COMPARISON OF CONVERTIBLE STATIC COMPENSATOR (CSC) PERFORMANCE IN A POWER SYSTEM APPLICATION

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Electrical and Electronic Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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ABSTRACT

In order to deal with transient stability limits faced by transmission systems, the Flexible Alternating Current Transmission System (FACTS) technology was introduced. Along with it came controllers that can help solve the ever rising demand of electric power. Since its introduction in the 1980s, FACTS devices have evolved to improve the performance of the power network as well as raise the transient stability limit of the transmission system. The latest generation of device to be introduced is the Convertible Static Compensator (CSC). Its versatility proved advantageous as this device is able to operate in many modes similar to many devices of previous generations. This study focuses on the Unified Power Flow Controller (UPFC), which is a previous generation device available in one of the many modes of the CSC device, and the Generalized Unified Power Flow Controller (GUPFC). The GUPFC device is a new concept that is introduced alongside the CSC device. While the function of it is essentially the same as the UPFC device, it has the ability to control power flow at multiple lines. This report studies and compares the performances of these two configuration modes available in the CSC device. Using two generators as comparison, the load angle of the two generators are compared to determine the stability of the power system. The GUPFC device has shown to be able to get the two generators into synchronism faster than the UPFC device.

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LIST OF SYMBOLS / ABBREVIATIONS

AC	alternating current
DC	direct current
FACTS	flexible alternating current transmission system
GUPFC	generalized unified power flow controller
IPFC	interline power flow controller
SMIB	single machine infinite bus
SSSC	static synchronous series compensator
STATCOM	static synchronous compensator
SVC	static VAR compensator
TCSC	thyristor-controlled series compensator
UPFC	unified power flow controller

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CHAPTER 1

INTRODUCTION

1.1 Background

Ever since AC power systems have been popularized and commercialized, transmission systems have been in place to deliver this power to consumers. Due to the lower demand of electric power in the past, engineers did not have to worry too much about exceeding power demands. Transient instability was also much easier to handle since the likely fault that would have caused any instability to happen was in the unlikely event that lightning has struck the transmission systems. However, since the rapid advancements in technologies related to electrical and electronics, and the growing reliance on such products, the demand of electrical power has grown exponentially for decades. This posted a problem to the old transmission systems installed beforehand. Although most existing transmission systems have the capability to operate with better efficiency since its thermal rating haven’t been peaked yet, transient stability has become a major issue for these older transmission systems as they were not designed to handle the more flexible and complicated power network that exist nowadays.

Power networks that exist before electricity was commercialised was only used to provide electricity power to factories. Therefore, most power generation plants are built near the factories. Transmission of power was not a huge problem as the distance was short for many problems to occur. However, modern power networks are more complicated as the generation of electric power is now centralised and away from urban areas. The transmission and distribution system has become more complicated due to this since generated power will have to travel a long distance before reaching its clients. Centralised power generations have also gave rise to interconnected power network whereby more than one power generation plant is connected on the same power network system. Although new transmission systems can be made to replace the old ones, the cost of replacing the transmission system would be very high. Therefore, new control devices were designed instead to handle transient stability problems faced by the system.

The two of the most significant technologies introduced are the High Voltage DC (HVDC) transmission system and the Flexible AC Transmission System (FACTS). Although the HVDC provides a more optimized and profitable operation, the high cost of its converters has made many companies shy away from the usage of it. Other than that, many other factors are also taken into consideration when opting for which transmission system to use. For transmission system that is being newly constructed and has a long distance of transmission, a HVDC transmission system may be more desirable as it provides less line losses. However, for transmission lines and systems that has already existed before, if the FACTS devices control capacity is lower than the throughput rating of the transmission system. The many advantages of using FACTS system has also made it more popular. The FACTS system is mainly used because the power electronic equipment in the FACTS devices is able to handle system events in a rapid fashion, and improve the quality of the delivered power. The devices used for a FACTS system can also perform much better than its predecessor as they are based on the static electronic design while most were mechanical before this. With this new device, the transmission lines are now able to operate at a higher power delivery and the stability of the power delivery is also ensured with the fast acting capability and compensating behaviour of the FACTS devices.

One of the most famous and most utilized FACTS devices is the Unified Power Flow Controller (UPFC). With its ability to control real and reactive power in the system continuously at high speed, its usage has been increasing rapidly since its introduction. However, like most FACTS devices, the UPFC device can only control the line in which it is installed. Besides that, simpler functions are not accessible using the UPFC since its controllers are designed so. Therefore, to allow for better flexibility of the FACTS devices and also to improve the functions and capabilities of it, a new device called the Convertible Static Compensator (CSC) is developed.

The main objective for the creation of the CSC is to allow greater flexibility and enhance the control concept of the FACTS devices. With the ever increasing demand for electric power, the CSC is also able to increase the power flow limit of the transmission system. The CSC is able to do so because it can change into various different modes depending on the various events that happen in the system. Most of the modes included are the basic FACTS devices made prior to the CSC such as the Static Compensator (STATCOM), Interline Power Flow Controller (IPFC), and UPFC. This makes the CSC very versatile as it can handle any situation accordingly by changing its mode. Other than that, the CSC can also control more than one line or bus depending on the number of converters built into it.

1.2 Problem Statement

Transient stability has been of high importance as of late. The ability for a transmission system to be transiently stable is getting harder as demand for electricity is on a steady rise. If the transmission system was to become unstable due to system disturbances, power fluctuation may occur. Synchronous generators are also put under great risk as the generator may fall out of step and affect the entire power network. In order to reduce cost of restructuring the whole transmission system, controllers are designed instead to increase the transient stability limit of the system. The most widely used controllers nowadays use the FACTS technology, particularly the 2nd generation devices which include the STATCOM and UPFC. As powerful as these devices are, it is simply not versatile enough to cope with the rate of evolution of transmission system these days. A new type of FACTS device is then developed, which is the CSC. While still not widely used, it is claimed to be more powerful than the 2nd generation FACTS devices and much more versatile and flexible. This study will be used to carry out tests to compare the performance of the CSC and older generations of FACTS devices.

1.3 Aims and Objectives

The main aim of this project is to compare the performance of the CSC with other FACTS devices in a power system application. The power system applied in this project will be a 12 bus test system designed specifically for this project. In this case, one of the modes of the CSC is chosen to compare with the FACTS device that is most utilized in the industry now. The mode of the CSC in question will be the Generalized Unified Power Controller (GUPFC) device while the FACTS device chosen is the UPFC device. The objectives of the project are as indexed below:

1. To design a power system model in MATLAB. Then transient stability of the system will be evaluated before the installation of any FACTS devices.
2. To merge the UPFC into the test system and evaluate the performance of the device and the transient stability of the system.
3. To integrate the GUPFC into the model and evaluate the performance of the device and the transient stability of the system.
4. To compare the results of the transient stability of the system with conditions mentioned above.

1.4 Report Organization

This report has 6 chapters in total. The first chapter will go into the project's background. Other components that exist in the first chapter include the problem statement, aims and objective of this project. In the second chapter, any reviews done on works and researches related to the field covered by this project are covered. The summaries, analysis, and results of reviewed works are used as reference for the project.

The third chapter will introduce the FACTS devices. FACTS controllers are briefed upon while the system representation and modelling of the UPFC and

GUPFC are included in this chapter. The methodology of this project is included in the fourth chapter of the report. This chapter will go into detail how the project is being carried out.

The fifth chapter will cover the results produced from this project. Using the results produced, a discussion is done to further detail the meaning of the results. A conclusion is then drawn based on the results and discussion produced. Recommendations are also done to allow further improvements on the project. Both the conclusion and recommendation are included in the sixth chapter of the report.

CHAPTER 2

LITERATURE REVIEW

With the demand of electric power increasing every year, many engineers have sought for solutions to cope with it. One of the biggest challenges faced is the transient stability of the transmission system. Since then, studies to improve the transmission system’s transient stability have been increasing. A power transmission system that has good transient stability is able to synchronize well with other respective systems connected to it even when severe disturbance has occurred (Kundur, 1994). Transient stability is of much importance because it keeps the power delivery of the system stable. Whenever disturbance in a system occurs, the system is expected to recover quickly to avoid power delivery disturbance, voltage fluctuation, and machine malfunctions, which if a system is not transiently stable will cause a lot of money to repair the damages. Therefore, various devices and controllers are designed to cope with these challenges.

B.K. Johnson (2003) has studied how a FACTS controller functions in an AC system. Johnson used TCSC, SSSC and the GUPFC as the basis of his studies. It is stated in the report that such study is carried out because the response of a synchronous generator may not be rapid enough to maintain the stability in a system. Therefore, FACTS devices are needed to help stability maintenance. Using the devices mentioned, he was able to show how a FACTS controller functions when a system disturbance occur. However, only the functions of the FACTS devices were carried out in this study. Very little is mentioned on how those devices are able to improve the performance of the power system.

S.F.B. Shakil, N. Husain, M.D. Wasim, and S. Junaid (2014) has investigated and shown that FACTS controllers do indeed increase the performance of the power network. As reference, Shakil used various FACTS devices such as the STATCOM, SVC and UPFC and compare their performances in a power network compared to conventional methods of improving performance of the power network. The results have shown that FACTS devices do improve the performance of the power network by a big margin compared to conventional methods. Not only that, the response time of the FACTS devices are generally quicker than older controllers. They conclude that STATCOM is by far the best device amongst other FACTS devices when reactive power compensation is needed in a power network. When compared to the SVC, it is also shown to be able to response better and deliver power under low voltage condition. Their research have proven that FACTS device do indeed give better performance to the power network, but their focus on particular devices such as the STATCOM and SVC meant that other devices were less mentioned in their discussion. However, they do state that if one device were to be chosen for the problems faced by the power network, the UPFC would be the most suitable device.

