

**University of Bahrain**

**Collage of Engineering**

**Department of Electrical  
& Electronic Engineering**



# **Design of a UPFC based Controller Using Adaptive Schemes**

A Thesis submitted in partial fulfillment of the requirements for the  
Master Degree in Electrical and Electronics Engineering

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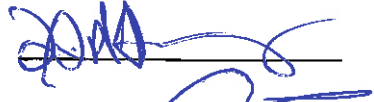
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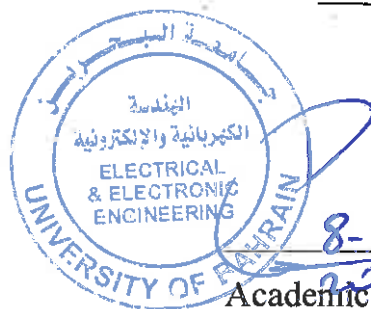
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# **Abstract**

Over the past years, it has been clearly noticed that the power demand has undergone a rapid growth worldwide due to increase in the rate of population, industrial growth and consequently the need of electric power. As a result, power grids have undergone to a significant evolution in generation, transmission and distribution systems and has become more complex and challenging. A better utilization of the existing electricity transmission networks to the maximum extent will be more effective and economical as long as the system security, stability, and reliability are not compromised. So, an innovative solution was proposed to obtain better utilization and controlling of power over the transmission network in steady state and transient conditions is by using the Flexible AC Transmission System (FACTS) devices which are considered as power electronics technology.

In this research, Unified Power Flow Controller is being studied as it is considered the most powerful and versatile model of FACTS devices family. Moreover, the controllers which are being used in UPFC are very important to control the transmission lines parameters as desired. One of the conventional controllers which are being used today is the conventional PI controllers.

In this study, the conventional PI controllers will be replaced by a Model Predictive Controller and Controllers based on an Artificial Neural Networks such as Neural Network Predictive Controller and Nonlinear autoregressive moving average controller. This is in order to investigate the robustness, effectiveness and the capability of such controllers to accommodate any sudden change in the transmission lines parameters such as the voltage magnitude, impedance and the phase angle.

## **Dedication**

To my father, mother, wife and my family for their usual prayers and support. Your love, motivation and understanding are highly appreciated.

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## List of Abbreviation

| Abbreviations | Description                                        |
|---------------|----------------------------------------------------|
| AC            | Alternating Current                                |
| ANN           | Artificial Neural Network                          |
| BBO           | Biogeography-Based Optimization                    |
| DC            | Direct Current                                     |
| EPRI          | Electric Power Research Institute                  |
| FACTS         | Flexible AC Transmission System                    |
| IPFC          | Interline Power Flow Controller                    |
| MIMO          | Muti Input Multi Output                            |
| MPC           | Model Predictive Controller                        |
| NARMA-L2      | Nonlinear autoregressive moving average Controller |
| NNMPC         | Neural Network Model Predictive Controller         |
| SISO          | Single Input Single Output                         |
| SMIB          | Single Machine to Infinite Bus                     |
| SSSC          | Static Synchronous Series Compensator              |
| STATCOM       | Static Compensator                                 |
| SVC           | Static VAr compensator                             |
| TCPS          | Thyristor Controlled Phase Shifter                 |
| TCR           | Thyristor controlled reactors                      |
| TCSC          | Thyristor Controlled Series Capacitor              |
| TSC           | Thyristor switched capacitors                      |
| UPFC          | Unified Power Flow Controller                      |
| Var           | Volt-ampere reactive                               |
| VSC           | Voltage Source Converter                           |
| RHC           | Receding Horizon Control                           |

# Chapter 1

## Introduction

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# **Chapter 1**

## **Introduction**

### **1.1 Overview**

Electric power is considered as one of the important necessities in the human life. Over the past years, it has been clearly noticed that the power demand has undergone a rapid growth worldwide due to increase in the rate of population and industrial growth and consequently the need of electric power. Accordingly, power grids are undergoing a significant evolution in generation, transmission and distribution systems. As a result, the power system has become more complex and challenging.

Usually, the power generation plants are located at distant locations for various reasons such as economic viability, environmental constraints, safety, depending on their type and the resource requirements to run the plants like hydro, nuclear, coal, gas, wind, solar...etc. Accordingly, it is essential to have a robust transmission lines to transfer the power generated from the different plants to the load centre, sharing of generation reserves and economy gained from the use of large efficient units without affecting the reliability. Less transmission lines lead to more generation resources would be required (Hingorani, N. G. et. al 2005).

A better utilization of the existing transmission network to the maximum extent will be more effective and economical as long as the system security, stability, and reliability are not compromised (Manoj Ninoria & Nitin Saxena 2013). The developments in power electronics had a significant impact on the way utilizing and operating power systems. The power electronics assist in having the system to become

more reliable, controllable, and efficient. An innovative solution which were proposed to obtain better utilization and controlling of power over the transmission network in steady state and transient conditions is by using the Flexible AC Transmission System (FACTS) technology (Anulekha Saha, Priyanath Das & Ajoy Kumar Chakraborty 2012). FACTS is the jargon used to describe a wide range of the use of high speed power electronic controllers to control the electric power system. FACTS Controllers are able to control the line parameters such as the voltage magnitude, impedance and the phase angle. Accordingly, this technology possesses various attributes such as controlling of power flows, increasing the loading on power lines to their thermal limits, enhancing the system ability to transfer power between different areas, and damp power system oscillations, (Dipti Mohanty, Aziz Ahamad & M. A. Khan (2013)). There are many types of the FACTS devices such as:

- Static VAr compensator (SVC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Controlled Phase Shifter (TCPS)
- Static Condenser (STATCOM)
- Static Synchronous Series Compensator (SSSC)
- Unified Power Flow Controller (UPFC).

