative and bipolar load in the bipolar DC system, respectively. $\mathbf{G}$ represents the conductance matrix with the conventional representation, including the source conductance.

However, as have discussed, one unique technological development is the operation of network to be grid isolated. As a result, to analyze the power flow between the energy sources, the model of the sources and the loads are separated. The power flow equation can be re-expressed as (4-10). The derivation of the separation of the sources and loads is shown in Appendix A. The proposed bipolar DC power flow model then takes precedence in the modeling of the load nodes and then models the source components next.

$$\begin{bmatrix} 2\mathbf{I} & -\mathbf{I} & \mathbf{I} \\ -\mathbf{I} & 2\mathbf{I} & \mathbf{I} \\ \mathbf{I} & \mathbf{I} & 2\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix}_L = \begin{bmatrix} \mathbf{G}_L & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_L & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_L \end{bmatrix} \begin{bmatrix} \mathbf{V}_p \\ \mathbf{V}_n \\ \mathbf{V}_b \end{bmatrix}_L + \sum_{i=0, n+1}^N \begin{bmatrix} \mathbf{G}_{s,p,i} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_{s,n,i} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_{s,b,i} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{s,p,i} \\ \mathbf{V}_{s,n,i} \\ \mathbf{V}_{s,b,i} \end{bmatrix} \quad (4-10)$$

where $[\mathbf{I}_p \ \mathbf{I}_n \ \mathbf{I}_b]_L^T$ and $[\mathbf{V}_p \ \mathbf{V}_n \ \mathbf{V}_b]_L^T$ represent the steady state load current model and network load nodal voltage. $\mathbf{I}$ represents the identity matrix. $[\mathbf{V}_{s,p,i} \ \mathbf{V}_{s,n,i} \ \mathbf{V}_{s,b,i}]^T$ represents the voltage level of the source node ' i ' where ' i ' = 0 or ' $n + 1$ ' to ' m '. $V_{s,j,i}$ represents the pole type voltage source vector ' i ' where ' i ' = 0 or from ' $n + 1$ ' to ' m ' and ' j ' = p, n, b i.e. $V_{s,p,0} = [V_{p,0} \ \dots \ V_{p,0}]^T$.

As DC sources are integrated at both the positive rail and negative rail, the source conductance matrix can be re-expressed as $\mathbf{G}_{s,l} = \mathbf{G}_{s,p,i} = \mathbf{G}_{s,n,i} = \mathbf{G}_{s,b,i}$. The load conductance matrix is represented as $\mathbf{G}_L = \mathbf{G}_1 - \sum_{i=0, n+1}^m \mathbf{G}_{s,i}$, with $\mathbf{G}_1$ represents the conventional representation of self-conductance and cross-conductance of each distribution cable excluding the sources and their network conductance, i.e. $g_{ij} = g_{ji}$ for $i \neq j$. $g_{ii} = -\sum_{j=1}^n g_{ij}$, for $1 < i < n$ and $1 < j < n$. The diagonals of the source conductance matrix, $\mathbf{G}_{s,l}$, represents the cross-conductance of the distribution cable between the source and the load nodes, i.e. $g_{ik} = g_{ki} = 0$ for $i \neq k$, with $1 < k < n$, i representing the load node and l the source node and $g_{ii} = g_{il}$, with $1 < i < n$ and $l = 0$ or $n + 1 < l < m$.

4.3.4 DC Network Load Modeling

DC loads can be directly driven by the DC network or be interfaced using power electronics which behave as a constant power load [151]. While there are different load models in the literature [152], their behavior is complex in nature and they do not have reactive power, this paper uses the polynomial active power ZIP load model to model the DC loads [153], [154]. The load model can be defined as (4-11). In this paper, the load model used is a voltage-dependent load model as described in [156]. Based on the

ZIP load model in (4-11), it can be reduced to (4-12) such that it is a linearized voltage-dependent load with $a_0 = 0$.

$$P = P_0(a_0 + a_1V + a_2V^2) \quad (4-11)$$

$$I = \frac{P}{V} = P_0\left(\frac{a_0}{V} + a_1 + a_2V\right) \quad (4-12)$$

where P and V represents the input power and voltage of the load and P_0 , a_0 , a_1 and a_2 are the coefficients the parameters of the model which depends on the actual load composition and load study.

In linear algebraic form, the load model can be expressed as (4-13). The steady state power flow model is then iterated with the load model until the error between the current and previous iteration reaches a threshold using Gauss–Seidel methodology.

$$\begin{bmatrix} I_p \\ I_n \\ I_b \end{bmatrix}_L = \begin{bmatrix} P_0 a_{2,p} & 0 & 0 \\ 0 & P_0 a_{2,n} & 0 \\ 0 & 0 & P_0 a_{2,b} \end{bmatrix} \begin{bmatrix} V_p \\ V_n \\ V_b \end{bmatrix}_L + \begin{bmatrix} P_0 a_{1,p} \\ P_0 a_{1,n} \\ P_0 a_{1,b} \end{bmatrix} \quad (4-13)$$

where $P_0 a_{2,p/n/b}$ and $P_0 a_{1,p/n/b}$ represent the matrices of the linearized load parameters for a positive, negative and bipolar role distribution load, respectively.

4.3.5 Modified Network Modeling using Voltage Drop Compensation

The steady state power flow model for bipolar DC network in (4-10) has the following assumptions: 1) The DC sources are assumed to be symmetrically integrated to both phases of the DC network with the same balanced voltage in each phase across all DC sources and; 2) The currents of each of the two phases are flowing in the opposite direction in the neutral cable, respective of the DC network operations. The modified power flow modeling takes precedence by modeling the load nodes first and then models the impacts of the integration of DC sources next.

The above assumptions are invalid when DC energy source is integrated to one of the two phases which results in a same directional flow of current in the neutral cable. As a result, the bipolar DC power flow model is not suitable to model the nodal voltages of the network as the bipolar DC power flow model is characterized by the opposite directional flow of current in the neutral cable. As a result, it is a case of poor DC system design which causes an excessive voltage drop to one of the phases and an

overvoltage problem to the DC loads in the other phase. One such case is when the network experiences single phase DC power sources integration as shown in Fig. 4-4.

To model the nodal voltages accurately with single phase integration, the bipolar DC power flow model has to be extended. The operation of the network can be decomposed to three distinct cases as shown in Fig. 4-4. The 3 cases are as follow: Case 1) Nodes that establish the opposite directional flow of current and symmetrical balanced voltage source integration; Case 2) Nodes that establish the same directional flow of current and symmetrical balanced voltage source integration and; Case 3) Nodes that establish the same directional flow of current and single voltage source integration. It has to be noted that the impacts of bipolar DC loads and DC sources are not examined here as the concept of voltage drop compensation is similar and the bipolar DC sources can be integrated to the 3 terminals instead of just across the positive or negative rail due to voltage level differences.

Figure 4-4: A single phase DC power source integration to a bipolar DC network

To model the nodal voltages accurately, the bipolar DC power flow is extended with the use of voltage drop compensation technique. The general approach to model the voltages of the abovementioned three cases of smaller networks is as follows:

- 1) Identify the nodes that violate the bipolar DC power flow characteristics to segregate the network into the above three different cases.
- 2) Remove the source conductance matrix and the load model of the corresponding nodes for the integrated DC power source phase. Obtain the voltages of the nodes that exhibit the bipolar characteristics in the phase integrated with the single phase DC power source using Gauss-Seidel iteration method between the bipolar DC power flow and the new load model.

- 3) Remove the source conductance matrix and the load model of the corresponding nodes for the integrated DC power source phase. Determine the node-to-node voltage drop compensation in the non-integrated DC power source phase caused by the single source integrated phase. Obtain the nodal voltages of the non-integrated phase by iterating between the original bipolar DC power flow and the load model. Update the voltage of the nodes power by the bipolar DC network but violate the neutral current flow characteristics using voltage drop compensation determined by the forward-backward iteration.
- 4) Identify the nodes powered by the single DC power source network. Determine the node-to-node voltage drop compensation in the single source integrated phase caused by the bipolar DC network. Obtain the nodal voltages of the integrated DC power source phase by iterating between the unipolar DC power flow and the corresponding load model. Update the nodal voltage of the nodes powered by the single DC power source network using voltage drop compensation due to the load currents bipolar DC network determined by the forward-backward iteration.

The nodes are identified first through searching for the minimum voltage level of the integrated phase using the bipolar DC network power flow. The load current that is distributed by the single phase DC source can be determined in (4-14). This is due to the network characteristic that a load can be distributed by two power sources. The node to node voltage drop compensation in the neutral cable is shown in (4-15)

$$\sum I_{load} = I_{ph} = \frac{(V_{source} - V_{node,nearest})}{2 * R_{DC}} \quad (4-14)$$

$$Vd_j = R_{ij} * I_i \quad (4-15)$$

Where I_{load}, I_{ph} represents the individual load currents and the total phase currents distributed by the single phase DC source integration, respectively. V_{source} , $V_{node,nearest}$, R_{DC} represents the source node voltage, the load node nearest to the source and the DC resistance between them, respectively. Vd_j, R_{ij}, I_i have the same representation as in (3-5). The variables used are shown in Fig. 4-5.

The voltage drop compensation is determined iteratively by direct observation where the ‘parent’ node and the ‘child’ node are to be determined. Fig. 4-5 shows the situation when the DC power source is integrated to the positive rail and voltage drop

compensation is determined. The same approach of determining the voltage drop compensation can be used for negative rail integration.

Figure 4-5: Voltage drop compensation for single phase positive DC source rail integration

In the case of non-optimal system design, one other architecture that can arise in a bipolar DC network is the presence of two single-phase networks as shown in Fig. 4-6. The architecture is a type of the third case that requires voltage drop compensation in each of the two unipolar DC network.

Figure 4-6: Bipolar DC network with single phase negative rail DC source integration

4.4 Solution Flowchart

Gauss-Seidel iterative methodology is used to iterate the power flow model and the load model. The model-based approach flowchart starts with all the DC power sources connected, symmetrically or asymmetrically. In the case of asymmetrical DC source integration, the voltage drop compensation is used to model the nodal voltages that violate the bipolar DC characteristics. The solution flowchart follows that of the approach described in Section 4.3.5. Then, the DC ESS output voltage values are decreased and updated to reflect the new state of charge or network operating mode. Depending on the new voltage values, the DC power sources can be disconnected or the bidirectional loads can be changed to a power sinking mode. In either case, the

power flow model is updated to easily reflect the changes in operation mode of the electrical network until there is no change to the operation mode of the various components in the DC electrical network. The model-based approach flowchart, as described above, is shown in Fig. 4-7.