S. Manoj and Dr. Puttaswamy (2011) focused their research on the importance of having FACTS devices installed into a power network. The study is mainly focused on the advantages of installing FACTS devices and comparing the types of FACTS devices installed in various countries as well as its performance. In this study, it is mentioned that with FACTS technology, power transfer capability can be boosted by around 20-30%, due to the flexibility of the power system introduced by FACTS technology. Other than that, FACTS controllers also allow for addition of loads without the need to expand the transmission and generation facilities. By gathering information from various power systems from around the world, they have compared the impact of 4 particular FACTS devices, namely the SVCS, TCSC, STATCOM and UPFC. In the end, they have concluded that SVC, TCSC, FSC, and SSSC are already sufficient enough to match the requirements of most AC transmission system. The UPFC and STATCOM are devices that are only needed when special circumstances are present. This study may have shown the need for a FACTS device to be present in a transmission system, but the results can be skewed and biased as the devices are not judged and investigated based on a common system.

N. Acharya, A. Sode-Yome, and N. Mithulananthan (2005) made similar investigations in their study but chose to focus on the advantages, disadvantages, and practical cost in installing a FACTS device. While the advantages of the device are still being presented, practical disadvantages are also investigated. Acharya has stated that although power network that is installed with FACTS devices do experience better power transfer and higher flexibility, the initial cost of the installation of such device could turn most investors off. This coupled with the reason that FACTS devices are not yet deployed widely would make investors doubt its capability. Another issue that is addressed is that FACTS devices are more prone to higher losses when compared to conventional controllers (Acharya, 2005). Other than that, in order to obtain the desired performance from the FACTS device, its location of installation is very important as well. This means that a longer planning stage will be required to find the best location for the installation of the device. In conclusion, FACTS devices do in fact improve the performance of power network in general. However, based on this study, deployment of such devices should be made cheaper and more accessible to encourage more countries to install these devices.

After investigating on the effect of FACTS devices on power networks, it is clear that these devices are more reliable than conventional methods. However, improvements have to be made to fully utilize the functions of FACTS devices. Therefore, various control schemes have been devised to improve the performance of these devices. W. Dai and Z. Liu (2007) successfully devised 12 control modes to allow the UPFC device function at better efficiency. The UPFC device was chosen for its versatility and powerful operations when compared to other FACTS devices. Their motivation to conduct this study and to device more control modes for the UPFC device is because they felt that the UPFC has been underused and more control modes should be introduced to compliment the device’s versatility. By incorporating the device with their proposed control modes into a Newton-Raphson power flow algorithm, they were able to prove that the UPFC device is capable of doing more by introducing various control modes into it.

N.K. Sharma and P.P. Jagtap (2010) tried a different approach by developing a new controller based on ANFIS and compared it with controllers based on

Proportional-Integral (PI) and PID. The ANFIS based controller developed uses an inference system known as the Takagi-Sugeno inference system. The effectiveness of all three controllers is then judged based on the performances of the UPFC device under various operating modes. After running through several simulations on the MATLAB program, it is concluded that the proposed ANFIS based controller is definitely more effective than the PI based controller due to lower overshoot and steeling time. It is also shown that the proposed controller can increase the power flow control by a slight amount.

H. Fujita, Y. Watanabe, and H. Akagi (1999) have also proposed a control scheme more advanced than used previously for the UPFC device. They claimed that when in transient states, the UPFC actually induces power fluctuation when a conventional power feedback control scheme is used. The reason given is that the control scheme is not able to attenuate the fluctuation of the power, therefore the independency of the time constant of damping is not helping in reducing the power fluctuation. By modifying from the base model of the controller of the UPFC, the device has effectively damped power fluctuations normally caused using a conventional controller for the UPFC.

M. Kavitha, N. Ratnakar and M. Reddy (2013) have found alternatives to improve power network performance as well by combining the use of energy storage system with FACTS devices. They claimed that FACTS devices’ degree of freedom will be limited without the use of energy storage device with it. Three devices are chosen for their study as they claimed that only FACTS devices which utilizes voltage source converter interface with the dc bus connected to a capacitor are able to benefit the most with an energy storage system. The three FACTS devices mentioned are the SSSC, UPFC and STATCOM. The results have shown that when the STATCOM is connected to the Superconducting Magnetic Energy Storage System (SMES), the stability of the circuit has shown great improvements. When the number of STATCOMs is increased in the circuit, the power quality has shown to be increased as well. However, it is stated that such device enhancement can suffer from performance degradation as such devices are very sensitive to the location in which it is installed with respect to the generator and the load. Although, this study may have generated the idea that the combination of the energy storage system and the FACTS device is able to improve power quality, no study has been made to test the capability of this enhanced device when dealing with system disturbance is a power network, which is one of the main functions of the FACTS device as well.

During the late 1990s, power electronic devices have seen a burst in advancement. FACTS devices are no exception to that as well. To counter the problems that FACTS devices sometimes face, a new device was designed. This device is called the Convertible Static Compensator (CSC). The CSC is a device able to change into many different modes to cater for any problems it needs when facing system disturbance. Furthermore, it is also able to control more than one line of the network which saves the need to install multiple FACTS devices. The New York State (NYS) Transmission System is the first to install such device and many researches have been done to determine its effectiveness compared to other FACTS devices.

B. Fardanesh et al (1998) studied the application of such device in detail. According to this study, the CSC was designed with a few objectives to be fulfilled. The first would be the ability of the device to adapt to any needs from an evolving system. Next would be to be able to provide maximum flexibility if future system changes are needed. The CSC used in the NYS transmission system is able to operate in a few configurations never seen before in other generation of FACTS devices. Its ability to operate as a STATCOM, UPFC, IPFC, GUPFC and more assured that the device is able to meet any compensation requirements. This meant that the CSC is able to control the real and reactive power independently on two or more lines with just one controller. The IPFC control mode has also never been used before the creation of the CSC. This study has also shown the basic functionality of IPFC. The idea of the IPFC approach is so that the real and reactive power flow of two lines can be equalized to solve practical power flow problems. The GUPFC is basically of the same concept as well but is able to control more than just two lines. From this study, it is evident that the CSC is designed to be multifunctional and cost efficient. Its ability to control multiple lines with only a single device is particularly interesting and the versatility of the device meant that is it able to supply the needs to an ever involving system without much problem.

The GUPFC configuration of the CSC device has been more focused as of lately due to its similarity to the UPFC device in terms of functions. M.Z. El-Sadek, A. Ahmed and M.A. Mohammed (n.d.) studied the GUPFC by incorporating it using various model. The models used are the injection power flow and the PV/PQ/PQ. The power flow program they used was based off the Newton-Raphson algorithm. By testing the GUPFC on a IEEE-30 test bus system on MATLAB, it was concluded that the GUPFC is a very powerful FACTS device to control the bus voltage magnitude. Results have also concluded that it is capable of controlling the flow of real and reactive power in multiple lines. However, due to the fact that the computation of the GUPFC control variables is done only after the convergence of the load flow, the limit of the control variables is not known.

R.S. Lubis, S.P. Hadi, and Tumiran (2011) were able to model the GUPFC using the nonlinear predictor-corrector primal-dual interior-point Optimal Power Flow (OPF) algorithm. It is then tested in an IEEE 30 bus power system. While many other papers have solved the power flow equation for the GUPFC model based on other techniques, this study is the first to use this technique for the device. This is also a study on the difference a GUPFC can make when installed into a power system. By using this OPF method, the iteration number and time of computation is greatly reduced when compared to other general algorithms. It is also stated that the general algorithms perform worst when there is minimum time constraint upper and lower, resulting in difficulty to find feasible individual in generation. Overall, the GUPFC has shown to prove its worth as the results have indicated that it is able to reduce the losses in networks, increase power transfer capability, and lower the operating cost of the power system. As the GUPFC, which is part of the CSC configuration, is a fairly new FACTS device controller, the price of installing one may be unappealing to some. But this study has shown that the benefits of implementing one outweighs the any initial disadvantages faced by promised investors.

CHAPTER 3

INTRODUCTION TO FACTS DEVICES

3.1 FACTS controllers

Every FACTS device consists of multiple controllers, rather than a single controller doing all the work. This collection of controllers can be applied individually or collectively to control the power network parameters desired (Stella, 2005). There are four basic categories for the FACTS controller, namely the shunt controller, series controller, combined series-shunt controller and the combined series-series controller.

The first to be discussed is the series controller. One example of a series controller for the FACTS device is the SSSC. The series controller's main function would be to absorb and produce reactive power. Practically, when current and power flow needs to be controlled, and the system's oscillation needs dampening, the series controller is an effective one (Satish, 2003).

The shunt controller is not dissimilar to the series controller. The main difference between these two controllers is that when the shunt controller is connected to a point, it will inject current at that position. One example of the shunt controller is the STATCOM. By injecting active or reactive current, the voltage can be controlled around the point where the shunt controller is connected (Satish, 2003).

Both these basic controllers can then be combined to create new types of controllers. The combined series-series controller is done by combining two series controller as its name states. This type of controller can be used to control two lines at a time. The basic function is still the same as a series controller. The IPFC is an example of this controller.

The combined series-shunt controller is one of the more widely used one as it combines the advantages of the series and shunt controller. The best example that can be given here would be the UPFC. As stated, the UPFC can control the real and reactive power flow of a bus or a line.