UPFC is considered as multivariable devices among the FACTS devices (Murali, D., Rajaram, M. & Reka, N., 2010). UPFC is considered as the most powerful controller among all FACTS controllers. It has the capability of controlling concurrently or selectivity the transmission line parameters such as the voltage magnitude, impedance and phase angle, or alternatively the flow of the active and reactive power in the transmission line. Moreover, UPFC is capable of damping the system oscillations at

low frequencies (Yong, S. & Allan, J. 1999). The power flow in specific transmission line can be also controlled by using UPFC (Shahgholian, G., et. al. 2017).

The UPFC have a positive impact in enhancing the power quality and system performance (Priyankara, T. et al 2017) and (Hatnapure, H. B. and Chandrakar, V. K., 2017).

Different load flow models are available to study the impact of UPFC in load flow solution, which are power injection model and voltage source based model of UPFC. The advantage of the voltage source model in UPFC is that, it considers the dynamics associated with the d.c. link capacitor and the power injection of shunt and series converter (Parvathy, S. et. al. 2017).

UPFC can be operated in different mode (Makkar, C. R. and Dewan, L., 2016) which will be elaborated in chapter 3. Moreover, UPFC can improve the phase angle deviation which increase the security margin of the system (Singh, M. and Gupta, S., 2016). Its capability extends to alleviate the under and over voltage of ac buses, where the reactive power setting of the UPFC is only adjusted when the bus voltage limits are violated (Song, P. et. al. 2017).

One of the UPFC installation project was commissioned in December 2015 in Nanjing Western Power System. The UPFC was connected to the 220 kV system in China with capacity around 300 MVA. The analysis shows that the UPFC application can effectively solve the problem of power flow misdistribution and huge investment for constructing new transmission lines (H, Cai. et. al. 2017). The recent UPFC installation assumed to be installed at the end of 2017 in Suzhou

Southern Power Grid, China. This UPFC will be with the highest voltage level and maximum capacity all over the world (500 kV/750 MVA). So, till now five UPFC sets have put into service. One in Inez district, USA with capacity of 320 MVA connected to 138 kV network. The second one is in Marcy, USA with capacity of 200 MVA connected to 345 kV network. The third one is in Kangjin, South Korea with capacity of 80 MVA connected to 154 kV network. The fourth and fifth ones are Jiangsu, China in Nanjing Western Power System and Suzhou Southern Power Grid with capacity of 300 and 750 MVA connected to 220 and 500 kV network respectively. The studies for the UPFC, which was installed in Suzhou Southern Power Grid, showed that the UPFC played an important role in power flow control and dynamic reactive compensation (Wang, H. et al. 2017).

Using the intelligent controllers in UPFC for coordination between shunt and series converters can improve the UPFC performance (Krishna, T. M. and. Anjaneyulu, K.S.R., 2015). The back propagation feed forward artificial network scheme used in UPFC for different loading condition is recommended and propose an acceptable solution (Sumathi, S. and Bansilal., 2015), so it will be considered in this study.

The adaptive controller is also useful to maintain the transmission line limit equal to the desired value. A research was conducted by (Wu-wei., et. al. 2017) on 500 kV UPFC. It has been noticed that if the transmission line reaches its limit, the controller will automatically generate new control target to ensure that the line cannot be overloaded. So, the control strategy does not need the dispatch operation.

Model predictive controller considered as an effective solution for improving the system oscillation in single machine to infinite bus and improve the system stability (Shahriar, M. S., et. al. 2013). It can be also

used in the UPFC control scheme to prevent transmission system overloading (Sun, J., et. al. 2016).

## **1.2 Research Objective**

During the past years, it was obvious that beside the importance of the electric power to the human life, various constrains and challenging are facing the electricity sector due to the main following factors:

- Rapid growth due to increase in the rate of population & industrial growth and consequently the need of robust electric power.
- Scarcity of the natural resources which are being used to operate the generation plants. This will minimize the approach of constructing new plants to a certain extent.
- Complexity of the generation, transmission and distribution systems as the demand on the renewable energy is in growing.

From the above constraints, a proper utilization of the existing transmission lines need to have more attention since the transmission network is considered as the back bone of the power system grid. Based on the aforementioned explanations, this research will study the most versatile FACTS devices entitled as UPFC. So, one of the research objectives is to model the UPFC and deploy it in a Single Machine to Infinite Bus (SMIB) system to test its performance, capability and ability to support the system operations during study-state and transient period.

Moreover, several studies were conducted to investigate the UPFC controller's performance to control the real and reactive power flow in the transmission lines, and to enhance steady state and dynamic behaviour of the power system. Most of the controllers used for UPFC were based on conventional PI controllers, where its coefficients in fact need to be adjusted and optimized if there is any change in the system

structures or parameters in order to get better response (Al-Awami, A. T. et. al. 2007). Accordingly, a new design of an adaptive control schemes to control active power, reactive power and terminal line voltage in SMIB will be investigated and compared with the conventional PI controllers that has been proposed by the previous study such as (S.A. Alqallaf, S.A. Al-Mawsawi & A. Haider, 2014).

