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COMPARISON OF DYNAMIC PERFORMANCES OF IPFC, UPFC AND BACK TO BACK HVDC TRANSMISSION ON DAMPING OF POWER SYSTEM OSCILLATION

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Mohammed HAMAD

ABSTRACT

COMPARISON OF DYNAMIC PERFORMANCES OF IPFC, UPFC AND BACK TO BACK HVDC TRANSMISSION ON DAMPING OF POWER SYSTEM OSCILLATION

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The permanent goal in the field of electrical power systems is to find new ways of transmission and distribution of electrical energy in terms of low cost and reliability. Due to increasing growth in power demand, transmission side of the power systems has faced with stability problems much ever than before. Local and inter-area oscillations are the important types of these stability problems which are the results of insufficient/inadequate damping in the power systems. These oscillations can be observed as the swinging of system parameters such as buses voltages, phase angles, and real/reactive power flow on transmission lines. These oscillations are due to the normal change in the increase or decrease of sudden load or external changes such as a fault occurs in the system. The purpose of this thesis is to research the damping of both local and inter-area oscillations by using three different types of power electronic based compensators. These devices are as follows: “Unified Power Flow Controller (UPFC)", "Interline Power Flow Controller (IPFC)" and "Back to Back High Voltage Direct Current (BTB-HVDC) Transmission". UPFC and IPFC are voltage source converter based FACTS devices. BTB-HVDC is also voltage source converter based one which are mostly preferred in long transmission of bulk power. In the thesis, “Kundur System” and IEEE 9-Bus System” are used as example power systems to test the dynamic performances of the aforementioned devices on damping of both local and inter-area oscillations.

Key Words: FACTS, IPFC, UPFC, BTB-HVDC, VSC, Kundur, Local, inter-area, 2-Area, Damping Oscillations.

ÖZET

IPFC, UPFC VE SIRT SIRTA BAĞLI YGDA İLETİMİN GÜÇ SİSTEMLERİ SALINIMLARININ SÖNÜMLENDİRİLMESİNDEKİ DİNAMİK PERFORMANSLARININ KARŞILAŞTIRILMASI

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Elektriksel güç sistemleri alanındaki kalıcı hedef düşük maliyet ve güvenirlik bakımından elektrik enerjisinin iletimi ve dağıtımı için yeni yollar aramaktır. Güç talebindeki artışlardan dolayı, güç sistemlerinin iletim tarafı kararlılık problemleriyle daha önceki yıllara nazaran daha fazla karşılaşmaktadırlar. Güç sistemlerinde yeterli gelmeyen/uygun olmayan sönümlendirmenin sonuçları olan yerel ve bölgesel-arası salınımlar bu kararlılık problemlerinin önemli birer türüdür Bu salınımlar, bara gerilimleri, faz açıları ve iletim hatları üzerindeki aktif/reaktif güç akışları gibi sistem parametrelerinin sallanması şeklinde gözlemlenebilir. Bu salınımlar, ani yük artması veya azalması veya sistemde meydana gelen bir arıza gibi harici değişikliklerden kaynaklanabilir. Bu tezin amacı üç farklı güç elektroniği tabanlı kompanzatör kullanarak hem yerel hem de bölgeler-arası salınımların sönümlendirilmesini araştırmaktır. Bu cihazlar şunlardır: "Bütünleşik Güç Akış Denetleyicisi (UPFC)", "Hatlar-Arası Güç Akış Denetleyicisi" ve "Sırt-Sırta Bağlı Yüksek Gerilim Doğru Akım (BTB-HVDC) İletimi"' dir. UPFC ve IPFC gerilim kaynaklı çevirgeç tabanlı birer FACTS cihazıdır. BTB-HVDC ise daha çok çok büyük güçlerin uzun mesafe iletiminde tercih edilmektedir. Tezde, "Kundur Sistemi" ve "IEEE 9-Baralı Sistemi" hem yerel hem de bölgeler-arası salınımların sönümlendirilmesinde adı geçen cihazların dinamik performanslarını karşılaştırmak için örnek güç sistemleri olarak kullanılmıştır.

Anahtar Kelimeler: FACTS, IPFC, UPFC, BTB-HVDC, VSC, Kundur, Yerel, Bölgeler-Arası, 2-Alan.

To my mother, brother, wife children and friends I dedicate this humble work

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LIST OF SYMBOLS

AC	Alternative Current
DC	Direct Current
F	Frequency
P	Active Power Flow
Q	Reactive Power Flow
V	Voltage
I	Current
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
FACTS	Flexible Alternating Current Transmission Systems
VSC	Voltage Source Converter
SVC	Static Var Compensation
STATCOM	Static Synchronous Compensator
TCSC	Thyristor Controlled Series Compensation
SSSC	Static Synchronous Series Compensator
IPFC	Interline Power Flow Controller
UPFC	Unified Power Flow Controller
BTB-HVDC	Back to Back High Voltage Direct Current
PSS	Power System Stabilizer
IGBT	Insulated Gate Bipolar Transistor
GOT	Gate Turn-Off Thyristor
X_L	Inductive Reactance of the Coupling Transformer
V_{bus}	Voltage of Bus
V_{vsc}	Output Voltage of FACTS Device
V_s	Voltage Sending
V_R	Voltage Received

δ	Phase Angle
LFO	Low Frequency Oscillations
LM	Local Mode
IAM	Inter Area Mode
σ	Damping Factor
ξ	Damping Ratio
γ	Oscillatory Mode
ω_o	Harmonic Oscillator Frequency
θ	Phase Angle for Transmission Lines
T	Time
PWM	Pulse Width Modulation
PI	Proportional Integral Controller
dq	Direct-Quadrature Axis
ref	Parameter Reference
PLL	Phase Locked Loop
$theta$	Rotor Mechanical Angle
ω	Rotor Speed Generator
$3-\phi$	Three-Phase
V_{dc}	DC Link Voltage

CHAPTER 1

INTRODUCTION

1.1 General Overview

Nowadays, the power systems have become very complex and extensive grids, which contain many generators, transmission lines, transformers, loads and other electrical systems. Many reasons are behind the power system development, including the expansion of demand for power consumption and reduce costs and the development in the field of electronics. Therefore, there are some transmission lines in grids, which are more loaded than previously planned when it was created. There is difficulty in stabilizing after an error occurred in those grids, so the transmission-limiting factor becomes dependent on the initial operating conditions of the system and also external factors [1]. Therefore, since the last three decades, scientific and economic developments demand a review of power theories, of how to use traditional power transmission and the development of new ideas that would benefit the development of power systems to fully utilize of power generation and transmission facilities. In this regard, from the late of 1980s, both researchers and developers have worked to improve the power transfer and reduced the establishment of transmission lines. The aim behind this improvement is to develop FACTS systems in terms of structures, switches and control systems [2]. For this reason, they have been able to address this problem by introducing high-power electronic controllers that can quickly control the regulation of power flow and voltages and reduce power losses in power transmission grids.

Many problems are accompanied along with the power transmission grids, the most two common types of problems are related with stability which they are local and inter-area oscillations, which are resulted due to insufficiently damping of power systems. Due to the normal change in an unexpected increase or decrease and possible external changes, these oscillations can be observed as a result of swinging parameters such as bus voltages, phase angles, and active/reactive power flow on transmission lines after any fault occurs in power grids [3-5].

These low-frequency oscillations restrain the power flow on transmission lines, so system security is more likely to be threatened and possible damage to system devices or to occur in shutdown systems. Therefore, it is very important to damp the oscillations of the power system and to find better solutions to provide damping for those problems. Thus, power stability is enhanced. Among the most important of these solutions is the introduction of FACTS devices to the transmission lines. These devices are distributed to all parts of the power systems and to accelerate the provision of damping by depending on the reliability and high efficiency [6,2]. The damping is generally accomplished by the following methods:

- ❖ Modification of active power,
- ❖ Modification of reactive power,
- ❖ Modification of both active/reactive power,

FACTS devices can be divided into two categories according to their control method. The first one includes the thyristor, which was previously diffuse and probably used up to now and for examples of this variety are static var compensator (SVC) and thyristor-controlled series compensator (TCSC). The second category includes self-operated static transformers such as a voltage source converter (VSC), which are more sophisticated and modern than the thyristor class because it contains switches insulated-gate bipolar transistor (IGBT), gate turn off (GTO), etc. For examples of this variety are (UPFC), (IPFC) and (BTB-HVDC). Thus, the control circuits for the thyristor have a lower response to orders and need extinguish circuits, unlike the control circuits in the VSC which typically possess superior performance characteristics on the thyristor. As a result, FACTS-based VSC has gained popular control over the years [7].

For proper planning, FACTS-based VSC must be built and operated in power system grids, which is the ideal solution to power flow in grids. Therefore, the development of FACTS-based VSC models is of fundamental importance in improving power transfer. Recently observed in the history of the FACTS that components have been developed converters, switches, electronic parts, and control methods, compared to the old mechanical compensators because of the rapid advancement of the industrial revolution [6].

The FACTS have a faster dynamic response and are more able to controlling multi-power system parameters simultaneously and independently. Furthermore, FACTS already require less maintenance. It should be noted, VSC-HVDC has been at the forefront of FACTS devices that have improved grid stability [1]. In our current work, we are going to focus on research and comparing the potential of second-generation devices (UPFC, IPFC and BTB-HVDC) to damping oscillation, and presents the latest research and practice results for modelling and monitoring current and newly introduced FACTS. Which increases the power system stability and very high reliability if it compares to others.

1.2 Aim of the Thesis

Increasing need for electrical power, the tendency to deregulation of power systems, and the increasing ratio of distributed generation facilities such as wind and solar photovoltaic power plants, are of great importance to cope with both Local and Inter-Area oscillations. With this respect, the main aim of this thesis is to search the potential capabilities of three second-generation. IPFC, UPFC and BTB-HVDC have the same dual-VSC, but each device is different in the way of how connection with the grid) on oscillation damping which will increase power system stability and reliability.

1.3 Outline of the Thesis

This thesis is divided into six chapters:

Chapter 1: In this chapter fully, an overview of thesis objectives will be outlined among them the entire thesis structure with presenting a comprehensive introduction to the thesis.

Chapter 2: This chapter, we will shed the light on the background of FACTS devices as well as their impacts on the grids with reviewing of previous related literature studies in this regard.

Chapter 3: This chapter will deal with the various types of FACTS devices with fully explanatory details of theoretical studies in the related field.

Chapter 4: This chapter is going to be providing the close examination and comparison of IPFC, UPFC and BTB-HVDC models with focusing on the basis of their work such as configuration and controlling and their advantages.

Chapter 5: The obtained results for each model will be fully discussed in this chapter with an extra explanation of the difference between these models.

Chapter 6: This chapter is going to be clarifying thesis conclusion by proposing the outlook perspective in improving the performance of FACTS devices.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Electrical power requirements have been rapidly increased due to the needs increasing as well as the fast growth of population. This case has put a big pressure on traditional power systems which require either grid operation near to its technical limits or the grid expansion. Ever since that day, effective power transmission and ideal operation for grids are under research, this comes up with rapid technological development and vastness of power transmission grids over the last decades. Many studies have investigated these devices (IPFC, UPFC and BTB-HVDC), and extensive research has been taken place in every aspect of these devices.

2.2 Related Works

Saeedifard (2010), VSC-BTB-HVDC device was designed on seven levels by developing the mathematical model design. It explained the results the device that based on proper arranged controllers, supplies the good dynamic response, under balanced and unbalanced grid condition [8].

Parkhideh (2010), presented the results of the study in alternative ways to enhance the VSC-BTB-HVDC response under faults in power grids. He proposed two different control structures for monitoring to reduce the oscillations in the grids. It has been proven analytically that the VSC-BTB-HVDC can change the power on both ends of the buses and can enhance the grid well under faults in power systems [9].

Jiang (2011), Studied the performance of two FACTS devices (UPFC and IPFC) and after the development of the control devices. It was observed that the results of both IPFC and UPFC have two VSC in their structure with the ability to mitigate oscillations under critical conditions, which in turn reduces equipment damage or shut down for the system [10].

Jananisri (2012), entered UPFC into the IEEE-14 bus to monitor the behaviour of active/reactive power flow for the damping oscillation case and observed the performance of UPFC under fault conditions and processed to damp low-frequency [11].

Okba (2012), extrapolated the concepts and types of HVDC where it was displayed developments for it through its history and reported that switches and converters can be developed to be better, also pointed to technological development for VSC (from the second generation) to be used in power systems, therefore the study was considered to be the best one in comparison between HVDC and HVAC according to their applications and structures [12,13].

Rezaei (2013), has designed IPFC device then inserted it into Kundur power system and introduced methodology study and applied on IPFC by using Particle Swarm Optimization algorithm (PSO) method. PSO has approved a strong and reliable capability of finding the optimal solution for reducing oscillations in case PSO was compared with others Algorithms [14].

Banaei (2014), has carried out parallel comparison study of HVDC system with HVAC system by using VSC-HVDC and used Singular Value Decomposition (SVD) method to take control on VSC-HVD inputs to get oscillation damping, this SVD showed good simulation results, this has led to a good dynamic response of rotor angle deviation and rotor speed under different loads conditions or sudden disturbances that may occur in the transfer of power [15].

Patnaik (2015), placed UPFC between two areas in Kundur power system and also 3-phase faults were placed with UPFC but on another bus. The wind was connected with 4 synchronous generators which are distributed to both areas and used three options for UPFC operations. First one was, by utilising it as STATCOM, second one was as SSSC and finally was used as UPFC and then all these three options were compared [16].

Bayindir, Vural (2015), used Fuzzy approach to control IPFC device so as to improve damping oscillation in the power system. This method of IPFC-based on a Fuzzy controller has led to mitigate the inter-area mode of oscillations in a multi-generation power system. Also, this device is considered be the best performing for controlling the power flow (real/ reactive) in transmission lines, which in turn improves voltages in buses if a fault occurs [17].

Vaishali (2016), designed IPFC to Investigate performance of control over quantity power flow and size damping oscillation during disorders. By dividing the studies into three cases normal load, 10 % load increase and under 3-phase fault. The comparison of the analysis of these cases have been done according to reduce damping oscillation and also to Improve system stability [18].

Ambedkar (2017), analysed the performance of the FACTS controller SSSC and UPFC with and without PSS in the IEEE (3-Machines, 9-Bus) power system for 10 seconds. Also, compared the performance with MBPSS and GPSS to observe the effect of oscillations created during or after a fault in the grid with the SSSC and UPFC. It was clear from the simulation results for UPFC with MBPSS, It performed better than previous cases and there was a significant improvement in system performance [19].

2.3 Place of Work in the Literature

This thesis presents a method which can be used to damp local and inter-area oscillation damping by designing three devices (UPFC, IPFC and BTB-HVDC) in order to know which one of these devices can Improve the stability of power systems and apply these devices into two different grids (Kundur and IEEE9bus 3-Machine) to elucidate the comparison.

CHAPTER 3

THEORETICAL BACKGROUND

3.1 Overview of FACTS Devices

Electronic systems have been developed rapidly, this development has led to thinking about the creation possibility of electronic equipment with a high efficiency in a high voltage system to sort out power flow transmission problems. One of the systems used in power transmission is known as FACTS, which was originally initiated and launched into use by the 1980's. this technology has provided a new method for controlling power flows and improving usable portability of transmission lines [20].

Recently, power grids have expanded and become more complex, due to the entry of new loads and new flows of power. Therefore, the restructuring of electricity grids has become a necessary requirement. Certainly, it is an additional reason to face FACTS and consider the development of its equipment. This interest in the analysis of power systems with FACTS controllers, surely, it is embedded development and improvement model FACTS. The FACTS focus mainly on how to regulate the flow of power or to damp method electromechanical oscillations [21].

In the last decades, due to technical and mechanical issues, FACTS equipment was not responding quickly that's why it was not the favour systems to be used in power systems. But, because of the electronic components improvement, it has been introduced as the systems that to be applied mostly in all volumes in power systems worldwide, and its modern controller has been enabled to provide voltage support and power flow simultaneously [7].

3.1.1 Voltage Source Converter

VSC is self-commutated converter, which converts from AC to DC, or vice versa depending on the direction of power flow [12].

VSC is usually applied in power transmission may be long distances, between AC systems at different frequencies and underground or underwater. VSC uses semiconductors (IGBT, GTO, etc.) as shown in Figure 3.1, which can turn on or off by control action. It also works as the control transistor, but it has the capacity as thyristor because it does not require the extinction circuits such Thyristor, so it is considered a fast-control and also fast-installation. The VSC is used in these systems STATCOM, SSSC, IPFC, UPFC and BTB-HVDC.

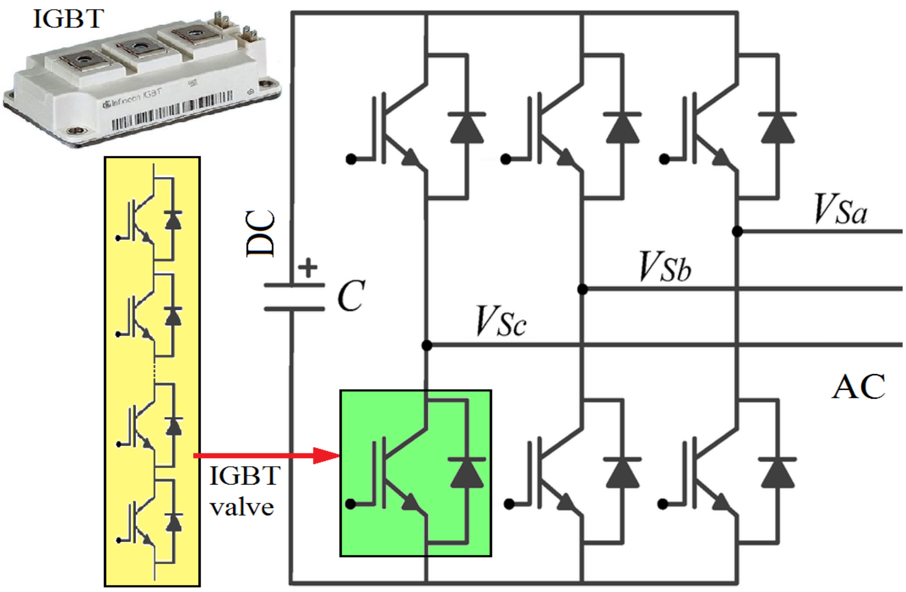

Figure 3.1 VSC structure [12].

It is worth to be mentioned, the thyristor valve is the previous generation of IGBT, where it was used to convert AC to DC as is the case in VSC and it has the ability to modify the value of delivering active/reactive power from the source to produce it according to the conditions required for it. Figure 3.2 shows the thyristor valves in the hanging piles of the roof structure of a transmission building that is called the valve hall. The thyristor valves are in a group of a 12-pulse converter with three quadruple valves, it is applied to each phase [13]. Each thyristor valve is connected series with others [13]. The applications that use of the thyristor valve are SVC, TCSC, UPFC and BTB-HVDC.

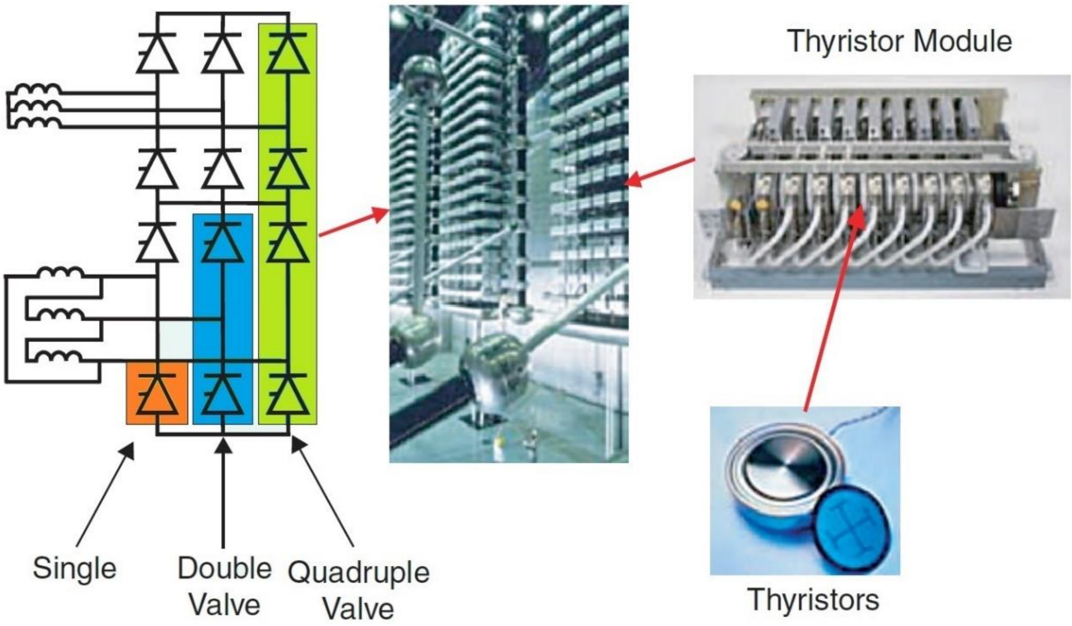

Figure 3.2 Thyristor structure [21].

3.1.2 Classification of FACTS Devices

The basic task of power system is to maintain the economic operation and security for large interconnected systems. This mission is one of the most important challenges that AC transmission faces. With these problems can be overcome by fast dynamic control of both real/reactive power using different types of FACTS devices distributed in grids [22]. Therefore, in this chapter is depending on the type of connection to the grid, FACTS devices can be divided into five categories:

- Shunt FACTS devices.
- Series FACTS devices.
- Series-Series FACTS devices.
- Shunt-Series FACTS devices.
- Shunt-Shunt FACTS devices.

FACTS devices are reinforced to damp oscillations and for improving system stability. In case of shunt devices modulation of voltage bus or reactive power, but it has very little influence on active power flow. Either in the case of series devices modulation of real power can be accomplished, but it has very little influence on voltage control. In case of shunt and series combination more than one VSC (combined series-series /combined series-shunt and combined shunt-shunt), it combines advantages series/shunt devices. For this reason, combined controllers have an efficiency greater than series or shunt devices, in terms of controlling active/reactive power flows and voltage buses stability [22].

There are many types of FACTS devices these are: SVC (Thyristor-based), TCSC (Thyristor-based), STATCOM (VSC-based), SSSC (VSC-based), IPFC (VSC-based), UPFC (VSC-based) and BTB-HVDC (VSC-based) [7]. It is worth to mention this chapter only reviews some of the FACTS devices that VSC-based. The modelling and simulation studies will be mentioned in detail in the next chapter.

3.1.2.1 STATCOM

STATCOM is a VSC-based FACTS device which is newer than SVC. STATCOM is also an alternative to controllable reactors and switched capacitors in SVC. The STATCOM has many advantages, including fast response, less size, and can be connected with power storage units. Figure 3.3 shows that the STATCOM is connected to the grid via a shunt transformer (known as coupling transformer). On the other side, STATCOM is connected to a DC capacitor [6]. Also, the main task of STATCOM is to control the voltage of buses by a generation or absorption reactive power like a variable capacitor-inductor [1].

