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THREE-PHASE MODULAR MULTILEVEL CONVERTER BASED UNIFIED POWER FLOW CONTROLLER

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EMILE NJODZEFON WIRSIY
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Three-Phase Modular Multilevel Converter Based Unified Power Flow Controller

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Assoc. Prof. Dr. A. Mete VURAL

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Emile Njodzefon WIRSIY

ABSTRACT

THREE-PHASE MODULAR MULTILEVEL CONVERTER BASED UNIFIED POWER FLOW CONTROLLER

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The power system needs to be flexible to cater for the increasing demand by its consumers. Flexible AC Transmission System (FACTS) devices use power electronic devices to achieve this by controlling some power system parameters. The Unified Power Flow Controller (UPFC) is the most versatile and flexible of FACTS devices. Modeling of UPFCs is not an easy task especially with the recent introduction of modular multilevel converters (MMC) as a new type of voltage source converter (VSC). Most models are average or equivalent circuit models which do not really depict the situation when UPFCs are implemented practically. This thesis provides a detailed model of an MMC based UPFC made up of half-bridge converter sub modules. An MMC has been designed and tested in a simulation environment before being connected in back to back mode with one end in series and the other in parallel with a transmission line (UPFC configuration). A dq real and reactive power flow control scheme has been proposed and results obtained from the numerous simulations will be presented. UPFC is able to control real and reactive power flows on the chosen line and at the same time, it can control the bus voltage dynamically while the power flow control loops are active.

Key Words: Flexible AC Transmission Systems (FACTS), Unified Power Flow Controller (UPFC), Voltage Source Converter (VSC), Modular Multilevel Converter (MMC), Half Bridge Sub-module, Real and Reactive Power Flow Control and Bus Voltage control.

ÖZET

ÜÇ-FAZLI MODÜLER ÇOK SEVIYELI DÖNÜŞTÜRÜCÜ TABANLI BIRLEŞIK GÜÇ AKIŞI KONTROLÖRÜ

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Güç sisteminin tüketiciler tarafından artan talebi karşılamak için esnek olması gerekmektedir. Esnek AC İletim Sistemi (FACTS) cihazları, bunu başarmak için güç elektroniği cihazlarını kullanarak bazı güç sistemi parametrelerini kontrol ederler. Birleşik Güç Akış Kontrol Cihazı (UPFC), FACTS cihazlarının en çok yönlü ve esnek olanıdır. UPFC'nin modellenmesi, özellikle yeni bir tür gerilim kaynağı dönüştürücüsü (VSC) olan modüler çok seviyeli dönüştürücülerin (MMC) yeni tanıtımıyla kolay bir iş değildir. Çoğu model, UPFC'ler pratik olarak uygulandığında durumu gerçekten betimleyemeyen ortalama veya eşdeğer devre modelleridir. Bu tez, yarım köprü konvertörü alt modüllerinden oluşan bir MMC tabanlı UPFC'nin ayrıntılı bir modelini sunmaktadır. Bir MMC, İletim hattına (UPFC konfigürasyonu) bir tarafı seri, diğer tarafı ise paralel bağlı olarak sırt-sırta bağlı modda bağlanmadan önce bir benzetim ortamında tasarlanmış ve test edilmiştir. Bir dq aktif ve reaktif güç akış kontrol şeması önerilmiştir ve birçok simülasyondan elde edilen sonuçlar sunulacaktır. UPFC, seçilen hattaki aktif ve reaktif güç akışlarını aynı zamanda kontrol edebilir ve güç akış kontrol döngüleri aktifken, bara gerilimini dinamik olarak kontrol edebilir.

Anahtar Kelimeler: Esnek AC İletim Sistemleri (FACTS), Birleşik Güç Akış Kontrol Cihazı (UPFC), Gerilim Kaynağı Çeviricisi (VSC), Modüler Çok Seviyeli Dönüştürücü (MMC), Yarım Köprü Alt Modülü, Gerçek ve Reaktif Güç Akışı Kontrolü ve Veriyolu Voltaj Kontrolü.

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Dedicated to my mother

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LIST OF ABBREVIATIONS

AAC	Alternate Arm converter
AC	Alternating Current
APOD	Alternate Phase Opposition Disposition
B2B	Back to Back
CHB	Cascaded H Bridge
CPS	Carrier Phase Shifted
CSC	Current Source Converter
DC	Direct Current
DCC	Diode Clamped Converter
FACTS	Flexible Alternating Current Transmission System
FB	Full Bridge
FC	Flying Capacitor
GUPFC	Generalized Unified Power Flow Controller
HB	Half Bridge
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IPFC	Interline Power Flow Controller
JFET	Junction Field Effect Transistor
KCL	Kirchhoff Current Law
KVL	Kirchhoff Voltage Law
MMC	Modular Multilevel Converter

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MSC	Mechanical Switched Capacitors
NLM	Nearest Level Modulation
NPC	Neutral Point Clamped
POD	Phase Opposition Disposition
PWM	Pulse Width Modulation
SCR	Silicon Controlled Rectifier
SHEPWM	Selective Harmonic Elimination Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SSR	Sub Synchronous Resonance
SSSC	Series Static Synchronous Compensator
STATCOM	Static Synchronous Compensator
SVPWM	Space Vector Pulse Width Modulation
TCR	Thyristor Controlled Reactor
THD	Total Harmonic Distortion
TSC	Thyristor Switched Capacitor
UPFC	Unified Power Flow Controller
VSC	Voltage Source Converter

LIST OF SYMBOLS

C	Capacitance
Ω	Ohm
Hz	Hertz
Id	Direct-axis Current
Idc	Direct Current
Iq	Quadrature-axis Current
$Ishunt$	Shunt Current
KV	Kilovolts
L	Inductance
N	Number of sub modules
P	Active Power
Pdc	DC Power
P_{in}	Input Power
P_{loss}	Lost Power
P_{out}	Output Power
R	Resistance
V	Voltage
VAR	Volt-Ampere Reactive
V_{dc}	DC Voltage
V_o	Output Voltage
V_{ref}	Reference Voltage
Vse	Series Injected Voltage

W	Watt
$\cos\delta$	Power Factor
dv/dt	Voltage Rise Speed
fc	Carrier Frequency
fr	Reference Frequency
ic	Circulating Current
k	Output Voltage Level Number
ma	Amplitude Modulation Index
ms	Millisecond
$n(t)$	Insertion Index
vla	Lower Arm Voltage
vua	Upper Arm Voltage
ωo	Fundamental Frequency

CHAPTER 1
INTRODUCTION

1.1 Introduction

Recently, the human population has been increasing at an alarming rate bringing about an increase in demand for basic commodities such as electrical energy. As if this is not enough, frequently occurring issues at the transmission end of an electrical power system like overloading of lines, loop flows, non-optimal loading of transmission corridors, voltage control problems and instability issues (dynamic and transient) only contribute in making matters worse. These energy demands and problems have to be solved by power system engineers in companies basically by adjusting grid parameters or by producing more energy. These engineers are tasked with improving the quality of the supplied power and broaden the network to cater for the increasing demand. The use of power electronic devices appears to be the most feasible option when compared to the establishment (or expansion of already existing ones) of new power plants [1]. That is why, recently they have been attracting a lot of interest from researchers because they can be used to convert energy from one form to another e.g. AC to DC and vice versa. Their numerous applications in High Voltage Direct Current (HVDC) systems and Flexible Alternating Current Transmission systems (FACTS) also accounts for this. The above mentioned issues were first solved by the application of power electronic devices in HVDC Transmission systems. But nowadays, these devices are being used preferable in FACTS for the main reasons with the same objectives.

FACTS devices offer more controllability to electric transmission systems by adjusting one or more variables of power systems hence enhancing their operational characteristics. FACTS can also redistribute power flow in transmission lines to avoid overloading of some lines while improving steady and transient state stability. These devices were first proposed by Hingorani NG and L. Gyugyi and their book "Understanding FACTS' published in 1999 [1] is a fundamental requirement for anyone interested in FACTS. These devices have undergone revolution in recent years with some being modified and some newly discovered. Static Synchronous Compensator (STATCOM) is an example of a shunt connected FACTS device which is typically a voltage source converter (VSC) connected in parallel with the power system with the control of reactive power or voltage as its main role. On the other hand, Static Series Synchronous Compensator (SSSC) is a Series FACTS device which is made up of a VSC connected to the transmission line via a series transformer. SSSC is responsible for active power control. Other series connected FACTS devices include the TCSC. Another type of FACTS device is composed of two or more converters (VSCs) which can be connected to the power system either in series or in parallel. Unified Power Flow Controller (UPFC) which is the core of this work falls under this category. Interline power flow controller (IPFC) is like a UPFC but differs in that all the VSCs are connected in series to the transmission line used for power transfer [2]. From the above examples, it can be seen that FACTS devices can be classified in four categories, Series connected, Shunt connected, combined Series and shunt connected and combined series and series connected FACTS devices. UPFC refers to a STATCOM and an SSSC put together. It is the most powerful and flexible FACTS device because it can be used for several purposes e.g. it can function as a STATCOM, SSSC or UPFC [3] controlling active power, reactive power on the transmission line depending on the condition.

The UPFC is a FACTS device which can control more than variable in a power transmission system hence making it a multi-variable controller. These devices can control voltage, impedance and phase angle of a transmission line at the same time or selectively. Reduction of system oscillations, voltage support, improvement of transient stability and independent control of real and reactive power are amongst the areas of application of these devices. UPFC like all other FACTS devices are not standalone devices and need other circuit components or devices for proper functioning. The power converters are the main building blocks needed to set up these devices. Voltage source converters (VSC) and current source converters (CSC) are the two types of converters [1] that exist but VSC are preferred because they are cheaper and the capacitor acts as a voltage source (can also serve as a storage device). VSC has evolved from one, two or three output voltage levels to the multi-level types, the modular multilevel converter (MMC) being an example of this. FACTS is a new promising technology and a UPFC based on MMC has been studied, modeled and incorporated in a transmission system to improve on the systems performance.

1.2 Motivation for the Thesis

In the past the power system grid was very simple because of the fact that power was flowing in one direction only with a power plant producing energy and transmitting to consumers via transmission lines. However, things have become more complex with the introduction of smart grids, renewable energy addition to systems, bidirectional and multidirectional power flow and also the adaptation of existing grids to be flexible to changing as well as fluctuating system parameters to meet the demand by consumers [4] and to cancel out faults. In an effort to understand the situation in order to look for solutions and test them in a simulation environment is the main aim of this thesis. FACTS devices can be used to vary or control system variables to make them operate at optimum without exceeding thermal, Dielectric and stability limits of the line used in transmission. The most important component in the design of a UPFC is the VSC converter which is connected in parallel and in series to the transmission line. Various VSCs (one, two or three level converters) have been used in the past, though they always have one problem or the other. Modular Multilevel Converters (MMCs) introduced in 2002 by R. Marquartz in 2002 [3] is a modified version of the CHB and the trans-bay cable 2010 by SIEMENS (400MW, ±200KV) was the first MMC-HVDC project. Multilevel converters have been in use for almost 40 years. Neutral Point Clamped (NPC), flying capacitor (FC) and CHB converters were the most common multilevel converters before the advent of MMC in 2002 [5]. Many papers support the use of MMC for HVDC applications [6] [7] [8] meanwhile the scope of utilization of MMCs in FACTS devices is not as prevalent showing that there is not enough information and research in this area. Therefore, the study of MMCs is necessary in order to apply this knowledge to the most flexible and powerful member of FACTS family (UPFC). The MMC which is a multilevel converter which shows very good characteristics and advantages but the design of a suitable model is the main puzzle. Many models have been proposed; average models [9], detailed models [9] and some equivalent circuit models [10]. Most of them don’t mimic what happens when the device is used practically in a real life situation, making them suitable only for theoretical studies since many assumptions are made. Detailed models exist but the computational speed is also an unresolved issue which varies greatly with increase in the number of sub modules in a phase leg while some of the components are in a black box where users just have to specify their own parameters. Thus the need to develop a detailed model showing how the semiconductor devices switch on and off when being implemented is the main motivation for this work. People need to understand what is happening inside the so called ‘black boxes’. This MMC model which is to be used in the UPFC should function properly and be stable in steady and transient conditions making the system stable and flexible.

1.3 Purpose of the Thesis

The main objectives of this thesis are;

- To study MMCs. FB and HB sub modules of an MMC will be studied but more emphasis will be laid on HB sub module since it is used in this work because semiconductor losses are lower and they are cheaper when compared to their counterpart’s reason why they are mostly used for commercial purposes.
- To Model and simulate a back to back MMC producing 30KV at its AC output.
- To model and design a UPFC made up of two MMCs, one connected in series and the other in shunt. The 30KV back to back MMC will be integrated to a 154KV voltage line of a transmission system via step up transformer.
- To study the real and reactive power flow in the transmission system in the presence of the UPFC and in the absence of the UPFC in a simulation environment.
- Finally, the dq reference frame real and reactive power control loop is designed and tested in several operation conditions to see the effects of the UPFC on the power system. The bus voltage control system is also designed and studied.

1.4 Significance of the Thesis

The power system is developing and growing at a fast rate especially with the introduction of smart grids, micro grids, large and renewable energy sources like large off-shore wind plants, solar in to the main grid. This increases the general structure and makes control of system parameters very difficult. Energy demands can never be matched and the gap between demand and supply keeps on increasing as years go by. All of this necessitates the utilization of high power converters build from semiconductor devices to curb these problems since research on these devices advances daily and has a promising future. In an attempt to control two or more system parameters, this work will provide a model of the strongest FACTS devices i. e UPFC. Some work has been done on the UPFC modeling using other multilevel converter types as the VSC type but these types of converters have inferior characteristics when compared to MMCs.

1.5 General Outline

This thesis will be presented in seven chapters with the information flowing from one chapter to the next in a well-organized manner.

As we have seen so far, introduction is covered in **Chapter 1**, in which we have looked at a brief background of what this thesis will cover as well as motivations and its importance.

Chapter 2 provides an in depth literature review on Modular Multilevel Converters and UPFC to bring everybody up to speed on what has already been done so that the objectives of this work will become clearer. Basically, it summarizes work that has already been done by researchers.

Chapters 3 will give a short description on FACTS devices which is not too detailed but mostly dueling on general information needed to understand the operation of these devices. Various FACTS devices have been studied but emphases are on the UPFC.

Chapter 4 starts with a brief introduction of multilevel converters before focusing on the MMC. The features which make the MMC superior to the others will be explained and the HB and FB sub module configurations will be studied and compared.

Chapter 5 covers the three phase modeling of an MMC based UPFC. This proposed model is simulated and the results have been presented in **Chapter 6**.

A conclusion will be reached at in **Chapter 7** where recommendations for future work are also be given by the author.

CHAPTER 2

LITERATURE REVIEW OF UPFC AND MMC

2.1 Introduction

This section covers past and ongoing research in the areas of UPFC and MMC. Research on UPFC and MMC is thought to have begun immediately after their introduction in 1992 (by Gyugyi) and 2002 (by R. Marquartz), respectively. Immediately after the introduction of the UPFC, most researchers focused on modeling, design and analysis of the UPFC in order to know their characteristics and various operation modes. This was followed by a series of works to determine the type of semiconductor devices to be used in the construction of the VSCs. The short comings (poor output voltage waveform, presence of harmonics, smaller capacity etc.) of the two and three level VSC based UPFC led to the discovery of MMC as a suitable replacement for the above mentioned converters. An MMC is one kind of VSC topology which although possesses good characteristics, existence of issues like unequal capacitor voltage of sub modules, circulating currents existence, DC fault occurrences and need for fast simulation and easily realizable models are being studied currently by researchers all over the world. Literature review has been done in two sections. Firstly, we have looked at the state of the art for UPFC which is followed by that for the MMC.

2.2 Literature Review on UPFC

L. Gyugyi et al. [11], proposed a more generalized independent real and reactive power flow control in 1995. Their work also included comparisons between the UPFC and the thyristor- controlled series capacitor (TCSC) from a power flow control point of view to determine the best. Simulation results obtained from different situations or cases showed that the UPFC had an upper hand.

A simple power control scheme was presented in [12] which is similar to the decoupled control but with the addition of a predictive control loop and DC voltage control allowing the UPFC to keep track of the real and reactive power reference values. I. Papic et al. (1997) made use of the NETOMAC program to check the validity of their scheme which showed a decrease in the current harmonic distortion and more stability in worst case scenarios when the decoupled control scheme is applied.

The behavior of a UPFC built with the help of a hysteresis current forced back to back converter was studied in the PSCAD/EMTDC environment by Toufan M. and U. D. Annakkage (1998). Improved stability, an approximately constant DC voltage and the ability of the UPFC to allow power flow in both directions were some of the observations made in [13].

Generally, all UPFC control systems should be able to control the real and reactive power flows in a line to be approximately equal to their references and also to make the system dynamically and transiently more stable [14]. K. R. Padiyar et al. (1998) in their paper controlled real power flowing in a transmission line by introducing reactive voltage (Real and reactive voltages are both parts of the introduced voltage and are in phase). Measurements recorded locally are used in regulating bus voltages and by so doing, controlling reactive power too. Results obtained were satisfactory.

In 2001, a rudimentary UPFC control system was introduced by D. G. Cho et al. which did not require a phase lock loop (PLL) since only the stationary frame was considered. This model appears cheaper and simpler when compared to others (Synchronous reference frame requires a PLL). A series and shunt inverter control block are built with PI controllers, sum etc. using PSCAD/EMTDC 3.0 and the output is the input of the SPWM modulation technique [15].

L. Zhang et al. in 2002, put forward control strategy of series and shunt parts of a dynamically developed model based on PI's. Park's transformation helps to turn the instantaneous voltage and currents to the d and q axis components for easy manipulation. Two types of series control are employed in their work [16], decoupled PQ control and the usual active and reactive power control. The designed UPFC was then placed at the center of a transmission line for the first simulation studies while for the second simulation studies a 2 – generator 11 bus system was used. The MATLAB and PSCAD/EMTDC output waveforms led them to conclude that the controller did not only control the transmission line power but also reduces system oscillations.

The modeling and design of a UPFC based on the sinusoidal pulse width modulation technique was carried out by R. Orizondo et al. (2006). Unlike the others, they proposed a control circuit made up of a PI controller and a fuzzy logic controller. Fuzzy logic was used in order to dynamically control the real and reactive power flow [17]. Alternative Transient Programs ATP/EMTDC and Matlab were the simulation programs needed for their study.

The series controller proposed in [18] by A.A Hossam et al. (2006), regulates power flow as can be seen from the set of differential equations (transformed to dq frame) derived from the current in the receiving end of the system. This series controller injects a series converter voltage whose magnitude and angle is varied to control the voltage at node 2. Three situations were used to study the controllers but no conclusion was given.

Y.Zhou et al (2012**)** proposed an economical, reliable and safer system topology of UPFC based on MMC with current limiting capabilities. The fault current limiting circuit offers zero reactance to the circuit when the system is working normally but its reactance eventually becomes high when a fault occurs to prevent fault current flow. They used the NLM (nearest level modulation) modulation technique as it was suitable for very large modules and also because of its flexibility. PSCAD/EMTDC was used as the simulation environment to study the behavior of this circuit [19].

A new configuration of UPFC made up of MMC used as a replacement for VSCs is presented by Zhuo Guying et al (2012) in their paper which also combines both voltage balancing and PS-PWM (Phase shifted- Pulse Width Modulation) as modulation technique with the advantages of low switching losses and a reduction in switching frequency. Studies were also made on circulating current, arm current and voltage of capacitors in order to look for a method to bring an end to the circulating current. Models were built and simulated on Matlab/Simulink to test the validity of their work [20].

The PSB (Power System Block set) and Simulink of MATLAB simulation environment was used by Natalia M.R Santos et al. to construct the transmission line and semiconductor switching blocks of a Neutral point clamped three level converter based UPFC in [21]. IGBT and the Gate turn off thyristors were the semiconductor devices used which provided higher power and could be easily controlled than the previously used devices. The UPFC circuit was made up of back to back multilevel converter (Neutral point clamped) connected to two generators each supplying 315KV at 50Hz. Results obtained from sliding mode real and reactive power control systems shows that the UPFC improves the system stability as well as the steady state load flow.

P. Li et al. (2017) conducted a feasibility study to assess the suitability of adding a UPFC based on MMC on the 500 kV Chinese Suzhou power grid in order to improve the power supply and voltage regulation. Reference [22] gives a detailed explanation as well as criteria for selection of the parameters of the equipment's to be used. Simulation studies are done for heavy load condition in summer and winter.

A 5 bus transmission line model of a UPFC is presented in [23]. This paper written by T. P. G. T. A. Priyankara et al. (2017) dwells on the modeling, design and implementation of a UPFC as well as its dq shunt and series controllers for power quality improvement during unforeseen circumstances like variation of load. Matlab/Simulink was the simulation environment used and while simulating, loads were connected or disconnected from the system to see how the system will respond to these changes. The results showed satisfactory performance with UPFC as opposed to without UPFC.

The need for the UPFC in wind power integration as well as the most suitable and efficient way to use the UPFC in such situations is put forward in [24]. Li et al. (2017) suggested a unit commitment with UPFC for applications involving wind power. They concluded that, the advantages of using UPFCs reduce whenever a specific value of the UPFC is exceeded.

In China, after the successful implementation of a 220kv and 500kv VSC based UPFC, in 2017 Xe et al. [25] aimed at modeling and simulating an accurate model of an MMC based UPFC using PSD-PS program which was quite difficult since it is not easy to build and simulate a MMC model. The only thing new in their model was the addition of a bypass circuit in parallel to the series part. Inner current control models, serial control models, parallel models and a starting control model to reduce the large disturbances resulting from UPFC start up. The output signals from these control models were then fed as gate signals to the IGBT's employing the nearest level modulation scheme. Finally, their simulation studies were done on IEEE bus 39.

Research on MMC-UPFC up till date has been focused on the structure, modeling and controller design according to Z. Pu et al. [26] that's why in 2018 they proposed a high reliable MMC-UPFC whose design included protection and fault characteristics studies. Single phase grounding fault and two phase short circuit fault were the two case studies used by them to study the operational characteristics of the MMC-UPFC. Results obtained from PSCAD simulation environment showed that the design made the device more stable and could be used in practical applications.

The instantaneous symmetric component technique is used by J. Hu et al. (2018), to separate the negative and positive components on an MMC-UPFC system under unbalanced situations. Power fluctuations, DC voltage fluctuations and over currents are brought about by unbalanced voltage conditions. Their paper [27] aimed at studying and providing a dq decoupled control system for both the negative and positive components in order to suppress their effects on an MMC-UPFC system for proper functioning.

References [28-30] provide an analysis and comparison on the control of power during several operation modes of the UPFC. The general contributions of the UPFC are investigated as well.

2.3 MMC Review

Multilevel converters offer great advantages when compared to one or two level converters that previously existed before. Jih-Sheng L. et al. (1996) in their paper [31] explained this transformer less converters, their operational principles and areas of possible applications in the nearest future. Their drawbacks were also pointed out including the voltage imbalance between levels.

R. Marquardt in his work [32] presented in 2010, investigated the MMC, outlining key facts about these devices and how they are used for HVDC applications. He concluded that MMCs were reliable and could be used in multi terminal HVDC networks due to their outstanding characteristics in terms of power losses, failure management etc.

Lennart B. and Axel M. (2011) proposed a Hexverter in [33] to replace the back to back MMC. After testing the system in a laboratory, they concluded that the hexverter uses less number of sub modules than the MMC and has lower energy demands. Though the performance of the system was satisfactory, it wasn't made to function in a faulty environment to see how the system will try to recover from such faults.

Elisabeth N. and Marta M. (2012) developed a continuous model based on the assumptions that each multivalve has an infinite amount of sub modules and that the converters frequency of switching is also infinite in [34]. Using the thevenin equivalent structure of the converter to make the computation accurate and faster. Control was mainly due to the conversion of the model into the dq reference frame for the control of active power, reactive power, DC voltage and AC voltage magnitude. However, they didn't perform simulations to test their model and controllers.

Most MMC models are derived under unbalanced or balanced grid conditions but M. Guan and Zheng X. (2012) were able to provide a control model for an MMC based HVDC System in both balanced and unbalanced situations. Their MMC was composed of 60 sub modules per arm outputting an AC voltage of 100KV. In addition to the positive and negative sequence controllers, they included a zero-sequence controller to get rid of the zero current components which only come into play when a fault occurs otherwise it is disabled. Simulations carried out in PSCAD/EMTDC platform shows that the zero-sequence controller works well with the others as can be seen in their paper [35].

Conventional half-bridge sub module MMCs have no DC fault suppressing ability and their full-bridge counterparts can do so but produce high losses and are more costly that is why Ahmed K. H. et al.(2014) made changes to the half-bridge sub module structure to make them suitable for DC fault elimination. Two topologies were proposed in [36] and comparison of results to those obtained from using full-bridge sub modules, showed a similarity in behavior when DC faults occur.

A complete MMC-HVDC system including control system was studied in [7] by M. Barnes and A. Beddard (2015). According to them, a majority of earlier publications and research concentrates only on one or a maximum of two components of the overall system. Their work was to bring together these individual components to form a whole MMC-HVDC system in order to study them in a simulation environment. Offshore wind farms were used and a Multi terminal Direct Current (MTDC) was designed to connect these wind farms. Designs of the HVDC cables used as well as the parameters used were clearly explained. EMT simulation package showed the effects of this MTDC on the lower and upper arms of the MMC.

Different equivalent circuits (four in total) of the half bridge MMC was studied in [37] by LIU X. et al. (2016) without any control strategy i.e. no control of circulating current, no capacitor voltage balancing control and no voltage modulation technique is provided. Controlled voltage sources, diodes, resistors, inductors and switches were the main constituents of their models. These four models were simulated and their simulation times compared in PSCAD. Short coming here was the in ability of the models to be used for transient analysis as only steady state conditions could be simulated.

A simple and highly improved model of an MMC was proposed by R.Vidal-Albalate et al. in 2016 [38]. Alternative phase opposition disposition PWM technique was used for modulation. Their model also included a voltage balancing algorithm and a circulating current control which was then verified using a 5-level MMC and 151-level MMC simulation model on PSCAD. It is worth noting that this model of theirs was suitable for transient situations (ac and dc short circuits) as well as steady state scenarios.

Detailed MMC models always take much time when being simulated and the sub module structure to be used in the building of a converter has to be decided by the researcher. Hani Saad et al (2016), reduced the computational time of the MMC model by using resistors in place of IGBTs (on resistors meant the sub module was inserted and off resistor meant that it was bypassed), voltage sources and diodes. Their work [39] can be easily understood and applied by people with little or no information in the field because it is clear, written in a step by step manner and requires no coding. Normally most models do not take into account the blocking states of sub modules but theirs included these states which also considered both half bridge as well as full bridge sub modules. The problem of reverse voltage DC polarity associated with full bridge sub modules was tackled. To validate their model, an HVDC made up of MMCs (full bridge and half bridge modules) was studied under several conditions like DC faults and the results were compared with other modules which showed that their model was faster.

An energy storage device (battery) was added to the MMC structure via a buck-boost converter and a control technique was proposed for this configuration by C. Jin et al. in 2017. This configuration allows bi-directional flow of power and can be utilized when renewable energy techniques are integrated into the power system to reduce power fluctuations. Paper [40] gives information on their studies which includes state of charge (SOC) balancing method, buck-boost controller, MMC controller and capacitor voltage balancing scheme.

K. Srivastav et al. (2018), proposed an asymmetrical MMC model in [41] which provides several benefits like high efficiency, low cost, size and a reduction in the number of semiconductor devices required. An asymmetrical MMC can produce an output with more levels than the same conventional MMC with the same number of semiconductors. A new voltage balancing algorithm and circulating current controls were also introduced which also reduces the voltage ripples and the second harmonics in the arm currents. Matlab/Simulink was used to study the differences between these devices and conventional MMCs with regard to harmonic distortion, voltage ripples, converter losses, circulating currents and quality of output voltage.

CHAPTER 3

OVERVIEW OF FACTS DEVICES AND UPFC

3.1 Introduction

In this chapter, explanatory notes with the aim of providing general information on FACTS devices (emphasis will be laid on the UPFC), their configuration, operational characteristics, areas of application and their benefits has been given.

FACTS is an acronym which stands for Flexible Alternating Current Transmission systems and Hingorani was the first person to propose it in 1988. These devices are power electronic controllers used in transmission systems to improve power system operation. IEEE defines FACTS as “Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability [1].”

In order to understand FACTS and their role in a transmission system, one has to have a mastery of the functioning of a basic power transmission network. So in the next section, we will look at this in brief before continuing to study FACTS.

3.2 Basics of Power Transmission

Power is transmitted from production sites to consumers through transmission lines. Transformers, circuit breakers and other circuit elements are also involved. Transmission involves high voltages which are stepped down by transformers at the receiving end. Lines with different voltages are connected with the help of transformers operating at high efficiency. AC is mostly used for overhead transmission lines while DC is suitable for underground transmission as well as for very long power transmission. Circuit breakers are protective devices that open circuits when a fault occurs in the system. Most of them are mechanically operated and tend to wear out faster than their static counterparts after a certain number of opening and closing, making them inappropriate for controlling the flow of power on a transmission line [42]. AC transmission lines control power flow on their own (self-regulatory characteristics) since power flows from either the sending or receiving end depending on the condition at hand.