Figure 4-7: Power flow modeling solution flowchart

4.5 Simulation and Experimental Results

The proposed DC network power flow model takes into account of the unique characteristics of DC network at the distribution level and the technological advancement such as directly integrating the DC ESS. The proposed model is based on voltage values of the DC energy sources which allows for steady state power flow transition analysis between energy sources due to system voltage drop and decreasing open circuit voltage with decreasing state of charge. The power flow model is analyzed using different simulated case studies and actual mock-up systems.

4.5.1 Single Source 24V Unipolar DC Network Mock-Up

Using the same 11-node DC LED lighting system for high rise building stairwell, described in Chapter 3, Fig. 4-8 compares the simulation results based on 1) the existing power flow model for AC transmission line and 2) the proposed nodal based approach model. In Fig. 4-8, it can be seen that the proposed model has a higher accuracy than the existing power flow model in modeling DC distribution network which has a non-negligible voltage drop. This is because, for the case of the transmission network, it is based on single line diagram but for the case of DC network, the return cable of the DC unipolar network plays an additional role in the modeling of the DC network. The phenomenon of using a single line diagram for transmission power flow is taken into consideration and is used to model a bipolar DC transmission system [127]. The labeling of the nodes follows the case study as described in Chapter 3.

Figure 4-8: Comparison of nodal voltages of proposed and existing power flow models

The simulation parameters are described in Chapter 3. Gauss-Seidel methodology is used to iterate between the power flow model (4-10) and the load equation (4-13) until the error between the current and previous iteration reaches a threshold. The power flow model used in this case study is shown in (4-16)

$$2\mathbf{I}_L = \mathbf{G}_{L,0}\mathbf{V}_L + \mathbf{G}_{s,0}\mathbf{V}_{s,0} \quad (4-16)$$

where $\mathbf{G}_{L,0} = \mathbf{G} - \mathbf{G}_{s,0}$, with $\mathbf{G}$ represents the conventional representation of self-conductance and cross-conductance of each distribution cable excluding the sources and their network conductance, i.e. $g_{ij} = g_{ji}$ for $i \neq j$. $g_{ii} = -\sum_{j=1}^n g_{ij}$. The diagonals of $\mathbf{G}_{s,0}$ represents the cross-conductance of the distribution cable between the

source and the load nodes, i.e. $g_{ij} = g_{ji} = 0$ for $i \neq j$ and $g_{ii} = g_{ij}$ for $1 < i < 11$ and j as the source node i.e. $j = 0$ or $n + 1 < j < N$. $\mathbf{V}_{s,0}$ represents the source voltage i.e. $[V_0 \quad \dots \quad V_0]^T$.

4.5.2 Single Source 48V Bipolar DC Network Mock-Up

Similarly, using the 11-node DC LED lighting system with the same simulation parameters in Chapter 3, the single source 48V DC bipolar LED lighting network is simulated. Fig. 4-9 shows the comparison between the simulation results and experimental data. It can be seen that the proposed power flow model is accurate in modeling bipolar DC distribution network which has non-negligible voltage drop. In the actual mock-up case study, it has to be taken note that there are no loads drawing current across the bipolar DC rail.

Figure 4-9: Comparison diagram of simulated and measured nodal voltages

$$\begin{bmatrix} 2\mathbf{I} & -\mathbf{I} \\ -\mathbf{I} & 2\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \end{bmatrix}_L = \begin{bmatrix} \mathbf{G}_L & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_L \end{bmatrix} \begin{bmatrix} \mathbf{V}_p \\ \mathbf{V}_n \end{bmatrix}_L + \sum_{i=0, n+1}^N \begin{bmatrix} \mathbf{G}_{s,p,i} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_{s,n,i} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{s,p,i} \\ \mathbf{V}_{s,n,i} \end{bmatrix} \quad (4-17)$$

where the terms in (4-17) are the same representation as in (4-10)

4.5.3 Single Source 15-node Bipolar DC Network

The next case study is a case study of a bipolar DC LED lighting network with loads of different power level and bipolar loads distributed is shown in Fig. 4-10. The case study is used to exhibit the non-negligible voltage drop effect due to the bipolar DC loads.

Figure 4-10: System diagram of bipolar DC radial 15-node network

Table 4-1: Load type and power level for bipolar DC radial 15-node network

Node	Type	Rated Power (W)	Node	Type	Rated Power (W)
0.	Source	-	8	L (U+)	14
1	L (B)	21	9	L (U+)	14
2	L (U+)	21	10	L (B)	21
3	L (U+)	21	11	L (U-)	14
4	L (U+)	17.5	12	L (U-)	14
5	L (B)	21	13	L (U-)	10.5
6	L (U+)	17.5	14	L (U-)	10.5
7	L (U+)	17.5	15	L (B)	21

Table 4-2: Electrical network parameters of bipolar DC network

	Parameters	Values
Electrical Network Properties	Cable Size	14 AWG
	Line Resistance	0.0074Ω/m
	The length between LED Lightings	5m
	The length between the converter and the first LED lighting	20m
	Derated Factor	0.8
	Rated line voltage	24V DC

Table 4-3: DC LED lighting load parameter value for simulation

Power (W)	P_0	a_0	a_1	a_2
21 (B)	3	0	-0.0108	0.9768
7 (B)	1	0	-0.0108	0.9768
21 (U)	3	0	-0.012004	0.586634
17.5 (U)	2.5	0	-0.012004	0.586634
14 (U)	2	0	-0.012004	0.586634
10.5 (U)	1.5	0	-0.012004	0.586634
7 (U)	1	0	-0.012004	0.586634

Table 4-4: Error comparison of nodal voltage for 15-node bipolar DC network

Error (10^{-5} V DC)			Error (10^{-5} V DC)		
Node	$V_{p(i)}$	$V_{n(i)}$	Node	$V_{p(i)}$	$V_{n(i)}$
0	0	0	8	9.3207	9.2614
1	8.5828	8.1210	9	9.3328	8.9309
2	8.9763	8.6374	10	9.3243	8.5707
3	9.0695	8.4539	11	9.3135	9.5083
4	8.1938	8.9050	12	9.3054	9.4903
5	9.2132	8.7084	13	9.2372	8.6925
6	9.2542	7.5335	14	9.3039	9.2151
7	9.2140	8.6492	15	9.2725	9.2937

The placement of the loads in the 15-node 2-phase bipolar network, electrical network parameters, and the different DC LED lighting load power are listed in Tables 4-1, 4-2 and 4-3, respectively. The basic DC LED load model uses the DC LED lighting of OSRAM DURIS S5 LEDs of array seven series by six parallel, of total 7W, powered by the RECOM RCD-24 or RCD-48 DC driver which has been described in the front chapters. The basic DC LED load model is used as the fundamental block for higher power LED load model as have depicted in Table 4-3.

Table 4-4 shows the error comparison between the mathematical model and the Simulink model. It can be observed that the model is close to the Simulink results with an error of order of magnitude of 10^{-5} against the Matlab Simulink values. This validates the bipolar 2-phase power flow mathematical model with the consideration of bipolar DC loads.

4.5.4 Multi-Source 24V Unipolar DC Network Mock-Up

At distribution level, DC ESS can be directly integrated to the DC system and distribute power to the lighting loads. Due to direct integration of DC ESS and the drop in the state of charge, the output DC voltage of DC ESS decreases. As a result, the network changes its operation from grid islanding to grid-connected mode. To model the phenomenon, a multi-source 24V DC LED lighting system with directly integrated DC ESS is emulated experimentally using a battery emulator as shown in Fig. 4-11. The system diagram is shown in Fig 4-12. The DC ESS is isolated from the DC network as the state of charge decreases to a point when the voltage has dropped to 21V DC. It has to be taken note that the DC LED lighting is powered by both the DC ESS and the grid power during the entire operation. It has also be taken note that the DC ESS is directly integrated to the last node of the DC LED lighting network.

Figure 4-11: Mock-up of a directly integrated DC ESS 24V DC LED lighting system

Figure 4-12: Block diagram of a directly integrated DC ESS 24V DC LED lighting system

A simulation using Matlab Simulink and the proposed power flow model is used to compare the DC network simulation, modeling, and experimental emulation accurately, the grid interfacing voltage is set at 22.0V DC while the terminal end of the DC voltage for ESS of node 11 is simulated to be at the voltage level of 23V DC to 20.5V DC as the voltage of the DC ESS decreases with decreasing state of charge. The system diagram is shown in Fig. 4-13.

Figure 4-13: System diagram of a directly integrated DC ESS 24V DC LED lighting system

The electrical network parameters used for the simulation is the same as what has been described in Chapter 3. In Fig. 4-14 to Fig. 4-16 shows the nodal voltage measurements for the actual mock-up lighting system, a simulated system using Matlab Simulink and the mathematical modeling using the proposed power flow model. Fig. 4-17 and Fig. 4-18 shows the per unit percentage error comparison plot between Matlab Simulink simulated and measured nodal voltage and between Matlab Simulink and proposed power flow modeling. It can be seen that the two comparisons have low

percentage error in their values which can safely conclude that the proposed power flow model is highly accurate in modeling the DC network.

Figure 4-14: Measured nodal voltages using a mock-up DC LED lighting system

Figure 4-15: Simulated nodal voltages using Matlab Simulink

Figure 4-16: Simulated nodal voltages using proposed power flow modeling

Figure 4-17: Error comparison plot between simulated and measured nodal voltage

Figure 4-18: Error comparison plot between Matlab Simulink and power flow modeling

Compared to the single source network, it is observed that the DC lighting system is powered by both DC power sources. As a result, (4-10) can be modified to (4-18) to model multi-source DC network.

$$2\mathbf{I}_L = \mathbf{G}_{L,1}\mathbf{V}_L + \sum_{j=0,11}^{11} \mathbf{G}_{s,j}\mathbf{V}_{s,j} \quad (4-18)$$

where $\mathbf{G}_{L,1} = \mathbf{G} - \mathbf{G}_{s,0} - \mathbf{G}_{s,11}$, with $\mathbf{G}$ represents the conventional representation of self-conductance and cross-conductance of each distribution cable excluding the sources and their network conductance, i.e. $g_{ij} = g_{ji}$ for $i \neq j$. $g_{ii} = -\sum_{j=1}^n g_{ij}$. The diagonals of $\mathbf{G}_{s,j}$ represents the cross-conductance of the distribution cable between the different source and the load nodes, i.e. $g_{ij} = g_{ji} = 0$ for $i \neq j$ and $g_{ii} = g_{ij}$ for

$1 < i < 10$ and j as the source node i.e. $j = 0$ or 11 . $V_{s,j}$ represents the source voltage i.e. $[V_j \quad \dots \quad V_j]^T$ with $j = 0$ or 11 .