If the output voltage of STATCOM exceeds the value of system voltage, the reactive flows from STATCOM to system to generate reactive power and the generated reactive power is transferred to the system via the coupling transformer. STATCOM is operating in capacitive mode; STATCOM produces reactive power If the output voltage is smaller than the AC voltage system. STATCOM is operating in inductive mode; STATCOM consumes reactive power from the system [24]. The active and reactive power can be expressed in Equation (3.1), and Equation (3.2) respectively [25].

$$P = \frac{V_{bus} * V_{VSC}}{X_L} \sin \delta \tag{3.1}$$

$$Q = \frac{V_{bus}^2 - V_{bus}\ V_{VSC}\ \cos \delta}{X_L} \tag{3.2}$$

Where X_L is the inductive reactance of the coupling transformer, V_{bus}, V_{vsc} and δ are voltage of bus, output voltage of STATCOM and δ the phase angle respectively.

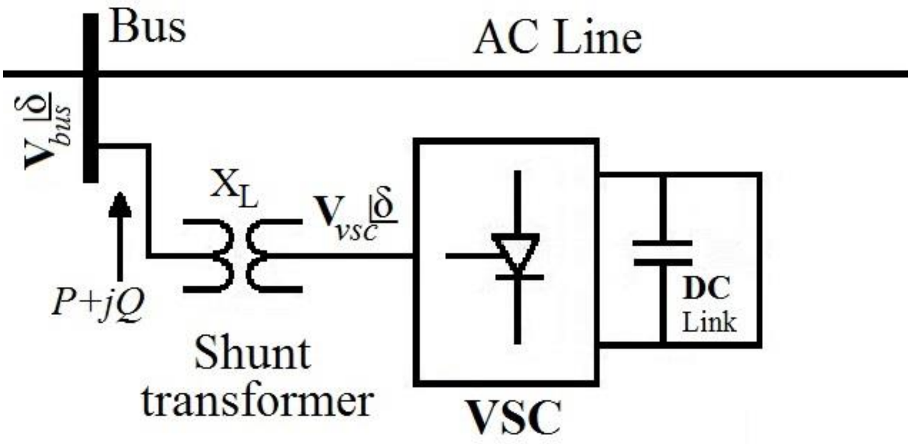

Figure 3.3 Typical configuration for STATCOM.

3.1.2.2 SSSC

SSSC is connected in series to the transmission line as shown in Figure 3.4. SSSC produces a three-phase voltage whose phase angle is perpendicular to the line current that can be dynamically adjusted. With SSSC, it is possible to control active/reactive power flow and on the transmission line [6].

SSSC can be regarded as a dynamic series capacitor or reactor. The magnitude and phase angle of output voltage of VSC can be controlled by changing modulation index of the VSC. in another meaning, If the VSC output voltage is 90 degrees lagging the current, SSSC provides capacitive reactive power to reduce line reactance. If the VSC output voltage is 90 degrees leading the current, SSSC provides inductive reactive power to increase the line reactance. In this way, SSSC can control power flow from the transmission line to the device or vice versa [25,27].

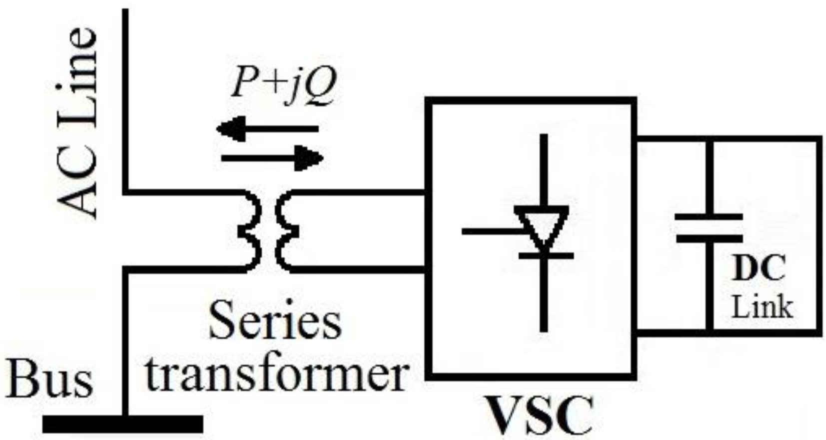

Figure 3.4 Typical configuration for SSSC.

3.1.2.3 IPFC

SSSC is one member of FACTS device family. IPFC has two VSCs which are connected to each other from their DC link and the AC side of each VSC is connected to the one transmission line in series through series coupling transformers [28,6], as shown in Figure 3.5.

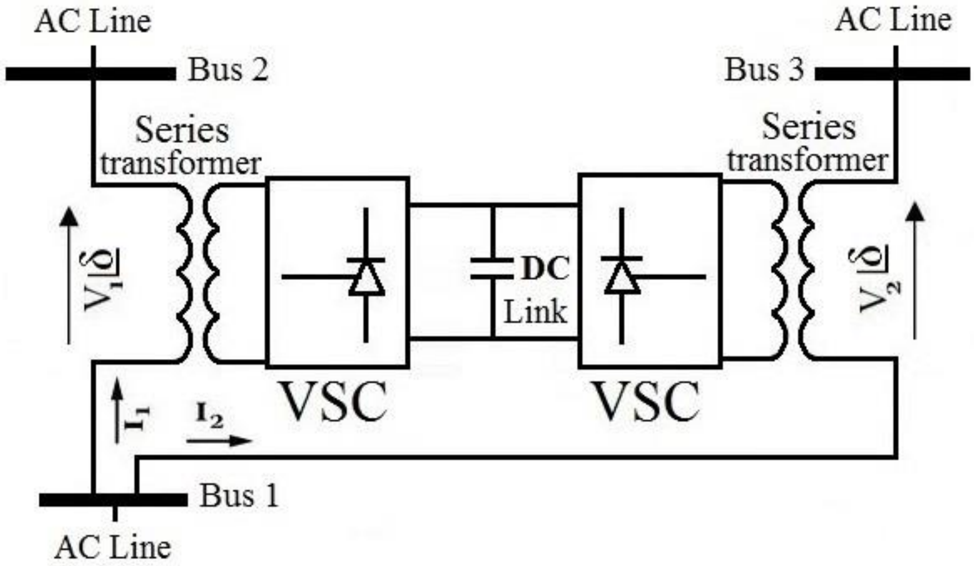

Figure 3.5 Typical configuration for IPFC.

The real and reactive power can be extracted as shown in equation (3.3) and (3.4) to given as below:

$$P = \frac{V_1\, V_2\, sin(\delta)}{X_L} \tag{3.3}$$

$$Q = \frac{V_1(V_1 - V_2\, cos(\delta))}{X_L} \tag{3.4}$$

Where P, Q are the active/reactive power flow. V_1, V_2 are the voltage at the ends of the lines, X_L is the reactance of the transmission line, δ *is* the phase angle between the bus voltage and current. From the equations above (3.3) (3.4) [28].

3.1.2.4 UPFC

This device is also considered as a member of family of FACTS devices. UPFC has two VSCs which are connected to each other from their DC link. One VSC is connected to a selected bus in shunt trough shunt coupling transformer, while the other

VSC is connected to the transmission line in series through a series coupling transformer [6], as shown in Figure 3.6.

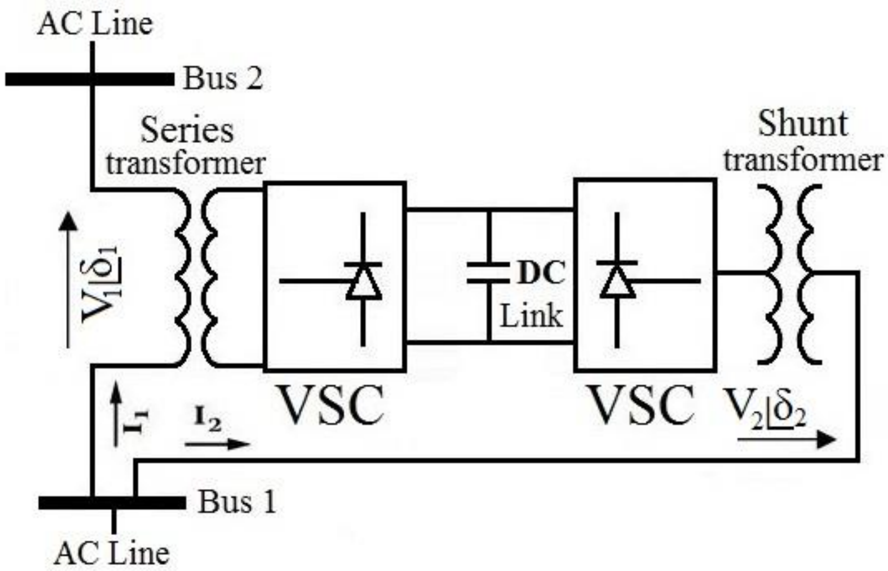

Figure 3.6 Typical configuration for UPFC.

Active/reactive power flow extracted as shown in equations (3.5) and (3.6), respectively [2,6].

$$P = \frac{V_1\, V_2\, sin(\delta_1 - \delta_2)}{X_L} \tag{3.5}$$

$$Q = \frac{V_1(V_1 - V_2\, cos(\delta_1 - \delta_2))}{X_L} \tag{3.6}$$

V_1, and V_2 are the voltage at the ends of the lines, X_L is the reactance for the transmission line, δ is the phase angle between the bus voltage and current. As shown in equations (4.3) and (4.4), real and reactive power depends on parameters (V, δ, and X_L).

3.1.2.5 BTB-HVDC

Actually, the BTB-HVDC arrangement is not usually considered as a FACTS device, but it has similar topology as in case of IPFC and UPFC. BTB-HVDC has two VSCs which are connected to each other from their DC link and the AC sides of each VSC is connected to the independent transmission line in shunt through shunt coupling transformers [6], as shown in Figure 3.7.

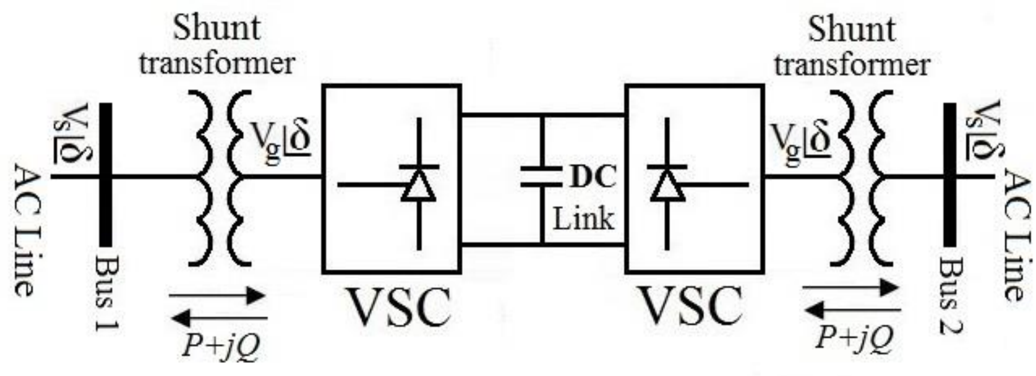

Figure 3.7 Typical configuration for BTB-HVDC.

The active/reactive power flow between the VSC and AC grid can be calculated according to equation (3.7) and (3.8) for VSC1 or VSC2, but when ignoring the losses of the phase reactor.

$$P = \frac{V_g}{X_L} * (V_s\, sin(\delta)) \tag{3.7}$$

$$Q = \frac{V_g}{X_L} * (V_g - V_s \cos(\delta)) \tag{3.8}$$

Where δ is the phase angle between the primary voltage (V_g) generated by the VSC and the AC voltage (V_s) on the AC bus. Finally, X_L is the reactance of the transmission line [29,59].

3.2 Power Oscillation Damping for Low-Frequencies

The electrical grids have become a huge and large development, also very complex. Those phenomena produce problems in the stability of power flow and voltage buses. In addition, should be used to maximum load limits power flow for transmission lines, so it has to find optimal solutions to reduce the cost of creation of power transmission lines [29].

In the field of power transmission engineering, it is possible to determine any dynamic system and restore the state of equilibrium after the system is exposed to a disturbance [30]. Therefore, when evaluating the stability of the power system, it is necessary to monitor the quantities of voltage and frequency. Of course, the stability of these quantities is a good sign of the stability of the power system. The power system is a nonlinear system that is always exposed to many random disturbances that are either small or large, for example, change of demand or occurrence of short circuits in the system. Therefore, the stability of the power system depends on the initial operating conditions as well as the nature of the disturbances [6,29].

Therefore, electromechanical oscillations are occurring between interconnected synchronous generators, which are one of the most important challenges facing power transmission lines. These oscillations are phenomena latent in power systems [3]. To ensure proper operation, these frequencies should be reduced that make the system stable and reduces damages and that is done by adding the IPFC, UPFC and BTB-HVDC devices to power transmission lines.

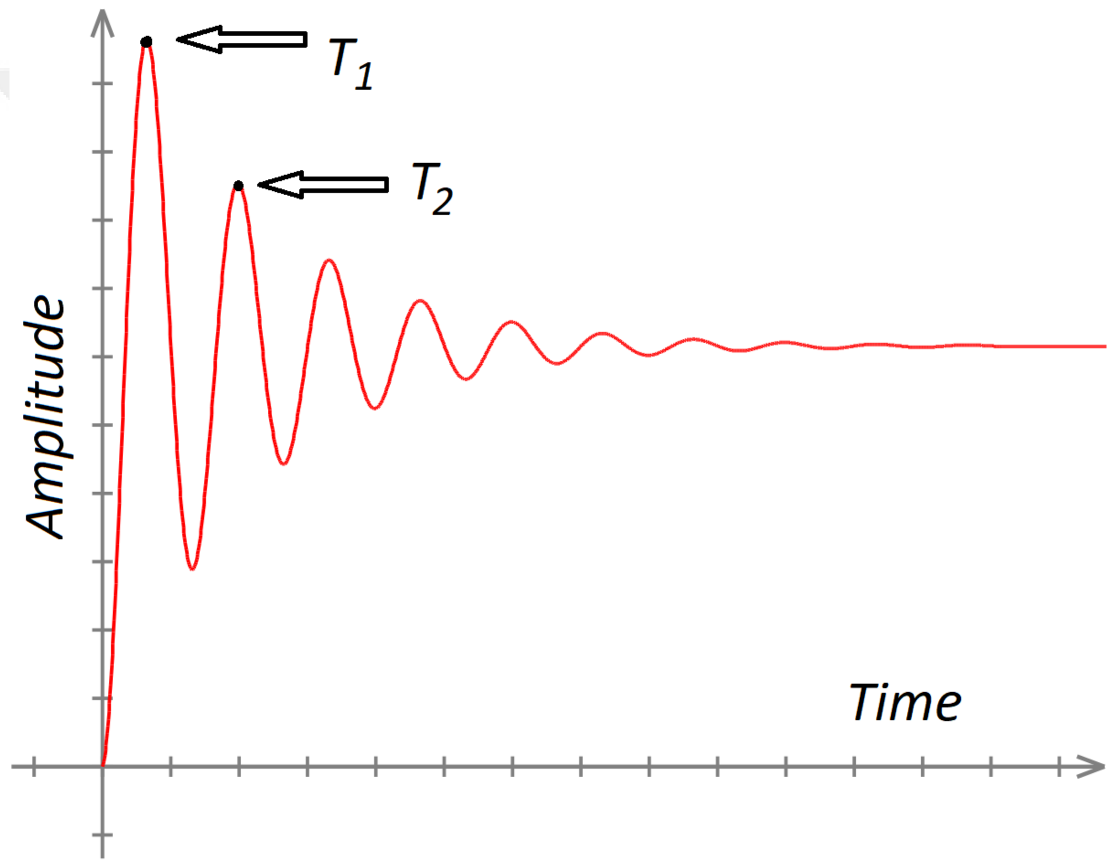

Figure 3.8 Frequency oscillation.

The damping ratio should be less than 5% In case of oscillation according to local and inter-area oscillation studies and the frequency of oscillation (f) is calculated from the Figure 3.8 and written in Equation (3.9) [3].

$$f = \frac{1}{T_2 - T_1} \tag{3.9}$$

And the complex conjugate pair which is shown in equation (3.10) describes an oscillatory mode (γ), that leading to find the value of the damping ratio (ξ) as shown in equation (3.11) [3].

$$\gamma = \sigma \pm j2\pi f \tag{3.10}$$

$$\xi = \frac{\sigma}{\sqrt{\sigma^2 - \omega^2}} \tag{3.11}$$

Where (σ) is the damping factor and (f) is the frequency of oscillation and ($\omega = 2\pi f$).

3.2.1 Classification of Low-Frequency Oscillations

The need for dynamic analysis of power systems has increased significantly in recent years. This is due to the desire to take advantage of transmission grids for more flexible exchange transactions [31]. While dynamics and stability have been monitored for years in a long-term planning and design environment, there is also an urgent need to conduct this analysis in the operating environment. Electromechanical oscillations occur in the range of 0.1-2 Hz and classified into two main categories as shown in Figure 3.9 [34].

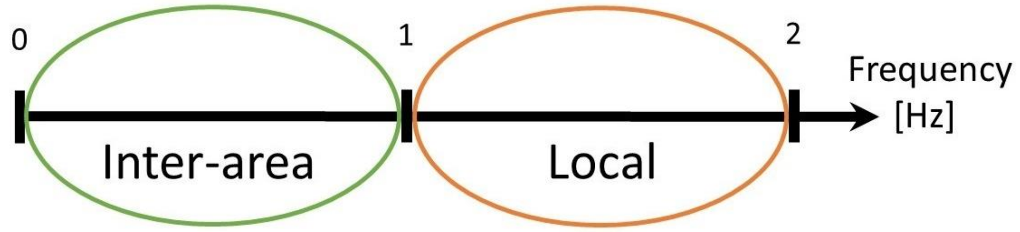

Figure 3.9 Electromechanical oscillation modes.

Table 3.2 below is clarified the modes of oscillations damping which is used to analyse the stability of power system for both local and inter area [33].

Table 3.1 Oscillation damping evaluation schedule.

Range of oscillation	Oscillation damping evaluation
0 > damping ratio	Unstable
0 < damping ratio < 5%	Insufficient
5% < damping ratio < 15%	Good
15% < damping ratio < 25%	Excellent

It is worth mentioning that the processing of the damping of these oscillations are not done only by the IPFC, UPFC and BTB-HVDC devices, but also excitation systems and PSS are also considered as the methods to enhance oscillation damping [35].

3.2.1.1 Local Mode of Oscillation

When power plants are connected together in the same area. any emergency problem occurs for that area or in grids, the system will be unstable in terms of voltage, frequency and power flow. Therefore, it can be defined of the Local mode, which is as the oscillations (Low-frequency) that occur between the generators in the same area, where those frequencies are usually approximate between 1 and 2 Hz [3,33].

3.2.1.2 Inter-Area Mode of Oscillation

With the expansion of transmission grids, where the new generators and loads are added in these grids. the areas should be considered after occurring any emergency problem, and the system can be unstable in terms of voltage, frequency and power flow. Therefore, it can be defined of the inter mode, which are oscillations of a group of generators in one area swinging versus a group of generators in another area, where those frequencies are usually approximate between 0.1 and 1.0 Hz [3,33].

CHAPTER 4

DYNAMIC MODELLING OF IPFC, UPFC AND BTB-HVDC

4.1 Introduction

The power has been increasing with expansion of power systems. This expansion is introduced by new loads and power plants to the power systems. Transmission lines have become in these years more complex. In this context, if any sudden problem happens in the transmission lines such as short circuits or sudden load changes, then it will cause a severe damage to the power systems.

The engineers have sought to solve these problems in less expensive and innovative ways. One of these proposed solutions to solve these problems is unexpected loads or short circuits in AC lines. Three devices (namely IPFC, UPFC and BTB-HVDC) are added to power systems which are one of the possible solutions for power flow control and damping oscillations.

4.2 Dynamic Modelling of IPFC

4.2.1 Overview of IPFC

IPFC was proposed in 1998 by Gyugyi with Sen and Schauder [36]. This device aims at solving many problems in AC transmission lines. IPFC is a development version of SSSC which consists of two or more SSSC [37].

As shown in Figure 4.1, the IPFC consists of two VSC connected in different AC transmission lines. VSCs are connected to each other through a common DC link, while VSCs are connected to the AC lines through the series transformers. Each VSC structure is able to generate three voltage levels. Each bypass switch is connected in a parallel way with a series transformer to ensure that each VSC turned on or off. This DC link consists of a capacitor and allows movement of the power flow between the converters in a bidirectional way that IPFC providing the ability to transfer the power flow directly between the lines independently or altogether [17,36].

IPFC also maintains the balance of power flow between the lines by the DC link between VSCs. IPFC is able to extract the power flow from the first line and inject it into the other line or vice versa, unlike SSSC [16,38,39].

This transmitted power facilitates the following functions to be possible [37];

- To equalize both active/reactive power flow between lines.
- To reduce the overload of excess lines by moving active power.
- To increase the effective dynamic of the compensation systems.
- To provide reactive power for compensation versus resistive voltage drops.

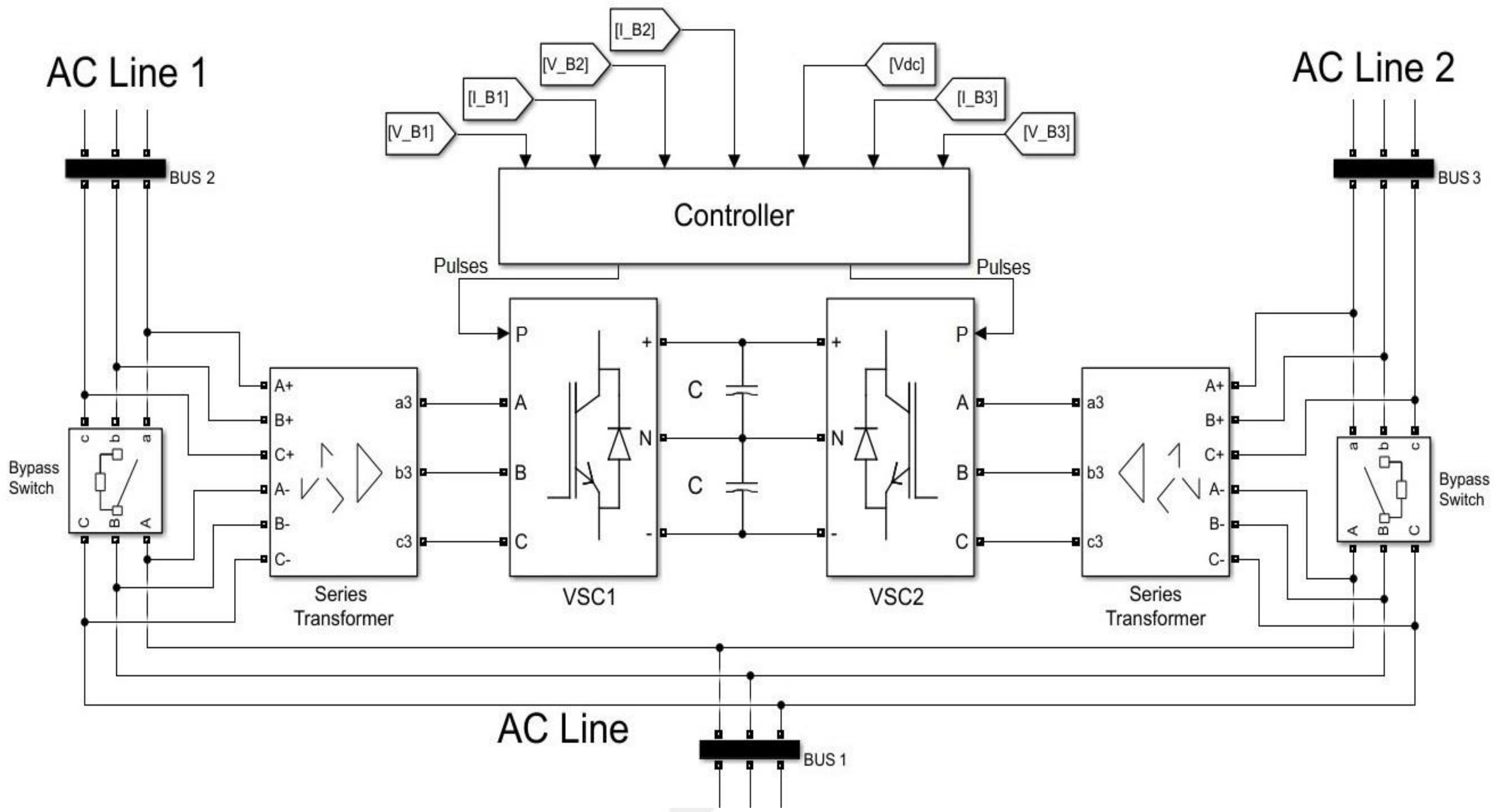

Figure 4.1 Basic IPFC configuration.