3.2 Convertible Static Compensator (CSC)

The CSC is the newest addition to the FACTS device family, being the 3rd generation in line of many other devices. It is the most powerful and versatile device when compared to others as the CSC is able to operate in many different modes and configuration. Not only that, this device is also able to control more than one line, making it very viable if controls had to be done on more than one line is a system. The CSC is said to be able to operate in 49 different modes, with some of the more common modes being the STATCOM, UPFC, IPFC and GUPFC (Jiang, et al., 2005). Each configuration has its special function and when combined makes the CSC device very versatile and powerful as it is able to overcome many problems with a change in configuration whereas before this the system had to be studied and a FACTS device had to be chosen that fits the problem.

3.3 Unified Power Flow Controller (UPFC)

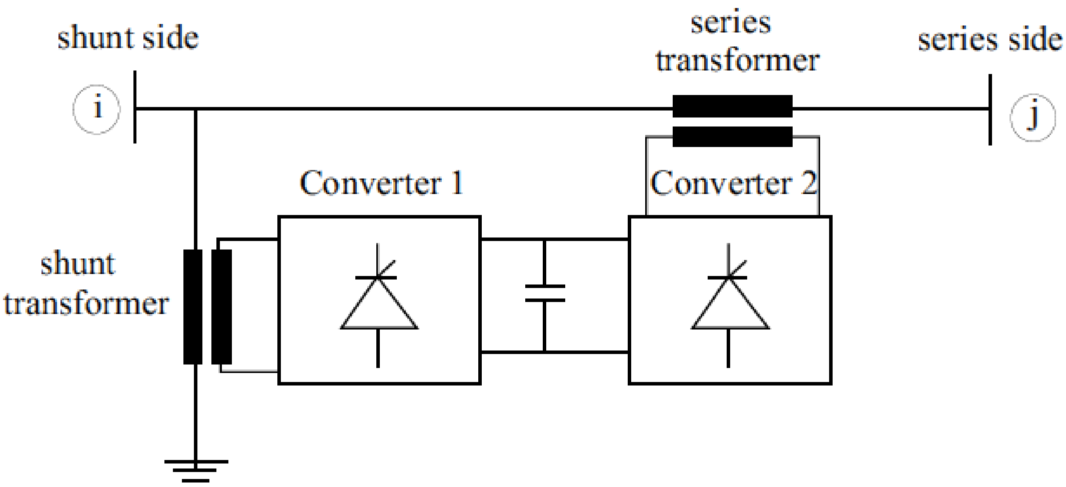

Figure 3.1: Basic circuit arrangement of UPFC device

The UPFC device is the most universally used FACTS device nowadays for its powerful functions. It has the capability to regulate voltage, do phase shifting as well as series compensation. The UPFC device as shown in Figure 3.1 is built using a shunt converter and a series converter. The two converters are then linked by a DC bus using a capacitor. The shunt converter acts as the control to reactive power as it can generate or absorb it. Other than that, it can also provide real power if the series converter demands it. This allows the shunt converter to provide independent shunt reactive compensation. The series converter on the other hand is designed as a booster that injects AC voltage that has controllable magnitude and phase angle. This injection is done in series with the line, and when the line current travels through this voltage, real and reactive power exchange will occur. This is not only able to improve the power flow capability but also able to increase the limit of the transient stability limit. The UPFC device also has another function that is able to improve the transient stability of the system. The UPFC device is able to do so by suppressing power system oscillations.

3.3.1 System Representation and Modelling

To model the UPFC device in detail, the real and reactive power injections at the sending bus and receiving bus will have to be obtained. The following equation is used to determine the parameters mentioned (Stella, 2005):

$$S_s = P_s + jQ_s = V_s I_s^* + \frac{|\mathrm{V_s}|^2}{\mathrm{jx_{sh}}}$$

$$= |V_s|\angle\delta_s \left\{\rho_{sh}|V_s|B_{sh}\angle\left(\delta_s + \alpha_{sh} - 90^\circ\right) + \rho_{se}|V_s|B_{se}\angle(\delta_s + \alpha_{se} - 90^\circ)\ \right\}^* + \frac{|V_s|^2}{jx_{sh}}$$

$$= |V_s|\angle\delta_s \left\{\rho_{sh}|V_s|B_{sh}\angle\left(90^\circ - \delta_s - \alpha_{sh}\right) + \rho_{se}|V_s|B_{se}\angle(90^\circ - \delta_s + \alpha_{se})\ \right\}^* - j\frac{|V_s|^2}{B_{sh}}$$

$$= \rho_{sh}|V_s|^2 B_{sh}[\cos(90 - \alpha_{sh})] + j\sin(90 - \alpha_{sh}) + \rho_{se}|V_s|^2 B_{se}[\cos(90 - \alpha_{se})] + j\sin(90 - \alpha_{se}) - j|V_s|^2 B_{sh}$$

$$P_s = \rho_{sh}|V_s|^2 B_{sh}\sin\alpha_{sh} + \rho_{se}|V_s|^2 B_{se}\sin\alpha_{se}$$

$$Q_s = \rho_{sh}|V_s|^2 B_{sh}\cos\alpha_{sh} - B_{sh}|V_s|^2 + \rho_{se}|V_s|^2 B_{se}\cos\alpha_{se}$$

Using different arrangements, the receiving bus real and reactive power can also be obtained:

$$S_r = P_r + jQ_r = V_r I_r^*$$

$$= |V_r|\angle\delta_r\{-\rho_{se}|V_s|B_{se}\angle(\delta_s + \alpha_{se} - 90^\circ)\}^*$$

$$= -\rho_{se}|V_s||V_r|B_{se}\angle\{90 - (\delta_s - \delta_r + \alpha_{se})\}$$

$$= -\rho_{se}|V_s||V_r|B_{se}\angle\{90 - (\theta_{sr} + \alpha_{se})\}$$

$$= -\rho_{se}|V_s||V_r|B_{se}[cos\{90 - (\theta_{sr} + \alpha_{se})\}] + j\sin\{90 - (\theta_{sr} + \alpha_{se})\}$$

$$= -\rho_{se}|V_s||V_r|B_{se}[\sin(\theta_{sr} + \alpha_{se}) + jcos(\theta_{sr} + \alpha_{se})]$$

$$P_r = -\rho_{se}|V_s||V_r|B_{se}\sin(\theta_{sr} + \alpha_{se})$$

$$Q_r = -\rho_{se}|V_s||V_r|B_{se}\cos(\theta_{sr} + \alpha_{se})$$

The sending and receiving bus real and reactive power is now obtained. This can then be converted to two controllable load Y_s and Y_r:

$$Y_s = \frac{P_s - jQ_s}{|V_s|^2} \quad and \quad Y_r = \frac{P_r - jQ_r}{|V_r|^2}$$

After the controllable load is calculated for the UPFC device, another thing that has to be modelled is the dc link. The dc link voltage can be represented using the equation shown below:

$$\frac{dV_{dc}}{dt} = \frac{1}{CV_{dc}}\left[|V_s||I_s| - \rho_{se}|V_s||V_r|B_{se}\sin(\theta_{sr} + \alpha_{se}) + \rho_{se}|V_s|^2 B_{se}\sin\alpha_{se}\right]$$

Whereby,

P_s = Bus real power (sending end)

Q_s = Bus reactive power (sending end)

P_r = Bus real power (receiving end)

Q_r = Bus reactive power (receiving end)

V_s = Bus voltage (sending end)

V_r = Bus voltage (receiving end)

α_{sh} = Voltage angle (shunt)

ρ_{sh} = Magnitude ratio of voltage (shunt)

α_{se} = Voltage angle (series)

ρ_{se} = Magnitude ratio of voltage (series)

B_{sh} = Susceptance of converter transformer (shunt)

B_{se} = Susceptance of converter transformer (series)

δ_s = Bus voltage angle (sending end)

δ_r = Bus voltage angle (receiving end)

θ_{sr} = $\delta_s - \delta_r$

V_{dc} = Voltage across DC link capacitor

C_{dc} = Capacitance of DC link capacitor

X_{sh} = Shunt reactance

3.4 Generalized Unified Power Flow Controller (GUPFC)

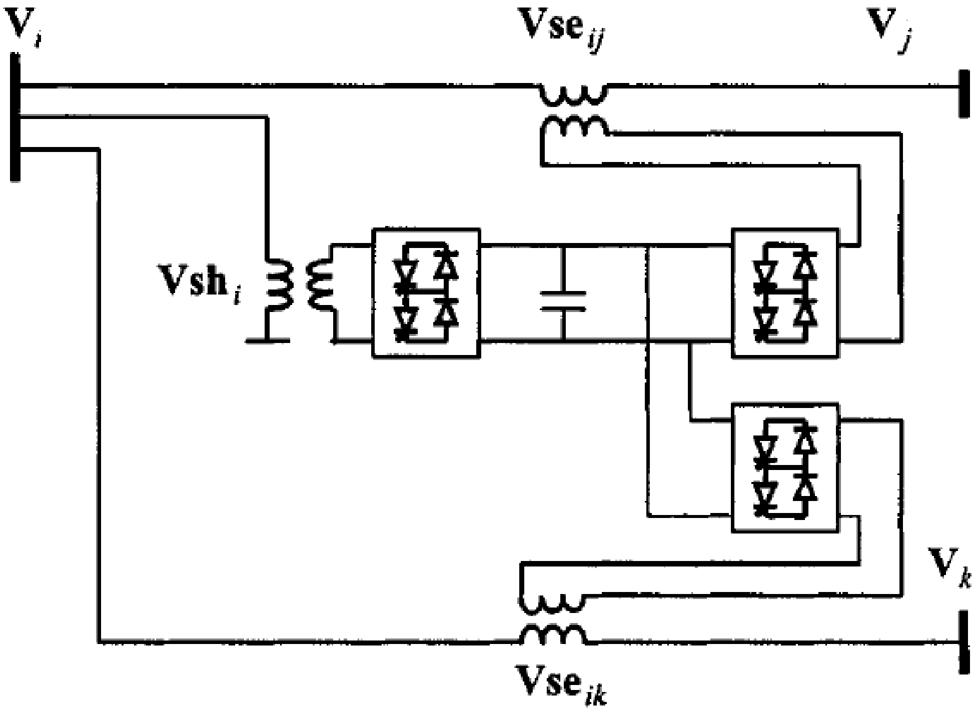

Figure 3.2: Basic circuit arrangement of GUPFC device

The GUPFC device is similar with the UPFC device in terms of functions and design in many ways. However, while the UPFC device only has one shunt converter and one series converter, the GUPFC device has more than one series converter. This allows the GUPFC device to control more than one line using only one device. As mentioned previously, the series converter is responsible for injecting AC voltage into the line it is connected at. The GUPFC device has more than one of this converters, which means that power flow capability will be more effective than UPFC and the transient stability limit can be increased higher than when an UPFC device is installed. Moreover, the ability to control more than one line at a time is a huge advantage for the GUPFC device.