Power supplied by generators should be equal to demand from loads or consumers. If at any time inequality exists, then system parameters like frequency, voltage etc. will be negatively affected. In a case, where the load demand is higher than supply, there will be a decrease in frequency and voltage drops in the transmission line. Reactive power which flows back and forth in power lines helps in regulating the voltage of a system. Inductive loads like transformers require reactive power to be able to maintain an appropriate voltage needed for electromagnetic field generation. If reactive power is low, then there will be voltage collapse [42]. Active power which does useful work flows from the generation centers to the loads. Figure 3.1 shows the path of real power flow in a line. V_1 is the voltage at bus 1 and V_2 is the voltage at bus 2.

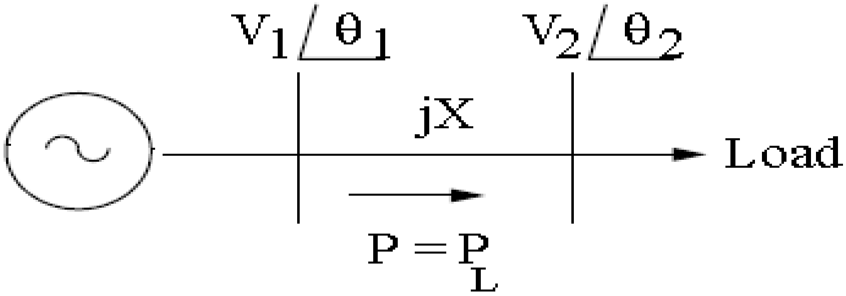


Figure 3.1 Power flow in a line [58].

Assuming that power flows from generator G to load and that there are no line losses, the active power flowing is given by;

$$P = \frac{V_1 V_2}{X} \sin \theta_1 - \theta_2 \tag{3.1}$$

If V_1 and V_2 are kept constant, then the real power P will depend only on the line reactance X. The relationship between the two is an inverse one in that as reactance increases, power decreases and as it reduces power increases. More than one transmission lines are usually used to connect the generators to loads as well as two or more generators connected to a single load in order to avoid complete blackout incase a fault occurs and also to avoid overloading. This goes a long way to improve the systems reliability. The introduction of more lines can lead to the creation of loops which makes it very difficult to control the power flow in lines because Kirchhoff's voltage law (KVL) determines the flow.

When power flows through two parallel lines, a situation arises when the power flow in the lower reactance line is more than the other. Consequently, the line will become overloaded and the line will reach its loading limits though the high impedance line can still be loaded. Loading capabilities of a line are limited by thermal, voltage and stability limitations. Thermal limitations are due to environmental conditions like wind conditions, surroundings temperature, ground clearance etc. and history of loading of the line. Transient stability, steady state stability, dynamic stability, voltage and frequency collapse all contribute to the stability limitation. These limitations can be overcome or improved with the introduction of FACTS

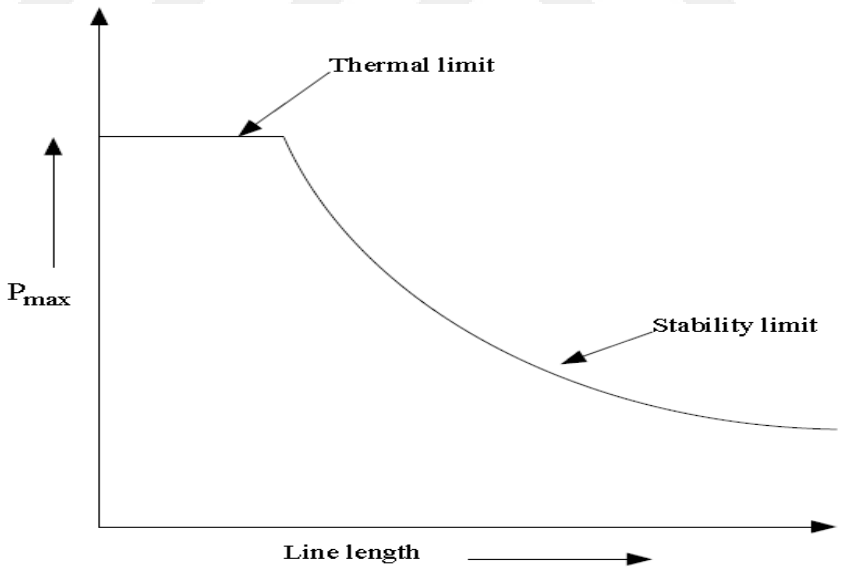


Figure 3.2 Variation of active power with line length [58].

3.3 Classification of FACTS Devices

The introduction of FACTS devices enables systems to function efficiently without exceeding their limits or to transmit power under optimum conditions. FACTS devices can be classified into various groups based on the way they are connected to the network and also on the switching properties (e.g. frequency) of the semiconductor devices they are made of.

Using the manner of connection as a property for classification, the following five groups can be obtained;

- Series FACTS devices.
- Shunt FACTS devices.
- Combined Series-Series FACTS devices
- Combined shunt-shunt FACTS devices.
- Combined shunt-series FACTS devices.

Looking at them from the perspective of switching properties of their semiconductor devices, they can be grouped into two categories [2];

- First generation or conventional FACTS that involve mainly semiconductor devices with turn on possibilities without turn off possibilities. This generation has slower response times of approximately 2-3 cycles. Thyristors are the switching elements used.
- Second generation or converter based FACTS with a faster response (1-2 cycles) compared to their first generation counterparts and use power semiconductors with turn on and turn off possibilities (e.g. IGBTs, IGCTs, GTO etc.). This generation makes use of VSCs though the two and three level forms are being gradually replaced with MMCs since their introduction by Marquardt in 2002.

An overview of the main FACTS devices is shown in Figure 3.3 where the first generation or conventional FACTS devices are on the left and the second generation ones on the right. FACTS devices are fast and can easily be controlled because of the use of thyristors and voltage source converters (VSCs).

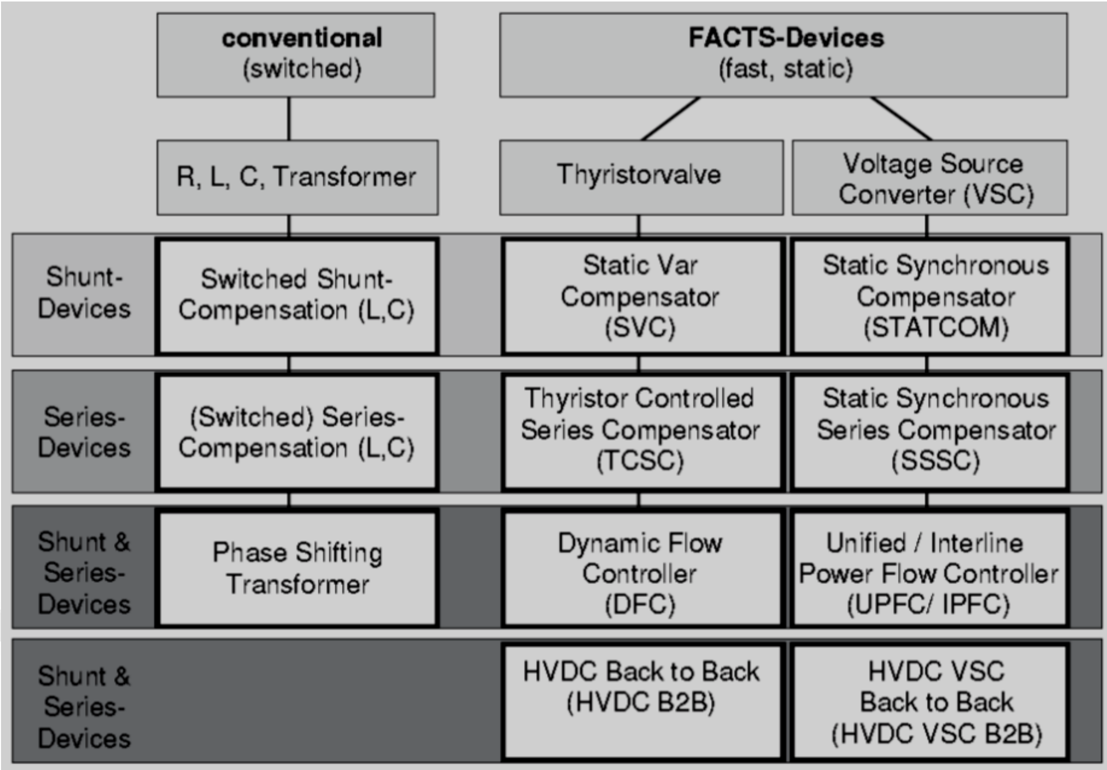


Figure 3.3 Overview of FACTS devices [4].

3.3.1 Series Connected FACTS Devices

These devices are sometimes called series controllers and are connected in series with the transmission line [1]. Series connected FACTS devices change or affect the effective impedance of a line hence influencing stability and power flow. They are basically variable impedances or controlled voltage sources that inject a voltage which is in series with respect to the line's voltage. Series voltage originates from the impedance being multiplied with the current flowing in the line. These FACTS devices can provide or consume reactive power given that the voltage is in phase quadrature with the current flowing through the line. Reduction of voltage fluctuations, short circuit currents limitations, damping of oscillations are some functions that can be achieved with this type of FACTS devices.

3.3.1.1 Thyristor Controlled Series Capacitor (TCSC)

TCSC is a combination of thyristor controlled reactor (TCR) and a capacitor connected in parallel as shown in Figure 3.4. The first TCSC version was developed in 1996 [4]. The firing angle of the TCR determines how it functions. Fault current limiting mode is activated when the firing angle of the TCR is 90 degrees as the impedance increases or becomes inductive since the TCR is now fully conducting. In a situation in which the firing angle is 180 degrees, the TCR doesn't function and only the impedance of the capacitor can be seen on the line. Decreasing this firing angle from 180, results in the inclusion of the reactors impedance into the system. Series impedance control, increasing damping and overcoming sub synchronous resonance (SSR) mitigation is their main objective.

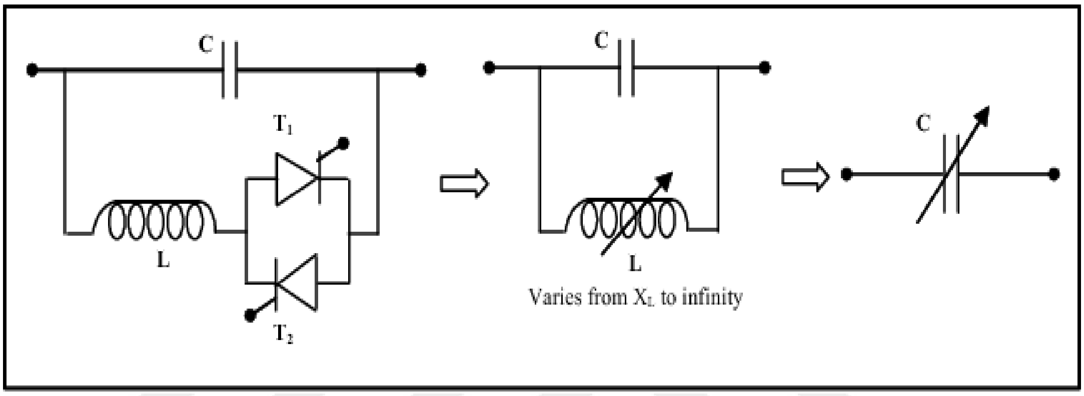


Figure 3.4 TSCS equivalent circuit [88].

3.3.1.2 Static Series Synchronous Compensator (SSSC)

Unlike the TCSC, SSSC is a VSC coupled with a transformer which in addition to the functions of a TCSC can also be used for VAR compensation and doesn't require reactors and capacitors. SSSC is a modified version of series compensation offering the possibility of adding an energy source or battery to exchange real power with the AC transmission network at the DC side. This type of series FACTS devices have not yet been tested on their own. Practical versions exist but only as a part of other FACTS devices like UPFC [58, 89]. Figure 3.5 shows the circuit diagram and the equivalent circuit for an SSSC. An SSSC is composed of a transformer, a VSC or a CSC and a storage device (optional).The connecting transformer parameters, winding resistance(r) and leakage reactance (x) are connected in series to the voltage source (Vc) in the equivalent circuit. SSSC injects a variable voltage (Vc) which is independent of the line current and either leading (inductive mode) or lagging (capacitive mode) the line current by 90 degrees.

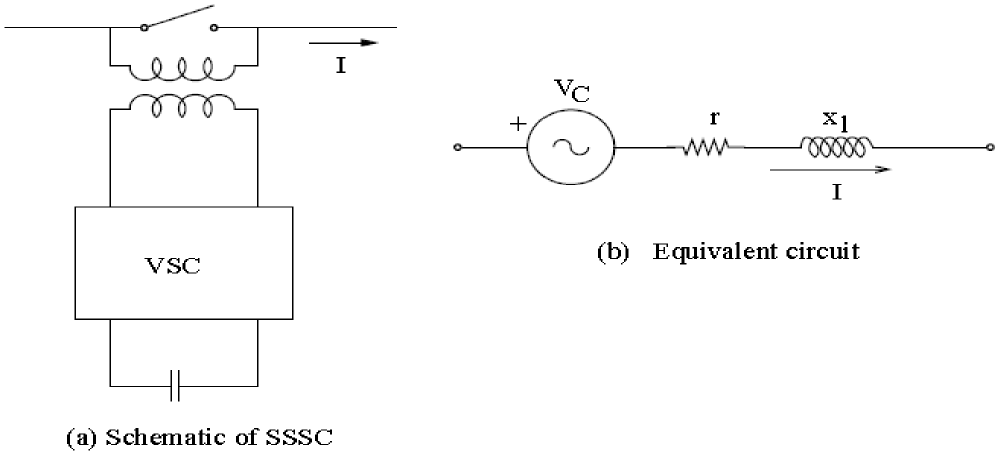


Figure 3.5 SSSC [58].

3.3.2 Shunt Devices

Devices connected in parallel to the transmission line are called shunt controllers. Similar to series devices above, they may be made up of variable voltage sources or impedances or the two combined. In contrast to them, they inject current that can be varied into the line which if it is in phase quadrature with the line voltage, reactive power can be controlled or otherwise real power control will be initiated too. Some areas of application of these devices are in improvement of static stability, power quality improvement, reduction in unwanted reactive power flows and real power exchange while keeping reactive power constant.

3.3.2.1 Static VAR Compensator (SVC)

SVCs are static absorbers or generators having no moving parts connected in parallel with a power system to control the systems variables. Thyristor-controlled reactors (TCR), Thyristor-Switched Capacitor/Reactor (TSC/TSR), Mechanical Switched Capacitors (MSC) are all types of SVCs. TSC supplies reactive power while TCR or TSR consumes reactive power. Thyristors without controlled gate turn-off capabilities are the semiconductor devices used in building them. Their main application areas are, temporal overvoltage control, transient stability improvement, damping of systems oscillations and voltage collapse prevention. SVCs are similar to STATCOM but from an economic point of view they are cheaper. The first SVC on a transmission line was installed in 1979 [4].

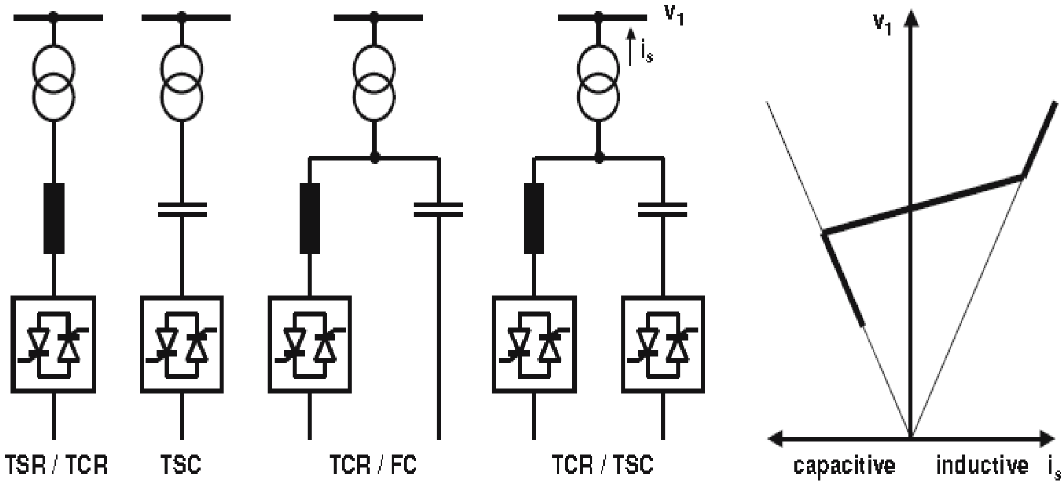


Figure 3.6 Static VAR system and VI characteristics [4].

3.3.2.2 Static Synchronous Compensator (STATCOM)

STATCOM devices use a VSC or CSC in place of capacitors and reactors as is the case with SVCs. VSCs are preferred for various reasons amongst which are low cost and simplicity. The first STATCOM constructed with VSC was installed in 1999 [4]. Superior performance, faster response, less space requirement, easily re-locatable and the possibility of interfacing them with real power sources makes STATCOM devices preferable to SVCs. Japan in 1991 built a ± 80 MVAR STATCOM with GTO power converters. STATCOM in the past was called STATCON (Static Condenser) before it was later changed [43].

In the process of supplying or consuming reactive power to a transmission system, STATCOM controls the voltage at its own end. Considering Figure 3.7 as shown below, VSCs built with force commuted semiconductor devices (IGBTs or GTOs) vary the reactive power at the secondary side of the transformer. E_t is the voltage of the line while E_s is the STACOM's voltage [43]. Under normal operating conditions, E_t is equal to E_s and there is no exchange of reactive power between the system and the device. If $E_s > E_t$ (Capacitive mode), current *Iq* flows from the STATCOM to the AC system resulting in the supply of reactive power to the AC system while if $E_s < E_t$ (inductive mode), current flows from the AC system to the STATCOM and it also absorbs reactive power in order to try to maintain the balance. VSC produces AC voltage from the DC energy source. STACOM can also function as an active filter in order to reduce or completely eliminate harmonics.

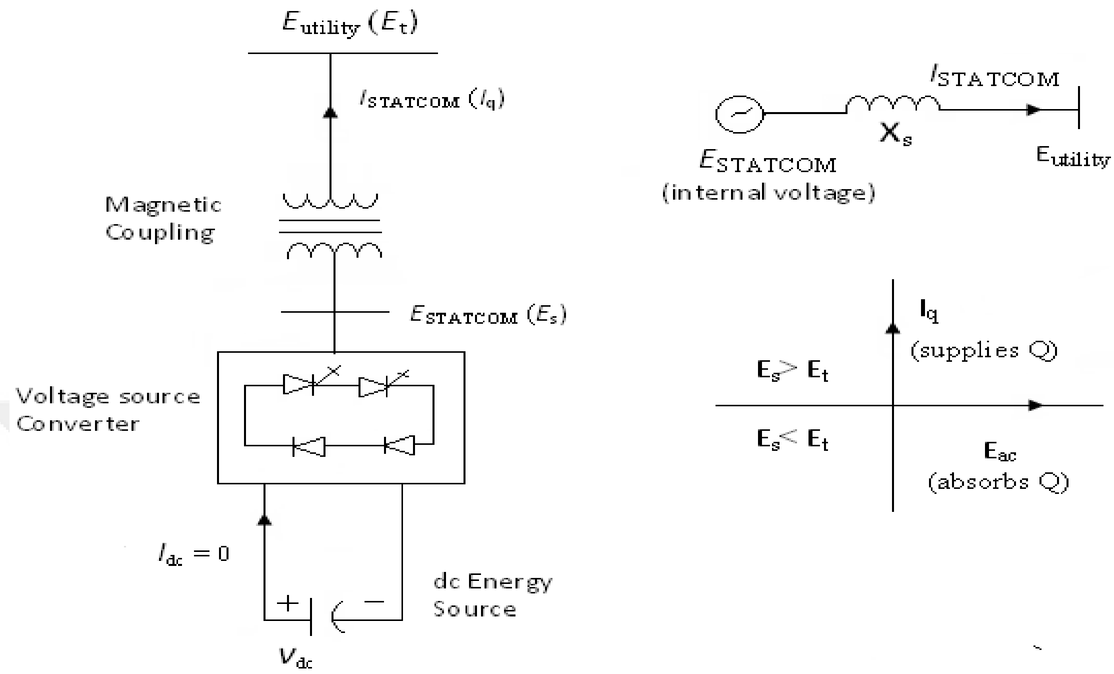


Figure 3.7 STATCOM circuit diagram and its equivalent circuit [43].

FACTS devices have various functions and one or more FACTS devices can be suitable for a particular function. Figure 3.8 shows which FACTS device is preferable depending on the desired function.

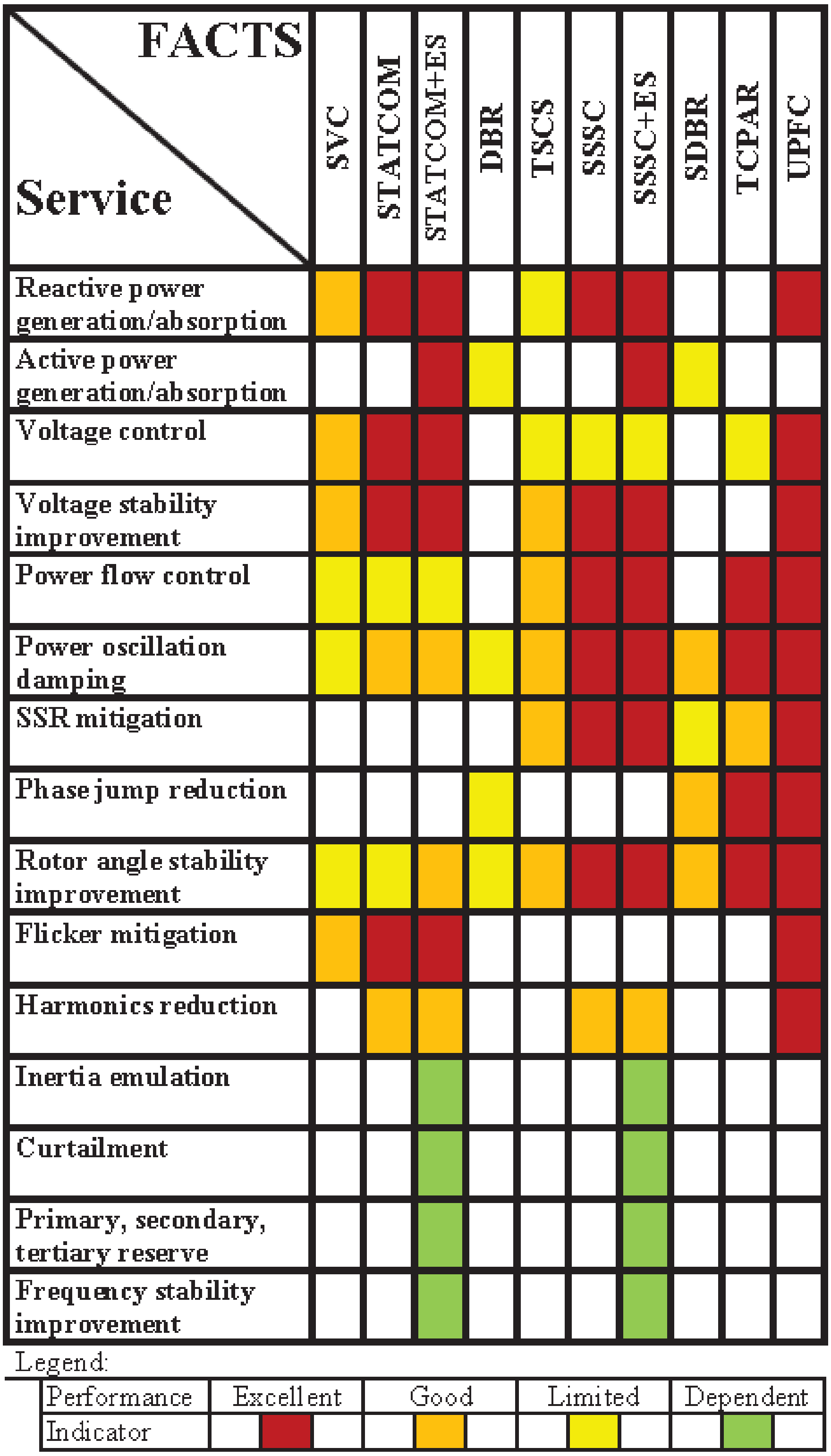


Figure 3.8 Comparison of the functions of some FACTS devices [44].

3.3.3 Combined Series - Shunt Devices

This type of device consists of a series and shunt FACTS part controlled by a controller. UPFC which falls under this category is a one of the most powerful FACTS device. Series and shunt parts function the same as we have seen above by either injecting a series voltage or current. Real power can be exchanged between the series and shunt part if they are unified as in the case of UPFC.

3.3.3.1 Unified Power Flow Controller (UPFC)

UPFC is the most versatile, flexible and powerful multi-function FACTS device having 3 degrees of freedom; can vary voltage, impedance and phase angle hence controlling the power transmitted and voltage unlike its other counterparts. It was introduced by Gyugyi [1] and it is made up of two VSCs, one connected in series and the other in parallel to the transmission line via a coupling transformer as shown in Figure 3.9. The converters are connected via a common DC link, forming a closed loop for active power exchange.

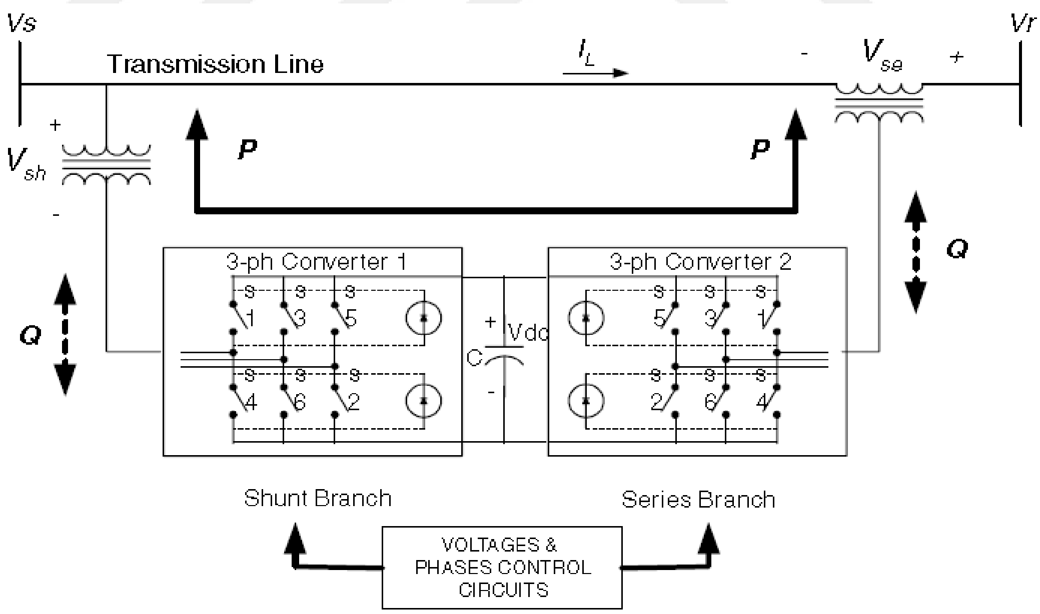


Figure 3.9 UPFC configuration [45].

Placing an open switch at the common DC node will allow the device to function as a STATCOM and an SSSC independently. Converter 1 is connected in parallel to the system via a transformer while converter 2 which injects a series voltage (V_{se})

variable from 0 to V_{se} max as well as its phase angle from 0 to 360 degrees is connected in series to the line via a series transformer. These converters synthesize a symmetrical AC voltage from the DC input. Both converters can control reactive power at their ends individually but for real power control they have to be coordinated to function like one for real power to be able to flow from converter 1 to converter 2. Generally, real power demanded by the series converter is obtained by the parallel converter from the line and supplied to it via the DC link.

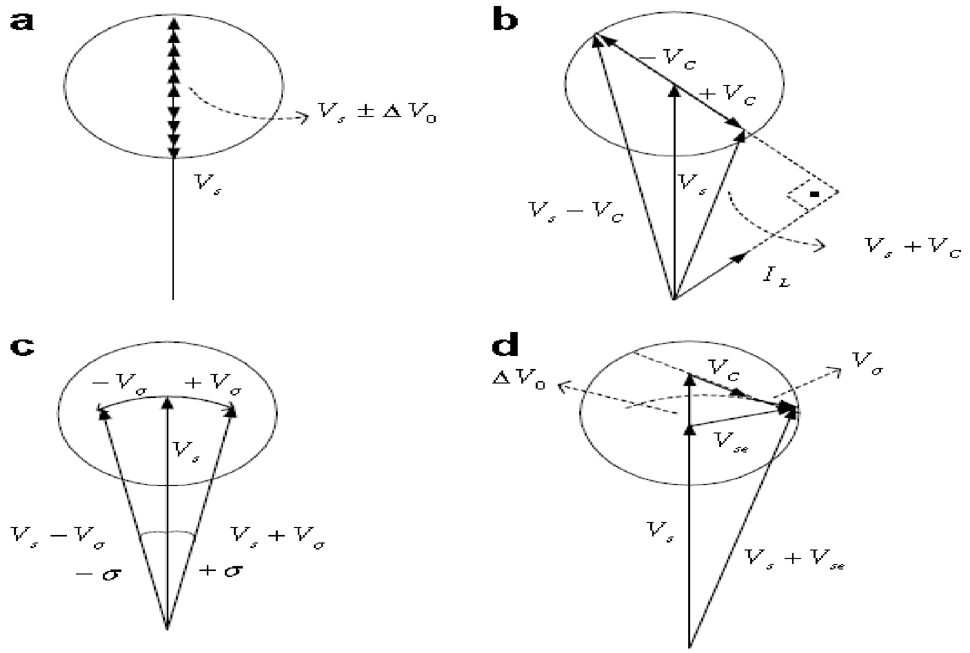


Figure 3.10 UPFC control functions [45].