4.2.2 Basic Operating Principle of IPFC

This arrangement of IPFC works as an AC-DC-AC converter where the active/reactive power of two VSCs can pass freely between the terminals of VSCs. Each VSC can generate or consume reactive power independently or simultaneously and injects these values in the transmission line. Power flow of IPFC is adjusted by changing the phase angle of each VSC that is compared with the phase angle of AC line. Interestingly, the DC link takes power to pass through it from VSCs and works as switch of the power [40].

In this case, the VSC output voltage is 90 degrees lagging the current, the VSC provides capacitive reactive power to reduce line reactance. If the converter output voltage is 90 degrees leading the current, the VSC will provide inductive reactive power to increase the line reactance. In this way, power flow of the transmission line is controlled dynamically [28]. IPFC can be considered as a dynamic series capacitor or reactor, depending on the voltage applied to the transmission line. Also, IPFC controls active/reactive power flow in AC lines through DC link [40]. Power flows through two VSCs by DC link and transfers into the AC line through series of transformers. Also, each VSC can provide active/reactive power to AC line simultaneously or independently [60].

4.2.3 Control of IPFC

As we have mentioned earlier, IPFC consists of two VSCs that connected through a DC link from side to another side connected to the grid via series transformers. While mentioning the basic operation of the IPFC, it turns out that the device that does not have many cases to control the AC line. But the main purpose of installing IPFC in power systems is controlling the flow of power on the AC lines [34].

This thesis is going to study three devices (IPFC, UPFC and BTB-HVDC). The common factor in these devices is controlling the power flow. In terms of control cases as shown in Figure 4.2, both VSCs of IPFC provide active/reactive power for AC lines via DC link. This power flow is either in or outside to DC link. This exchange of power is between the AC system and the IPFC, which is subjected to control the phase angle and voltage value [41]. The power flow control mode is selected for IPFC in automatic control mode. An important point in control is that when controlling the power flow by IPFC, it is advisable to change gradually and carefully to avoid potential dynamic disturbances in the system [34,43].

Figure 4.2 shows the basic control scheme of IPFC which is a combination of two SSSCs. The basic principle of control is to compare the reference value with the measured variable and to handle the value of output in several control blocks to obtain the required pulses. The voltage and current signals are inserted into the measurement block to produce sine signals depending on the incoming signals. After that, these signals are converted to the values of the direct-quadrature axis (d-q) and synchronized with the AC grid voltage by a phase locked loop (PLL). In order to supply the phase synchronous angle ($\theta = \omega\tau$) for the d-q transformations of the AC three-phase voltages (V_{abc}) and currents (I_{abc}) (labelled as V_d, V_q or I_d, I_q in Figure 4.2), the PLL is provided.

Figure 4.2 explains the form of the control that consisted of two blocks and the mutual signal between them is DC voltage (V_{dc}). The V_{dc} signal is compared with the V_{dcref} reference to enter in the block of DC voltage controller for producing $I_d$and the same process is for the block of an active/reactive power controller for creating I_{dref} and I_{qref}. The I_d is subtracted from I_{dref^*} and this value is combined with I_{qref} value for forming I_{dqref} and that is compared with the output value of the current controller block (I_{dq}) to enter into PI controller.

The PI controller is utilized with the d-q values in order to generate a static voltage under differing loads conditions or a new input so that voltage remains constant. After that, the signal of PI controller is entered into transformation block to turn the signal from the V_{dq0} to the V_{abc}. A pulse width modulation (PWM) is utilized to process V_{abc} as a final stage before the generation of the converter pulses and the signal is deported to VSC1 and the same idea is applied to VSC2 [44].

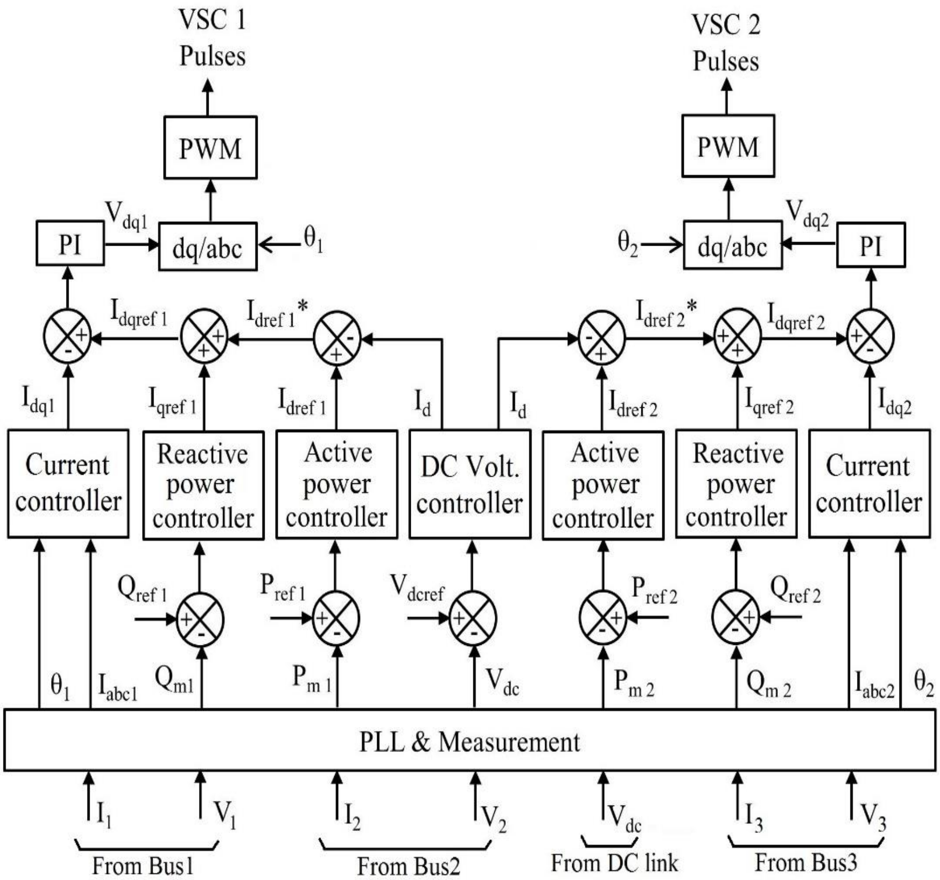

Figure 4.2 Basic control scheme of IPFC.

4.3 Dynamic Modelling of UPFC

4.3.1 Overview of UPFC

UPFC is the most versatile FACTS device [2]. In 1991, Laszlo Gyugyi was the first to propose UPFC [2]. When IPFC was browsed in the previous section, a UPFC looks like the IPFC device, but the link and way of working are a bit different. The IPFC is the latest version of UPFC in terms of modernity, but the UPFC is more widespread than the rest of the FACTS devices because the UPFC is multifunctional and providing flexible control of power system parameters [47].

The basic configuration of UPFC is shown in Figure 4.3, which has two VSC devices connected to each other through a common DC link. But on the other hand, UPFC is connected with one AC line unlike IPFC. VSC1 is connected to the line through the shunt transformer, and in shunt VSC2 is connected to the same line through a series transformer. Each VSC topology is composed of three voltage levels. The first one of bypass switch is connected series to the shunt transformer while the second is connected parallel to the series transformer to ensure operation of each VSC upon request. The DC link facilitates the real flow in a bidirectional way between the VSCs [25,28].

It is worth noting, UPFC is a combination of STATCOM and SSSC. VSC1 is similar to the work of STATCOM and VSC2 is similar to the work of SSSC. This device works primarily as an AC-to-AC power converter for transmission lines, which allowing the power to flow in both directions between two VSCs. In addition, each VSC can be used to generate or absorb reactive power independently [45].

Worthwhile, UPFC is considered to have many functions such as control of active/reactive power flow and voltage regulation. Each VSC can provide a different function, VSC1 operates to compensate for the reactive power or regulate the voltage of the bus, as in the case of the STATCOM. As for VSC2 works to compensate for the reactive/active power flow in the AC line, as in the case of the SSSC [25,49].

Under conventional power transmission concepts, UPFC can control all the parameters that affect the power flow in AC line (voltage, active and reactive power), and this unique ability is indicated by the adjective "unified" in its name [26]. Wherefore, UPFC provides and improves a very flexible operating environment against changing conditions and gives an ideal solution to solve numerous problems in transmission lines such as low-frequency oscillations that leads to the instability of power systems [46].

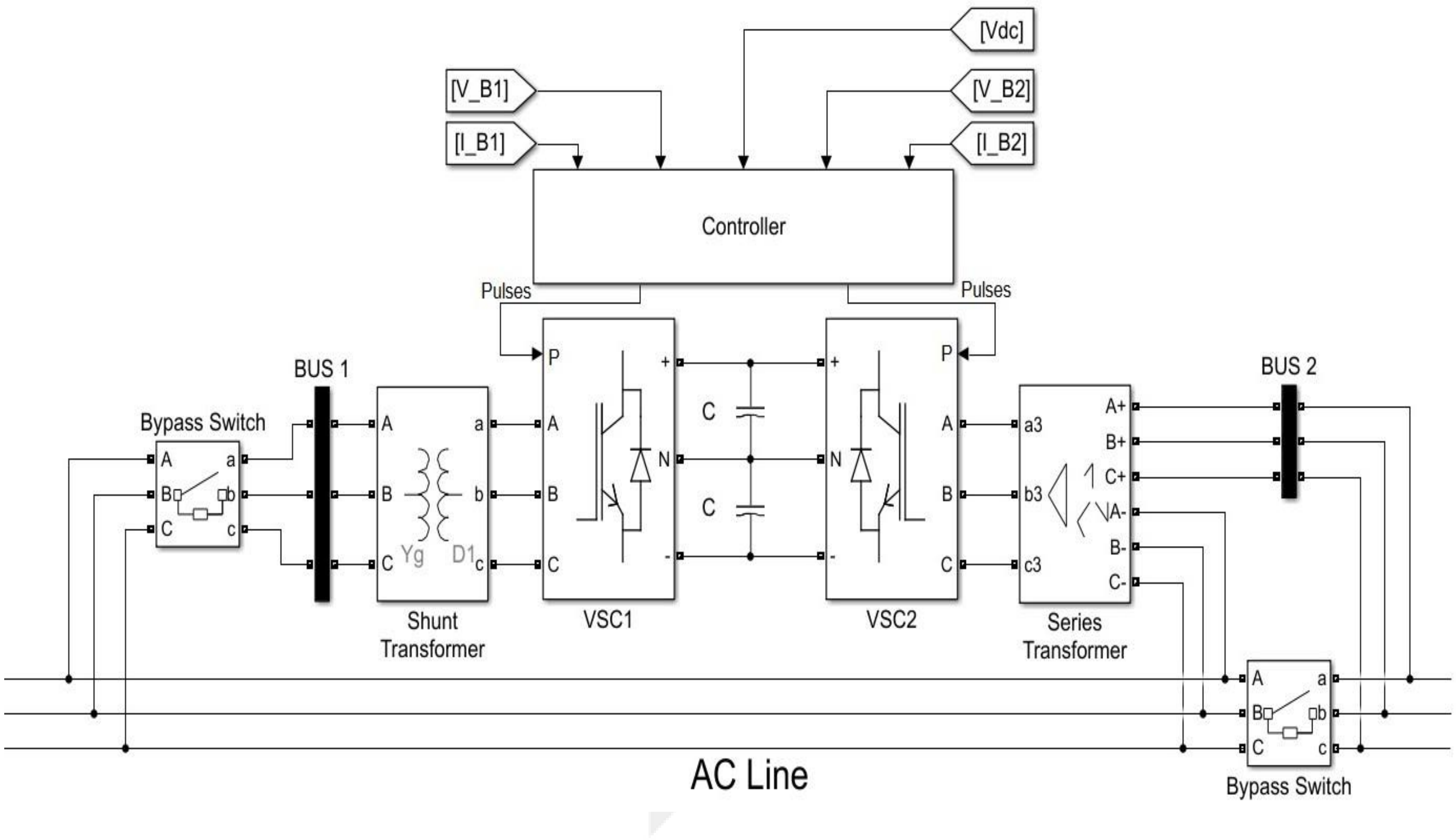

Figure 4.3 Basic UPFC configuration.

4.3.2 Basic Operating Principle of UPFC

Figure 4.3 shows that the UPFC is a three-phase device using IGBT valves, which consists of two VSC linked by DC Link. But each VSC differs from the other in case of connecting with the AC line. VSC1 is connected to the AC line through the series transformer and the second one is through the shunt transformer [47,51]. Each VSC can generate or consume reactive power independently and simultaneously. This arrangement of VSCs works as an AC-DC-AC power converter as in case of IPFC [48,52].

VSC1 works as STATCOM, that means if the output voltage of VSC1 exceeds the value of system voltage, the current will flow from VSC1 into a system generating reactive power injected into the AC transmission line via the shunt transformer. If the output voltage is bigger than the AC voltage system, the device will operate in capacitive mode conversely. If the output voltage of VSC1 is smaller than the system voltage, the device will operate in an inductive mode, that means consuming reactive power from the transmission line [10,53]. VSC2 operates as the SSSC as previously mentioned.

The real power flows through two transformers and this power is transferred to AC line. In case if UPFC operates as an active/reactive power flow mode, then this mode allows passing the power flow from VSC1 to VSC2 through a DC link. Otherwise, if UPFC operates as a voltage regulated or reactive power flow modes, then this mode allows passing the power flow from VSC2 to VSC1 through the DC link.

4.3.3 Control of UPFC

UPFC consists of two VSCs connected through a common with a DC link. UPFC has many cases in the control modes as shown in Table 4.1 [34].

Table 4.1 UPFC control modes.

Mode	Controlled power system parameter
1	Bus Voltage, Line Active and Reactive Power Flow (PQV)
2	Line Active and Reactive Power Flow (PQ)
3	Active Power Flow and Bus Voltage (PV)
4	Reactive Power Flow and Bus Voltage (QV)

This thesis focuses on controlling power flow because this mode (PQ) is similar to the rest of the IPFC and BTB-HVDC is to damp out oscillations when occurring faults in transmission lines. This feature is utilized for the comparison between IPFC, UPFC and BTB-HVDC.

As shown in Figure 4.3, VSC1 controls the active power to meet the demand of VSC2, so that VSC2 can control active/reactive power flowing on the transmission line. This exchange of power is subjected to control the phase angle and voltage between the AC system and the VSC2 [55]. The active/reactive power flows of the AC line are maintained at certain values in the automatic power flow control mode setpoint. To avoid potential dynamic disturbances in the system, power flow should be changed gradually and cautiously. This is a fundamental point controlling UPFC [43,55].

Figure 4.4 shows the basic control scheme of UPFC which is a combination of two STATCOM and SSSC. The left side of Figure 4.4 is similar to the control of STATCOM. In general, the VSC 1 operates in two control modes either voltage regulator mode or reactive power control mode and VSC 1 is often operated in the voltage regulator mode [56].

The principle of control is to compare the reference value with the measured variable and to handle the value of output in several control blocks to obtain the required pulses. The voltages and current signals are introduced into the measurement block to make sine signals depending on the incoming signals. These signals are converted to the values of the direct-quadrature axis (d-q) and synchronized with the AC grid voltage by PLL. This PLL also provides the phase synchronous angle ($\theta = \omega\tau$) for the d-q transformations of the AC three-phase voltages and currents.

The voltage reference (V_{ref}) is compared with the voltage measured (V_m) to be inserted in voltage controller block for producing I_{qref1} and the same process is for the block of a reactive power controller. The DC voltage reference (V_{dref}) is compared with the DC voltage measured (V_{dc^*}) to be inserted in DC voltage controller block for producing I_{dref1} and this I_{dref1} is combined with I_{qref1} to generate I_{dqref1}. The I_{dq1} is extracted from the current controller block to comparing with I_{dqref1} for inserting the PI controller block that this signal is processed into it. After that, the signal of PI controller is entered into transformation block to turn the signal from the V_{dq0} to the

V_{abc}. The PWM is utilized to process V_{abc} as a final stage before the generation of pulses of the converter and this signal is deported to VSC1 pulses [55].

The right side of Figure 4.4 describes the control scheme of series VSC which is similar to the control of SSSC. After the input values processed into the active/reactive controller blocks, these values (I_{dref2} and I_{qref2}) are combined together and compared to the value of the current controlled block (I_{dq2}) that entering into PI controller block for processing this signal. After that, the output of the PI controller (V_{dq2}) is entered into transformation block to turn the signal from the V_{dq0} to the V_{abc}. The PWM is utilized to process V_{abc} as a final stage before the generation of the converter pulses and this signal is deported to VSC2 pulses [55].

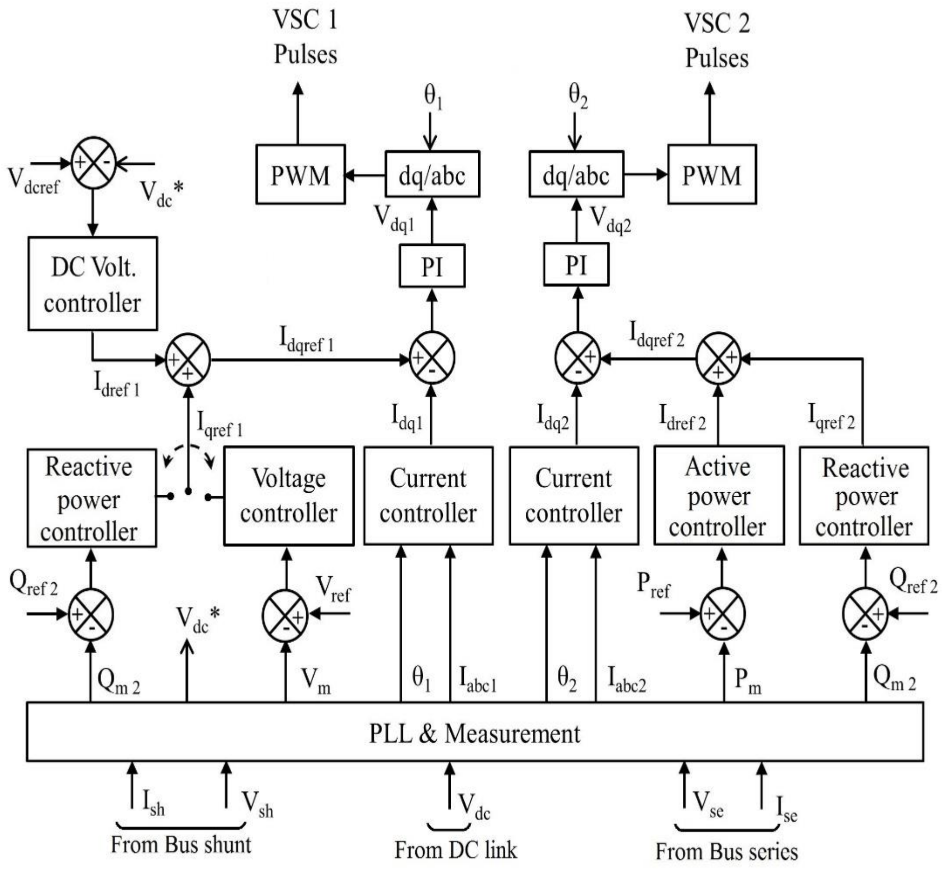

Figure 4.4 Basic control scheme of UPFC.

4.4 Dynamic Modelling of BTB-HVDC

4.4.1 Overview of BTB-HVDC

BTB-HVDC has been developed since 1990 [57]. BTB-HVDC has received great attention from designers. For this reason, it is considered as a high-power electronic technology used in power systems and constantly evolving. As previously mentioned in the last two devices (IPFC and UPFC), BTB-HVDC, it seems such as the two devices (IPFC and UPFC), but the link and principle of work differ a little bit [34].

BTB-HVDC can be defined as shown in Figure 4.5, BTB-HVDC has two VSCs. These VSCs are connected in shunt to the grid and the DC link side of each VSC is connected through a common DC link. Thus, BTB-HVDC has a reverse IPFC's connection on the transformers side of the connection to the AC line. Each VSC is formed by three voltage levels. As for a bypass switch, it is connected in parallel with the BTB-HVDC in full to ensure of the device on-demand. It is clear that BTB-HVDC arrangement is not considered of FACTS family through studying the internal parts of this device [2]. However, it has a methodology that looks like to most devices of second-generation FACTS.

Worthwhile, the features of VSCs are in the same place which have the ability to facilitate the power flow in a bidirectional way and BTB-HVDC can provide a function conversion AC system to DC and then to the AC system, this approach is utilized to control active power flows and to regulate the voltage effectively [60]. Thus, BTB-HVDC operates the transfer of real power within two grids in different circumstances (synchronized, asynchronous, or even in the case of different frequencies). It can be exploited that each VSC control injected reactive power, which in turn leads to regulating bus voltages can dynamically [3]. Therefore, the main purpose of installing BTB-HVDC in the system is to control active power flow or AC voltage and BTB-HVDC is considered as an effective solution for the dynamic of low-frequency transmission line [8].