3.4.1 System Representation and Modelling

The modelling process of a GUPFC device can be said to be very similar to UPFC device since both have around the same structure. However, the difference between the two FACTS devices is that while a UPFC device only has one sending end and receiving end, a GUPFC device can have more than one receiving end. From the figure shown above, the GUPFC device is shown to have one shunt converter and two series converter. Following the steps of the modelling for the UPFC device, the GUPFC device can be modelled as well. Only a few of the equations have to be changed to accommodate for an extra series converter.

From the UPFC device modelling shown before, the sending end real and reactive power can be derived by changing the equation to add in an extra receiving end element.

$$P_s = \rho_{se1}|V_s|^2 B_{se1} \sin\alpha_{se1} + \rho_{se2}|V_s|^2 B_{se2} \sin\alpha_{se2} + V_s I_s$$

$$Q_s = \rho_{se1}|V_s|^2 B_{se1} \cos\alpha_{se1} + \rho_{se2}|V_s|^2 B_{se2} \cos\alpha_{se2}$$

As stated, since the GUPFC device modelled here has two receiving ends, the receiving end real and reactive power can be modified as shown below:

$$P_{r1} = -\rho_{se1}|V_s||V_{r1}|B_{se1}\sin(\theta_{sr} + \alpha_{se1})$$

$$Q_{r1} = -\rho_{se1}|V_s||V_{r1}|B_{se1}\cos(\theta_{sr} + \alpha_{se1})$$

$$P_{r2} = -\rho_{se2}|V_s||V_{r2}|B_{se2}\sin(\theta_{sr} + \alpha_{se2})$$

$$Q_{r2} = -\rho_{se2}|V_s||V_{r2}|B_{se2}\cos(\theta_{sr} + \alpha_{se2})$$

The sending and receiving end bus real and reactive power are now obtained. This can then be converted to two controllable load bus Y_s, Y_{r1} and Y_{r2}:

$$Y_s = \frac{P_s - jQ_s}{|V_s|^2} \quad and \quad Y_{r1} = \frac{P_{r1} - jQ_{r1}}{|V_{r1}|^2} \quad and \quad Y_{r2} = \frac{P_{r2} - jQ_{r2}}{|V_{r2}|^2}$$

After the controllable load is calculated for the GUPFC device, another thing that has to be modelled is the dc link. The dc link voltage can be represented using the equation shown below:

$$\frac{dV_{dc}}{dt} = \frac{1}{CV_{dc}}\left[|V_s||I_s| - \rho_{se1}|V_s||V_{r1}|B_{se1}\sin(\theta_{sr} + \alpha_{se1}) + \rho_{se1}|V_s|^2 B_{se1}\sin\alpha_{se1} - \rho_{se2}|V_s||V_{r2}|B_{se2}\sin(\theta_{sr} + \alpha_{se2}) + \rho_{se2}|V_s|^2 B_{se2}\sin\alpha_{se2}\right]$$

Whereby,

P_s = Bus real power (sending end)

Q_s = Bus reactive power (sending end)

P_{r1} = First bus real power (receiving end)

Q_{r1} = First bus reactive power (receiving end)

P_{r2} = Second bus real power (receiving end)

Q_{r2} = Second bus reactive power (receiving end)

V_s = Bus voltage (sending end)

V_{r1} = First bus voltage (receiving end)

V_{r2} = Second bus voltage (receiving end)

α_{sh} = Voltage angle (shunt)

ρ_{sh} = Magnitude ratio of voltage (shunt)

α_{se1} = First voltage angle (series)

α_{se2} = Second voltage angle (series)

ρ_{se} = Magnitude ratio of voltage (series)

B_{sh} = Susceptance of converter transformer (shunt)

B_{se1} = First susceptance of converter transformer (series)

B_{se2} = Second susceptance of converter transformer (series)

δ_s = Bus voltage angle (sending end)

δ_{r1} = First bus voltage angle (receiving end)

δ_{r2} = Second bus voltage angle (receiving end)

θ_{sr1} = $\delta_s - \delta_{r1}$

θ_{sr2} = $\delta_s - \delta_{r2}$

V_{dc} = DC link capacitor voltage

C_{dc} = DC link capacitance

X_{sh} = Shunt reactance

CHAPTER 4

METHODOLOGY

4.1 Plan Overview

1. Using MATLAB, a 12 bus test system is designed. Then, a test will be carried out to test the system's transient stability. This result will act as a buffer as no FACTS devices will be installed into the system.
2. A UPFC device is modelled using MATLAB coding. The coding is done by using the equations shown in chapter 3. It is then fitted into the power system mentioned above for testing. A no fault test is done to ensure that the UPFC device is represented correctly using coding.
3. Various faults will be simulated and the power system's transient stability will be investigated.
4. A GUPFC device is modelled as well using MATLAB coding. The coding is also done by using the equations shown in chapter 3 to model the device. It is then fitted into the power system for testing. A no fault test is done to ensure that the GUPFC device is represented correctly using coding.
5. Faults will be simulated at different locations and the power system's transient stability will be investigated.
6. The performance of the UPFC and GUPFC is compared and discussed.

4.2 MATLAB

For the purpose of researching for this project, the MATLAB (Matrix Laboratory) software is used. This software is a programming software that is meant for complex mathematical calculations. Since the power system and the FACTS devices can be represented in mathematical form, the software is therefore an appropriate tool for the project.

4.3 Transient stability analysis

Transient stability of a system is determined by the system being able to keep in synchronism with other connected system when a severe disturbance has affected it. To perform a transient stability analysis, there are many parameters that can be recorded to analyse it. In this project, the difference of angle between two generators is chosen as the parameter used to study transient stability. For a machine to become transiently unstable, it will have to fall out of step with other machines in a system. For that to happen, the machine would have to operate above a critical angle. When a machine falls out of step, it will start to lose its synchronism with other machines, and that will lead to instability in the whole system. In this project, a reference generator will be chosen as a reference point, while another generator will be chosen to compare its phase with the reference generator. To study which device is able to perform better, a fault will be introduced into a test system. Better performance is determined by how fast a device is able to bring the two generators back into synchronism.

4.4 Simulation model of power system

The IEEE-12 bus test system is chosen for this project as reference. The parameters used for this project are given in the appendix. The system will be modelled using MATLAB. The power system model will comprise of three main parameters, which is the line data, load data and the generator data. A reference generator will be chosen out of the four generators present in the system for per unit calculation purposes. In the power system, generator at bus 3 is chosen as the reference generator. This generator will also be specified as a slack bus for load flow study purpose. The information will be coded and compiled under one ‘m file’ for ease of use later on. The data for the test system is included in the appendix.

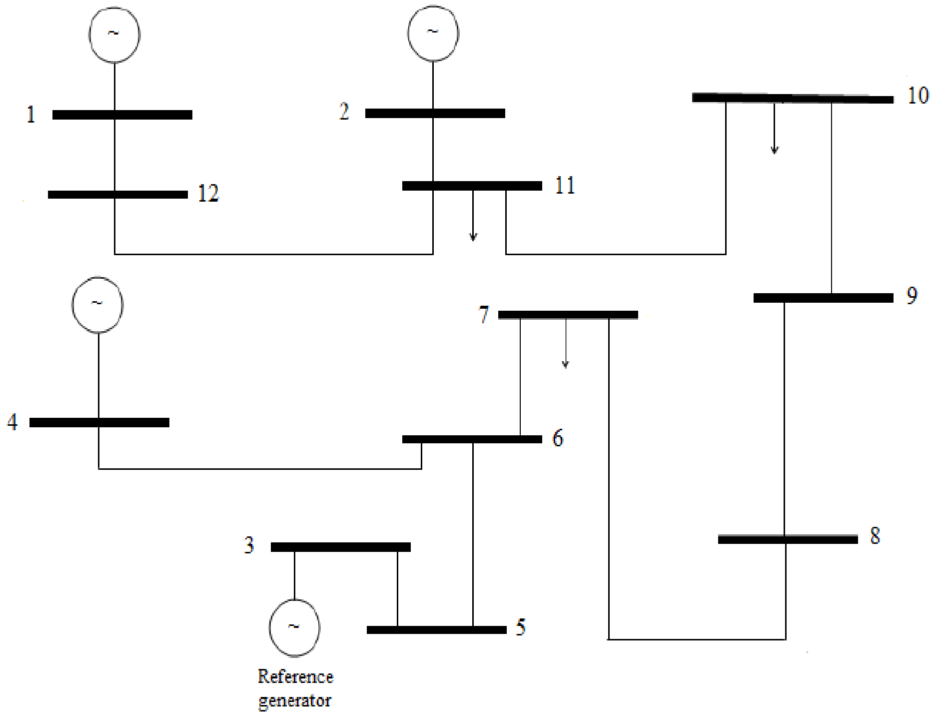

Figure 4.1: IEEE 12 bus test system

4.5 Modelling of UPFC Device

The modelling of a UPFC device is fairly simple if the equation for the device is known. In this case, the equation for the UPFC device is already shown in the previous chapter. As shown in that chapter, the UPFC device will be modelled as a controllable admittance to be fitted into the power system shown in Figure 4.1. Once the UPFC device is coded as an admittance, it will be implemented into the power system using an admittance bus matrix. The UPFC device will be fitted between bus 8 and bus 9. The controllable admittance that represents the shunt converter will be placed at bus 9 while the other controllable admittance that represents the series converter will be placed at bus 8.

