ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

THE PLANNING OF LOW VOLTAGE DC DISTRIBUTION SYSTEMS UNDER MULTIPLE CRITERIA AND CONSTRAINTS

M.Sc. THESIS

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Department of Electrical Engineering

Electrical Engineering Programme

JULY 2024

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ALÇAK GERİLİM DOĞRU AKIM DAĞITIM ŞEBEKELERİNİN ÇOKLU KRİTERLER VE KISITLAR ALTINDA PLANLANMASI

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Oğuzhan ÖZÇELİK, a M.Sc. student of İTU Graduate School student ID 504211029 successfully defended the thesis entitled "THE PLANNING OF LOW VOLTAGE DC DISTRIBUTION SYSTEMS UNDER MULTIPLE CRITERIA AND CONSTRAINTS", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family,

FOREWORD

First and foremost, I would like to acknowledge my thesis supervisor, Prof. Dr. Mustafa BAĞRIYANIK for his invaluable guidance on my studies. Without his insightful help, this work would not have been possible at all.

Next, I am forever grateful for my father, mother and brother, who have always believed in me and supported me throughout my entire life. Their unending love and patience always made me believe in myself.

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May 2024

Oğuzhan ÖZÇELİK
Electrical Engineer

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ABBREVIATIONS

AC	: Alternating Current
ANN	: Artificial Neural Network
App	: Appendix
BESS	: Battery Energy Storage Systems
CAPEX	: Capital Expenditure
DAB	: Dual Active Bridge
DC	: Direct Current
DCF	: Discounted Cash Flow
DCF	: Discounted Cash Flow
DSO	: Distribution System Operator
EMRA	: Energy Market Regulatory Authority
EMT	: Electromagnetic Transient
EV	: Electrical Vehicle
FRT	: Fault Ride Through
GFL	: Grid Following
GFM	: Grid Forming
IBR	: Inverter Based Resources
IGBT	: Insulated-gate Bipolar Transistor
IMD	: Insulation Monitoring Device
LCC	: Line Commutated Converter
LVDC	: Low-voltage Direct Current
MHI	: Manitoba Hydro International
MMC	: Multi-modular Converter
MOSFET	: Metal Oxide Semiconductor Field Effect Transistor
NPV	: Net Present Value
NPV	: Net Present Value
OPEX	: Operational Expenditure
PCC	: Point of Common Coupling
PLL	: Phase-locked Loop
PSCAD	: Power Systems Computer Aided Design

PV : Photovoltaic

PWM : Pulse Width Modulation

RES : Renewable Energy Sources

SCR : Short-circuit Ratio

SG : Synchronous Generator

SVPWM : Space Vector Pulse Width Modulation

TEDC : Turkish Electricity Distribution Corporation

TSO : Transmission System Operator

VSC : Voltage Source Converter

VSG : Virtual Synchronous Generator

SYMBOLS

$\mathbf{C_{ref}}$	: The minimum size of capacitance required in diode bridge rectifier
$\mathbf{d_{mw}}$	: Distance covered by maintenance workers
$\mathbf{d_{rw}}$	: Distance covered by meter reading workers
$\mathbf{C_{distribution}}$	: Price of energy distribution
$\mathbf{C_{energy}}$	: The price for unit energy in bills
$\mathbf{C_{fixed}}$	: Fixed price
$\mathbf{C_{loss}}$	: Cost of energy that cannot be billed
$\mathbf{C_{outage}}$	: Cost of energy that could not be distributed
$\mathbf{c_{tr}}$	: Cost of travel per one kilometer
$\mathbf{C_{vo}}$	: The total cost of vehicle operation
$\mathbf{I_{d\_meas}}$	: The actual measured d-axis current at the AC side of the converter
$\mathbf{I_{d\_ref}}$	: The desired d-axis current at the AC side of the converter
$\mathbf{I_{line}}$	: The current magnitude
$\mathbf{I_{q\_meas}}$	: The actual measured q-axis current at the AC side of the converter
$\mathbf{I_{q\_ref}}$	: The desired q-axis current at the AC side of the converter
$\mathbf{k_{load}}$	: Load factor
$\mathbf{K_p}$	: Frequency droop gain
$\mathbf{K_q}$	: voltage droop gain
$\mathbf{L}$	: Filter inductor size at the AC side of the converter in Henry
$\mathbf{l_{line}}$	: Line length
$\mathbf{l_{max}}$	: Maximum line length
$\mathbf{N_{customers}}$	: The number of customers that are affected.
$\mathbf{P_{loss}}$	: Total maximum losses that occurs in the system
$\mathbf{P_{meas}}$	: The actual measured active power at the DC side of the converter
$\mathbf{P_{ref}}$	: The desired active power at the DC side of the converter
$\mathbf{p^{set}}$	: Active power setpoint
$\mathbf{Q_{meas}}$	: The actual measured reactive power at the AC side of the converter
$\mathbf{Q_{ref}}$	: The desired reactive power at the AC side of the converter
$\mathbf{q^{set}}$	: Reactive power setpoint
$\mathbf{r_{dc}}$	: DC resistance of the line

$\upsilon_{0,*}^{q}$	: Voltage set-point
$\upsilon_{0,set}^{q}$	: Steady-state voltage
V_{ac_meas}	: The actual measured AC voltage at the AC side of the converter
V_{ac_ref}	: The desired AC voltage at the AC side of the converter
V_d	: d axis current
V_{d_meas}	: The actual measured d-axis voltage at the AC side of the converter
V_{dc_meas}	: The actual measured DC voltage at the DC side of the converter
V_{dc_ref}	: The desired DC voltage at the DC side of the converter
V_{nom}	: Nominal voltage level.
V_o	: Zero axis current
V_q	: q axis current
V_{q_meas}	: The actual measured q-axis voltage at the AC side of the converter
V_{q_ref}	: The desired d-axis voltage at the AC side of the converter
ΔV	: Voltage drop
θ_r	: Internal angle used for the voltage source converter control
ω	: The angular frequency in the network
ω_n	: Nominal angular frequency

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THE PLANNING OF LOW VOLTAGE DC DISTRIBUTION SYSTEMS UNDER MULTIPLE CRITERIA AND CONSTRAINTS

SUMMARY

DC-based electrical energy consumption and production have exhibited a notable growth in recent years. As the demand for DC-consuming home appliances increases each year, the need for a more efficient AC-DC conversion with higher power output has also increased. Electric vehicles and intercity railways represent additional examples of DC-consuming systems with significantly higher power demands. Moreover, there has been a rapid increase in the generation based on renewable energy resources which produces electrical energy in its DC form. All of these DC consumer and producer units must be interconnected to the network which is dominantly AC. Consequently, distribution system operators and researchers worldwide have been actively seeking more efficient methods to integrate these DC systems in to their AC networks. Several researches have proposed the utilization of low-voltage DC (LVDC) distribution systems which would eliminate the need for additional conversion steps. Additionally, various benefits enabled by low-voltage DC distributions, such as improved power quality, reduced voltage oscillations, and easier integration of renewable energy sources, can be advantageous for both customers and distribution system operators.

In this study, a comprehensive literature review is conducted to present the results of research in this field and the challenges that lie ahead. The structure of LVDC distribution networks is examined, and these networks are classified based on various aspects such as the number of poles, grid topology, and network configuration. The discussion covers the equipment used, grounding and protection methods, and voltage level selection methods in LVDC distribution networks. Pilot implementations of LVDC distribution networks around the world are described, with detailed discussions of the experiences gained. The study also outlines the methodology for performing cost/benefit analyses to assess the viability of investing in an LVDC distribution network from the perspective of a distribution system operator.

The study demonstrates that LVDC distribution systems can be an optimal alternative to conventional AC grids under certain circumstances. As the economic lifespan of power electronics improves and costs continue to decline, LVDC distribution has the potential to become a viable alternative in many cases.

ALÇAK GERİLİM DOĞRU AKIM DAĞITIM ŞEBEKELERİNİN ÇOKLU KRİTERLER VE KISITLAR ALTINDA PLANLANMASI

ÖZET

DC tabanlı elektrik enerjisi tüketimi ve üretimi son yıllarda kayda değer bir büyüme göstermiştir. DC tüketen ev aletlerine olan talep her yıl arttıkça, daha yüksek güç çıkışına sahip daha verimli AC-DC dönüşümüne olan ihtiyaç da artmıştır. Elektrikli araçlar ve şehirlerarası demiryolları, önemli ölçüde daha yüksek güç talepleri olan DC tüketen sistemlerin ek örneklerini temsil etmektedir. Ayrıca, DC formunda elektrik enerjisi üreten yenilenebilir enerji kaynaklarına dayalı üretimde de hızlı bir artış olmuştur. Tüm bu DC tüketici ve üretici birimlerin, ağırlıklı olarak AC olan ana şebekeye bağlanması gerekmektedir. Sonuç olarak, dünya çapındaki dağıtım sistemi operatörleri ve araştırmacılar, bu DC sistemleri AC şebekelere entegre etmek için aktif olarak daha verimli yöntemler veya sistemler aramaktadır. Çeşitli araştırmalar, ek dönüştürme adımlarına olan ihtiyacı ortadan kaldıracak alçak gerilim DC (AG DC) dağıtım sistemlerinin kullanılmasını önermiştir. Ayrıca, alçak gerilim DC dağıtım şebekelerinin sağladığı daha yüksek güç kalitesi, daha düşük gerilim salınımları ve yenilenebilir enerji kaynaklarının daha kolay entegrasyonu gibi çeşitli avantajlar hem müşteriler hem de dağıtım sistemi operatörleri için avantajlı olabilir.

Bu çalışmada, bu alandaki araştırmaların sonuçlarını ve önümüzdeki zorlukları ortaya koymak için kapsamlı bir literatür taraması yapılmıştır. AG DC dağıtım şebekelerinin yapısı incelenmiş ve bu şebekeler direk sayısı, şebeke topolojisi ve şebeke yapılandırması gibi çeşitli hususlara göre sınıflandırılmıştır. Tartışma, AG DC dağıtım şebekelerinde kullanılan ekipmanları, topraklama ve koruma yöntemlerini ve gerilim seviyesi seçim yöntemlerini kapsamaktadır. Dünya çapında LVDC dağıtım şebekelerinin pilot uygulamaları, elde edilen deneyimlerin ayrıntılı tartışmalarıyla birlikte anlatılmaktadır. Bir dağıtım sistemi operatörünün bakış açısından bir LVDC dağıtım şebekesine yatırım yapmanın faydalı olup olmadığını belirlemek için maliyet/fayda analizleri yapmaya yönelik metodoloji de sunulmuştur.

Çalışma, AG DC dağıtım sistemlerinin belirli koşullar altında geleneksel AC şebekelerine optimum bir alternatif olabileceğini göstermektedir. Çalışma sonucunda, güç elektroniği dönüştürücülerinin ekonomik ömrü arttıkça ve maliyetler düşmeye devam ettikçe, AG DC dağıtım şebekelerinin birçok durumda uygulanabilir bir alternatif olma potansiyeline sahip olduğu sonucu ortaya konmuştur.

1. INTRODUCTION

DC-based electrical energy consumption and production have exhibited a notable growth in recent years. As the demand for DC-consuming home appliances increases each year, the need for a more efficient AC-DC conversion with higher power output has also increased. Electric vehicles and intercity railways represent additional examples of DC-consuming systems with significantly higher power demands. Moreover, there has been a rapid increase in the generation based on renewable energy resources (RESs) which produce electrical energy in its DC form.

All of these DC consumer and producer units must be interconnected to the network which is dominantly AC. Consequently, distribution system operators and researchers worldwide have been actively seeking more efficient methods to integrate these DC systems in to their AC networks. Several researches have proposed the use of DC distribution systems which would eliminate the need for additional conversion steps. In recent decades, low-voltage DC (LVDC) distribution systems have emerged as a topic of interest. Numerous studies have sought to establish LVDC as a feasible alternative for distribution system operators, utilizing simulations, laboratory tests, and pilot implementations.

1.1 Purpose of Thesis

The purpose of this study is to conduct a comprehensive literature review on public LVDC distribution grids, in order to demonstrate their techno-economic feasibility, and to provide insight into the design of such grids considering multiple criteria and constraints. This study investigates various grid and converter topologies that can be implemented in LVDC distribution grids. The study also addresses the importance of standardization in public LVDC grids and ongoing standardization efforts in the area. Additionally, it highlights pilot and commercial implementations of LVDC distribution grids around the world. Then, a representative distribution network is simulated using a computational tool to further examine the aforementioned findings.

Finally, cost/benefit analyses are carried out to demonstrate techno-economic feasibility of the public LVDC distribution grids.

1.2 Literature Review

Low-voltage DC (LVDC) distribution systems have been the subject of numerous journal articles and conference papers. The literature covers a wide range of topics, including LVDC grid topologies, power electronic converters, protection systems, communication protocols, techno-economic feasibility, and the results of pilot implementation projects. Researches around the world have been striving to establish fundamental principles underlying the LVDC distribution systems via a combination of mathematical calculations, simulations and laboratory experiments.

Sannino, Postiglione, and Bollen [1] proposed a DC supply system for offices and commercial facilities. In their study, they compared the existing AC supply system with the proposed DC system, considering various DC voltage levels.

Salomonsson and Sannino [2] discussed the design process of a DC supply system for sensitive loads and presented the measurement results from a scaled laboratory test. In their study, the authors determined that DC supply system exhibits lower losses compared to an AC system.

Salonen, Kaipia, Nuutinen, Peltoniemi and Partanen [3] discussed various LVDC distribution system topologies, LVDC system connections, grounding arrangements in LVDC distribution systems, utilization of existing cables in LVDC systems, power electronic converters and electrical safety. The authors of the study also performed a cost/benefit analysis for the renovation of an actual distribution network to LVDC distribution.

In their publication [4], Hakala, Lähdeaho, and Järventausta examined the potential utilization of LVDC distribution in a large-scale distribution system operator’s network. The authors provided a method to calculate the power transfer capacity of LVDC distribution systems in their study. Additionally, they asserted that LVDC distribution systems can replace all MVAC branches that are equipped with a single transformer.

Amin, Arafat, Lundberg and Mangold [5] provided a comparison of losses in some common household appliances. In their study, the authors determined that the utilization of 48 V DC can eliminate additional conversion steps, thereby resulting in lower losses.

Kaipia, Salonen, Lassila and Partanen [6] examined the utilization potential of LVDC distribution systems from various aspects such as power quality, power transfer capacity and losses.

In their publications [7] and [8], the authors introduced technical specifications for LVDC distribution systems which were the findings of an ongoing project at the time of their study.

Hur and Baldick [9] conducted a cost/benefit analysis to evaluate the feasibility of substituting an existing AC distribution network with an LVDC distribution network. The authors utilized the Discounted Cash Flow (DCF) method to derive the Net Present Values (NPV) of several LVDC distribution system topologies.

Afamefuna, Chung, Hur, Kim, and Cho explored the feasibility of implementing LVDC distribution systems for electrification of rural areas in South Korea in their publication [10]. The authors employed simulation tools to gather the required data for cost/benefit analysis and established that LVDC distribution can have a NPV equal to or lower than AC distribution. Additionally, the authors asserted that as the costs of power electronics decrease, LVDC can become a more feasible solution.

In [11], an efficiency comparison is presented between AC and DC distribution systems, considering various topologies for DC systems.

Niiranen and Routimo [12] reported the measurement outcomes from a back-to-back converter-fed island microgrid in Finland. The authors described the topology implemented in their system and assessed the measurement results from various aspects, including voltage stability, system reliability, harmonics, and power quality.

In their publication [13], the authors introduced a research site for LVDC distribution networks. LVDC distribution network implemented in the research site consists of one rectifying substation and three inverters to supply the customers. The DC system operates at a voltage of ±750 V and is powered by a 20/0.4 kV transformer. In their study, the authors discussed the system design, control methods of converters, communication network, response during faults, power quality and protection of both customer and DC networks. The authors also presented various measurement results from the research site.

In their publication [14], the authors introduced and described a pilot implementation of an LVDC distribution system in an island which was funded by Korean Electric Power Corporation (KEPCO).

In their publication [15], the authors presented an LVDC distribution network in Korea and described the system in detail. The authors presented various measurement results and several actual photographs from the implementation site.

In publication [16], the design and construction plan of an LVDC distribution network is presented, along with a discussion of the potential of LVDC distribution systems using techno-economic analysis. In a related paper [17], the authors introduce the implemented LVDC distribution grid, based on the findings of publication [16]. The authors presented various measurement results and discuss their experiences with problems encountered at the research site.

Jager, Bos, Melnik and Brand [18] presented the details of the first public DC distribution network in the Netherlands, including the development process of the LVDC distribution system according to the utility's specifications, as well as the various components to be used in the system and simulation results. The authors reported that the first DC substation is operational, and the first customers were expected to be connected in 2018. Additionally, the authors shared several photographs from the implementation site.

In publication [19], the authors introduced DC power quality indices for modern MV and LVDC systems. In their study, the authors used measurements from six actual DC projects and laboratory tests to verify the proposed methods.

In publication [20], the authors introduced a methodology for the planning and evaluation of LVDC systems in buildings. In their study, the authors also included a case study to validate the proposed method.

In their publication [21], Hakala, Kaipia and Alaperä presented their experiences from an implementation and operation of a battery energy storage system (BESS) integrated distribution network. The authors also discussed the possibility of utilization of LVDC distribution systems in such networks.

In their publication [22], the authors discussed the potential of utilization of multi-terminal LVDC distribution systems to enhance the integration of plug-in electric vehicles into existing distribution networks.

In their publication [23], the authors aimed to identify techno-economically feasible voltage levels for LVDC distribution systems. They presented optimization methods to determine these voltage levels, and found that voltage levels above 600 V DC are feasible for various applications of LVDC distribution systems.

Emhemed and Burt [24] presented a new protection scheme for LVDC distribution networks. The authors asserted that the proposed scheme provides swift and selective protection necessary in LVDC distribution systems.

Emhemed, Fong, Fletcher and Burt [25] introduced a novel protection strategy for LVDC networks. The authors validated the proposed method through an actual experimental setup of a low-power LVDC circuit.

Salonen, Nuutinen, Peltoniemi, and Partonen [26] proposed a protection scheme for LVDC distribution networks taking into account various technical aspects.

In their publication [27], the authors examined how the choice of voltage level impacts the earthing/protection strategies in LVDC networks.

In their study [28], the authors proposed a selective protection strategy for LVDC distribution systems. The proposed scheme was validated by the authors through the use of simulation tools, and the resulting simulation results were presented in their study.

Salehi, Taher, Sadeghkhani, and Shahidehpour [29] proposed a protection strategy for LVDC microgrids based on a poverty index. The possibility of utilization of the proposed method in public LVDC networks should be considered.

In their publication [30], the authors proposed a protection system for radial LVDC distribution systems that uses an inverter and DC circuit breakers. In their study, the authors validated the proposed method through experimental tests.

In their publication [31], the authors proposed a fuse-based protection strategy for LVDC networks. They discussed both the limitations and advantages for use of fuses in LVDC networks.

Jin and Chen [32] proposed the utilization of superconducting fault-current-limiting cables and magnetic energy storage devices in LVDC distribution systems. In their study, the authors conducted an analysis of the ground faults in such systems and discussed the corresponding protection methods.

In their publication [33], the authors discussed two types of converter topologies to be employed in LVDC distribution networks. In their study, the authors presented a comparison of efficiency, power quality and various technical aspects between the two converter topologies.

In their publication [34], the authors delved into the design process of customer-end inverters for LVDC distribution systems. Through their study, the authors determined that, from an efficiency perspective or in terms of losses, higher inductance values in the LC filter and lower switching frequencies are desirable in the design of customer-end inverters.

Wang, Fu and Wong [35] introduced an AC/DC converter for hybrid AC/LVDC grids. In their study, the authors also proposed a novel droop-based control technique for the converter. The authors presented simulation and experimental measurement results to demonstrate the effectiveness of the converter.

Zhong, Finne, and Hollida [36] presented a comparison of power losses between a multi-modular converter (MMC) and an insulated-gate bipolar transistor (IGBT) based 2-level converter, for their application in LVDC distribution systems.

Cui, Hu and Zhao [37] presented a novel converter for LVDC distribution networks. The converter proposed by the authors features bipolar operation capability, which facilitates the integration of distributed generation units into LVDC distribution systems. In their study, the authors validated the proposed converter through simulation and experimental results.

In their publications [38] and [39], the authors introduced a novel converterless integration method for incorporating BESS into LVDC distribution systems. The authors presented the control method for the BESS and shared their experiences acquired from the on-site implementation of the proposed method. The authors also presented several measurement results of the proposed control method.

In their publication [40], the authors discussed the design process, lifetime cost analysis and implementation possibilities of a modular inverter for LVDC distribution systems.

Nilsson and Sannino [41] presented methods for modelling loads in LVDC distribution systems in steady state and transient analyses. In their study, the authors utilized measurement results from several loads supplied with low voltage DC to develop the proposed methods.

Pinomaa, Ahola, Kosonen and Nuutinen [42] proposed the utilization of DC power line communication method for implementation in LVDC distribution systems.

In their publication [43], the authors discussed different protection requirements and methods for LVDC distribution systems and presented measurement results from an LVDC distribution laboratory prototype.

In their publication [44], the authors discussed the necessity of galvanic isolation in LVDC distribution systems. In their study, the authors also presented an output LC filter design for an AC/DC converter.

In their publication [45], the authors discussed possible implementation of galvanic isolation in LVDC distribution systems.

Weiss, Ott, and Boeke [46] discussed the potential utilization of LVDC distribution in buildings. The authors presented a laboratory prototype of an LVDC distribution network and measurement results in their study. Through their analysis, the authors determined that the LVDC system's efficiency is 5% higher than the AC system and the energy conversion losses are lower in the DC system for photo-voltaic generation units.

Sannino, Postiglione and Bollen [47] discussed the feasibility of LVDC distribution systems for offices and commercial facilities.

In their publication [48], the authors discussed high resistance faults in LVDC grids and proposed a new overcurrent relay for fault detection in such conditions.

Bhargav, Bhalja and Gupta [49] proposed a novel fault detection and localization method for LVDC microgrids.

In their publication [50], the authors presented a review of LVDC distribution networks for household use. In their study, the authors discussed the efficiency, possible grid topologies and overall advantages of LVDC distribution systems. The authors also presented existing pilot implementations of LVDC distribution systems at the time of their study.

In their publication [51], the authors presented a Metal-Oxide Semi-conductor Field-Effect Transistor (MOSFET) based MMC for their applications in LVDC distribution systems. In their study, the authors conducted a comparison of efficiency between several converter topologies.

Lazzari and Piegari [52] introduced a novel hybrid DC circuit breaker for use in LVDC distribution systems. In their study, the authors discussed the operational principle and component dimensioning of the proposed breaker. Additionally, the authors presented measurement results obtained from the prototype of the device.

In their publication [53], the authors introduced a method for controlling bipolar LVDC distribution systems under asymmetrical operations. In their study, the authors provided a theoretical analysis of the proposed method and also presented the measurement results from their test system.

In their publication [54], the authors proposed a novel solid state type circuit breaker for implementation in LVDC distribution networks. In their study, the authors presented experimental results to validate the effectiveness of the proposed circuit breaker.

Table 1.1 : LVDC Distribution Systems Literature Review

Study	Reference	Purpose
Fundamental Concept	[1]	Investigate whether DC distribution systems are practical and applicable
	[2], [47], [50]	Study the utilization potential of LVDC distribution in buildings
	[3]	Review of LVDC distribution systems for replacing conventional AC systems
	[4]	Investigate the utilization of an LVDC distribution network by DSOs
	[5]	Comparison of 230 V AC distribution against LVDC distribution
	[6], [46]	Examine the utilization potential of LVDC distribution systems
	[7], [8]	Propose technical specifications for LVDC distribution systems
Cost/Benefit Analysis	[9]	Investigate cost reductions from implementing LVDC distribution systems.
	[10]	Carry out a cost/benefit analysis for LVDC distribution networks
	[11]	Investigate the efficiency of LVDC distribution networks
Pilot or Demonstration	[12]	Discuss the experiences from a pilot LVDC grid
	[13]	Discuss the system design of a pilot LVDC distribution grid
	[14]	Introduce a pilot LVDC distribution grid in an island
	[15]	Review and discuss constructing an actual LVDC distribution system
	[16]	Introduce the design and construction of a pilot LVDC distribution system in Korea
	[17]	Application of a pilot LVDC distribution system in Korea
	[18]	Discuss the design of a public LVDC distribution grid
	[19]	Discuss the DC power quality in real LVDC distribution systems
	[20]	Propose a method for planning LVDC distribution systems in buildings
	[21]	Discuss the experiences from a pilot LVDC distribution system in Finland
	[22]	Discuss the potential utilization of LVDC distribution systems
Protection and Grounding	[23]	Propose a voltage selection method based on grounding, protection and safety
	[24], [25]	Propose a novel protection scheme based on converters

Table 1.1 : (continued) LVDC Distribution Systems Literature Review

Study	Reference	Purpose
Protection and Grounding	[26], [43], [54]	Propose a protection scheme based on fuses and breakers
	[27]	Examine the effects of voltage levels on grounding and protection
	[28], [48], [49], [52]	Propose a novel protection system for LVDC distribution systems
	[29]	Propose a protection system for LVDC grids
	[30]	Propose a novel protection system based on converters
	[31]	Propose a protection scheme for LVDC distribution networks that utilize fuses
	[32]	Propose a protection scheme for LVDC distribution systems based on a superconducting cable
Power Electronic Converters	[33], [55]	Evaluation of converter topologies for LVDC distribution systems
	[34], [51]	Propose a design of Inverter for LVDC distribution systems
	[35], [53]	Examine the operation and control of a converter for LVDC distribution systems
	[36]	Investigation of high efficiency inverters for LVDC distribution systems
	[37]	Propose a novel converter topology for LVDC distribution systems
Energy Storage	[38], [39], [40], [41]	Examine, study and investigation of BESS integrated LVDC distribution systems
Communication	[42]	Propose a power line based communication for LVDC distribution systems
Galvanic Isolation	[44], [45]	Investigate and examine the isolation requirement in LVDC distribution systems

2. STRUCTURE OF THE LVDC DISTRIBUTION GRIDS

LVDC distribution grids could be described or classified based on several aspects of the network structure such as including but not limited to number of poles, grid topology and network configuration. Such classification and labeling are crucial for conducting various analyses and comparisons in the upcoming sections of the study, as they help eliminate the risk of confusion.