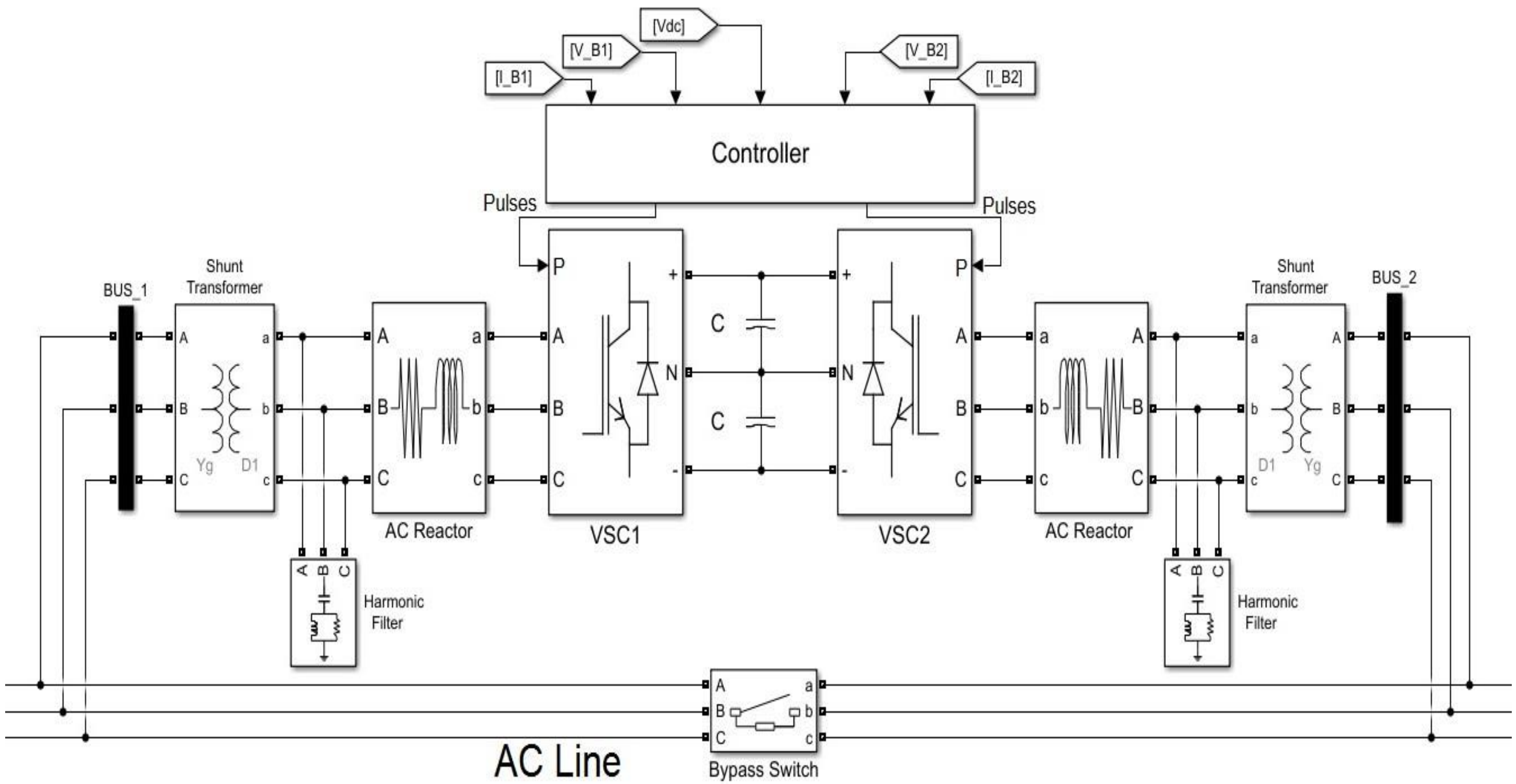

Figure 4.5 Basic BTB-HVDC configuration.

4.4.2 Operating Principle of BTB-HVDC

As previously mentioned about the configuration of BTB-HVDC and shown in Figure 4.5, each VSC can control power flow by adjusting the amount of flow. This arrangement of converters works as an AC-DC-AC converter, where the power flow of two VSCs can pass freely between the VSCs simultaneously but not independently [3,61].

The converters (VSC1, VSC2) are almost similar to a VSC used in STATCOM but these VSCs differ from the operational aspect. STATCOM is based on the injection of the reactive power in the grid, while the BTB-HVDC device works as a power transporter from one end to the other or conversely, like other HVDC transmission devices [62].

The flowing of power will be occurred from high voltage value to low value according to the variation in the magnitude of the voltages and currents in both of buses terminals. This means that if the power flows from VSC 1 to VSC 2 or vice versa according to the direction of the loads, BTB-HVDC can control the amount of power flow. BTB-HVDC is an effective device for processing the problems of power flow. It can inject or absorb active/reactive power according to the demand, as well as it can control the parameters (voltage and frequency) so it is considered as a successful device [61,63].

4.4.3 Control of BTB-HVDC

As mentioned previously in the section of the configuration of BTB-HVDC, BTB-HVDC has many control modes as shown in Table 4.2 [64].

Table 4.2 BTB-HVDC control modes.

Mode	Controlled power system parameter
1	Line Active Power flow (P)
2	Active Power Flow and Bus Voltage (PV)
3	Bus Voltage (V)

It is worth mentioning, that BTB-HVDC can control the active power flow. Therefore, BTB-HVDC equips an extra controller which is either manual or automatic. The choice of any type of control units depends on the type of application, for example, BTB-HVDC can control the active power flow or voltage for improving weak systems which suffered from low voltage and loss of power flow that can be also put in the frequency difference systems [12,13]. However, the flow of power across the DC link must be stable to achieve power balance. The difference is a result from a fast change in the DC voltage on the link which leads to adjust any value of the power flow in another converter according to the requirements of the system [60].

The internal structure of BTB-HVDC control is a combination of control blocks which combined of two VSCs. Figure 4.6 shows the basic control scheme of BTB-HVDC. The principle of BTB-HVDC is to compare the reference value with the measured variable and handle the value of output in several control blocks to obtain the required pulses.

The voltages and current signals are inserted into the measurement block to produce sine signals and these signals are converted to the values of the d-q. These values are synchronized with the AC system by PLL. This PLL provides a phase synchronous angle ($\theta = \omega\tau$) for the d-q transformations. On a left side of Figure 4.6, the voltage reference (V_{ref}) is compared with the voltage measured (V_m) to enter into the voltage-controller unit for producing I_{qref1} and the same process is accomplished with the reactive control block.

The I_{qref1} is obtained through either a voltage controller block or a reactive controller block to compare with the signal of current controller block (I_{q1}) for creating I_{q1^*}. The active power reference (P_{ref}) is compared with the active power measured (P_m) to enter into the active power controller unit for producing I_{dref1} and the same process is accomplished with the DC voltage control block. The I_{dref1} is obtained through either the active power controller block or the DC voltage controller block to compare with the signal of current controller block (I_{d1}) for forming I_{d1^*}. The I_{q1^*} is combined with the I_{d1^*} to insert into PI controller block for handling these signals.

After that, the signal of PI controller is entered into transformation block to turn the signal from the V_{dq} to V_{abc}. The PWM is utilized to process V_{abc} as a final stage before the generation of VSC pulses and this signal is deported to VSC1. On a right side of Figure 4.6, the same process is accomplished to generate the pulses of the converter and deported the signal to VSC2 pulses [61,65].

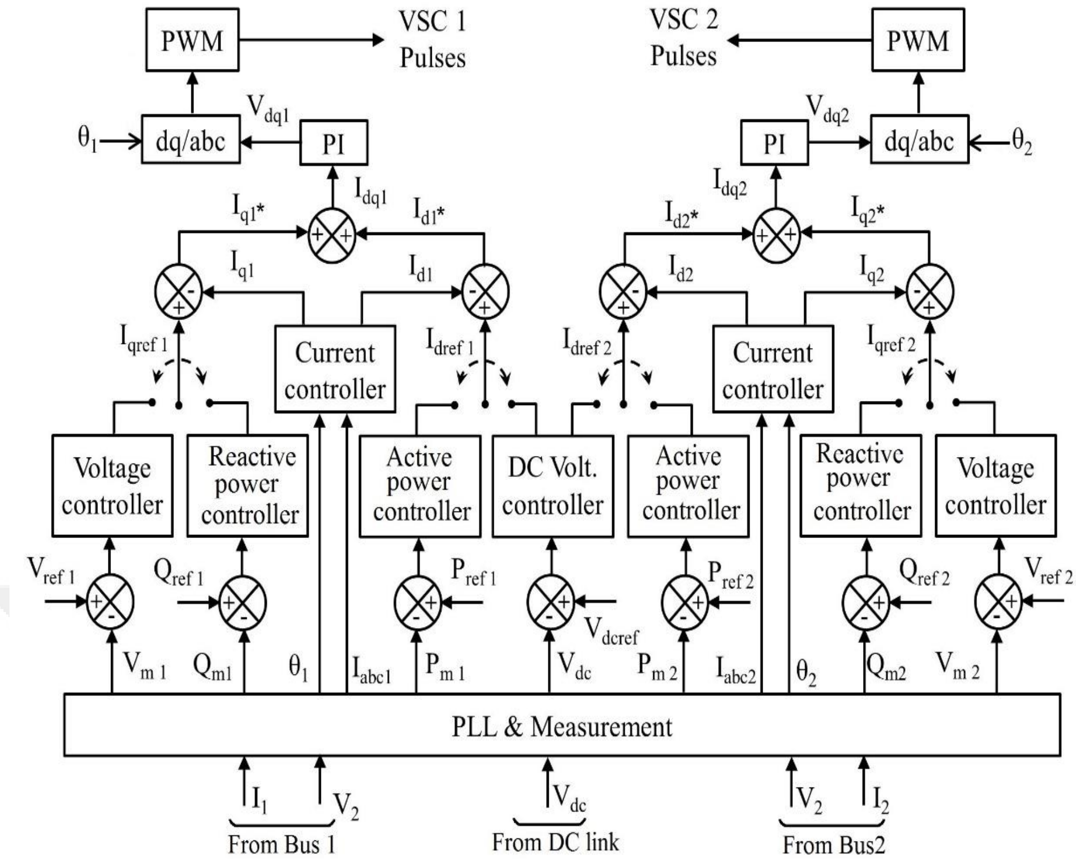

Figure 4.6 Basic control scheme of BTB-HVDC.

4.5 Comparison of IPFC, UPFC and BTB-HVDC

It can be concluded from the operating principles of each device that were explained previously the comparison are given briefly in Table 4.3 [3,61,69,70].

Table 4.3 Comparison of IPFC, UPFC and BTB-HVDC.

No.	Types	IPFC	UPFC	BTB-HVDC
1.	Control of voltage	Yes	Yes	Yes
2.	Control of impedance	Yes	Yes	Yes
3.	Control of active power flow	Yes	Yes	Yes
4.	Control of reactive power flow	Yes	Yes	No
5.	Operate of VSCs independently	Yes	Yes	Yes
6.	Operate of VSCs simultaneously	Yes	Yes	Yes
7.	Working in different frequency grids	No	No	Yes
8.	Control of damping oscillations	Yes	Yes	Yes
9.	Transient and dynamic stability	Yes	Yes	Yes
10.	Reactive compensation	Yes	Yes	Yes
11.	Limitation of short circuit current	Yes	Yes	Yes
12.	Adjust of line reactance	Yes	Yes	Yes
13.	Operating in more than one line simultaneously	Yes	No	No
14.	Stability improvement	Yes	Yes	Yes
15.	Improving of system performance improvement	Yes	Yes	Yes
16.	Increase of transmission capacity	Yes	Yes	Yes
17.	Reduces operating cost	Yes	Yes	Yes
18.	The cost of designing	Medium	Medium	High

CHAPTER 5

SIMULATION RESULTS AND DISCUSSIONS

5.1 Introduction

In this chapter, three devices namely (IPFC, UPFC and BTB-HVDC) will be simulated and the results will be compared to each other. These devices will be added to two different example power systems, these systems are Kundur 2-Area power system [71] and IEEE 2-Area 9bus power system [65].

At first, these devices are applied to Kundur system then applied to IEEE 9bus system. A fault is 3-phase to the ground which subjected to each power system at specific time duration and the changes are monitored that occurred for each device separately in both of local area and inter-area modes. The conducted results will be clarified the nature of control for these devices and the ability of these devices. This study is helpful to specify and to know which device is better to damp the oscillation that leads to enhance power system stability and to transfer power through transmission lines.

5.2 Cases Studies

The main objective of this study of these three devices is to damp out oscillation after an urgent problem that might occur. This chapter presents 16 case studies, as shown below in Table 5.1. These three devices were added to power systems according to the studies of local and inter-area modes for each device and applied to independent grids with equal parameters of these power systems. This study also includes the cases when there no device is applied in the systems. These will be the base cases of the measurements which are obtained, such as bus voltages/phase angles, active /reactive are conducted in the upcoming lines

.

Table 5.1 Case studies.

Power systems	Local oscillation damping	Inter-area oscillation damping
Kundur system (11 bus, 4 machines, 2-Aera)	NO DEVICE	NO DEVICE
	IPFC	IPFC
	UPFC	UPFC
	BTB-HVDC	BTB-HVDC
IEEE system (9 bus, 3 machines, 2-Area)	NO DEVICE	NO DEVICE
	IPFC	IPFC
	UPFC	UPFC
	BTB-HVDC	BTB-HVDC

5.2.1 Overview of Kundur System

In order to be able to study the abilities of these devices and to investigate their operational characteristics. Kundur system was used. Kundur system was used to detect low-frequency oscillations that were involved in power systems. Kundur system emulates almost the actual operation of the typical power system [66]. Kundur system contains two similar areas connected to each other by three 220km/230kV transmission lines. Each zone has two thermal generators rated of 18kV/1000 MVA with total power production about 800MVA [72]. The synchronous machines have equal parameters. The total load is 2750MW. This load is divided between the areas in such a way that allows 263MW of power to be transferred from area 1 to area 2 as shown in Figure 5.1. The proposed study shows an applying of three devices IPFC, UPFC and BTB-HVDC between bus No. 8 and bus No. 9, the fact that the location is considered to be a better place to detect low-frequency oscillation due to it is a weak region. This place connects to the two regions with a distance of 110 km for both sides [35,67,68,69].

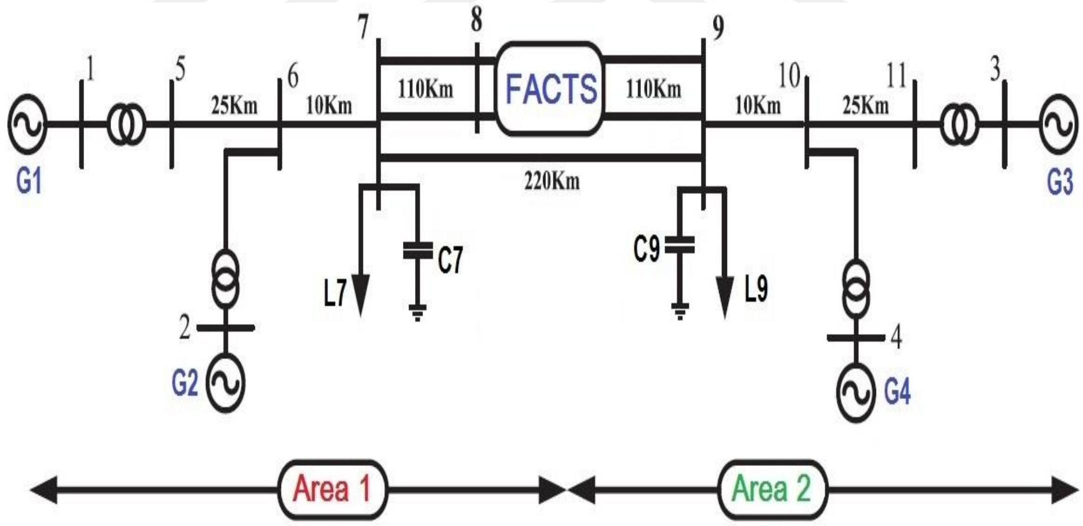

Figure 5.1 Kundur system [66].

Application of Kundur grid is as a base system of the simulation study. The proposed grid can be used to check the performance of each device. Figure 5.2 represents the simulation model of Kundur system as a base case. Figure 5.3, Figure 5.4, and Figure 5.5 represent the simulation model of Kundur system with UPFC, IPFC and BTB-HVDC inserted respectively and comparing the results of each device separately.

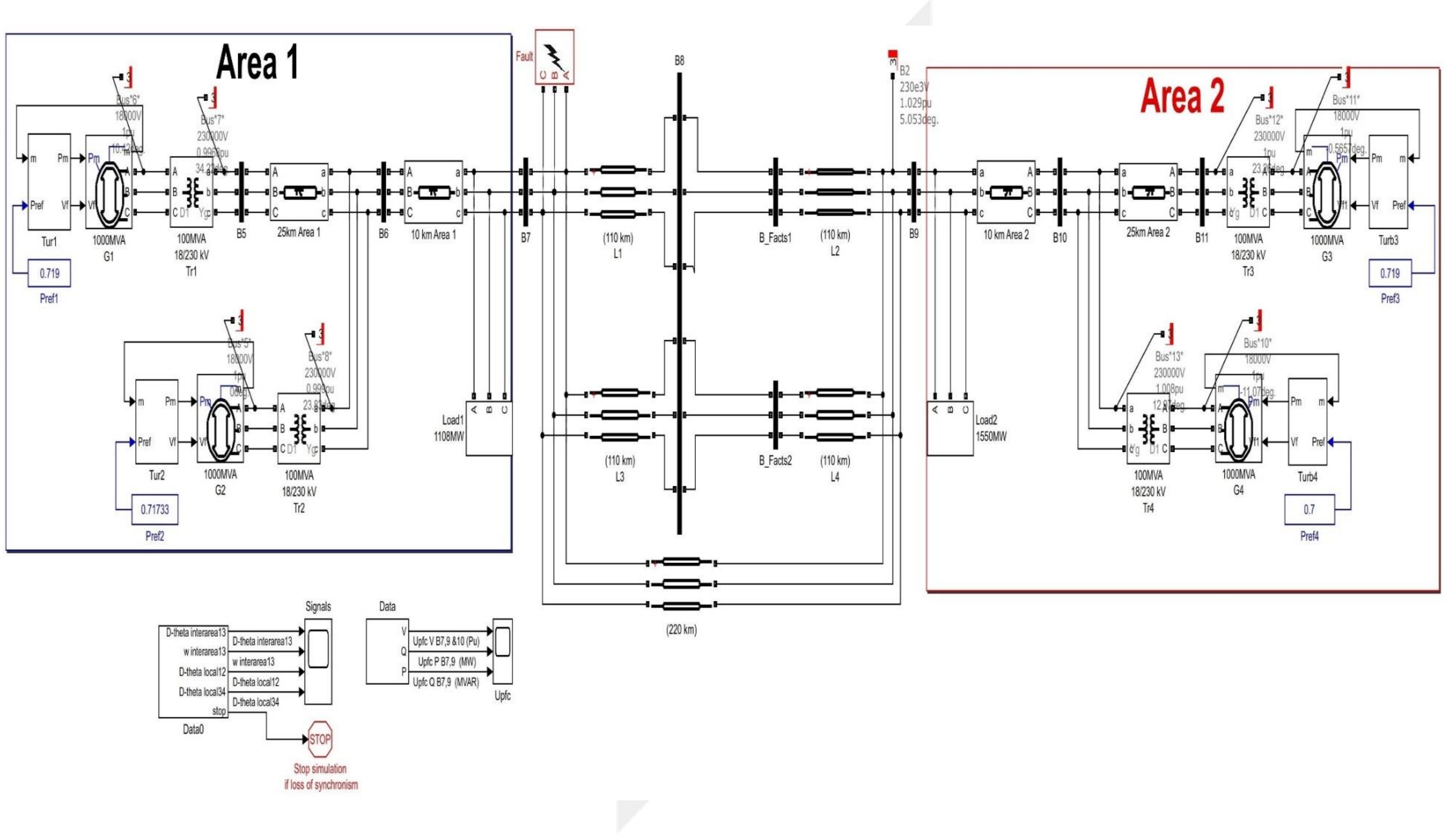

Figure 5.2 Simulation model of Kundur system as base case.

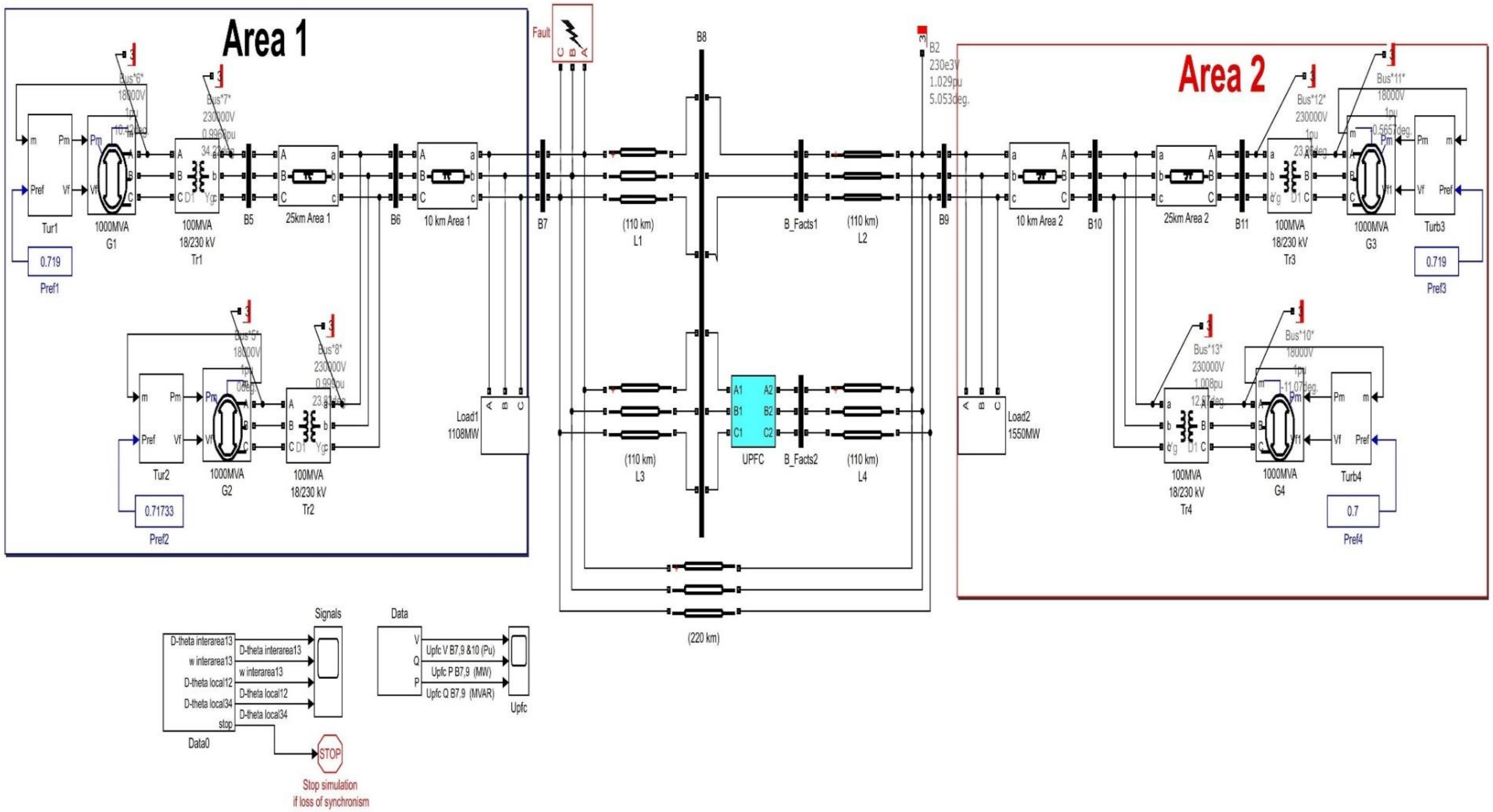

Figure 5.3 Simulation model of Kundur power system with UPFC inserted.