Since the Artificial Neural Networks controller with its capability offer better solution for control problem (P.J. Antsaklis, 1990), the performance of using such adaptive control schemes will be studied accordingly. The adaptive control schemes which will be studied, designed and implemented by using Matlab® program are:

- Model Predictive Controller (MPC)
- Neural Network Predictive Controller (NNPC)
- Nonlinear autoregressive moving average Controller (NARMA-L2)

The contribution of this project is to propose advanced adaptive controllers that have been mentioned above to be used for the UPFC to control real power, reactive power and terminal line voltage in SMIB to obtain better optimization and power controlling.

### **1.3 Research Methodology**

The study will cover the importance of the FACTS devices in general and demonstrate the difference between the most popular devices of FACTS family in chapter 2. UPFC is considered as the most versatile devices in FACTS technology, so the details of the UPFC model and operation will be studied in chapter 3 of this research. Moreover, chapter 3 will concentrate on modelling and simulation of the UPFC, SMIB and

the different type of controllers that have been mentioned above, by using Matlab® program

UPFC controllers are very important to stabilize the system and control the transmission line parameters in order to enhance the system performance. Chapter 4 will be dedicated to discuss the UPFC Controllers and explain the difference between:

- PI controllers
- Adaptive scheme controllers such as MPC.
- Artificial Neural Network (ANN) controllers such as NNMPC and NARAM-L2.

Chapter 5 will analyse the proposed controller performance and discuss the findings. Finally, chapter 6 will conclude the study.

# **Chapter 2**

## **FACTS Devices**

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# **Chapter 2**

## **FACTS DEVICES**

### **2.1 Introduction**

Electricity networks mainly contain of power plants, transmission lines and loads. Usually, the power plants are not located near to the load centres. Consequently, the power flow must be transmitted over long distances which result into power losses. So, there will be a need to maximize the efficiency of generation, transmission and distribution of electric power and adding new lines to the new power plants in order to meet the load growth and electric market demands. Moreover, series/shunt capacitors/inductors to be deployed in transmission lines to push the lines physical limits and control the power flow and load bus voltage via mechanical switch devices such series and shunt VAr compensators. These devices are working satisfactorily but they are very slow in responding to transient changes in the system and can't be operated frequently due to mechanical constrains and wear out frequently. Therefore, these challenges along with a rapid load growth and system complexity introduced the need of new technology called as FACTS, which considered as an important and effective option.

According to the IEEE definition, FACTS is defined as “The Flexible AC Transmission System(FACTS) is a new technology based on power electronic devices which offers an opportunity to enhance controllability, stability and power transfer capability of AC Transmission Systems” (Hingorani, N. G., et al. 2000).

Electric Power Research Institute (EPRI) introduced the concept of FACTS technology in late 1981s. It has a great value to enhance the

security, capacity and flexibility of power transmission systems. It uses the power electronic switching device and dynamic controllers to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of Alternating Current (AC) transmission Systems. So, FACTS controllers are called for any controllers which are designed based on the concept of FACTS technology which consists of high power electronics based equipment with its real-time operating control.

FACTS technologies provide an appropriate solution to the system with respect to enhancing the controllability and increase power transfer capability. It can be used for power flow control, increase of transmission capability to transfer the power, voltage control, reactive power compensation, stability improvement, improve system damping, etc.

## **2.2 Classifications of FACTS Controllers**

FACTS controllers can be classified in two different principles. The first classification is based on the type of connection of the FACTS controllers in the transmission system such as series controllers, shunt controllers and hybrid controllers. The second classification of the FACTS controllers is based on the operation technology such as Thyristor controlled FACTS devices and Voltage Source Converter (VSC) based FACTS devices.

### **2.2.1 FACTS Controllers Based on Connection Type**

#### **2.2.1.1 Series Controllers**

Series controller can be switched variable impedance, such as capacitor, reactor, or power electronics based variable source. The variable impedance which is provided by some of the FACTS controllers, multiplied by the current flow through the transmission line represents an

injected series voltage in the line. Likewise, the voltage injected by the voltage source is in series with the line voltage. If the voltage is in phase quadrature with the line current, the Series Controllers only supplies or consumes variable reactive power and this will consequently control the real power. SSSC and TCSC are considered as Series Controllers.

#### **2.2.1.2 Shunt Controllers**

Shunt controller can be switched variable impedance, such as capacitor, reactor, or power electronics based variable source. The Shunt FACTS controllers inject current into the system at the point of connection. If the current is in phase quadrature with the line voltage, the Shunt Controllers only supplies or consumes variable reactive power and this will consequently control of real power. SVC and STATCOM are considered as the most widely used Shunt Controllers. The objectives of the shunt devices in transmission, distribution and industrial networks are as follows:

- Poor factor correction.
- Voltage regulation.
- Improvement of transient stability.
- Improvement of power quality

#### **2.2.1.3 Hybrid Controllers**

Hybrid Controllers can be:

- Combined series-series FACTS controllers: These Controllers are the combination of separate Series FACTS Controllers, which are controlled in a co-ordinated manner, in a multi-line transmission system such as Interline Power Flow Controller (IPFC). The series controllers provide independent series

reactive compensation for each line but also transfer real power among the lines Direct Current (DC) link.