4.6 Modelling of GUPFC device

Essentially, the GUPFC device has almost the same design as the UPFC device. The device can also be represented as a controllable admittance like the UPFC device. The equation required to model the GUPFC device as a controllable admittance is shown in the chapter before. The main difference between the GUPFC device and the UPFC device is that while the UPFC device will only have two controllable admittances, the GUPFC device will have three of it. This is because each controllable admittances represents the converters that the device has. For the UPFC device, there are only one shunt converter and one series converter, hence only two controllable admittances. The GUPFC device used in this project has one shunt converter like the UPFC device, but two series converter to signify the two receiving end that a GUPFC device has. For the GUPFC device, the shunt converter and first series converter will be placed at the same location as the UPFC device. The third controllable admittance that will represent the second series converter will be placed at bus 10 to complete the GUPFC model.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Simulation Results and Discussion (Case 1)

To be able to compare the effect of the two FACTS devices on the test system, the rotor angle of two generators will be compared to determine whether the system is transiently stable. The two generators used for the comparison are the reference generator and generator 2. The reference generator in this case will be generator 3. Since generator 3 is a slack bus, the values need not be set. The other generators will be calculated into per unit value using a real power reference of 800MW and a reactive power reference of 600MVA. The fault generated will be a line fault. The line fault will be generated a three different transmission line. The chosen transmission lines are the lines between buses 5-6, 7-8, 9-10. The pre-disturbance conditions of operation are as follows:

Table 5.1: Operation of generator before disturbance (Case 1)

Generator number	Real Power, P_0 (p.u.)	Reactive Power, Q_0 (p.u.)
1	0.7334	0.2056
2	0.5556	0.2611
3	-	-
4	0.5556	0.2244

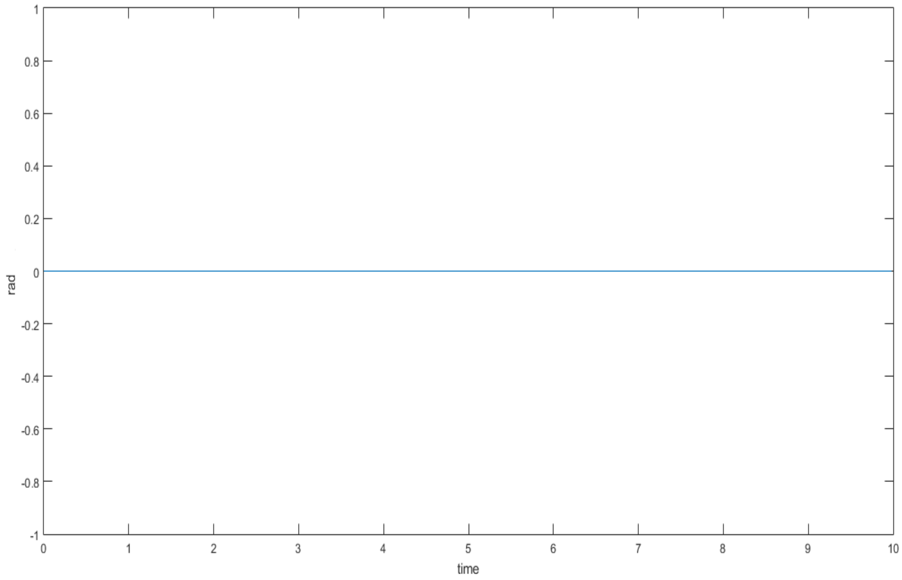

Figure 5.1: Case 1 no fault

To ensure that the FACTS devices are functioning properly, a graph with no fault introduced is generated. Next, a graph with fault introduced but not cleared is also generated to show the presence of a fault. After that, the FACTS devices will be introduced to clear the fault.

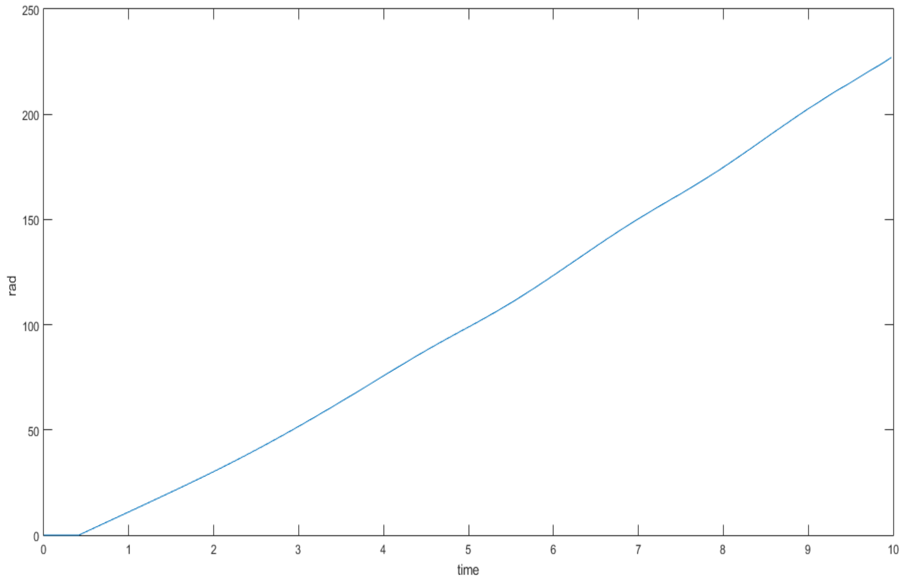

Figure 5.2: Case 1 fault between bus 5 and 6

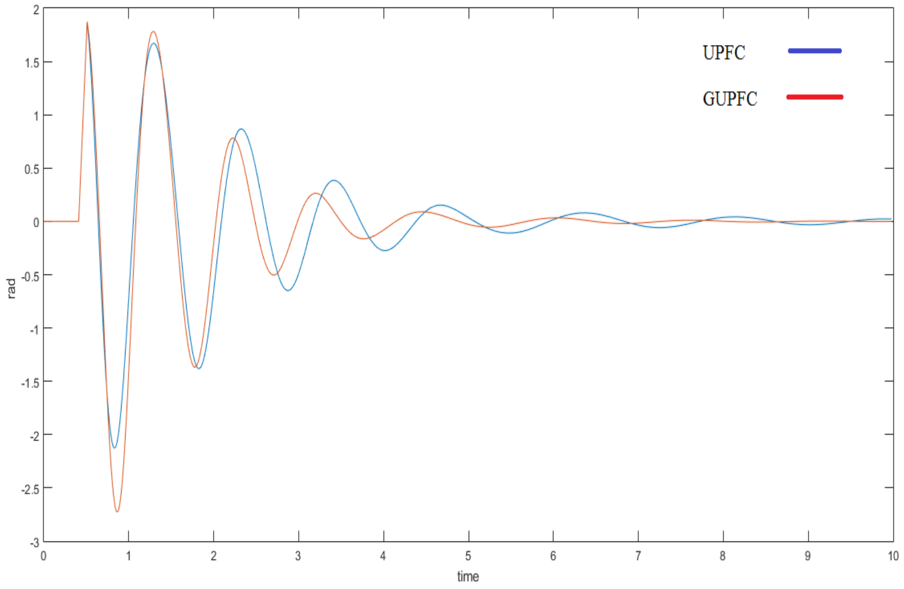

Figure 5.3: Case 1 comparison of performance of UPFC and GUPFC (bus 5-6 fault)

The results shown above are when a fault has occurred at the transmission line between bus 5 and bus 6. The fault is introduced into the 12 bus test system during the 0.5s mark. The FACTS device will then respond during the 0.6s mark. In Figure 5.2, it is shown that when a line fault has occurred, the generators have gone out of synchronism, thus the increasing differences in the rotor angle. This is a sign of a system going unstable and is very harmful for the generators. Not only that, situations like this will normally cause power supply fluctuation and sometimes even a black out as well.

Figure 5.3 shows the recovery of the system when FACTS devices are introduced into the system 0.1s after the fault had occurred. That is the time that is set for the FACTS devices to respond when instability has been detected in the system. From the figure, it is clear that the GUPFC device is able to stabilize the system and get the generators back into synchronism faster than the UPFC device. Although the GUPFC device has allowed the system to swing at a higher angle during the first swing, it is able to recover the system faster and thus reaching transient stability faster than the UPFC device.