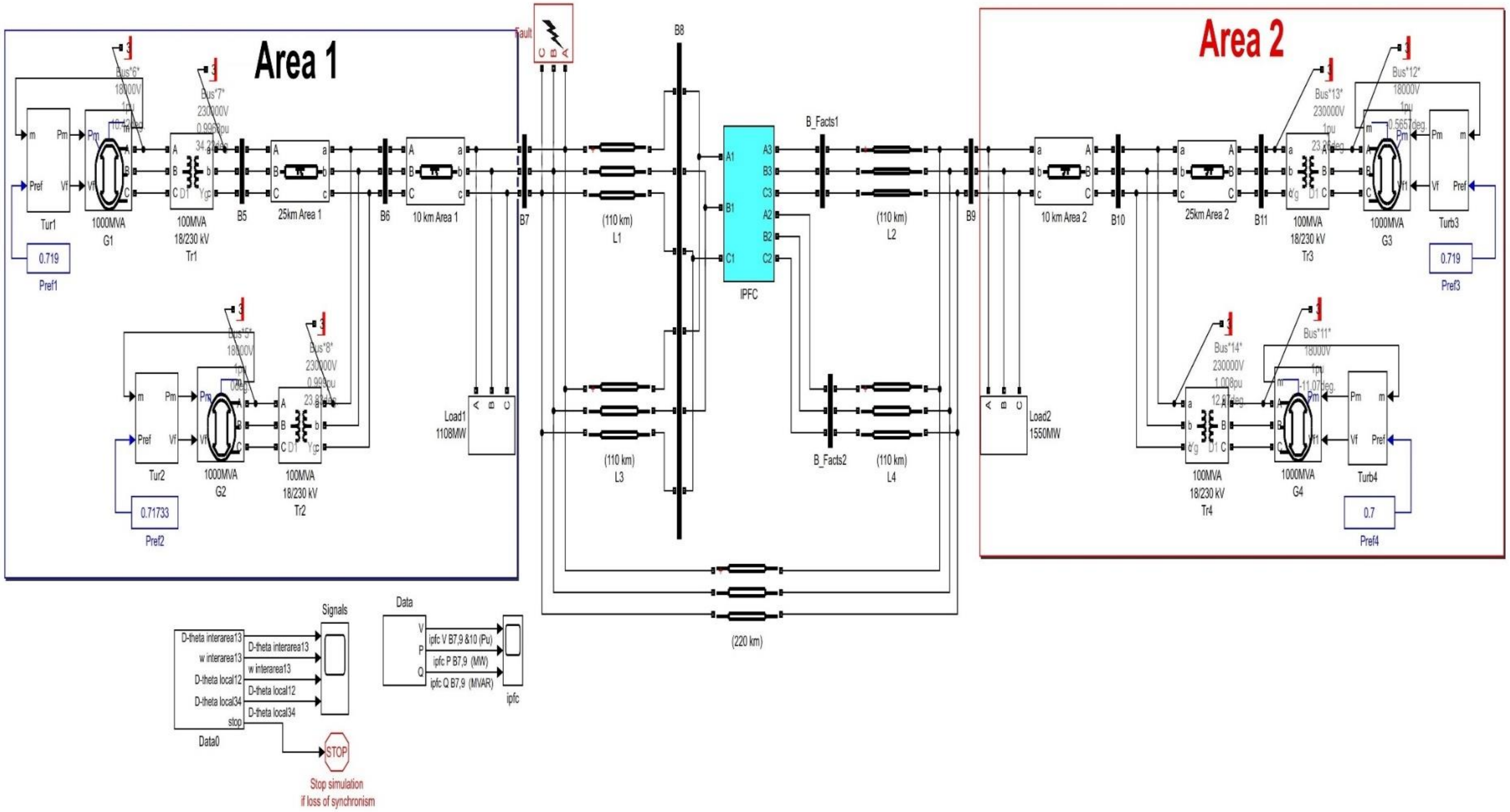

Figure 5.4 Simulation model of Kundur power system with IPFC inserted.4

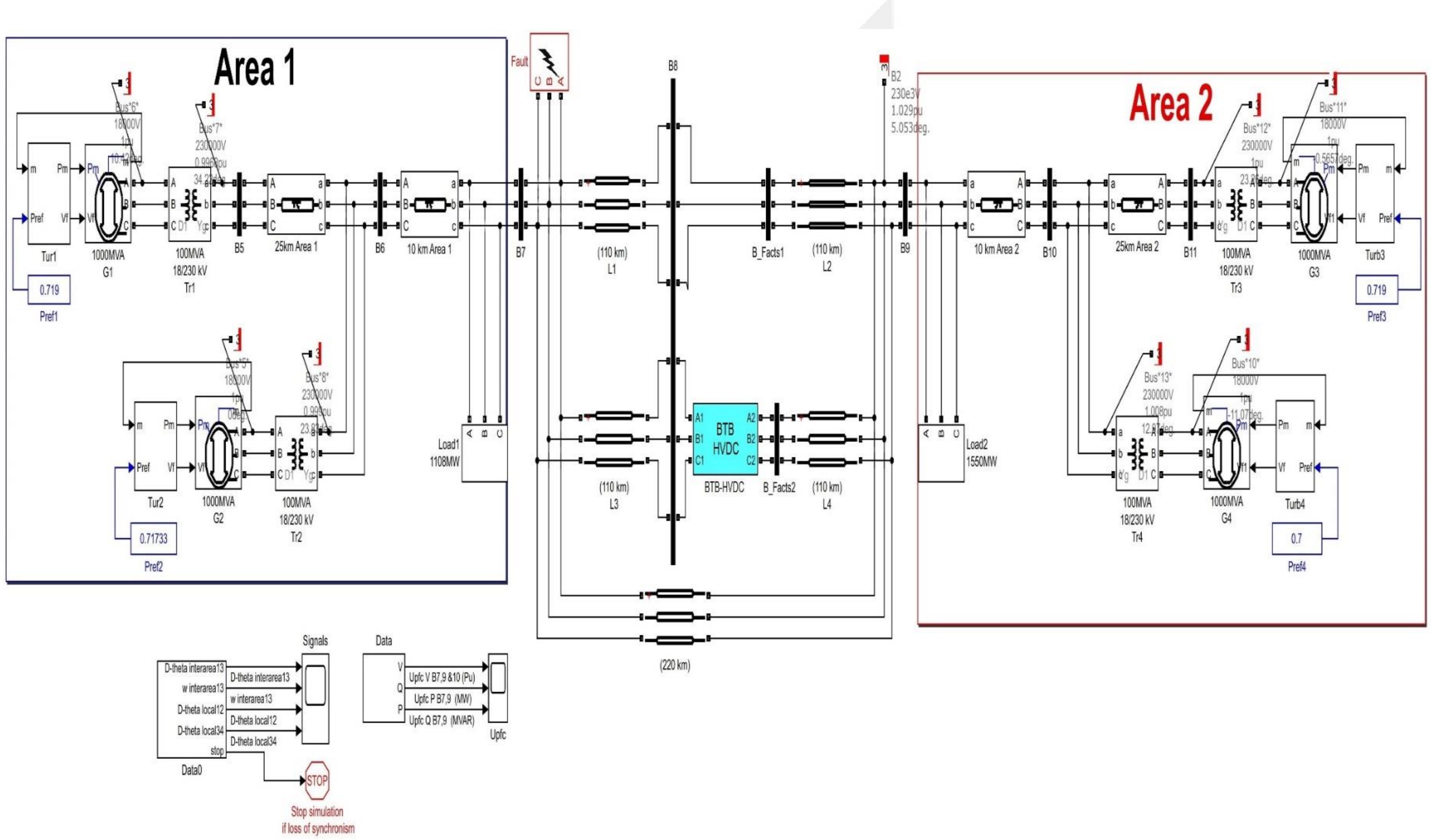

Figure 5.5 Simulation model of Kundur power system with BTB-HVDC inserted.

5.2.1.1 Local Oscillation Damping Studies in Kundur System

The work of electrical system during operation is exposed to many problems that directly affecting the stability and reliability of the system such as low-frequencies, sudden problems of the system and fluctuation of voltages in a harmful manner, etc. One of these oscillations is local oscillation. Local oscillations are occurred when the generator in a specific region oscillates with a system in the same area. These oscillations include sudden changes that occurred in the system such as a short circuit or load outages [73]. In this section, the oscillation analysis is going to be presented when three devices are added to Kundur system to perform the oscillations damping study.

The main feature of this local mode is low-frequency oscillation which ranges between (1.0-2.0) Hz in one area only. Later, three devices IPFC, UPFC and BTB-HVDC are added to Kundur power system to form three cases of study and compared with no device as a base case. The comparison of these cases has been accomplished and the fourth one was investigated without the device. The four systems are subjected to a 3-phase fault to ground at a specific time and the changes monitored that occur in these systems in all cases, to compare the performance of each device among them. The measurements are collected for two areas of Kundur system. For example, the first area of all cases, the simulation results for each system have used the parameters rotor mechanical angle (*theta*), generator power active (P_a) and generator rotor speed (ω) The same work also applies to the second area due to Kundur symmetrical configuration.

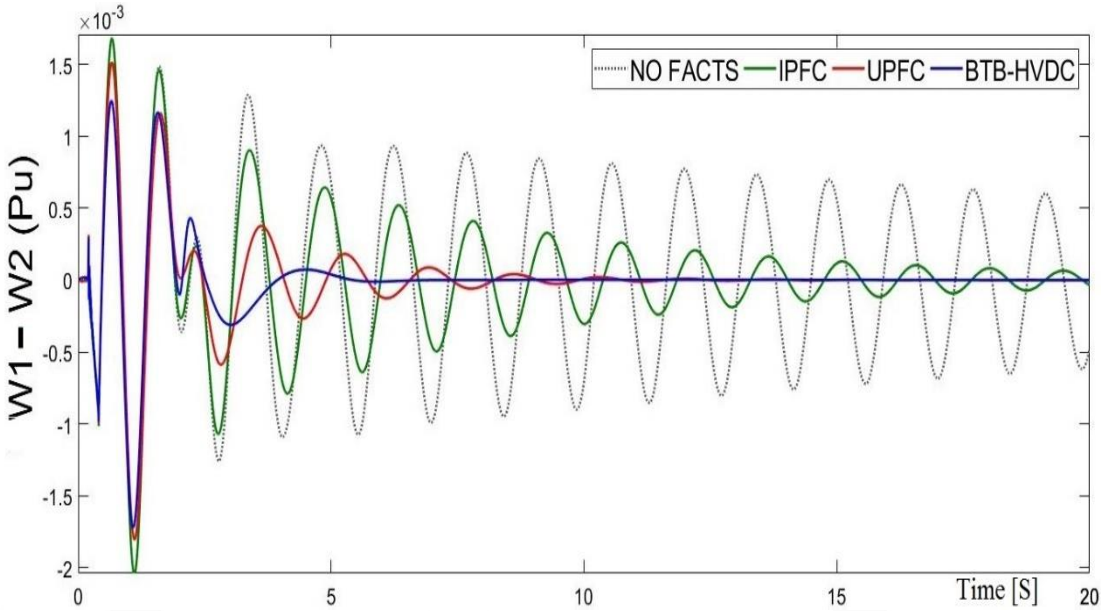

Figure 5.6 Rotor speed of generator 1 against generator 2.

The blue line represents the BTB-HVDC's case, the red line represents the case of UPFC, the green line represents the case of IPFC and the black line represents the case without device as shown in Figure 5.6. This description applies to all figures in this section later.

Figure 5.6 explains the difference between the rotor speed of generator 1 (ω_1) and the rotor speed of generator 2 (ω_2) in the first area of Kundur system for all cases. The values of all cases show zero pu, due to all parameters are 1 pu and when these values are subtracted from each other, the value is almost zero. The values of generator rotor speed are directly affected by the oscillations after occurring the fault at 0.4 sec and these oscillations continue in the system for a period of time, about 20 sec. The value without device observes high oscillation and clarifies unstable of the system, unlike the rest. The blue curve (representing BTB-HVDC device) shows a better damping of oscillation than the other curves after a time of 0.4 sec. As for the UPFC and IPFC, which are worked to eliminate the oscillations with different rates.

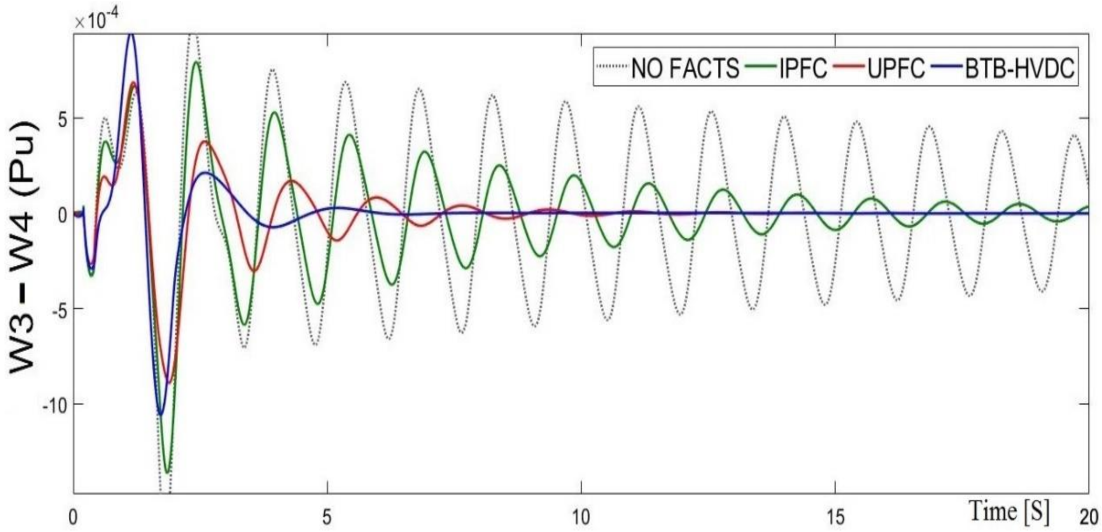

Figure 5.7 Rotor speed of generator 3 against generator 4.

Figure 5.7 shows the dissimilarity between the rotor speed of generator 3 (ω_3) and the rotor speed of generator 4 (ω_4) in the second area of Kundur system. The values are almost zero pu because of all parameters are 1 pu and when these values are subtracted from each other, the result is almost zero per the curve. The fault is inserted into Kundur system at 0.4 sec.

The values of generator rotor speed are directly influenced by the oscillations and these oscillations continue in the system for a period of time, about 20 sec. The curve of BTB-HVDC (blue) illustrates a better way of oscillation damping than the other curves after a period of 0.4 sec, but the value without device is observed by high oscillation which clarifies unstable of the system. These oscillations in power system affect solid mechanics of rotor dynamics that cause damage to those systems.

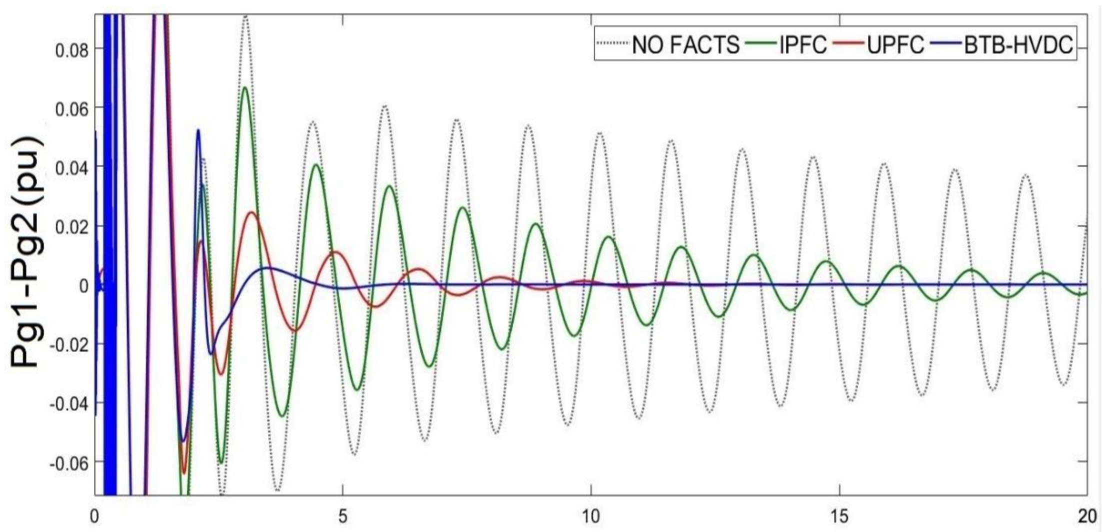

Figure 5.8 Active power flow generator 1 against generator 2.

Figure 5.8 illustrates the difference between the active power of generator 1 (P_{g1}) and generator 2 (P_{g2}) in the first area of Kundur system for all cases of study. The values of all cases show zero pu, due to all parameters are 1 pu and when these values are subtracted from each other, the value is almost zero.

The values of active power generator are directly affected by the oscillations after occurring the fault at 0.4 sec and these oscillations continue in the system for a period of time, about 20 sec. The value without device is observed by high oscillation which clarifies unstable of the system, unlike the rest. The blue curve (representing BTB-HVDC device) shows a better damping of oscillation than the other curves after a period of 0.4 sec.

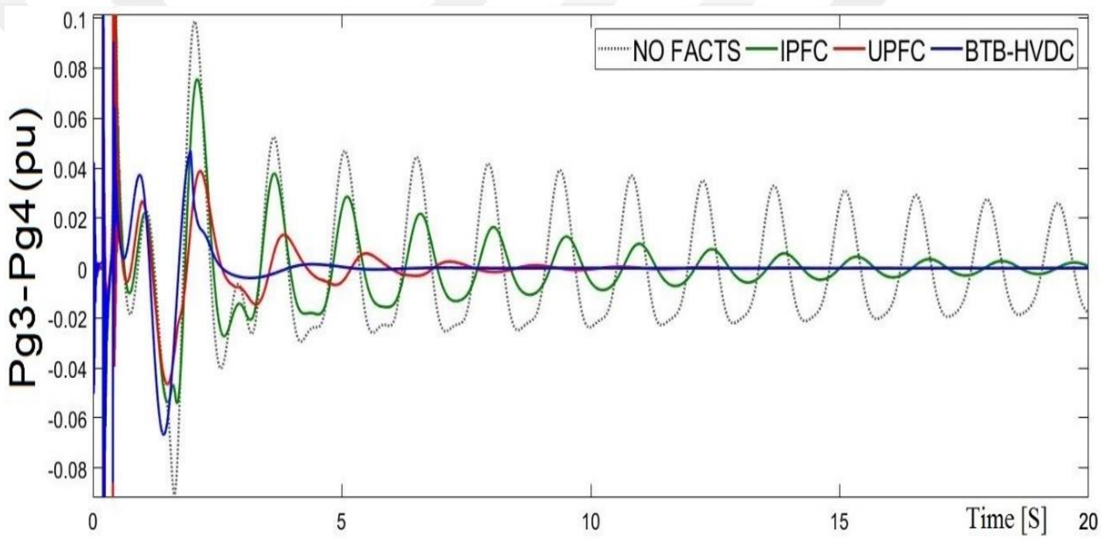

Figure 5.9 Active power flow generator 3 against generator 4.

Figure 5.9 shows the difference between the active power of generator 3 (P_{g3}) and generator 4 (P_{g4}) in the second area of Kundur system for all cases of study. The values are almost zero pu because of all parameters are 1 pu and when these values are subtracted from each other, the result is almost zero per the curve.

When the fault is inserted into Kundur system at 0.4 sec, the values of active power of generator are directly affected by the oscillations and these oscillations continue in the system for a period of time, about 20 sec. The curve of BTB-HVDC (blue) shows a better damping of oscillation than the other curves after a time of 0.4 sec, but the value of without device is observed by high oscillation which clarifies unstable of the system. For UPFC and IPFC, which also eliminates oscillations with different rates.

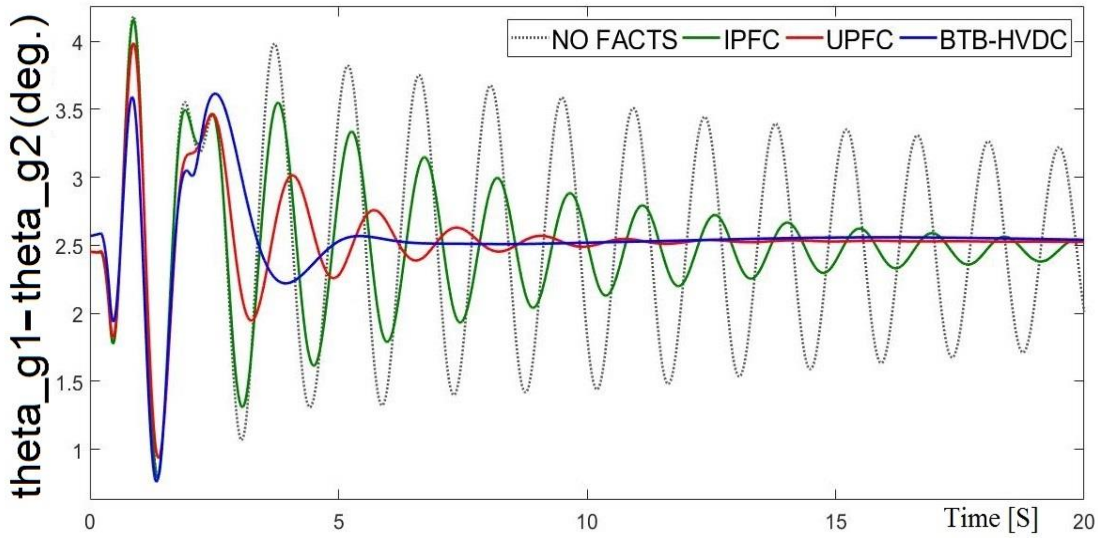

Figure 5.10 Rotor mechanical angle of generator 1 against generator 2.

Figure 5.10 describes the difference between the rotor mechanical angle of the first generator ($theta_{g1}$) and the rotor angle of the second generator ($theta_{g2}$) in the first area of Kundur system for all cases of study.

The values swing around 4 deg to 0 deg, where the black curve is shown high oscillations because the system does not have any device. These oscillations indicate an unstable system after applying the fault at t= 0.4 sec which is continuous during the time period from 0.4 - 20 sec. The curve of BTB-HVDC (blue) shows a better damping of oscillation than the other curves after a period of 0.4 sec, unlike the black curve (which is representing the case of without device).

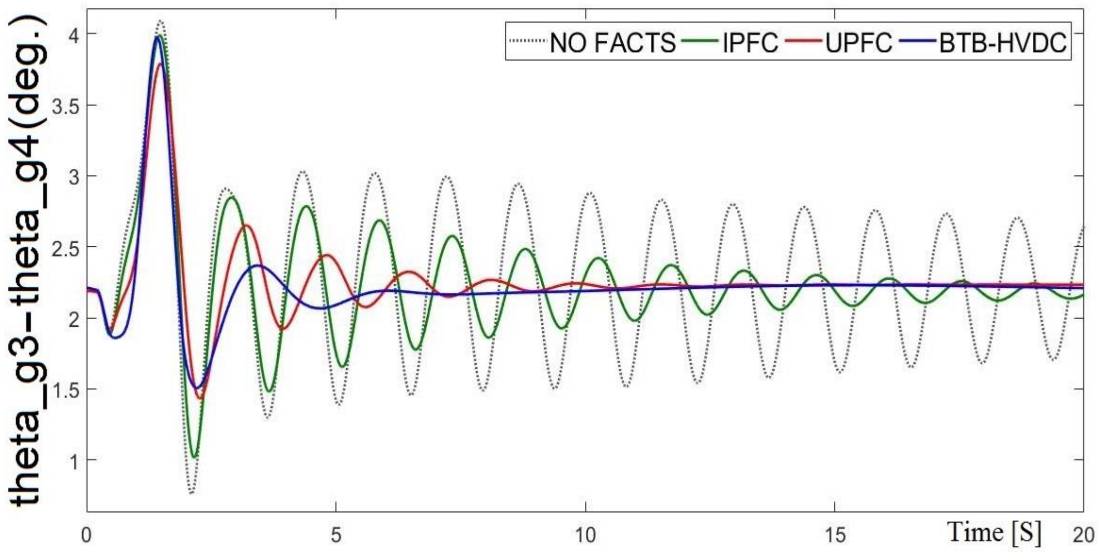

Figure 5.11 Rotor mechanical angle of generator 3 against generator 4.