4.5.5 Multi-Source 24V Unipolar DC Islanded Network

The previous subchapters have identified that the proposed power flow model is capable of modeling the nodal voltages when different DC energy sources are integrated to the DC network. This subchapter aims to extend the mathematical modeling verification to the situation when the power flow changes between sources such that the network operates from grid islanded to grid-connected as the state of charge of the DC ESS decreases. To model the phenomenon, the DC ESS voltage is simulated from 27V DC to 21V DC and the DC ESS is isolated from the DC network at 21V DC. It can be observed in the simulation the following from Fig. 4-19 and Fig. 4-20: 1) when the DC ESS is between 27V DC to 23.7V DC, the DC network is powered by DC ESS and is operating in grid islanded mode, 2) when the DC ESS is between 23.7V DC to 21V DC, the DC network is powered by DC ESS and the grid and 3) when the DC ESS is isolated at 21V DC, the DC network is powered by the grid.

Figure 4-19: Plot of power flow diagram from grid isolated to grid-connected

Figure 4-20: Plot of system nodal voltage from grid isolated to grid-connected

To study the impact towards power flow modeling accuracy, different modifications to the power flow models are explored. The nodal voltages of the modifications are then compared with the Matlab Simulink model based on the same 11-node case study. A surface plot using the per unit percentage error is then generated. The power flow models to be explored are as follows:

- 1) Unipolar DC power flow model in (4-10)
- 2) Conventional AC power flow model with no modification during each transition of the grid operation
- 3) Unipolar DC power flow model with only voltage modification during each transition of the grid operation without modifying the source conductance matrix.

It has to be taken note the convention used for the conductance matrix follows the conventional node to node conductance of AC power flow using single line diagram. In the unipolar DC power flow model, it is assumed that the node to node conductance of both live and return cable is equal. The modification to the source conductance matrix due to the internal resistance of the DC sources is not investigated as the resulting model is trivial due to a negligible lower value compared to the network conductance value. It can be seen that, in Fig. 3-21 to Fig. 3-23, the percentage error for the above 3 cases differs greatly with the proposed power flow model having the smallest error as it describes the network operation accurately.

Figure 4-21: Error surface plot against AC power flow model

Figure 4-22: Error surface plot against proposed power flow model

Figure 4-23: Error surface plot against proposed power flow model with voltage modification

The modified power flow model is able to effectively model the power flow of the DC network because it captures the different cases from grid isolated to grid connected network which results in the modification in the source side modeling and the conductance matrices. Fig. 4-24 shows the power flow diagram from grid isolated to grid connected network, where red represents that the source is in operation while black represents that the source is not in operation. In the grid connected network, the transition between sources occurs due to the isolation of DC ESS with reducing state of charge. The modified power flow that models the entire grid transition is shown in (4-19) which describes that for each transition, the conductance matrices used are modified.

Figure 4-24: Power flow system diagram from grid isolated to grid-connected network

$$2I_p = \begin{cases} \mathbf{G}_{L,2} \mathbf{V}_p + \mathbf{G}_{s,11} \mathbf{V}_{s,11}, & \text{for } 23.7\text{V DC} < V_{DC,ESS} < 27\text{V DC} \\ \mathbf{G}_{L,1} \mathbf{V}_p + \sum_{i=0,11}^{11} \mathbf{G}_{s,i} \mathbf{V}_{s,i}, & \text{for } 21.0\text{V DC} < V_{DC,ESS} < 23.7\text{V DC} \\ \mathbf{G}_{L,0} \mathbf{V}_p + \mathbf{G}_{s,0} \mathbf{V}_{s,0}, & \text{for } V_{DC,ESS} < 21\text{V DC} \end{cases} \quad (4-19)$$

where $\mathbf{G}_{L,0} = \mathbf{G} - \mathbf{G}_{s,0}$, $\mathbf{G}_{L,1} = \mathbf{G} - \mathbf{G}_{s,0} - \mathbf{G}_{s,11}$, $\mathbf{G}_{L,2} = \mathbf{G} - \mathbf{G}_{s,11}$, with $\mathbf{G}$ represents the conventional representation of self-conductance and cross-conductance of each distribution cable excluding the sources and their network conductance, i.e. $g_{ij} = g_{ji}$ for $i \neq j$. $g_{ii} = -\sum_{j=1}^n g_{ij}$. The diagonals of $\mathbf{G}_{s,j}$ represents the cross-conductance of the distribution cable between the source and the load nodes, i.e. $g_{ij} = g_{ji} = 0$ for $i \neq j$ and $g_{ii} = g_{ij}$ for $1 < i < 10$ and j as the source node i.e. $j = 0$ or 11 . $\mathbf{V}_{s,j}$ represents the source voltage i.e. $[V_j \dots V_j]^T$ with $j = 0$ or 11 .

4.5.6 Multi-Source 48V Bipolar DC Network with Single Phase Integration

Besides the impact of grid operation, one other analysis of interest is the impact of single phase integration to the bipolar DC power flow model in (4-10). In the power flow model, it is assumed that the sources are integrated to both of the two phases sourcing power. However, DC power source can be integrated to just one phase of the 2-phase network. As such, there is a need to model the voltage of the non-integrated phase to prevent unnecessary overvoltage or under voltage issues to the DC loads.

The electrical network details are such that the node to node distances are set at 10m with the load models having $P_0 = 2$, $a_0 = 0$, $a_1 = -0.012004$ and $a_2 = 0.58663$. The loads are distributed alternately along the bipolar DC network as the case study. The grid interfacing voltage source is integrated directly to the first LED lighting load with very small cable resistance. The DC ESS is integrated with 20m length of 2.5mm² cable to the Node 11 of the DC LED lighting. Both DC sources output voltages are set at 24V DC. The case study electrical diagram is shown in Fig. 4-25.

Figure 4-25: System diagram of a single phase positive rail DC source integration

As have discussed above, the proposed bipolar DC power flow modeling in (4-10) assumes the following: 1) The DC sources are assumed to be symmetrically integrated to both phases of the DC network with the same balanced voltage in each phase across all DC sources and; 2) The currents of each of the two phases are flowing in the opposite direction in the neutral cable, respective of the DC network operations. For nodes that violate the two assumptions, voltage drop compensation is carried out to model the additional voltage drop due to the same directional flow of current in the other phase.

To study the voltage drop impacts due to 1-phase DC source integration and validate the proposed power flow model, the nodal voltages of the proposed method with voltage drop compensation is compared with the Matlab Simulink simulated system. The case studies to be used are when the DC source is integrated to the positive or negative rail are shown in Fig. 4-25 and Fig. 4-26. It has to be noted that the case of the DC source integrated to the bipolar DC pole is not investigated as the DC source can be integrated to both the 2-phases. However, the same approach of voltage drop compensation can be applied to the bipolar DC pole. Fig. 4-27 to Fig. 4-30 shows the nodal voltages comparison of the two rails when comparing against the Matlab Simulink system, original proposed power flow model and the modified power flow

approach. It can be seen that the modified approach is able to model the nodal voltages with a higher degree of accuracy.

Figure 4-26: System diagram of a single phase negative rail DC source integration

Figure 4-27: Positive rail voltage comparison for negative rail DC source integration

Figure 4-28: Negative rail voltage comparison for negative rail DC source integration

Figure 4-29: Positive rail voltage comparison for positive rail DC source integration

Figure 4-30: Negative rail voltage comparison for positive rail DC source integration

Comparing the nodal voltages of the proposed and modified power flow modeling approach against the Matlab Simulink results, Table 4-5 shows the mean square error of the two approaches. It can be seen that the mean square error of the nodal voltages decreases when the modified power flow modeling approach using voltage drop compensation is used. Table 4-6 shows the nodal voltages of the three approaches.

Table 4-5: Mean square error comparison of original and proposed power flow model

	Positive Rail Integration		Negative Rail Integration	
	Original	Modified	Original	Modified
Positive Rail	5.8829E-05	1.6091E-04	8.5733E-02	5.3262E-06
Negative Rail	2.8852E-01	5.2607E-07	2.2068E-05	7.0243E-05

Table 4-6: Nodal voltages of the Matlab Simulink, proposed and modified power flow model

		Integrated to Positive Rail				Integrated to Positive Rail		
		Matlab Simulink	Proposed Model	Modified Model		Matlab Simulink	Proposed Model	Modified Model
Positive Rail Node	1	24.000	24.000	24.000		24.000	24.000	24.000
	2	23.888	23.885	23.888		23.646	23.694	23.645
	3	23.719	23.715	23.720		23.236	23.332	23.234
	4	23.662	23.656	23.664		22.939	23.084	22.938
	5	23.548	23.540	23.550		22.587	22.780	22.585
	6	23.546	23.537	23.549		22.352	22.591	22.349
	7	23.486	23.476	23.489		22.060	22.346	22.057
	8	23.539	23.529	23.542		21.887	22.219	21.884
	9	23.532	23.523	23.536		21.658	22.036	21.655
	10	23.638	23.630	23.605		21.550	21.972	21.547
	11	23.684	23.679	23.662		21.386	21.852	21.384
	12	24.000	24.000	24.000		21.302	-	21.300
Negative Rail Node	1	24.000	24.000	24.000		24.000	24.000	24.000
	2	23.646	23.694	23.645		23.820	23.819	23.819
	3	23.236	23.332	23.234		23.751	23.749	23.748
	4	22.939	23.084	22.938		23.625	23.622	23.621
	5	22.587	22.780	22.585		23.612	23.607	23.607
	6	22.352	22.591	22.349		23.540	23.534	23.533
	7	22.060	22.346	22.057		23.580	23.574	23.573
	8	21.887	22.219	21.884		23.561	23.555	23.553
	9	21.658	22.036	21.655		23.655	23.649	23.645
	10	21.550	21.972	21.547		23.688	23.683	23.677
	11	21.386	21.852	21.384		23.832	23.829	23.816
	12	21.302	-	21.300		24.000	24.000	24.000

Besides the single-phase integration, one other architecture of interest is the presence of single phase networks in a bipolar DC architecture as have shown in Fig. 4-6. Such architecture is a type of the third case where the unipolar DC power flow is used together with voltage drop compensation. One limitation of using the proposed power flow model is that it is unable to obtain the nodal voltages of the node that is initially a source node, i.e Node 12, as have observed in Table 4-6. The voltage drop compensated modified power flow model is used to obtain the voltage and is validated against the Matlab Simulink results. It can be seen that again, the modified approach is able to model the nodal voltages with higher accuracy as have seen in Fig. 4-31 and Fig. 4-32.