Various operation modes of the UPFC and their phasor diagrams are shown in Figure 3.10 above. Figure 3.10(a) represents voltage regulation where the injected voltage is either out of phase or in phase with the sending end voltage. Reactive series compensation is shown in Figure 3.10(b). Phase shifting and multi-function control modes are represented in Figure 3.10(c) and 3.10(d), respectively.

3.3.3.2 Generalized Unified Power Flow Controller (GUPFC)

GUPFC consists of three or more series and shunt FACTS devices as shown in Figure 3.11. As the name implies, it is a UPFC for generalized use i.e. it is a UPFC that can be used to control power flow in a multi-line system. Though GUPFC provides many control options and advantages, their complex nature has made them difficult for implementation in real life and less attractive for solving power transmission related issues [45].

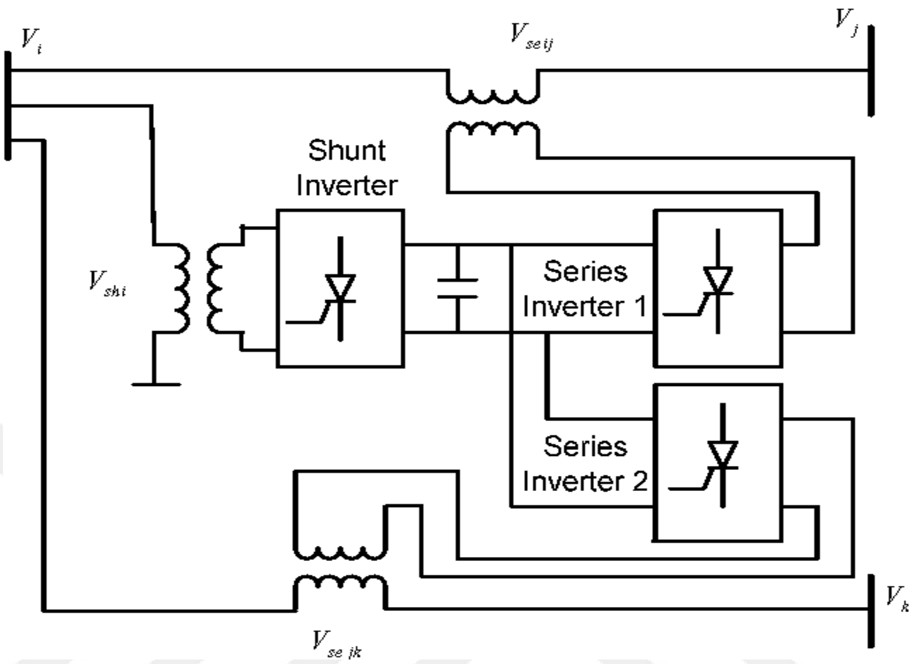


Figure 3.11 GUPFC layout [121].

3.3.4 Combined Series-Series Devices

Two separate series FACTS devices coupled together via a common DC link are connected with more than one transmission line, aiming to control reactive power flow on the lines. Real power can also be regulated if the two series devices are connected via a common DC link. Interline Power Flow Controller (IPFC) is an example of this type of devices.

3.3.4.1 Interline Power Flow Controller (IPFC)

The main objective of this device is to control power flow in multiple lines. Similar to the UPFC, this device has 3 degrees of freedom but it is not as popular as the UPFC because it was just discovered recently and setting it up will be more costly compared to the UPFC [2, 43]. They consist of two VSCs connected together by a DC capacitor to ease the flow of real power between the two converters as illustrated in Figure 3.12. When they are in operation, they determine the line on which power can flow and by so doing, prevents overloading of some lines while others are under loaded. Compared with other series FACTS devices like SSSC and TCSC, IPFCs can control real and reactive power independently [58].

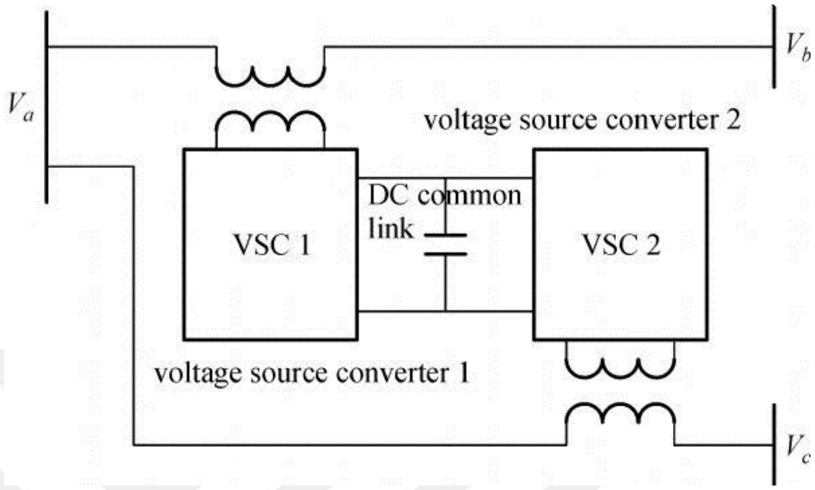


Figure 3.12 IPFC layout [53].

3.3.5 Back to Back (B2B) Devices

HVDC B2B systems use either conventional thyristors or VSCs as power converters. These devices are mostly used for power transfer while decoupling the receiving end and sending end frequencies, to stabilize weak links, to provide more real power where the AC system already is at the limit of its short-circuit capability and for grid power-flow control within synchronous AC systems [94]. Figure 3.13 shows an example of an HVDC B2B setup. The first converter which is a rectifier converts AC to DC before passing it to the second converter which carries out the inverting action. All the converters are located in the same place. B2B HVDC is suitable for neighboring systems with unequal parameters like differences in their frequency and voltage that need to be coupled.

B2B HVDC systems using thyristors as converters are bulky in size because of the space taken up by the filters and cannot control reactive power. The introduction of VSC has led to a considerable reduction of size in the newly introduced B2B VSC HVDC systems [4]. The latter can control both real and reactive power as well as providing all the benefits associated with the use of VSCs. B2B system with STATCOM used as the VSC converter is an illustrative example [102].

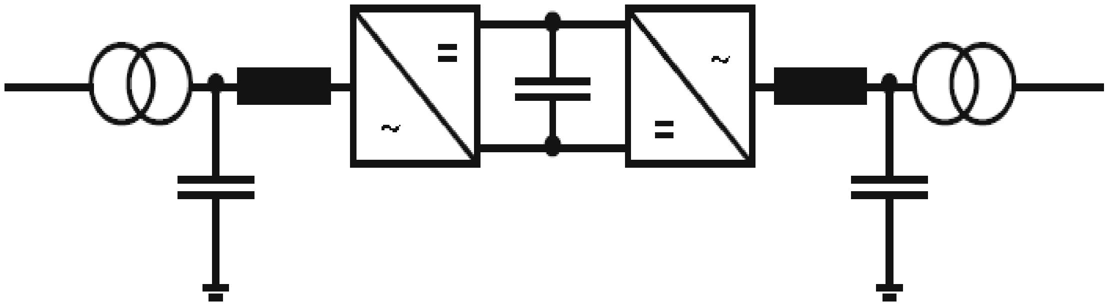


Figure 3.13 HVDC B2B configuration [4].

3.4 Semiconductor Devices for FACTS Devices

FACTS devices mainly comprise of VSCs. Semiconductor devices are the main building blocks for power converters and so require careful analysis of performance and characteristics in order to determine which one is the most suitable. Improvements in power semiconductor devices have led to an advance and decrease in cost of FACTS devices [1]. A good semiconductor device is expected to produce minimal conduction losses and minimal switching losses for high frequency switching. Cost of these devices at times cannot be used as a deciding factor because more often, the most expensive ones have the needed characteristics and voltage /current ratings [4].

Power semiconductor devices can be classified as two-terminal devices and as three-terminal devices. These are the emitter, collector and the gate terminals for an IGBT. The thyristor or silicon controlled rectifier (SCR) which is a four layer three-terminal semiconductor device was introduced in 1957 by General Electric [4]. Existence of a gate terminal allows this device to be easily controlled by applying a pulse to it which keeps it on before the current reaches zero. Thyristors are line-commutated and forced commutated devices. Commutation is the process of turning off a thyristor. Turning off a thyristor without the use of an external circuit is known as line commutation. Meanwhile turning them off with the help of an external circuit is referred to as forced commutation [91]. As can be seen in Figure 3.14, thyristors have the highest voltage and power ratings when compared to other power semiconductor devices. This explains why they are used for most high HVDC-FACTS applications. Since conventional thyristors could not be switched off directly, researchers had to modify them to make them fully controllable [1]. Gate Turn off (GTO) Thyristors and Insulated Gate Commutated Thyristors (IGCT) are being used now in place of conventional thyristors. GTOs and IGCT are similar to conventional thyristors but differ in that turn off and turn on can be controlled at the gating terminal.

Figure 3.15(a) shows a diode which is a device made up of a cathode and an anode and conducts only in the forward direction. The gate terminal is not present for this kind of semiconductor device [1].

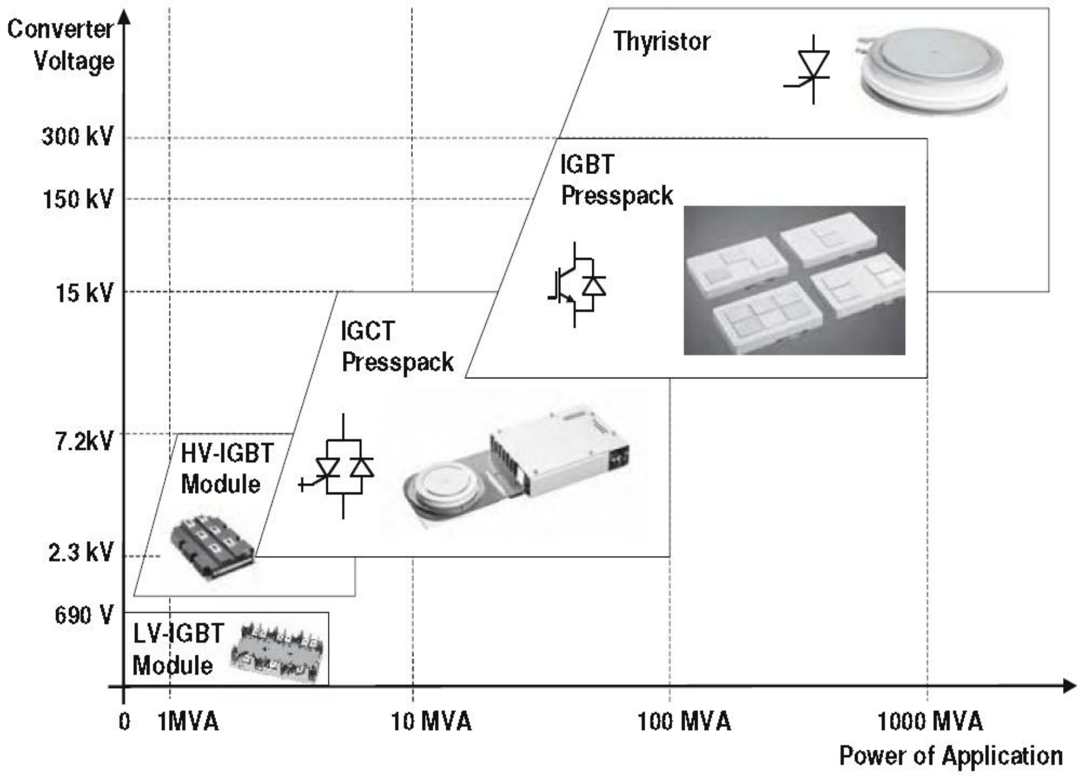


Figure 3.14 Converter voltages and power of application for various power semiconductor devices [4].

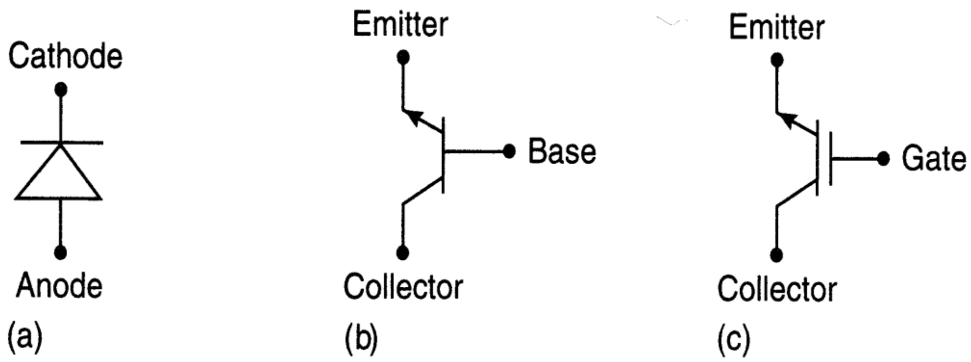


Figure 3.15 (a) Diode (b) Transistor (c) IGBT [1].

Transistors are three-terminal devices like thyristors mostly used for low and medium power applications in amplifying and switching electrical signals and electrical power as illustrated in Figure 3.15(b). Field effect transistors (FET) and bipolar junction transistor (BJT) are types of transistors. Insulated gate bipolar transistor (IGBT) shown in Figure 3.15(c), falls under BJT category and is being made use of for VSC controllers for FACTS for high power applications because of their superior switching characteristics, low switching losses and current limiting capabilities. Also, they have simple driver circuits and fast turn-on and turn-off times making them suitable for high frequency operations. IGBTs have the second highest voltage and power ratings justifying their use in medium to high power applications (10MW or more). Transistors are easy to control as a positive voltage will switch them on while zero voltage will switch them off. IGBTs will be used in building the simulation model of the converter in this thesis because of the above mentioned superior properties. Limitations also exist in IGBT devices, amongst which are, high forward voltage drop and cooling complexities [1].

3.5 Application of FACTS Devices

FACTS devices are complex and very expensive devices thus before considering building them, their benefits and needs have to be justified. FACTS devices are useful in numerous applications amongst which are;

I. SVCs and STATCOMs are used in railway projects. Trains need to be supplied with stable and non-fluctuating voltages at all times. FACTS devices play a role in the control of fluctuating voltages and harmonics [96].

II. FACTS for smart grid and renewable energy applications. Smart grids are a combination of power grids and renewable energy sources like solar, wind etc. When these renewable sources are added to the existing power network, stability of the system will depend on the variation of the output of the renewable sources. FACTS devices make it easy to integrate renewable techniques by controlling the system variables. TCSC can also be used for power control. Their influence in on shore and off shore wind applications cannot be undermined [92, 93, 97, 98].

III. FACTS can also be implemented in oil and gas industries. Most pipes that carry oil need pumps to move the oil through them. Faults can occur, voltage drop hence disrupting the normal system operation. FACTS in the form of SVC can maintain the necessary voltage for optimum performance [99].

IV. FACTS have applications in metal industries in flicker reduction, metal smelters (especially steel), reduction of harmonics, increase productivity, voltage and unbalance control [100].

V. FACTS are essential for mining operations and structures [101].

3.6 Benefits of FACTS

- To make the transmission network more reliable.
- Reactive and real power flow control, allowing power to flow via desirable routes.
- FACTS increases line loading capabilities while keeping line parameters within their thermal limits.
- They raise the transient stability limits thus increasing system security.
- FACTS devices provide flexibility.

CHAPTER 4

OVERVIEW OF MODULAR MULTILEVEL CONVERTERS

4.1 Introduction

This chapter provides an insight into the functional principle of a modular multilevel converter (MMC) while also providing information on their origin as well as application areas of these converters. MMC which is a type of VSC is a promising technology and is a very important component in a UPFC. Understanding them thoroughly is necessary before jumping into the next chapters.

MMC also known as M2C produces an almost sinusoidal AC output that is suitable for most medium and high voltage applications. MMCs show some superiority over multilevel converters like redundancy, scalability, and lower semiconductor losses etc. that have been existing before their introduction in 2002 [46]. Also their popularity comes from the fact that they can be used in medium and high power applications like HVDC and FACTS and they were proposed mainly to be used in high power applications. A brief and concise study on history and other types of multilevel converters before continuing with MMC for better understanding and correlation of ideas will be presented next.

4.2 Multilevel Converter History and Topologies

Converters are electronic circuits built with semiconductor devices used to convert power from one form to another. An inverter which is one type of a converter converts DC to AC, a rectifier converts AC to DC, a chopper converts DC to DC and an AC controller (fixed frequency) or a cycloconverter (variable frequency) converts AC to AC. As can be seen clearly from above, two types of power exist when talking about converters; DC in which only its magnitude can be varied during the conversion process and AC where frequency, amplitude and number of phases can be altered in the conversion phase. Figure 4.1 shows the classification of high power converters including the semiconductor device used for each particular type [48].

Multilevel converters were first introduced in the late 1960s by Baker and Bannister with the H-bridge series connected converter as the first model [47] [48]. Following this was the neutral point clamped (NPC) that came around the end of the 1970s [49]. These two were then studied and new types were developed from them. Neutral point clamped (NPC), Capacitor clamped (flying capacitor) and Cascaded H Bridge (CHB) converters were the most common before the MMC and new converter topologies are just a modification of these three basic converters.

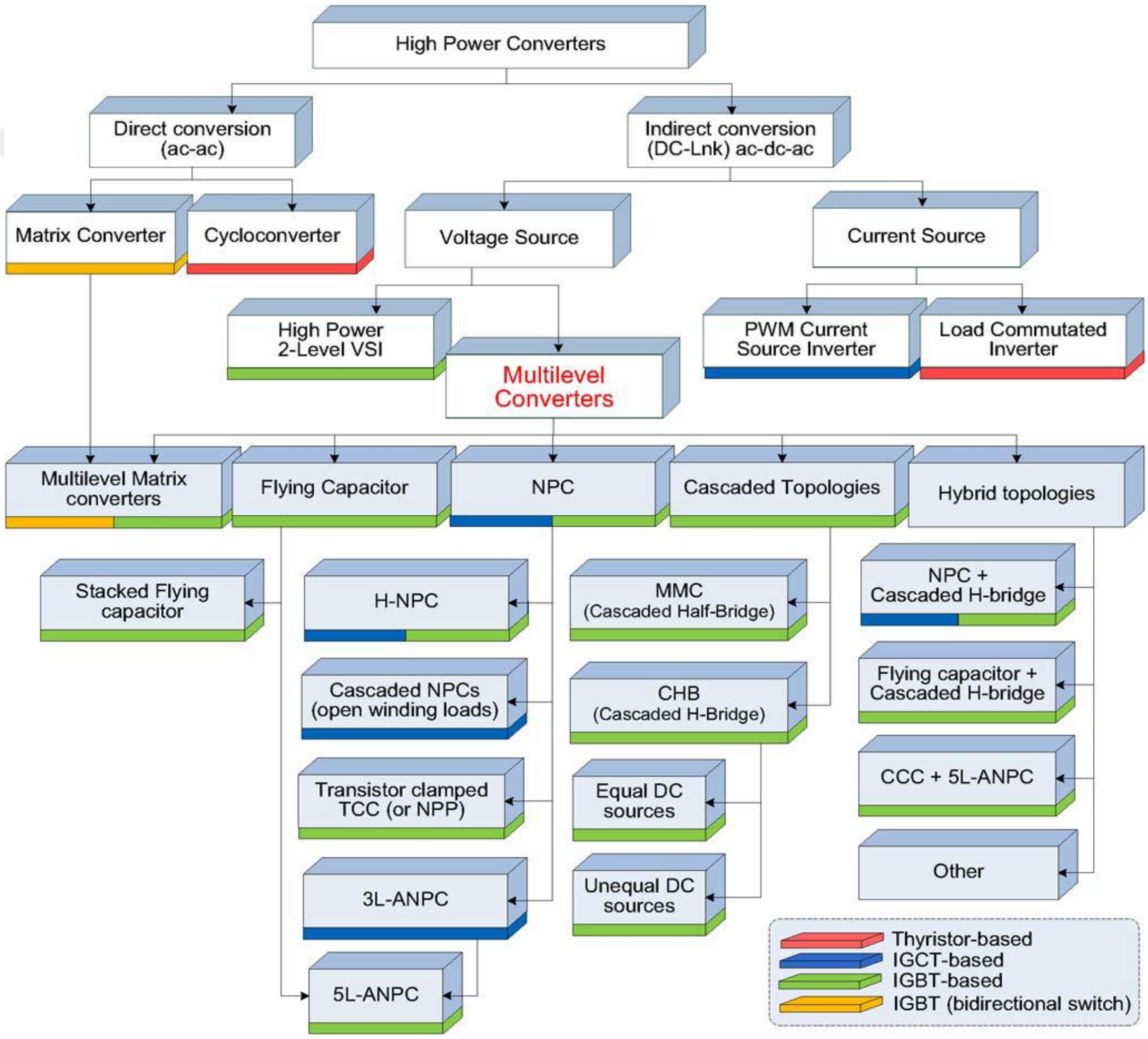
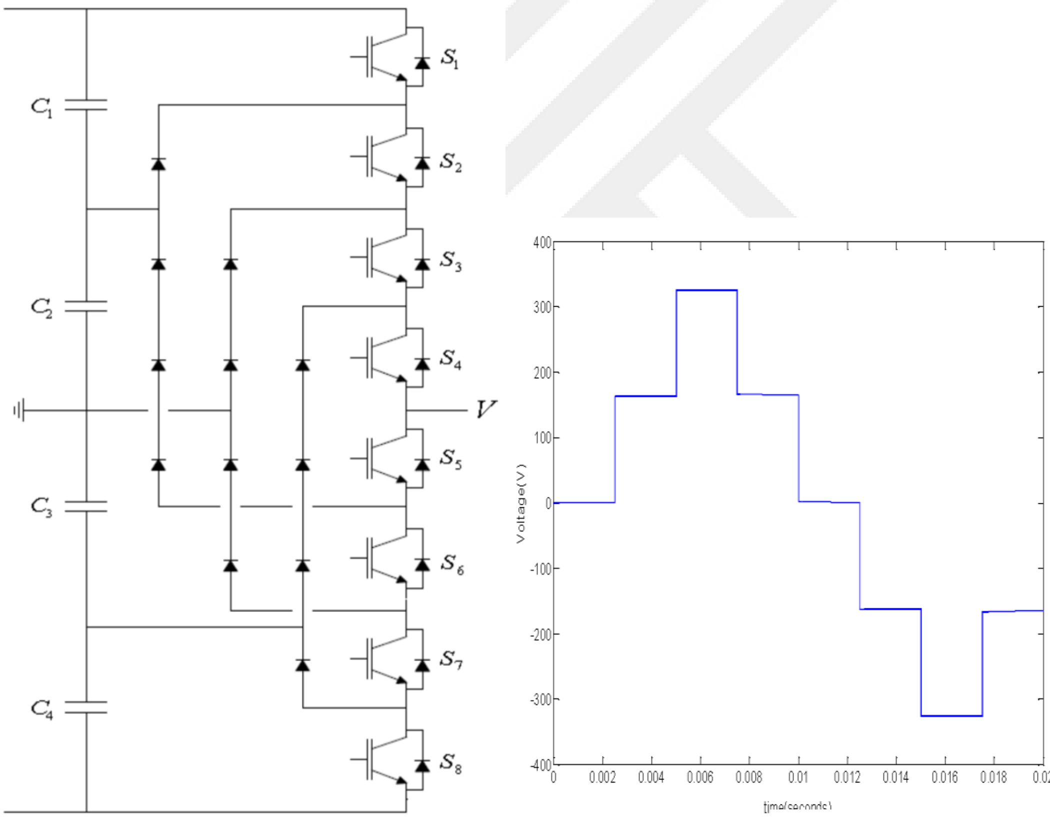


Figure 4.1 Classification of high power converters [48].

4.2.1 Neutral Point Clamped (NPC) Converter

NPC is also known as diode clamped converter (DCC) and it's said to be the first multilevel converter that was utilized for medium voltage applications. Nabae, Akagi and Takahashi presented it in 1981 [50]. One phase of a 5-level NPC is shown in Figure 4.2. V_{dc} is the voltage across all the capacitors. For an n-level inverter, the number of capacitors (voltage sources) and clamping diodes needed is equal to $n-1$ and $2n-2$, respectively. Switches S1, S2, S3, S4 are complementary to switches S5, S6, S7, S8 respectively and cannot be switched on at once i.e. when one is ON the other has to be OFF and vice versa. The main disadvantage of this type of multilevel inverter is the fact that the output voltage cannot exceed half of the input. Higher number of clamping diodes as output level increases, voltage balancing between the capacitors and the fact that the capacitors at the DC side cannot be minimized or eliminated are other disadvantages associated with them. Number of levels is usually limited to 3 because of their complex nature.



(a) (b)

Figure 4.2 NPC (a) diagram (b) waveform.

4.2.2 Capacitor Clamped (flying capacitor FC) Multilevel Converter

Inferring from the name of this converter we can see that it differs from the diode clamped in that capacitors replace the clamping diodes in Figure 4.2. These types of converters proposed in 1992 by Ford and Meynard [51] are advantageous in that in case of an outage and fall in the voltage level, the large number of capacitors can sustain the system for certain time duration. Phase redundancy also exists in that several switching combinations can give the same output. The switching pattern is the same as for an NPC as seen in Table 4.1. To produce an n-level output voltage, $n-1$ capacitors at the DC side and $(n-2)\ (n-1)/2$ clamped capacitors are required and the voltage imposed across each capacitor is $Vdc\ /\ (n-1)$. Drawbacks of this topology are high cost of capacitors as voltage level increases, capacitors voltage balancing, control, packaging and dimensioning become complex as the size increases.

Table 4.1 Switching pattern for FC [51].

Output voltage	**S1**	**S5**	**S2**	**S6**	**S3**	**S7**	**S4**	**S8**
Vdc/2	1	0	1	0	1	0	1	0
Vdc/4	0	1	1	0	1	0	1	0
0	0	1	0	1	1	0	1	0
-Vdc/4	0	1	0	1	0	1	1	0
-Vdc/2	0	1	0	1	0	1	0	1

4.2.3 Cascaded H Bridge (CHB) Converters

These are H-Bridge converters stacked together in series to produce an AC output whose value is the sum of the outputs of all the series connected modules. CHB converters were introduced in 1974 by Baker et al. [47]. The number of voltage levels can be calculated using $2H+1$ where H is the number of H bridges in one phase leg. It can be deduced that the number of voltage levels produced by this type of a converter is always an odd number which is not the case for the other two types because they can produce either an odd or even number of AC output voltage levels. The number of switches is given by $4H$. Figure 4.3 shows a CHB multilevel inverter with 3H-bridges per phase leg. Advantages of this topology are that it requires fewer components when compared to the other types making it cheaper, modularized nature and easy packaging. The main issue with this converter is that each H Bridge requires a separate DC source increasing its overall cost.

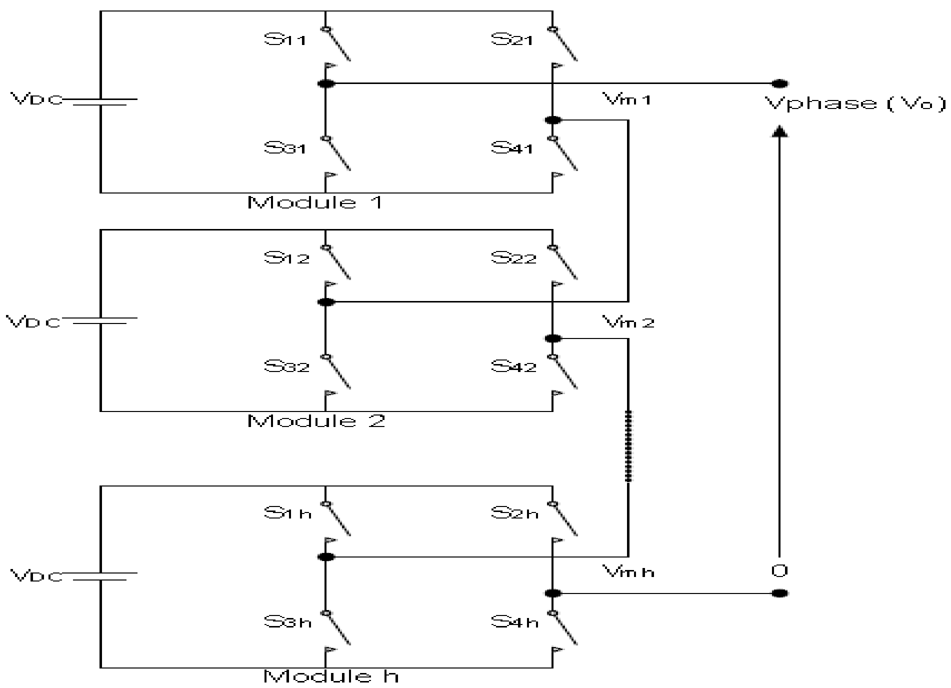


Figure 4.3 CHB multilevel inverter.