Figure 5.11 explains the difference between the rotor mechanical angle of the third generator ($theta_{g3}$) and the rotor angle of the fourth generator ($theta_{g4}$) in the second area of Kundur system for all cases of study.

Where all curves start with the fault at 0.4 sec to swing unusually, but the damping of these oscillations appears gradually after the BTB-HVDC, IPFC and UPFC controllers begin operation except the black curve that represented without adding any device to Kundur system. This oscillation of black curve indicates an unstable system after applying the fault which is continuous during the time period from 0.4-20 sec, so damping with a sufficient controller is required. The BTB-HVDC controller successfully damped these oscillations (which represents the blue curve) and the settling time is around 5 second as shown in Figure 5.11, unlike the other curves.

5.2.1.2 Inter-Area Oscillation Damping Studies in Kundur System

Inter-area oscillations of power system grids are a coherent phenomenon. These oscillations can be observed after any emergency problem occurs. These oscillations have occurred between a group of generators which are distributed over more than one location that interconnected in the transmission grid. These oscillations have a frequency range between 0.2 to 0.8 Hz.

This part of the study presents of an inter-area oscillation in four cases according to Table 5.1. IPFC, UPFC and BTB-HVDC are added to Kundur power system individually. These devices are added between bus No. 7 and bus No. 9. The comparison of these cases has been accomplished with a Kundur system. The four cases are subjected to a fault that is 3-phase to the ground at a specific time and the changes are observed oscillations for all grids, this comparison is useful to analyse the performance of these devices in damping out local and inter-area oscillations.

The readings are collected for all cases, for example, the parameters result of active/reactive power, voltage of the line, and also the rotor mechanical angle (*theta*) and generator rotor speed (ω) for generator 1 versus generator 3 as shown in Figure 5.12, Figure 5.13, Figure 5.14, Figure 5.15 and Figure 5.16.

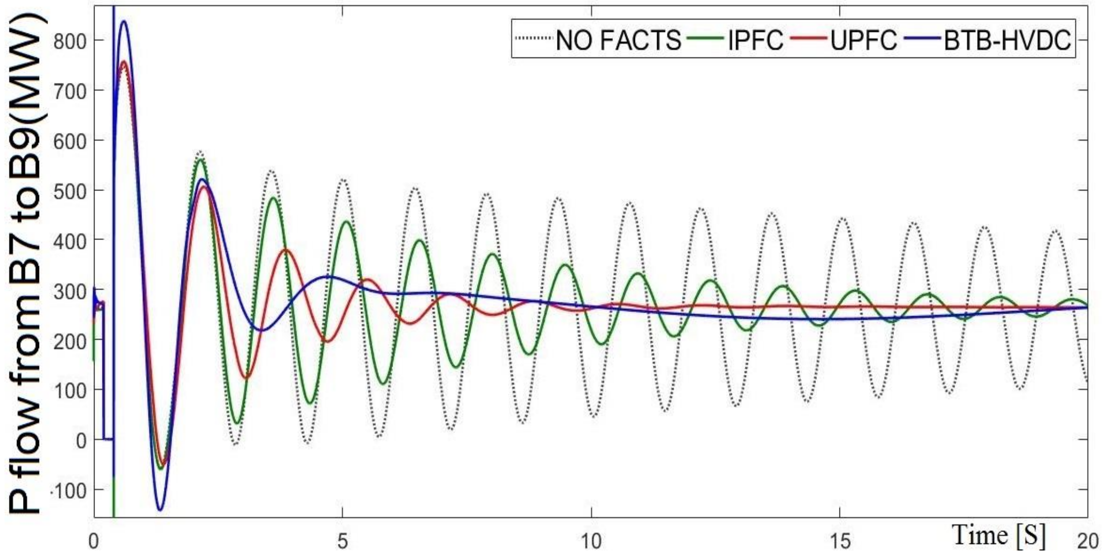

Figure 5.12 Active power flow from B7 to B9.

The black line represents the case of without the device, the green line represents the case of IPFC, the red line represents the case of UPFC and the blue line represents the case of BTB-HVDC as shown in Figure 5.12. This description applies to all figures in this section later. Figure 5.12 illustrates the active power flow (P) between bus No. 7 and bus No. 9 for all cases of study.

This study represents the inter-area mode that is located between the area 1 and the area 2 in Kundur system. The values of active power flow are directly affected by the oscillations after occurring the fault at 0.4 sec and these oscillations continue in the system for a period of time, about 20 sec. The maximum value of the power flow reaches around 800 MW to -90 MW. The value of without the device is observed by high oscillation which clarifies unstable of the system, unlike the rest of the curves. The blue curve (representing BTB-HVDC device) shows a better damping of oscillation than the other curves after a period of 0.4 sec. As for the UPFC and IPFC accomplished to eliminate the oscillations, but they are less than BTB-HVDC.

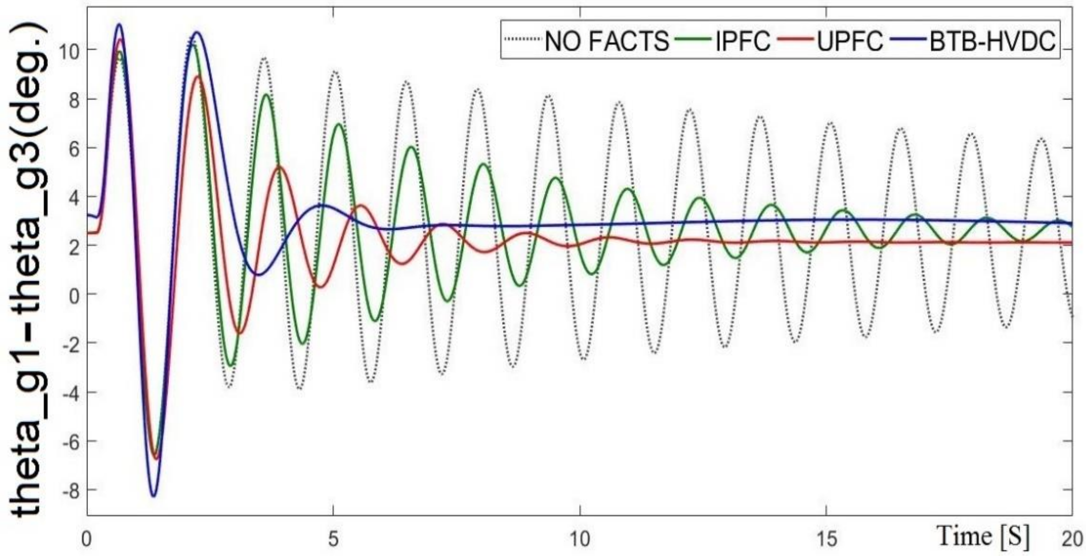

Figure 5.13 Rotor mechanical angle of generator 1 against generator 3.

Figure 5.13 clarifies the difference between the rotor mechanical angle of the first generator1 ($theta_{g1}$) in the first area and the rotor mechanical angle of the third generator3 ($theta_{g3}$) in the second area of Kundur system.

Where all curves start with the fault at 0.4 sec to swing unusually, but the damping of these oscillations gradually appears after the BTB-HVDC, IPFC and UPFC controllers begin operation except the black curve that representing without adding any device to Kundur system. This oscillation of black curve indicates an unstable system after applying the fault which is continuous during the time period from 0.4-20 sec, so damping with a sufficient controller is required.

The BTB-HVDC controller successfully damped these oscillations (which represents the blue curve) and the settling time is around 5 second as shown in Figure 5.11, unlike the rest of the other curves. For UPFC and IPFC, which also operating to eliminate the oscillations with different rates.

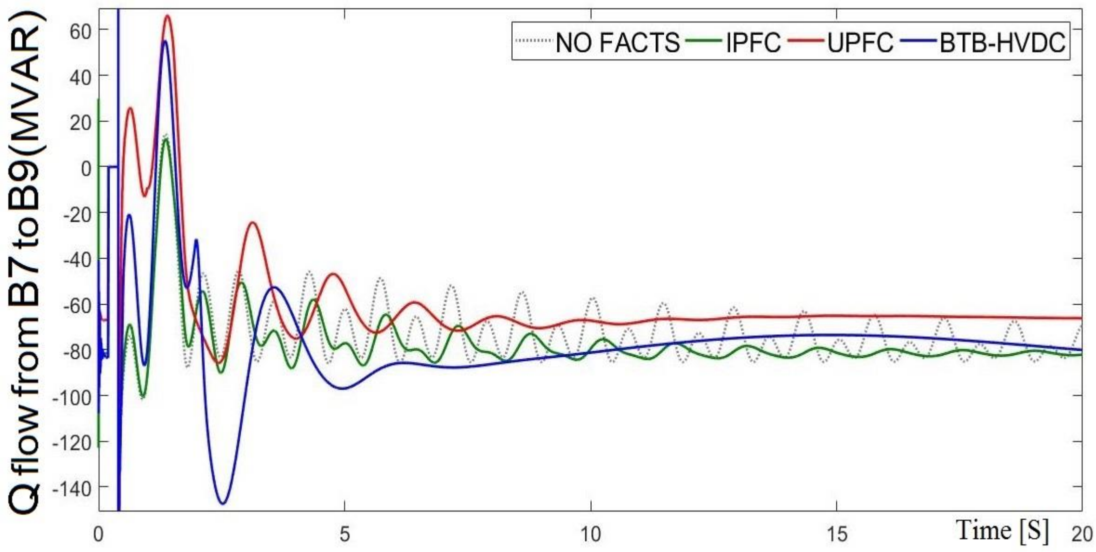

Figure 5.14 Reactive power flow from B7 to B9.

Figure 5.14 the comparison of reactive power flow Q between bus No. 7 and bus No. 9. This case explains the inter-area mode that is located between the area 1 and the area 2 in Kundur system.

After the fault at 0.4 sec, the dotted curve shows a lot of oscillation which might damage the system. The maximum value of the reactive power flow reaches around 60 $MVAR$ to -140 $MVAR$ as shown in Figure 5.14. The oscillations are reduced in different ratings with the rest cases to reach a better result of damping by adding IPFC, UPFC and BTB_HVDC devices to independent of Kundur system. The BTB-HVDC controller successfully damped these oscillations and the settling time is around 5 sec, as shown in Figure 5.14.

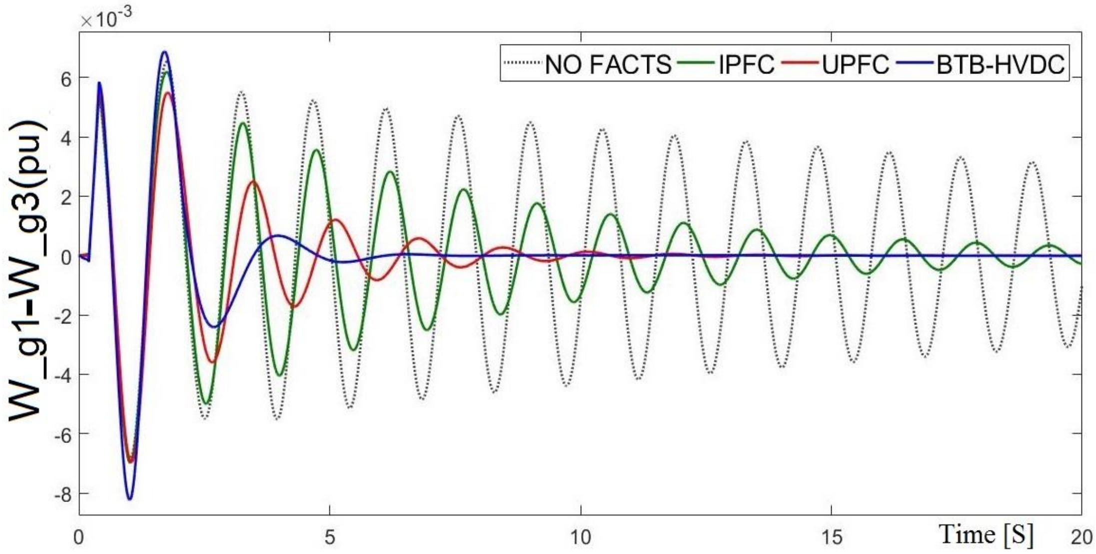

Figure 5.15 Rotor speed of generator1 against generator3.

Figure 5.15 shows the difference between the rotor speed of the first generator (ω_{g1}) in the first area compared to the rotor speed of the third generator (ω_{g3}) in the second area of Kundur system for all cases. The values are almost zero pu because of all parameters are 1 pu and when these values are subtracted from each other, the result is almost zero per the curve.

When the fault is inserted into Kundur system at 0.4 sec, the values of generator rotor speed are directly affected by the oscillations and these oscillations continue in the system for a period of time, about 20 sec. The curve of BTB-HVDC (blue) shows a better damping of oscillation than the other curves after a time of 5 sec, but the value without device is observed by high oscillation which clarifies unstable of the system. These oscillations in power system affect solid mechanics of rotor dynamics that causing damage to those systems. As for the UPFC and IPFC achieved to eliminate the oscillations with different rates.

5.2.2 Overview of IEEE 9-Bus System

IEEE 9-Bus system is a grid utilized for testing with a total number of buses. These buses are connected with the transmission lines and a total of three generators [65]. This system has two areas. The first area has three buses, one thermal generator rated of 16.5kV/350MVA and one 100km/230kV transmission line, while the second area has five buses, two thermal generators (the first generator is rated 13.8kV/350MVA and the second generator is rated of 18kV/350MVA) and three 100km/230kV transmission lines. The synchronous machines have equal parameters for turbine and excitation systems.

The total load is 316MW. This load is divided between the areas in such a way that allowing the load No.1 takes 31MW of the first area and 91MW of the second area so that total load 122MW. While the load No.2 takes 70MW of generator No.2 and 29MW of generator No.3 in the same area so that total load 99MW. Finally, the load No.3 takes 54MW of the second area and 35MW of the first area so that total load 89MW as shown in Figure 5.16. UPFC, IPFC and BTB-HVDC devices will be placed on the bus No. 5 which is located between bus No. 7 and bus No. 4 due to it is a neutral area useful for comparison [71,72,73].

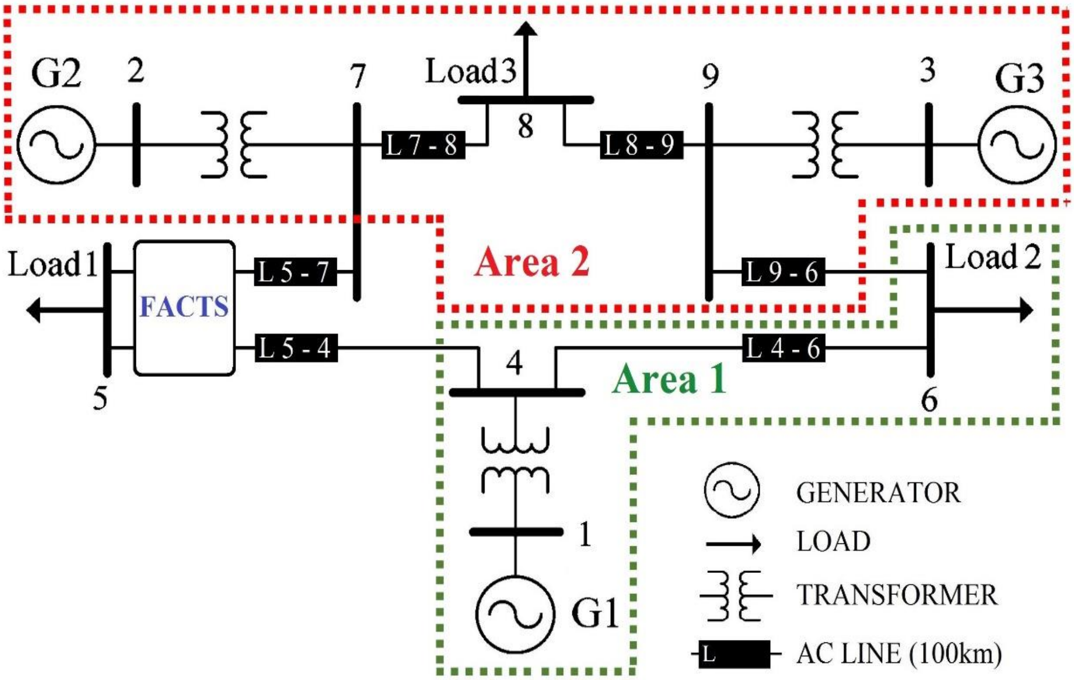

Figure 5.16 IEEE 9-Bus system [65].

Application of IEEE 9-Bus grid is as a base system of this study. The proposed grid is used to check the performance of each device (IPFC, UPFC and BTB-HVDC) when running the grids. The Figure 5.17, Figure 5.18, Figure 5.19, Figure 5.20 represents the application for these devices and compares the results of each device separately

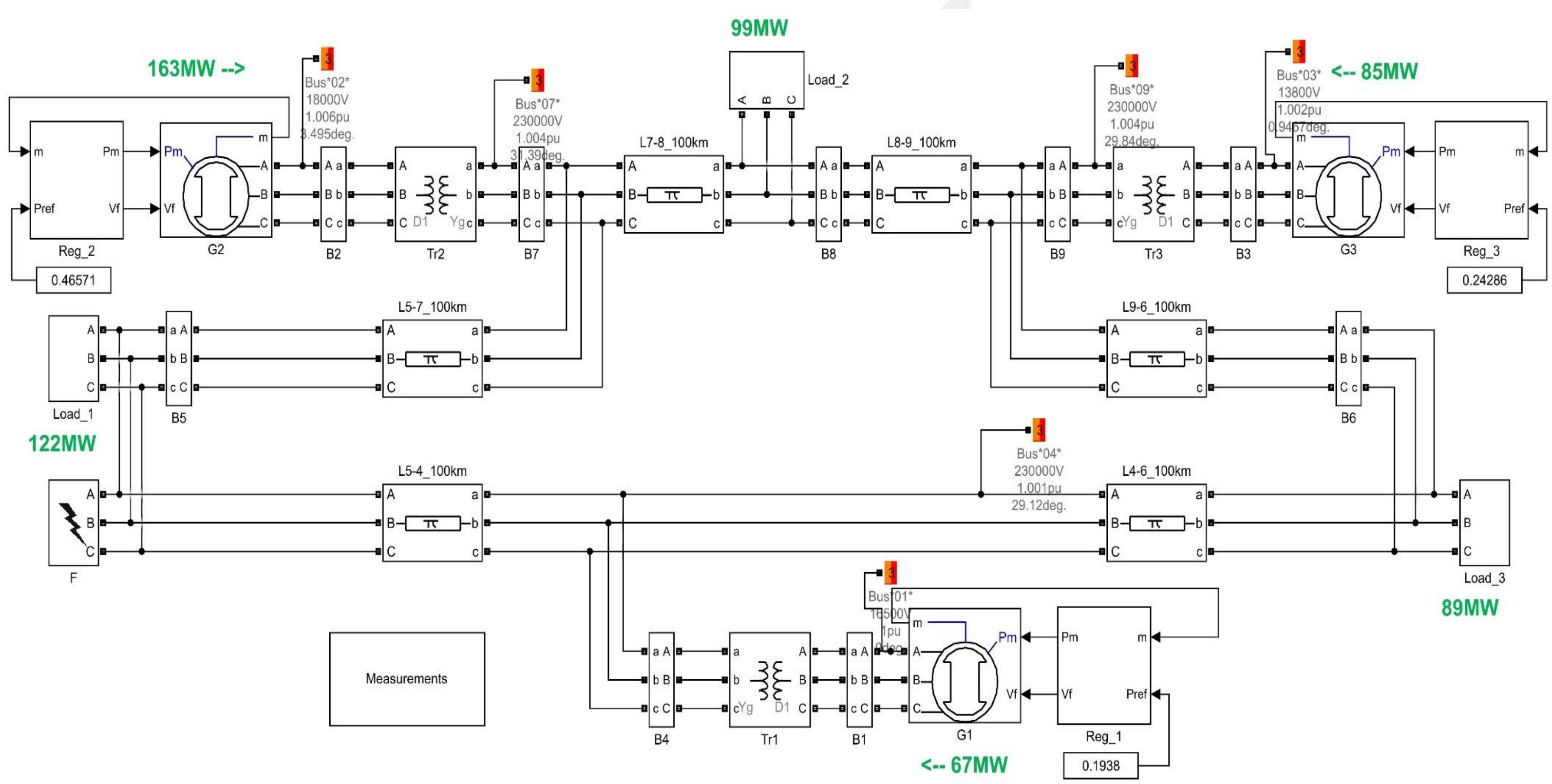

Figure 5.17 Simulation model of IEEE 9-Bus power system as base case.

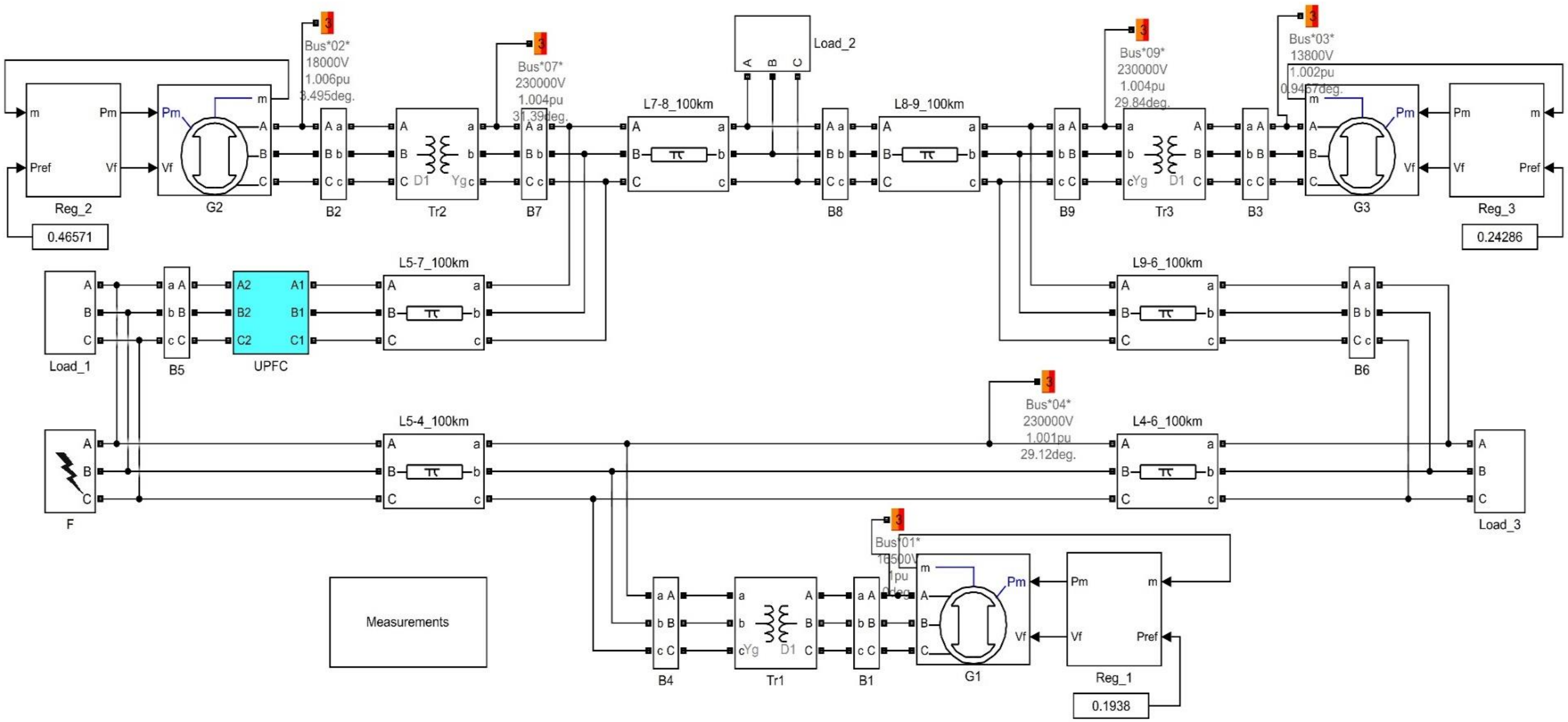

Figure 5.18 Simulation model of IEEE 9- Bus power system with UPFC inserted.