Figure 4-31: Positive rail voltage comparison for single phase bipolar DC architecture

Comparison Plot of Negative Rail Nodal Voltage for Single Phase Circuits

Figure 4-32: Negative rail voltage comparison for single phase bipolar DC architecture

4.5.7 Multi-Source 33-node Bipolar DC Network

The power flow model is also used to validate a larger network with the consideration of multiple sources integrated to the network. The larger case study is used to show the difficulty in directly modeling the ‘parent’ and ‘child’ nodes iteratively. A larger case study of 33-node network using the bipolar DC LED lighting network as an example is shown in Fig. 4-33. Fig. 4-33 illustrates the distribution of loads and their power level in the bipolar DC network.

Figure 4-33: System diagram of bipolar DC radial 33-node network

Table 4-7: Error comparison of nodal voltage for 33-node bipolar DC network

Error (10^{-4} V DC)			Error (10^{-4} V DC)		
Node	$V_{p(i)}$	$V_{n(i)}$	Node	$V_{p(i)}$	$V_{n(i)}$
0	0	0	17	1.5230	1.1700
1	1.3565	0.5737	18	1.3918	1.0210
2	1.5814	0.6681	19	2.9464	0.5410
3	1.7639	0.7837	20	3.1094	0.4594
4	1.9680	0.8561	21	3.2316	0.3984
5	2.1301	0.9494	22	3.3130	0.3577
6	2.0862	1.1428	23	3.3537	0.3373
7	2.0005	1.3571	24	1.3301	2.7007
8	1.9362	1.5287	25	1.2472	2.8665
9	1.8300	1.7213	26	1.1851	2.9906
10	1.7450	1.8714	27	1.1438	3.0734
11	1.7614	1.8118	28	1.1231	3.1147
12	1.7990	1.7098	29	2.1177	1.4934
13	1.7945	1.6289	30	2.1587	1.5371
14	1.8113	1.5054	31	2.2210	1.5380
15	1.7860	1.4030	32	2.2415	1.5598
16	1.6757	1.2759	33	2.2834	1.5389

Similarly, in carrying out the Gauss Seidel iteration between the bipolar DC power flow model (4-10) and the load model (4-13), Table 4-7 shows the error comparison between the mathematical model and the Simulink model. It can be observed that the model is close to the Simulink results with an error of the order of magnitude of 10^{-4} against the Matlab Simulink values. This validates the bipolar 2-phase power flow mathematical model with the consideration of bipolar DC loads and multiple DC sources.

4.5.8 Multi-Source 33-node Bipolar DC Network with Single Phase Integration

The modified power flow model is also used to validate a larger network with the consideration of single-phase networks integrated. The larger case study with single phase integration in extending the 33-node network using the bipolar DC LED lighting network as an example is shown in Fig. 4-34. Fig. 4-34 illustrates the distribution of sources, loads and their power level in the bipolar DC network. Fig. 4-35 and Fig. 4-36

show the nodal voltages comparison between the original and modified power flow modeling approach of the positive and negative rail respectively.

Figure 4-34: System diagram of bipolar DC network with single-phase integration

Figure 4-35: Positive rail voltage comparison of bipolar DC network single-phase integration

Figure 4-36: Negative rail voltage comparison of bipolar DC network single-phase integration

Table 4-8: Mean square error comparison of original and proposed power flow model

	Positive Rail Voltages	Negative Rail Voltages
Original Power Flow Model	9.0027E-04	1.0351E-03
Modified Power Flow Model	1.2993E-05	3.3715E-06

4.6 Results Discussion and Analysis

The analysis of the proposed power flow model using nodal modeling approach is carried out in this chapter, with the consideration of 1) multi-source multi-pole network such as the bipolar DC network; 2) different operation of the network such as grid-connected and grid isolated and, 3) the impact of single phase source integration.

- 1) It has been discussed in Chapter 3 that for highly resistive networks, there is a need for power flow modeling to accurately get the overall view of the system in the design and operation of DC power systems so that network optimization can be carried out in the planning stage [64]. Conventional, P and V buses in power transmission systems and conventional methods for power flow analysis are becoming no longer suitable at distribution level [17]. Specific to distribution system in built environment which has multiple slack buses, one limitation is the

presence of voltage-only measurements due to direct integration of DC energy sources [10]. As a result, the proposed power flow model has to be robust to account for voltage-only measurement of the DC energy sources. The proposed power flow approach takes precedence in the modeling of the load nodes and then models the source components next.

- 2) It can be seen that comparing the proposed modeling approach against the actual mock-up system, the power flow model (4-10) is able to accurately model the nodal voltages. When compared against Matlab simulated system, the model is able to accurately model with errors in the range of 10^{-5} . However, this is true only if the entire network and nodes have the following characteristics: 1) The DC sources are assumed to be symmetrically integrated to both phases of the DC network with the same balanced voltage in each phase across all DC sources and; 2) The currents of each of the two phases are flowing in the opposite direction in the neutral cable, respective of the DC network operations.
- 3) Compared the proposed power flow modeling to the conventional power flow model, the proposed power flow has higher accuracy as it accounts for the return cable path of the current. Furthermore, the proposed power flow model is able to account easily for the switching out and switching in of the sources without having to explicitly re-formulate the admittance matrix. However, one limitation of using the proposed power flow model is that it is unable to obtain the nodal voltage of the node that is initially a source node due to the switching out of the source.
- 4) For nodes that violate the two assumptions, the modified power flow approach using voltage drop compensation is used. This is because such networks exhibit the same directional flow of current in the neutral cable which requires the additional voltage drop cause by the single-phase circuit. The voltage drop compensation is used to compensate the additional voltage drop iteratively. To accurately model such networks, the network is segregated into three sections with each section having a specific modified approach using the original power flow model.
- 5) The difference in accuracy of the unmodified and modified power flow is prominent in larger networks such as the 33-bus network with single phase integration. While the mean square error may be small, the inaccuracies of the voltages are very clearly shown in Fig. 4-35 and 4-36. The modeling of the nodal voltages is required to prevent unnecessary overvoltage or under voltage issues to

the DC loads due to the presence of single-phase networks in a bipolar DC architecture.

Furthermore, the rationale of using a DC LED lighting system mock up is to illustrate the following:

- 1) Using the mock up system, the voltage level and the non-negligible voltage drop over the DC system can be validated. Furthermore, using the conventional single line based modelling methodology, the voltage across the system is modelled with some degree of inaccuracy when compared to the mock up system
- 2) Using the mock up system, there is a need to validate the simulation steady state model for bipolar DC system in Matlab Simulink by comparing against the voltage levels across the bipolar DC system. This is due to the opposite flow of the current in the neutral cable of the bipolar DC system.
- 3) Using the mock up system extended with backup batteries, there is a need to validate the simulation steady state model in Matlab Simulink during grid islanding mode by comparing the voltages of the simulated system and the conventional steady state modelling methodology. This is due to the transition of the energy sources of the actual system and the impact towards the conventional steady state mathematical modelling methodology.

The mock up system provide the ground truth comparison using an existing theory and the measured voltage is compared against the proposed mathematical steady state modelling and simulated model using Matlab Simulink. This is required as the existing steady state modelling methodology, which is currently for AC systems, are based on the following assumptions: 1) Every source that is connected has to be at 1.0 per unit voltage and allowed to be varied within a certain level of margin. 2) The steady state modelling methodology for AC systems follows a balanced 3 phase system and uses the single line diagram for modelling. However, as technology advances at distribution level, such assumptions have to be re-examined in the case of DC systems. As such, the mock up system is necessary in performing this role as a ground truth comparison.

Hence, this chapter discusses the power flow modeling approach for different network designs and operations. The proposed and modified power flow modeling is able to accurately model the nodal voltages with a high accuracy, considering the physics of the DC network behavior. Compared with Chapter 3 which uses an iterative approach

that requires the identification of ‘parent’ and ‘child’ node labeling, the nodal based approach gives a generic approach for modeling the power flow for networks where the identification of these nodes is not easy to be determined.

4.7 Concluding Remarks

With the development of power electronics and DC energy sources, DC power system at distribution level emerges. There is a need for accurate power flow modeling to accurately get the overall view of the system in the design and operation of DC power systems so that network optimization can be carried out in the planning stage. Besides, in using DC, direct integration of DC energy sources such as DC ESS to the DC network is possible and this is complicated by the operation of DC power system from a grid islanded to a grid-connected network. Furthermore, directly integrating DC ESS poses a challenge of having the DC voltage that varies with the DC ESS state of charge.

Conventionally, power flow analysis is model using by nodal voltage analysis of the P and V buses in DC system [148]. However, such features are distinct in power transmission systems and conventional methods for power flow analysis are becoming no longer suitable at distribution level [17]. One limitation is the presence of voltage-only measurements due to the direct integration of DC energy sources [8]. As a result, the proposed power flow model has to be robust to account for voltage-only measurement of the DC energy sources. The proposed power flow approach takes precedence in the modeling of the load nodes and then models the source components next.

In the proposed nodal based power flow modeling approach, the power flow of the DC unipolar network has been successfully modeled from a grid islanded operational mode to a grid-connected operational mode. The model accounts for the transition of the different DC energy sources by separating the load and source nodes and modifying the respective conductance matrices. The power flow model has also successfully modeled the nodal voltage of larger multi-bus multi-pole network such as the bipolar DC network.

The proposed power flow model is then modified to account for cases that have violated the assumption of symmetrically integrated DC sources and opposite directional flow of current in the neutral cable, allows for power flow analysis between the grid and the DERs to be carried out. The error in modeling is magnified for larger

networks as have seen in the 11 node and 33 node case studies which are not observed in the modified power flow model.

The proposed power flow modeling is also able to provide an overall view of the DC power systems for further network optimization to be carried out in the design and planning stage. It is able to be integrated with emerging technological advances such as direct integration of DC energy storage systems, direct connection and disconnection of DC energy sources and improving power flow analysis together with the consideration of droop control and virtual impedance. In the next chapter, the power flow model is used for voltage balancing of the two-phase DC bipolar network for system efficiency is discussed in the next chapter. The application towards voltage balancing shows one of the usefulness in the proposed modeling in the design and operation of DC power systems such that network optimization can be carried out in the planning stage.