2.1 Number of Poles

LVDC distribution grids could be designed as either unipolar or bipolar systems, as shown in Figure 2.1 and Figure 2.2. Unipolar systems have only one available operating voltage, while bipolar systems have three different available operating voltages in the network. Customers in a unipolar LVDC distribution grid can utilize the V_{dc} voltage level while the customers in a bipolar LVDC distribution grid can utilize the $+V_{dc}$, $-V_{dc}$, and $2V_{dc}$ voltage levels, which provide more flexibility.

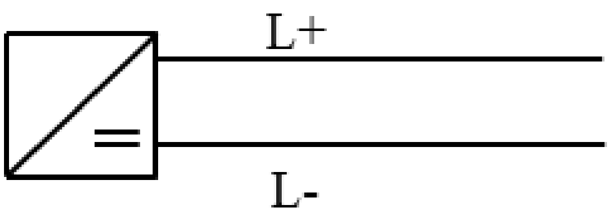

Figure 2.1 : Unipolar LVDC network.

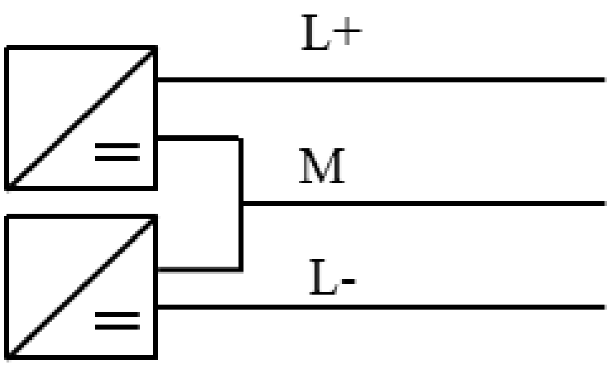

Figure 2.2 : Bipolar LVDC network.

Unipolar systems are typically denoted with a nominal voltage level accompanied by an unsigned V_{dc} annotation, whereas bipolar systems are conventionally denoted with a ± sign, such as ± V_{dc}. For example, a bipolar LVDC distribution grid utilizing the 750 V DC voltage level is denoted as ±750 V DC.

Unipolar grids consist of one positive pole (L+) and one return (L-) conductor, whereas bipolar grids consist of one positive, one negative and one middle (M) conductor. In a unipolar grid, customer inverters are required to connect between the positive pole and return conductor. In contrast, customer inverters in a bipolar grid can connect between the positive pole and middle conductor, between the negative pole and middle conductor, or between positive and negative poles, thereby enabling the utilization of the full $2V_{dc}$ voltage level. It can be observed that in a unipolar grid, losses are limited to the positive pole conductor alone, while in a bipolar grid, losses occur on both the positive and negative pole conductors. Furthermore, the current in the middle conductor in a bipolar grid is equal to the difference in current between the two poles, which can result in additional losses. Nevertheless, due to the fact that power transmission in a bipolar grid occurs across two poles, the currents carried are half the magnitude compared to a single pole in a unipolar grid. This leads to reduced losses for the same nominal power, even though there are losses in both the positive and negative pole conductors, as well as additional losses in the middle conductor.

It can be noted that unipolar grids can be constructed using a straightforward 2-level voltage source converter (VSC). In contrast, bipolar grids can be established using either a 3-winding transformer and two 2-level VSCs, as depicted in Figure 2.3, or by employing a specialized neutral point-clamped VSC, as depicted in Figure 2.4.

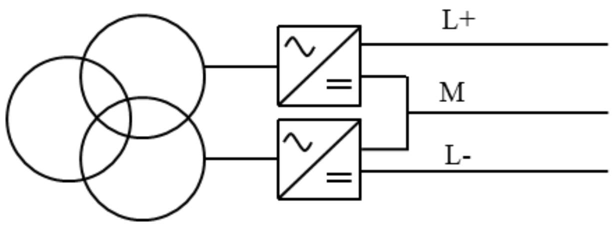

Figure 2.3 : Bipolar LVDC network with a 3-winding transformer.

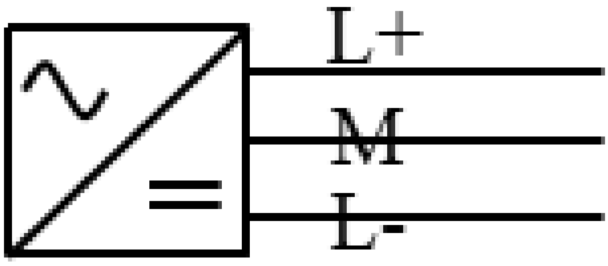

Figure 2.4 : Bipolar LVDC network with a neutral point-clamped converter.

Bipolar grids offer certain distinct advantages, including greater flexibility, lower inverter ratings and losses, as previously discussed. However, it should be noted that control and protection of bipolar grids can be more challenging compared to unipolar grids. This is due to the fact that maintaining voltage balance across the two poles is more complex in bipolar grids, as different numbers of customers may be connected to the positive and negative poles, thereby requiring sophisticated control and protection measures to ensure safe and reliable operation of the network.

2.2 Grid Topology

LVDC distribution grids can be categorized into three distinct topologies based on the infrastructure of the DC network, namely Point-to-Point, Link Type, and Full-DC. The choice of topology determines how customers are supplied with electrical power or how they are connected to the network. In the present study, it is assumed that LVDC distribution grids are constructed using a medium to low voltage transformer, together with a rectifier that is utilized to obtain the desired DC voltage level.

2.2.1 Point-to-point LVDC distribution

The customers in a Point-to-Point LVDC distribution network are supplied electrical power via a single inverter, as shown in Figure 2.5. This topology represents the simplest means of achieving the fundamental advantages of LVDC distribution grids. If the AC-to-DC and DC-to-AC conversion takes place in the same converter station, this topology may also be referred to as a Back-to-Back LVDC distribution grid.

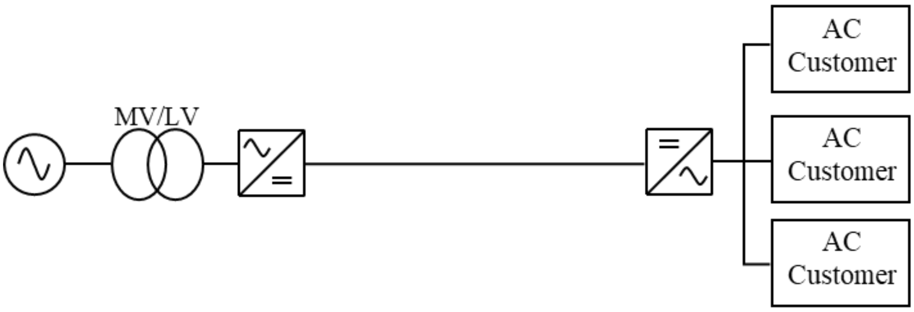

Figure 2.5 : Point-to-Point LVDC Distribution Topology.

2.2.2 Link type LVDC distribution

In a Link Type LVDC distribution grid, customers are supplied electrical power via their individual inverters, as Figure 2.6 illustrates. This topology offers certain advantages over the Point-to-Point topology, such as improved reliability, enhanced power quality, and higher efficiency. However, the increased investment costs and greater complexity of control and protection are among the drawbacks associated with this topology.

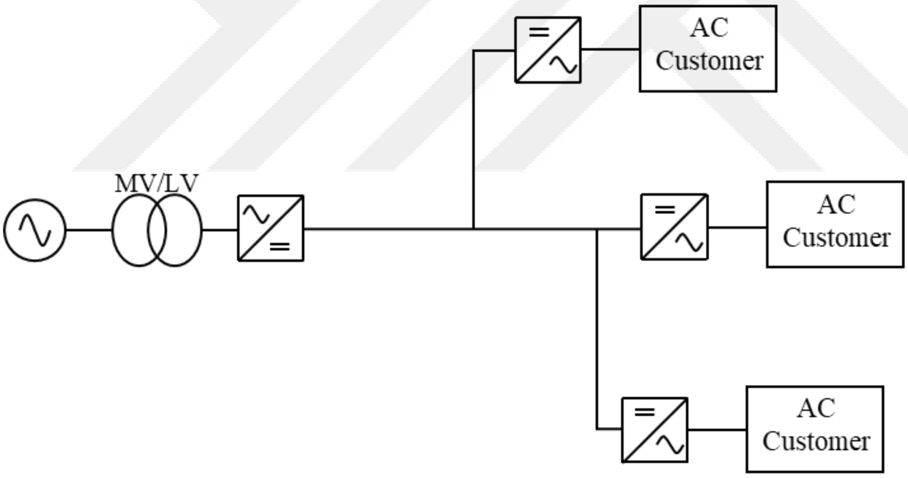

Figure 2.6 : Link Type LVDC Distribution Topology.

2.2.3 Full-DC LVDC distribution

In a Full-DC LVDC distribution topology, it is assumed that all customers are supplied DC electrical power, as shown in Figure 2.7. The Full-DC topology is particularly well-suited for deployment in a smart campus or industrial area where there is a high demand for electrical power from DC-based consumption.

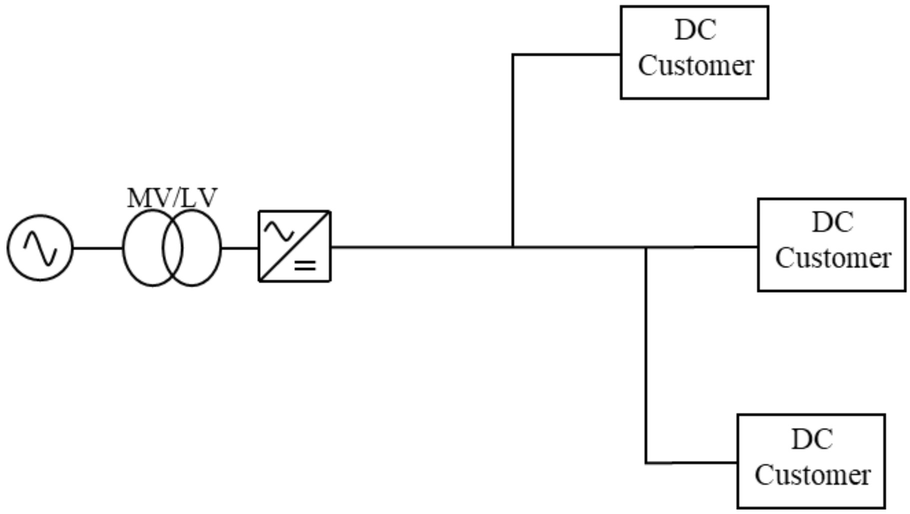

Figure 2.7 : Full-DC LVDC Distribution Topology.

2.3 Network Configuration

Configuration of an LVDC distribution grid determines how the network is connected to main grid or other grids. The radial configuration is depicted in Figure 2.8, the Interconnected Unloop is illustrated in Figure 2.9 and the Ring Configuration is illustrated in Figure 2.10. It should be noted that the figures presented in this section are intended for illustrative purposes only, and do not provide comprehensive technical explanations of the various configurations discussed.

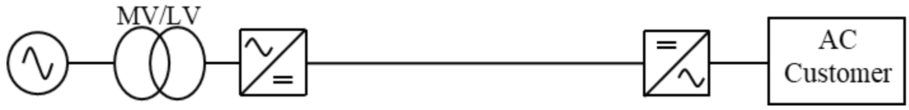

Figure 2.8 : Radial Configuration of the LVDC Distribution Grids.

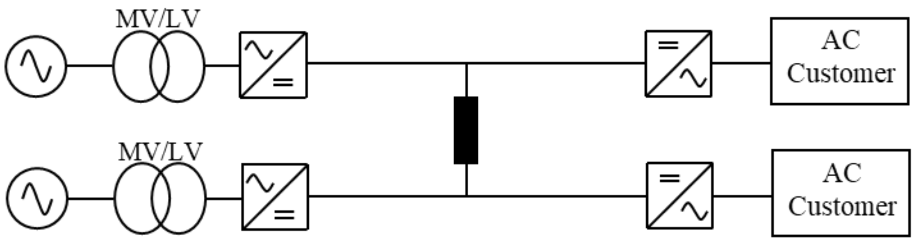

Figure 2.9 : Interconnected Unloop Configuration of the LVDC Distribution Grids.

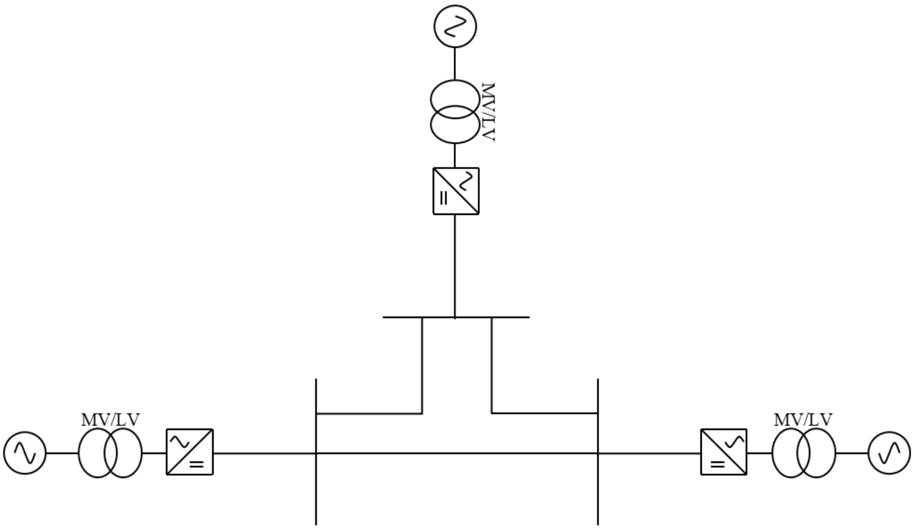

Figure 2.10 : Ring Configuration of the LVDC Distribution Grids

Radial configuration is a well-established topology in conventional grids, as it offers a relatively simple and straightforward means of control and protection, as well as lower complexity and initial investment costs compared to other topologies. However, if a fault occurs in any section of the grid, it can compromise the reliability of the entire network and potentially result in supply interruption for all customers. Ring configuration provides the highest reliability compared to three other configurations. However, more sophisticated control and protection techniques are required for safe operation of a ring grid. Implementing such configuration also requires higher investment costs. Interconnected unloop configuration is a simple and economic way to achieve higher reliability for LVDC distribution grids. It provides less reliability compared to ring configuration and requires more complex protection and control strategy compared to radial configuration. Regardless of the topology chosen for the LVDC distribution grid, distribution system operators (DSOs) must carefully evaluate the various techno-economic challenges associated with each possible configuration during the design process. This requires a comprehensive analysis of factors such as investment costs, operational efficiency, reliability, control and protection requirements, and other technical considerations. Ultimately, the goal is to develop a safe, efficient, and techno-economically feasible LVDC distribution grid that meets the specific needs and requirements of the customers, while also ensuring the overall reliability of the grid.

3. EQUIPMENT AND OPERATION

3.1 Power Electronic Converters in LVDC Distribution Grids

Power electronic converters are essential components of LVDC distribution grids, as they convert the AC voltage received from the main grid into the desired DC voltage waveform required by the DC network. Essentially, two types of power electronic converters are used in LVDC distribution grids. As aforementioned, AC/DC converters namely rectifiers convert the AC voltage received from the main grid into the desired DC voltage waveform required by the DC network. In some cases, DC/DC converters may also be employed to change the DC voltage level to meet specific customer requirements, such as voltage matching or isolation.

3.1.1 Diode bridge rectifier

The diode bridge rectifiers are considered to be the most straightforward and uncomplicated topology for obtaining a DC voltage output. It comprises of 6 diodes that are arranged in a bridge configuration, permitting current to flow in a single direction as depicted in Figure 3.1.

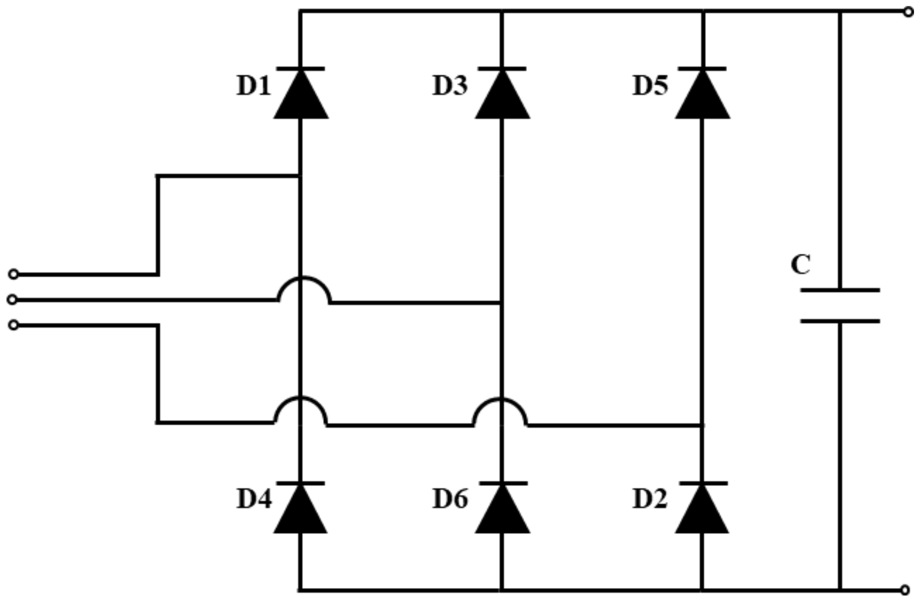

Figure 3.1 : Diode Bridge Rectifier

The diode bridge is considered to be a cost-effective rectifier topology due to its simplicity and relatively low power losses. In addition, it operates using passive elements, thereby eliminating the need for control methods. However, the absence of control also implies that the diode bridge rectifiers have limited ability to control the current/voltage in the DC network. This limitation can lead to adverse effects on the DC network when voltage deviations occur in the main grid, as the diode bridge rectifiers cannot control the DC voltage in response. Additionally, diode bridge rectifiers cannot provide bi-directional power flow capability since they permit the current to flow in a single direction. Bi-directional power flow is an essential capability in order to allow the integration of RESs and distributed generation.

In order to eliminate voltage ripples in the DC network produced by diode bridge rectifiers, capacitors must be employed. Correct dimensioning of the capacitors depends on various factors such as maximum permissible DC voltage drop, desired power losses and the inverter topology [55]. The minimum size of capacitance required in the DC network for the implementation of diode bridge rectifiers can be calculated as given in equation 3.1 where C_{rec} is the capacitor size [56].

$$C_{rec} = 30 \frac{\mu F}{kW} \tag{3.1}$$

One of the challenges associated with using diode bridge rectifiers in LVDC distribution grids is the startup of the DC network. To ensure that the DC network is fully operational, network capacitors must be charged to regulate the DC voltage. However, during the charging of the capacitors, the inability of the diode rectifier to control the current can result in dangerous voltage and current spikes in the DC network. This limitation presents another disadvantage for the diode bridge rectifier topology thereby limiting the possibility of utilization in LVDC distribution grids.

3.1.2 Thyristor bridge rectifier

Thyristor bridge is a controlled rectifier topology which can be utilized to overcome many disadvantages of the diode bridge rectifiers such as control capability over power flow and startup of the network. Thyristor bridge rectifiers utilize thyristor type semiconductors, which can be triggered to begin conduction by applying a high logic signal to their gate electrode. This allows current to flow in a similar manner as a diode.

A 6-pulse thyristor bridge rectifier is shown in Figure 3.2 as an example. In a 6-pulse thyristor bridge rectifier, the thyristors are usually fired in a sequence where the second thyristor (T2) is triggered 60° electrical degrees after the first thyristor (T1), the third thyristor (T3) is triggered 60° after T2 and so on. The capability to permit the current as desired allows thyristors bridge rectifiers to control DC voltage output.

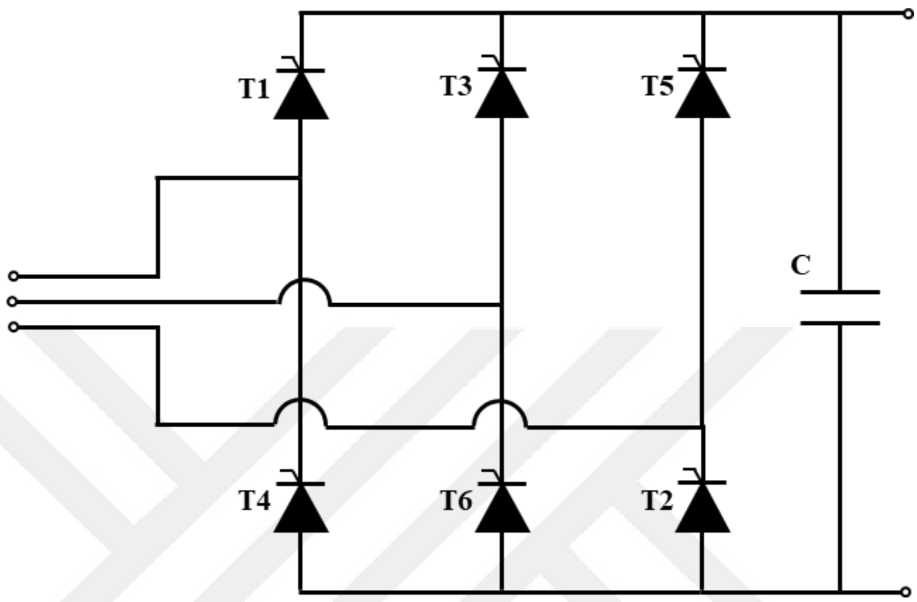

Figure 3.2 : Thyristor Bridge Rectifier.

However, thyristor bridge rectifiers are line commutated converters (LCC). Thyristors require the AC voltage waveform to cross the zero voltage threshold in order to stop conducting hence limiting the control capability. Also, thyristor bridge rectifiers can't control the reactive power flow in the AC side of the converter. They require a certain amount of reactive power for operation, proportional to the active power they control. Additionally, bi-directional power flow cannot be achieved with the utilization of thyristor bridge rectifiers in LVDC distribution grids.

Thyristor bridge rectifiers can be a better solution compared to diode bridge rectifiers in LVDC distribution grids as they provide certain level of control capability over power flow. However, the VSCs must be utilized in order to achieve full-control over the network as discussed in the next section of the study.

3.1.3 Voltage source converters

The denotation "Voltage Source Converter" is a general term for converters that comprise of semi-conductors such as IGBT or MOSFET and employs specialized control techniques. As an example, a two-level VSC circuit diagram is illustrated in

Figure 3.3. However, three-level or modular multi-level converters (MMC) can also be utilized to form voltage source converters.

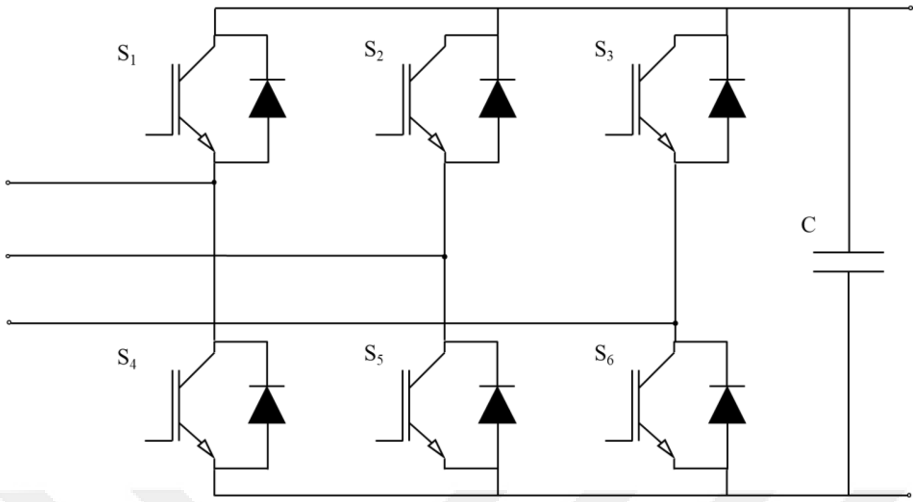

Figure 3.3 : IGBT Based Two-Level Voltage Source Converter.

In contrast to thyristors, IGBTs have the capability of self-commutation, which enables them to stop conducting, independent from the voltage waveform, when a low logic signal is applied.

Voltage source converters are capable of bi-directional power flow which enables them to operate both as an inverter and as a rectifier. Nevertheless, without the sophisticated control techniques, which will be described in the later sections of the study, they are limited to functioning as basic 6-pulse inverters. Voltage source converters can control AC voltage, DC voltage, active power, reactive power and frequency at the two sides of the converter, depending on the control method selected for the converter. Aforementioned capabilities enable voltage source converters to outweigh the cost advantages of both diode and thyristor-based rectifiers. Furthermore, with the declining costs of semiconductors, diode and thyristor-based converters lose their greatest advantage, which is the costs.

VSCs also require LC or LCL filters to obtain the sinusoidal AC voltage which presents additional power losses. The optimal filter design can be obtained either through the transfer function of the system or through trial-and-error methods using simulation tools. However, the filters must generate low active power losses, avoid voltage or current harmonics, and prevent frequency resonances in the system.

3.1.3.1 Grid-following control

Grid-following (GFL) control is a technique in which the voltage phase angle is extracted from the AC side of the converter and utilized, or "followed," by the converter. Phase angle of the voltage is obtained using the phase-locked loop (PLL) control. PLL control employs the Park Transformation, or abc-dq0 transformation, which is given in equation 3.2 where, V_a, V_b and V_c are the three phase voltages at the AC side of the converter; Vd is the direct (d) axis voltage, Vq is the quadrature axis voltage, V_0 is the zero axis voltage and θ is the phase angle of the voltage at the AC side of the converter.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.2}$$

Figure 3.4 illustrates a basic schematic of a PLL. Auxiliary functions such as frequency limiting or integral resetting are not included in the figure. The PLL serves as a tool for the converter to continuously track the voltage phase angle. Under minor disturbances such as load changes or remote faults, the PLL must be able to maintain the desired operation. However, during major disturbances such as faults that occur near the converter, the PLL may lose its ability to track the voltage phase angle.