- **Combined Series-Shunt FACTS Controllers:** These could be a combination of two different lines where one line has a separate shunt controller and the other line has series controllers such as UPFC. Series-Shunt FACTS Controllers are controlled in a co-ordinated or unified manner. If the Shunt and Series FACTS Controllers are unified; there can be a real power exchange between the series and shunt controllers via the DC power link.

## **2.2.2 FACTS Controllers Based on Operation Technology**

### **2.2.2.1 Thyristor controlled FACTS devices**

In this category, the reactive impedances are controlled by thyristor switches. The effective compensation depends on the thyristor firing angle. There are three type of thyristor controlled FACTS devices such as SVC, TCSC and TCPS.

#### **(a) Static VAr compensator**

SVC is a shunt device connected to the transmission line and consists of thyristor controlled reactors (TCR) or/and thyristor switched capacitors (TSC) as shown in Figure (2.1).

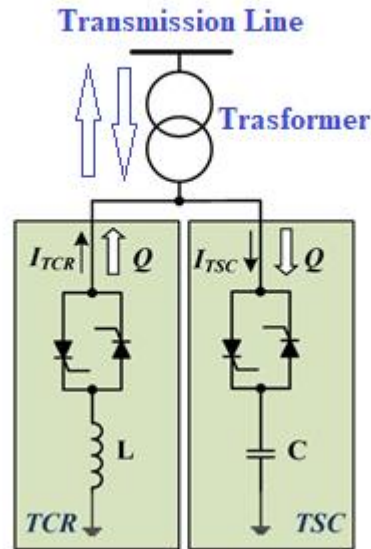


Figure (2.1)

Static VAR compensator

SVC is able to generate or absorb reactive current and regulate the voltage at a chosen bus by proper controlling of its equivalent reactance via capacitor switching and reactor phase angle control. Moreover, SVC may be controlled to enhance the transient and dynamic stability of the transmission system. The V-I characteristics curve of the SVC is shown in Figure (2.2).

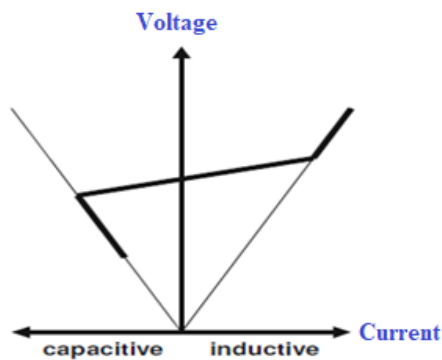


Figure (2.2)

V-I characteristics curve of the SVC

## **(b) Thyristor Controlled Series Compensator (TCSC)**

TCSC is designed based on the thyristor based FACTS technology. It is used to control the voltage across the series impedance in the transmission line and subsequently increase the capability of transferring the power flow in the line. Moreover, it has also the ability to enhance the transient and steady-state stability limit. There are two type of TCSC as shown below:

### **(i) Thyristor switched capacitors**

The compensation level in the TSC increase or decrease as long as the capacitor banks which are connected to the line varies by controlling the firing angle of each of corresponding thyristor pair. The capacitor bank may be connected or bypassed by selecting an appropriate firing angle as shown in Figure (2.3).

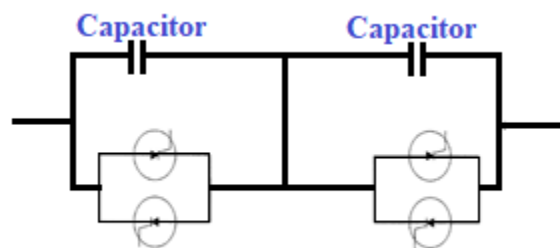


Figure (2.3)

Thyristor switched capacitors (TSC)

### **(ii) Fixed capacitor in parallel with a Thyristor controlled reactors(TCR)**

For the Fixed Capacitor in parallel with TCR, the maximum series compensation is achieved when the TCR is off and is

minimum when the firing angle equal zero. So, the series compensation varies by controlling the thyristor conduction period via the firing angle.

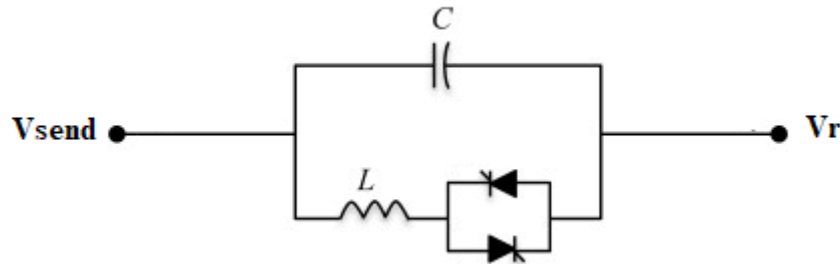


Figure (2.4)

Thyristor controlled reactors(TCR)

### (iii) Thyristor Controlled Phase Shifter (TCPS)

TCPS injects a quadrature voltage to the supply voltage and in series with the transmission line. Each injected voltage is derived from the other two phases via shunt connected transformers as shown in Figure (2.5). The injected voltage is variable based on the power electronics topology. This is to provide a rapidly variable phase angle, which subsequently control the power flow in the transmission line. It is important to indicate that the TCPS is not capable to generate or absorb the real or reactive power, but the power support should be from the entire connected system which may lead to increase the power loss. Accordingly, the TCPS shall be located close to the power generation bus bar. TCPS consists of a multiple tap-changing shunt transformer, a booster series transformer and set of thyristor connected to the booster series transformer.