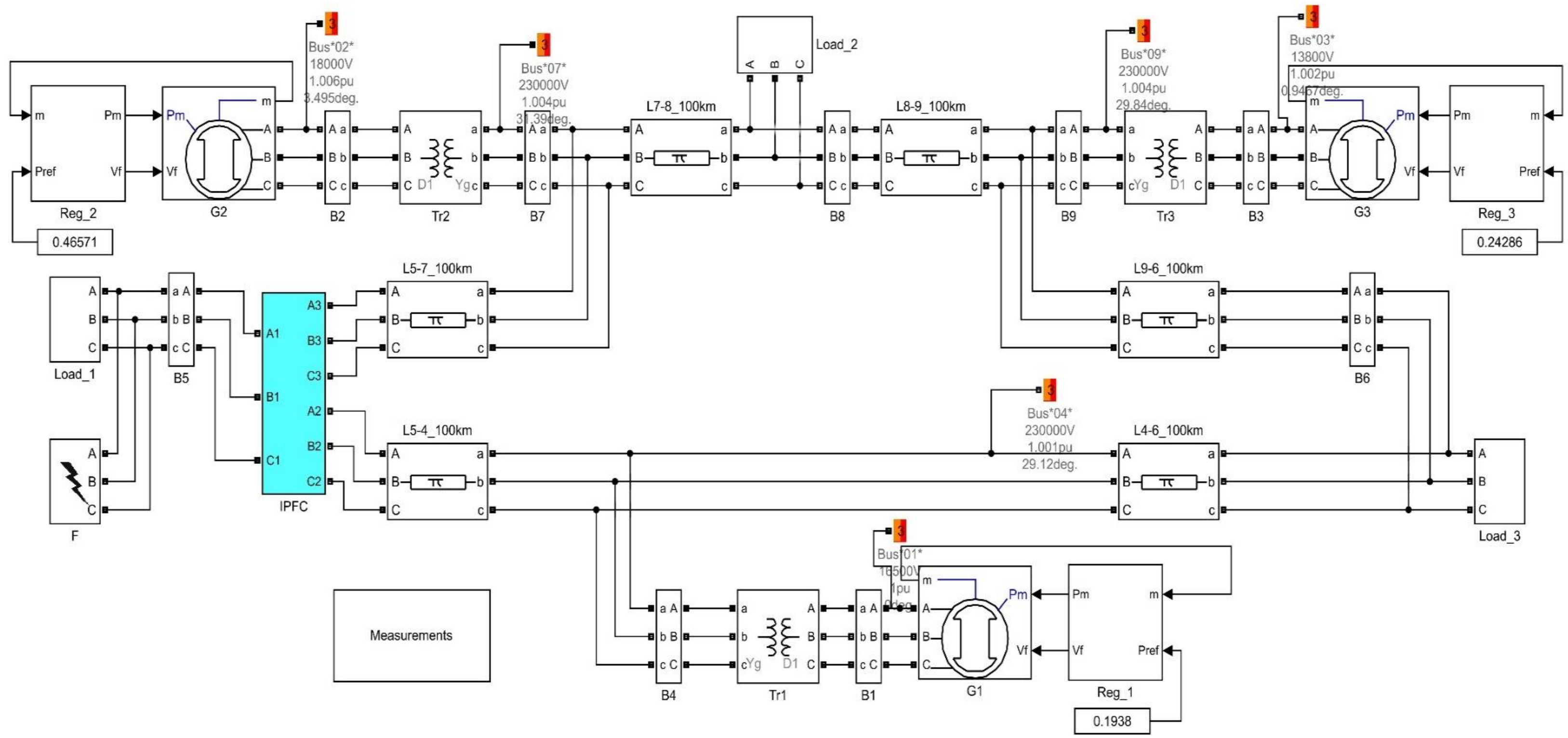

Figure 5.19 Simulation model of IEEE 9-Bus power system with IPFC inserted.

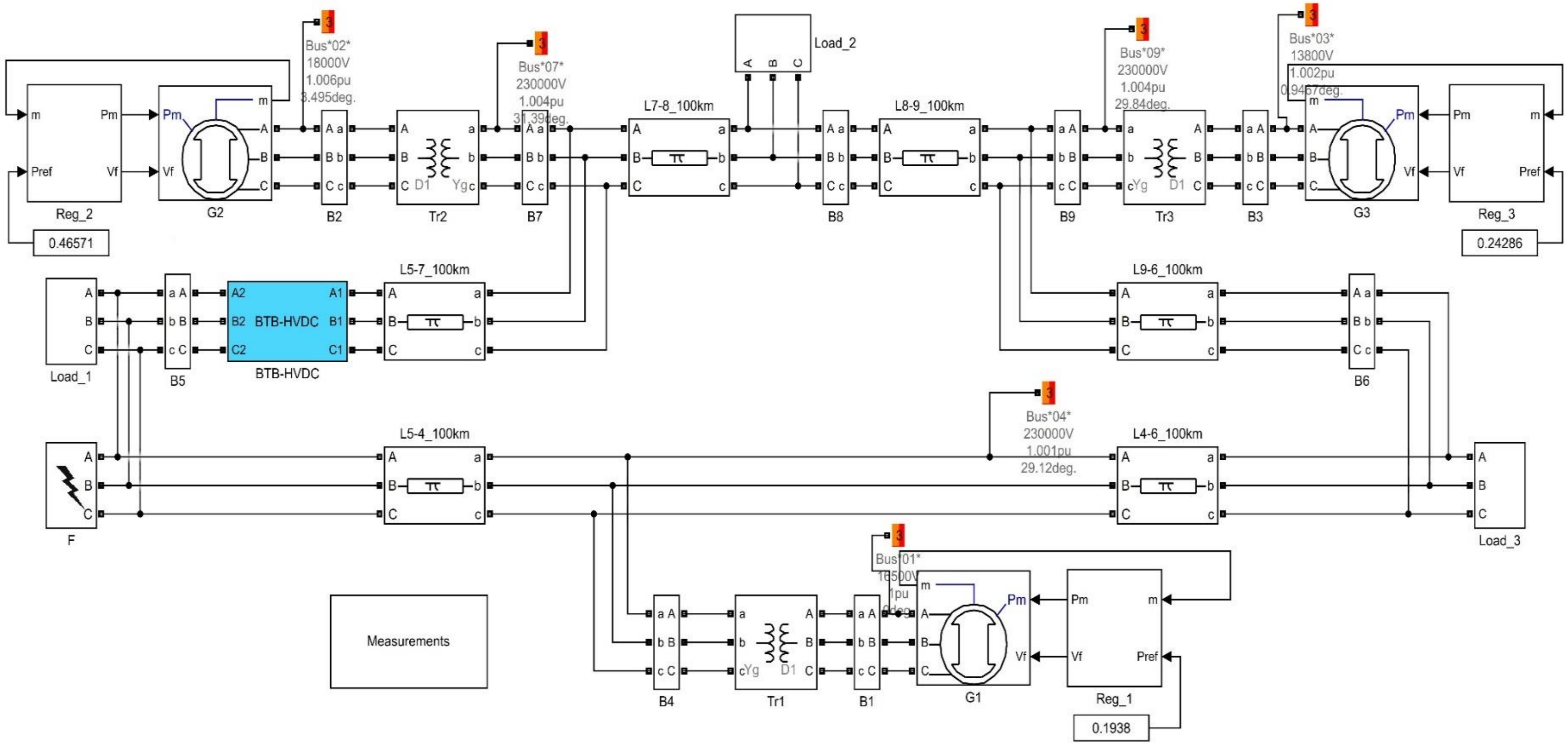

Figure 5.20 Simulation model of IEEE 9-Bus power system with BTB-HVDC inserted.

5.2.2.1 Local Oscillation Damping Studies in IEEE 9-Bus System

The power systems face many problems that directly affecting the stability and reliability of the system such as local oscillation. These oscillations are occurred between one generator and another generator in the same area. This part of the research focuses on the analysis of local area oscillations when three devices IPFC, UPFC and BTB-HVDC are added to IEEE 9-bus system independently to perform oscillations damping study [73].

The local area oscillations have frequencies are ranging between (1.0-2.0 Hz) IEEE 9-bus power system is considered as a base system for operation. These three devices are added to this independent power system to create cases of study and these devices are compared with no device as the base case. The comparison of these cases has been accomplished with the one without device to be considered as a fourth case in this section. The four grids are subjected to a fault 3-phase to the ground at a specific time and conduct the results for all grids, in order to compare the performance of these devices among them.

The readings were collected for one area of the IEEE 9-Bus system. The simulation results for system have used the parameters which are rotor mechanical angle ($theta$), generator power active (P_a) and generator rotor speed (ω). The results are only going to be selected from the second area because IEEE 9-Bus is asymmetric in configuration. The first area and the second are not identical, due to the first area contains one generator, but the second area contains two generators as shown in Figure 5.16.

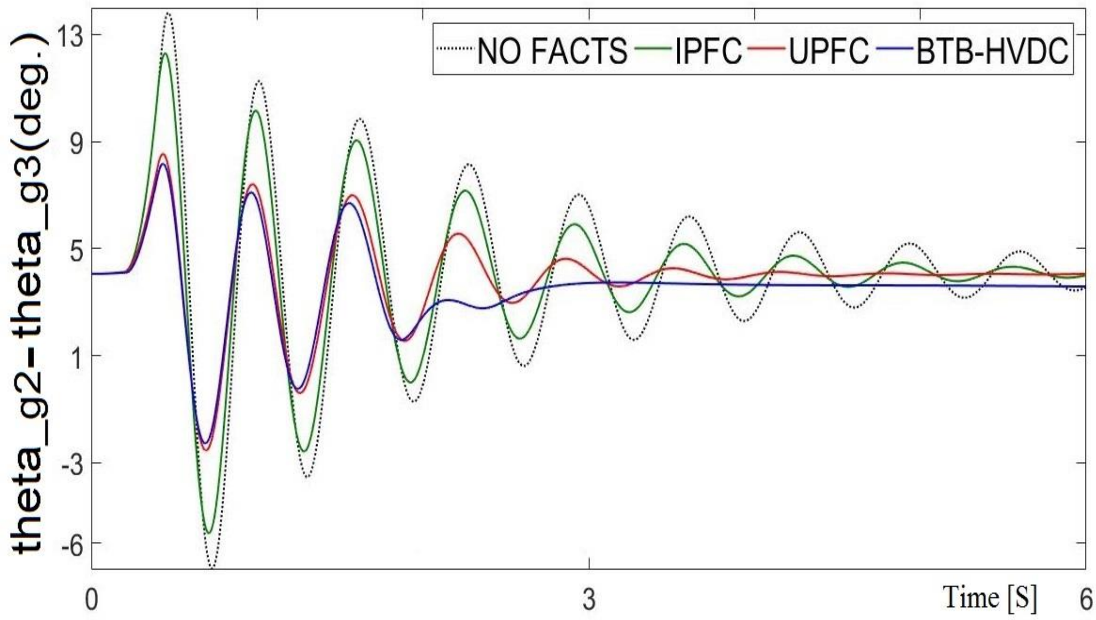

Figure 5.21 Rotor mechanical angle of generator 2 against generator 3.

The blue line represents the case of BTB-HVDC, the red line represents the case of UPFC, the green line represents the case of IPFC and the black line represents the case without device as shown in Figure 5.21. This description applies to all figures in this section later. Figure 5.21 shows the difference between the rotor mechanical angle of the second generator ($theta_{g2}$) and the rotor mechanical angle of the third generator ($theta_{g3}$) in the second area of IEEE 9-Bus system.

The values swing around 13 to -5 deg, where the black curve is shown high oscillations because the system does not have any device. These oscillations indicate an unstable system after applying the fault at t=0.4 sec which is continuous during the time period from 0.4-0.6 sec. The curve of BTB-HVDC (blue) shows a better damping of oscillation than the other curves after a period of 2.5sec, unlike the black curve which represents the case without device.

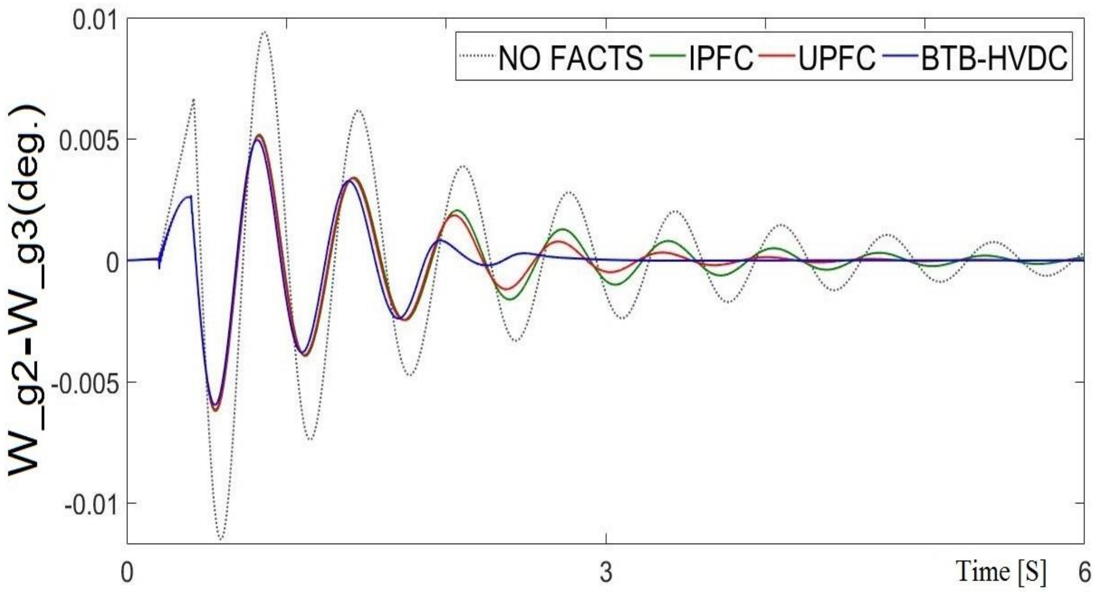

Figure 5.22 Rotor speed of generator 2 against generator 3.

Figure 5.22 explains the difference between the rotor speed values of the second generator (ω_{g2}) with the same parameter of the third generator (ω_{g3}) in the second area of IEEE 9-Bus system. The values of all cases show zero pu, due to all parameters are 1 pu and when these values are subtracted from each other, the value is almost zero.

The values of generator rotor speed are directly affected by the oscillations after occurring the fault at 0.4 sec and these oscillations continue in the system for a period of time, about 6sec. The value without device is observed high oscillation which clarifies unstable of the system, unlike the rest of the curves. The blue curve (representing BTB-HVDC device) shows a better damping of oscillation than the other curves after a time of 2.5 sec.

5.2.2.2 Inter-Area Oscillation Damping Studies in IEEE 9-Bus System

In this section, the observation of inter-area oscillations is going to be clarified in four cases for study according to Table 5.1. Three devices (namely IPFC, UPFC and BTB-HVDC) are applied to an independent system which is IEEE 9-Bus separately. These devices are added between bus No. 7 and bus No. 4 which shown in Figure 5.18, Figure 5.19 and Figure 5.20. After that, the comparison of these cases is completed to the IEEE 9-Bus system without adding any device as shown in Figure 5.17. The four cases are exposed to a fault that is 3-phase to the ground at a specific time and unified for all grids, then any changes are monitored to occur in the power systems to compare the performance of these devices.

The readings are collected between the two areas in the IEEE 9-Bus grid for all cases, the measurements of parameters are taken from the bus 4 towards the area 2 (Bus 5 and Bus 6). For example, the simulation results for each case has used the parameters which are active/reactive power flow (P) and also rotor mechanical angle ($theta$), and generator rotor speed (ω) for generator G_1 versus generator G_2 or generator G_3 to form a difference.

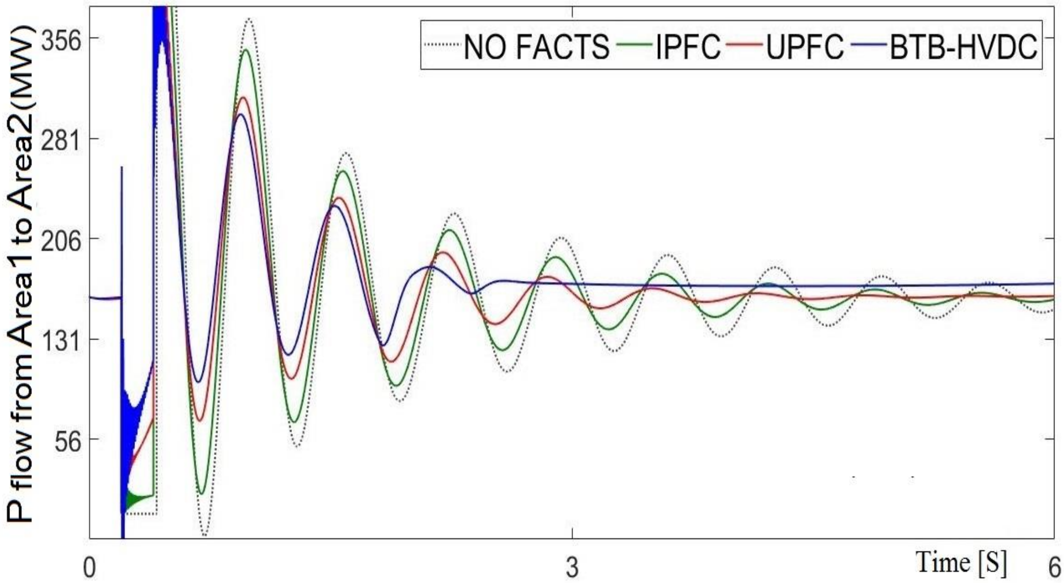

Figure 5.23 Active power flow from area 1 to area 2.

The black line is representing the case without the device, the green line represents the case of IPFC, the red line represents the case of UPFC and the blue line represents the case of BTB-HVDC as shown in Figure 5.23. This description applies to all figures in this section later. Figure 5.23 illustrates the active power flow from the bus 4 (area 1) towards the bus 5 and bus 6 (area 2) for all cases of study.

This study represents the inter-area mode that is located between the area 1 and the area 2 in IEEE 9-Bus system. The values of active power flow are directly affected by the oscillations after occurring the fault at 0.4 sec and these oscillations continue in the system for a period of time, about 6 sec. The maximum value of the power flow reaches around 360 MW to 1 MW. The value without the device is observed high oscillation which clarifies unstable of the system, unlike the rest of the curves. The blue curve (representing BTB-HVDC device) shows a better damping of oscillation than the other curves after a time of 2.5 sec. As for the UPFC and IPFC worked to eliminate the oscillations with different rates.

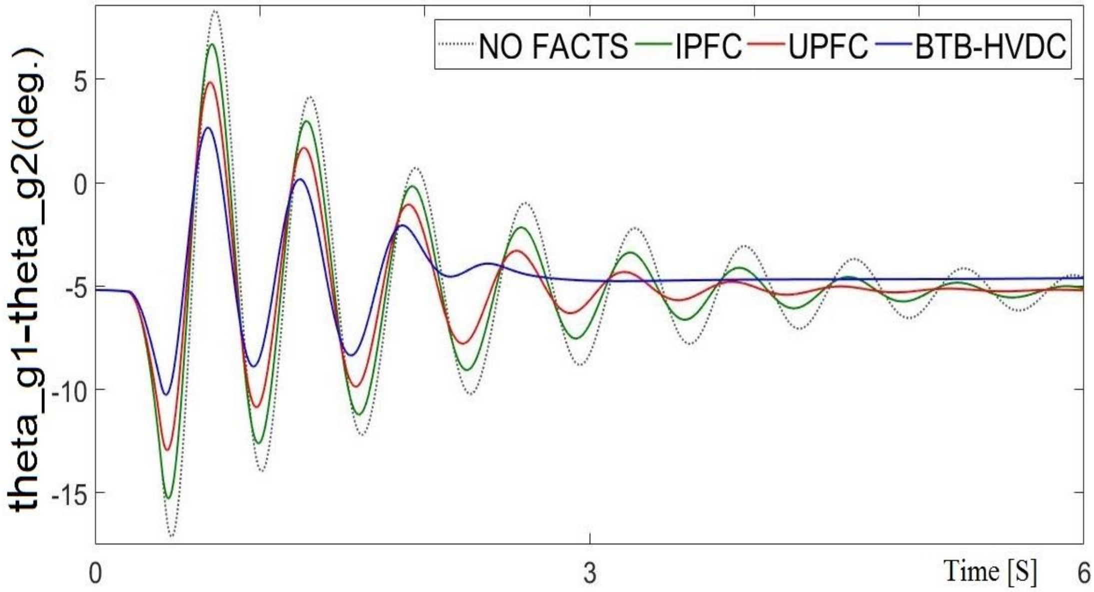

Figure 5.24 Rotor mechanical angle of generator 1 against generator 2.

Figure 5.24 clarifies the difference between the rotor mechanical angle of the first generator ($theta_{g1}$) in the first area and the rotor mechanical angle of the second generator ($theta_{g2}$) in the second area for all cases of study.

Where all curves start with the fault at 0.4 sec to swing unusually, but the damping of these oscillations gradually appears after the BTB-HVDC, IPFC and UPFC controllers begin operation except the black curve that represents without adding any device to Kundur system. This oscillation of black curve indicates an unstable system after applying the fault which is continuous during the time period from 0.4-6 sec, so damping with a sufficient controller is required. The BTB-HVDC controller successfully damped these oscillations (which is representing the blue curve) and the settling time is around 2.5 sec as shown in Figure 5.24, unlike the rest of the other curves. For UPFC and IPFC, which also eliminating oscillations with different rates.