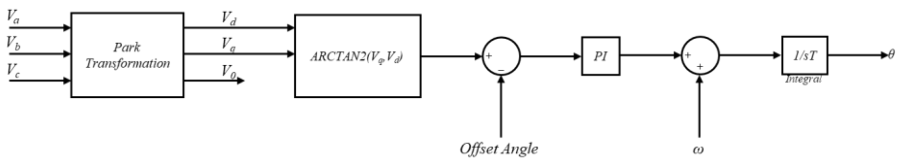

Figure 3.4 : Phase Locked Loop.

The PLL is a critical component in the GFL control method. The inner loop of the control logic utilizes the voltage phase angle, which is extracted using the PLL, to perform Park transformation on the phase voltages and currents. Park transformation simplifies the control by utilizing the two-axis rotating reference frame rather than 3 sinusoidal waveforms. During the Park transformation process, an offset angle of π is typically incorporated into the PLL in order to optimally position the d and q axes. This strategic alignment enables the d-axis current to regulate active power, DC voltage, and frequency, while the q-axis current manages reactive power and AC voltage.

The previously mentioned GFL control employs the Space Vector Pulse Width Modulation (SV-PWM) method. This approach facilitates the independent control of d-axis and q-axis currents, thereby enabling the decoupled management of reactive power and active power within the network [57]. The Park transformation is employed to derive the necessary d-axis and q-axis currents and voltages, which are essential components of the GFL control methodology. The required reference phase angle for Park transformation is obtained through PLL. If DC voltage is desired to be controlled in the network, the required control loop is shown in Figure 3.5 where:

- **V_{dc_ref}**: The desired DC voltage at the DC side of the converter.
- **V_{dc_meas}**: The actual measured DC voltage at the DC side of the converter.
- **I_{d_ref}**: The desired d-axis current (obtained from the previous PI control) at the AC side of the converter.
- **I_{d_meas}**: The actual measured d-axis current at the AC side of the converter.
- **V_{d_meas}**: The actual measured d-axis voltage at the AC side of the converter.
- **I_{q_meas}**: The actual measured q-axis current at the AC side of the converter.
- **L**: Filter inductor size at the AC side of the converter in Henry.
- **V_{d_ref}**: The desired d-axis voltage at the AC side of the converter.
- **ω**: The angular frequency in the network (2π*frequency)

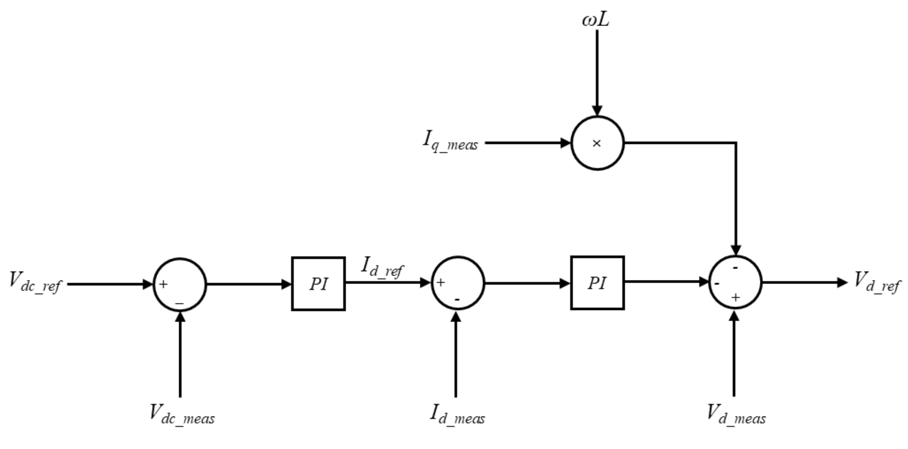

Figure 3.5 : DC Voltage Control Loop.

The DC voltage control loop is given as an example for GFL control method. As previously mentioned, d-axis current can regulate the active power, DC voltage and frequency while q-axis current can regulate the reactive power and AC voltage. The AC voltage control is illustrated in Figure 3.6, where:

- $\mathbf{V_{ac\_ref}}$: The desired AC voltage at the AC side of the converter.
- $\mathbf{V_{ac\_meas}}$: The actual measured AC voltage at the AC side of the converter.
- $\mathbf{I_{q\_ref}}$: The desired q-axis current (obtained from the previous PI control) at the AC side of the converter.
- $\mathbf{V_{q\_meas}}$: The actual measured q-axis voltage at the AC side of the converter.
- $\mathbf{V_{q\_ref}}$: The desired d-axis voltage at the AC side of the converter.

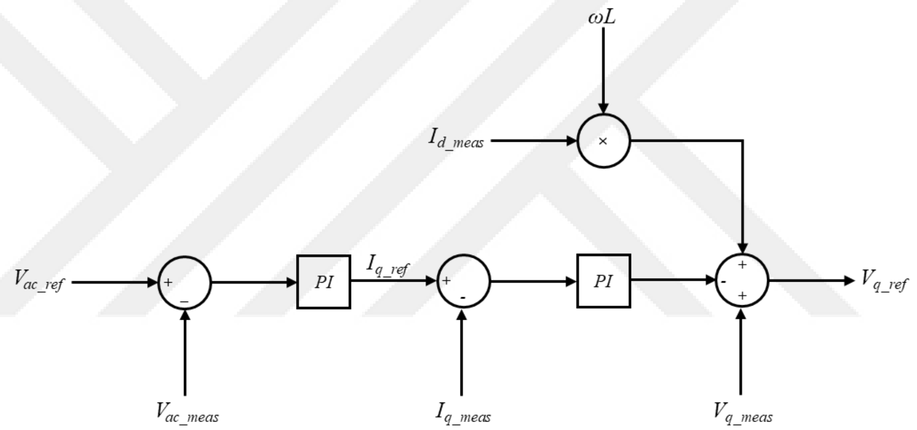

Figure 3.6 : AC Voltage Control Loop.

The final voltage reference, V_{d_ref} and V_{q_ref} are utilized in PWM to obtain the required gate signals for the IGBTs in the converter. Within the PWM technique, a carrier signal exhibiting a frequency equivalent to the switching frequency of the converter is compared against a sinusoidal waveform, thereby generating the necessary gate signals for the IGBTs. The necessary sinusoidal waveforms for PWM, representing phase voltages, are derived through the application of the Inverse Park Transformation on d and q-axis voltage references.

The d-axis and q-axis currents can be effectively employed to accomplish any control mode in conjunction with one another, provided that the V_{d_ref} and V_{q_ref} values are obtained from the respective control loops. Nonetheless, in order to obtain the required DC voltage of LVDC distribution grids, DC voltage control must be employed in AC/DC converter of the network. Generally, reactive power control is used alongside

DC voltage control because zero reactive power is desired during the normal operation of the system. However, the converter's reactive power capability can be utilized to provide reactive power support during faults in the AC system.

The active and reactive power control loops are depicted in Figure 3.7 and Figure 3.8 respectively, where:

- $\mathbf{P_{ref}}$: The desired active power at the DC side of the converter.
- $\mathbf{P_{meas}}$: The actual measured active power at the DC side of the converter.
- $\mathbf{Q_{ref}}$: The desired reactive power at the AC side of the converter.
- $\mathbf{Q_{meas}}$: The measured reactive power at the AC side of the converter.

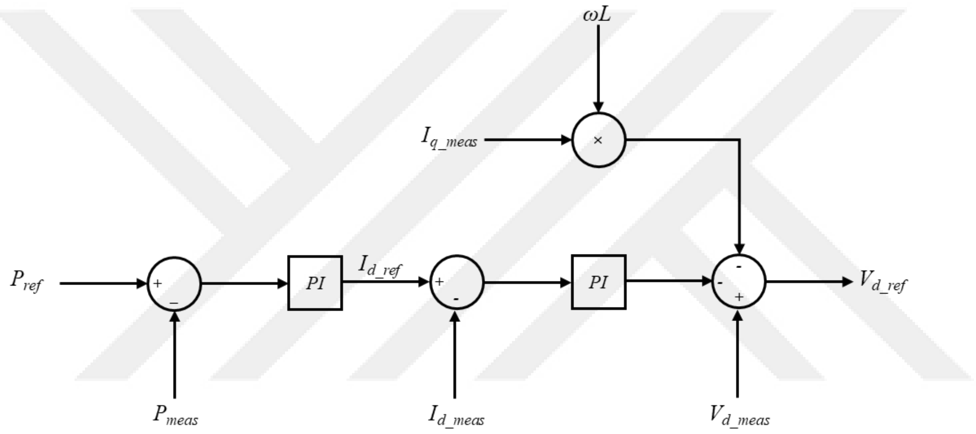

Figure 3.7 : Active Power Control Loop.

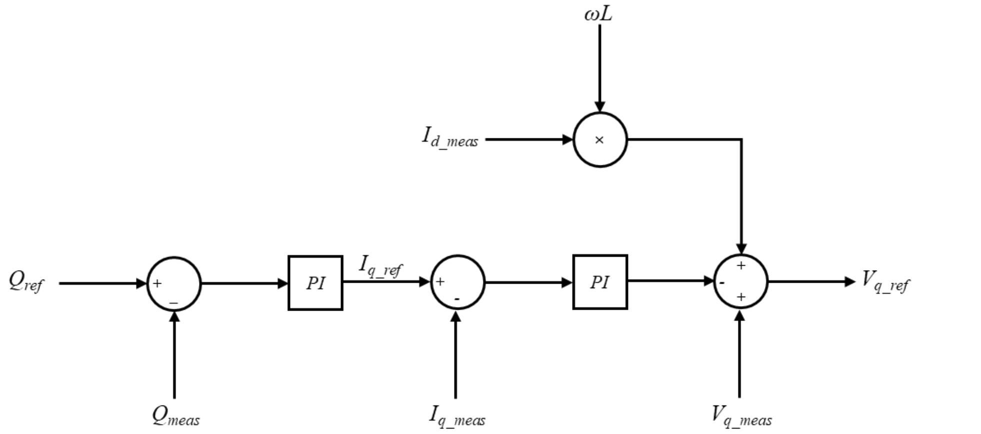

Figure 3.8 : Reactive Power Control Loop.

Diagram of a generic VSC is given in Figure 3.9 where; Us is the DC voltage source, Rd is the DC circuit resistance, Id is the DC current, Ud is the DC voltage. The capacitor on the DC side of the converter stabilizes the DC voltage. The inductor on the AC side of the converter stabilizes the AC current and it controls active and reactive power output from the converter. The diagram is adopted from IEC 62543 Technical Report.

As previously mentioned, VSC can provide bi-directional power flow, wherein the VSC functions as an inverter when $I_d \times U_d$ has a positive value and as a rectifier when $I_d \times U_d$ has a negative value. VSC can also operate in capacitive and inductive modes independent of the active power flow direction. If the imaginary part of $I_L \times U_L$ has a positive value, the VSC injects reactive power into the AC side; conversely, if the imaginary part of $I_L \times U_L$ has a negative value, the VSC absorbs reactive power from the AC side of the converter. The term 'voltage sourced converter' is employed because the VSC's function relies on a voltage source on the DC side. If the AC side of the converter connects to a passive network, VSC can only operate as an inverter.

Another important aspect to consider regarding VSCs is their active and reactive power control principles. When the phase angle of the VSC output voltage leads the AC grid voltage, the VSC operates as an inverter. Conversely, when the phase angle of the VSC output voltage lags the AC grid voltage, the VSC operates as a rectifier.

When the VSC output voltage is higher than the AC grid voltage, VSC will operate in capacitive mode. Conversely, When the VSC output voltage is lower than the AC grid voltage, VSC will operate in inductive mode. Because capacitive and inductive are relative terms, they are utilized from the perspective of the AC grid. The VSC injects reactive power into the AC grid in capacitive mode and absorbs reactive power from the AC grid in inductive mode.

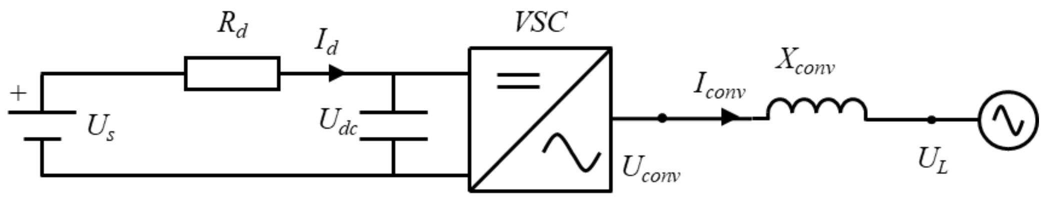

Figure 3.9 : Generic Voltage Source Converter.

3.1.3.2 Grid-forming control

Our modern-day power system relies on synchronous generators which generate electrical energy at a pre-determined frequency. All synchronous machines, in fact, all electrical energy sources in a power system must produce the electrical energy at system frequency or convert it to the system frequency. System frequency determines how balanced the supply and demand are in a power system and for synchronous generators to be able to remain connected to the system, they must ensure that frequency (or angular velocity) and voltage stays within the specific range. Synchronous generators not only have to stay connected to the system in steady-state, they also have to stay connected during transient events which may be faults. They provide electrical power during these events and remain connected to the grid which is also known as Fault-Ride-Through (FRT) capability. Synchronous generators also provide inertia thanks to stored energy in rotating parts of the machine which increases the general or transient stability of a system. To sum up, synchronous generators are cornerstone of our well-established power systems today.

However, with the ever-increasing penetration of inverter-based generation in recent years, system operators began exploring properties of our networks that we have taken for granted since the early years of the 20th century. Renewable based generation such as wind and solar depends on the power electronic converters to connect to networks and provide electrical power. Since power electronic converters' (Mostly, inverters are meant for converters) operation depends and relies on the operation of a strong grid, Researchers have been looking for weak grid operation of inverters.

The primary purpose of the GFL inverter control technique is to export a predetermined quantity of power into an energized system. The GFL inverter control method is typically tailored for operation in strong grid conditions. Consequently, its performance hinges on a robust grid infrastructure, implying that a GFL inverter's dynamic response following a fault in a weak grid may not yield satisfactory results. Therefore, an inverter utilizing the GFL control method may lack the capability to provide FRT capabilities.

To address such challenges in grids dominated by Inverter-Based Resources (IBRs), Grid-Forming Inverter (GFM) control method has been proposed. This method eliminates the dependence on a strong grid for IBR operation. Inverters equipped with the GFM control method can establish grid voltage and frequency, enabling them to operate in weak grids or even in islanded mode. Additionally, this capability empowers them to provide black-start capabilities to the grid.

The behavior of a GFL inverter following a fault in two different grids is shown in Figure 3.10. As can be seen from the below figure, the GFL inverter has been able to recover from the fault in the strong grid (blue color) with higher Short-Circuit Ratio

(SCR). However, the GFL inverter has not been able to maintain steady active and reactive power outputs, resulting in oscillations in the voltage output in the weaker grid.

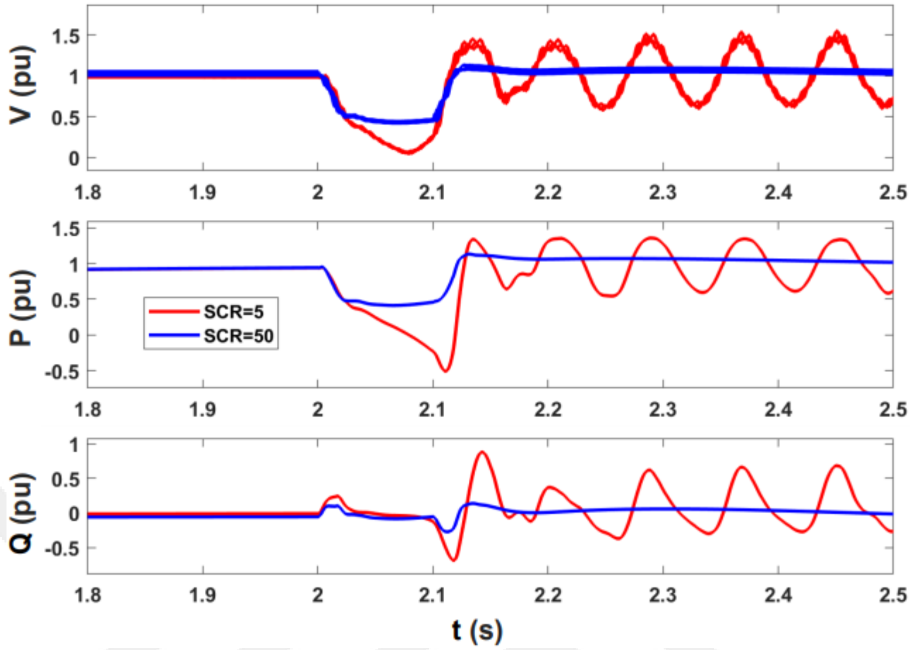

Figure 3.10 : GFL Behavior Following a Fault in Weak Grids [58].

The objective of GFL and GFM control methods during sub-transient, transient and steady-state time scales differ from each other. During sub-transient time scale, objective of GFL control method is to set up constant output current for active and reactive power while the objective of GFM control method is to set up constant output voltage for voltage and frequency control. During transient time scale, the objective of GFL control method is to maintain steady active and reactive power while the objective of the GFM control method is to maintain voltage and frequency. During the steady-state, both control methods may follow their expected characteristics.

There are several different GFM control methods in the literature such as virtual synchronous machine control, droop-based control, matching control and virtual oscillator control. However, among GFM control methods discussed in the literature, the droop-based control and virtual synchronous generator (VSG) methods are the most common.

Virtual Synchronous Generator Control: VSG control utilizes the synchronous generators' (SG) swing equations and governor controls. The active power of the inverter is measured. Then, a SG dynamic behavior mathematical model is utilized to obtain the necessary voltage and phase angle references for the inverter. A basic scheme for the VSG-based GFM control is shown in Figure 3.11.

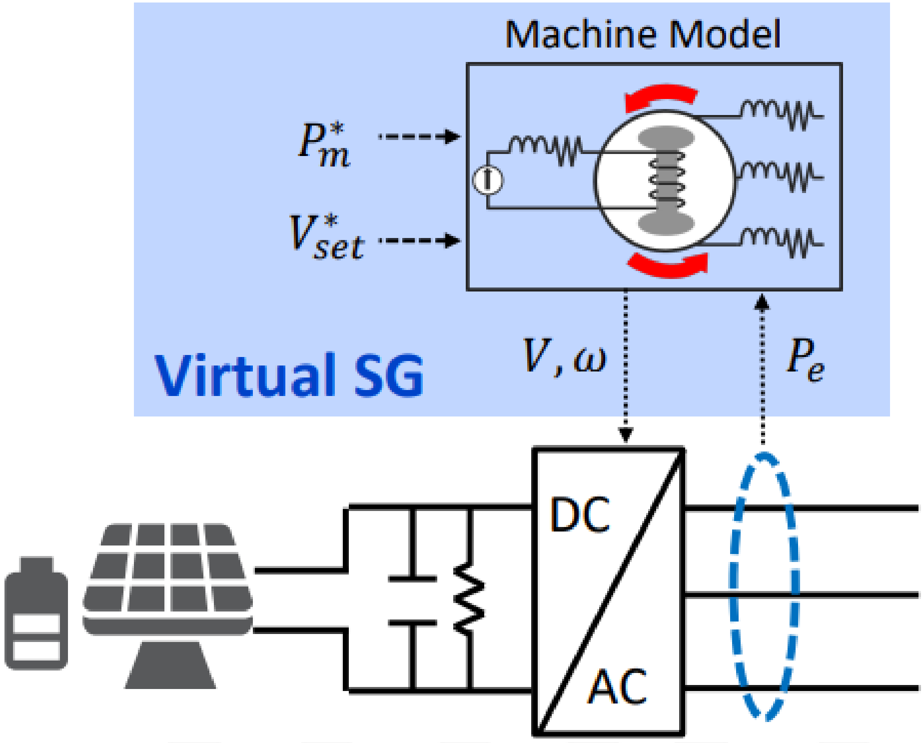

Figure 3.11 : VSG-based GFM Control Scheme [58].

Droop Control: The current and voltage outputs of the inverter are measured. Then, these values are used to obtain the necessary voltage and phase angle for the inverter. Voltage is calculated using the predefined reactive power - voltage relation namely Q-V droop. Angular frequency is calculated using the predefined active power – frequency relation namely P-f droop.

Droop equations are given in Equation 3.3 and Equation 3.4. Where, θ_r is an angle used in the control, ω_n is the nominal frequency, K_p is the droop gain for frequency, p^{set} is active power setpoint, q^{set} is the reactive power set point, K_q is the droop gain for voltage, $v_{0,*}^q$ is the voltage set-point and $v_{0,set}^q$ is the steady-state voltage. The values p^{avg} and q^{avg} are calculated using the Equation 3.5 and 3.6. The active and reactive power magnitudes in the dq pane are calculated and then they are filtered through a low-pass filter with the cutoff frequency of measured angular frequency [60].

$$\theta_r = \omega_n + K_p(p^{set} - p^{avg}) \tag{3.3}$$

$$v_{0,*}^{q} = v_{0,set}^{q} + K_q(q^{set} - q^{avg}) \quad (3.4)$$

$$\dot{p}^{avg} = \omega_{meas} + (p - p^{avg}) \quad (3.5)$$

$$\dot{p}^{avg} = \omega_{meas} + (p - p^{avg}) \quad (3.6)$$

A basic scheme for the VSG-based GFM control is given in Figure 3.12.

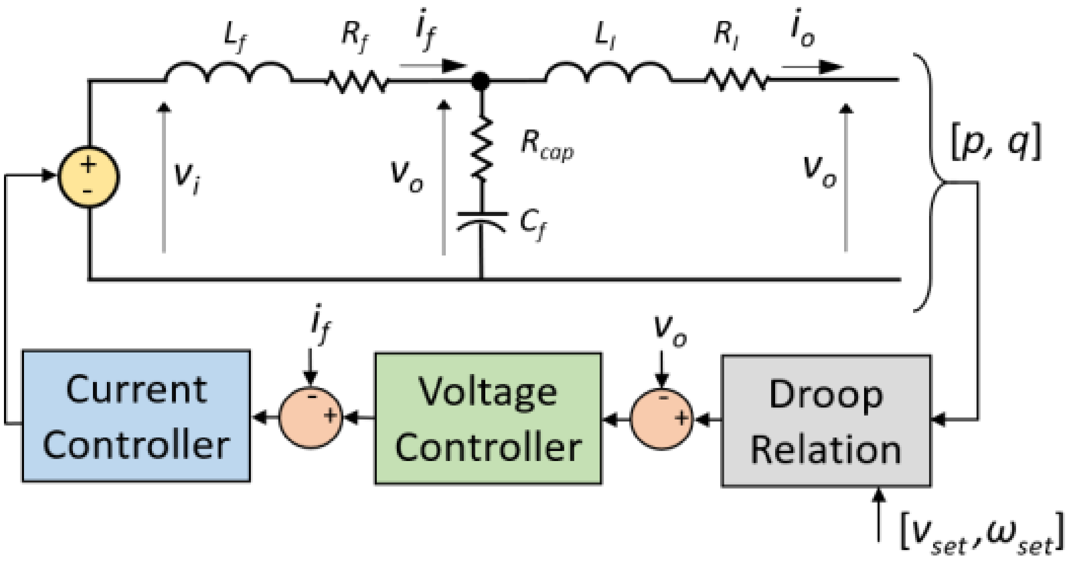

Figure 3.12 : Droop-based GFM Control Scheme [60].

The utilization of grid-forming inverters in LVDC distribution systems has become a focal point for researchers and system operators worldwide. While there are some similarities, opting for GFM over GFL in an LVDC distribution system fundamentally alters the expected network behavior.

However, GFL inverters still hold value when properly utilized. In a conventional distribution grid, where the distribution network is supplied from a strong transmission grid, GFL inverters can be employed without drawbacks. Nevertheless, it's crucial to thoroughly assess disturbance conditions to make sure that the reliable and safe operation of the system can continue.

3.2 Grounding in LVDC Distribution Systems

Grounding is a critical aspect in all types of power systems, whether they are based on AC or DC. The various grounding schemes available have different impacts on the network. Since LVDC distribution systems depend on power electronic converters for their operation, choosing the right grounding scheme for LVDC distribution systems is a complex task.

Several grounding schemes are employed in LVDC distribution systems, which fundamentally boil down to whether the return conductor is earthed. Grounded unipolar and bipolar systems are depicted in Figure 3.13 and Figure 3.14.

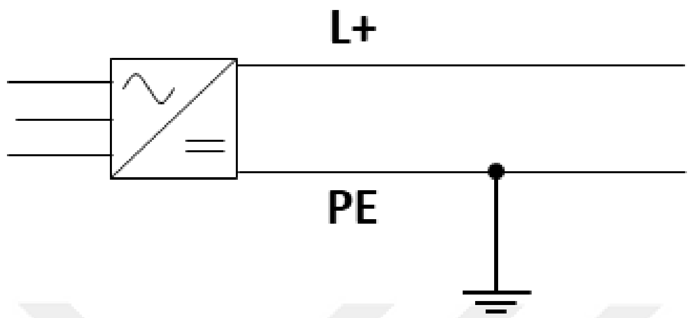

Figure 3.13 : Unipolar Grounded System.

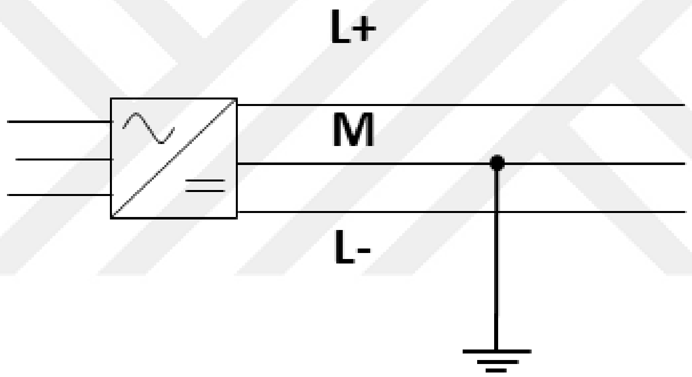

Figure 3.14 : Bipolar Grounded LVDC System.