5 Voltage Balancing for Bipolar DC Network using Power Flow Modeling

5.1 Introduction

In Chapter 4, the power flow modeling is developed and analyzed for DC networks. Power flow analysis acts as a basic state analysis tool to get the overall view of the system in the design and operation of DC power systems so that network optimization can be carried out in the planning stage [64]. Voltage balancing is explored to improve on the efficiency of the DC network such as the DC LED lighting system. Voltage unbalance occurs when there is asymmetric loading in the 2-phase DC network.

Existing literature works look at voltage balancing using the iterative approach such as minimizing the neutral wire current [143] or adjusting the DC voltage output of the interfacing converter when the load end voltage range is unbalanced [144]. Other methods include distributing the load to the phase with a higher voltage due to voltage drop phenomenon using the forward-backward iterative approach. The existing methodologies are iterative methods and require the identification of “parent” and “child” nodes of the network. They do not provide a mathematical model based approach towards the balancing of the voltage in the two-phase DC network.

Chapter 5 explores the use of power flow model, together with a binary load distribution model, to minimize the voltage unbalance and system power loss across the two-phase DC network using a binary integer multi-objective optimization. The optimized result is compared with existing iterative voltage balancing methodologies.

5.2 Problem Description

The need for voltage balancing arises because of ground corrosion when current flows in the neutral conductor and back to the ground, depending on the different grounding systems. Furthermore, voltage balancing is able to reduce system power loss. The existing limitations are as follows: 1) The use of net neutral current for analysis does not take into account the effects of voltage drop due to the distribution of bipolar DC loads. This is analogous to voltage unbalance between single and 3-phase loads in AC networks [157]. 2) The existing methodologies mainly utilize an iterative method such as the backward-forward sweep for analysis. The iterative method is designed for simple radial distribution systems and is popular due to its intuitive solution procedure

[155]. However, one main disadvantage of iterative methods is that the relationships among components are built by a direct observation. If the network is large, the preparation can be difficult, as can be observed in [17], and prone to errors or when the observed network is non-observable such that the numbering of the “parent node” and “child node” arrangement is not easily constructed, iterative methods are not applicable [18]. One example of non-observable network architecture is the ladder architecture when power sources are integrated at the opposite ends of a radial distribution [10].

The effectiveness of existing voltage balancing iterative approach in a bipolar DC distribution system is then compared with the proposed model based optimized approach in this chapter.

5.3 Optimization-based Modeling

A binary integer load distribution model is developed to model the distribution of unipolar DC loads to either the positive or negative distribution pole of the two-phase bipolar DC network. It is used with the power flow model to develop system voltage unbalance and power loss model for multi-objective optimization for the planning of two-phase bipolar DC network.

5.3.1 Bipolar Load Distribution Model

In the two-phase network, while a bipolar load is distributed by the bipolar pole, the unipolar loads can be distributed to either of the positive or negative pole distribution pole. As voltage unbalance occurs due to the serious asymmetrical loading of the unipolar loads, the unipolar loads are re-distributed into two sets of load at roughly similar power levels defined as I_u and I_v such that serious asymmetrical loading does not occur as shown in Fig. 5-1.

Figure 5-1: System diagram of load re-distribution for 2-phase DC network.

As the load re-distribution involves two distribution poles, a binary integer is used to model the selection. By convention, a binary integer of 1 implies the distribution of the load current to the positive pole while a binary integer of 0 implies the distribution of the load current to the negative pole. As such, in the positive distribution pole, a binary integer of 1 on the current set $\mathbf{I}_u$ to the positive pole implies a binary integer of 0 on the current set $\mathbf{I}_v$. The opposite is true for the negative rail. In vector form, the binary distribution vector $\mathbf{X}$ on one of the current set vectors, $\mathbf{I}_u$ and $\mathbf{I}_v$, implies the distribution vector of $(\mathbf{1} - \mathbf{X})$ onto the other set. The resulting unipolar load vector across the positive and negative distribution pole can be defined as the following (5-1) and (5-2), respectively.

$$\mathbf{I}_p = \mathbf{X}\mathbf{I}_u + (\mathbf{1} - \mathbf{X})\mathbf{I}_v \quad (5-1)$$

$$\mathbf{I}_n = (\mathbf{1} - \mathbf{X})\mathbf{I}_u + \mathbf{X}\mathbf{I}_v \quad (5-2)$$

Equations (5-1) and (5-2) can be re-expressed into linear algebraic form in (5-3). The linear algebraic equation is a linear dependent function of the distribution binary vector $\mathbf{X}$.

$$\begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix}_L = \begin{bmatrix} \mathbf{I}_v \\ \mathbf{I}_u \\ \mathbf{I}_b \end{bmatrix} + \begin{bmatrix} \mathbf{I} & -\mathbf{I} \\ -\mathbf{I} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \text{diag}(\mathbf{I}_u) & \mathbf{0} \\ \mathbf{0} & \text{diag}(\mathbf{I}_v) \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{I} \end{bmatrix} [\mathbf{X}] \quad (5-3)$$

where $\mathbf{I}$ is the identity matrix. $\mathbf{I}_{p/n/b}$ are current vectors representing the positive, negative and bipolar pole load current. $\mathbf{I}_u$ and $\mathbf{I}_v$ are the load current vectors representing two sets of roughly similar power levels. $\mathbf{X}$ is the independent vector representing the binary load distribution selection of 1 and 0. 1 represents the selection of the $\mathbf{I}_u$ and $\mathbf{I}_v$ to be distributed to the positive rail while 0 represents the distribution to the negative rail.

5.3.2 System Power Loss Model

Without the loss of generality, the system power loss model for bipolar DC network is modeled as the summation of the squares of the distributed load currents with the network resistance. Mathematically, it can be represented in linear algebraic form as (5-4)

$$\mathbf{P}_L = \begin{bmatrix} \mathbf{I}_+ \\ \mathbf{I}_N \\ \mathbf{I}_- \end{bmatrix}_L^T \begin{bmatrix} \mathbf{G}_L & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_L & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_L \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{I}_+ \\ \mathbf{I}_N \\ \mathbf{I}_- \end{bmatrix}_L \quad (5-4)$$

where $[\mathbf{I}_+ \quad \mathbf{I}_N \quad \mathbf{I}_-]_L^T$ represents the load nodes network current, respectively, and $\mathbf{G}_L$ presents the load conductance matrix in (4-10).

Taking the definition of current as the summation of load type currents in (4-3) to (4-5), (5-4) can be decomposed to (5-5).

$$\mathbf{P}_L = \left(\mathbf{D} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix}_L \right)^T \mathbf{R} \left(\mathbf{D} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix}_L \right) \quad (5-5)$$

Substituting the load distribution model in (5-3), (5-5) can be expressed as (5-6). Upon expansion, (5-6) can be simplified to a binary integer quadratic model in (5-7). Vector $\mathbf{X}$ represents the binary distribution of the unipolar loads.

$$\mathbf{P}_L[\mathbf{X}] = (\mathbf{D}[\mathbf{E} + \mathbf{F}\mathbf{X}])^T \mathbf{R}(\mathbf{D}[\mathbf{E} + \mathbf{F}\mathbf{X}]) \quad (5-6)$$

$$\mathbf{P}_L[\mathbf{X}] = \mathbf{X}^T \mathbf{A} \mathbf{X} + \mathbf{B} \mathbf{X} + \mathbf{C} \quad (5-7)$$

$$\mathbf{A} = [\mathbf{D}\mathbf{F}]^T \mathbf{R}[\mathbf{D}\mathbf{F}], \mathbf{B} = 2[\mathbf{D}\mathbf{E}]^T \mathbf{R}[\mathbf{D}\mathbf{F}], \mathbf{C} = [\mathbf{D}\mathbf{E}]^T \mathbf{R}[\mathbf{D}\mathbf{E}]$$

where $\mathbf{D} = \begin{bmatrix} \mathbf{I} & \mathbf{0} & \mathbf{I} \\ -\mathbf{I} & \mathbf{I} & \mathbf{0} \\ \mathbf{0} & -\mathbf{I} & -\mathbf{I} \end{bmatrix}$, $\mathbf{E} = \begin{bmatrix} \mathbf{I}_v \\ \mathbf{I}_u \\ \mathbf{I}_b \end{bmatrix}$, $\mathbf{F} = \begin{bmatrix} \mathbf{I} & -\mathbf{I} \\ -\mathbf{I} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \text{diag}(\mathbf{I}_u) & \mathbf{0} \\ \mathbf{0} & \text{diag}(\mathbf{I}_v) \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{I} \end{bmatrix}$, and

$$\mathbf{R} = \begin{bmatrix} \mathbf{G}_L & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_L & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_L \end{bmatrix}^{-1}$$

5.3.3 System Voltage Unbalance Model

System voltage unbalance represents the degree of asymmetrical loading in the two-phase network. The system voltage unbalance is calculated by taking the summation of the square difference of both positive and negative distribution pole voltages as shown in (5-8). In the case of symmetrical voltage, the difference is zero. In vector form, it is represented in (5-9)

$$V_{un} = \sum_{i=1}^n [(V_{p(i)} - V_{n(i)})^2] \quad (5-8)$$

$$\mathbf{V}_{un} = (\mathbf{V}_p - \mathbf{V}_n)^T (\mathbf{V}_p - \mathbf{V}_n) \quad (5-9)$$

Taking the definition of voltage as the potential difference between two voltage nodes, i.e., $\mathbf{V}_p = \mathbf{V}_+ - \mathbf{V}_N$ and $\mathbf{V}_n = \mathbf{V}_N - \mathbf{V}_-$, (5-9) can be decomposed in (5-10).

$$\mathbf{V}_{un} = (\mathbf{V}_+ - 2\mathbf{V}_N + \mathbf{V}_-)^T (\mathbf{V}_+ - 2\mathbf{V}_N + \mathbf{V}_-) \quad (5-10)$$

Using the nodal analysis equations (4-3) to (4-5), (5-10) can be reduced to (5-11) with the assumption made that the cable is multi-core and the node to node resistance is the same for each distribution cable, ie $\mathbf{G}_L = \mathbf{G}_+ = \mathbf{G}_N = \mathbf{G}_-$. $\mathbf{G}_L$ presents the load conductance matrix in (4-10). In linear algebraic form, it is represented as (5-12)

$$\mathbf{V}_{un} = \left(3\mathbf{R}(\mathbf{I}_p - \mathbf{I}_n) \right)^T \left(3\mathbf{R}(\mathbf{I}_p - \mathbf{I}_n) \right) \quad (5-11)$$

$$\mathbf{V}_{un} = \left(\mathbf{R}\mathbf{H} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix}_L \right)^T \left(\mathbf{R}\mathbf{H} \begin{bmatrix} \mathbf{I}_p \\ \mathbf{I}_n \\ \mathbf{I}_b \end{bmatrix}_L \right) \quad (5-12)$$