4.3 Modular Multilevel Converters (MMC or M2C)

MMC is an example of a voltage source converter that produces a multilevel AC output depending on the number of sub modules connected in series per arm. R. Marquartz in 2002 proposed the MMC which was a modified version of the CHB [72]. The need for this type of converters arose from the fact that the previously introduced two or three level VSCs could only be used in low and medium voltage applications hence requiring a new type for high voltage applications [52]. MMCs are far superior to the other types of multilevel converters we have seen because of the following properties;

- Modular (Scalable) construction: the output voltage and level can be increase easily by placing more sub modules in series.

- Low losses and low harmonics: semiconductor losses as well as harmonics are relatively low and output voltage is of higher quality.
- Redundancy: these converters are made up of many sub modules per arm and in a situation where one of these becomes defective, it is bypassed and the system continues to function normally hence making it highly reliable.
- Low switching frequency. Generally a switching frequency which is approximately 3 times the system frequency should be enough. This goes a long way to improve the efficiency of the converter.
- Low EMI and acoustic noise due to low di/dt value obtained from the currents flowing through the converter arms.
- Small number or no filters at all are required at all**.** This reduces expenses in building them practically.
- At the DC side, no need for DC-link capacitors.

Though the pros are so many, drawbacks still exists. Some of which are

- The existence of circulating currents within the converter arm due to unequal capacitor voltages.
- Balancing the capacitor voltages at any given time is difficult hence requiring a control strategy.

In the next subsection we will look at the principle of operation of MMCs.

4.3.1 Functional Principle and Description of the MMC

Figure 4.4 shows three legs or phases of a three phase MMC. There are all together six arms (3 upper arms and 3 lower arms) with each arm consisting of N sub modules connected in series, an inductor and a resistor. The inductor is meant to balance the voltage difference between the upper and lower arms in each phase and also to prevent the current from getting too high in case of a fault (short circuit). Arm resistor values should be very low to reduce the converter power losses. N sub modules results to $N + 1$ or $2N + 1$ levels depending on the modulation technique used [95]. It should be noted that the number of sub modules in the upper arm is always the same as the number in the lower arm and this number influences the output as will be seen later. Depending on the sub module topology used, the number of IGBTs, reversing diodes and DC capacitors varies. If HB sub modules are involved then there will be two IGBTs, two reversing diodes and one DC capacitor per sub module but if the sub modules are built with FB topology then four IGBTs, four antiparallel diodes and one DC capacitor are the main constituents. HB and FB sub modules are the simplest and the others basically are just adjustments made to them or a mixture of the two by adding some other components. Examples of these are, FBs with a reduced number of IGBTs [86], HB mixed with FB [87], cross coupled HB sub modules [83], clamp-double sub module (CD-SM) [32], FB plus director switches or alternate arm converter (AAC) [84], semi FB sub module topologies [85] etc.

Depending on the gating signals applied at the gate of the semiconductor devices and the direction in which current flows, a given sub module can be inserted or bypassed. Complementary switches cannot be ON at the same time because a short circuit can occur. So when one is ON the other must be OFF. The direction in which current flows affects the voltage of the capacitor, if this current direction is positive or towards the capacitor, then the capacitor will be charged hence increasing its voltage. On the other hand, if the current is flowing away from it or negative, then the capacitor will be discharging. This work will look at both the HB and FB sub module topologies though much emphasis will be laid on the half-bridge type because of reasons which will be explained later.

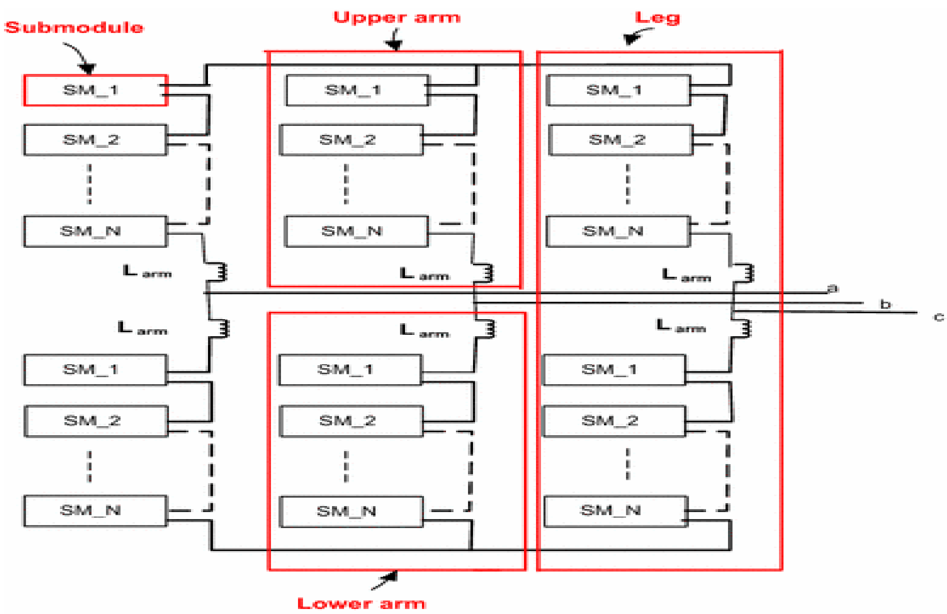


Figure 4.4 MMC structure [53].

4.3.2 Half-Bridge (HB) Sub Module

This sub module type is made up of two transistors or switches (S1 and S2), two anti-parallel diodes and a storage capacitor as displayed in Figure 4.5. Three operating states, inserted, bypassed and blocked states exists for each sub module. Switches S1 and S2 cannot be ON at the same time (forbidden state). When S1 is OFF and S2 is ON, the state is bypass and the output voltage Vo is equal to zero. When S1 is ON and S2 is OFF, the state of the sub module is "Inserted" and the output voltage Vo is equal to the voltage across the capacitor Vc. The current direction will then decide if the capacitor will charge or discharge. Positive means charging and negative discharging. Table 4.2 gives the necessary information on which transistor to switch on or off in order to obtain the various operating states. Each sub module has its own capacitor whose value is a fraction of the input DC voltage. Lack of ability to suppress fault currents caused by DC side short circuits is one of the disadvantages of this configuration. To solve this issue, expensive circuit breakers are usually added. This sub module structure is the simplest and is extensively used for inverter and rectifier purposes and applications that require unipolar arm voltages. The semiconductor losses are low because fewer semiconductor devices are used.

Table 4.2 HB sub module operation.

States	**S1**	**S2**	**Current Direction**	**Output Voltage (Vo)**
Inserted	ON	OFF	> 0	Vc & Charging
	ON	OFF	< 0	Vc & discharging
Blocked	OFF	OFF	> 0	Vc & Charging
	OFF	OFF	< 0	0
Bypassed	OFF	ON	$> 0\ OR\ < 0$	0

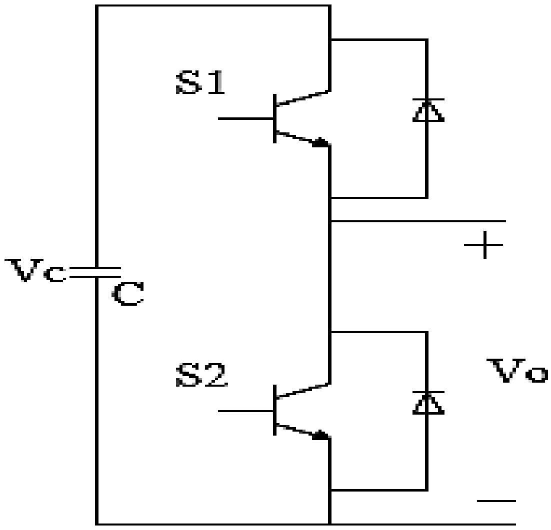
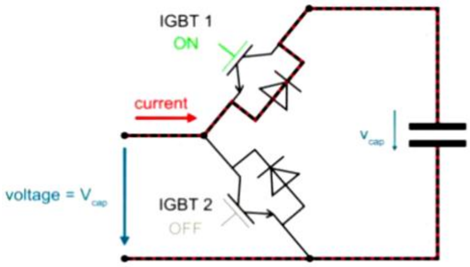
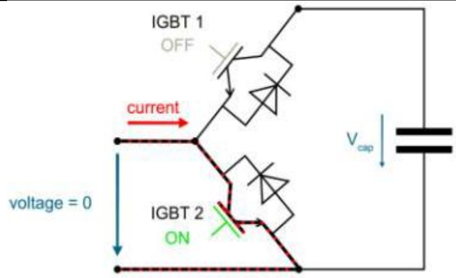
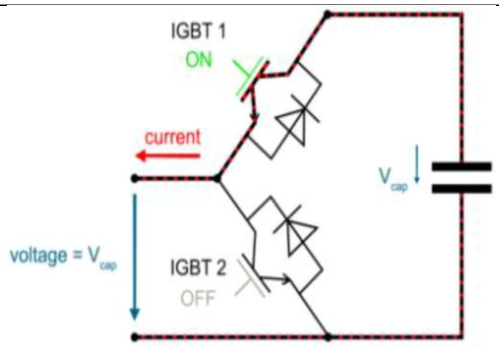
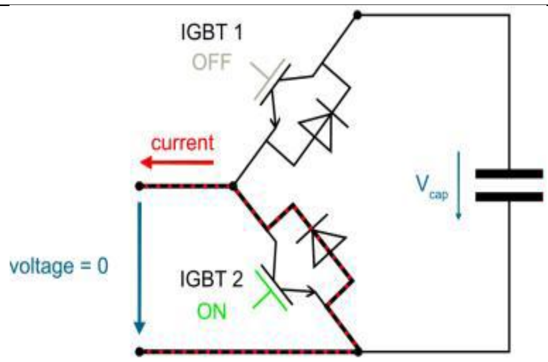


Figure 4.5 Half-bridge topology.

Table 4.3 HB states and current directions [71].

Current direction	**Inserted cell**	**Bypassed cell**
i>0	 Charging	
i<0	 Discharging	

4.3.2 Full Bridge (FB) Sub Module

This sub module structure consists of 4 switches (S1, S2, S3 and S4), 4 anti-parallel diodes and a DC storage capacitor as shown in Figure 4.6. FB is able to reverse the voltage and produce bipolar arm voltages reason why they find application in AC to AC systems and matrix systems.

DC fault currents can be minimized by this structure but needs more semiconductor devices (two times the number needed by HB) resulting in higher power losses. The output from each sub module is either $-Vsm$, 0, or Vsm where Vsm refers to the voltage of the sub module. Though they can also be utilized for applications that require unipolar arm voltages (DC to AC), the losses reduces their popularity for such cases. Normally the $-Vsm$ output is not made use of except in the case of a fault at the DC side.

Table 4.4 FB switch states.

S1	**S2**	**S3**	**S4**	**Output voltage Vo**
ON	OFF	ON	OFF	0
OFF	ON	OFF	ON	0
ON	OFF	OFF	ON	$+Vc$
OFF	ON	ON	OFF	$-Vc$

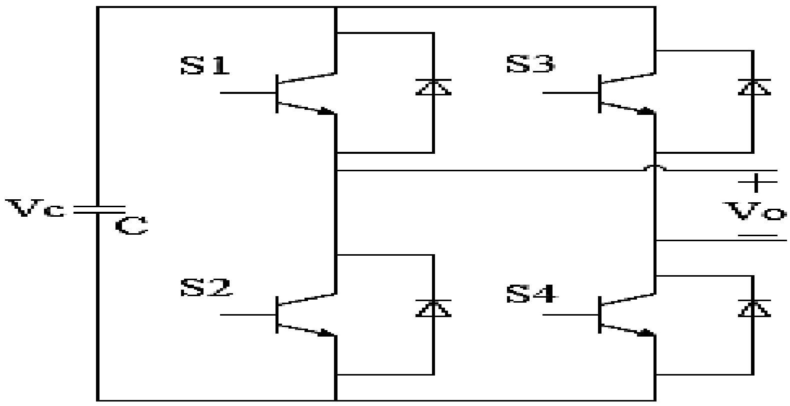


Figure 4.6 FB sub module.

4.3.3 Differences between HB and FB Sub Modules

Table 4.5 HB and FB comparison.

Half-Bridge	Full-Bridge
1. DC capacitor terminals polarity cannot be reversed	DC capacitor can be connected to the terminal in either polarities
2. DC line faults cannot be cleared without the addition of circuit breakers.	DC faults can be cleared by simply reversing the voltage.
3. AC voltage (positive or zero) is always less than the DC voltage.	AC voltage can be positive, negative or zero.
4. Low semiconductor losses	Higher semiconductor losses
5. Mostly used for commercial purposes because it is cheaper and highly efficient.	Mostly used for overhead lines and are more costly when compared to HB.

4.4 Modulation Techniques

Modulation refers to the derivation of the gate signals for semiconductor devices. This can also be known as switching methods. They are also vital in energy control and sub module control. High, low and mixed switching modulation techniques exist according to Figure 4.7 [74]. The high frequency methods are basically a comparison of a reference signal to a carrier waveform to give rise to the gate signals while in the low frequency methods a signal or pulse that has already been calculated is used as inputs to the semiconductor gates. The last type is a combination of the two. High efficiency and low switching count are amongst the advantages of low frequency modulation techniques but they have a problem in that since the signal is pre calculated it is suitable for static response and not dynamic response. Selected harmonic elimination (SHE) and nearest level modulation (NLM) are some examples of low frequency modulation methods [80-82]. High frequency switching methods are the mostly used for MMCs with a small number of sub modules because they are easy to put into operation though their switching losses are high due to high switching count. Low frequency switching methods are preferred for a converter with a large number of sub modules and they also have lower losses. The reference signal's frequency and magnitude is similar to the desired output signal and the carrier signal has a fixed magnitude and frequency. These two signals are compared, at the point where the meet each other switching occurs. If the reference signal is higher than the carrier, a high pulse (1) is sent to the gate and a low (0) when it is lower. Level shifted and phase shifted pulse width modulation (PWM) are the most common examples of high frequency switching techniques for MMC applications and fall under carrier based modulation methods. Modulation methods directly or indirectly influences harmonics of the output at the AC end, current and voltage ripple on the DC side, switching frequency and currents flowing in the sub module arms [54, 95].

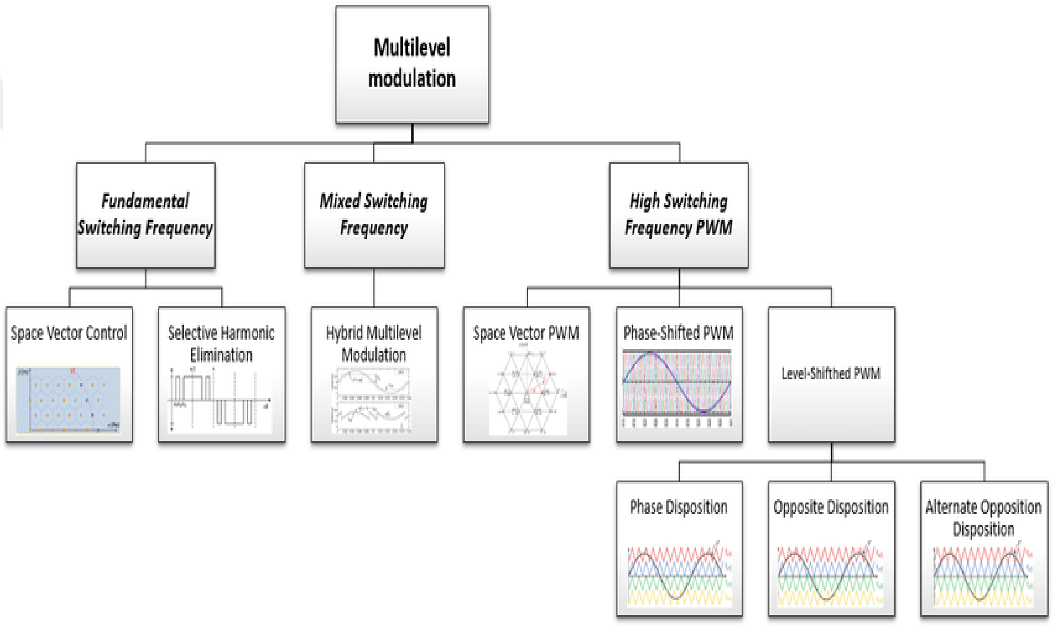


Figure 4.7 Classification of multilevel converter modulation techniques [74].

4.4.1 Level Shifted PWM (LS-PWM)

In this scheme, carrier waves are either below or above one another with the number of carrier waves equal to the number of the sub modules. That is one carrier wave is dedicated to one sub module. Carriers here are of the same frequency and do not cross each other and the amplitude of these waves are given by Vdc/N. The disadvantage with this technique is the unequal distribution of voltage ripples across sub modules causing high circulating currents to flow and AC voltage harmonic distortions. LS-PWM can be grouped into three categories based on the way carrier waves are shifted from each other:

4.4.1.1 Phase Disposition (PD)

Carriers are in phase and have the same frequency and amplitude in this type of level shifted PWM. Figure 4.8(a) illustrates an example of PD in which 8 triangular carrier waves are used.

4.4.1.2 Phase Opposition Disposition (POD)

Carriers above and those below the zero line or origin are 180 degrees out of phase as shown in Figure 4.8(b).

4.4.1.3 Alternative Phase Opposition Disposition (APOD)

Alternate carriers are 180 degrees out of phase and have the same amplitude. This technique is illustrated in Figure 4.8(c). $N-1$ carriers give rise to N levels at the output. These three techniques produce similar AC output waveforms and the frequency of the reference signal used is always less than that of the carriers.

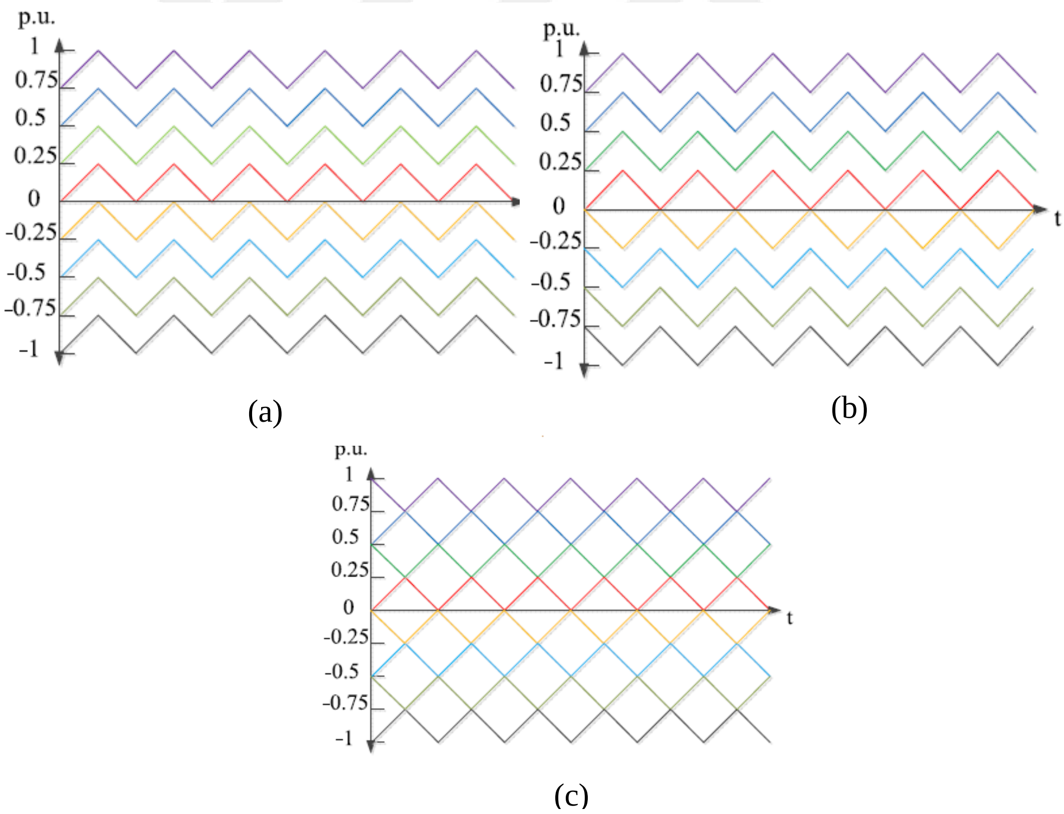


Figure 4.8 (a) PD (b) POD (C) APOD [122].

4.4.2 Phase Shifted Pulse Width Modulation (PS-PWM)

In this scheme all the carriers have the same level (amplitude Vdc) but are phase shifted from one another, the value of the shifting depends on the number of sub modules per arm. If $N = 6$, then the carrier waves will be shifted by $360/6$ as is the case in Figure 4.9. Carriers here cross each other and have the same frequency. The advantage with this technique is that all sub modules are used equally and it produces low output harmonics [46]. On the other hand, the frequency of switching is higher than in LS-PWM leading to high switching losses. PS-PWM has been chosen for this work because it is easy to implement, equal usage of sub modules, its suitability for a system with a small number of sub modules per arm and its ability to self-balance the capacitor voltages.

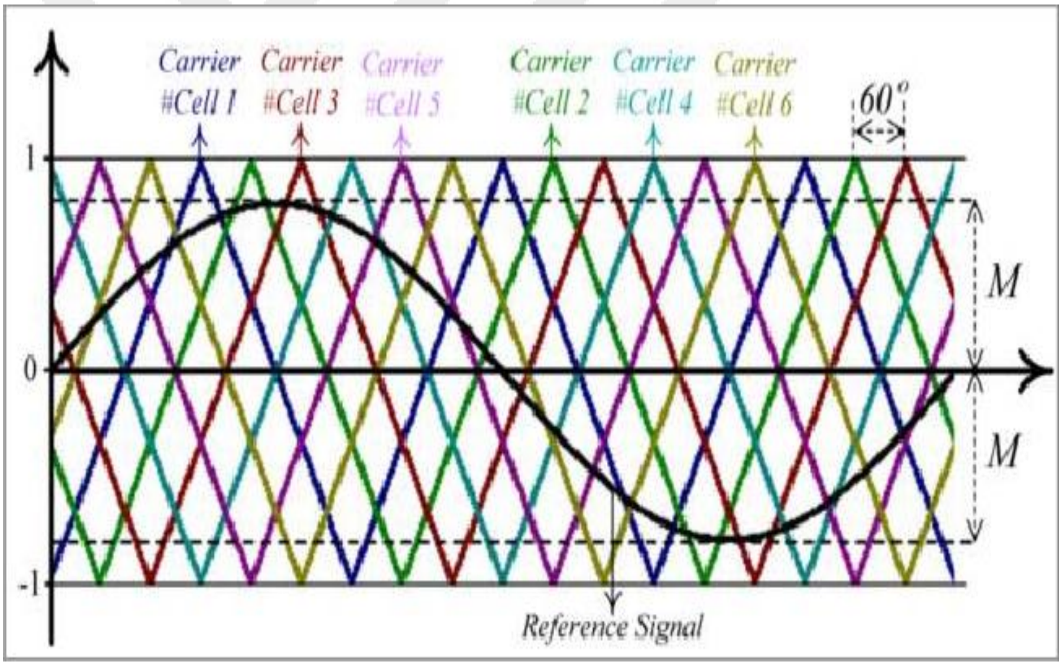


Figure 4.9 PS-PWM [73].

4.5 Capacitor Voltage Balancing

Important factors to be considered when choosing a modulation technique for MMCs are the switching losses, its ability to balance the capacitor voltages and the quality and nature of the output waveform. So whatever decision is to be made the above factors should be considered. Inequalities in capacitor voltages of sub modules results from a situation when there is need for a new sub module to be inserted or a sub module needs to be bypassed. In the first situation, if the current is positive, then the capacitor of the sub module will be charged and if it is negative, it will discharge. Without a control mechanism or algorithm, any given sub module can be charged or discharged at any given time resulting to some having high voltage values and others low voltage values. Reference [55] proposes an algorithm in which the sub module with the lowest voltage value is selected during the charging and that with highest voltage to be selected in discharging condition. Reference [56] introduces a constant known as voltage sharing balancing factor which is applied to the modulation signal of each sub module in order to balance the sub module capacitor voltages. Compared to the above method, this one is quite easy since no sorting and classification of sub modules is needed. In this work the balancing of capacitor voltages will be done solely by the modulation technique CPS-SPWM because of its self-balancing properties.

4.6 Circulating Currents

Another issue with MMCs are the circulating currents flowing within converter arms that need to be suppressed shown in Figure 4.10. Circulating currents originate from unbalanced arm energies and consists of a DC component and an AC component. The circulating currents originating from the AC component are undesirable because they increase the power loss and the sub module capacitor voltage ripple while the DC component of the current is responsible for transferring power to the output. They can only be seen inside the converter as they have no effect on the output as their sum is always equal to zero i.e. $i_{cc1}(t) + i_{cc2}(t) + i_{cc3}(t) = 0$, where i_{cc} stands for the internal circulating current. The easiest way to suppress these currents is to increase the arm reactance and by so doing increases the overall cost of the device. Different techniques to control these circulating currents are covered in [76-79].

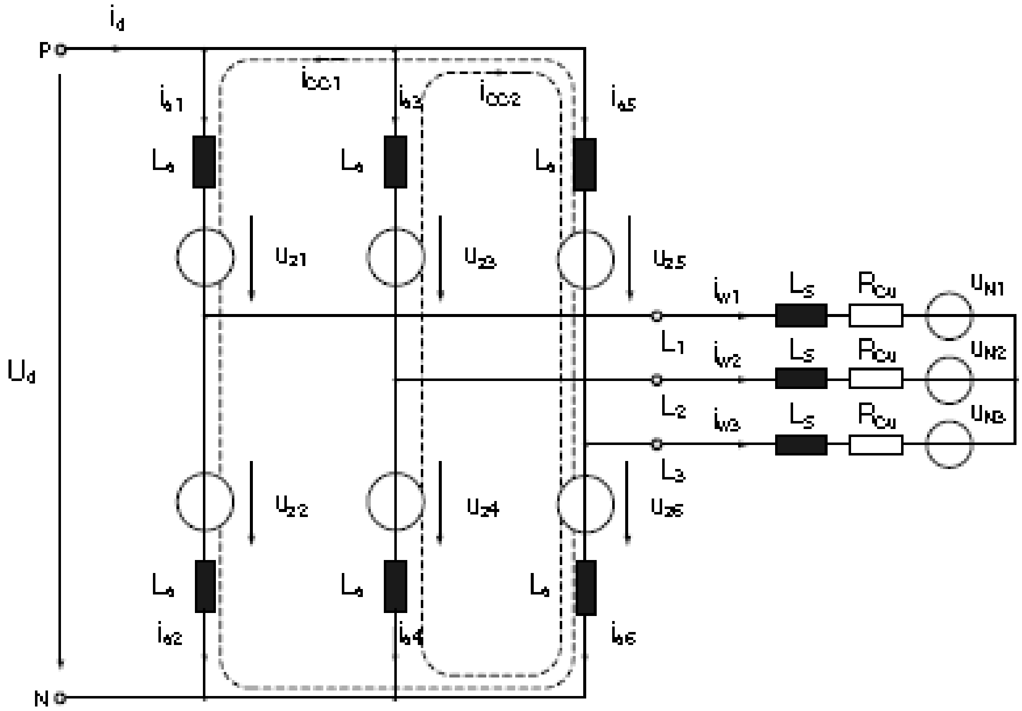


Figure 4.10 Circulating currents in MMC [75].

4.7 Mathematical Modeling of an MMC

The development of a mathematical model of an MMC necessitates some assumptions.

- Sub modules are many and are summarized as one voltage source. *N* represents the number of sub modules per arm.
- DC voltages and currents are constant.
- AC currents are sinusoidal.
- infinite switching frequency
- Half bridge sub modules are used.

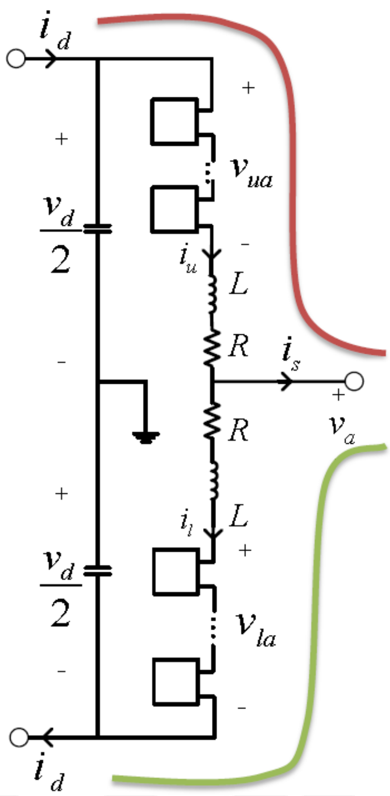


Figure 4.11 One phase leg of an MMC.