Conventional LVAC distribution systems are invariably grounded at a specific point in the network, such as the transformer's neutral point. The protection of these systems is predicated on distinguishing between healthy and faulted phases. Employing earthed DC systems can introduce electrical safety concerns, including elevated touch voltages during earth faults. Addressing this challenge necessitates either reducing the DC voltage, thereby diminishing transmission capacities, or improving the earthing system, which can be costly [23]. If a grounding scheme where one pole is grounded is utilized, the behavior during a fault mirrors that of a short-circuit in the poles, or if the middle conductor is earthed, a ground fault on a conductor leads to a voltage increase in the healthy conductor [62].

In an earth-isolated system, safety is predicated on the absence of a path for fault currents, hence an earth fault does not immediately result in interruption or pose a safety risk. However, it is required to detect and clear earth faults immediately and use insulation monitoring devices (IMD) to constantly observe isolation between the system and the earth. Ungrounded unipolar and bipolar systems are depicted in Figure 3.15 and Figure 3.16.

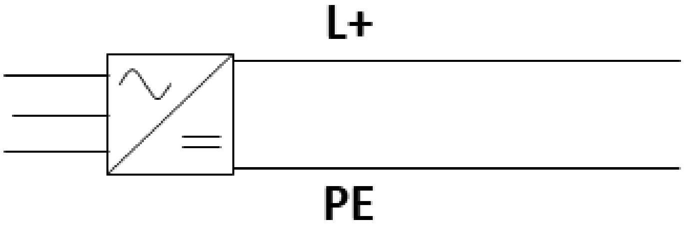

Figure 3.15 : Unipolar Ungrounded System.

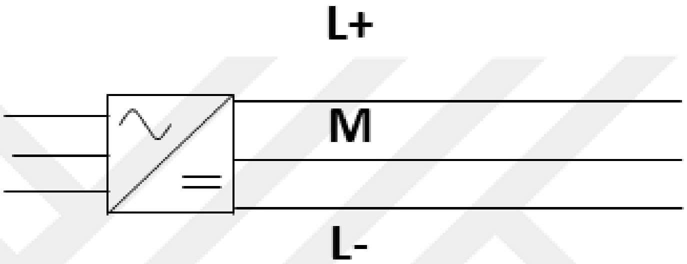

Figure 3.16 : Bipolar Ungrounded System.

Employing varied grounding schemes across different sections of an LVDC distribution, as illustrated in Figure 3.17, necessitates isolation between these sections to ensure that a fault in one segment does not impact others. This isolation is typically achieved through transformers, which offer galvanic separation between primary and secondary sides. Isolation transformers or converters incorporating transformers are commonly utilized for this purpose.

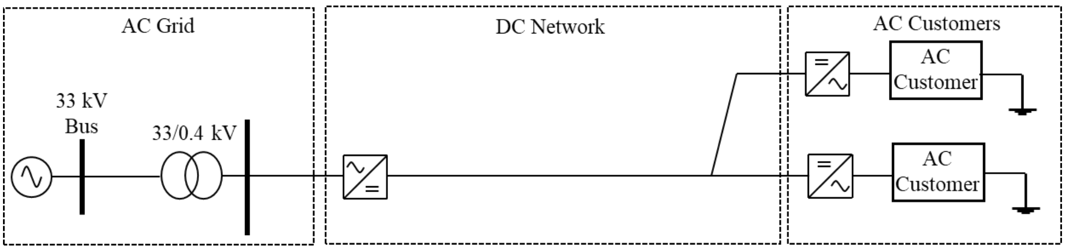

Figure 3.17 : Different Sections of an LVDC Distribution System.

3.3 Protection in LVDC Distribution Systems

In AC distribution systems, protection usually relies on the realization of overcurrent relays. Overcurrent relays, which are straightforward to implement, detect fault currents and issue a trip command to the circuit breakers of the line or line section if the current persists beyond a certain threshold, thereby clearing the fault. Circuit breakers depend on the zero-crossing feature of the sinusoidal waveform of AC current. Whenever the current approaches zero, circuit breaker contacts start to separate for a safe switching operation.

The inherent characteristics of DC add complexity to the protection of LVDC distribution systems. For high power applications circuit breakers may not be so easy to implement because direct current naturally does not have a zero-crossing feature. Consequently, researchers have proposed methods to artificially create a zero-crossing or momentarily force the current to zero, enabling the circuit breaker to operate safely. However, that is not the only challenge to overcome in protection of DC distribution systems. Distinct types of faults and their respective locations require unique solutions.

Possible faults in the DC network are: fault in a pole, fault between poles and fault between poles with earth connection. Protection against faults within the DC network can be achieved through the use of molded case circuit breakers, which may be positioned on either the AC or DC side of the converter. Protection against faults within the customer network can be facilitated by fuses, and within the converter itself through control algorithms. The converter's FRT capability can be enhanced by the over dimensioning of IGBTs [26]. While these approaches are effective in AC systems and applicable to DC systems, the ever-increasing growth of distributed energy generation necessitates a selective and rapid protection scheme. Using these methods, faults are typically considered to impact the entire network, leading to its disconnection.

However, novel approaches, such as those outlined in [24], advocate for the utilization of solid-state circuit breakers (SSCBs), offering a promising alternative. The protection scheme described in [24], utilizes the SSCBs and intelligent electronic devices (IEDs).

In the LVDC network given in Figure 3.18, point of common coupling (PCC), each feeder, each customer and each generation unit have their own SSCBs. DC current magnitudes and directions are constantly monitored. When a measured DC current exceeds a threshold, the protection scheme detects the faulted section of the network and acts as predefined fault clearing protocol. For example, during a fault at PCC, the fault will be fed by the AC grid and generation units which results in reverse direction current in all SSCBs. In order to clear the fault, all SSCBs will be blocked and AC side circuit breaker will be opened. However, a fault in one of the feeders will lead to reverse current in the remaining feeders and only the faulted feeder will be tripped.

This kind of protection scheme requires safe and fast communication between the converter and feeder SSCBs and between customer SSCBs and feeder SSCBs as given in Figure 3.19.

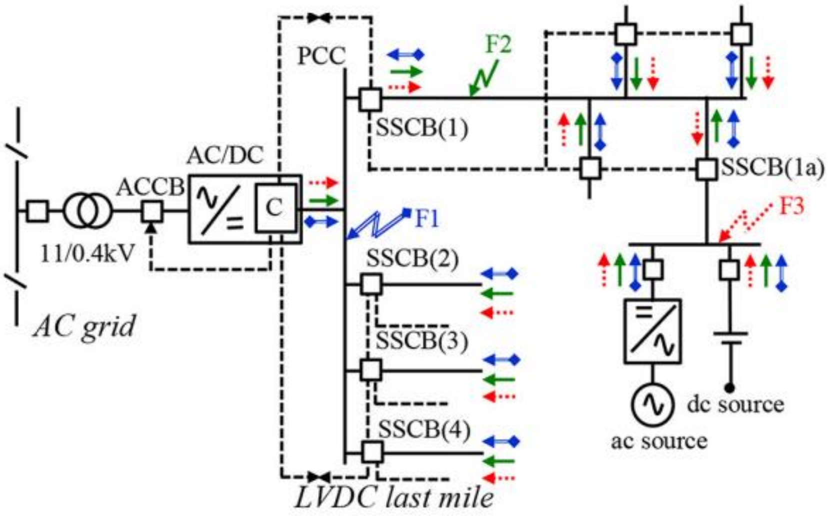

Figure 3.18 : An LVDC Network That Utilizes Solid-State Circuit Breakers [24].

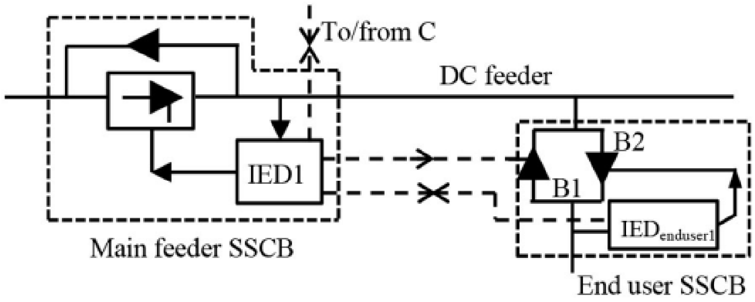

Figure 3.19 : An LVDC Network That Utilizes Solid-State Circuit Breakers [24].

The literature also references fuse-based protection schemes, as detailed in [31], and protection schemes based on high-frequency solid-state transformers, as outlined in [63]. Additionally, converter-based protection schemes are discussed in [30], alongside superconducting current limiter cable-based protection schemes, as mentioned in [32].

However, the protection methods, schemes, and equipment mentioned herein are not exhaustive. DC distribution systems possess considerable potential for enhancement and development, prompting the proposal of novel approaches on a daily basis.

3.4 Voltage Level Selection

The determination of the DC voltage level for use in a DC network involves assessing various factors and parameters, such as the maximum permissible voltage drop, losses, protection coordination, cost implications relating to the sizing of power electronic converters, the grounding system, and implications for human health. For instance, a higher voltage can decrease losses but also increase the initial investment required for power electronic converters. Moreover, a higher voltage level may pose greater risks to human health in case of contact. Given that LVDC grids are intended to replace existing AC infrastructures, it is economically prudent to continue utilizing current equipment as much as feasible. For example, if existing overhead lines or underground cables have not yet reached the end of their economic lifespan and are compatible with the planned DC network voltage, they should be employed. Similarly, if the existing network contains economically valuable equipment, the voltage levels of the planned DC network should accommodate the continued use of this equipment. Consequently, the selection of voltage levels must carefully balance economic, technical, and public health considerations.

One method to establish the voltage level involves using the permissible DC voltage drop in the network. By calculating the load distance based on the maximum voltage drop, it is possible to determine the optimum DC voltage for the area under study. Utilizing the DC voltage drop equation, the cable length corresponding to a given current magnitude can be ascertained. Subsequently, by applying the maximum voltage drop, the maximum cable length that accommodates the desired power transfer capacity can be calculated which is defined as load distance [4].

Voltage drop equation is given in Equation 3.7 where; ΔV is the DC voltage drop, r_{dc} is the DC resistance, l_{line} is the line length and I_{line} is the current magnitude. Using the maximum permissible voltage drop, maximum line length l_{max} can be calculated as given in Equation 3.8. Since the lines have a maximum current capacity, the equation can be re-written as given in Equation 3.9 where; V_{nom} is the nominal voltage level.

$$\Delta V = r_{dc} \times l_{line} \times I_{line} \tag{3.7}$$

$$l_{max} = \frac{\Delta V_{max} \times V_{min}}{r_{dc} \times P} \tag{3.8}$$

$$l_{max} = \frac{V_{nom} \times I_{max} - P}{I_{max}^2 \times r_{dc}} \quad (3.9)$$

With this method, it is assumed that the loads are lumped at the end of the line which may not be realistic. However, the drawbacks of this assumption can be eliminated by using a computer load flow program.

An example calculation of load distance is given in Figure 3.20. In this example, the DC voltage is 750 V, line DC resistance is 0.191 Ω/km, maximum permissible voltage drop is 5% and maximum current is 366 A.

As can be seen from the Figure 3.20, 250 kW load can be transferred to a distance about 600 meters within the voltage drop limits. Increasing the permissible voltage drop will decrease the load distance greatly. However, maintaining a certain level of voltage drop will affect the power quality in the network.

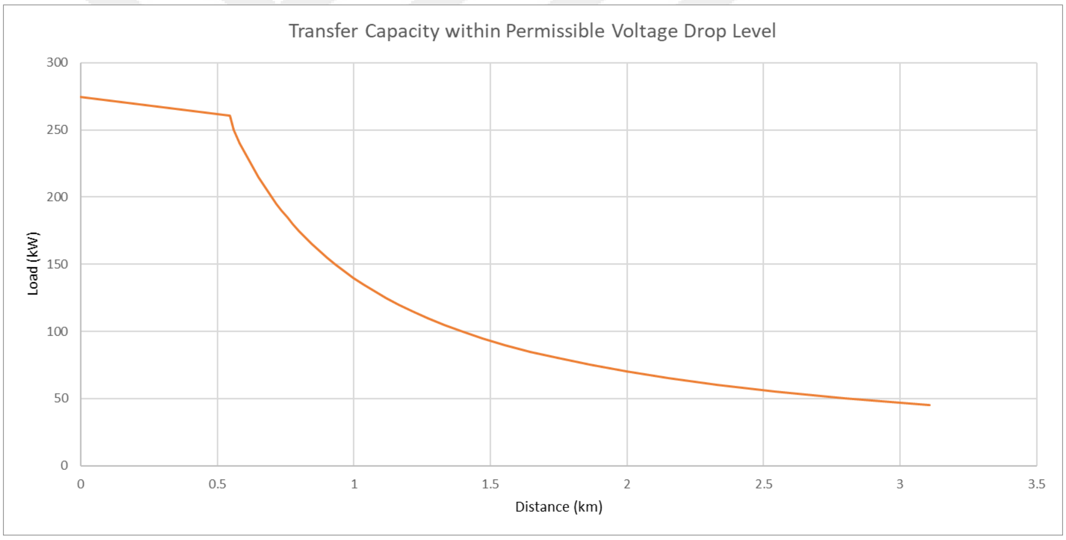

Figure 3.20 : Load Distance Calculation For 750V DC and 5%.

The same calculation for 1500 V DC voltage level is provided in Figure 3.21. 250 kW load can be transferred to a distance more than 2 kilometers which is more than the double that of 750 V DC.

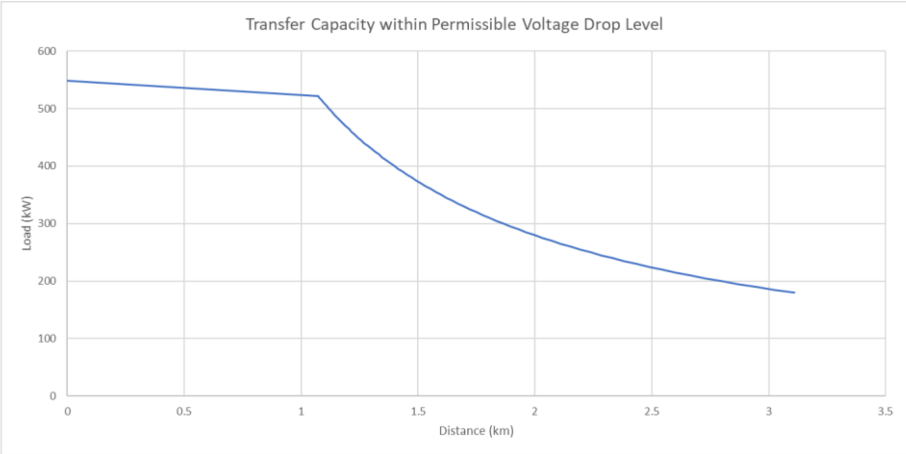

Figure 3.21 : Load Distance Calculation For 1500V DC and 5%.

Voltage level significantly influences the choice of equipment used in the network. Higher voltage levels correspond to greater transmission capacity and reduced losses; however, they also result in increased equipment costs. As illustrated in Figure 25, different voltage levels must be analyzed to ascertain the optimum voltage level for the area under study.

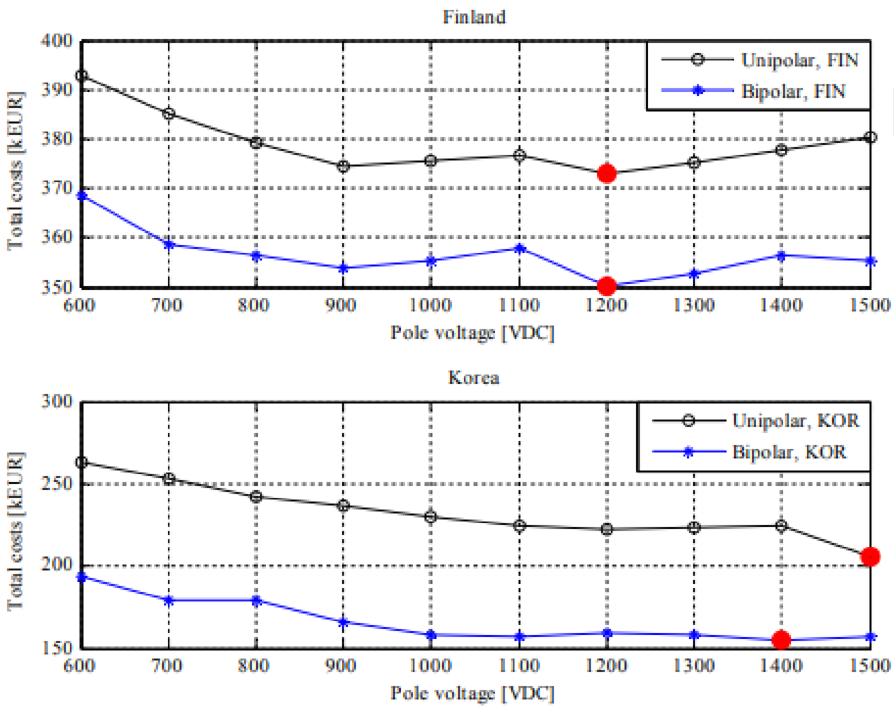

Figure 3.22 : Voltage Level and Total Costs for LVDC Networks [23]

A study cited in [23] demonstrates that total cost outcomes vary with voltage level adjustments: while one scenario reveals that higher voltage levels lead to reduced costs, another scenario presents the exact opposite result as shown in Figure 26.

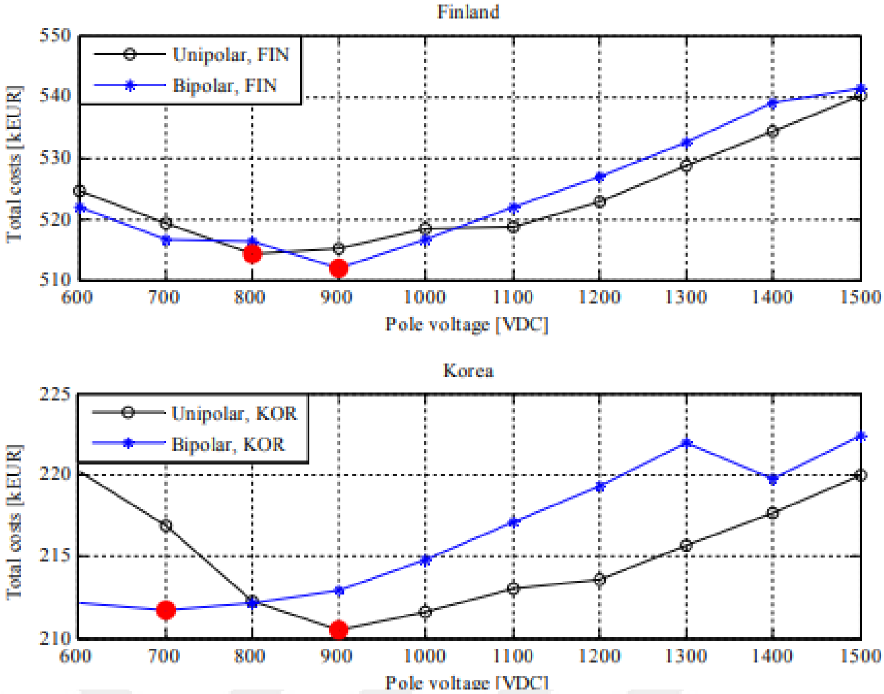

Figure 3.23 : Voltage Level and Total Costs for LVDC Networks [23]

Voltage level also affects the protection system design, touch voltages, electrical safety, control strategies and equipment characteristic [27]. IEC Technical Report 63282 lists common voltages used in LVDC networks. These voltage levels are given in Table 3.1 and 3.2 and recommended by the IEC 63282 report for implementation in IEC 60038 standard.

Table 3.1 : IEC 63282 Recommended Voltage Levels for Unipolar Systems.

$U_{nominal}$	U_{min}	U_{max}
350 V	320 V	380 V 440 V
700 V	640 V	760 V

Table 3.2 : IEC 63282 Recommended Voltage Levels for Bipolar Systems.

$U_{nominal}$	U_{min}	U_{max}
±350/700 V	640 V	760 V 880 V
±700/1 400 V	1280 V	1500 V

4. IMPLEMENTATIONS OF LVDC DISTRIBUTION NETWORKS

Pilot implementation of a new technology is crucial for testing the technology's performance in real-life scenarios within a controlled environment. Should the technology fail to perform as it did in its development setting, such as a laboratory, adjustments can be made. They provide huge amount of data and information for standardization of the LVDC distribution networks to the researchers.

There are several pilot implementations of LVDC distribution networks globally with countries such as Finland, China, Korea, Germany and Netherlands. Researchers in [21] have discussed the necessity to renew the majority of the 20 kV lines in Finland, highlighting how LVDC could offer advantages over LVAC in terms of long-term investment. They also present their experiences and results from a pilot LVDC distribution system in a rural area of Finland. The customers are fed by a 120 kVA IGBT based back-to-back converter. The main purpose of this converter is to increase the transmission capacity of the network. Converters used the pilot site are ABB’s ACS800-11-5 converters.

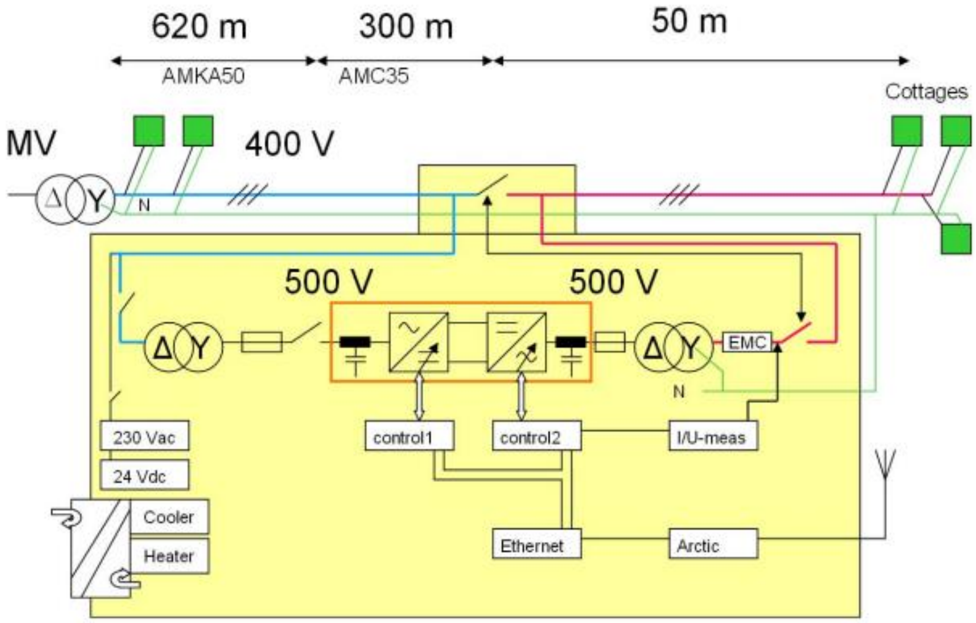

Figure 4.1 : Single Line Diagram of The Network [21]

The cabinet and ABB ACS800-11-5 converter installation at the site are given in Figure 4.2 and Figure 4.3.

Figure 4.2 : Converter Cabinet Installation at the Site [21]

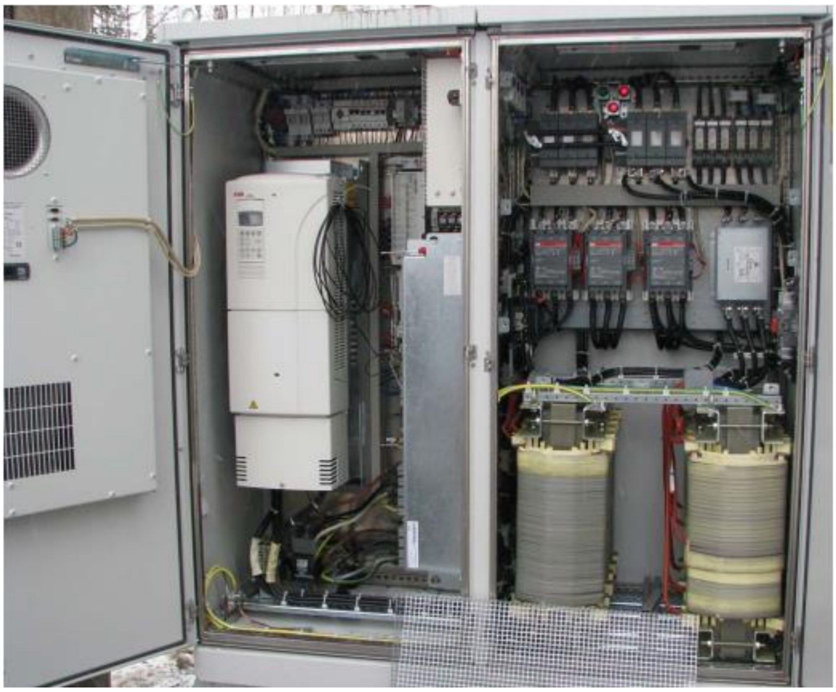

Figure 4.3 : ABB ACS800-11-5 Converter Installation [21]

Power quality index measurements from the site are provided in Figure 4.4. According to the authors, high levels of voltage drops were observed prior to the pilot implementation. However, following the implementation of the LVDC network, there has been a significant improvement in power quality.

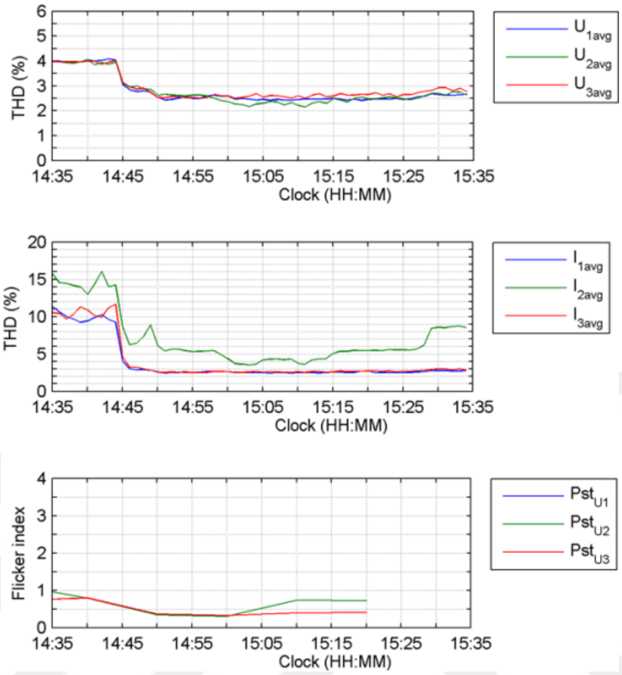

Figure 4.4 : Power Quality Measurements from the Test Site [21]

The line voltage and line current during a clearing a fault are given in Figure 4.5.