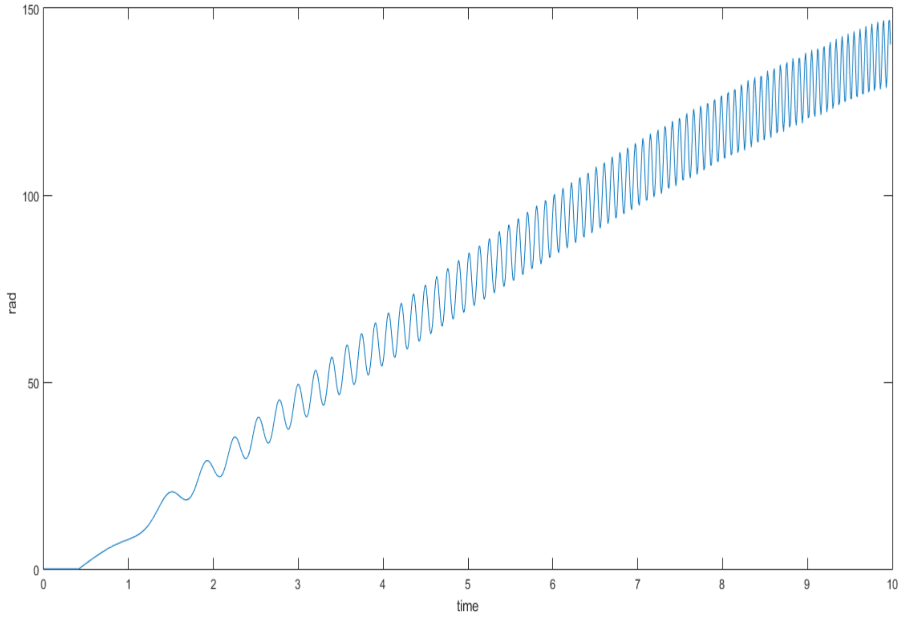

Figure 5.4: Case 1 fault between bus 7 and 8

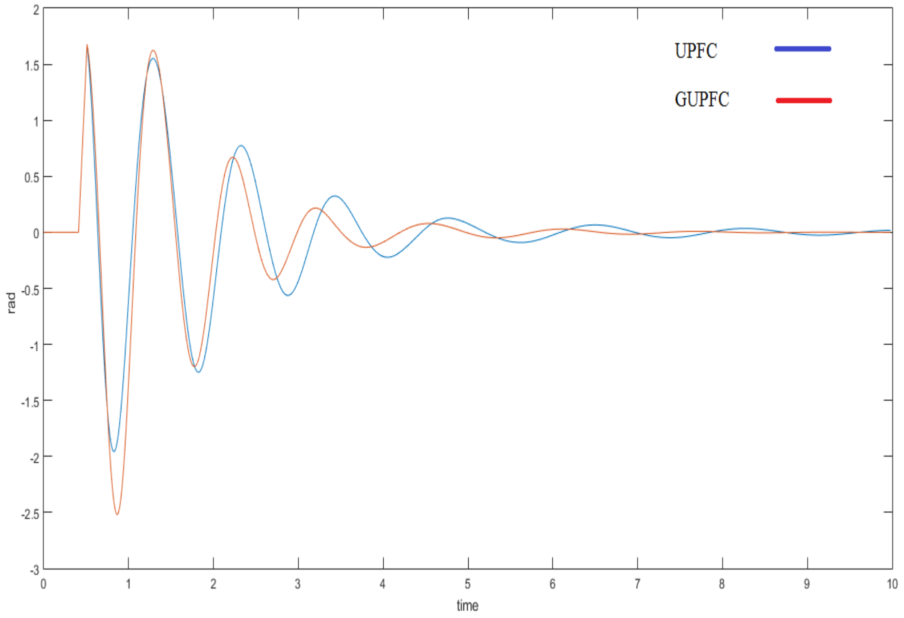

Figure 5.5: Case 1 comparison of performance of UPFC and GUPFC (bus 7-8 fault)

Now the line fault is being generated at a different location which is at the transmission line between bus 7 and 8. From Figure 5.4, it can be seen that the fault pattern is different as well. Figure 5.5 shows that performance of the FACTS devices in handling the fault shown in Figure 5.4. At a glance, the waveform can be seen to be very similar to the one shown in Figure 5.3. However, since the fault is generated at a different location, the fault is also less steep compared to the line fault generated between bus 5 and 6. As a result, when the FACTS devices respond to the fault that has occurred, the angle is slightly less than the one shown in Figure 5.3. That being said, the waveform in Figure 5.5 has shown that although the fault has occurred at a different location, the performance of the FACTS devices remain. This is evident as the GUPFC device is able to bring the system to a transient stability state faster than the UPFC device.

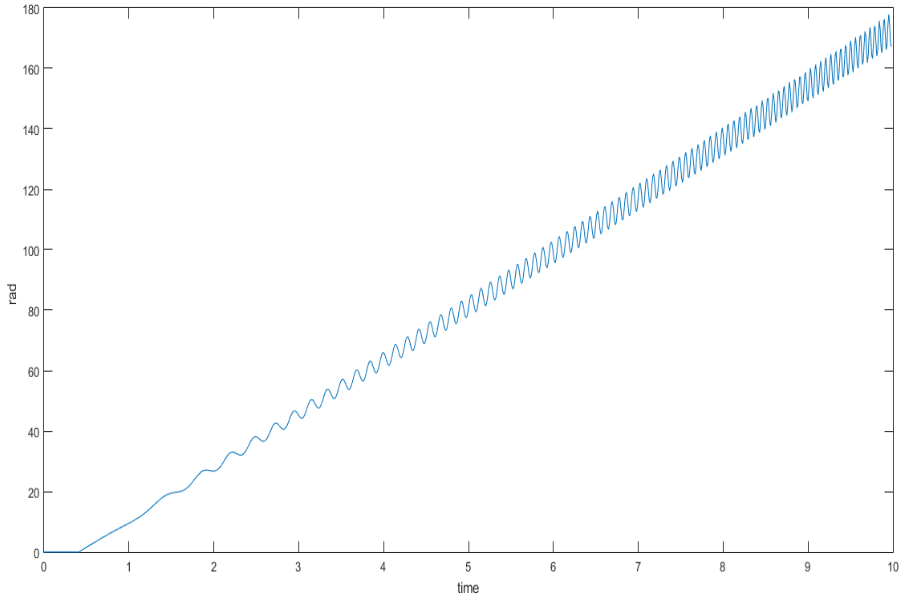

Figure 5.6: Case 1 fault between bus 9 and 10

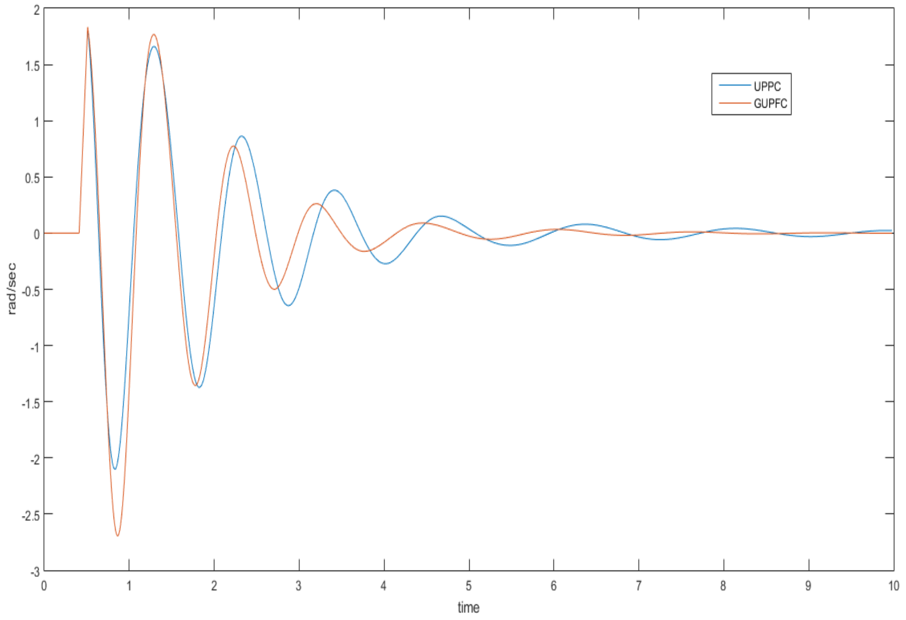

Figure 5.7: Case 1 comparison of performance of UPFC and GUPFC (bus 9-10 fault)

The third location for the transmission line fault to occur is in between bus 9 and 10. Figure 5.6 shows again that the fault waveform is different since the location of fault has now changed as well. This result shows a similar pattern to all the comparison of performance of the FACTS devices as shown in previous results. From all the three results shown above, it is evident that the GUPFC device is able to respond to faults better when compared to a UPFC device. Although not by much, the GUPFC device is able to bring the system to a state of transient stability faster than the UPFC device. Not only that, it is also able to stabilize the system faster than the UPFC device as shown in Figure 5.3, Figure 5.5 and Figure 5.7.

Another way of determining the performances of both the UPFC and GUPFC devices is to check its ability to maintain the voltage of its sending end and receiving end buses. The series converters of both FACTS devices are able to maintain the voltage of the buses that it is controlling. Normally, the voltage between buses is maintained at a fixed rating. However, if fault is introduced to the system, the voltage may increase or decrease. Fluctuation like this is undesirable in a power system. The results shown in Table 5.2 are the recorded voltages during the simulation shown above.