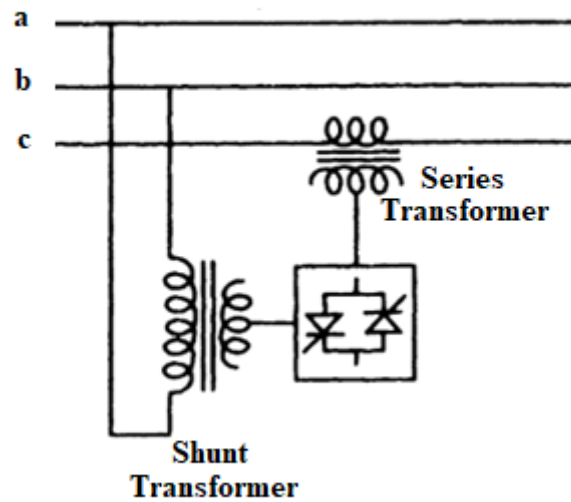


Figure (2.5)

Thyristor Controlled Phase Shifter (TCPS)

#### 2.2.2.2 Voltage Source Converter (VSC) based FACTS devices

The VSC is a converter based technology, which is considered more advance than the thyristor based technology that has only anti parallel thyristor. VSC contains of DC. storage or supply, which create real power flow between the AC and DC segment in VSC. The reactive power flow can be also supplied or drawn at the AC part of the VSC. it is important to mention that in the lossless converter switches, the power at A.C side is equal to the power at DC side. Among the SVC based Facts devises are the Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) as shown in Figure (2.6) (Kalyan K. and; Mey Sen. 2009).

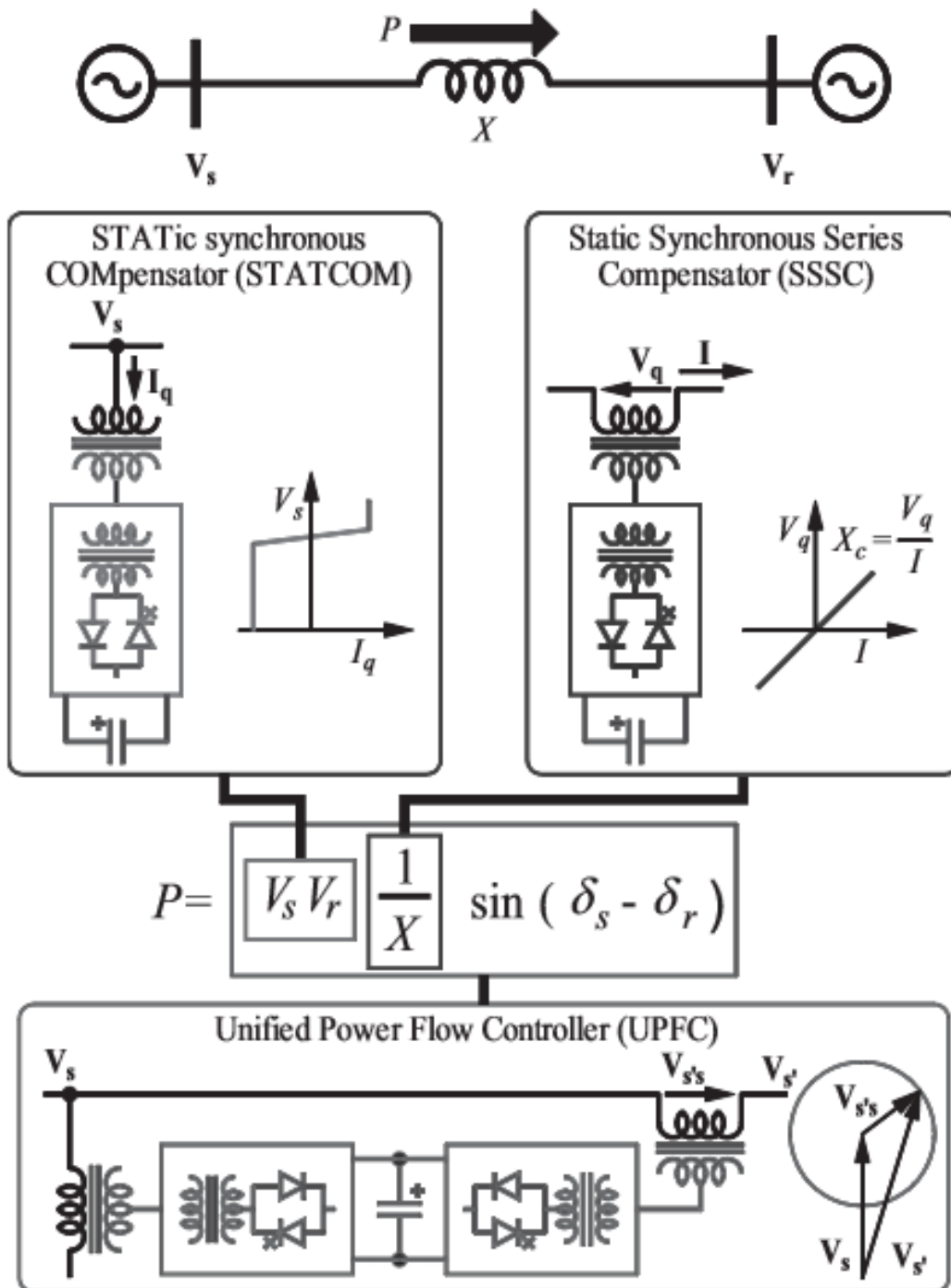


Figure (2.6)