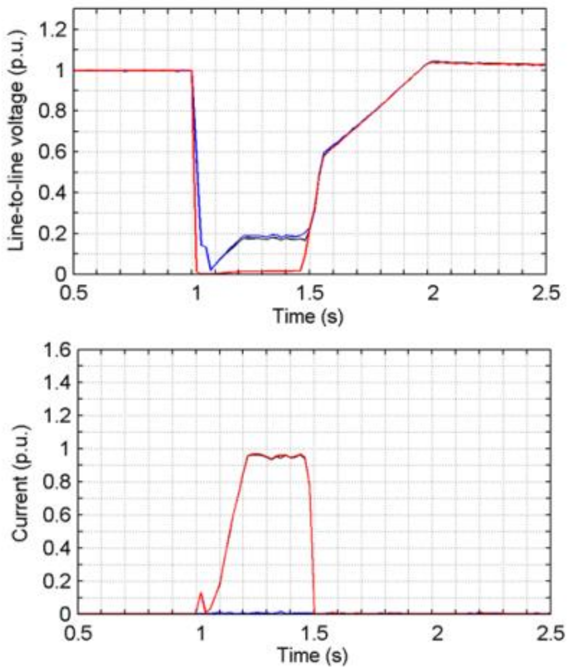

Figure 4.5 : Clearing of a Three-Phase Fault [21]

Another pilot implementation of an LVDC network in Finland is being carried out by Järvi-Suomen Energia Oy DSO in collaboration with Lappeenranta University of Technology. This network supplies four different customers using three inverters, and the topology of the LVDC network is depicted in Figure 4.6. The test site employs a bipolar ±750 V topology, with the single line diagram of the network provided in Figure 4.7.

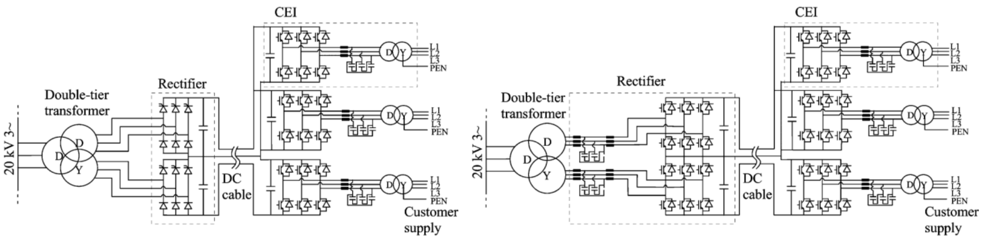

Figure 4.6 : Topology of the LVDC Network [13]

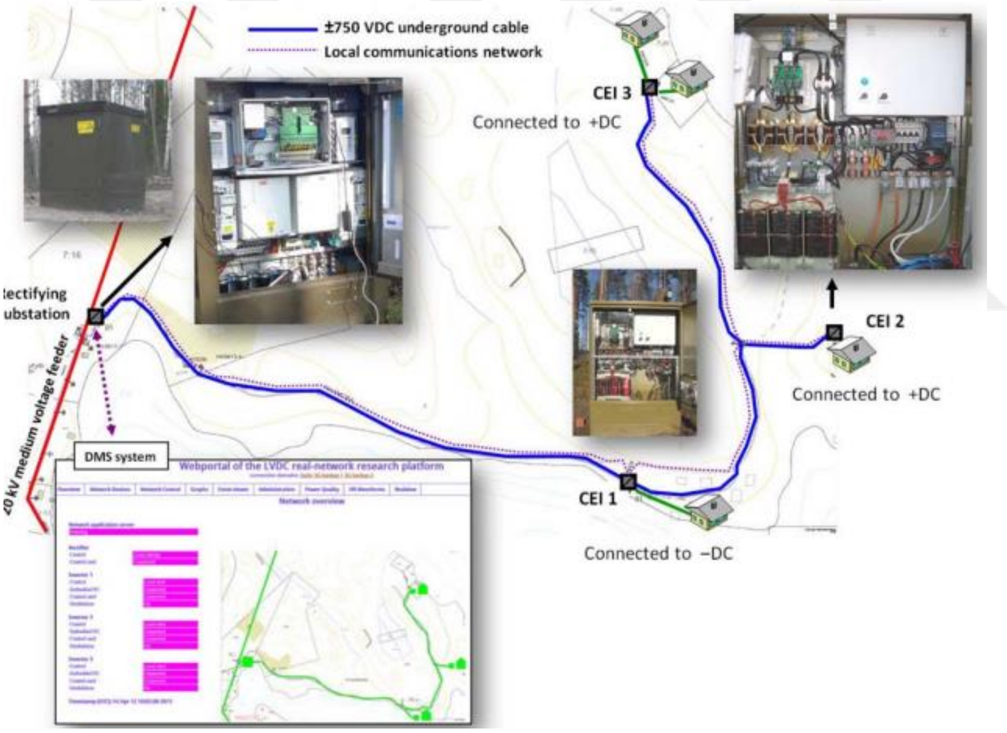

Figure 4.7 : Topology of the LVDC Network [13]

The network extends for a total of 1.7 km and continues to use the existing underground cable, which is suitable for the planned project, thereby avoiding the need for new cable installation. This arrangement ensures that, in the event of operational issues, the region can still be powered from the AC network. Although the initial project designs depicted in Figure 4.6 show rectifiers with IGBTs, thyristors were initially preferred due to cost considerations. However, after 9000 hours of operation, the IGBTs were replaced with transistors to facilitate the bidirectional power flow required by the energy storage systems planned for future installation. Currently, isolation between the AC and DC terminals is achieved using 50 Hertz transformers, but there are plans to replace these with the Bidirectional Active Bridge DC/DC converters [13].

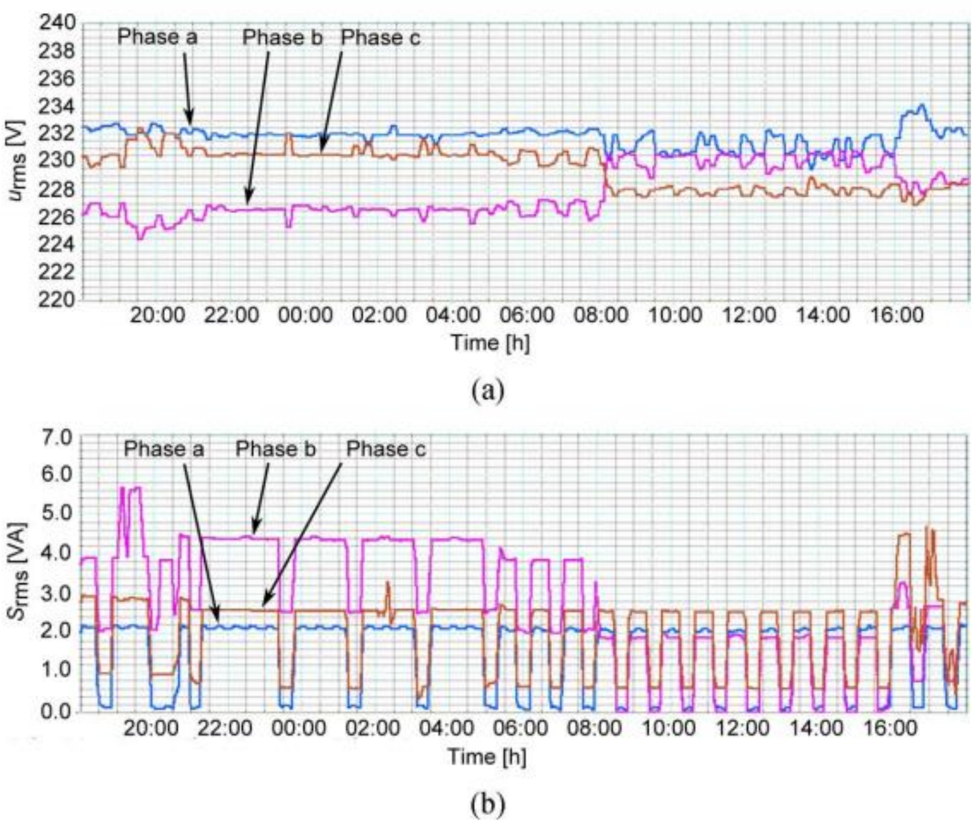

Figure 4.8 : Topology of the LVDC Network [13]

Researchers have shared their experiences and findings from their pilot LVDC implementation site in their article [64], with the single line diagram presented in Figure 4.9 and Figure 4.10. The LVDC network has 750 V voltage level and the site has total of 1.5 km length.

Figure 4.9 : Single Line Diagram of the Site [64]

Figure 4.10 : Topology of the LVDC Network Test Site [64]

The DC distribution concept demonstration project in the Baolong industrial zone, situated in the Longgang district of Shenzhen, includes several nationally recognized high-tech companies. The project employs a hand-to-hand connection type to enhance the absorption and storage capacities for renewable energy within the area. This topology connects the DC distribution line to the AC distribution line in two different points, offering greater power supply reliability compared to a radial connection type.

While the nested connection type minimizes power interruption losses by improving the stability of the supplied power and facilitating faster fault location, it also heightens the demands for protection control and fault identification coordination [65].

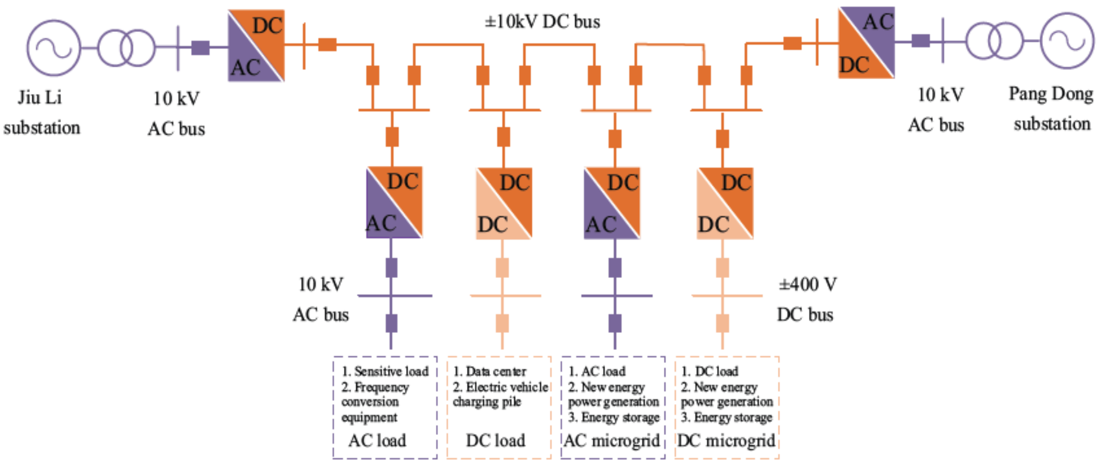

Figure 4.11 : Baolong DC Demonstration Project Site [65]

Researchers in [66] present the design, configuration and experiences from their pilot LVDC site in Geochado Island, Korea. Single line diagram of the site is illustrated in

Figure 4.12. Ten residential and two commercial existing loads, 4 new electrical vehicle charging station with vehicle-to-grid capabilities, 1 new DC home and 10 DC street lamps are planned to be supplied by the LVDC distribution network. The network has two different DC voltage levels which are ±190 V and ±750 V.

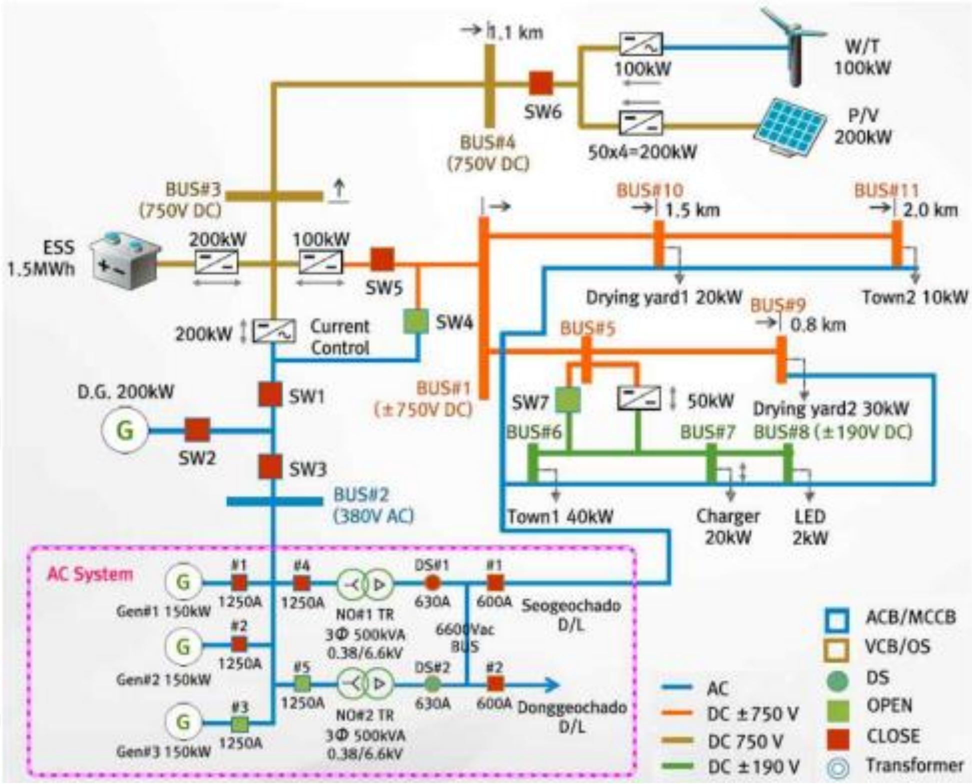

Figure 4.12 : Geochado Island LVDC Pilot Site [66]

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5. METHODOLOGY

In designing a LVDC distribution network, multiple criteria and constraints must be considered, as discussed in previous sections. However, the considerations are not limited to those already mentioned and encompass a broader range of factors essential for effective planning. These criteria and constraints can be utilized during the technic analysis of the network such as:

- Topology
- Voltage level
- Converter topology and control strategy
- Protection and grounding
- Communication Infrastructure

However, technical aspects should not be the sole focus of the criteria and constraints in the LVDC distribution network design process. From any engineering perspective, the technical advantages of a design often carry an economic burden. Therefore, engineers must always seek a balance between technical benefits and economic drawbacks, while also taking into account sociological concerns. In this regard, cost/benefit analysis methods are a great way to analyze a design from both technical and economical perspectives.

The first step in a cost/benefit analysis is to determine the benefits of the system under study. Recognizing both direct and indirect benefits is crucial as it aids in the formulation of costs. Employing flowcharts or hierarchy charts can enhance the visualization of these benefits. While it may not be feasible to analyze every benefit from a cost perspective, documenting these advantages can still underscore the potential benefits of implementing an LVDC system.

After identifying all the benefits of the system, the next step is to formulate the associated costs. The parameters for this formulation can be derived using various methods, such as employing generally accepted or standard values, utilizing data obtained from simulations, or referencing exchange rates published by governments or financial institutions. This method guarantees a thorough and precise economic evaluation of the system being considered.

The direct and indirect costs of LVDC distribution networks, as defined in this study, are illustrated in Figure 5.1. Costs associated with these benefits will be analyzed through a comprehensive economic analysis. Methods such as DCF and NPV will be employed in this analysis, with detailed explanations provided in later sections of the study.

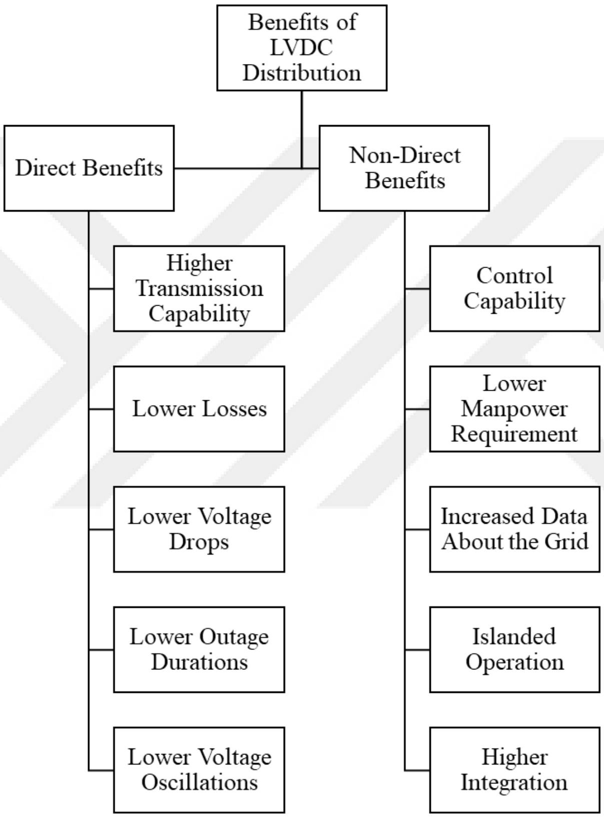

Figure 5.1 : Benefits of LVDC Distribution Networks

Costs can be divided into two as Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

CAPEX: CAPEX refers to money used by a company to buy (or invest in) physical assets such as property, buildings, technology, or equipment. Capital expenditures are capitalized, meaning their value is depreciated or amortized over the life of the asset. For a distribution system operator, examples of CAPEX include transformers, underground cables, overhead lines, and converters.

OPEX: OPEX covers the costs for a company's activities that could occur every day. These costs are incurred in the ongoing operations of a business and are typically shorter-term costs. For a distribution system operator, examples of OPEX include salaries, fuel costs, maintenance and repairs, customer service, regulatory compliance or energy losses.

Higher Transmission Capacity: As described in Section 3.4, LVDC distribution systems can transfer a higher amount of power in comparison to AC systems, even using the same voltage level. This benefit can be quantified as a reduction in investments, either through the deferral or cancellation of planned expenditures.

Depending on the load growth rate in the region where an LVDC distribution network investment is planned, the number of years n until additional capacity investment will be necessary if the region continues to operate as an AC network can be calculated using Equation 5.1.

$$n = \frac{\log\left(\frac{Capacity}{Peak\ Load}\right)}{\log(1 + Load\ Growth)} \tag{5.1}$$

Lower Losses: Due to the inherent characteristics of DC systems, which do not involve reactive power, and the control capabilities of the converters used, LVDC distribution systems typically exhibit lower active power losses. These losses are undesirable for DSOs as they translate directly into operational costs.

Active power losses represent energy that cannot be billed by DSOs, directly impacting revenue. These losses can be quantified using the cost of unit energy, as detailed in Equation 5.2.

$$C_{loss} = P_{loss} \times 8760 \times k_{load} \times (C_{distribution} + C_{energy}) \tag{5.2}$$

Where C_{loss} is the cost of energy that cannot be billed, P_{loss} is total maximum losses that occurs in the system, $C_{distribution}$ is the price of energy distribution, C_{energy} is the price for unit energy in bills and k_{load} is the load factor which is used by DSOs in planning of a network to correctly determine the necessary transformer or any other equipment ratings. The load factor can be calculated using Equation 5.3. If the parameters are unknown, the load factor can be estimated as 0.3-0.4 depending on the network.

$$k_{load} = \frac{Average\ Load}{Peak\ Load} \tag{5.3}$$

Lower Voltage Drops: Long distribution lines typically experience voltage drop issues towards their far ends. However, the control capabilities of LVDC inverters effectively mitigate this problem. Although voltage drops contribute to additional losses, distinguishing these losses from those inherently differing between AC and DC distribution systems can be challenging. Therefore, it will be assumed that the benefits of reduced voltage drops are encompassed within the overall lower loss figures.

Lower Outage Durations: Integrating power electronic converters into the grid enables the addition of features such as system restarts in the event of a fault, akin to automatic reclosing breakers. These capabilities help reduce the effect of transient faults or prevent false tripping, enhancing the continuity of supply in DC grids compared to AC grids. Such improvements yield economic benefits for the distribution operators, manifesting as reductions in both undistributed energy and the penalties incurred from prolonged outages.

Distribution operators experience reduced revenue from consumers due to energy that could not be distributed. Therefore, when calculating the financial losses incurred due to outages and the number of affected users, the cost of energy is used as a reference. This approach helps quantify the direct impact of unsupplied energy on revenue. The cost of energy that could not be distributed can be calculated using Equation 5.4.

$$C_{outage} = ([SAIDI \times k_{load} \times Peak\ Load] \times C_{energy}) \times N_{customers} \tag{5.4}$$

Where C_{outage} is the cost of energy that could not be distributed and $N_{customers}$ is the number of customers that are affected.

Since DSOs have to pay a penalty to the customers if they exceed the predefined outage durations or frequency, the monthly penalties can be calculated using Equation 5.5 and Equation 5.6.

$$C_{SAIDI} = C_{fixed} + (SAIDI - 24) \times 2 \times C_{distribution} \times N_{customers} \tag{5.5}$$

$$C_{SAIFI} = C_{fixed} + (SAIFI - 6) \times \left(\frac{SAIDI}{SAIFI}\right) \times 2 \times C_{distribution} \times N_{customers} \tag{5.6}$$

Where; C_{fixed} is a fixed price which is defined as $100 in this study.

Lower Voltage Oscillations: Converters used in LVDC distribution networks are capable of actively controlling voltage to the desired level with minimal oscillations. Voltage oscillations that exceed the thresholds defined by regulatory authorities can be considered as unsupplied energy. However, this metric does not fully capture the impact of voltage oscillations.

Control Capability: As outlined in section 3.1.3, VSCs possess the ability to regulate the active power of a system independently from the reactive power. This feature enables LVDC distribution networks to operate with zero reactive power under normal conditions, thereby reducing the penalties paid by DSOs that are incurred by exceeding reactive power limits. Also, converters can support the AC grid by supplying reactive power during faults.

Lower Manpower Requirement: Distribution system operators incur significant expenditures on manpower and fuel for maintenance, repair, and meter reading activities. However, LVDC networks typically demand lower maintenance, which can lead to reductions in operational costs. Additionally, since converters in LVDC networks require extensive measurements to operate safely, this data collection capability of customer-end inverters can also be leveraged for billing purposes, further optimizing operational efficiency.

Annual salary costs of field crew C_s can be calculated using Equation 5.7 where; N_{rw} is the number of personnel in meter reading crew, N_{mw} is the number of personnel in maintenance crew and c_s is the monthly salary of these crew. Since the personnel do not spend their entire workhours for a single area, the cost of salary must be multiplied by a factor such as 0.25.

$$C_S = [(N_{rw} * e_s + N_{mw} * c_s) \times 12] \times 0.25 \tag{5.7}$$

The annual cost of vehicle operation for these crew can be calculated using Equation 5.8 where; C_{vo} is the total cost of vehicle operation, d_{rw} and d_{mw} are the distance covered by workers and c_{tr} is the cost of travel per one kilometer.

$$C_{VO} = (d_{rw} * N_{rw} + d_{mw} * N_{mw}) \times c_{tr} \times 12 \quad (5.8)$$

Increased Data About the Grid: Distribution system operators require extensive data to manage their networks effectively, plan maintenance, and strategize future upgrades. The necessity for detailed measurements in converter operations for safety not only meets this requirement but also offers the advantage of providing DSOs with more comprehensive data about the grid. This enhanced data availability can lead to improved operational insights and decision-making.

Islanded Operation: As described in section 3.1.3.2, grid-forming inverters can provide black-start and islanded operation capability which decreases the outage durations.

Higher Integration: LVDC distribution networks enable the higher and easier integration of electric vehicles and charging stations, distributed generation and battery energy storage systems.

NPV is a critical financial measure used to assess investment opportunities. It works by projecting all future cash inflows and outflows associated with an investment, then discounting these cash flows to their present value and summing them up. The sum of these discounted cash flows represents the investment's NPV. If the ΔNPV is positive, it indicates that the investment is expected to yield a profit when considering the time value of money.

Since investments are made with today's money, today's value of a future cost which are operational costs must be calculated. Then, CAPEX and OPEX can be summed together to find the Net Present Value as given in Equation 5.9.

$$Net\ Present\ Value = CAPEX + \frac{OPEX}{(1+r)^a} \quad (5.9)$$

Where: r is the interest rate and a is the time period in years.

6. ANALYSIS, EXAMPLE CASES, MODELLING AND SIMULATION

In this chapter, multiple examples will be given to illustrate the application of the analysis method discussed.

Algorithm of the analysis method discussed in Chapter 5 is given in Figure 6.1.

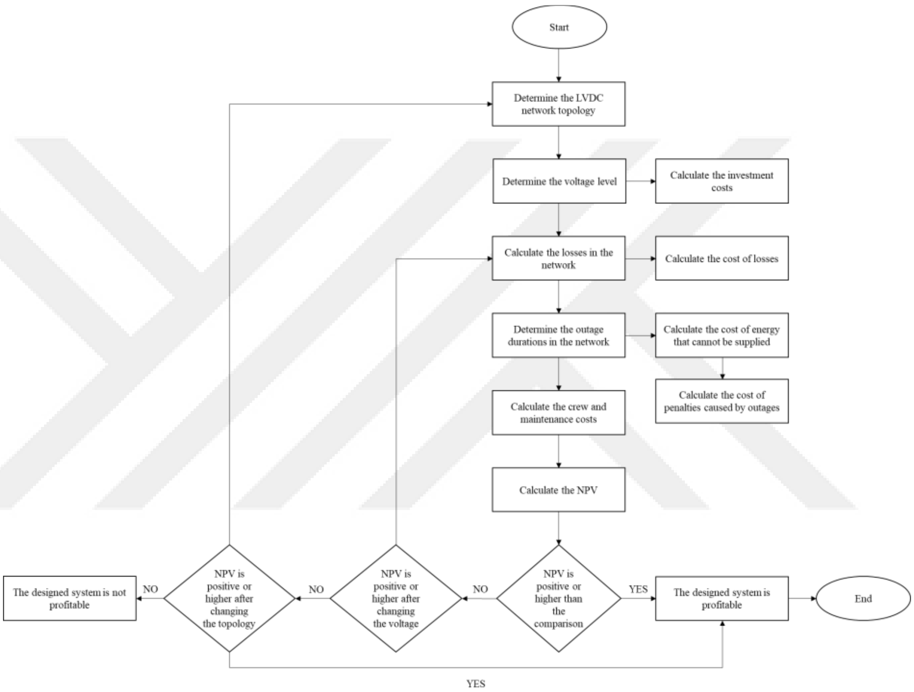

Figure 6.1 : Algorithm of the Proposed Analysis Method.