DC voltage is divided equally between the upper and lower arms each having $V_{DC}/2$. Since there are N sub modules per arm, the maximum voltage that can exist across any capacitor is V_{DC}/N. Considering one phase leg of an MMC as shown in Figure 4.11, circuit analysis can be made. Applying KVL and KCL we obtain the following equations;

$$\frac{v_d}{2} = R_{i_U} + L\frac{di_U}{dt} + v_U + v_a \tag{4.1}$$

$$\frac{v_d}{2} = R_{i_l} + L\frac{di_l}{dt} + v_l - v_a \tag{4.2}$$

$$i_s = i_u - i_l \tag{4.3}$$

$$i_c = \frac{i_u + i_l}{2} \tag{4.4}$$

$$v_{ua} = \frac{v_d}{2} - v_a \tag{4.5}$$

$$v_{la} = \frac{v_d}{2} + v_a \quad (4.6)$$

$$w_0 = 2NC_0\mathrm{U}_{co}^2 \quad (4.7)$$

where i_c is the circulating current flowing, v_a is the AC output voltage of phase A, v_{ua} and v_{la} are the upper arm and lower arm voltages respectively. Taking a critical look at Equations (4.3) and (4.4), we can observe that the output current i_s has no direct relationship with the circulating current which appears to have effects only in the upper and lower arms. Adding Equation (4.5) and (4.6) gives us a very interesting Equation (4.8) proving the fact that at any given time of conduction, the sum of the upper and lower arms voltages must be equal to the DC voltage at the input. Also the insertion index $n(t)$ determines which sub modules are inserted and which are bypassed in order to satisfy this equation. The formula for insertion index is given in Equation (4.9) and it can hold values in the range $0 < n(t) \leq 1$ i.e. its values are between 0 and 1, 0 means no sub module is inserted and 1 means that all sub modules are inserted. The sum of the insertion indexes of the upper and lower arms should always be 1.

$$v_{ua} + v_{l_a} = v_d \quad (4.8)$$

The energy w_0 of each sub module is calculated from Equation (4.7). The total energy in any given arm can be gotten from summation of all the individual sub modules energy. These analyses are only for one phase (phase A) of an MMC. Analysis for phases B and C are the same and can be derived by changing the variables (in most cases where you have a, you just need to replace with b or c depending on the phase).

$$n(t) = \frac{N_{inserted}}{N} \quad (4.9)$$

$$C^{arm} = \frac{C_o}{N} \quad (4.10)$$

The effective capacitance is

$$C^m = \frac{C^{arm}}{n(t)} \quad (4.11)$$

The AC voltage obtained at the output as a function of the modulation index m is given by Equation (4.12). The maximum AC voltage is obtained when the modulation index is 1 which gives $V_{DC}/2$.

$$v_a = \frac{V_{DC}}{2} * m \tag{4.12}$$

4.8 Applications of MMC

MMCs in the past decade have been a topic of interest to many researchers and companies like Siemens, Alstom, ABB etc. because they can be used in a variety of tasks amongst which are:

- Back to back MMCs are used for HVDC projects and HVDC cable transmission [66-67].
- Used in FACTS devices e.g. STATCOM, UPFC, SVC, SSSC [64, 65].
- Most medium and high voltage rectifiers and inverters are built with MMCs [70].
- Frequency conversion applications [61].
- Motor drive applications [59].
- Smart grids applications [68].
- Application of MMC for Railway [60].
- Offshore wind power and solar applications [62, 63].
- Energy storage systems applications due to their redundancy [69].

Figure 4.12 Interior view of a converter station HVDC-MMC link [57].

CHAPTER 5

MODELLING OF 3-PHASE MMC BASED UPFC

5.1 Introduction

The main objective of this chapter is to provide a comprehensive study on recent developments in modeling of VSC based FACTS. Mathematical models of UPFC and MMC will also be covered. UPFC is a versatile FACTS device member because of its ability to control three line parameters simultaneously, selectively or independently. Much research work has been done on the modeling of UPFC in power flow analysis for steady state local voltage control and real and reactive power flow control [103] [104]. Though various control modes exist for the UPFC, active and reactive power control modes are the most common reason why their mathematical models are easily available [4]. Modeling refers to "designing and analyzing a mathematical representation of an economic system to study the effect of changes to system variables [105]." Basically, two mathematical models of UPFCs exists, steady state models and dynamic or transient models [105]. Steady state models are for power flow analysis meanwhile; dynamic models are used to study power, voltage and stability of system when system parameters change. Steady state models include power injection models, decoupled models, and impedance models.

A power injection model of a UPFC was proposed by A. M. Vural et al., for power flow studies taking into consideration the operational losses [45]. Reference [106] and reference [107] introduced the impedance and decoupled model of a UPFC respectively. All the above models are steady state models with the main objective of keeping a balance between the input real power on the shunt side and output real power on the series part of UPFC. References [108-110] proposed dynamic models for UPFC operation in unforeseen circumstances like unbalanced conditions, fault occurrences etc. Generally, they are suitable for situations where one or more system variables changes.

5.2 Mathematical Model of UPFC under Synchronous Rotating Coordinate

In order to better understand the principle of operation, basic behavior and design of control circuits for UPFCs, a mathematical model is required. Considering the UPFC equivalent circuit in Figure 5.1 and under the assumption that there is voltage balance in the AC system, the mathematical model of UPFC in the synchronous rotating frame will be established.

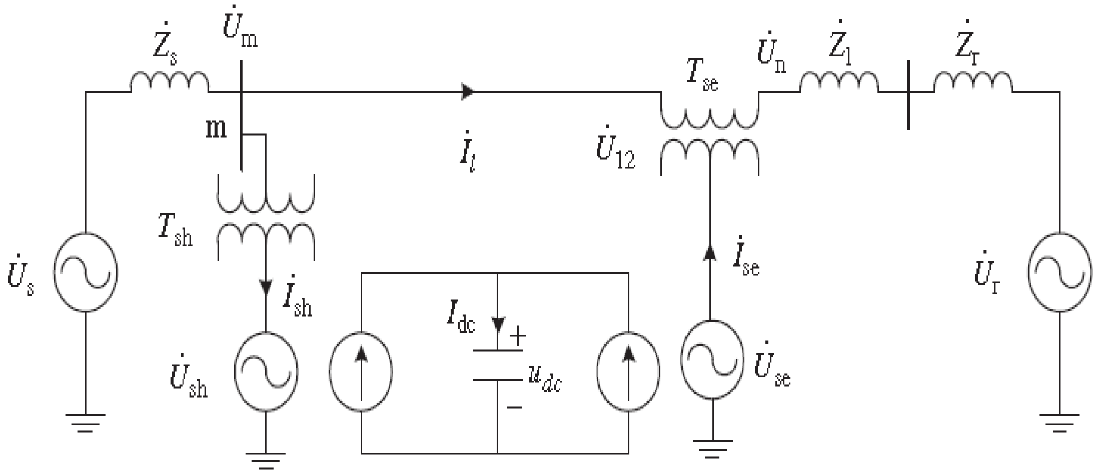


Figure 5.1 UPFC equivalent circuit [105].

In Figure 5.1, $\dot{U}_{sh}$, $\dot{U}_{se}$, represent the equivalent voltage sources for the shunt and series converters. $\dot{U}_{n}$, $\dot{U}_{m}$ are the AC side line voltages of the series and shunt converters, respectively. T_{sh}, T_{se} stands for the shunt and series transformers. $\dot{U}_{s}$, $\dot{U}_{r}$ denotes the transmission line equivalent voltage sources for the sending and receiving ends as well as their impedances, $\dot{Z}_{s}$, $\dot{Z}_{r}$. $\dot{I}_{sh}$, $\dot{I}_{se}$ represents the input and output current of the series converter. I_{dc} , U_{dc} are the DC capacitor current and voltage. The output of the series transformer is $\dot{U}_{12}$.

5.2.1 Shunt Converter Model

The three-phase shunt converter model in the static coordinate system can be written as seen below assuming the three-phase system is symmetrical. The line voltages u_{ma}, u_{mb} and u_{mc} of the shunt converter can be obtained from

$$u_{ma} = u_{sha} + R_{sh} i_{sha} + L_{sh} \frac{di_{sha}}{dt} \tag{5.1}$$

$$u_{mb} = u_{shb} + R_{sh}i_{shb} + L_{sh}\frac{di_{shb}}{dt} \quad (5.2)$$

$$u_{mc} = u_{shc} + R_{sh}i_{shc} + L_{sh}\frac{di_{shc}}{dt} \quad (5.3)$$

where subscripts a, b and c represents a three-phase system; u_{sha} u_{shb} u_{shc} are the three-phase alternating voltages; i_{sha} i_{shb} i_{shc} are the three-phase input currents into the shunt converter; L_{sh} R_{sh} denotes the equivalent inductance and resistance of the shunt converter.

In order to convert the system from the three-phase static system to the two-phase synchronous rotating coordinate, the Park transform matrix in Equation (5.4) is used for this purpose.

$$C = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \end{bmatrix} \quad (5.4)$$

In Equation (5.4), θ is the phase angle and ω_s is the synchronous angular velocity. They are related by the formula, $\theta = \omega_s + \theta_0$ where θ_0 stands for the initial phase angle.

When the above Park's transformation is applied to Equations (5.1), (5.2) and (5.3), the following equations are obtained.

$$u_{md} = u_{shd} + R_{sh}i_{shd} + L_{sh}\frac{di_{shd}}{dt} - \omega_s L_{sh} i_{shq} \quad (5.5)$$

$$u_{mq} = u_{shq} + R_{sh}i_{shq} + L_{sh}\frac{di_{shq}}{dt} - \omega_s L_{sh} i_{shd} \quad (5.6)$$

where d and q denotes the direct and quadrature axes, respectively.

5.2.2 Series Converter Model

The series converter's three-phase output voltages u_{sea}, u_{seb} and u_{sec} on the AC end can be calculated from the expressions below

$$u_{sea} = u_{12a} + R_{se}i_{sea} + L_{se}\frac{di_{sea}}{dt} \quad (5.7)$$

$$u_{seb} = u_{12b} + R_{se}i_{seb} + L_{se}\frac{di_{seb}}{dt} \quad (5.8)$$

$$u_{sec} = u_{12c} + R_{se}i_{sec} + L_{se}\frac{di_{sec}}{dt} \quad (5.9)$$

where R_{se} and L_{se} are the equivalent resistance and inductance of the series converter; u_{12a}, u_{12b}, and u_{12c} are the series transformer's three-phase output voltages; i_{sea}, i_{seb}, and i_{sec} are the output currents from the series converter.

By applying the Park transformation matrix in (5.4) to (5.7), (5.8), and (5.9) we obtain the following equations in the synchronous rotating frame system

$$u_{sed} = u_{12d} + R_{se}i_{sed} + L_{se}\frac{di_{sed}}{dt} - \omega_s L_{se} i_{seq} \tag{5.10}$$

$$u_{seq} = u_{12q} + R_{se}i_{shq} + L_{se}\frac{di_{shq}}{dt} - \omega_s L_{se} i_{sed} \tag{5.11}$$

where d and q stands for the direct and quadrature axes. The variables have the same definition as in the static coordinate system differing in only the subscript d and q replacing a and b , respectively.

5.2.3 DC link Mathematical Model

The DC link that connects the shunt converter to the series converter in a UPFC provides a closed path in which real power can be exchanged between the two converters. The power balance equation of the DC link is

$$p_{dc} = p_1 - p_2 - p_{loss} \tag{5.12}$$

where p_{dc} is the DC power and can be calculated from Equation (5.13). p_1 is the consumed power by the shunt converter which can be gotten from Equation (5.14). The converter losses are denoted by p_{loss}.

$$p_{dc} = Cu_{dc}\frac{du_{dc}}{dt} \tag{5.13}$$

$$p_1 = \frac{3}{2}\left(u_{shd}i_{shd} + u_{shq}i_{shq}\right) \tag{5.14}$$

The output active power p_2 of the shunt converter can be expressed as

$$p_2 = \frac{3}{2}\left(u_{sed}i_{sed} + u_{seq}i_{seq}\right) \tag{5.15}$$

Substituting p_{dc}, $p_1$and p_2 in Equation (5.12) with their expressions from Equations (5.13), (5.14) and (5.15) gives the expression of the mathematical model of the DC link as

$$Cu_{dc}\frac{du_{dc}}{dt} = \frac{3}{2}\left(u_{shd}i_{shd} + u_{shq}i_{shq} - u_{sed}i_{sed} - u_{seq}i_{seq}\right) - p_{loss} \tag{5.16}$$

The UPFC is made up of a series and shunt converter connected to a transmission line. The series converter injects a series voltage of magnitude V_{se} and phase p which are all variable within a given range. The shunt converter on its part is a current source which either absorbs or supplies the real power demanded by the series converter and also controls reactive power independently at its connected bus. Now we are going to look at the effects of the real and reactive power on a transmission system with and without the UPFC. Considering the transmission line in Figure 5.2, the following equations can be derived according to reference [112].

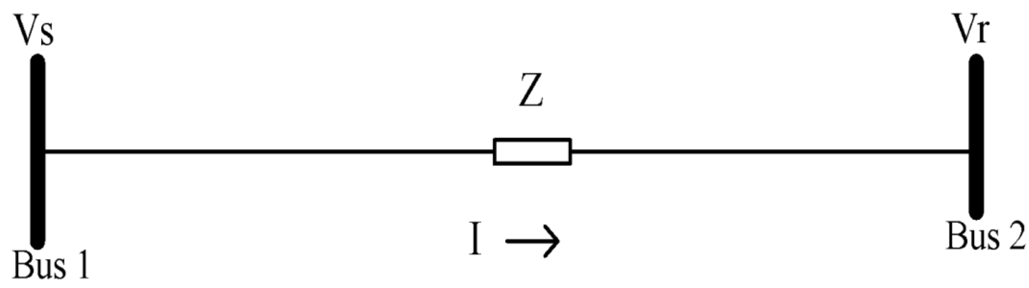


Figure 5.2 A transmission line.

The voltage at the sending end is $V_s = Ve^{-j\varphi 1}$ and the receiving end voltage is $V_r = Ve^{-j\varphi 2}$. Z is the line impedance in complex form and the current flowing through the line is given by $I = (V_s - V_r)/Z$. The apparent AC power transmitted from the sending end to the receiving end is

$$S = V_r I^* = V_r \left[\frac{V_s - V_r}{Z}\right]^* \tag{5.17}$$

$$\delta = \varphi 2 - \varphi 1 \tag{5.18}$$

δ is called the "power angle" which is the difference between the phases of the voltages at bus 1 and 2.

The resistance of the line is ignored, implying that $Z = X$. The real and reactive power flowing on the line without UPFC insertion can be expressed as

$$P = \frac{V_s V_r}{X} \sin\delta \tag{5.19}$$

$$Q = \frac{V_r}{X}(\cos\delta - V_r) \tag{5.20}$$

With the insertion of a UPFC, the above equations become

$$P - jQ_r = V_r\left[\frac{V_s+V_{se}-V_r}{jX}\right] \quad (5.21)$$

where V_{se} is the injected series voltage by the UPFC, $V_r = Ve^{\frac{-j\delta}{2}}$ and $V_s = Ve^{\frac{j\delta}{2}}$.

The total real power P is

$$P(\delta,\rho) = P_o(\delta) + P_{se}(\rho) \quad (5.22)$$

$$P(\delta,\rho) = \frac{V^2}{X}\sin\delta - \frac{VV_{se}}{X}\left(\cos\frac{\delta}{2} + \rho\right) \quad (5.23)$$

The total reactive power Q is

$$Q(\delta,\rho) = Q_o(\delta) + Q_{se}(\rho) \quad (5.24)$$

$$Q(\delta,\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{VV_{se}}{X}\left(\sin\frac{\delta}{2} + \rho\right) \quad (5.25)$$

$Q_o(\delta)$ and $P_o(\delta)$ stands for the reactive and active power flow without the UPFC while $Q(\delta,\rho)$ and $P(\delta,\rho)$ are expressions for the reactive and real power when the UPFC is connected to the transmission line. As can be seen from Equation (5.25), the UPFC can influence the real and reactive power flowing in a line depending on the magnitude and phase angle of the voltage injected by the series converter of the UPFC. The series injected voltage can be varied from 0 to V_{semax} while the angle p can be varied from 0 to 360 degrees. Figure 5.3 shows the effect of changing the power angle δ on the UPFC control area. When $\delta = 90^{\circ}$, the UPFC influence on the system is at its maximum [113]. This improves the operational range of the system without exceeding the stability limits.

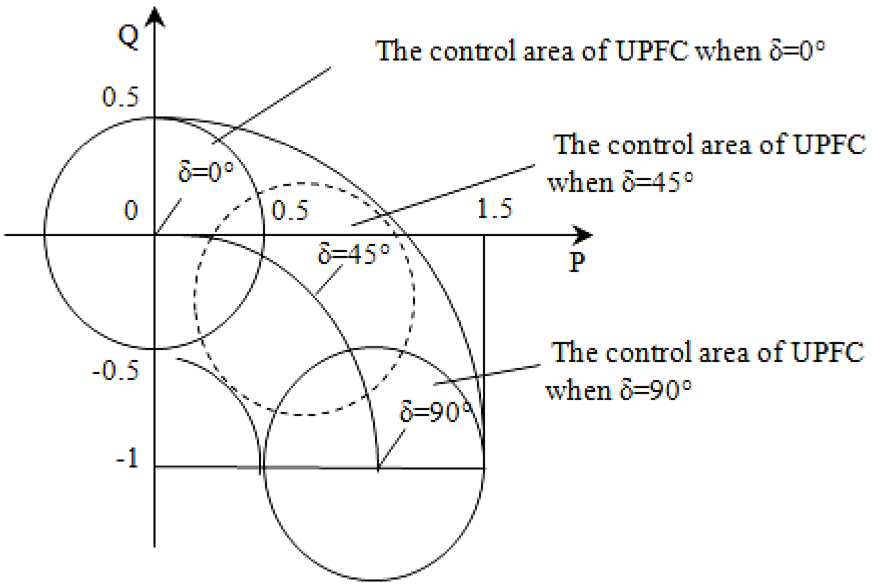


Figure 5.3 P and Q control area curve of UPFC for different values of the power angle [113].

5.3 Modular Multilevel Converter (MMC)

MMC is the VSC type chosen for this thesis because it improves the quality of the output waveform and doesn't require extra filters. A three-phase MMC has 6 arms; 3 upper arms and 3 lower arms. Each arm is made up of equal n-sub modules as in Figure 4.4 which are switched on and off by a gating signal applied at the gate of the IGBT. HB sub modules are selected for this thesis because they require fewer components, have low losses and they are easy to implement. Each sub module is a controllable voltage source whose output is either 0 or the voltage of the capacitor (V_c). The mathematical modeling of MMC was presented in chapter 4. In this work, $n = 10$ sub modules were used and the dc link voltage $V_{dc} = 60KV$. This implies that the capacitor voltage of each sub module $V_c = 60/10 = 6KV$. If the MMC is to function well, the capacitor voltages of each cell should be approximately 6KV at all times irrespective of the modulation technique put in place. Presence of an upper and lower arm means that at any particular time of operation, the sum of the voltages in the two arms should not exceed the DC link voltage.

The energy in the upper and lower arms of an MMC is defined as [56],

$$W_{cu}^{\Sigma} = \frac{C^{arm}}{2} \left(u_{cu}^{\Sigma}\right)^2 \tag{5.26}$$

$$W_{cl}^{\Sigma} = \frac{C^{arm}}{2}\left(u_{cl}^{\Sigma}\right)^2 \quad (5.27)$$

The total energy and difference in energy in each phase leg can be expressed as

$$W_{c}^{\Sigma} = W_{cu}^{\Sigma} + W_{cl}^{\Sigma} \quad (5.28)$$

$$W_{c}^{\Delta} = W_{cu}^{\Sigma} - W_{cl}^{\Sigma} \quad (5.29)$$

Difference in the energy of the upper arm and lower arm as well as unequal capacitor voltages of sub modules gives rise to circulating currents. To summarize, for an MMC circuit to function properly, circulating currents should be minimized, capacitor voltages of sub modules should be approximately equal at all times and the DC link voltage should be kept constant. The CPS-SPWM was chosen for this work because it tries to minimize or solve the above issues without an additional circuit since the number of inserted sub modules is always constant and because of their simplicity [123]. Table 5.1 provides information on the circuit parameters and their values that were used in the B2B MMC simulation.

Table 5.1 MMC parameters and values.

Parameter	**Value**	**Parameter**	**Value**
V_{dc}	60KV	N	10
C_o	6000V	f	50Hz
R_{arm}	0.005 Ω	R_{out}	100Ω
L_{arm}	1mH	f_c	500Hz
C_{sm}	2mF	C_{dc}	10F

5.3.1 Dimensioning of Sub module's Capacitors and Arm Inductors

The capacitance of sub modules and inductance of the phase arm are two very important parameters that should be selected with care. The arm inductors minimize the circulating currents flowing through the converter arm. They also reduce the rise in current in a situation where a fault occurs. References [114-115] provided the following formulas for calculating these parameters.

$$C = \frac{P_s}{3kN\omega_o eV_c^2}\left[1 - \left(\frac{k\cos\emptyset}{2}\right)^2\right]^{\frac{3}{2}} \tag{5.30}$$

$$L = \frac{1}{8\omega_o{}^2 CV_c}\left[\frac{P}{3I_{2f}} + V_{dc}\right] \tag{5.31}$$

where P_s is the apparent three phase power; k is the modulation index of the voltage; $\cos\delta$ is the power factor; N is the number of sub modules; ω_o represents the fundamental frequency; e is the sub module voltage ripple and V_c is the mean of sub module voltages.

5.4 UPFC Operation Modes

The UPFC is made up of a series and shunt converter which can control three line parameters simultaneously or one at a time. These parameters are voltage magnitude, angle and impedance. This is the reason why the UPFC is the most versatile and powerful FACTS device. Depending on which of these parameters need to be controlled, various operation modes of the UPFC exist. Two control modes exist; shunt converter control mode and series converter control mode.

5.4.1 Shunt Converter Control Modes

The shunt converter main objective is to supply the real power demanded by the series converter through the DC link. It can also absorb the real power from the series converter and send it back to the transmission line via the shunt transformer. It also has reactive power compensation abilities. Since it is connected in parallel to the transmission line, it injects a current which can be divided into direct axis and quadrature components. The direct axis current is responsible for real power control and the quadrature takes care of the reactive power. If the shunt converters voltage is greater than the voltage of the line to which it is connected, the shunt current will flow to the line and the converter will supply reactive power to the line (capacitive mode). In the other case, current flows in the opposite direction and the converter consume reactive power (inductive mode). There are two ways of controlling the shunt converter i.e. VAR control and automatic voltage control modes.

5.4.1.1 VAR Control Mode

In this mode, the shunt converter responds to a VAR request by changing the shunt current's direction and adjusting the gating signals of its converter circuit according to the request. The request will either demand the shunt converter to supply reactive power to the line or consume reactive power from the line. Also under this operating mode, the voltage of the DC link has to be monitored and compared with the reference value to keep it constant.

5.4.1.2 Automatic Voltage control Mode

Here the shunt current from the shunt converter tries to keep the voltage of the bus to which it is connected at a specific value. The quadrature axis component of the shunt current is responsible for this [113].

5.4.2 Series Converter Control Modes

The series converter does the main function of the UPFC which is to inject a voltage whose magnitude and phase can be controlled in series with the transmission line. This injected voltage's phase relation with the line current determines which power will be handled. If it is in phase quadrature with the line current, then only reactive power can be controlled. The injected voltage can be obtained in several ways.

5.4.2.1 Direct Voltage Injection Mode

With respect to the reference, the series converter generates the voltage with a particular magnitude and phase angle. Real or reactive power can be compensated depending on the phase relationship between the injected voltage and the line current.

5.4.2.2 Phase Angle Shifting Mode

In this operation mode, the series converter injects a series voltage in such a way that the sending end voltage and the receiving end voltage are out of phase i.e. they are phase shifted by a stated angle value.

5.4.2.3 Line Impedance Control Mode

The input here is an impedance value which is in series with the line impedance. The impedance is obtained from the variation of the injected voltage with respect to the line current and thus the line views the injected series voltage as impedance [116].

5.4.2.4 Automatic Power Flow Control Mode

UPFC can independently control real and reactive power at a particular point on a transmission line to which it is connected. The real and reactive power reference values have to be kept constant at all times. The magnitude and phase of the injected voltage and its phase relationship with the line current are responsible for this control mode.

In this thesis, the series converter will be operated in automatic power flow control mode and the shunt converter in automatic voltage control mode. In addition to the above operation control modes, there is a possibility of operating these devices in Stand Alone Mode [116]. In this mode, the DC link is disconnected allowing the two converters to operate independently. The shunt converter function as a STATCOM and the series converter operates as an SSSC in this mode.

5.5 UPFC Control

UPFC controls the real and reactive power in a transmission line by varying the magnitude and phase of the injected series voltage. UPFC can allow power to flow in particular paths and prevents overloading of certain lines while others are under loaded. They are capable of operating lines closer to their thermal and stability limits without exceeding these limits. A UPFC control system should be able to achieve steady state objectives as well as improving the transient and dynamic stability of the system [14]. UPFC has 3 degrees of freedom; shunt reactive current, magnitude and angle of series voltage. Many d-q axis UPFC control strategies have been proposed in references [14, 18, 117-119]. These control strategies rely on the use of proportional-integral (PI), proportional–integral–derivative (PID), cross-coupling controllers.

The PI controller was chosen for this work because they are simple to implement and to tune [118]. In the next sections, the shunt converter control and series converter control will be explained in the synchronous rotating dq frame. The shunt converter will be operated in automatic voltage regulation mode and the series converter in automatic real and reactive power control mode.

5.5.1 Shunt Converter Control

The shunt current which flows through the shunt converter can be controlled by altering the magnitude and phase angle of the shunt converter's voltage [14]. The shunt converter is capable of controlling bus voltage, reactive power and the voltage of the DC link capacitor. The dq axis is used for the control system. The d-axis is responsible for the DC link's voltage while the bus voltage and reactive power of the UPFC bus can be controlled with the q-axis component. The first step is to convert the three phase voltage and current at the sending end from the abc stationary frame to the dqo stationary frame using the corresponding simulation block. The values obtained from this block are the values V_d, V_q, I_d and I_q. The voltage of the DC link capacitor will then be measured and compared with the reference value in order to get the error. This error will then be passed through a PI controller to minimize it. The d-axis shunt current which is the output from the PI controller then serves as one of the inputs for the current controller. The q-axis component is involved in the voltage control as follows. The bus voltage is converted to V_d and V_q and then their magnitude which can be calculated as shown in Equation (5.36) is compared with the reference bus voltage. The error is minimized by the application of a PI controller in order to obtain the q-axis shunt current reference as shown in Figure 5.4. The equations in the D-q rotating frame are [14],

$$\frac{di_D^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_D^{sh} - \omega_o i_Q^{sh} + \frac{\omega_b}{x_{sh}}\left(e_D^{sh} - v_D^{u1}\right) \tag{5.32}$$

$$\frac{di_Q^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_Q^{sh} + \omega_o i_D^{sh} + \frac{\omega_b}{x_{sh}}\left(e_Q^{sh} - v_Q^{u1}\right) \tag{5.33}$$

where, e_D^{sh}, e_Q^{sh} are the shunt converter's output voltage components; v_Q^{u1}, v_D^{u1} are the voltage components at bus 1 where the shunt converter of UPFC is connected; r_{sh}, x_{sh} are the transformer's resistance and leakage reactance. The reactive and real parts of the shunt current are given by

$$i_R^{sh} = i_D^{sh}\cos(\theta^{u1}) - i_Q^{sh}\sin(\theta^{u1}) \tag{5.34}$$

$$i_P^{sh} = i_D^{sh}\sin(\theta^{u1}) + i_Q^{sh}\cos(\theta^{u1}) \tag{5.35}$$

where,

$$V^{u1} = \sqrt{(v_D^{u1})^2 + \left(v_Q^{u1}\right)^2} \tag{5.36}$$

$$\theta^{u1} = \tan^{-1}\left[\frac{v_D^{u1}}{v_Q^{u1}}\right] \tag{5.37}$$

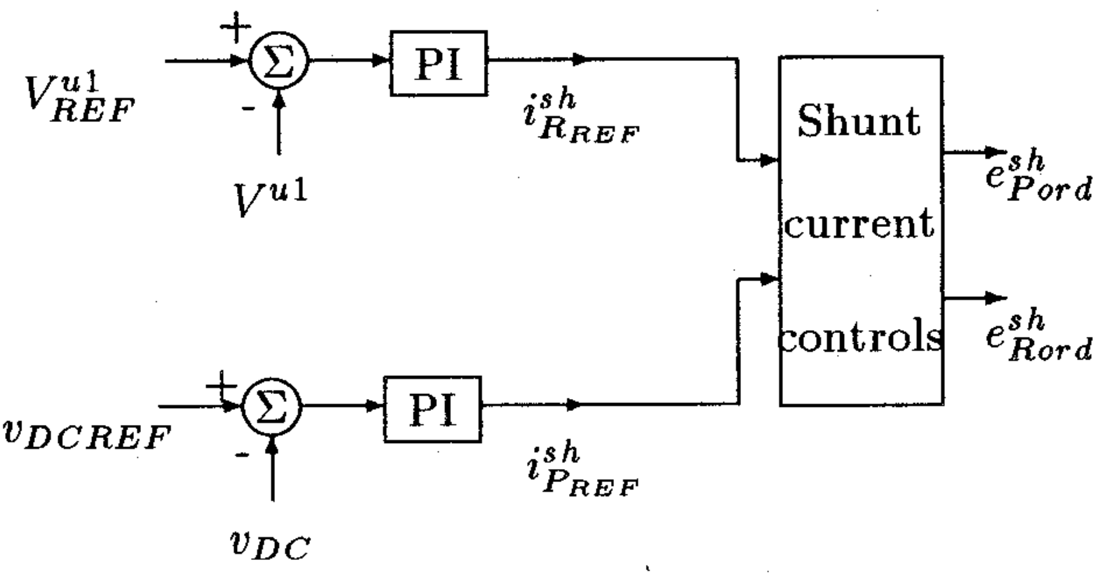


Figure 5.4 Shunt current controller [14].