Substituting the load distribution model in (5-3), (5-12) can be expressed as (5-13). Upon expansion, (5-13) can be simplified to a binary integer quadratic model in (5-14). Vector $\mathbf{X}$ represents the binary distribution of the unipolar loads.

$$\mathbf{V}_{un}[\mathbf{X}] = (\mathbf{R}\mathbf{H}[\mathbf{E} + \mathbf{F}\mathbf{X}])^T (\mathbf{R}\mathbf{H}[\mathbf{E} + \mathbf{F}\mathbf{X}]) \quad (5-13)$$

$$\mathbf{V}_{un}[\mathbf{X}] = \mathbf{X}^T \mathbf{J} \mathbf{X} + \mathbf{K} \mathbf{X} + \mathbf{L} \quad (5-14)$$

where $\mathbf{J} = [\mathbf{H}\mathbf{R}\mathbf{F}]^T [\mathbf{H}\mathbf{R}\mathbf{F}]$, $\mathbf{K} = 2[\mathbf{H}\mathbf{R}\mathbf{E}]^T [\mathbf{H}\mathbf{R}\mathbf{F}]$, $\mathbf{L} = [\mathbf{H}\mathbf{R}\mathbf{E}]^T [\mathbf{H}\mathbf{R}\mathbf{E}]$, $\mathbf{H} = \begin{bmatrix} 3\mathbf{I} & -3\mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$, $\mathbf{E} =$

$$\begin{bmatrix} \mathbf{I}_v \\ \mathbf{I}_u \\ \mathbf{I}_b \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \mathbf{I} & -\mathbf{I} \\ -\mathbf{I} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \text{diag}(\mathbf{I}_u) & \mathbf{0} \\ \mathbf{0} & \text{diag}(\mathbf{I}_v) \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{I} \end{bmatrix}, \text{ and } \mathbf{R} = \begin{bmatrix} \mathbf{G}_L & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_L & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_L \end{bmatrix}^{-1}$$

5.3.4 Flag Model

In analyzing the solutions, there are two cases which do not provide a unique answer, such that the binary vector $\mathbf{X}$ and $(\mathbf{1} - \mathbf{X})$ gives the same results. The mathematical representation can be expressed as (5-15) and is used as a constraint function in the optimization algorithm.

Case 1): The current set vectors, $\mathbf{I}_u$ and $\mathbf{I}_v$ are interchangeable. Without fixing either $\mathbf{I}_u$ or $\mathbf{I}_v$, the binary vector $\mathbf{X}$ and $(\mathbf{1} - \mathbf{X})$ gives the same results. Hence, a constraint is proposed such that the first unipolar load of $\mathbf{I}_u$ is distributed in the positive rail. This fixes the starting value of the distribution vector $\mathbf{X}$ to 1 which solves the problem of interchangeable current sets.

Case 2): The second case is when a system network node has the same load model in the set $\mathbf{I}_u$ and $\mathbf{I}_v$. An example is when a node is distributing only bipolar loads or the

same load model in both DC unipolar rails. Hence, the selection of 1/0 of the unipolar load current set affects the accuracy of the results as both gives the same value. Hence, to solve this problem, a constraint of value 1 is proposed at the node when the case of the same load model is identified in the system.

$$\mathbf{H}[\mathbf{X}] = \begin{cases} 1, & \text{case 1 or 2 detected} \\ 0, & \text{else} \end{cases} \quad (5-15)$$

5.4 Optimization Algorithm

5.4.1 Multi-Objective Weighted Sum Method

This paper proposes a multi-objective optimization (MOO) method for simultaneously minimizing the power loss and voltage unbalance. The objective is to minimize the two indices, the system power loss and the system voltage unbalance index, through a weighted sum of them. The constraint taken is the flag model which discusses the cases when the dependent variable does not output a unique value.

In the weighted sum approach, weights are attached to each of the individual objective function. The functions of the attached weights are to normalize the indices to its per-unit value and to represent their relative importance with respect to each index.

In addition, a scaling factor is added to the system power loss objective. A large scaling factor implies that the system power loss is a large multiplier of the normalized value of the system power loss. It must be noted that the use of DC systems for distribution is for higher energy efficiency and a large scaling factor implies high system inefficiency which is undesirable. The objective and constraints functions are formulated as (5-26) and (5-27), respectively.

$$\mathbf{G}[\mathbf{X}] = \min \frac{\alpha_1 * w_1}{n_1} \mathbf{P}_L[\mathbf{X}] + \frac{w_2}{n_2} \mathbf{V}_{un}[\mathbf{X}] \quad (5-16)$$

$$\text{s.t.} \quad \mathbf{H}[\mathbf{X}] \quad (5-17)$$

where $\mathbf{G}[\mathbf{X}]$ represents the multi-objective optimization function and $w_1, n_1, \mathbf{P}_L[\mathbf{X}]$ and $w_2, n_2, \mathbf{V}_{un}[\mathbf{X}]$ represents the weight, normalised value and the model for system power loss and system voltage unbalance respectively. α_1 represents the scaling factor of the system power loss to indicate an efficient system design.

The values used for normalizing the system power loss and the system voltage unbalance model, n_1 and n_2 are 15% of the rated load power and the number of nodes,

respectively. The weight is set as 0.5 to illustrate the equal weighting of the considerations during power system planning of the bipolar two-phase network. The scaling factor is selected to be within a conservative range from 0.8 to 2 to illustrate an energy efficient DC system design.

To solve a multi-objective programming model, another popular method is multi-objective evolutionary algorithms such as NSGA-II [158] and MOEA/D [159]. However, these algorithms usually need a very large number of generation and population number, thus considerable computing time; besides, they usually provide inconsistent solutions for multiple runs due to the random factors involved. Therefore, this paper uses the weighted-sum method.

5.4.2 Multi-Objective Optimization Algorithm

In solving for the multi-objective optimization model, the problem is divided into two parts. The first part is to obtain the load currents by formulating the matrices and solve the power flow equations for the bipolar DC network. The second part is to use the load current values and formulate the system power loss and voltage unbalance model and solve the model with the constraint function using the flag model. The flowchart of the described solution process is shown in Fig. 5-2 and commercial solvers such as IBM ILOG CPLEX can be used in practice.

Figure 5-2: Multi-objective optimization solution flowchart

5.5 Voltage Balancing Simulation Results

In this section, the voltage balancing methodologies in the existing literatures and proposed model-based optimization approach are discussed and compared. In the use of forward-backward iterative approach method, the distribution of load is based on 1) minimization of neutral current and 2) higher distribution voltage due to voltage drop.

One main disadvantage of iterative methods is that the relationships among components are built by a direct observation. If the network is large, the preparation can be difficult, as can be observed in [17], and prone to errors or when the observed network is non-observable such that the numbering of the “parent node” and “child node” arrangement is not easily constructed, then, iterative methods are not applicable [18]. One example of non-observable network architecture is the ladder architecture when power sources are integrated at the opposite ends of a radial distribution [10].

Hence, the proposed model-based optimization approach aims to address the issue of larger networks and non-observable networks such that the power flow is not able to be established using direct observation. The system performance indices are then compared between the methodologies used.

5.5.1 Existing Iterative Approach

In the use of iterative methods, two main methodologies of voltage balancing are presented. The first is to balance the neutral current wire [143] while the second is to distribute the loads based on voltage measurements, which is an indication of voltage drop [8]. The solution flowchart for both of the methodologies, as shown in Fig. 5-3, is a modification of the forward-backward iterative approach as discussed in Chapter 3. The algorithm is shown in Table 5-1 and Table 5-1. As iterative method is used, the case study uses a single source radial distribution network.

Figure 5-3: Voltage balancing solution flowchart based on a) net neutral current and b) voltage level

Table 5-1: Voltage Balancing Algorithm using Neutral Current

Algorithm 1: Minimize absolute value of neutral current

Label Network Nodes: 0 to n

Start: Node n

Distribute the last load to the positive rail

While (Node $\neq$ 1)

If (neutral cable current is positive),

 Distribute the next load to the negative rail

 Minus the value of the neutral cable current

Else

 Distribute the next load to the positive rail

 Add the value of the neutral cable current

End

Node = Node - 1

End

Table 5-2: Voltage Balancing Algorithm using Nodal Voltage

Algorithm 2: Distribute the loads based on voltage level

Label Network Nodes: 0 to n

Start: Node n

Distribute the last load to the positive rail

While (Node $\neq$ 1)

If (positive phase voltage > negative phase voltage),

 Distribute the next load to the positive rail

 Re-calculate the phase voltages

Else

 Distribute the next load to the negative rail

 Re-calculate the phase voltages

End

Node = Node - 1

End

5.5.2 A 15-Node System Voltage Balancing Simulation Results Comparison

The following cases are compared as follows: Case 1) Proposed MOO method with the following weights, $w_1, w_2 = 0.5$ and $0.8 < \alpha_1 < 2$. Case 2) Base case study. Case 3) Backward forward sweep based on the absolute value of the rated current in the neutral wire [143]. Case 4) Backward forward sweep based on network voltage with consideration of network impedance [8]. Case 5) MOO with the following weights, $w_2 = 0, w_1, \alpha_1 = 1$. Note that Case 1 represents a reasonable weightage for the power system planning while Case 5) represents when only the system power loss is considered.

For the proposed model-based optimization approach, the values used for normalizing, n_1 and n_2 , are 38.325 and 15, respectively for the discussed linear network case study. The weight is set as 0.5 to illustrate the equal weighting of the considerations during

power system planning of the bipolar two-phase network. The scaling factor is selected to be within a conservative range from 0.8 to 2.

Table 5-3: Binary distribution vector of the five cases

Cases						Cases					
Node	1)	2)	3)	4)	5)	Node	1)	2)	3)	4)	5)
1	1	1	1	1	1	9	1	1	1	1	1
2	1	1	1	1	1	10	1	1	1	1	1
3	0	1	0	0	0	11	0	0	0	1	0
4	1	1	1	1	1	12	0	0	1	0	0
5	1	1	1	1	1	13	1	0	0	0	1
6	0	1	0	1	0	14	1	0	1	1	1
7	0	1	1	0	1	15	1	1	1	1	1
8	1	1	0	0	0	-	-	-	-	-	-

Table 5-4: Comparison table of indices for 15-Bus network

Cases	Power Loss (15)		Voltage Unbalance (18)	
	(W)	(p.u)	-	(p.u)
1)	27.0744	0.7064	0.1822	0.0121
2)	34.4801	0.8997	120.2442	8.0163
3)	27.3073	0.7125	13.6397	0.9093
4)	27.2310	0.7105	7.1299	0.4753
5)	27.0490	0.7058	2.1790	0.1453

Table 5-3 shows the binary load distribution solutions of the 5 abovementioned cases and Table 5-4 compares the system power loss and system voltage unbalance values of the corresponding cases. Fig. 5-4 and Fig. 5-5 shows the unbalanced and balanced nodal voltages, respectively after voltage balancing and Fig. 5-6 shows the plot of the voltage balancing against system efficiency indices of the load distribution solutions.