To analyze an LVDC network design or investment, it is essential first to select an appropriate network topology. Following this, the voltage level must be determined to choose the necessary equipment, and the investment costs need to be estimated. Once the system design is finalized, a technical analysis of the designed network should be conducted using analysis software to assess parameters such as losses and voltage drop. In cases where an existing network is to be replaced with an LVDC network, it is crucial to determine outage durations and frequencies to estimate the costs associated with unsupplied energy. Subsequent to these evaluations, the maintenance costs should be calculated, and the net present value of the designed network must be computed. If the resulting NPV is positive, or higher than that of an alternative option in comparative scenarios, this indicates that the designed system is financially viable or offers greater profitability. Conversely, if the NPV is negative or lower than that of another option, the voltage level should be adjusted and the NPV recalculated. Should the NPV remain negative or inferior after this adjustment, a change in the network topology might be necessarily followed by another NPV calculation. If the NPV is still not favorable, it suggests that the design may not be economically beneficial.

6.1 Analysis and Example Cases

In this study, two different LVDC distribution topology have been considered for two different regions in Turkey. Cost/benefit and sensitivity analysis results were discussed. The example cases studied in this chapter as follows:

1. Unipolar Point-to-Point LVDC Distribution Network in a Rural Area
2. Link Type LVDC Distribution Network in an Urban Area

6.1.1 Example case 1

The single line diagram of the first example case is given in Figure 6.2. The area under study is located in a rural area in Türkiye. There are 20 customers in total which are located 1150 meters away from the distribution transformer. Total demand of the customers is 50 kW and 2 kVAr at 0.4 kV.

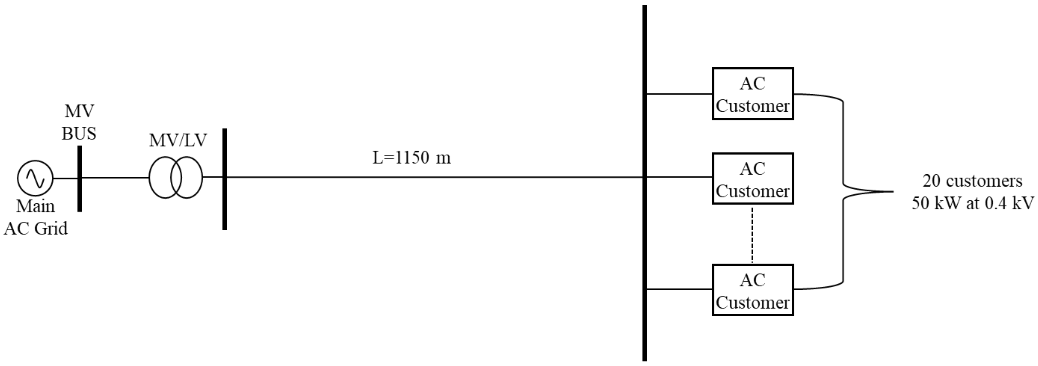

Figure 6.2 : Single Line Diagram of the AC Network in Example Case 1.

Since this is a new investment for the distribution system operator, an AC and an LVDC distribution network will be compared in case of costs and benefits. The rated data of the transformer is given in Table 6.1.

Table 6.1 : Ratings of the Transformer.

Parameter	Value
Rated Voltage	31.5/0.4 kV
Winding Type	DYn11
Rated Power	400 kVA
Leakage Reactance	4.6%
Copper Losses	0.0125 pu
Eddy Losses	0.002 pu

The distribution overhead line utilizes Aster type phase conductors and Rose type ground wires. The tower is 15 m high and there is 3 m distance between phase conductors.

The impedance of the line is given in Table 6.2 which is calculated using PSCAD software. PSCAD is an electro-magnetic transients (EMT) analysis software developed by Manitoba Hydro International (MHI).

Table 6.2 : Impedance of the AC Distribution Line.

Parameter	Value
Positive Sequence Resistance	0.4287 Ω/km
Positive Sequence Reactance	0.4429 Ω/km
Positive Sequence Susceptance	2.97×10^{-6} S/km
Zero Sequence Resistance	0.7348 Ω/km
Zero Sequence Reactance	1.332 Ω/km
Zero Sequence Susceptance	1.68×10^{-6} S/km

The PSCAD model of the developed AC network is given in Figure 6.3. The distribution line model is given in Figure 6.4.

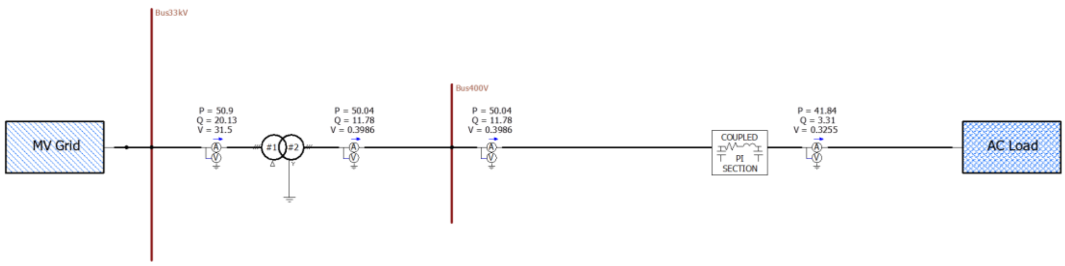

Figure 6.3 : PSCAD Model of the Example Case 1.

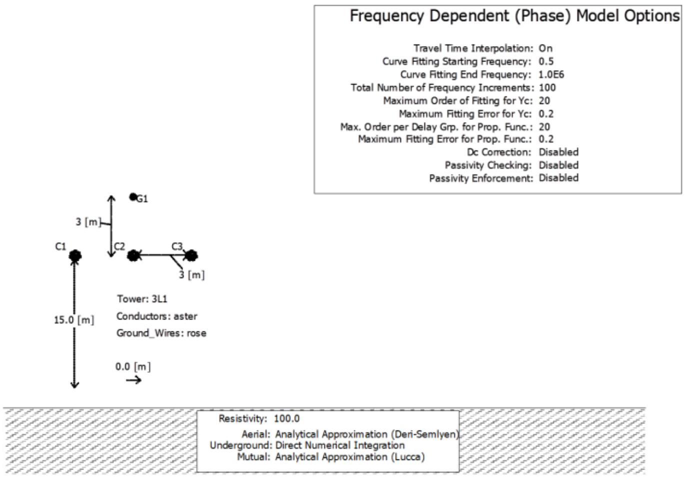

Figure 6.4 : PSCAD Model of the AC Distribution Line.

The single line diagram of the LVDC network is given in Figure 6.5. The topology of the network is Unipolar Point-to-Point LVDC Distribution Network. The DC voltage level of the network is 1.5 kV.

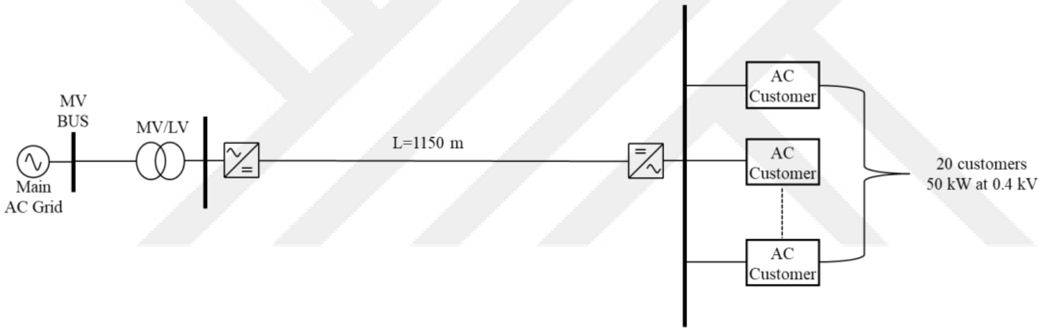

Figure 6.5 : Single Line Diagram of the LVDC Network in Example Case 1.

The LVDC network that is modelled in PSCAD is illustrated in Figure 6.6, employing a Grid-Following Voltage Source Converter topology. The same Aster and Rose type conductors are used for the DC line, facilitating direct comparison between the AC and DC networks. It is important to note that, due to the use of a unipolar topology, a tower configuration with two conductors is required. PSCAD model of the DC line is given in Figure 6.7. It is assumed that the same tower is used in both AC and DC networks.

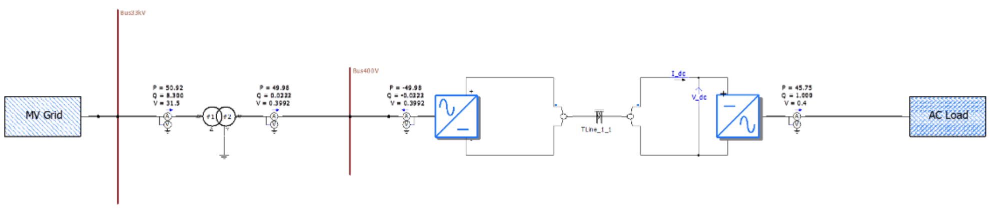

Figure 6.6 : Single Line Diagram of the LVDC Network in Example Case 1.

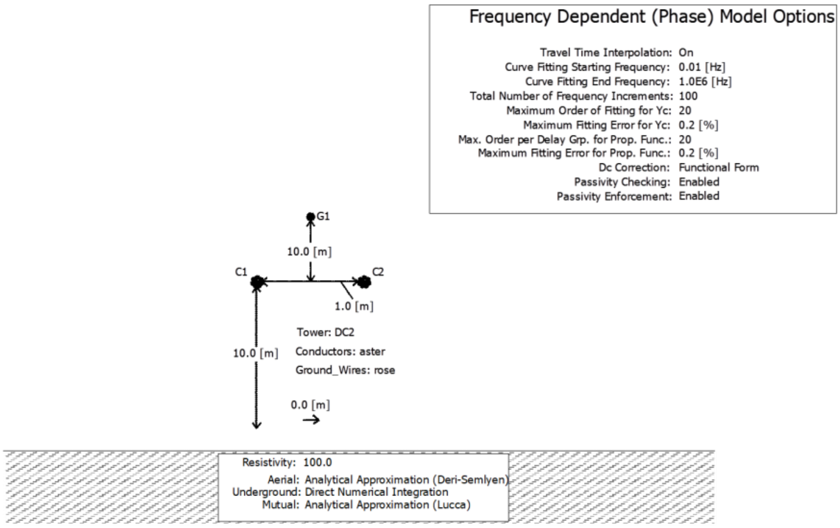

Figure 6.7 : PSCAD Model of the DC Distribution Line.

Parameters of the DC line calculated by PSCAD are given in Table 3.

Table 6.3 : Impedance of the DC Distribution Line.

Parameter	Value
Resistance	0.4917 Ω/km
Reactance	0.82×10^{-5} Ω/km
Susceptance	0.88×10^{-10} S/km

The voltage startup of the DC network is depicted in Figure 6.8. In this setup, the network's 1.5 kV DC voltage is regulated by the rectifier. As PSCAD functions as an EMT-type simulation software, all electrical properties of any network transition from an initial transient state to a steady state. Accordingly, the rectifier is activated only after the simulation reaches steady state, which occurs 0.25 seconds after the simulation commences.

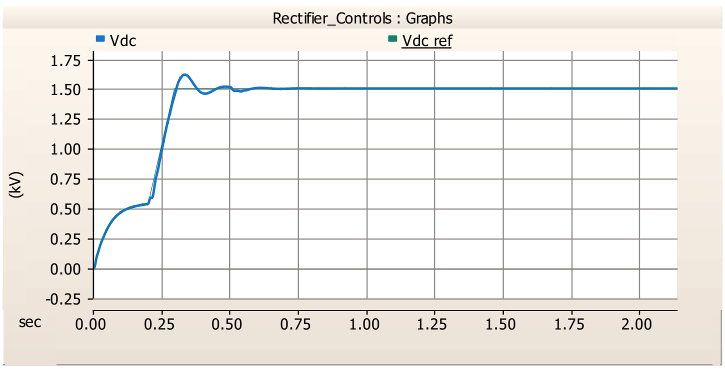

Figure 6.8 : The Startup of DC Voltage in the Network.

The AC voltage output of the inverter is given in Figure 6.9. The inverter is activated 0.25 seconds after the activation of the rectifier because inverter requires a DC voltage input in order to operate.

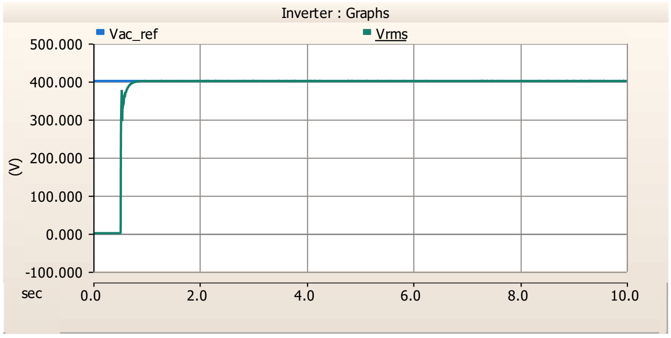

Figure 6.9 : The Startup of AC Voltage of Customers in the Network.

The 2022 Annual Electricity Sector Report, which is the latest at the time of writing, published by Turkish Energy Market Regulatory Authority (EMRA) is used in the study because the report includes many useful information about the Turkish electricity distribution networks. The 2022 Unit Price List published by Turkish Electricity Distribution Corporation is used for cost calculations.

The parameters used in calculations are given in Table 6.4. Energy and distribution prices are obtained from the 2022 tariff lists published by EMRA. Load factor, SAIDI and SAIFI values are obtained from the 2022 Annual Electricity Report. Interest rate is assumed to be 7% in the study.

Table 6.4 : Parameters Used in Calculations in Example Case 1.

Parameter	Value
Energy Price	$0.0939/kWh
Distribution Price	$0.0471/kWh
Load Factor	0.4205
SAIDI	92.09 hours
SAIFI	85.1
Interest Rate	0.07
Personnel Salary	$423.72
Maintenance Personnel	3
Monthly Distance Covered by Maintenance Personnel	10 km
Meter Reading Personnel	2
Monthly Distance Covered by Meter Reading Personnel	5 km
Fuel Price	$0.0283/km
Analysis Period	40 years
TL/$ Rate	16.52

Since both networks employ a distribution transformer, active power value measured from the transformer's secondary side is used to calculate power losses. As it can be seen from the Figure 6.3, the active power losses are 8.2 kW when the active power value at the transformer's secondary side is measured as 50 kW. However, as it can be seen from the Figure 6.6, the active power losses are 4.25 kW when the active power value at the transformer's secondary side is measured as 50 kW.

Only major costs such as transformers, line towers, cables and conductors are included in the economic analysis to calculate investment costs. Annual maintenance costs for the AC network are assumed to be 2.5% of the investment costs and 1% for the DC network.

Investment costs for the AC network is provided in Table 6.5.

Table 6.5 : Investment Costs for the AC Network in Example Case 1.

Equipment	Unit Price	Total
400 kVA Transformer	$13,557.93	$13,557.93
Tower, 15 m, 4070 kg	$760.99	$17,502.81
Aster Conductor	$689.49/km	$792.91
Rose Conductor	$217.30/km	$249.30
Installation	$1,350.28	$1,350.28
Total		**$33,453.83**

Operational cost calculations for the AC network is summarized in Table 6.6. Total operational costs are calculated as $1,147,840.79 and the present value of the operational costs are calculated as $335,370.86. Therefore, the net present value for the AC network is calculated as $368,824.69 at the end of study period.

Table 6.6 : Operational Costs for the AC Network in Example Case 1.

Parameter	Total
Cost of Losses	$336,905.04
Cost of Energy Not Supplied	$287,636.66
Cost of SAIDI Penalties	$64,547.67
Cost of SAIFI Penalties	$80,395.98
Cost of Salaries	$254,237.29
Cost of Vehicles	$475.42
Cost of Maintenance	$33,453.83
Total	**$1,147,840.79**
Net Present Value	**$335,370.86**

Investment costs for the DC network is summarized in Table 6.7. Same transformer, towers and conductors with the AC network are utilized in the DC network. Converter datasheet and prices are obtained from [67].

Table 6.7 : Investment Costs for the DC Network in Example Case 1.

Parameter	Unit Price	Total
400 kVA Transformer	$13,557.93	$13,557.93
Tower, 15 m, 4070 kg	$ 760.99	$17,502.81
Aster Conductor	$689.49/km	$792.91
Rose Conductor	$217.30/km	$249.30
Installation	$3,182.19	$3,182.19
530 Amps. Rectifier	$6,149.35	$6,149.35
430 Amps Inverter	$16,445.00	$16,445.00
Total		**$63,718.90**

Operational cost calculation for the DC network is summarized in Table 6.8. SAIDI and SAIFI values are assumed to be decreased by 60% in the DC network. Power electronic converters have an economic lifespan of 15-20 years. That means over the analysis period of 40 years, converters in the DC network must be replaced at least once. Therefore, converters are assumed to be replaced in the 20th year of the analysis. Total operational costs are calculated as $552,146.85 and the present value of the operational costs are calculated as $162,136.39. Therefore, the net present value for the DC network is calculated as $225,855.29 at the end of study period.

Table 6.8 : Operational Costs for the DC Network in Example Case 1.

Parameter	Total
Cost of Losses	$174,615.42
Cost of Energy Not Supplied	$115,054.67
Cost of SAIDI Penalties	$59,621.11
Cost of SAIFI Penalties	$75,469.42
Cost of Salaries	$101,694.92
Cost of Vehicles	$203.75
Cost of Maintenance	$25,487.56
Total	**$552,146.85**
Net Present Value	**$162,136.39**

The net present value comparison for AC and DC networks over the analysis period is illustrated in Figure 6.10. The investment costs for the LVDC network are twice as high as those for the AC network. However, at the end of 40 years, benefits gained from the LVDC network result in lower costs which means LVDC network investment is more profitable than the AC network investment. LVDC network becomes more profitable than the AC network at the end of 3rd year.

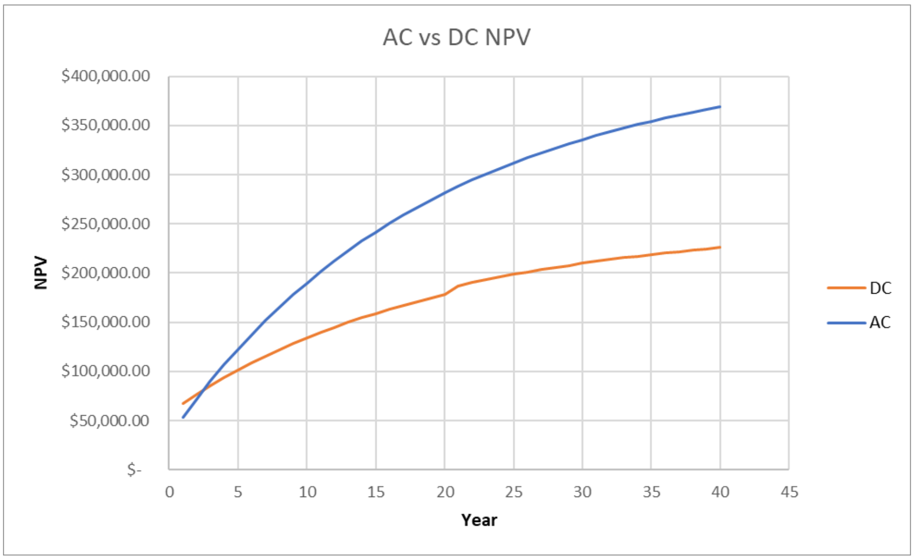

Figure 6.10 : The Net Present Value Comparison in Example Case 1.

6.1.1.1 Sensitivity analysis for example case 1

A few assumptions have been made in the analysis since some of the required data couldn’t be directly obtained or calculated. In order to review the effects of these assumptions on the results, sensitivity analysis must be carried out.

The primary factor contributing to the significant difference in the NPV of the two systems is the cost associated with losses. The variation in the difference in NPV between the two systems is depicted in Figure 6.11. Notably, even when the two systems incur the same amount of losses, the LVDC network remains more profitable than its AC counterpart.

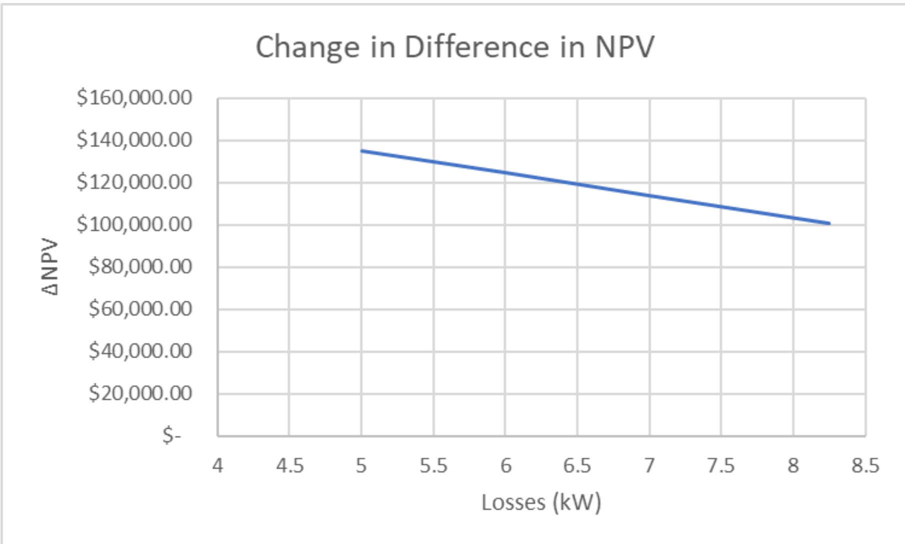

Figure 6.11 : The Variation in the Difference in NPV.

Including SAIDI and SAIFI values into the sensitivity analysis results in graph given in Figure 6.12.

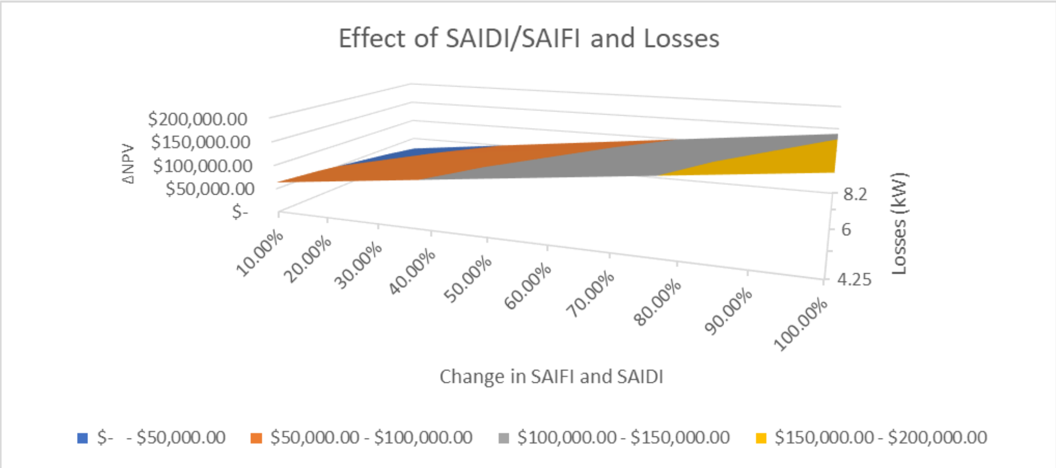

Figure 6.12 : The Variation in the Difference in NPV.

The number of variables could be expanded to enhance the sensitivity analysis; however, given that the current variables represent the largest assumptions in this example, these two should suffice for the purpose of this study.

6.1.2 Example case 2

The single line diagram of the second example case is given in Figure 6.13. The network is located in an urban area in Türkiye. There are 60 customers in total scattered around the 917 meters line. Total demand of the customers is 179 kW and 51 kVAr at 0.4 kV. Since this is an existing network, system operator wishes to explore the upgrade the network to an LVDC system.

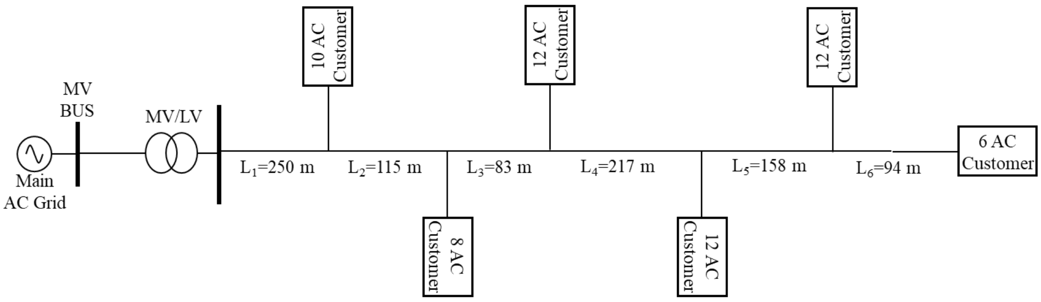

Figure 6.13 : Single Line Diagram of the Example Case 2.

The rated data of the transformer is given in Table 6.9.

Table 6.9 : Rated Data of the Transformer.

Parameter	Value
Rated Voltage	31.5/0.4 kV
Winding Type	DYn11
Rated Power	400 kVA
Leakage Reactance	6.2%
Copper Losses	0.01381 pu
Eddy Losses	0.008737 pu

The distribution overhead line utilizes Aster type phase conductors and Rose type ground wires. The tower is 15 m high and there is 3 m distance between phase conductors. The impedance of the line is given in Table 6.10.

Table 6.10 : Impedance of the AC Distribution Line.