Voltage Source Converter (VSC) based FACTS devices

### **(a) Static Synchronous Compensator (STATCOM)**

STATCOM design and characteristic as shown in Figure (2.7) and (2.8) (X. Ping Zhang, Christian R., Bikash P. (n.d)) is based on Voltage source converter (VSC) electronic device and consists of Gate turn off thyristor and dc capacitor coupled with a step down transformer connected to transmission line. STATCOM characteristics is better than SVC. Moreover, it is used for shunt reactive power compensation by controlling the VSC output voltage which have the same frequency and almost in phase with the A.C. system voltage. One of the controlling strategy is to keep the D.C. Voltage is constant and controlling the output voltage via switching strategy like PWM. So, based in the output voltage magnitude, the reactive power can be controlled independently by VSC controller. If the magnitude of the VSC output is greater than the A.C. system voltage, then the current will flow from the converter to the transmission line and lead the system voltage by 90 degrees i.e. generate capacitive power. While, If the magnitude of the VSC output is less than the A.C. system voltage, then the current will flow from the transmission line to the converter and lags the system voltage by 90 degrees i.e. absorbs inductive reactive power.

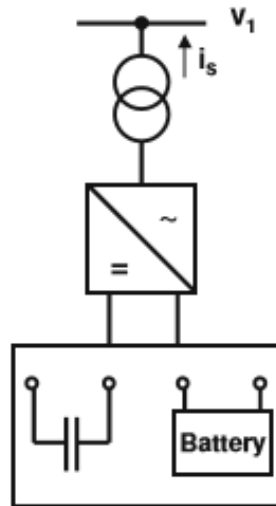


Figure (2.7)

Static Synchronous Compensator (STATCOM)

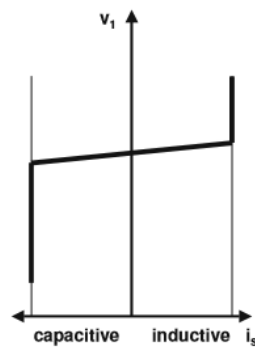


Figure (2.8)

STATCOM characteristics

### (b) Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator consists of a converter, DC source and coupling booster transformer as shown in figure (2.9) (X. Ping Zhang, Christian R., Bikash P. (n.d). It is based on the concept of the source converter design

technology to inject a voltage with controlled magnitude into the transmission line, while the phase angle is kept in quadrature with the line current. It is like a STATCOM but the output ac voltage is in series with the line and also has the ability to exchange reactive power in a transmission line and the amount of compensation is depending on the injected voltage magnitude. The injected voltage angle can be maintained to lead or lag the system current by  $\pm 90$  degrees in order to add series capacitance or inductance impedance to the line.

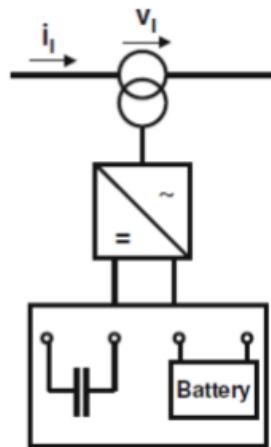


Figure (2.9)

Principle Setup of SSSC

### (c) Unified Power Flow Controller (UPFC)

UPFC consists of two voltage-sourced converters back to back. The converters are linked together through a common DC link capacitor. Each converter coupled to the ac line transformer as shown in Figure (2.10) (X. Ping Zhang, Christian R., Bikash P. (n.d)). This AC to AC arrangement of the

converters, real power can freely flow in either direction between the ac terminals of the two converters and each converter can independently generate or absorb reactive power at its own ac output terminal.

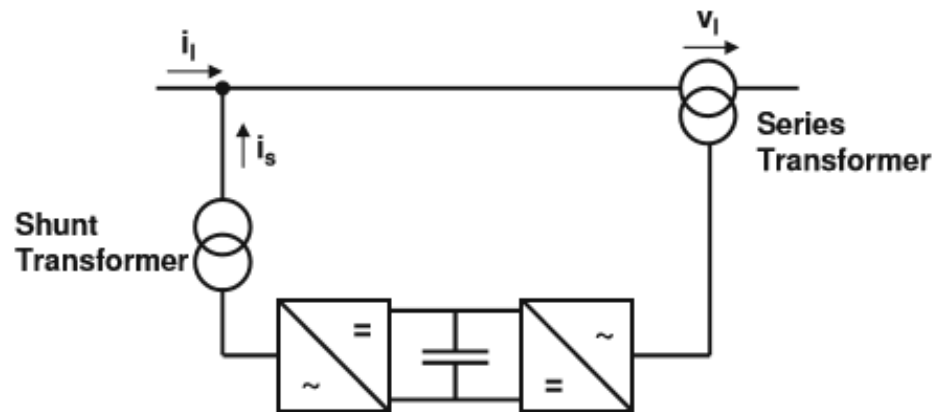


Figure (2.10)

Principle configuration of an UPFC

## 2.3 Conclusion

This chapter gives an introduction on various types of FACTS Devices and its classifications. The FACTS Devices can be categorized based on the connection type or operation technology. UPFC, which is considered as one of the most important FACTS Devices that consists of two voltage-sourced converters, will be adopted in this study and it will be analysed further in the next chapter.