Figure 5-4: Plot of phase node voltage in an unbalanced 15-Bus network

Figure 5-5: Plot of phase node voltage in a balanced 15-Bus network

Figure 5-6: Comparison plot of voltage balancing solutions for 15-Bus network

5.5.3 A Larger 33-Bus System Voltage Balancing Simulation Results

The proposed voltage balancing method formulates the problem into mixed integer quadratic problem (MIQP). It is well known that MIQP has a computational complexity which grows exponentially with the number of optimization variables [160]. The performance is discussed in a larger 33-bus system case study. In the case of the larger 33-bus system, the simulation uses the values of $w_1, w_2 = 0.5$, $\alpha_1 = 1$, $n_1 = 50$ and $n_2 = 33$.

Table 5-5: Comparison table of binary distribution vector for 33-bus network

Node	1	2	3	4	5	6	7	8	9	10	11
Case											
1	1	1	1	0	1	1	0	1	1	1	0
2	1	1	0	1	1	1	0	1	0	1	0
Node	12	13	14	15	16	17	18	19	20	21	22
1	1	0	1	1	1	0	1	0	0	1	0
2	1	0	1	1	1	0	1	1	1	1	1
Node	23	24	25	26	27	28	29	30	31	32	33
1	1	0	0	1	0	1	0	0	1	0	1
2	1	0	0	0	0	0	1	0	1	0	1

Table 5-6: Comparison table of indices for 33-bus network

	Power Loss (15)		Voltage Unbalance (18)	
Cases	(W)	(p.u)	-	(p.u)
1	53.3198	1.0664	1.4350	0.0435
2	69.1298	1.3826	181.4156	5.4974

Table 5-7: Comparison table of computational time for 15-bus and 33-bus network

Case Study	15-Bus System	33-Bus System
Computational Time	0.20 s	31132.75 s

The compared performances of the binary distribution solution are as follows: Case 1) Proposed multi-objective optimization method with the following weights, $w_1, w_2 = 0.5$, $\alpha_1 = 1$, $n_1 = 50$ and $n_2 = 33$. Case 2) Base case study. Table 5-5 shows the binary distribution solutions while Table 5-6 compares the system power loss and system voltage unbalance values of the corresponding cases. Table 5-7 compares the computational time in the voltage balancing planning for a 15-bus and 33-bus system. Using the 33-bus system as the case study, it can be seen from Table 5-6 and Table 5-7 that the proposed model-based MOO method has successfully shown that the voltage across the 2-phase bipolar DC network is balanced and can be carried out with reasonably fast solution speed (note that the proposed method is mainly for system analysis and planning studies, so the computational time is not a major concern as long as the solution can be obtained in a tolerable time, e.g., several hours). Fig. 5-7 and Fig.

5-8 shows the nodal voltages of the unbalanced and balanced 33-bus two-phase DC network, respectively.

Figure 5-7: Plot of phase node voltage in a balanced 33-bus network

Figure 5-8: Plot of phase node voltage in a balanced 33-bus network

5.6 Simulation Results Discussion

According to the voltage balancing simulation results, the following conclusion can be drawn:

- 1) In comparing between existing and proposed model-based voltage balancing strategies, the proposed methodology can reduce system voltage unbalance by up to 95%. As existing methodologies are based on iterative methods, the 15-bus radial network is used as the case study. The improvement in the results is due to the consideration of i) the effects of voltage drop from the distribution of bipolar DC loads and ii) the consideration of voltage balancing at the whole system level.

The proposed methodology is then applied to a 33-bus system and is able to reduce voltage unbalance tremendously.

- 2) The proposed voltage balancing methodology is then extended to a 33-bus unobservable power network case study. The proposed model-based multi-objective optimization method has successfully shown that the voltage across the two-phase bipolar DC network is balanced and can be carried out with reasonably fast solution speed.
- 3) Comparing the multi-objective optimized solutions of the 15-bus radial network, the power loss index of the network between cases 1) and 5) of Table V varies significantly. This is seen in the 15-bus radial network that before and after carrying multi-objective optimization, the power loss reduces by 15%. However, comparing between multi-objective optimization and power loss single optimization, the power loss reduces by less than 0.1% but the voltage unbalance doubles as seen in Table V. This is due to the presence of an upper bound to minimizing system power loss which arises from the rationale of energy efficient system design in using DC distribution.

5.7 Concluding Remarks

Chapter 5 looks into one application on how the steady state modeling using nodal based power flow modeling approach can be used in the design and operation of DC power systems so that network optimization can be carried out in the planning stage [64]. Voltage balancing is explored as the case of application to improve on the efficiency of the DC network, using DC LED lighting system as the example. Voltage unbalance occurs when there is asymmetric loading in the 2-phase DC network. Existing voltage balancing methodologies are based on iterative methods on linear networks with the distribution of loads based on i) net neutral current and ii) voltage level. In the existing literature, there has been no model-based approach at the system level for voltage balancing of the bipolar DC network.

In this chapter, a model-based optimization methodology for designing two-phase bipolar DC power system is discussed. A binary load distribution model is proposed which acts as an interlinking model with the power flow model to formulate a binary integer based system power loss and system voltage unbalance indices. Then, a multi-objective weighted sum binary integer quadratic optimization problem is formulated and solved.

Using the 15-bus radial network as the case study, the existing iterative methodologies are compared against the proposed model-based methodology for voltage balancing. The proposed model based method is able to improve the voltage balancing results. The improvement of the results is due to the consideration of i) the effects of voltage drop from the distribution of bipolar DC loads and ii) the consideration of voltage balancing at the whole system level. The proposed model based optimization methodology is then applied to a 33-bus system and is able to reduce voltage unbalance tremendously.

6 Conclusion

With the increase in electrical energy demand and technological development of distributed energy resources and power electronics, there is a need to re-evaluate the use of energy in the power distribution system. One such approach is to look into the co-existence of AC and DC distribution system while taking advantage of each of the system characteristics for different use cases.

With the technological advancement, DC distribution re-emerges as the preferred distribution system for some use cases due to higher efficiency, better performance and cost effectiveness. Some of the improved performances include higher distribution power capacity, efficient and cost-effective integration for the case of telecommunications and data centers. As a result, the use of DC distribution is then applied and investigated in the built environment context, primarily in the use case of LED lightings integrated with distributed energy resources. This is because LED lightings are essentially DC load in nature and it allows for a simple and cost-effective distribution without cables oversizing. One particular case study is the LED lighting system in a high rise built environment.

In designing efficient DC LED lighting system, there is a need to model the highly resistive DC distribution system and its impact of power flow between sources. This is because one unique distribution system characteristic is the ability of the system to achieve grid isolation when integrated with the distributed energy resources. Furthermore, with the development of human-centric lighting, powering LED lighting system using the extra-low voltage DC voltage level is demonstrated to be efficient. In using AC TN-S system architecture, the energy efficient bipolar DC distribution system architecture can be obtained and this emerging architecture requires power flow modeling investigation. The need for power flow modeling, which is the basic steady state analysis tool, is essential to get the overall view of the system for the design and operation of distribution system. It can then be applied to network optimization, component capacity optimization in the planning stage of the LED lighting distribution system. Hence, the research thesis aims to fill up the gap in power flow modeling for different operational architectures of highly resistive DC network presented in existing literature. The power flow model is validated against an actual mockup of extra-low voltage DC LED lighting system

In Chapter 3, iterative approach is used to model the unipolar and bipolar DC network by decomposing the cables of the distribution system individually and then performed a forward-backward iterative approach. The approach models the network starting from the last node in a backwards manner by observing directly how the current flows and then adjusts the last node voltage such that the source voltage is at the distribution voltage in a forward manner. The DC network used is a single source DC LED lighting system. The proposed iterative approach is then used to investigate the system performances of different electrical system topologies and DC LED lighting topologies. The conclusions for Chapter 3 are as follows.

- The approach of decomposing into the network individual cables and using the iterative method is validated and has modeled the unipolar and bipolar DC LED lighting system successfully.
- In using extra-low voltage for distribution purposes, the voltage drop and network cable losses are prominent.
- Comparing between different DC LED lighting topologies, a driver based DC LED lighting system is more efficient than a driverless current limiting based DC LED lighting system. For applications without the need of individual human-centric dimming, a driverless LED lighting system is able to provide a cost-effective option. In such a case, the design of an efficient system lies in the reduction of the values of the current limiting resistor. It has also been shown that different design approaches for driverless DC LED lighting has varying system performances.
- Comparing different driver-based DC LED lighting topologies, the efficiency of the system has to account for the losses due to the driver of the DC LED lighting. A unipolar 24V DC network is more efficient than a unipolar 48V DC network for small distribution networks because the cable losses experiences in a unipolar 24V DC network does not outweigh the driver losses in a unipolar 48V DC network, assuming the same lighting loads are distributed.
- Comparing 48V unipolar and bipolar DC distribution, a bipolar network has the capacity for a more efficient system distribution design due to the reduced voltage drop caused by the shared distribution line and the ability to distribute the loads using a lower rated voltage which results in a more efficient driver used.

In Chapter 4, a nodal based analysis approach power flow model is proposed to model the DC network to account for more robust network operation. This is because, with the advancement of technology, the DC LED lighting system can be operating in grid isolating mode. Furthermore, at distribution end, direct integration of DC ESS is possible and this results in having only the voltage measurements of the DC energy sources being known. The proposed modeling approach separates the network load and source nodes and models them individually. Using the concept of superposition and the operational properties of the sources, the related source nodes can be easily disconnected from the power flow model. The proposed power flow model is then validated using a mock up DC LED lighting system on actual case study. Besides the operational characteristics of the network, the proposed power flow model is modified to account for system designs that violate bipolar DC characteristics. The proposed power flow model has successfully modeled the nodal voltages using a simulated Matlab Simulink system.

The conclusions for Chapter 4 are as follows.