Parameter	Value
Positive Sequence Resistance	0.4287 Ω/km
Positive Sequence Reactance	0.4429 Ω/km
Positive Sequence Susceptance	2.97×10^{-6} S/km
Zero Sequence Resistance	0.7348 Ω/km
Zero Sequence Reactance	1.332 Ω/km
Zero Sequence Susceptance	1.68×10^{-6} S/km

The PSCAD model of the developed AC network is given in Figure 6.14.

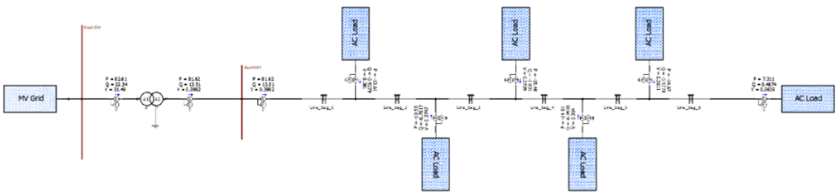

Figure 6.14 : PSCAD Model of the Example Case 2.

The single line diagram of the LVDC network is given in Figure 6.15. The LVDC network topology is chosen as Link Type LVDC distribution network.

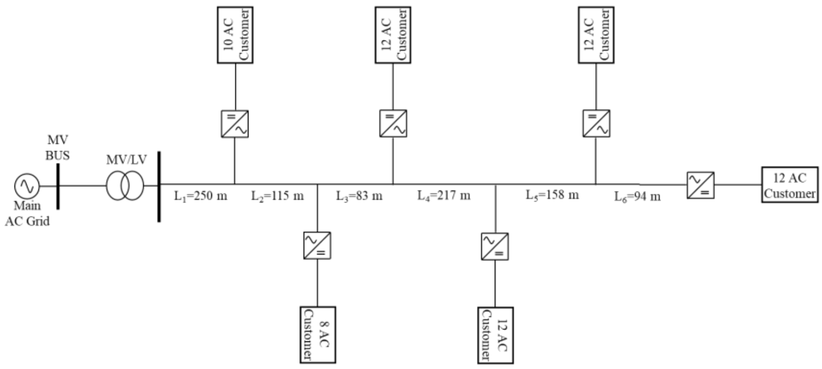

Figure 6.15 : Single Line Diagram of the LVDC Network of Example Case 2.

PSCAD model of the LVDC network of the Example Case 2 is illustrated in Figure 6.16.

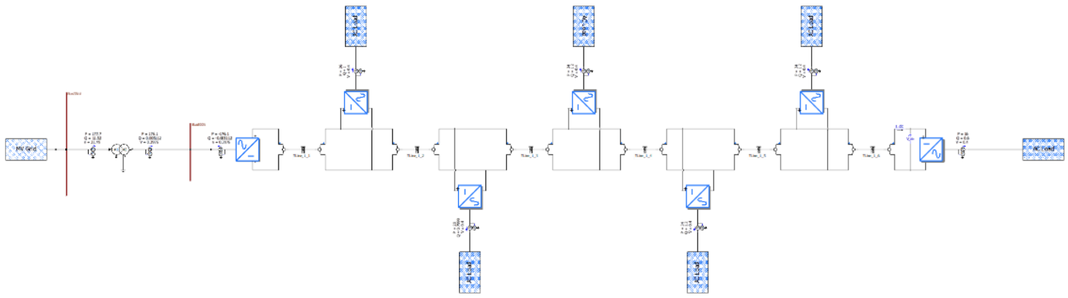

Figure 6.16 : PSCAD Model of the LVDC Network of Example Case 2.

The parameters used in the calculations in Example Case 2 are given in Table 6.11. Since this is an existing network, there are not any investment costs for the AC network. Operational costs of the AC network will be compared against the total of investment and operational costs of the LVDC network.

Table 6.11 : Parameters Used in Calculations in Example Case 2.

Parameter	Value
Energy Price	$0.0939/kWh
Distribution Price	$0.0471/kWh
Load Factor	0.4205
SAIDI	24.08 hours
SAIFI	23.8
Interest Rate	0.07
Personnel Salary	$423.72
Maintenance Personnel	2
Monthly Distance Covered by Maintenance Personnel	10 km
Meter Reading Personnel	2
Monthly Distance Covered by Meter Reading Personnel	5 km
Fuel Price	$0.0283/km
Analysis Period	40 years
TL/$ Rate	16.52

Operational costs for the AC network are given in Table 6.12. Total operational costs are calculated as $2,437,733.50 and the present value of the operational costs are calculated as $664,753.70.

Table 6.12 : Operational Costs for the AC Network in Example Case 2.

Parameter	Total
Cost of Losses	$944,977.57
Cost of Energy Not Supplied	$1,009,854.88
Cost of SAIDI Penalties	$64,579.82
Cost of SAIFI Penalties	$109,147.09
Cost of Salaries	$203,389.83
Cost of Vehicles	$407.51
Cost of Maintenance	$105,376.80
Total	**$2,437,733.50**
Net Present Value	**$664,753.70**

To ensure that the loads are balanced across customer inverters, one customer inverter is allocated for every three customers which means a total of 21 inverters. Power electronic converters have an economic lifespan of 15-20 years. That means over the analysis period of 40 years, converters in the DC network must be replaced at least once. Therefore, converters are assumed to be replaced in the 20th year of the analysis. Investment costs for the DC network are given in Table 6.13.

Table 6.13 : Investment Costs for the DC Network in Example Case 2.

Parameter	Unit Price	Total
25 Amps. Inverter	$4,547.10	$95,489.10
730 Amps. Rectifier	$7,994.16	$7,994.16
Installation	$6,841.71	$6,841.71
Total		**$63,718.90**

SAIDI and SAIFI values are assumed to be decreased by 20% in the DC network. Total operational costs are calculated as $1,889,815.05 and the present value of the operational costs are calculated as $515,717.78. Therefore, the net present value for the DC network is calculated as $729,526.02 at the end of study period. Operational costs for the DC network are given in Table 6.14.

Table 6.14 : Operational Costs for the DC Network in Example Case 2.

Parameter	Total
Cost of Losses	$702,570.28
Cost of Energy Not Supplied	$807,883.90
Cost of SAIDI Penalties	$48,228.13
Cost of SAIFI Penalties	$92,795.40
Cost of Salaries	$152,542.37
Cost of Vehicles	$271.67
Cost of Maintenance	$85,523.29
Total	**$1,889,815.05**
Net Present Value	**$515,717.78**

Comparison of Cumulative Net Present Value between the AC and LVDC networks is illustrated in Figure 6.17.

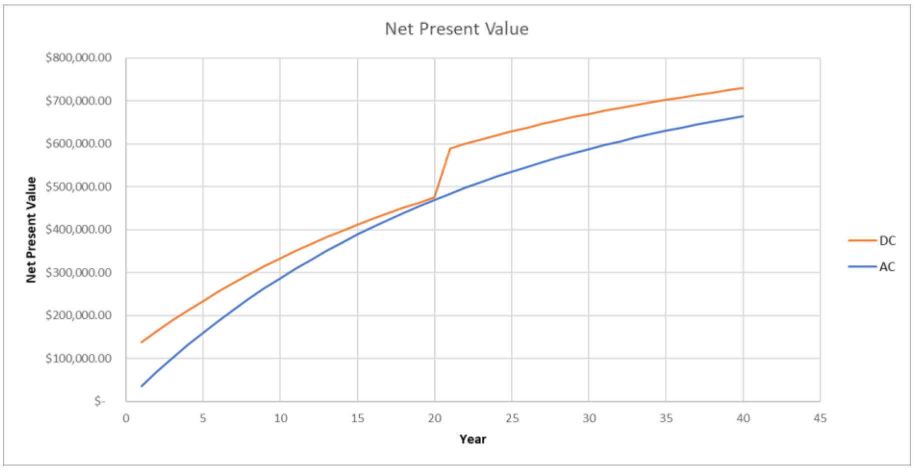

Figure 6.17 : Comparison of Cumulative Net Present Value in Example Case 2.

Although the LVDC network provides a 22% decrease in operational costs, the LVDC network has higher total costs at the end of study period because the DC network has high investment costs.

6.1.2.1 Sensitivity analysis for example case 2

The primary factor contributing to the significant difference in the NPV of the two systems is the investment costs of the LVDC network. The variation in the difference in NPV between the two systems which is caused by the power electronics costs is depicted in Figure 6.18. When the power electronic costs decrease more than 27.6%, the LVDC network investment becomes more profitable than the existing AC network.

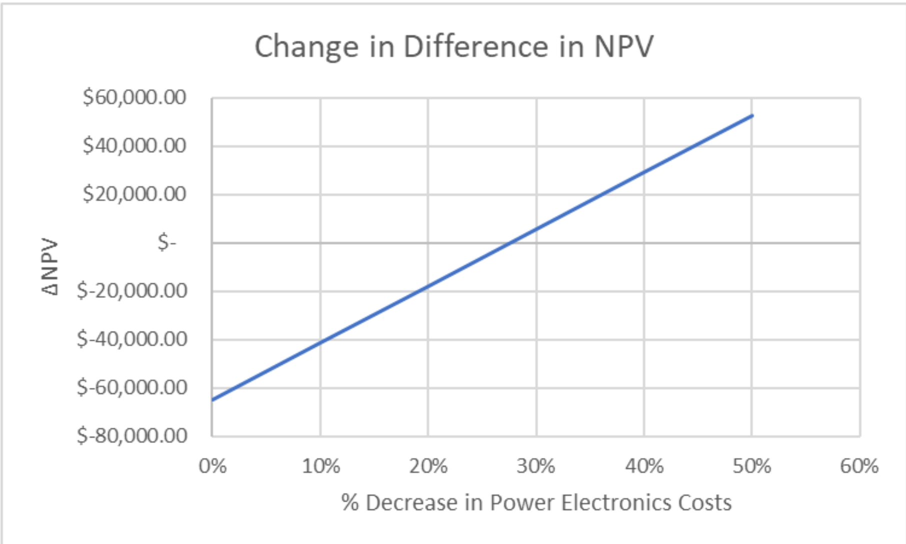

Figure 6.18 : Change in Difference in NPV Caused by Power Electronics Costs.

Change in Difference in NPV caused by decrease in power electronics costs and variation in losses is illustrated in Figure 6.19.

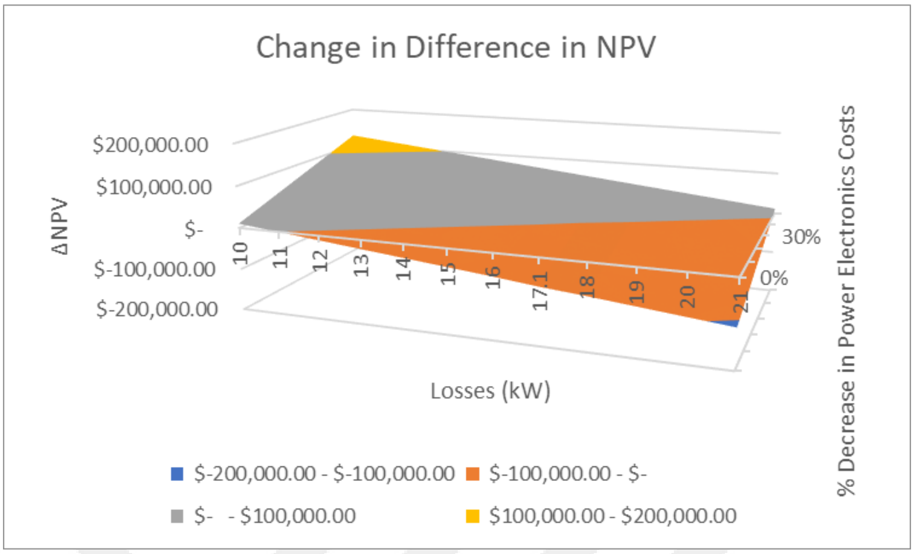

Figure 6.19 : Change in Difference in NPV.

6.2 Discussion and Comparison

In this chapter of the study, results of the example cases will be discussed and compared.

The investment costs per kW calculation for AC and LVDC networks in both example cases are illustrated in Figure 6.20. In the figure Example Case 1 is orange colored and the Case 2 is the blue colored bars. In both cases, LVDC networks have a higher investment cost per unit load. Also, the ratio of investment costs per unit load between DC and AC networks in Example Case 1 is 2 while it is almost 4 in the Example Case 2. This means that, in a long and radial line where high voltage drops occur, the AC networks have a high disadvantage against a long-time expensive investment with lower operational cost which are LVDC networks.

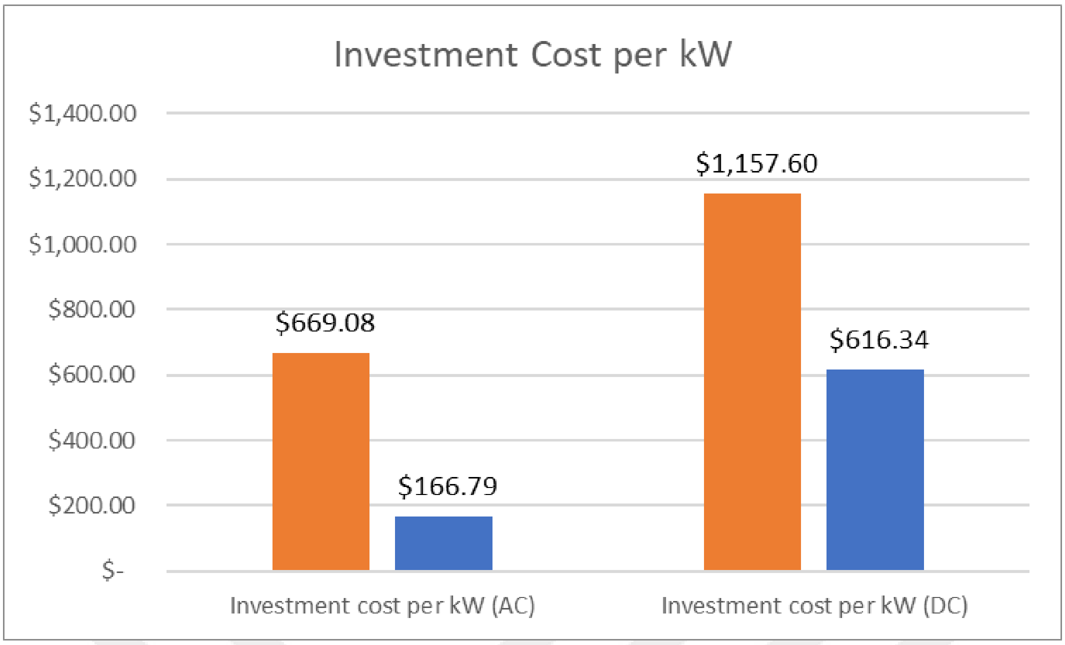

Figure 6.20 : Investment Costs per Unit Load in Example Cases.

Total operational costs in each year per unit load for AC and LVDC networks in both example cases are depicted in Figure 6.21. The AC network in Example Case 1 has the most operational costs per unit load while the LVDC network in Example Case 2 has the lowest operational costs per unit load.

Figure 6.21 : Total Operational Costs in Each Year per Unit Load.

Percentage of each operational cost against the total operational costs in AC network of the Example Case 1 are illustrated in Figure 6.22. The cost of losses has the highest percentage of all costs in this case while the maintenance costs are the lowest except the cost of vehicle operation.

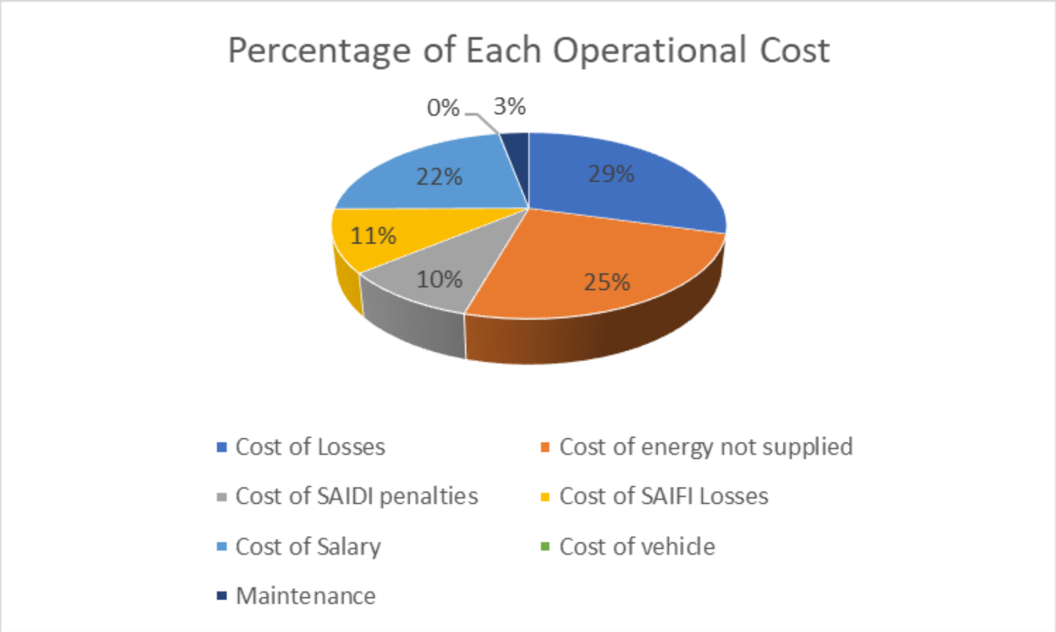

Figure 6.22 : Percentage of Each Operational Cost Against the Total Operational Costs in AC Network of the Example Case 1.

Percentage of each operational cost against the total operational costs in LVDC network of the Example Case 1 are illustrated in Figure 6.23. The cost of losses has the highest percentage of all costs in this case while the maintenance costs are the lowest except the cost of vehicle operation.

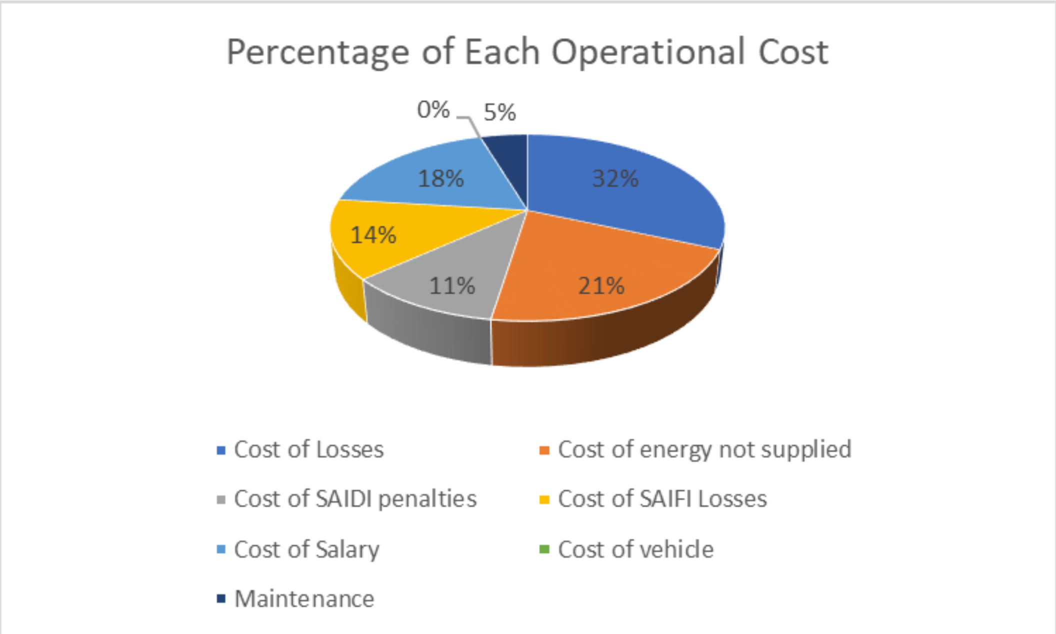

Figure 6.23 : Percentage of Each Operational Cost Against the Total Operational Costs in LVDC Network of the Example Case 1.

Percentage of each operational cost against the total operational costs in AC network of the Example Case 2 are illustrated in Figure 6.24. The cost of energy not supplied has the highest percentage of all costs in this case while the SAIDI penalties are the lowest except the cost of vehicle operation.

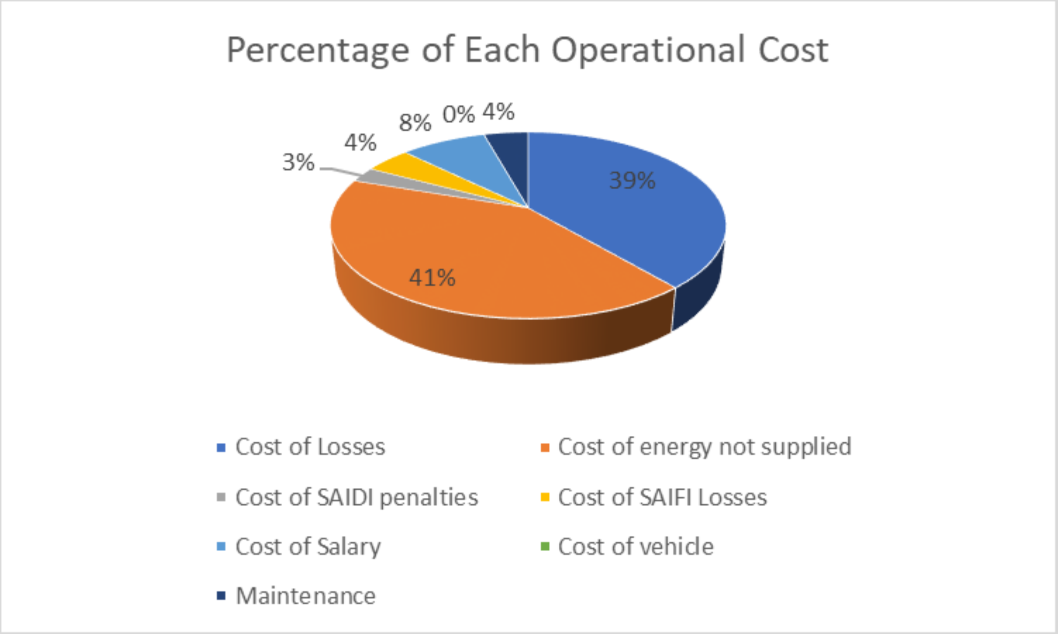

Figure 6.24 : Percentage of Each Operational Cost Against the Total Operational Costs in AC Network of the Example Case 2.

Percentage of each operational cost against the total operational costs in LVDC network of the Example Case 2 are illustrated in Figure 6.25. The cost of energy not supplied has the highest percentage of all costs in this case while the SAIDI penalties are the lowest except the cost of vehicle operation.

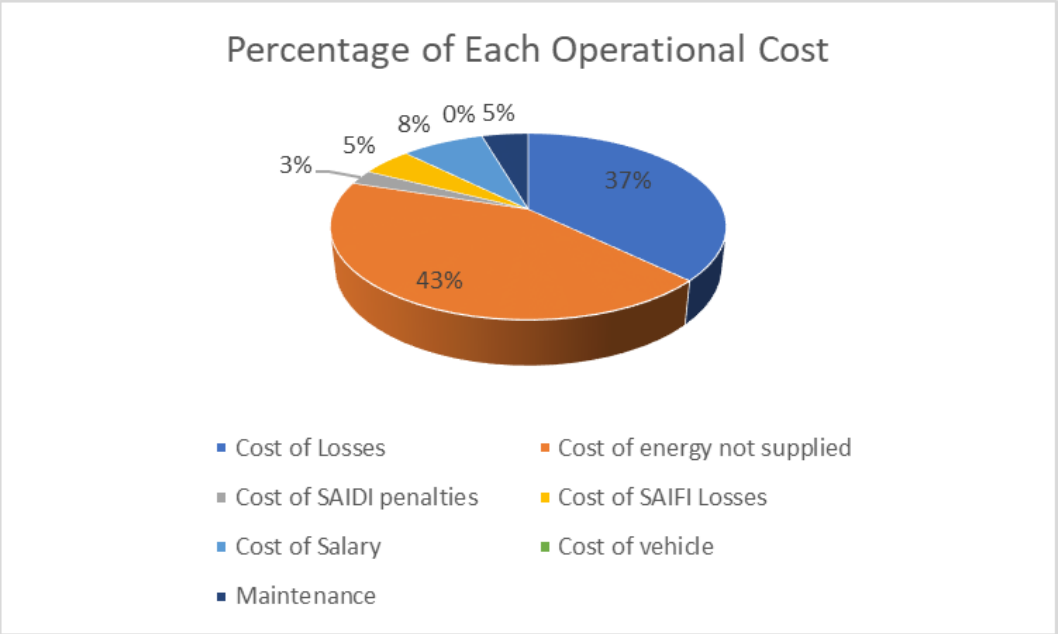

Figure 6.25 : Percentage of Each Operational Cost Against the Total Operational Costs in LVDC Network of the Example Case 2.

Additionally, percent decrease of operational costs provided by LVDC networks in the Example Case 1 are illustrated in Figure 6.26. The LVDC network provides an almost 60% decrease in cost of energy not supplied in the Example Case 1.

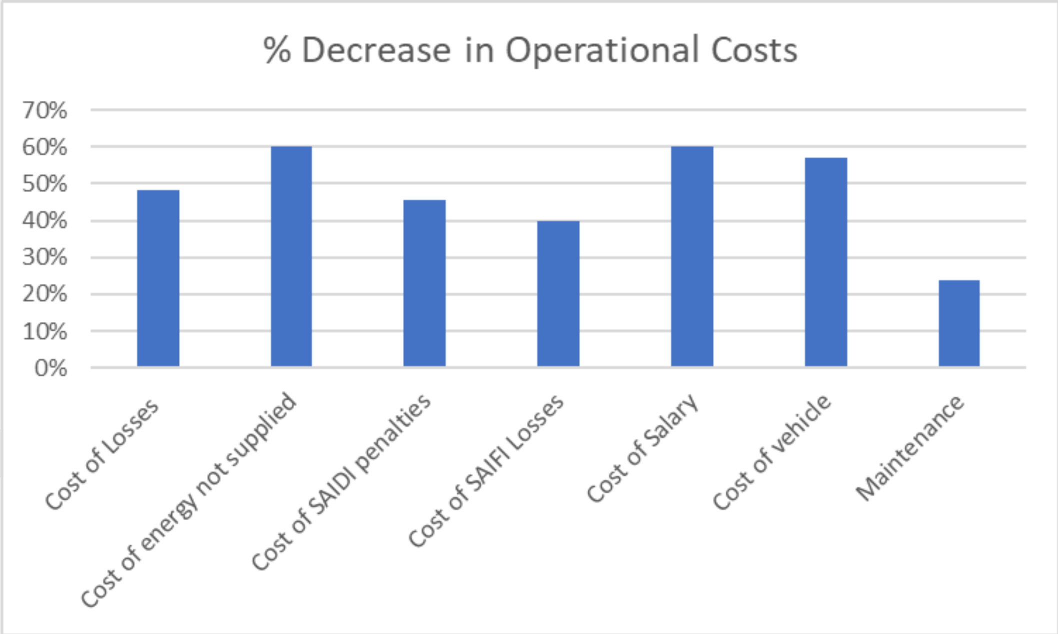

Figure 6.26 : Percent Decrease of Operational Costs Provided by LVDC Networks In Example Case 1.