# Chapter 3

## Steady-State and Dynamic Model of UPFC

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## Chapter 3

### Steady-State and Dynamic Model of UPFC

#### 3.1 UPFC Concept

UPFC is considered as one of the most important device in the FACTS devices family. It can control, independently or simultaneously, all parameters that affect the active and reactive power flow on the transmission line.

#### 3.2 UPFC Structure

The UPFC consists of two parts which are:

- Shunt transformer connected to the voltage source converter with a DC link to perform A Static Synchronous compensator.
- Series transformer connected to the voltage source converter with a DC link to perform A Static Series Compensator.

Both are connected together and share a common DC link as shown in Figure (3.1).

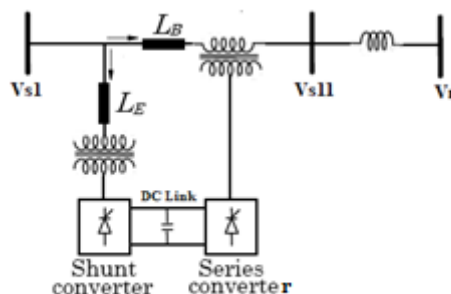


Figure (3.1)

UPFC Structure

The two voltage source converters are connected via a common DC link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The UPFC system is considered lossless, so the power input to the converter is equal to the power output from the converter. The UPFC controls the system parameters such as the voltage magnitude, impedance and phase angle to provide concurrent real and reactive series line compensation without an external electric energy source.

### **3.3 UPFC Modes of Operation**

Depend on the system requirements, the voltage regulation, active and reactive power compensation can be performed throughout the series and shunt compensation by injecting an appropriate voltage magnitude and angle. UPFC controllers need to be ready to toggle between the modes as required. In this study, the voltage is considered as a reference to study the UPFC modes of operation.

#### **3.3.1 Series Converter Modes of Operations**

##### **3.3.1.1 Voltage Regulation**

The voltage at the sending end  $V_{send}$  can be increased or decreased by injecting  $V_{inj}$  in phase or anti-phase of the bus voltage as shown in Figure (3.2).

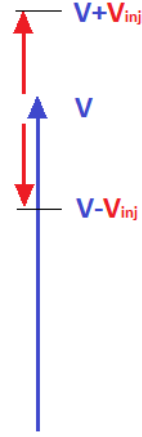


Figure (3.2)  
Voltage Regulation Mode

The voltage magnitude of the  $V_{inj}$  can be determined based on the required percentage of voltage regulation. The actual voltage will be equal to:

$$V_{inj} = \% * V \quad (3.1)$$

$$V_{send} = V \pm V_{inj} \quad (3.2)$$

$$V_{send} = V(1 \pm \%) \quad (3.3)$$

$$Real\ Power = \frac{V_{send} * V_{recive}}{X} * \sin \delta \quad (3.4)$$

$$Reactive\ Power = \frac{V_{send}^2}{X} - \frac{V_{send} * V_{recive}}{X} * \cos \delta \quad (3.5)$$

### 3.3.1.2 Line Impedance Compensation

It is obtained by injecting a quadrature voltage  $V_{inj}$  to the line current  $I$ . This will change the total effective inductance or the capacitance of the line and the level of compensation depend on the voltage injected magnitude as shown in Figure (3.3). Subsequently the real and reactive power will be changed as per the resultant  $X$ .

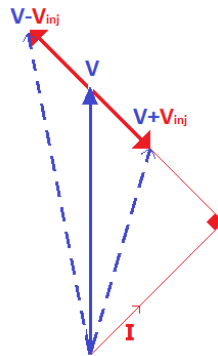


Figure (3.3)  
Line impedance compensation Mode

### 3.3.1.3 Phase shifter

The phase shifter can be performed to enhance the power transfer capability. This can be achieved by injecting voltage  $V_{inj}$  with angle to the bus voltage, provided that the resultant of the two voltage vectors are equal to the same voltage magnitude of the bus voltage as shown in Figure (3.4).

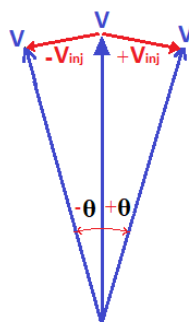


Figure (3.4)  
phase shift Mode

#### 3.3.1.4 Phase Angle Regulator

In this mode, the bus voltage and angle can be both regulated by injecting different voltage magnitude  $V_{inj}$  and angle.

### 3.3.2 Shunt Converter Modes of Operations

#### 3.3.2.1 Voltage regulation (Reactive Compensation)

In the shunt converter, the injected voltage  $V_{inj}$  is in phase or anti-phase of the bus voltage in order to maintain the bus voltage at the desired level. In fact, there will be very small angle between the injected voltage and bus voltage in order to allow the shunt converter to exchange real power with the AC system throughout the series converter as shown below in Figure (3.5).