The output of the shunt current controls is then used as the reference signal in the modulation technique to generate pulses for the shunt converter.

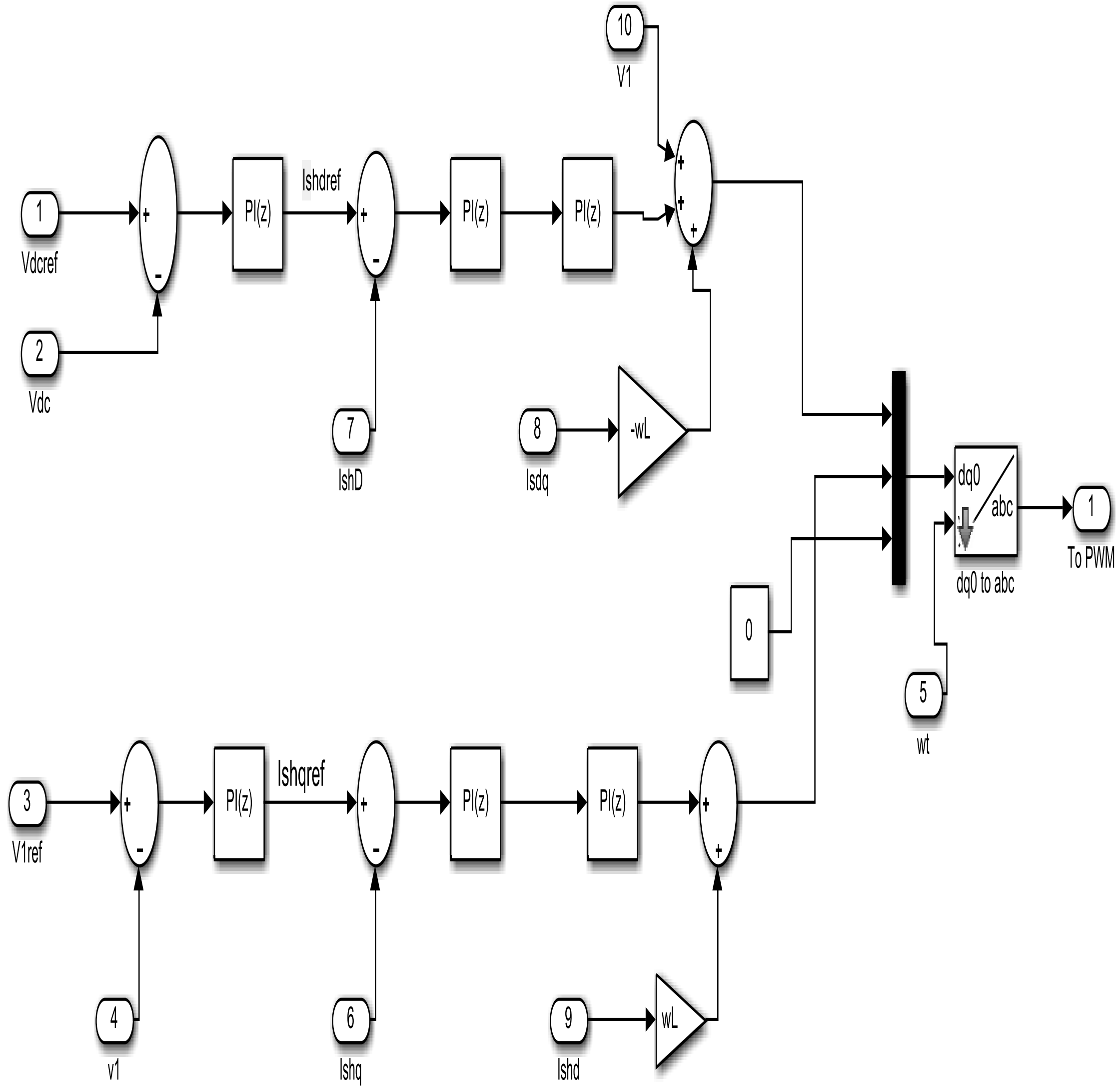


Figure 5.5 Shunt controller implementation.

5.5.2 Series Converter Control

The series converter can control real and reactive power independently. This converter injects a series voltage of variable magnitude and angle. Reference d-axis and q-axis current components taken from the comparisons between reference power values; $Pref/Qref$ and the measured values; $Pline/Qline$ are fed as input to the PI controller [120]. The real and reactive power control strategy is shown in Figure 5.6. The q-axis voltage component controls real power while the d-axis voltage component controls reactive power. Vd is the d-component of the voltage at bus 2.

The outputs from the PI controllers are then transformed to the rotationary abc frame before being used as the reference wave for the CPS-SPWM modulation technique.

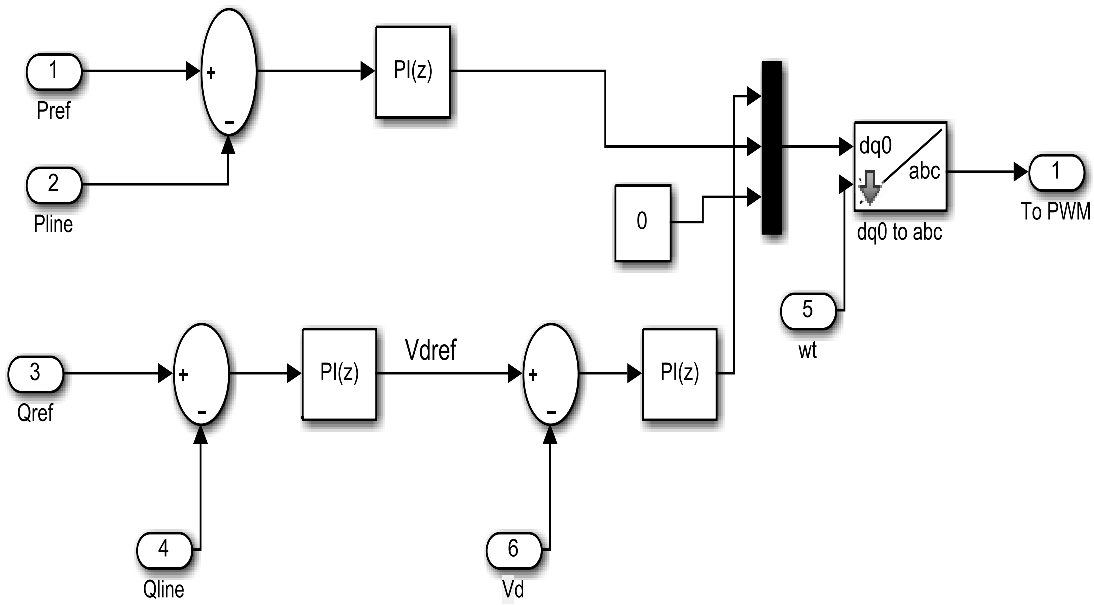


Figure 5.6 Series converter power control scheme implementation [120].

CHAPTER 6

SIMULATION STUDIES

6.1 Introduction

This chapter will focus on the circuit design of the UPFC system on Mat lab/Simulink simulation environment. The modulation technique; CPS-SPWM, MMC converter and the UPFC circuits will be studied and their results will be presented. First of all, the B2B MMC converter has been implemented with 10 sub modules per converter arm. This has been followed by the integration of this B2B MMC to a 154KV high voltage line of a power system via series and shunt transformers. Lastly, simulation studies have been carried out to verify the system. Several case studies have been done to verify the power control loop where it has been observed that the UPFC can control real and reactive power simultaneously and independently.

6.2 Modulation Technique

CPS-SPWM was used because of its self-balancing properties i.e. it is able to balance the sub modules capacitor voltages on its own without an additional circuit. This is possible owing to the fact that the number of inserted sub modules at any time is always constant. An 11 level AC output voltage is required at the output. The following calculations are done to get the number of carrier waves needed and their phase difference.

$$n_{carriers} = n_{levels} - 1 = 11 - 1 = 10 \quad (6.1)$$

$$\varphi_{carriers} = \frac{360^{\circ}}{n_{carriers}} = \frac{360^{\circ}}{10} = 36^{\circ} \quad (6.2)$$

From the above calculations, 10 carrier waves are used with a phase difference of 36°. Carrier waves have amplitude 1 while the reference sine wave has amplitude of 0.9. The two waves are then compared and the results serve as gating signals for the IGBTs. The design of CPS-SPWM is shown in Figure 6.1. The modulation technique is illustrated in Figure 6.2, where the gating signals for the IGBTs are derived from. In order to obtain $N+1$ voltage levels at the output, the upper and lower arms are inversely commutated. For the upper arms, if the carrier wave is greater than the reference signal, the output is 'high' or 1 and 'low' or 0 otherwise. The lower arm's carrier waves use less than instead of greater than.

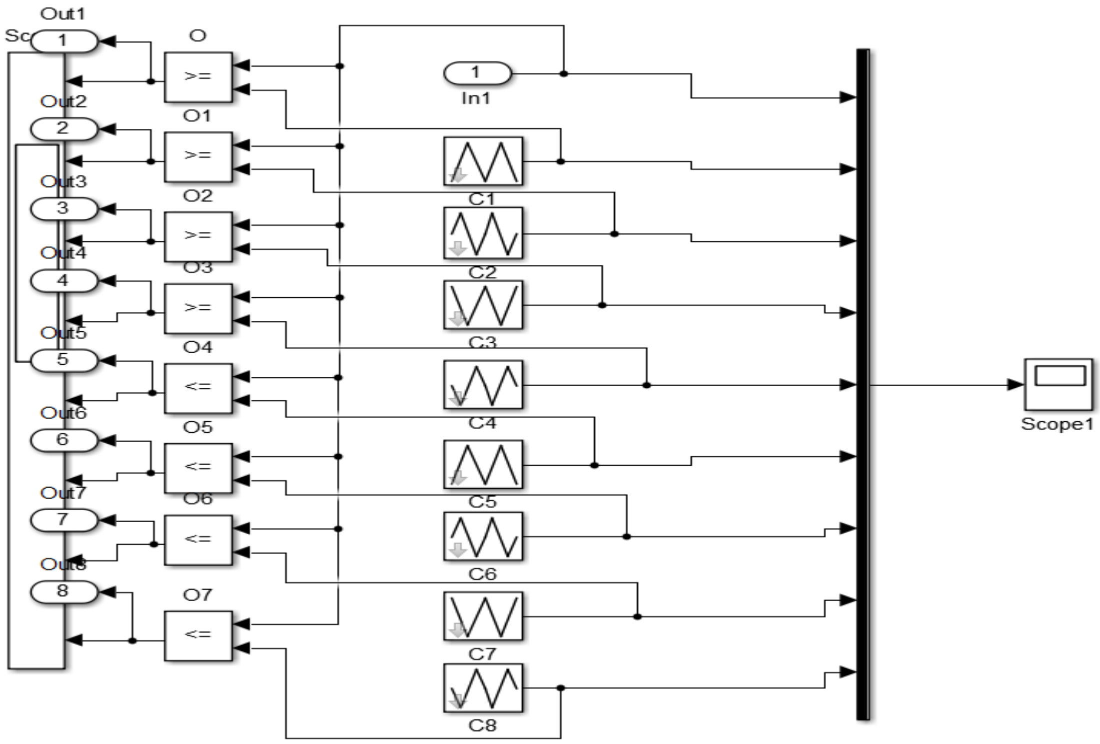


Figure 6.1 CPS-SPWM simulation circuit.

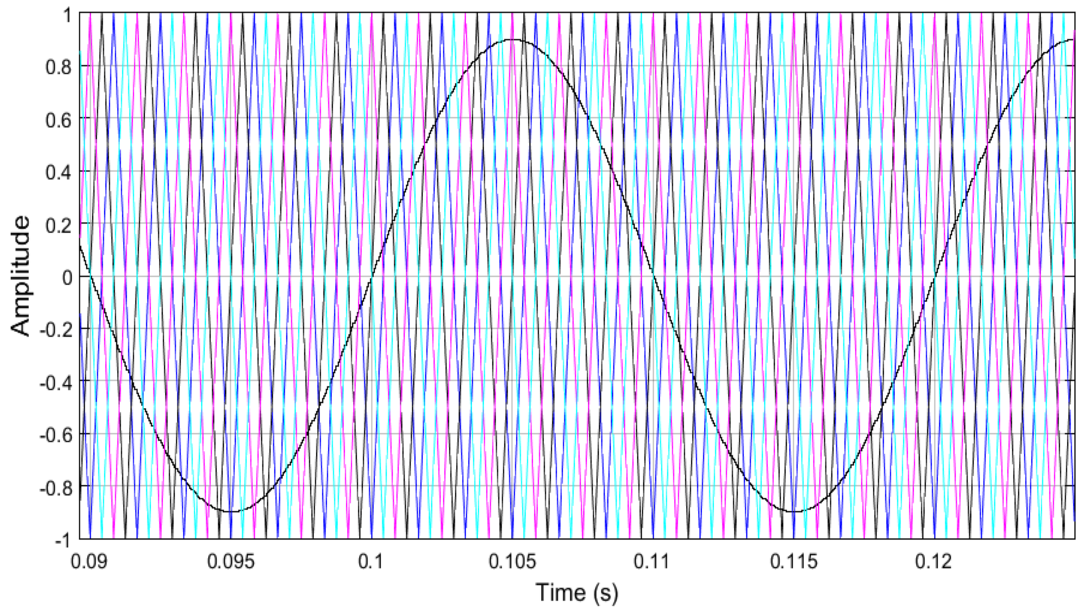


Figure 6.2 Carrier waves and reference signal.

6.3 MMC Design

The AC to AC MMC is a combination of two DC to AC MMCs connected in B2B mode. HB sub modules are used in building the MMC as illustrated in Figure 6.3. There are two IGBTs in one HB sub module and both of them cannot be switched on at the same time. The NOT gate ensures that only one of them is switched on at a time. The MMC parameters and their respective values are presented in Table 5.1. 30KV is the AC voltage at the MMC output when a DC link voltage of 60KV is connected across 10 series HB sub modules as shown in Figure 6.4. This voltage can then be stepped down or up depending on the requirement. The waveforms obtained for AC the current and voltage at both AC ends can be seen clearly in Figure 6.5.

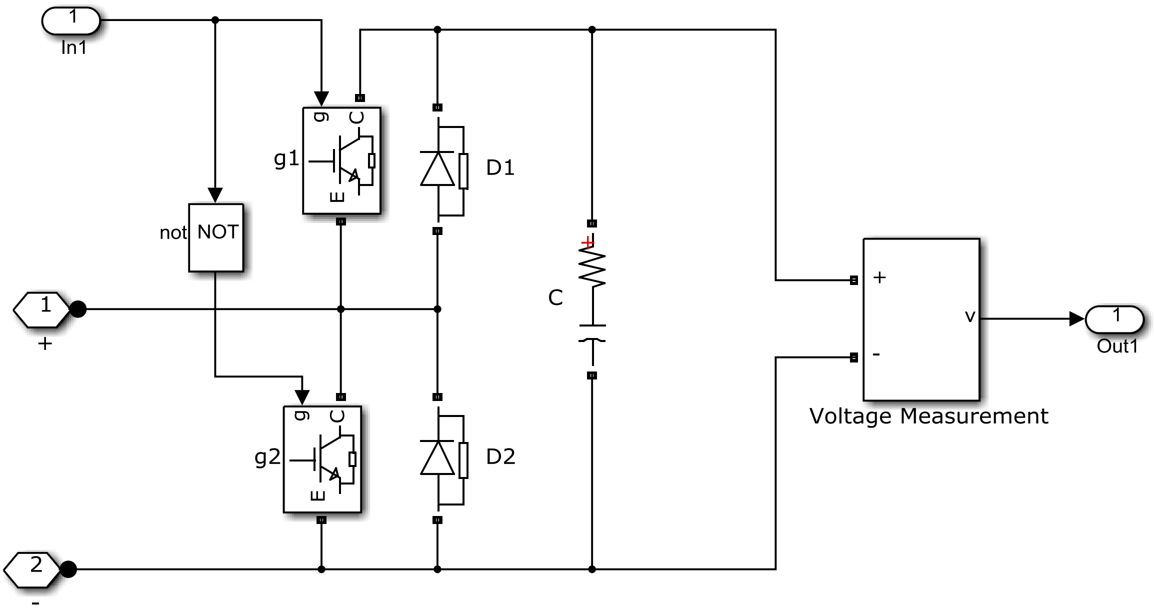


Figure 6.3 HB sub module simulation model.

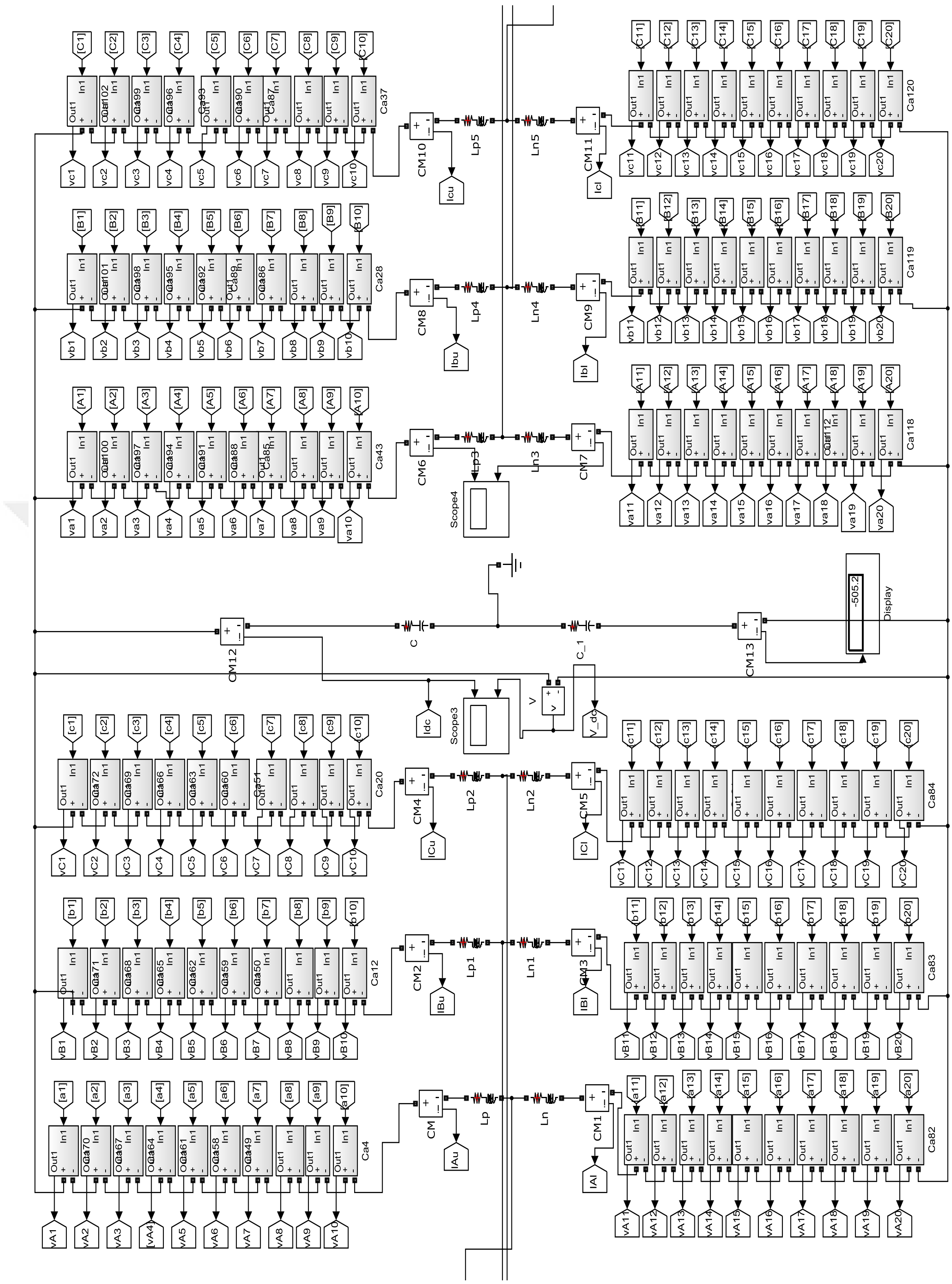


Figure 6.4 B2B MMC implementation.

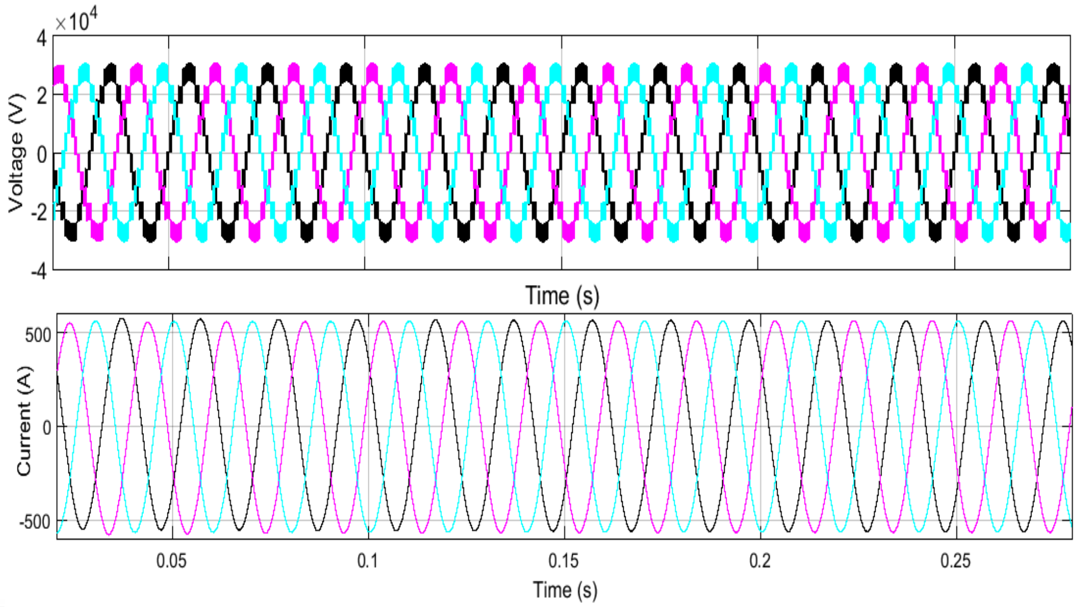


Figure 6.5 B2B MMC voltage and current waveforms.

6.4 UPFC Design

The VSC converter design is the fundamental step in a UPFC device. After the designing of the MMC, it is then integrated into a $154KV$ high voltage transmission line. Vs is the voltage at sending end and Vr is the voltage at receiving end. MMC is then connected in parallel through a shunt transformer to the sending end at bus 1 while the other side of the MMC is connected in series to the line via a series transformer at bus 2 as shown in Figure 6.6. The specifications of the transmission line are given in Table 6.1.

Table 6.1 Transmission line parameters.

Parameter	**Value**
Vs	$154e3 < 20^{\circ}$
Vr	$154e3 < 0^{\circ}$
X/R	10
Shunt transformer	$154K/30KV$
Series transformer	$30K/30KV$

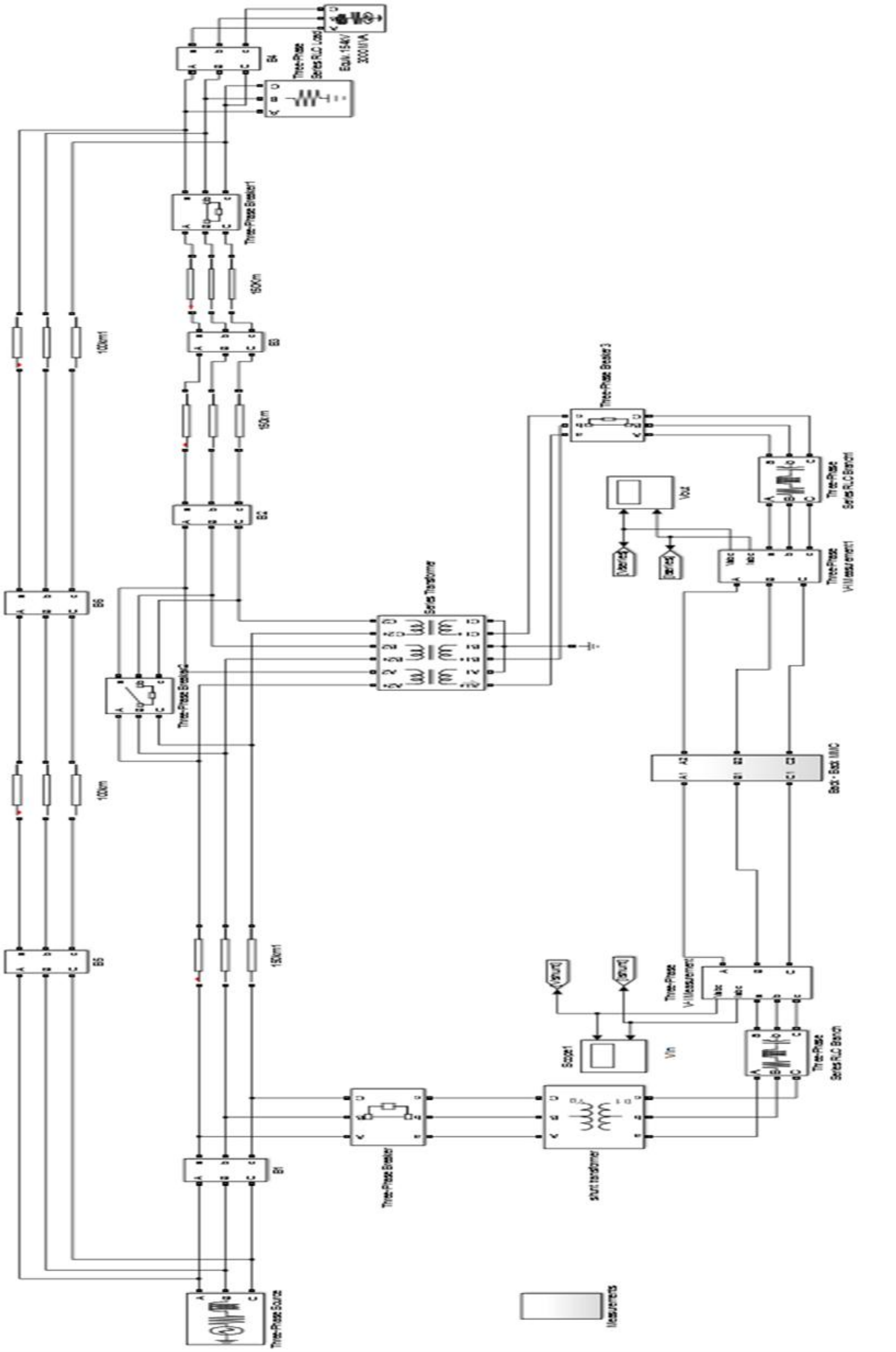


Figure 6.6 UPFC simulation model.

6.5 Case Studies

In order to understand the role of the UPFC several case studies are carried out. These case studies are scenarios aimed at verifying the various control schemes and to study the system.

6.5.1 Case One

This is the initial study of the system without UPFC. Here, measurements of the real and reactive powers at bus 1 (sending end) and bus 2 (receiving end) are taken without the UPFC connected to it. The three-phase breakers connecting the MMC to the transmission system at the shunt and series ends are kept open. The real power and reactive power values at bus 1, are $-3e7W$ and $-1.5e7VAR$, respectively as shown in Figure 6.9. Figure 6.10 gives the real and reactive powers at bus 2 which are initially $-3e7W$ and $-1.7e7VAR$. The DC link voltage and current of the MMC is also shown in Figure 6.11. The voltage is constant at $60KV$ because the MMC has not yet been connected to the transmission line. In this case study, there is no control scheme applied.