Percent decrease of operational costs provided by LVDC networks in the Example Case 2 are illustrated in Figure 6.27. The LVDC network provides an 25% decrease in cost of losses in the Example Case 2.

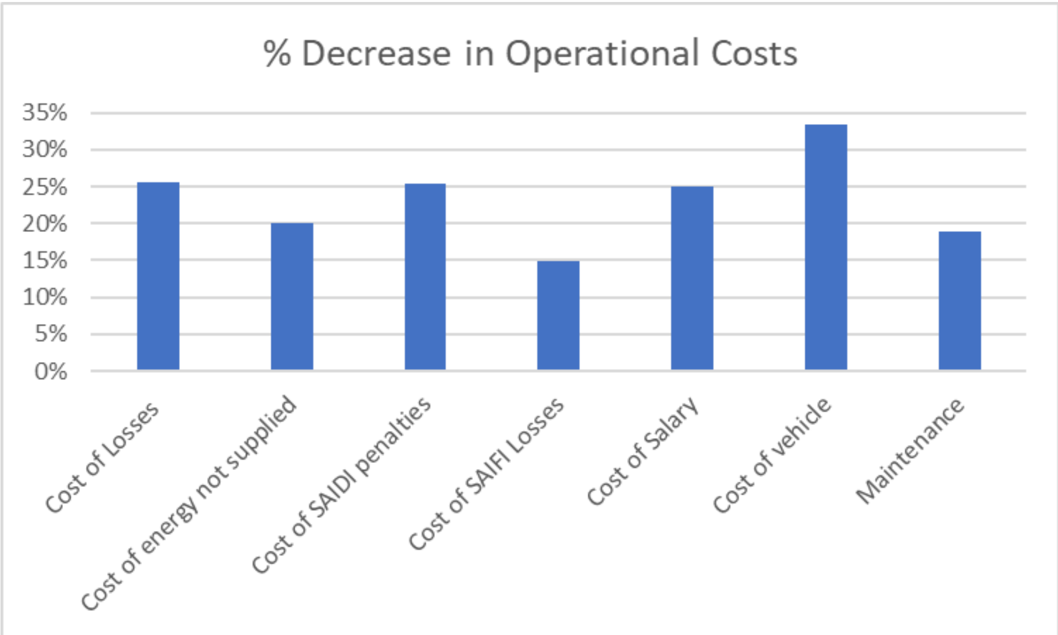

Figure 6.27 : Percent Decrease of Operational Costs Provided by LVDC Networks In Example Case 1.

6.3 Modelling and Simulation

Modelling methods and simulation results in PSCAD will be discussed in this chapter of the study.

Thevenin voltage source used in the PSCAD model is depicted in Figure 6.28. The voltage source was used to model the 31.5 kV AC main grid in the both AC and LVDC networks. The source has a 5.8 X/R ratio with 0.8929 Ω resistance and 0.01658 H inductance. Thevenin voltage source models are generally enough to be used in various studies such as faults, voltage transients and load flow.

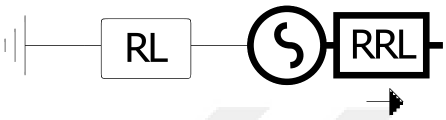

Figure 6.28 : Thevenin Voltage Source Model in PSCAD.

Grid-following VSC method was utilized to create the rectifiers and inverters in the PSCAD models. The outer current control loops of the rectifier used to form the DC grid in the models are depicted in Figure 6.29. The DC voltage control was selected for d axis current control reactive power control was selected for q axis current control. The rectifier is responsible for maintaining the DC voltage in the LVDC network and the reactive power at the AC side of the converter. The d and q axis current references are fed to the inner current control loops in order to obtain voltage references required by the Pulse Width Modulation.

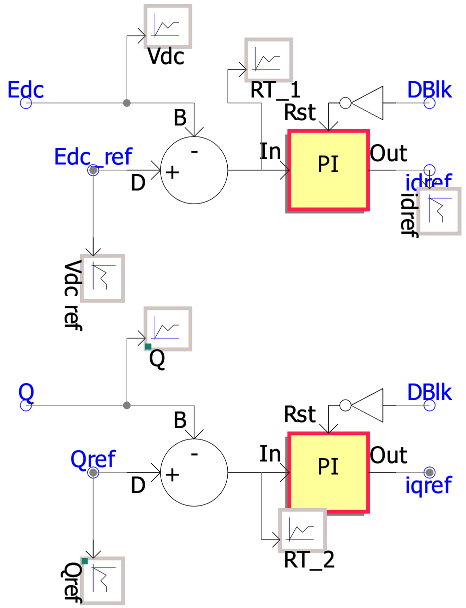

Figure 6.29 : Outer Current Control Loops of the Rectifier.

The inner current control loops of the rectifier used to form the DC grid in the models are depicted in Figure 6.30.

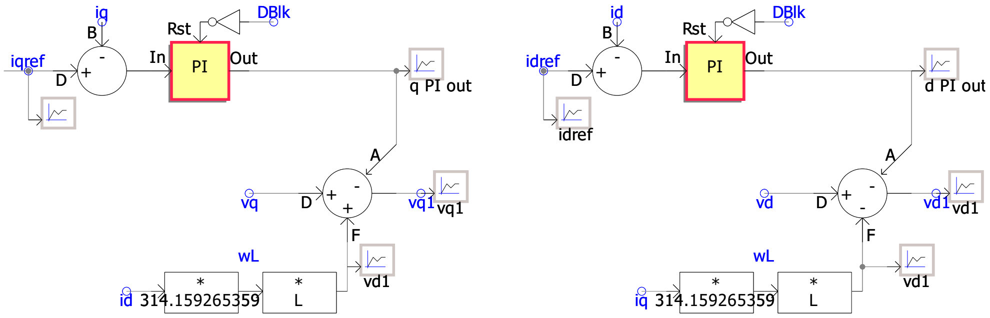

Figure 6.30 : Inner Current Control Loops of the Rectifier.

The outer current control loops of the inverter used to supply the customers in the models are depicted in Figure 6.31. The active power and AC voltage controls were selected for the d and q axis current controls respectively. The inverter is responsible for supplying the customers with 0.4 kV AC voltage.

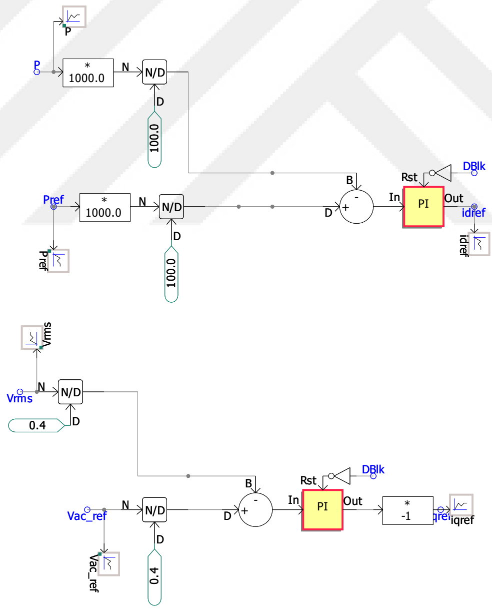

Figure 6.31 : Inner Current Control Loops of the Rectifier.

The parameters of the rectifier are given in Table 6.15.

Table 6.15 : Rectifier Parameters.

Parameter	Value
Switching Frequency	4 kHz
DC Side Capacitance	7800 µF
DC Voltage Reference	1.5 kV
Reactive Power Reference	0 kVAr
High Pass Filter Cutoff Freq.	300 Hz
Inductance	320 µH

The rectifier model is depicted in Figure 6.32. Since this is a voltage source converter, rectifier and inverter have the same circuit diagram. Only difference are the control parameters.

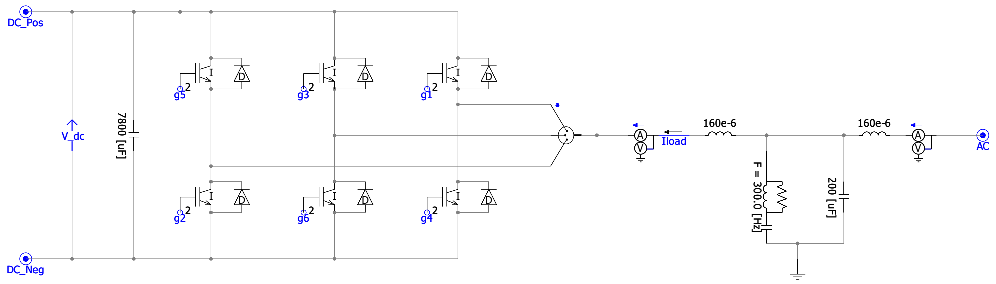

Figure 6.32 : Rectifier and Inverter Model.

The PI control coefficients of the rectifier are given in Figure 6.33 and the PI control coefficients of the inverter are given in Figure 6.34.

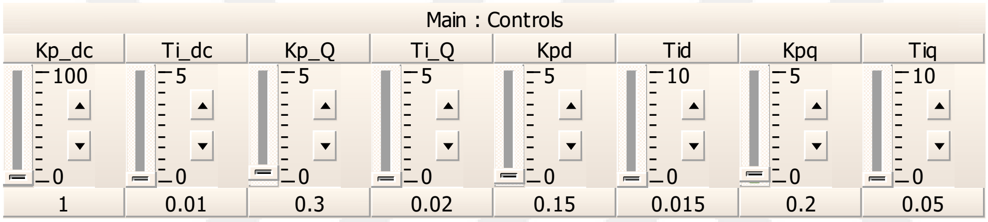

Figure 6.33 : PI Parameters of the Rectifier.

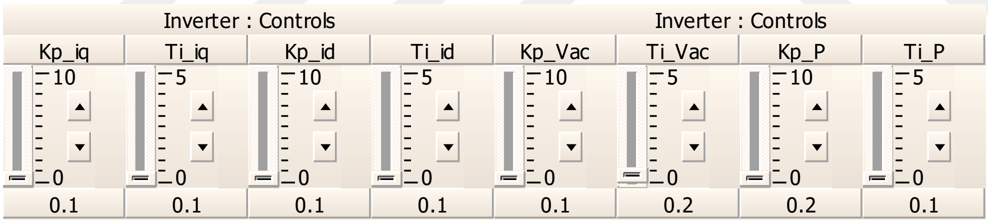

Figure 6.34 : PI Parameters of the Inverter.

The startup of the LVDC network voltage is given in Figure 6.35. The rectifier is activated 0.2 seconds after the start of the simulation.

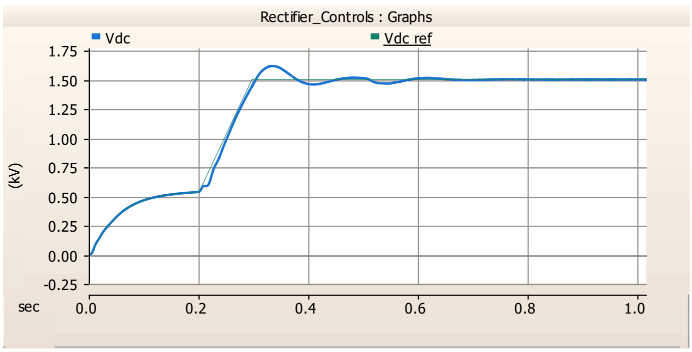

Figure 6.35 : The Startup Of The LVDC Network Voltage.

The startup of the AC voltage is given in Figure 6.36. The rectifier is activated 0.3 seconds after the activation of rectifier since the inverter requires a stable DC voltage in order to operate.

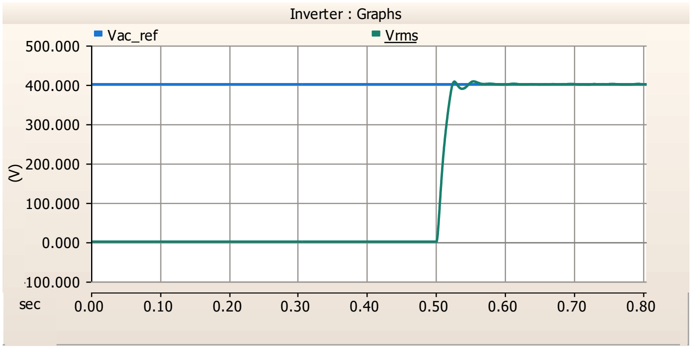

Figure 6.36 : The Startup Of The AC Voltage.

Harmonic distortions in the Example Case 1 caused by the rectifier on the AC grid current are depicted in Figure 6.37. According to IEEE-519 [69], systems rated 120 V through 69 kV have a 5% total harmonic current distortion limit. The total harmonic distortion caused by the rectifier is below 1% as can be seen from the Figure 6.38.

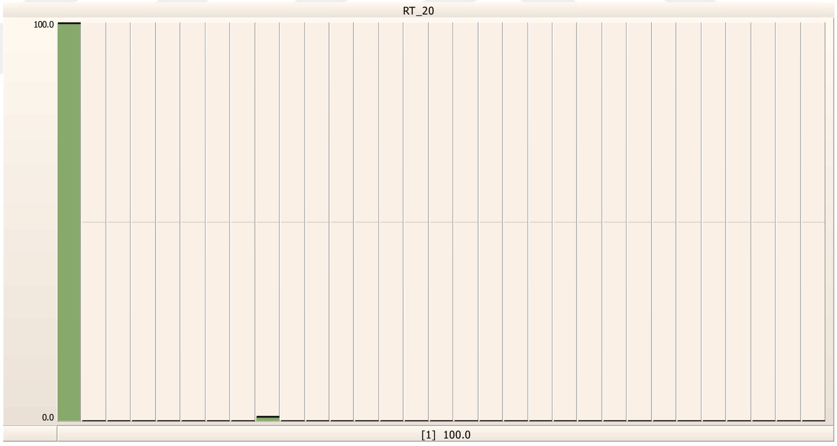

Figure 6.37 : Individual Harmonic Current Distortions Caused by The Rectifier.

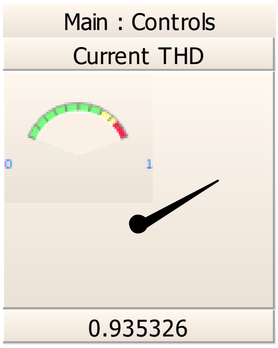

Figure 6.38 : Individual Harmonic Current Distortions Caused by The Rectifier.

Harmonic distortions caused by the inverter are depicted in Figure 6.39. The total harmonic distortion caused by the rectifier is below 0.5% as can be seen from the Figure 6.32.

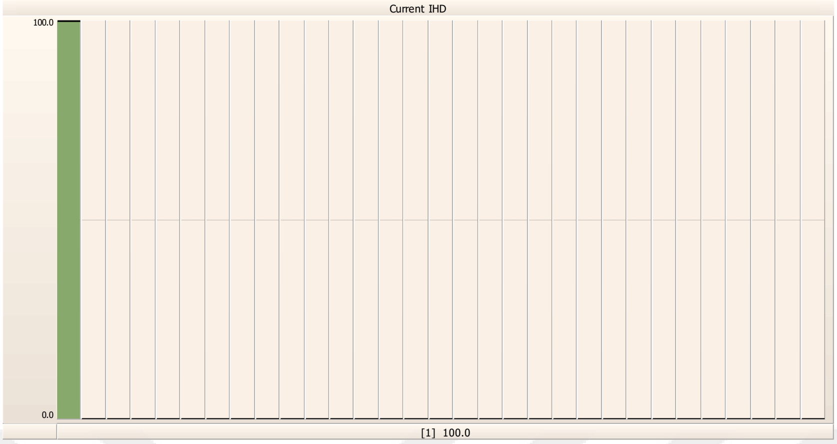

Figure 6.39 : Individual Harmonic Current Distortions Caused by The Inverter.

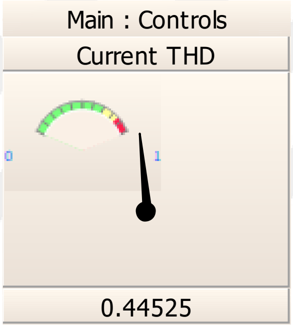

Figure 6.40 : Individual Harmonic Current Distortions Caused by The Inverter.

The customer supply voltage during a single phase to ground at the AC side of the rectifier is given in Figure 6.33. The faults at the main AC grid have minimum effects on the customer's supply voltage.

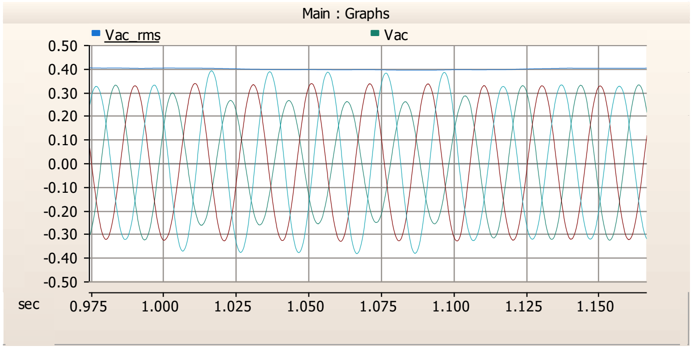

Figure 6.41 : The Customer Supply Voltage During A Fault.

The DC network voltage during the faults is depicted in Figure 6.34. The voltage source converter has FRT capability as previously discussed in the Section 3. The rectifier’s independent reactive power control capability can be utilized to support the main AC grid during faults. This can be achieved by enabling the rectifier to inject reactive power to the AC grid to support the voltage.

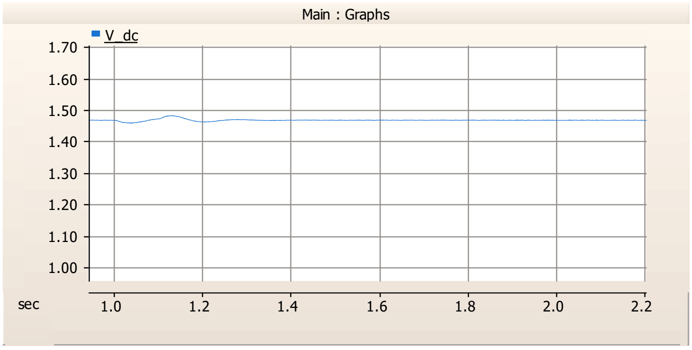

Figure 6.42 : The LVDC Network Voltage During A Fault.

Harmonic distortions in the Example Case 2 caused by the rectifier on the AC grid current are depicted in Figure 6.43. According to IEEE-519 [69], systems rated 120 V through 69 kV have a 5% total harmonic current distortion limit. The total harmonic distortion caused by the rectifier is below 1% as can be seen from the Figure 6.44.

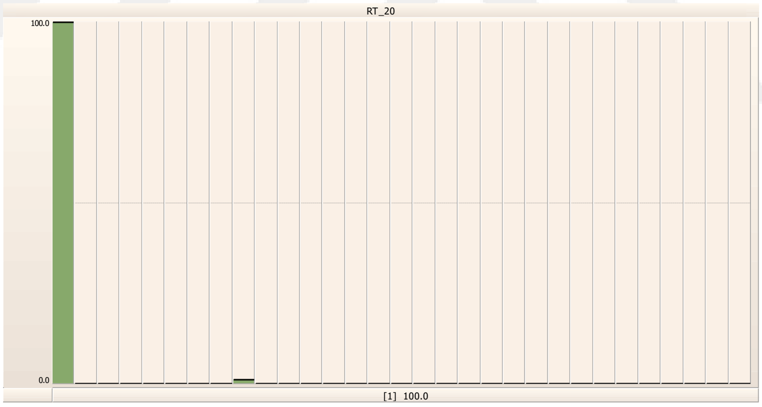

Figure 6.43 : Individual Harmonic Current Distortions Caused by The Rectifier.

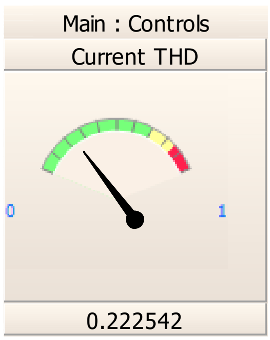

Figure 6.44 : Individual Harmonic Current Distortions Caused by The Rectifier.

Harmonic distortions caused by the customer inverter are depicted in Figure 6.45. The total harmonic distortion caused by the rectifier is below 0.5% as can be seen from the Figure 6.46.

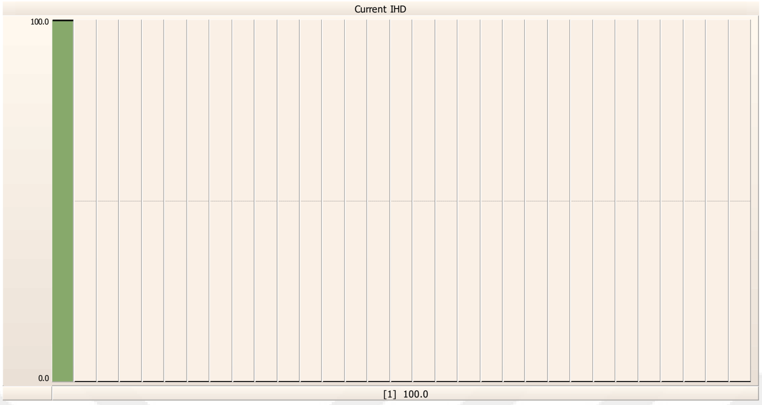

Figure 6.45 : Individual Harmonic Current Distortions Caused by The Inverter.

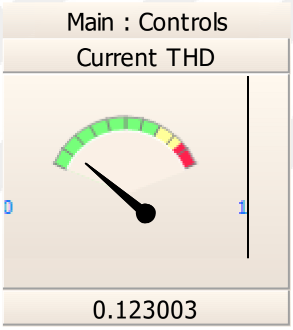

Figure 6.46 : Individual Harmonic Current Distortions Caused by The Inverter.

7. CONCLUSIONS AND RECOMMENDATIONS

The consumption and generation of electricity in its DC form are rapidly increasing, particularly at low voltage levels. This trend is evident in devices and applications such as home appliances, computers, mobile phones, electric vehicles, and roof-type photovoltaic (PV) and wind-based generation systems. Many conversion steps of electrical energy lead to additional losses which cause lower efficiency. Eliminating some or all conversion steps could contribute to a greener future and reduce costs for system operators. LVDC distribution networks appear to be a viable alternative to conventional AC distribution networks. However, extensive research is necessary to enable a safe transition to LVDC networks. It is crucial for system operators to carefully plan and analyze these networks to determine their investment viability. Consequently, cost/benefit analysis emerges as an essential tool to assist system operators in addressing this challenge.

In the example case 1, it was demonstrated that an LVDC distribution network could be a superior alternative to an AC network when customers are located at the end of a long distribution line. The long line's resistance results in significant voltage drops and higher system losses. However, the AC voltage control of the power electronic converter and the characteristics of DC voltage can reduce losses by 50%. Despite higher initial investment costs for the DC network, it proved to be more profitable than the AC network over a 40-year period. The NPV of the operational costs for the AC network was nearly double that of the DC network. The primary cost differences stemmed from energy not supplied and losses in the AC network. A sensitivity analysis indicated that even when both systems experienced the same amount of losses, the LVDC network remained more profitable than the AC counterpart.

In the example case 2, it was shown that replacing the existing AC network with an LVDC network was not worth the investment due to the high costs of power electronics, despite the LVDC network's significant reduction in operational costs. However, sensitivity analyses indicated that the LVDC distribution network could become a worthwhile investment if the costs of power electronics continue to decline annually [68]. The analysis showed that if the investment costs of converters decrease by more than 27.6%, the LVDC distribution network would be a viable investment. In a further sensitivity analysis, it was shown that even if the error margin in the calculated losses were higher than 20%, the LVDC distribution network would be a viable investment if the investment costs of converters decreased more than 43%.

In this study, it was shown that LVDC distribution systems can be an optimal alternative for the conventional AC grids under certain circumstances. As the economic lifespan of power electronics improves and the costs continue to decline, LVDC distribution has the possibility to become an alternative in many cases.

The study results indicate that choosing the optimal LVDC distribution topology is a significant factor influencing the outcome of the cost/benefit analysis. Obtaining accurate information and data about the area under study and modeling with high precision are among the most critical factors affecting the accuracy of the results. Another major factor affecting the results are the assumptions made in the costs or parameters. In this study, the interest rate is assumed to be 7% and the inflation rate is assumed to be 0% which corresponds to a 7% of real interest rate. NPV curve could become more linear if an inflation rate is assumed in the calculations. Another assumption made in the studies is that energy prices, distribution of energy prices, salaries, SAIDI and SAIFI are assumed to be constant during the 40-year period. Accounting a variable increase or decrease in the calculations may result in favorable outcomes for the LVDC distribution networks.

The methodology used in this study considers various benefits enabled by LVDC distribution networks. However, the cost/benefit analyses only account for the costs of losses, energy not supplied, manpower, and penalties. Although these are the most significant costs or benefits, including benefits such as improved power quality, enhanced control capabilities, and greater integration of renewables could lead to more precise and accurate results in favor of LVDC distribution networks. Additionally, incorporating a design acceptance criterion, such as voltage drops as a power quality measure, may be necessary for system design. This approach ensures that benefits not easily quantified as cost savings can still be recognized as excellence factors.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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