Table 5.2: Voltage comparison of UPFC and GUPFC device

Fault area	**Voltage between controlled bus (p.u.)**			
	UPFC		**GUPFC**	
	Steady state	**Highest recorded**	**Steady state**	**Highest recorded**
5-6	0.9641	1.1784	0.9653	1.1553
7-8	0.9653	1.1182	0.9653	1.1527
9-10	0.9652	1.1928	0.9653	1.1527

From the results shown in Table 5.2, it is shown that the FACTS devices are able to recover from the fault and maintain the voltage level from before fault condition. However, as seen from Table 2, the GUPFC device is able to give a more consistent result compared to the UPFC device which shows fluctuation depending on the location of the fault. This can be due to the fact that since the GUPFC device has more control on the power system due to the presence of an extra receiving end, it is able to control the voltage better than the UPFC device which only has one receiving end. Overall, this shows that the GUPFC device has more control of the power system when compared to the UPFC device.

5.2 Simulation Results and Discussion (Case 2)

A second case is presented to ensure that the results of the effectiveness of the FACTS devices are represented accordingly. The faults generated here will be the same as the ones in case 1. However, the pre-disturbance conditions of operation are changed. The reference generator and the reference power value remains the same as well. The comparison between the UPFC device and the GUPFC device are the same as case 1 as well. The pre-disturbance conditions are presented in Table 5.2:

Table 5.3: Operation of generator before disturbance (Case 2)

Generator number	Real Power, P_0 (p.u.)	Reactive Power, Q_0 (p.u.)
1	0.5556	0.2556
2	0.5556	0.4611
3	-	-
4	1.5556	0.2244

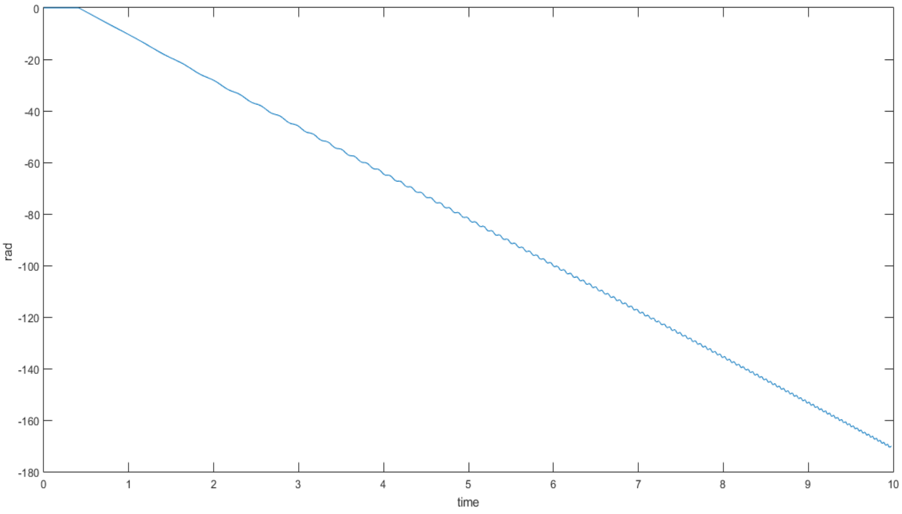

Figure 5.8: Case 2 fault between bus 5 and 6

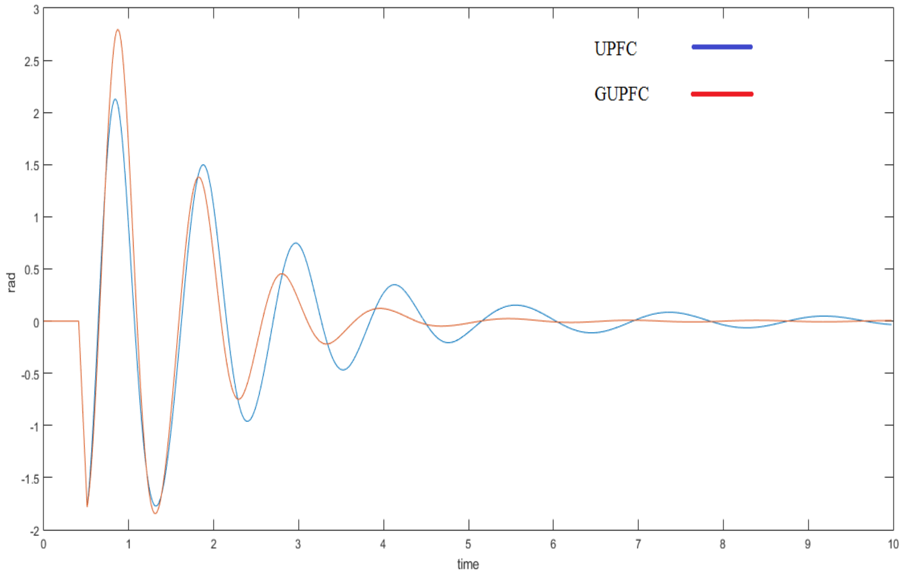

Figure 5.9: Case 2 comparison of performance of UPFC and GUPFC (bus 5-6 fault)

Case 2 is similar to case 1 in the sense that a line fault has occurred between buses in different locations. However, as seen from Table 5.2, generator 4 has its real power increased by 1 p.u. Figure 5.8 shows that the fault has occurred. Although the angle is in a different direction, a fault has still occurred that allowed the system to go out of control. Figure 5.9 shows the response of the FACTS devices in dealing with the fault that has occurred. Since the power has been increased, the system shows higher fluctuation and amplitude compared to the results obtained from case 1. Results in Figure 5.9 show a better comparison of performance of both FACTS devices. From the figure, it is apparent that the GUPFC device is able to bring the system into transient stability faster than the UPFC device. By the time, the GUPFC device has brought the system into a steady state, the system controlled by the UPFC device still shows signs of fluctuation.

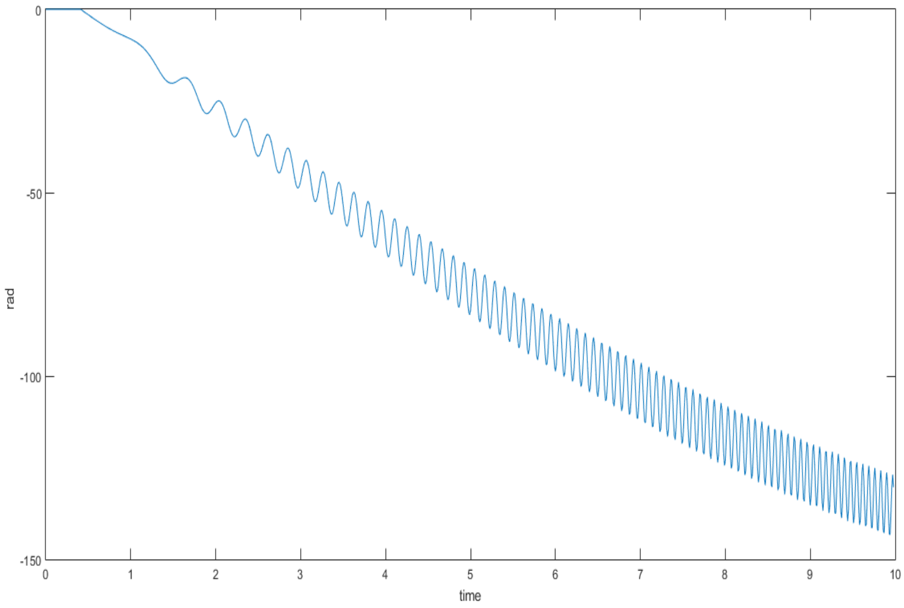

Figure 5.10: Case 2 fault between bus 7 and 8

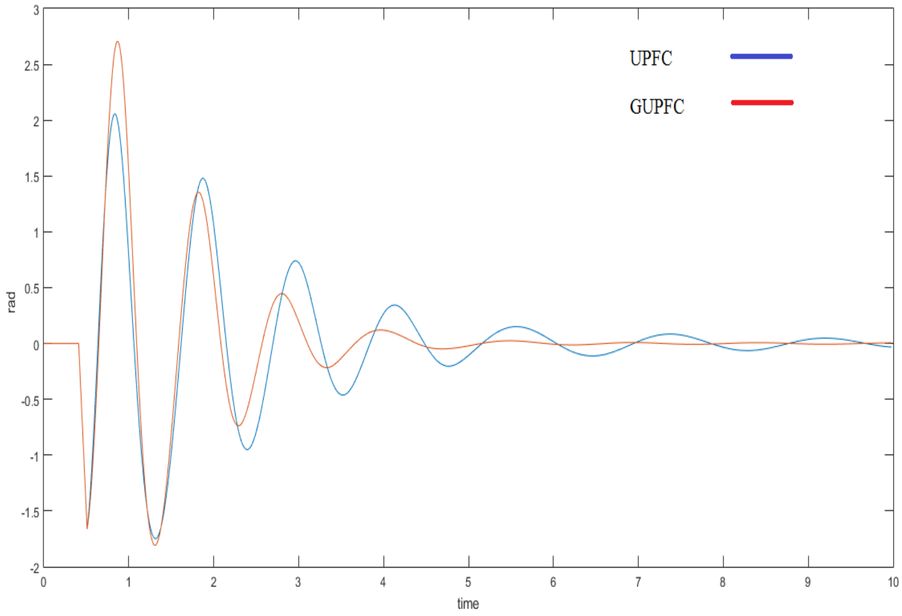

Figure 5.11: Case 2 comparison of performance of UPFC and GUPFC (bus 7-8 fault)

Result shown in Figure 5.11 shows very little difference from the result of Figure 5.9.