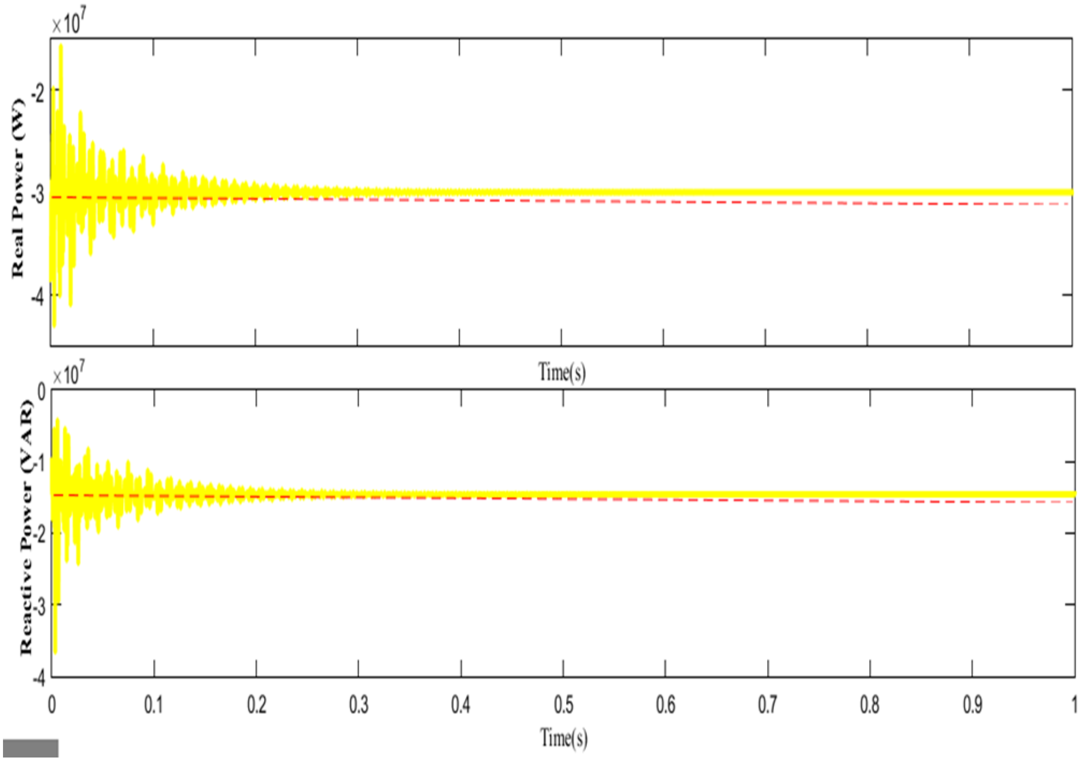


Figure 6.7 Power flow in bus 1 without UPFC.

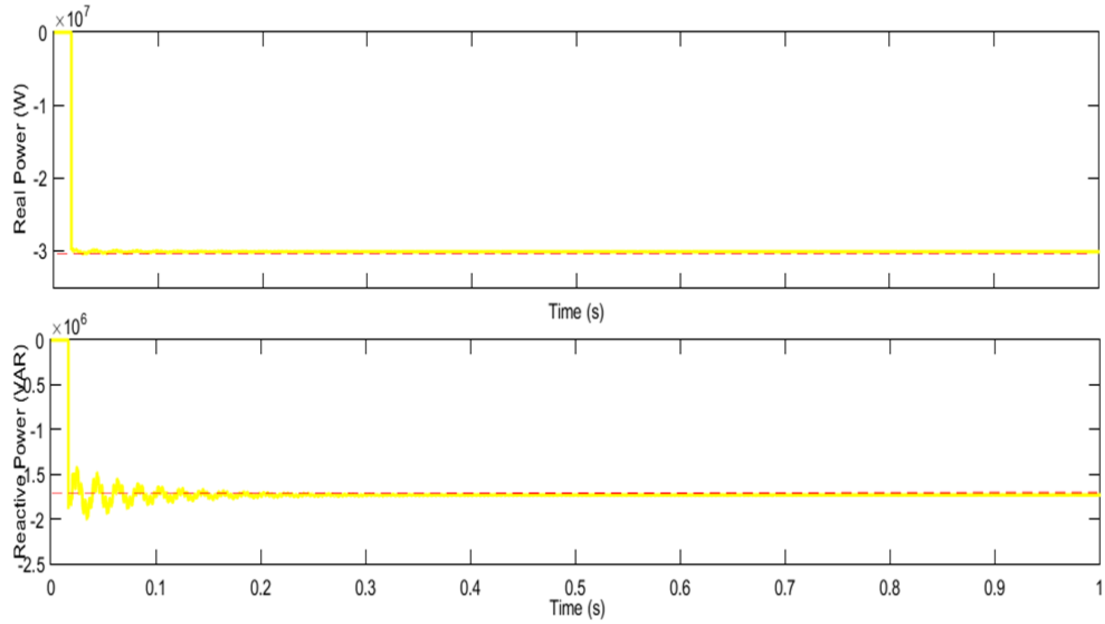


Figure 6.8 Power flow in bus 2 without UPFC.

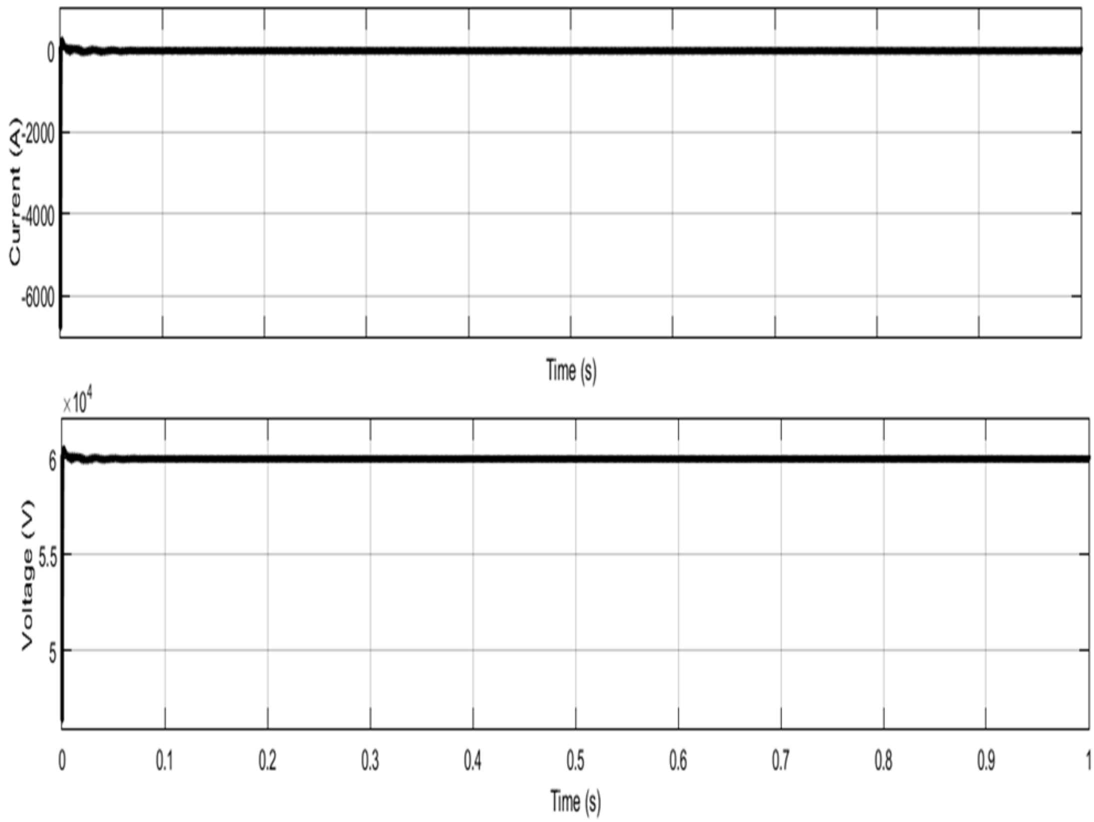


Figure 6.9 DC link voltage and current.

6.5.2 Case Two

The above procedure is done with the UPFC connected to the system via shunt and series transformers. The three phase breakers connecting the UPFC to the line are closed. The active and reactive powers are then measured and compared with the values obtained in case 1. At bus 1 there is an increase in real power from $-3e7W$ to $1.7e7W$. Reactive power also increases from $-1.5e7VAR$ to $1e7VAR$. At bus 2, an increase in both powers is recorded though reactive power shows a significant increase when compared to real power. Reactive power moves up to $2.5e7VAR$ while real power increases to $-1e7W$. The UPFC is applied here with no power or voltage control scheme. A slight decrease in the voltage across the DC link can be seen in Figure 6.14. The dynamics of the B2B MMC like the phase to ground voltage and current at the point where it is connected to the transmission line in series and shunt is shown in Figures 6.15 and 6.16. The red dotted lines indicate the reference value.

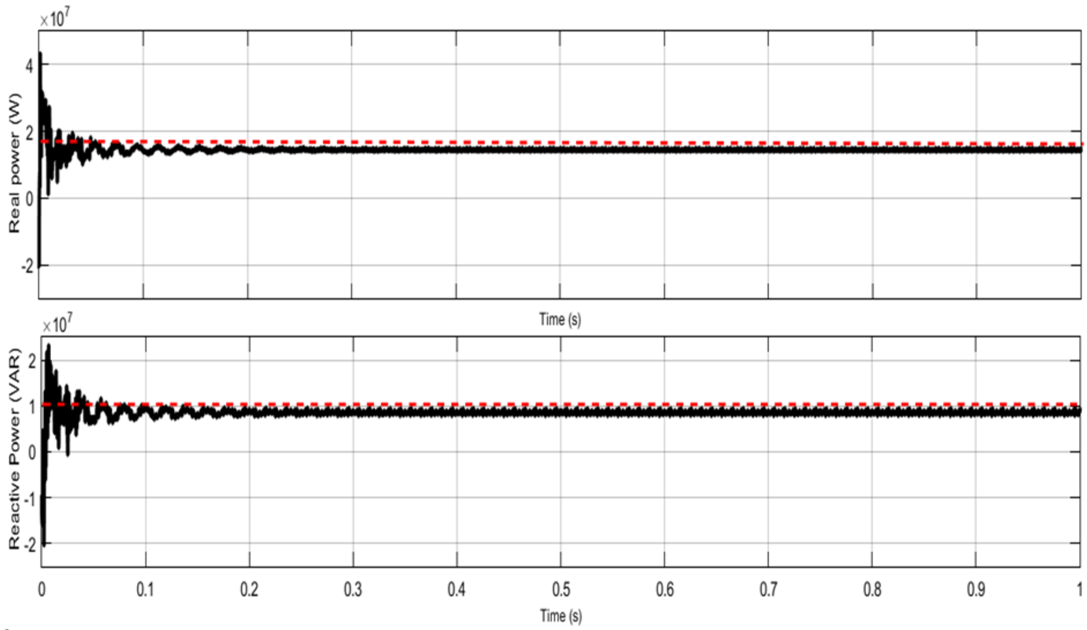


Figure 6.10 Power flow in bus 1 with UPFC.

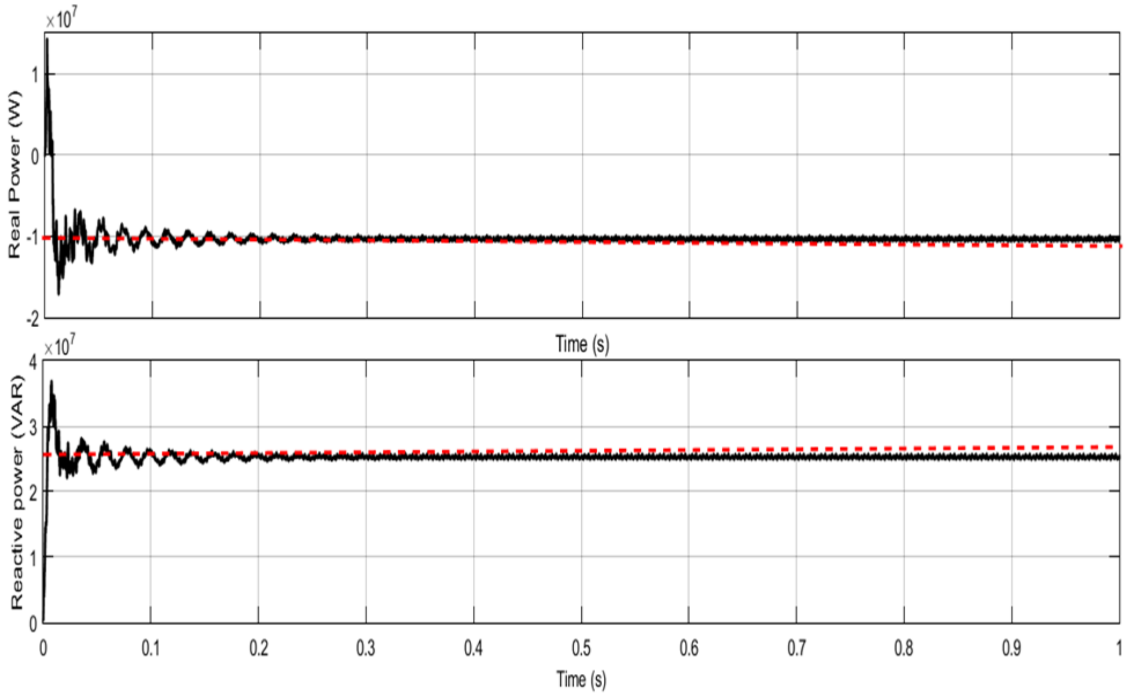


Figure 6.11 Power flow in bus 2 with UPFC.

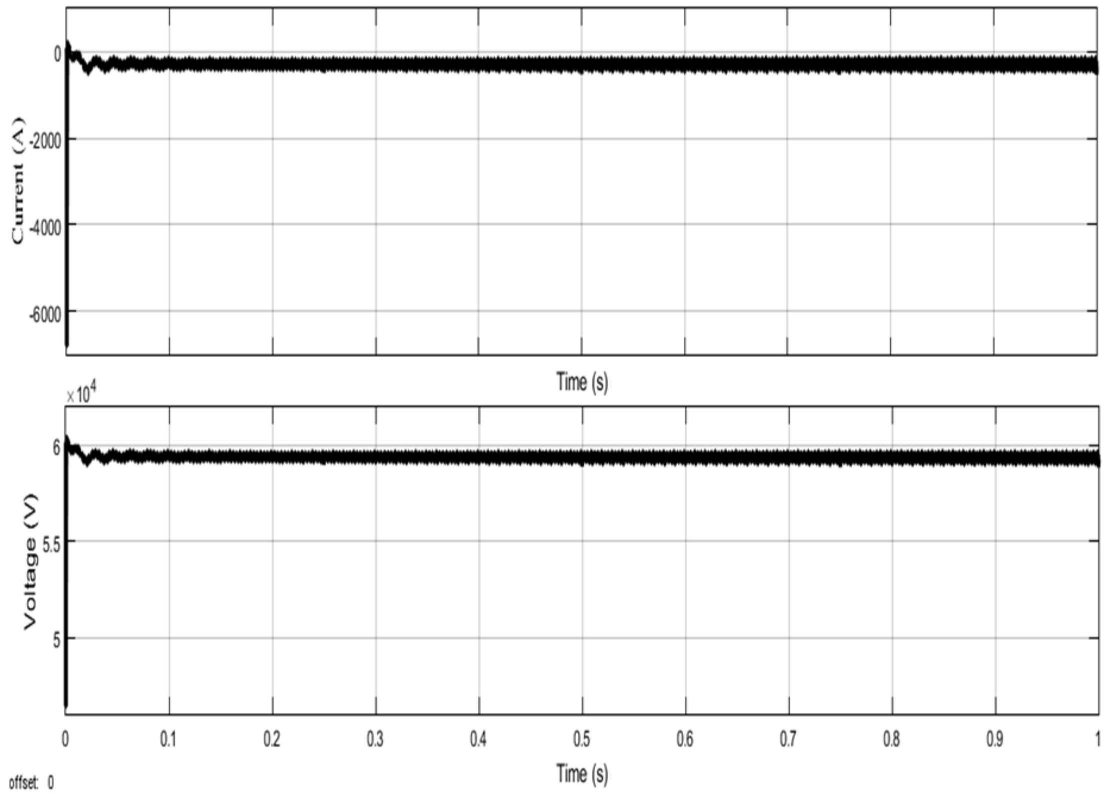


Figure 6.12 DC link voltage and current with UPFC.

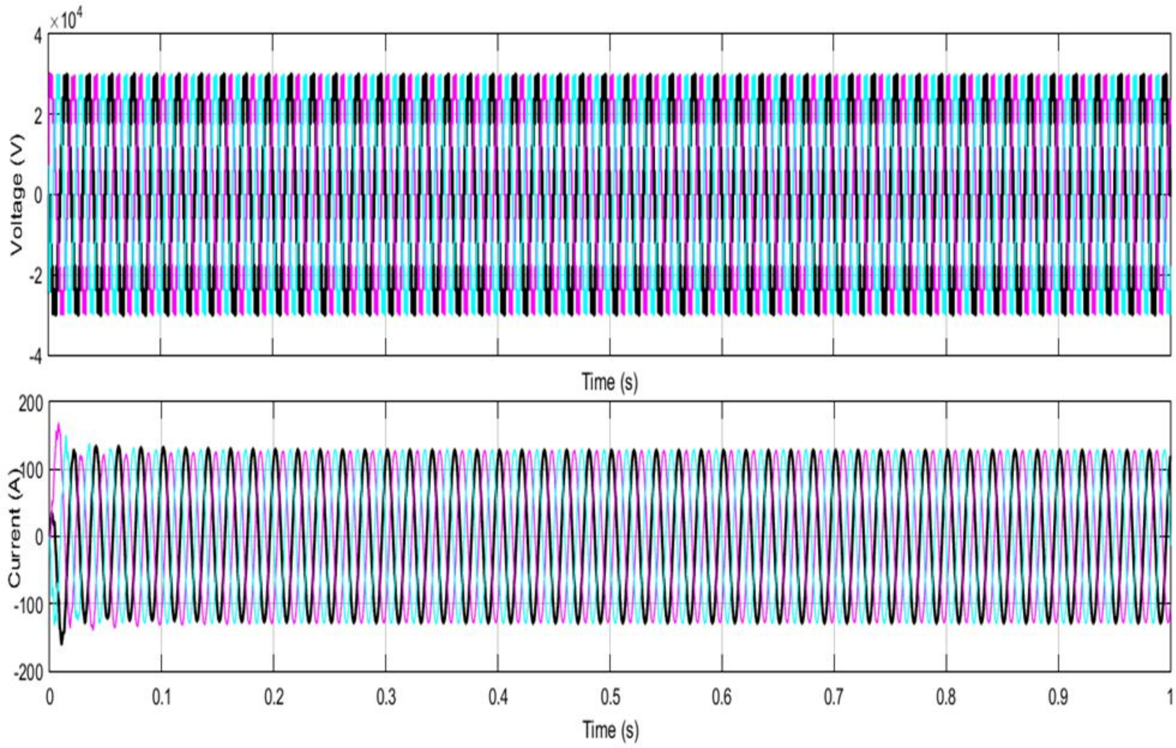


Figure 6.13 Voltage and current waveforms at MMC series end.

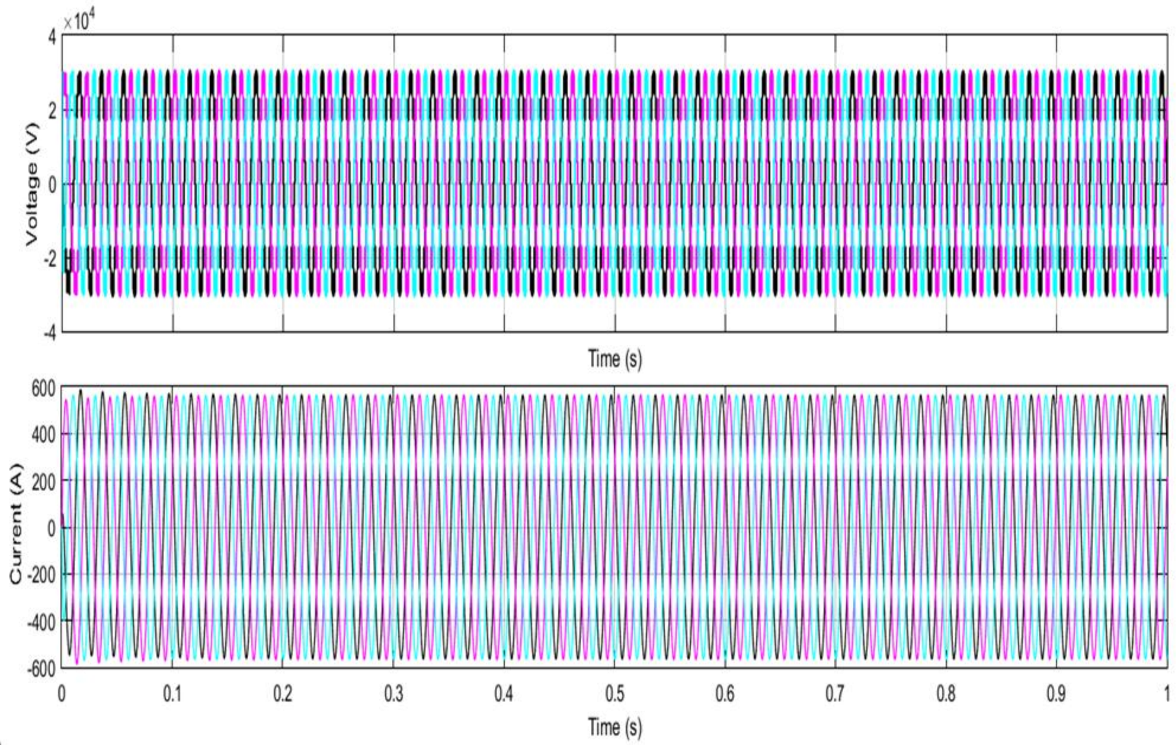


Figure 6.14 V and I at UPFC shunt side.

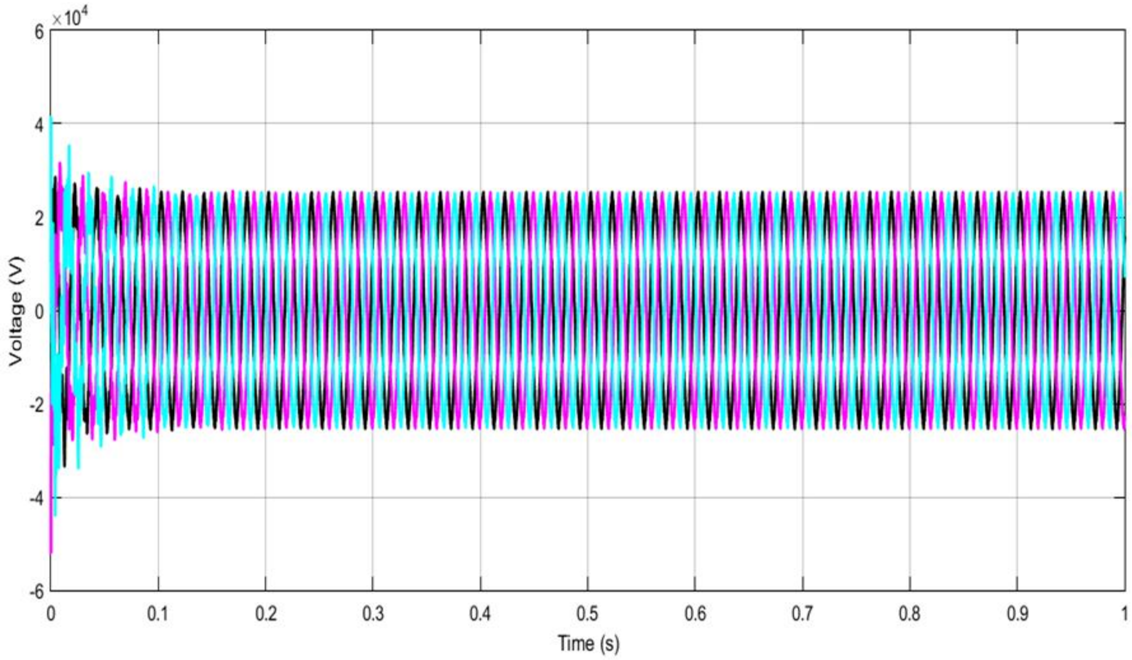


Figure 6.15 Injected series voltage at bus 2.

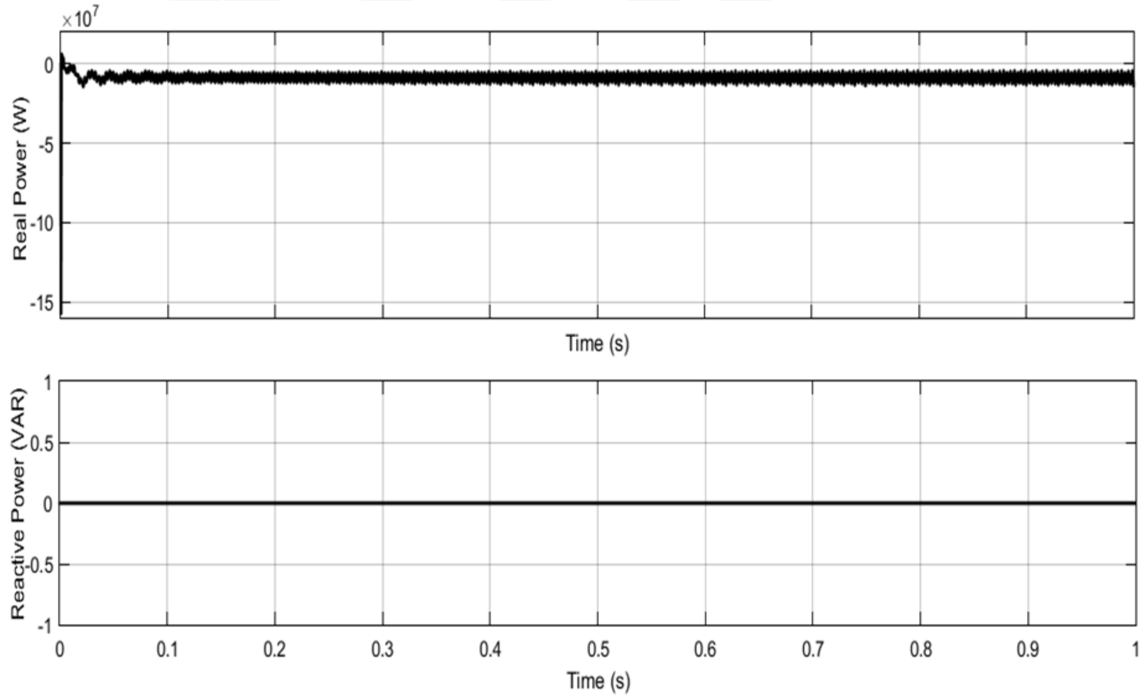


Figure 6.16 Power flow through DC link.

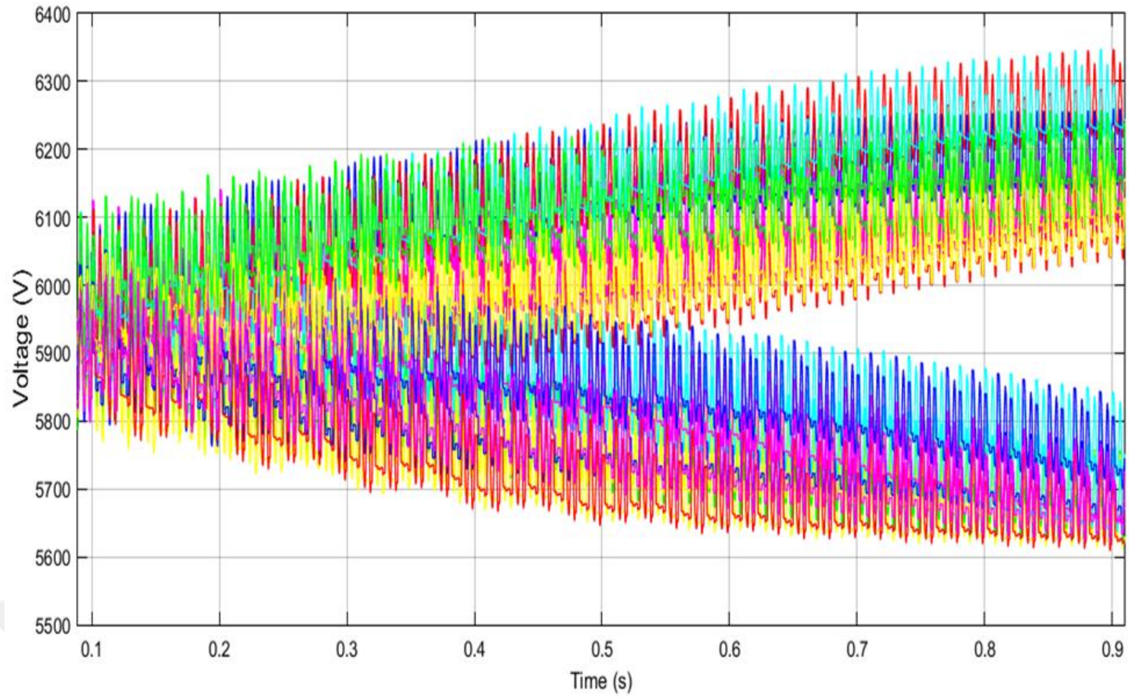


Figure 6.17 Capacitor voltage of sub modules with UPFC.

The capacitor voltages of one converter arm are plotted against time in Figure 6.17. There is a slight deviation from the 6KV reference point by $\pm 300V$.

6.5.3 Case Three

The power control loop is activated and a step response is applied to the real power while the reactive power is kept constant. In Figure, at t=0.3s, the real power is stepped down from 1.5e7W to -1.5e7W. The real power measurement at bus 2 is seen to follow the step change as the UPFC takes a short period of time to response to the step change. The red line represents the reference and the black one is the system's response. The reactive power is kept constant during this period as shown in Figure 6.19. Figure 6.20, shows that the series injected voltage by the MMC decreases to keep track of this step change.