- The proposed power flow model is able to accurately model the nodal voltages. When compared against Matlab simulated system, the model is able to accurately model with errors in the range of 10^{-5} . However, this is true only if the entire network and nodes have the following characteristics: 1) The DC sources are assumed to be symmetrically integrated to both phases of the DC network with the same balanced voltage in each phase across all DC sources and; 2) The currents of each of the two phases are flowing in the opposite direction in the neutral cable, respective of the DC network operations.
- Compared the proposed power flow modeling to the conventional power flow model, the proposed power flow has higher accuracy as it accurately accounts for the return cable path of the current. Furthermore, the proposed power flow model is able to account the switching in and out of the sources easily without having to explicitly re-formulate the admittance matrix. However, one limitation of using the proposed power flow model is that it is unable to obtain the nodal voltage of the node that is initially a source node due to the switching out of the source.
- For nodes that violate the two assumptions, the modified power flow approach using voltage drop compensation is used. This is because the networks exhibit

the same directional flow of current in the neutral cable which requires the modeling of additional voltage drop to the single-phase voltage. The voltage drop compensation is used to compensate the additional voltage drop iteratively. To accurately model such networks, the network is segregated into 3 sections with each section having a specific modified approach using the original power flow model. The difference in accuracy of the unmodified and modified power flow is prominent in larger networks such as the 33-bus network with single phase integration. The modeling of the nodal voltages is crucial to prevent unnecessary overvoltage or under voltage issues to the DC loads due to the presence of single-phase networks in a bipolar DC architecture.

In Chapter 5, the power flow model is used in the design and operation of DC power systems so that network optimization can be carried out in the planning stage [64]. Voltage balancing is explored as the case of application to improve on the efficiency of the DC network, using DC LED lighting system as the example. Voltage unbalance occurs when there is asymmetric loading in the two-phase DC network. Existing voltage balancing methodologies are based on iterative methods on linear networks with the load distributing based on i) net neutral current and ii) voltage level. In the existing literature, there has been no model-based approach at the system level for voltage balancing of the bipolar DC network. The conclusions for Chapter 5 are as follows.

- In comparing between existing and proposed model-based voltage balancing strategies, the proposed methodology can reduce system voltage unbalance by up to 95%. As existing methodologies are based on iterative methods, the 15-bus radial network is used as the case study. The improvement of the results is due to the consideration of i) the effects of voltage drop from the distribution of bipolar DC loads and ii) the consideration of voltage balancing at the whole system level. The proposed methodology is then applied to a 33-bus system and is able to reduce voltage unbalance tremendously.
- The proposed voltage balancing methodology is then extended to a 33-bus unobservable power network case study. The proposed model-based multi-objective optimization method has successfully shown that the voltage across the 2-phase bipolar DC network is balanced and can be carried out with reasonably fast solution speed.

- Comparing the MOO solutions of the 15-bus radial network, the power loss index of the network between cases 1) and 5) of Table V varies significantly. This is seen in the 15-bus radial network that before and after carrying multi-objective optimization, the power loss reduces by 15%. However, comparing between multi-objective optimization and power loss single optimization, the power loss reduces by less than 0.1% but the voltage unbalance doubles as seen in Table V. This is due to the presence of an upper bound to minimizing system power loss which arises from the rationale of energy efficient system design in using extra-low DC voltage for distribution.

In conclusion, in this research work, the power flow model for DC distribution networks, which is a basic steady-state analysis tool, is examined for the planning of DC distribution network such as DC LED lighting system at extra-low voltage DC level. The extra-low voltage DC LED lighting system is used as the case study as it has a relatively higher voltage drop to voltage level ratio. This is to account for the validity of the case study of non-negligible voltage drop. The research work examines from two methodologies, mainly the iterative method and the nodal analysis model-based approach, and validates using an actual mock-up DC LED lighting system. The model-based approach models the loads and sources nodes individually to account for the effects of technological advancement such as grid islanding and grid connection operation state. It decomposes the distribution network into its individual cables to account for the load types in the bipolar DC network topology. The power flow model is then modified to investigate on steady state network operations and single-phase networks in a bipolar DC architecture. The modified power flow model is able to accurately model the nodal voltages. In using the proposed power flow for the design and operation of DC power systems, voltage balancing is explored as the case of application to improve on the efficiency of the DC network. The proposed model based methodology using power flow is able to further reduce the system voltage unbalance due to the consideration of i) the effects of voltage drop from the distribution of bipolar DC loads and ii) the consideration of voltage balancing at the whole system level. In the next section, it will lay out the plausible extension and research works related to the proposed power flow model.

7 Future Work

7.1 Cost-benefit analysis and operational planning for bipolar DC network

In the research work, it investigates and validates the power flow model of bipolar DC network and carry out static analysis such as power flow and voltage balancing. For future work, the power flow model can be used to investigate the operational planning and analysis of bipolar DC network and the asymmetrical integration of DC energy sources. As the bipolar DC network does not exhibit phase coupling, the asymmetrical integration of DC energy sources allows for one of the two phases to distribute more loads. Furthermore, due to its lack of phase coupling, network reconfiguration can be achieved instead of total network isolation like in the case of 3-phase AC network when one of the phases is overloaded. As a result, the DC system can be designed to its voltage drop limits and various system analyses such as fault diagnostics and fault localization can be achieved at the distribution level. Besides, as the voltage of DC energy storage systems decreases with decreasing state of charge, a time-based planning from the direct integration of DC energy storage systems can be achieved as part of the future work.

7.2 Dynamic system modeling and analysis for bipolar DC network

In the research work, it lays out the methodology for modeling a bipolar DC network. However, as DC network is a power electronics based system, one of the main investigations in power electronics system is to look into the control and stability of the power electronics. While existing works have looked at the stability of the smaller power electronic system, there is a gap towards a network level stability analysis of DC power electronics system. Furthermore, one other issue with DC systems is the need for dynamic analysis such as fault diagnostics. Existing works have looked into DC transmission level [127] but there is a gap towards the investigation at distribution level which has a different network characteristic compared to the transmission system. As a result, the dynamic system modeling and analysis for bipolar DC network can be one of the future works to look into the system network level control, stability analysis and carry out fault diagnostics for a DC distribution network.

7.3 Power electronics interface for bipolar DC network

The bipolar DC network is the equivalent of the 3-phase AC network without phase coupling. From the network perspective, network reconfiguration is made possible through mechanical and electronic switches. However, there is a gap in the designs of such reconfiguration switches for bipolar DC network. While existing works have looked at the electronic switches at high voltage DC transmission level recently, there is a gap towards investigating at the distribution level, with a focus on conventional silicon-based technology for cost-effective reasons. One plausible future work is to look into power electronics interface design for bipolar DC network with the consideration of the system level advantages from the lack of phase coupling in the bipolar DC network using the matured silicon-based electronic switch technology.

Author's Publications

Related Journal Publications

- [1] **Benjamin S. H. Chew**, Y. Xu, and Q. Wu, "Voltage Balancing for Bipolar DC Distribution Grids: A Power Flow Based Binary Integer Multi-Objective Optimization Approach," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 28-39, 2019
- [2] **Benjamin S. H. Chew**, Yan Xu and King Jet Tseng, "An Iterative Approach for System Efficiency Analysis for DC LED Lighting System in High Rise Built Environment" In submission to *Energy and Buildings*, Elsevier
- [3] **Benjamin S. H. Chew** and Yan Xu, "A Modified Power Flow Model for Single-Source Bipolar DC Distribution Networks " In preparation for submission

Related Conference Publications

- [4] **S. H. Chew**, K. J. Tseng and Hoan Thong Nguyen, "An Energy Efficient 48Vdc Bipolar ELVDC LED Lighting System in a High-Rise Building." 11th IEEE International Conference on Power Electronics and Drive Systems (PEDS 2015), Sydney, Australia, 2015.
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- [7] **S.H.Chew**, Edwin Chan, N.H.Ardiyanto, Y.L.Sum, S.C.Chien, B.H.Soong, K.J.Tseng, "Design Considerations for ELVDC Power Distribution System Integrated Directly with DC Energy Sources for LED Lighting in High-Rise Built Environment." 37th IEEE PELS International Telecommunications Energy Conference (INTELEC 2015), Namba, Osaka, Japan, 2015.

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- [12] **S.H. Chew** and Yan Xu, "Operational Analysis of Static Transfer Switch for Bipolar DC Network" Accepted for IEEE International Power Electronics Conference (ECCE Asia 2018), Niigata , Japan, 2018

Inventory Disclosure, Technical Disclosure, Technical Know-how

- [13] **S.H. Chew** and Yan Xu, 2017, "Static Transfer Switch Design For 2-Phase Bipolar DC Network" Submitted to NTUitive (TD/286/17)

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Appendix

A-1 Steady State Nodal Based Modeling of DC Networks

Consider nodal based linear power flow equations.

$$\mathbf{I} = \mathbf{YV} \quad (\text{A1-1})$$

Separating the source and load nodes in the main equation, the source admittance matrix, $\mathbf{Y}_S$, corresponds to the impedance between sources and the load network.

$$\mathbf{I}_L + \mathbf{I}_S = \mathbf{Y}_1 \mathbf{V}_L + \mathbf{Y}_S \mathbf{V}_S \quad (\text{A1-2})$$

At distribution level, the source current is not always readily available but it can be determined by modeling the node load voltages with a high degree of accuracy. Consequently, the source current component is removed.

$$\mathbf{I}_L = \mathbf{Y}_1 \mathbf{V}_L + \mathbf{Y}_S \mathbf{V}_S \quad (\text{A1-3})$$

Re-expressing the load impedance matrix, $\mathbf{Y}_1$, as the sum of source and load impedance, $\mathbf{Y}_L$ and $\mathbf{Y}_S$, the equation can be decomposed into the following equation.

$$\mathbf{I}_L = (\mathbf{Y}_L + \mathbf{Y}_S)\mathbf{V}_L + \mathbf{Y}_S\mathbf{V}_S \quad (\text{A1-4})$$

where $\mathbf{I}$, $\mathbf{I}_L$, $\mathbf{I}_S$ represents the conventional load and generation current vector, only load current vector and only source current vector, respectively. $\mathbf{V}$, $\mathbf{V}_L$, $\mathbf{V}_S$ represents the conventional load and generation voltage vector, only load voltage vector and only source voltage vector, respectively. $\mathbf{Y}$, $\mathbf{Y}_1$, $\mathbf{Y}_L$, $\mathbf{Y}_S$ represents the conventional admittance matrix, the admittance matrix after removing the source, the conventional admittance matrix considering only load nodes and the resulting admittance matrix of the source nodes, respectively for equations A1-1 to A1-4.