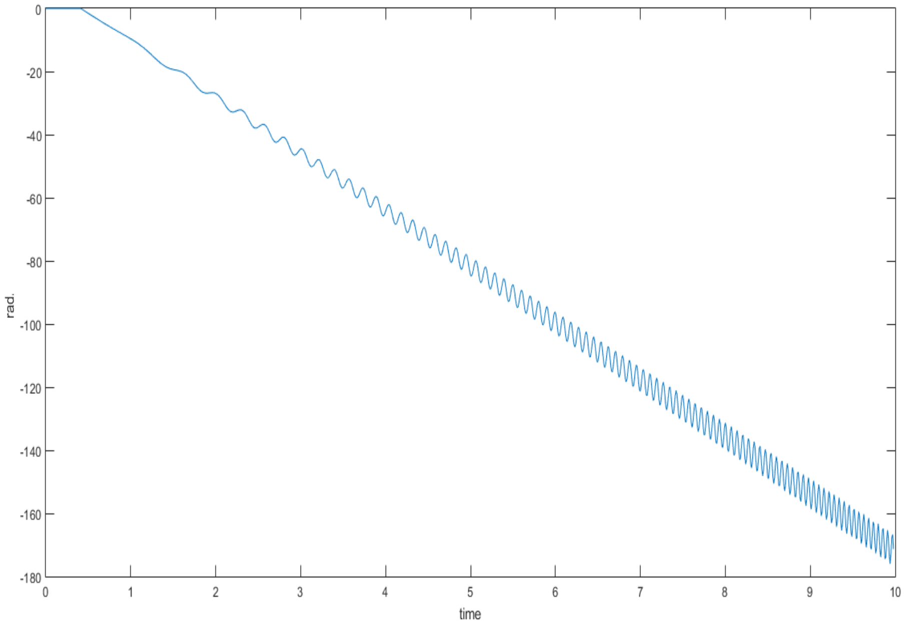

Figure 5.12: Case 2 fault between bus 9 and 10

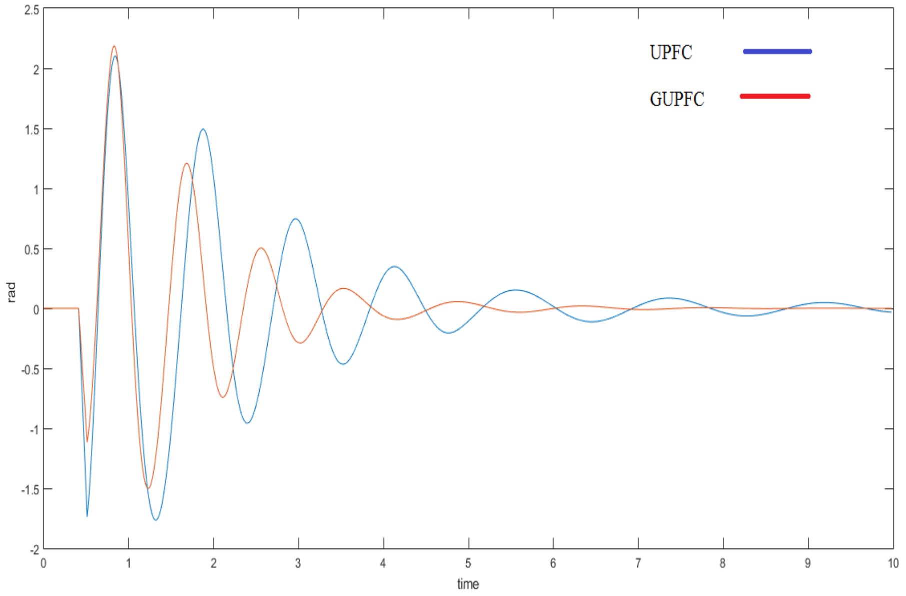

Figure 5.13: Case 2 comparison of performance of UPFC and GUPFC (bus 9-10 fault)

The result shown in Figure 5.13 differs from the results got in Figure 5.11 and Figure 5.9. The difference is the amplitude. The GUPFC device is able to keep the system from fluctuating too much. Although the fluctuation is reduced, the time taken for the GUPFC device to bring the system into transient stability and later to steady state is still almost the same. Nevertheless, the results still show that the GUPFC device responds better and faster compared to the UPFC device.

5.3 Simulation Results and Discussion (Case 3)

In case 3 of the project, a generator fault is being simulated to test the performance of the FACTS devices. The generator fault is done by reducing the power output of a generator in the power system for a short period of time before restoring its power output back to normal. The generator that is being reduced in this case is generator 1. Table 5.5 shows the power at the controlled line. The power before the reduction of power, during reduction of power, and after reduction of power is recorded. The pre-disturbance condition of case 3 will be similar to that of case 1, as shown in Table 5.4:

Table 5.4: Operation of generator before disturbance (Case 3)

Generator number	Real Power, P_0 (p.u.)	Reactive Power, Q_0 (p.u.)
1	0.7334	0.2056
2	0.5556	0.2611
3	-	-
4	0.5556	0.2244

Table 5.5: Results of generator fault

FACTS device		Power of controlled line (p.u.)		
		Before	Reduced	After
GUPFC	Line 1	0.3161	0.7561	0.4312
	Line 2	0.6096	0.7850	0.6082
UPFC	Line 1	0.7568	1.1182	0.7688

From the results shown in Table 5.5, the power of between the buses that the FACTS devices are controlling is shown. The table has shown that both FACTS devices are able to control the real power of the buses so that the system is able to achieve transient stability. In this case, for the system to stay transiently stable, the power flow is important. When the generator fault has occurred whereby the power of generator 1 is reduced, the FACTS device will be responsible to redirect power flow so that the whole power system can still remain transiently stable.

This can be seen from Table 5.5, as both FACTS devices show an increase in power flow between the buses that the devices control. That being said, since the GUPFC device is controlling more buses, it is able to redirect power flow more efficiently compared to the UPFC device. After the generator is returned to its normal state, the power flow is restructured to allow for optimum power flow in the system. This can be seen when the power at line 1 of the GUPFC device has risen from 0.3161 p.u. to 0.4312 p.u. to cater for the demand of the power system.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

To conclude this project, the comparison of performance of the GUPFC device and the UPFC device has shown significant results towards the improvement of transient stability in a power system application. The GUPFC device has shown that its performance is able to outshine that of the older FACTS model which is the UPFC device. By using the GUPFC device in a power system, the system is able to achieve transient stability faster than the UPFC device with a faster response as well. As a result, the system which uses the GUPFC device can be brought back to its steady state faster than when a UPFC device is used. Nevertheless, the UPFC device is still a viable FACTS device as it is still able to achieve the same results albeit a longer time taken. The UPFC device’s performance can be improved if a better controller can be installed alongside it. For a power system application of a smaller scale, it is viable to still use a UPFC device. However, when a larger scale of power system is involved, the GUPFC device will be a better option from then on. By working on this project, the CSC is definitely recommended for more power system application as the versatility it offers can be advantageous in many situations. In conclusion, the comparison of the CSC performance in a power system application posed positive results for it.

6.2 Recommendation

For starters, adding additional controllers to the FACTS device can slightly improve its transient stability performance. The controllers will have to be tuned to suit the power system involved as well. By using an optimal power flow programme, the parameters for the controller can be found out easily. Implementation of a controller together with the UPFC device will definitely improve its transient stability performance, although the performance might still not be able to match the performance of a GUPFC device. To further improve on this project, a third receiving end and even a second sending end can be added to the GUPFC device for better performance from the device. By controlling more buses in a power system, the GUPFC device will be able to control real and reactive power exchange at more buses, resulting in a better transient stability performance. Other than that, an energy storage system can also be paired with the GUPFC device to further improve the exchange of real and reactive power.

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APPENDICES

APPENDIX A: Tables of Data

The unit of the parameters of the studied system is in per unit (p.u.), unless otherwise specified.

Table A1: Load Data for IEEE 12 bus test system

Bus no.	Bus code	Load Impedance
1	2	0
2	2	0
3	1	0
4	2	0
5	0	0
6	0	0
7	0	(697-j100)/900
8	0	0
9	0	0
10	0	(1767-j250)/900
11	0	(786-j200)/900
12	0	0

(Bus code: 1. Slack bus, 2. PQ bus)

Table A2: Line Data for IEEE 12 bus test system

Sending end bus	Receiving end bus	Resistance, R (p.u.)	Reactance, X (p.u.)	Susceptance, B (p.u.)	Transformer Tap
1	12	0	0.15	0	0
12	11	0	0.0028	0	0
11	2	0	0.15	0	0
11	10	0	0.0011	0	0
10	9	0	0.0061	0	0
9	8	0	6.1111x10^-4	0	0
8	7	0	6.1111x10^-4	0	0
7	6	0	0.0011	0	0
6	4	0	0.15	0	0
6	5	0	0.0028	0	0
5	3	0	0.15	0	0

Table A3: Generator Data for IEEE 12 bus test system

Bus Number	1	2	3	4
d-axis reactance	1.8	1.8	1.8	1.8
q-axis reactance	1.7	1.7	1.7	1.7
d-axis transient reactance	0.3	0.3	0.3	0.3
Inertia constant	6.5	6.5	6.175	6.175
Maximum direct axis excitation voltage	7.8	7.8	7.8	7.8
Minimum direct axis excitation voltage	-6.7	-6.7	-6.7	-6.7
d-axis equivalent transient rotor time constant	8	8	8	8
q-axis transient reactance of the generator	0.65	0.65	0.65	0.65
q-axis equivalent transient rotor time constant	1.5	1.5	1.5	1.5