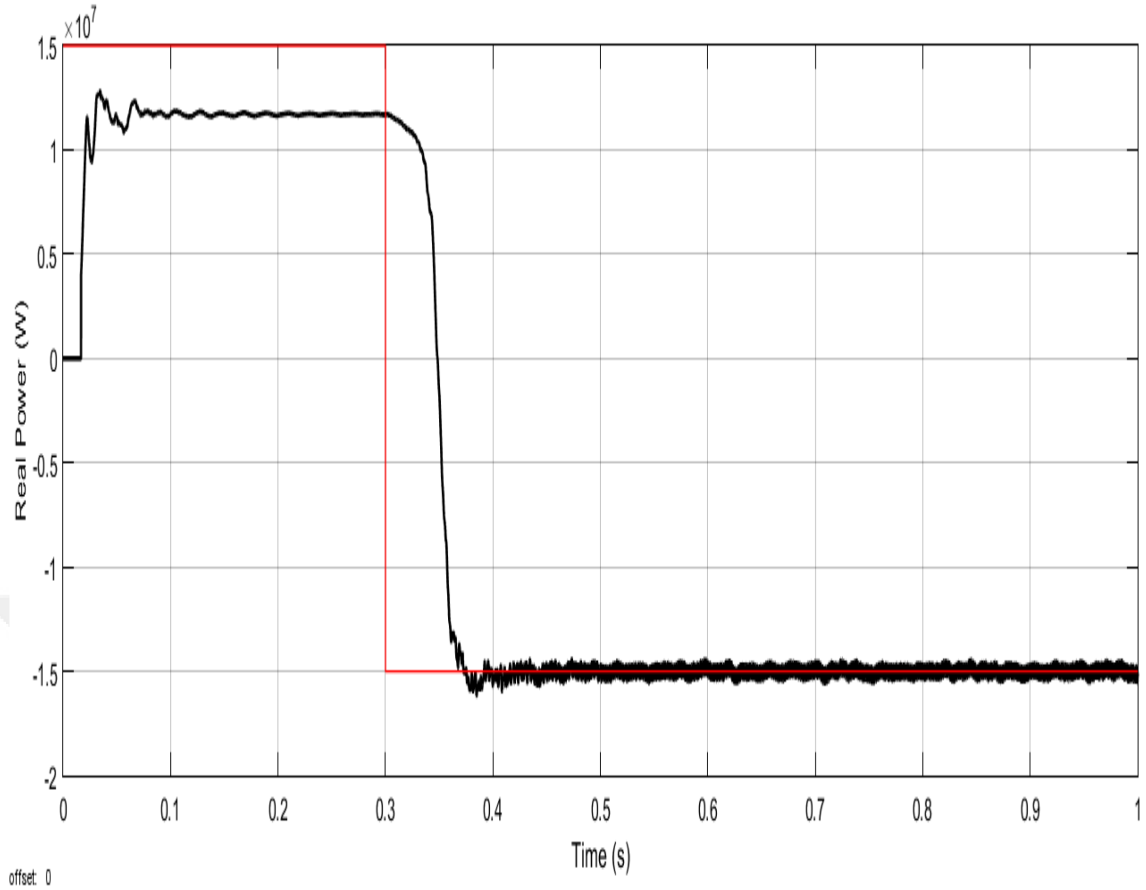


Figure 6.18 Real power response to a step change.

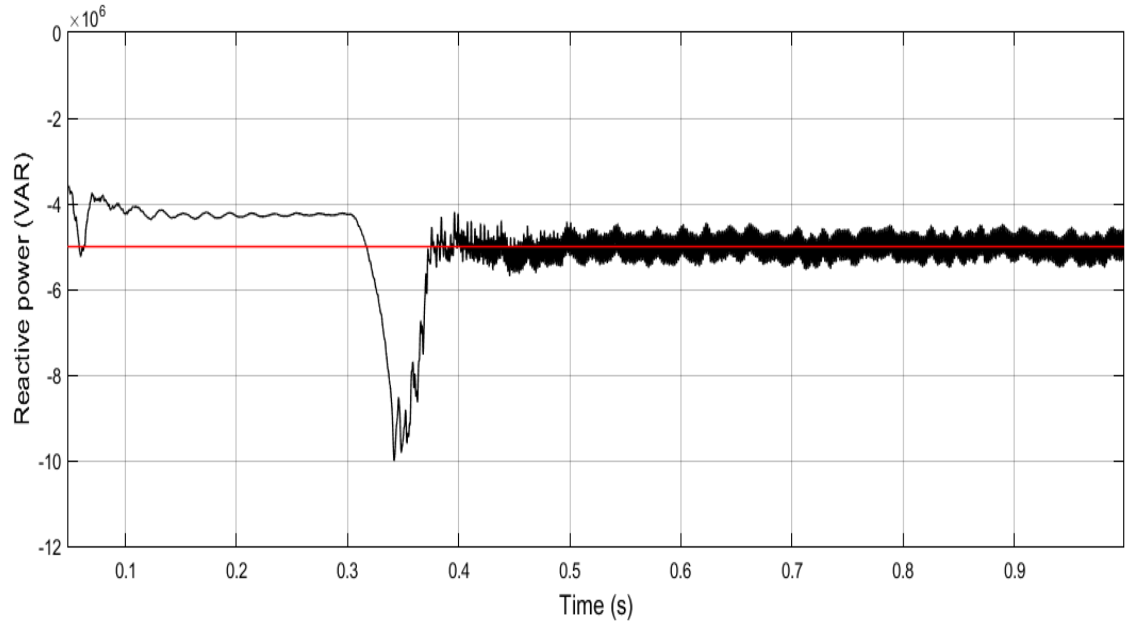


Figure 6.19 Reactive power as real power changes.

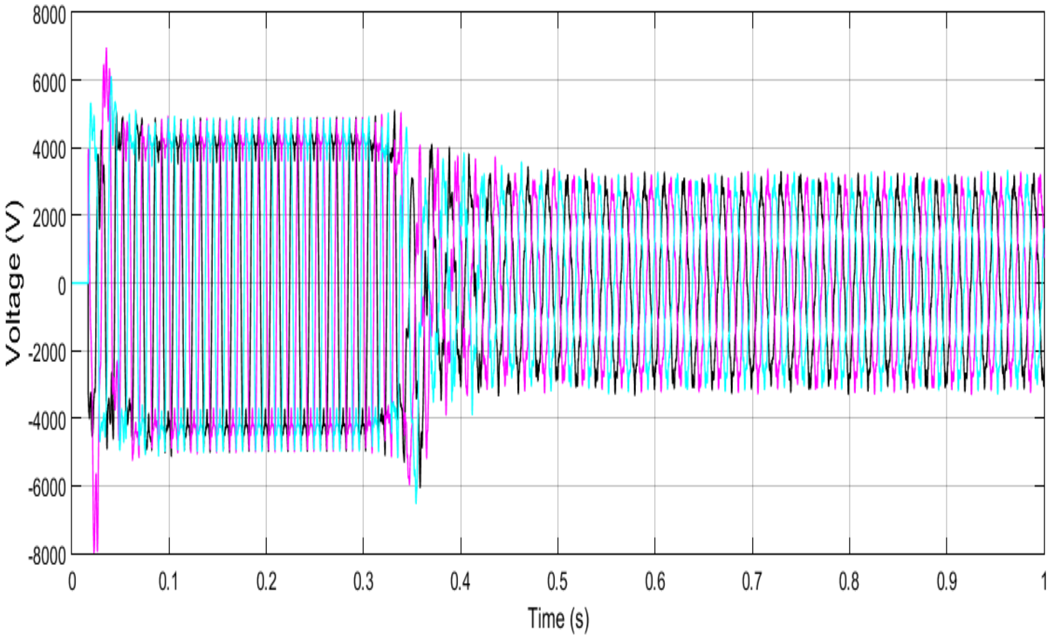


Figure 6.20 Series injected voltage when P changes.

6.5.4 Case Four

The series converter control is activated and measurements are taken for a step change in reactive power while the real power is kept at a -0.5e7W. At t=0.3s, reactive power changes from 1.5e7VAR to -1.5e7VAR and then measurements for the power at bus 2, series injected voltage, capacitor voltage of sub modules are taken and have been plotted against time in Figure 6.21 to Figure 6.23. The power controller keeps the real power constant though its waveform is not smooth while a step change is applied to the reactive power. Capacitor voltages of sub modules are seen to oscillate when the change occurs at t=0.3s according to Figure 6.22.

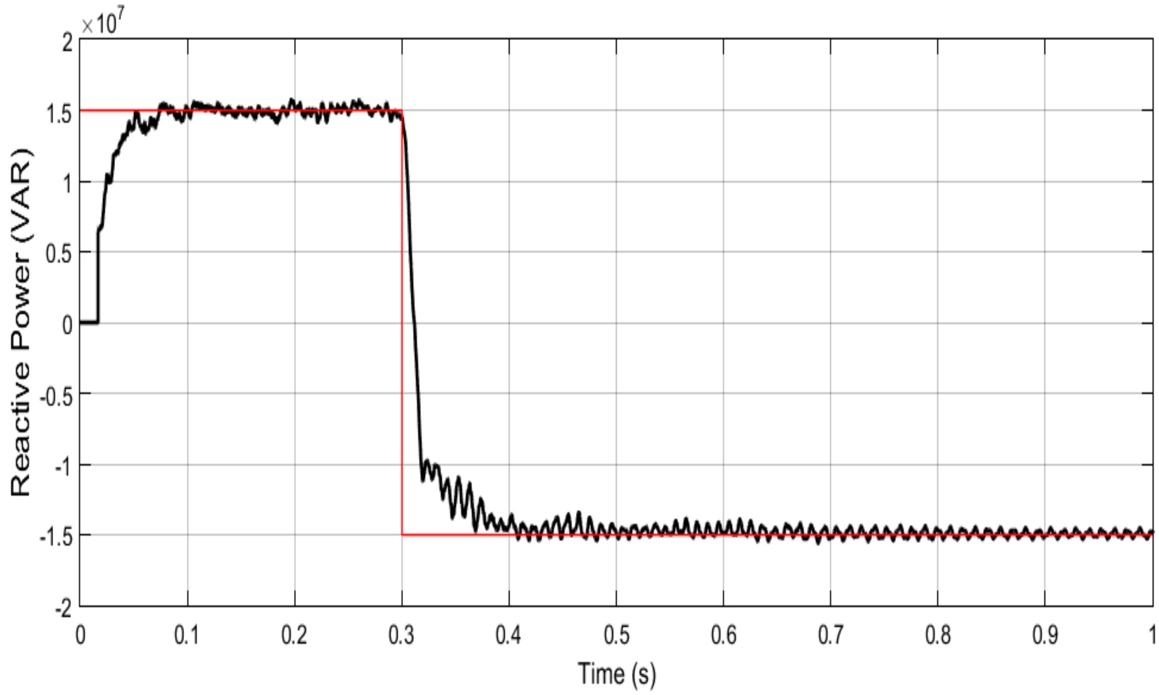


Figure 6.21 Reactive response to step change.

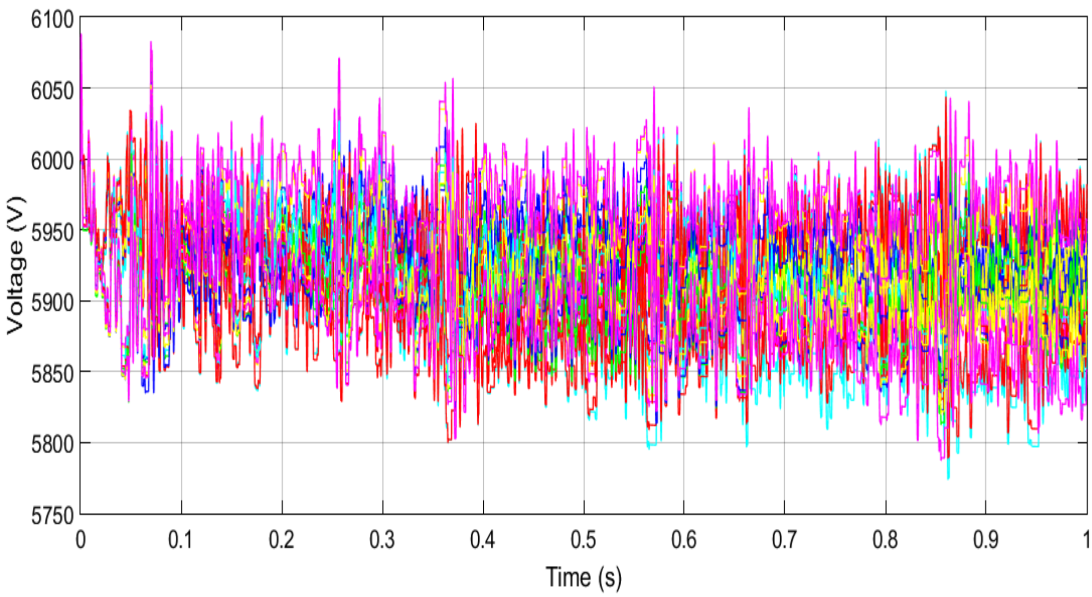


Figure 6.22 Capacitor voltages of sub modules.

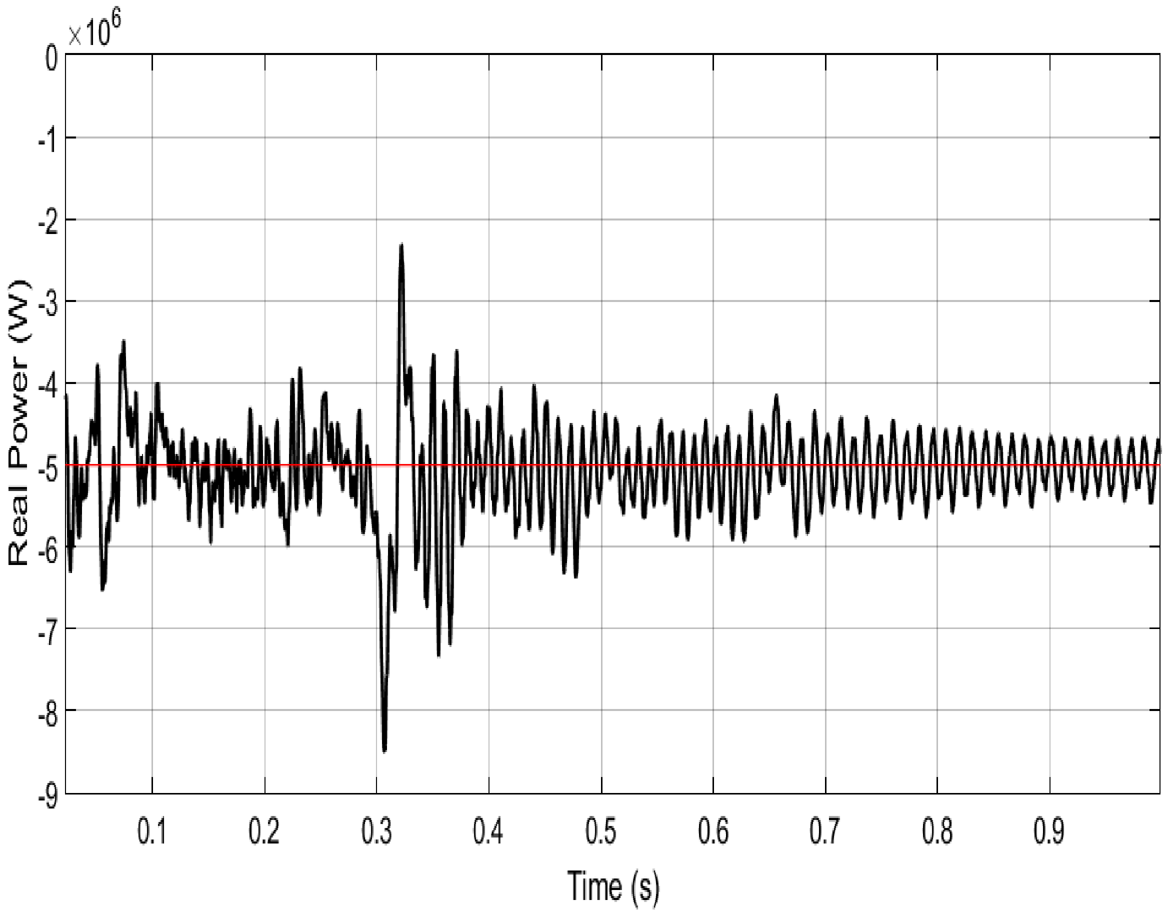


Figure 6.23 P when Q changes at t=0.3s.

6.6 THD Analysis

THD analyses are made for the phase to ground as well as phase to phase voltages and currents of the B2B MMC. These analyses are done at the 50Hz fundamental frequency. In order to do this, the variable is first saved to the workspace making it visible in the powergui fast Fourier transform (FFT) tool. The THD analysis for the phase to phase AC output voltage and current at the shunt end is shown in Figure 6.24 and Figure 6.25. The same analysis has been done for the phase to ground voltage and current at the series end and the results can be seen in Figure 6.26 and 6.27. THD value for phase to phase voltage is 11.98% while that for current is 0.43%. This means that the current waveform is almost completely sinusoidal.

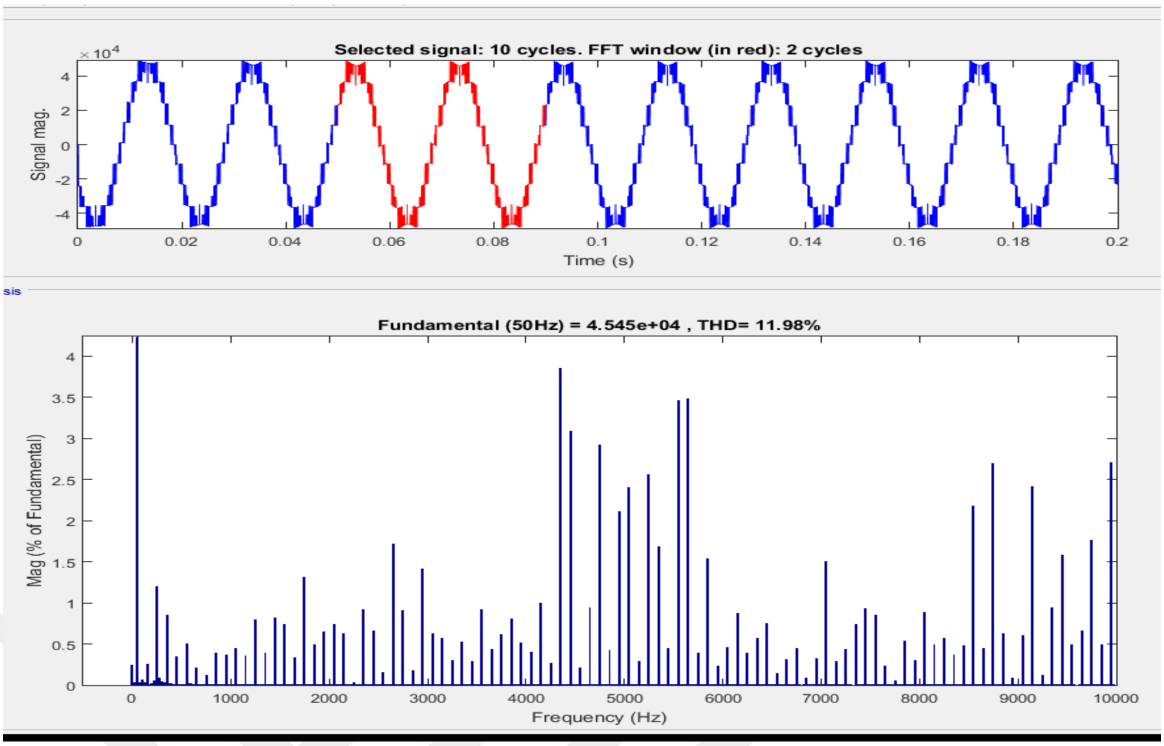


Figure 6.24 THD analysis for shunt side phase to phase voltage.

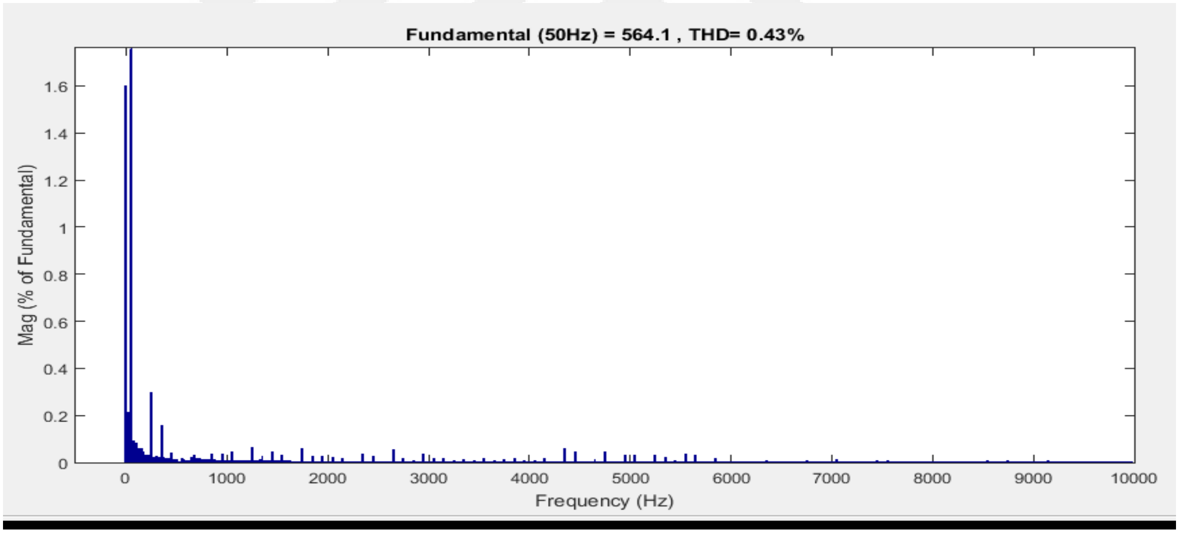


Figure 6.25 THD for phase to phase current waveform.

THD for output phase to ground voltage is 14.52% while THD for current phase to ground is 1.41%. Conclusively, the THD for current is lower in both cases when compared to the voltage this is because the current waveform has a more sinusoidal form than the voltage waveform.

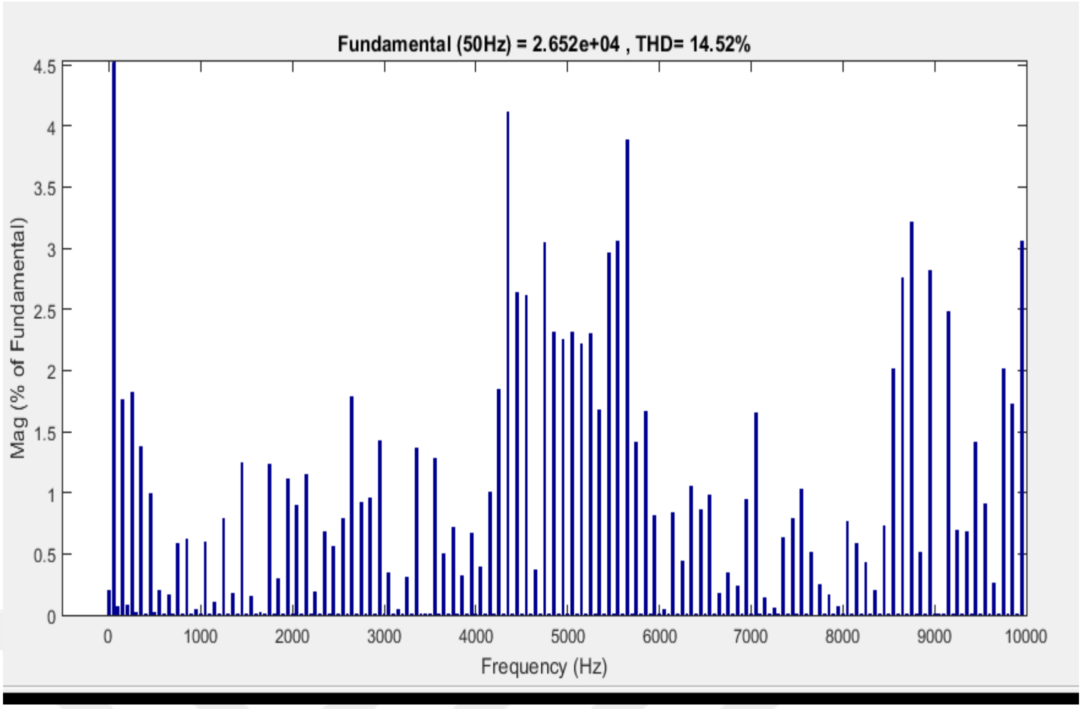


Figure 6.26 THD analysis phase to ground voltage at series end.

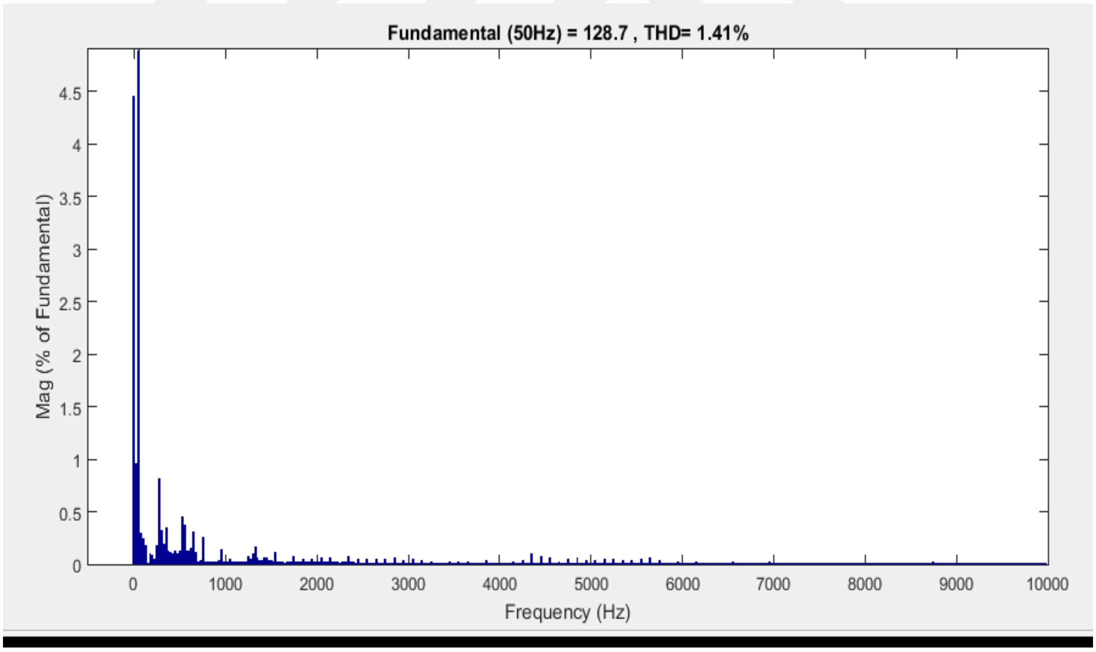


Figure 6.27 THD analysis for phase to ground current waveform at the series end.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

Increasing demand for electrical energy necessitates the expansion of the power system or the improvement of the existing system. That is why, the focus of this thesis lies on the modeling and simulation of a unified power flow controller using modular multilevel converters as the voltage source converter type.

A detailed MMC based UPFC is presented in this work. The converter build with HB sub modules shows superior characteristics justifying the presented literature. An 11 level 30KV good quality AC voltage waveform is produced. THD of the MMC AC output voltage is 14.51% which is logical considering the number of sub modules used per arm. The capacitor voltage balancing issue is solved to a certain extent with the CPS-SPWM modulation technique. This technique is limited in that as the number of sub modules increases, it becomes in effective as the phase angle between carrier waves become smaller.

Power measurements made when the UPFC is connected to the high voltage transmission line shows an increase in real and reactive power flowing in bus 1 and bus 2 to which the UPFC is connected. Bus 1 having a high real power value than bus 2 implies that the shunt converter absorbs real power from the series converter via the DC link and sends it to the transmission line via the shunt transformer. Also the DC link voltage is approximately constant (6KV) showing that there is a balance. A control scheme for real and reactive power is designed and its effectiveness is verified by simulation. The UPFC is able to control real and reactive power simultaneously and independently.

7.2 Future Work

In this work, the MMC based UPFC system has been simulated on a simulation environment. A small scale laboratory prototype of this 30KV MMC can be implemented using the parameters in this work. The MMC model can be applied to other FACTS devices like IPFC, GUPFC etc. to check its credibility. In addition to these, the following improvements can be done as future work.

- Replacements of HB sub modules with FB sub modules since they can minimize fault current when a fault occurs.
- The inclusion of a circulating current strategy to cancel circulating currents instead of increasing the arm inductance value as is the case in this work.
- Use of an optimization technique and neural networks in addition to the modulation technique to balance the voltages of the sub module's capacitors.
- Use of a better tuning method to tune the PI controllers instead of the trial and error method that has been used for this thesis.

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