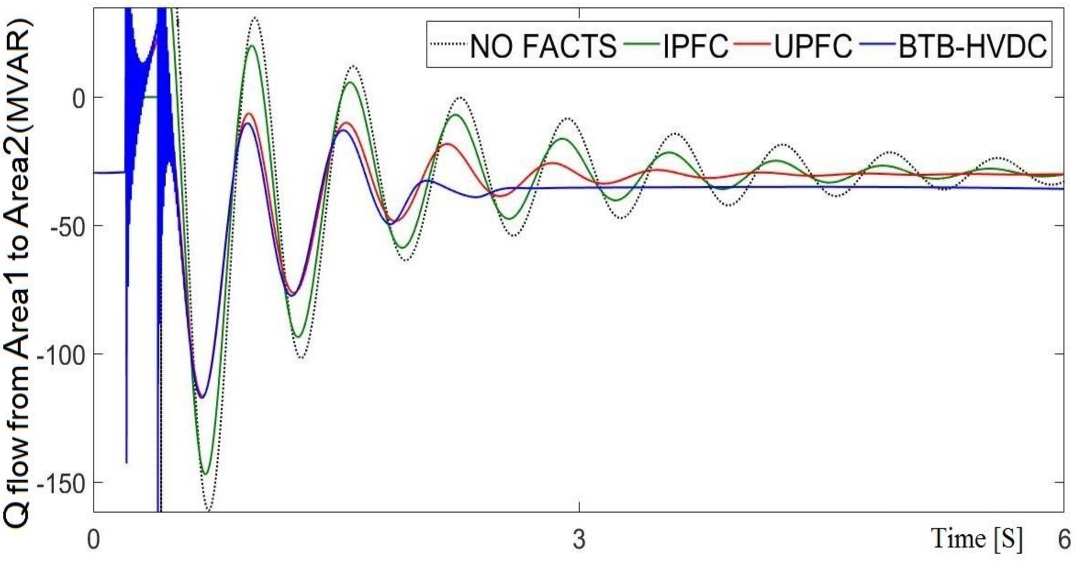

Figure 5.25 Reactive power flow from area 1 to area.

Figure 5.25 clarifies the reactive power flow from the bus 4 (area 1) towards the bus 5 and bus 6 (area 2) for all cases of study. This case represents the inter-area mode that is located between the area 1 and the area 2 of IEEE 9-Bus system.

After the fault at 0.4 sec, the dotted curve shows a lot of oscillation which might damage the system as shown in Figure 5.25. The maximum value of the reactive power flow reaches around 40 MVAR to -150 MVAR and these oscillations continue in the system for a period of time, about 6 sec. The oscillations are reduced in different ratings with the rest cases to reach a better result of damping by adding IPFC, UPFC and BTB_HVDC devices to independent of IEEE 9-Bus system. The BTB-HVDC controller successfully damped these oscillations and the settling time is around 2.5 sec, as shown in Figure 5.25.

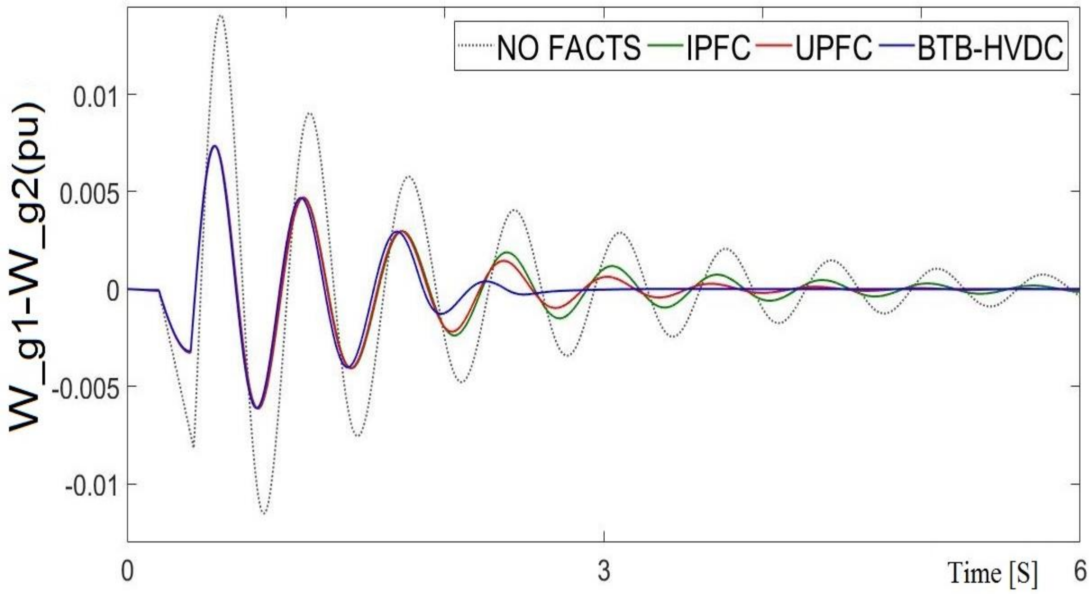

Figure 5.26 Rotor speed of generator 1 against generator 2.

Figure 5.26 explains the difference between the rotor speed of the first generator (ω_{g1}) in the first area and the rotor speed of the second generator (ω_{g2}) in the second area of IEEE 9-Bus system. The values of all cases show zero pu, due to all parameters are 1 pu and when these values are subtracted from each other, the value is almost zero pu.

The values of generator rotor speed are directly affected by the oscillations after occurring the fault at 0.4 sec and these oscillations continue in the system for a period of time, about 6 sec. The value without device is observed by high oscillation which clarifies unstable of the system, unlike the other curves. The blue curve (representing BTB-HVDC device) shows a better damping of oscillation than the other curves after a time of 2.5 sec.

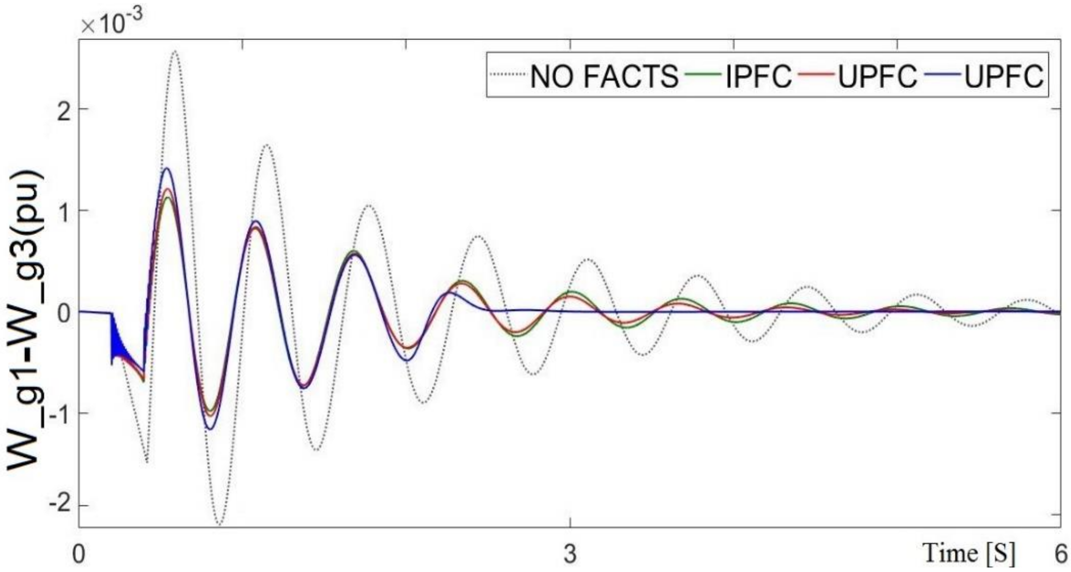

Figure 5.27 Rotor speed of generator 1 against generator 3.

Figure 5.27 shows the difference between the rotor speed of the first generator (ω_{g1}) in the first area and the rotor speed of the third generator (ω_{g3}) in the second area for all cases. The values are almost zero pu because of all parameters are 1 pu and when these values are subtracted from each other, the result is almost zero pu per the curve. The fault is inserted into IEEE 9-Bus system at 0.4 sec.

The values of generator rotor speed are directly affected by the oscillations and these oscillations continue in the system for a period of time, about 6 sec. The curve of BTB-HVDC (blue) shows a better damping of oscillation than the other curves after a time of 2.5 sec. As for the UPFC and IPFC worked to eliminate the oscillations with different rates, but the value without device is observed by high oscillation which clarifies unstable of the system. These oscillations in power system affect solid mechanics of rotor dynamics that cause damage to those systems

5.2.3 Comparison of Results for Damping Ratio

The main purpose of this study is to make a comparison of the dynamic performance of IPFC, UPFC, BTB-HVDC to specify the nature of each device and determine an appropriate controller that can be used by each device which previously mentioned. In addition, the comparison from these devices results three are necessary to identify dissimilarities in performance for each device. When all curves in the figures 5.6 to 5.15 and 5.21 to 5.27 in chapter five are observed, each colour is representing the study case of the independent grid. The black curve represents the state of without any device as a base case, while the green, red and blue curves indicate IPFC, UPFC and BTB-HVDC respectively which represent the states after application of these devices to the base grid.

The black curve showed high oscillation after operating the fault in 0.4sec in Kundur and IEEE 9-Bus power systems and the system was unstable because of these damaging oscillations that lasted for more than 20 Sec. The oscillations are reduced after the IPFC controller began to work in the independent grid, which representing the green line. The IPFC improved the system stability by reducing the oscillations, but not fast enough unlike other devices. The oscillations of the red line can be easily observed when applying UPFC device to the independent grid and UPFC was a faster than IPFC in the damping of the oscillations.

The final curve in the comparison is the blue curve which represents the application of the BTB-HDC controller that can eliminate the oscillations ultimately. The BTB-HVDC showed a stable condition of the systems and obtained the best damping in the base grids. The BTB-HVDC controller supplied an excellent damping for oscillations in an efficient manner, unlike other devices.

When the figures for local/inter-area modes in Kundur and IEEE9-Bus power systems are reviewed to understand the performance of each device in-depth manner and the comparison is fair between the devices. Thus, the tables are created by calculating the values of the frequency (Hz) and the damping ratio (ξ) as shown in Table 5.2 and Table 5.3.

Table 5.2 Damping Ratio (ξ) of local and inter-area modes for Kundur system.

Case studies		Local Mode Area 1	Local Mode Area 2	Inter-Area Mode
Without device	$f\ (Hz)$	1.3822	1.3119	0.7721
	$D.R\ (\xi)$	0.0698	0.0661	0.0361
IPFC	$f\ (Hz)$	1.3511	1.2849	0.6913
	$D.R\ (\xi)$	0.0838	0.0813	0.0649
UPFC	$f\ (Hz)$	1.2798	1.2511	0.6479
	$D.R\ (\xi)$	0.1001	0.1020	0.0827
BTB-HVDC	$f\ (Hz)$	1.1931	1.1918	0.5987
	$D.R\ (\xi)$	0.1090	0.1070	0.0935

Table 5.2 shows the oscillating frequencies and the damping ratios in local/inter-area modes of Kundur power system for all case studies. These values are derived depending on three equations (3.9), (3.10) and (3.11) from chapter three. These values are the basic standard for understanding the performances of these devices by the damping ratio. These oscillations are gradually suppressed after adding IPFC, UPFC and BTB-HVDC devices for optimum stability of the system. The BTB-HVDC controller works to improve the best stability of the system through damping rate of 10.90% with the frequency of 1.1931 in the first area of local mode, while the second area of local mode was the damping with rate of 10.70% with the frequency 1.1918, while the inter-area mode was the damping rate of 9.35% with the frequency 0.5987. Other devices supplied good damping ratios and the sufficient frequencies.

Table 5.3 Damping Ratio (ξ) of local and inter-area modes for IEEE 9-Bus system.

Case studies		Local Mode	Inter-Area Mode
Without device	$f\ (Hz)$	1.3471	0.7675
	$D.R\ (\xi)$	0.0678	0.0511
IPFC	$f\ (Hz)$	1.3182	0.6861
	$D.R\ (\xi)$	0.0826	0.0731
UPFC	$f\ (Hz)$	1.2654	0.6224
	$D.R\ (\xi)$	0.1045	0.0923
BTB-HVDC	$f\ (Hz)$	1.1724	0.5633
	$D.R\ (\xi)$	0.1181	0.1062

The values in Table 5.3 represent the oscillating frequencies and the damping ratios in local/inter-area modes of IEEE 9-Bus power system for all case studies. These values were obtained after applying three equations (3.9), (3.10) and (3.11) from chapter three as the basic standard for determining the performances of these devices through the damping ratio. When the IPFC, UPFC and BTB-HVDC devices are added they gradually reduced the oscillation values as shown in Table 5.3, these procedures improve the performance of the systems. The BTB-HVDC achieved the best values to eliminate the oscillations that are useful for the stability of the systems. Whereas the BTB-HVDC controller obtained the damping rate of 11.81% with the frequency 1.1724 in local mode, while the inter-area mode was the damping rate of 10.62% with the frequency 0.5633, as for other devices provided a good performance for damping ratios and the frequencies.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Recently, power systems have been expanded and enlarged to become very complex and extensive grids, which contain many generators, transmission lines, transformers, loads and other electrical systems. There are many reasons for the development of power systems, including the expansion of demand for power consumption and reducing costs and the development in the field of electronics. Therefore, there are some transmission lines in the grids, which are more loaded than previously planned. There is difficulty in stabilizing after an error occurred in those grids, so the transmission-limiting factor becomes dependent on the initial operating conditions of the system and also external factors. Low-frequency oscillations have always been a direct threat to the stability of the electrical system. They cause a significant damage if they are not properly controlled or have not been damped. This thesis presented a methodology for damping both local and inter-area oscillations. Through the formation of a model for generating and transmission of electric power as an emulation real power system, it includes the generators and power transmission lines and other equipment. Later, the changes are occurred in the system after any fault have been observing. IPFC, UPFC and BTB-HVDC are used by applying these devices with power systems. A first system is Kundur system that has two areas which are analogously composed of four generators and transmission lines. This utilizing of this system is to detect and to process the low-frequency oscillation for both local and inter-area modes.

After that, the simulation resulted of a parameters measurement was conducted to be used for creating a comparison and monitor of the enhancement of the system performance with and without FACTS devices.

IEEE 9-Bus is the second power system which is used in this research for applying a comparison in the case of the system with no adding IPFC, UPFC, BTB HVDC devices, then these devices were added to the IEEE 9Bus system separately and checked the results of the simulations to observe the possible improvements that may be occurring in all cases. The results of the previous simulation, it can be seen that oscillations are decreased with the addition of the FACTS devices. Therefore, BTB-HVDC seems better than the other devices to overcome the oscillations problem in Kundur or IEEE 9-bus power systems, unlike other devices. Because of the difference in the building of the internal structures of each device.

This will contribute to improve the network operation in terms of power transmission and reduce losses in power system, thus parameters are regulated and integrated resulting huge improvements in stability.

6.2 Future Work

The continuous development of power electronics always opens wider horizons for using in the development of equipment IPFC, UPFC and BTB-HVDC, and these devices utilize to improve the power transferring in power grids. This development has several aspects can be outlined as follows: -

- The huge numbers of models can influence control of devices and also can impact on the stability of systems.
- The newly developed parameters in this search can be used with more extended grids.
- Possible to extend the scope of this work to include the comparison of FACTS devices which are based-VSC and to investigate problems of power systems oscillation.
- The search stimulation outcomes can be applied and used in Iraqi national grids to improve Iraqi national power system and suppress the loss of power in the transmission line and control quick response in case of sudden problems might come up during the operation.

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APPENDIX A

Load flow study of Kundur power system

Total generation : P= 2855.33 MW Q= 135.04 MVAR

Total load consumption : P= 2784.12 MW Q= -748.66 MVAR

Total losses : P= 71.21 MW Q= 883.70 MVAR

Generator No.1 V= 1.000 Pu/18kV 10.42 deg Pn= 1000MVA

Generation : P= 719.00 MW Q= 62.16 MVAR

Load consumption : P= 2.00 MW Q= 2.00 MVAR

Generator No.2 V= 1.000 Pu/18kV 0.00 deg Pn= 1000MVA ; Swing bus

Generation : P= 717.33 MW Q= 46.92 MVAR

Load consumption : P= 2.00 MW Q= 2.00 MVAR

Generator No.3 V= 1.000 Pu/18kV -0.57 deg Pn= 1000MVA

Generation : P= 719.00 MW Q= 39.69 MVAR

Load consumption : P= 2.00 MW Q= 2.00 MVAR

Generator No.4 V= 1.000 Pu/18kV -11.07 deg Pn= 1000MVA

Generation : P= 700.00 MW Q= -13.74 MVAR

Load consumption : P=   2.00 MW Q=   2.00 MVAR

Load No.1 V= 1.012 Pu/230kV 15.67 deg

Generation   : P=   0.00 MW Q=   0.00 MVAR

Load consumption : P= 1135.86 MW Q= -294.21 MVAR

Load No.2 V= 1.029 Pu/230kV 5.05 deg

Generation   : P=   0.00 MW Q=   0.00 MVAR

Load consumption : P= 1640.26 MW Q= -462.44 MVAR

Distributed parameters lines V=1.000Pu/230kV

1: 'Area 1 :10km'

2: 'Area 2 :10km'

3: 'Area 1 :25km'

4: 'Area 2 :25km'

5: 'L 1   :110km'

6: 'L 2   :110km'

7: 'L 3   :110km'

8: 'L 4   :110km'

9: 'L 5   :220km'

APPENDIX B

Parameters of UPFC

Nominal voltage Vrms_L-L= 230kV

Shunt Converter rating Pnom_SH= 100 MVA

Shunt Converter impedance R_SH= 0.22/30 Pu

Shunt Converter impedance L_SH= 0.22 Pu

Series Converter rating Pnom_SE= 100 MVA

Series Converter impedance R_SE= 0.16/30 Pu

Series Converter impedance L_SE= 0.16 Pu

DC link total equivalent capacitance (F): 6000e-06

DC link nominal voltage VnomDC= 40 kV

Parameters of IPFC

Nominal voltage Vrms_L-L= 230 kV

Series Converter 1 rating Pnom_SE1= 100 MVA

Series Converter impedance R1= 0.16/30 Pu

Series Converter impedance L1= 0.16 Pu

Series Converter 2 rating Pnom_SE2= 100 MVA

Series Converter impedance R2= 0.16/30 Pu

Series Converter impedance L2= 0.16 Pu

DC link total equivalent capacitance (F): 6000e-06

DC link nominal voltage VnomDC= 40 kV

Parameters of BTB-HVDC

Nominal voltage Vrms_L-L= 230kV

Shunt Converter 1 rating Pnom_SH1= 100MVA

Shunt Converter impedance R_SH1= 0.003 Pu

Shunt Converter impedance L_SH1= 0.09 Pu

Shunt Converter 2 rating Pnom_SH2= 100MVA

Shunt Converter impedance R_SH2= 0.003 Pu

Shunt Converter impedance L_SH2= 0.09 Pu

DC link total equivalent capacitance (F): 6000e-06

DC link nominal voltage VnomDC= 40kV

APPENDIX C

Load flow study of the IEEE 9-Bus power system

Total generation : P= 315.83 MW Q= -14.57 MVAR

Total load consumption : P= 314.92 MW Q= 116.23 MVAR

Total losses : P= 0.91 MW Q= -130.80 MVAR

Generator No.1 V= 1.000 Pu/16.5kV 0.00 deg Pn= 350MVA ; Swing bus

Generation : P= 67.83 MW Q= -8.57 MVAR

Load consumption : P= 0.72 MW Q= 0.68 MVAR

--> Bus*04* : P= 67.11 MW Q= -9.26 MVAR

Generator No.2 V= 1.006 Pu/18kV 3.50 deg Pn= 350MVA

Generation : P= 163.00 MW Q= 5.00 MVAR

Load consumption : P= 0.73 MW Q= 0.69 MVAR

--> Bus*07* : P= 162.27 MW Q= 4.31 MVAR

Generator No.3 V= 1.002 Pu/13.8kV 0.95 deg Pn= 350MVA

Generation : P= 85.00 MW Q= -11.00 MVAR

Load consumption : P= 0.72 MW Q= 0.68 MVAR

--> Bus*09* : P= 84.28 MW Q= -11.68 MVAR

Bus*04* V= 1.001 Pu/230kV 29.12 deg

--> Bus*05* : P= 31.74 MW Q= 0.57 MVAR

--> Bus*06* : P= 35.34 MW Q= -10.88 MVAR

Bus*07* V= 1.004 Pu/230kV 31.39 deg

--> Bus*05* : P= 91.58 MW Q= 4.53 MVAR

--> Bus*08* : P= 70.42 MW Q= -6.18 MVAR

Bus*09* V= 1.004 Pu/230kV 29.84 deg

--> Bus*08* : P= 29.51 MW Q= -6.03 MVAR

--> Bus*06* : P= 54.70 MW Q= -7.32 MVAR

Load No.1 V= 0.992 Pu/230kV 27.92 deg

Load consumption : P= 123.08 MW Q= 49.21 MVAR

--> Bus*04* : P= -31.71 MW Q= -25.06 MVAR

--> Bus*07* : P= -91.37 MW Q= -24.15 MVAR

Load No.2 V= 0.999 Pu/230kV 28.73 deg

Load consumption : P= 99.79 MW Q= 34.93 MVAR

--> Bus*07* : P= -70.30 MW Q= -16.04 MVAR

--> Bus*09* : P= -29.49 MW Q= -18.89 MVAR

Load No.3 V= 1.000 Pu/230kV 27.78 deg

Load consumption : P=   89.94 MW Q=   29.98 MVAR

--> Bus*04*   : P= -35.31 MW Q= -13.76 MVAR

--> Bus*09*   : P= -54.63 MW Q= -16.22 MVAR

Distributed parameters lines V=1.000Pu/230kV

1: 'L4-6:100km'

2: 'L5-4:100km '

3: 'L5-7:100km '

4: 'L7-8:100km '

5: 'L8-9:100km '

6: 'L9-6:100km '

APPENDIX D

Parameters of UPFC

Nominal voltage Vrms_L-L= 230kV

Shunt Converter rating Pnom_SH= 100 MVA

Shunt Converter impedance R_SH= 0.22/30 Pu

Shunt Converter impedance L_SH= 0.22 Pu

Series Converter rating Pnom_SE= 100 MVA

Series Converter impedance R_SE= 0.16/30 Pu

Series Converter impedance L_SE= 0.16 Pu

DC link total equivalent capacitance (F): 6000e-06

DC link nominal voltage VnomDC= 40 kV

Parameters of IPFC

Nominal voltage Vrms_L-L= 230 kV

Series Converter 1 rating Pnom_SE1= 100 MVA

Series Converter impedance R1= 0.16/30 Pu

Series Converter impedance L1= 0.16 Pu

Series Converter 2 rating Pnom_SE2= 100 MVA

Series Converter impedance R2= 0.16/30 Pu

Series Converter impedance L2= 0.16 Pu

DC link total equivalent capacitance (F): 6000e-06

DC link nominal voltage VnomDC= 40 kV

Parameters of BTB-HVDC

Nominal voltage Vrms_L-L= 230kV

Shunt Converter 1 rating Pnom_SH1= 100MVA

Shunt Converter impedance R_SH1= 0.003 Pu

Shunt Converter impedance L_SH1= 0.09 Pu

Shunt Converter 2 rating Pnom_SH2= 100MVA

Shunt Converter impedance R_SH2= 0.003 Pu

Shunt Converter impedance L_SH2= 0.09 Pu

DC link total equivalent capacitance (F): 6000e-06

DC link nominal voltage VnomDC= 40kV