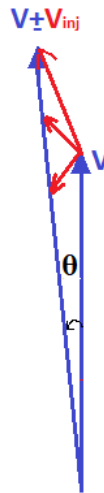


Figure (3.5)

Voltage Regulator of shunt converter

## **3.4 UPFC Modelling**

### **3.4.1 Overview**

The UPFC model and controller became an interesting subject for the engineers to develop and control the transmitted power over the electricity network. In this study, the most versatile FACTS devices entitled as UPFC will be applied to SMIB in order to compare the result with the earlier research work. Mathematical model for the steady state and dynamic model need to be employed in order to inspect the performance of the UPFC in the system. In the steady state model, the initial condition of the system will be determined to perform the load flow analysis. While, in dynamic model the UPFC performance during system disturbance will be verified to ensure that the model and its controllers are robust, respond to any sudden change in the system and effective. The contribution of this study is to propose an advance adaptive control schemes to be implemented to the UPFC in order to ensure better controlling of active power, reactive power and terminal line voltage in SMIB. The proposed controllers shall respond quickly to any sudden change in the system, stabilise the system and perform the desired controllability satisfactorily.

### **3.4.2 UPFC Steady-state Modelling**

#### **3.4.2.1 Steady-State Modelling Literature Review**

Vural, A., & Tumay, M. (2003) proposed a module for UPFC, where the voltage source is converted into a current source in parallel with transmission line. This module did not consider the shunt converter capabilities by neglecting the reactive power injection and the UPFC parameters adjustments were not elaborated. The adjustment of the power

flow is done through trial and error procedures (El-Sadek, M. Z., Ahmed, A., & Zidan, H.E., 2006).

Fuerte-Esquivel, C., Acha, E., & Ambriz-Perez, H. (2000) introduced another load flow modelling by using the equivalent circuit of the steady state to drive an extension of the power flow controller. The convergence and divergence of this model need to be taken in consideration.

Nabavi-Niaki, A., & Iravani, M. (1996,Nov) replaced the UPFC by equivalent bus representation (Decoupled Model). Then the power system can be solved by using any load flow method. Furthermore, the active power flow, reactive power injection to the sending end bus and regulate the receiving end voltage will be controlled.

Reference to the approaches presented by Vural, A., & Tumay, M. (2003) and Fuerte-Esquivel, C., Acha, E., & Ambriz-Perez, H. (2000), Nabavi-Niaki, A., & Iravani, M. (1996,Nov) model is considered as easier to be used, perform the same functionality and has no issue with initial condition problem. So, in this study the UPFC model introduced by Nabavi-Niaki, A., & Iravani, M. (1996,Nov) as shown in Figure (3.6) and Figure (3.9) will be adopted to get the system initial conditions, dynamic model and the concept of control design.

#### **3.4.2.2 Nabavi-Niaki, A., and Iravani, M. Steady-State Model**

UPFC contains of two voltage source converter coupled with DC link. The Shunt VSC connected to line through shunt transformer known as excitation transformer and the series VSC connected to the line through series transformer known as boosting transformer as shown in Figure (3.6).

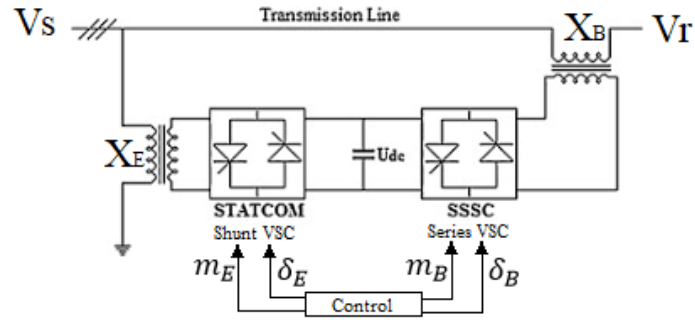


Figure (3.6)  
UPFC Model with control Signals

Reference to the Nabavi-Niaki, A., & Iravani, M. (1996,Nov) approach, which shown in Figure (3.7), the UPFC is replaced by equivalent bus representation in order to be transformed into a conventional power system, which can be analysed and solved by using load flow method. The main role of the UPFC in steady state is to perform the power flow analysis and the result will be used to determine the required converter control variables used for the PWM strategy such as modulation index and phase angle. The UPFC is considered as a losses system by negating the coupling transformer resistance. Moreover, the operation of the voltage source is not independent of each other and the total exchange UPFC power is equal zero.

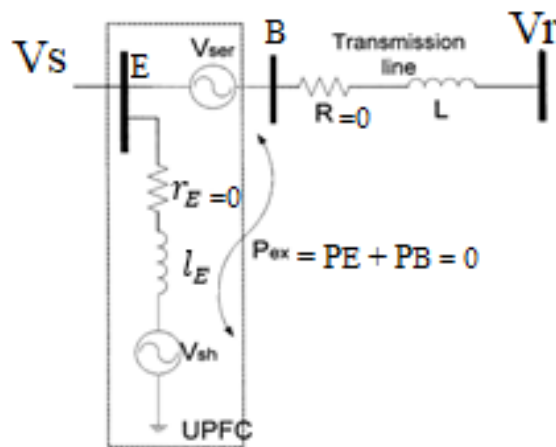


Figure (3.7)  
UPFC Decouple Model

$$P_E + P_B = 0 \quad (3.6)$$

So, the active power injection at the UPFC buses should be equal as the UPFC power exchange with the AC system is zero.

$$P_{Et} + P_{Bt} = 0 \quad (3.7)$$

Since the UPFC is replaced by its bus configuration equivalent as a decouple representation and the load flow problem is solved by using load flow procedure. So, UPFC control parameter can be determined by solving the power injection of the UPFC model as shown in the flow chart Figure (3.8).

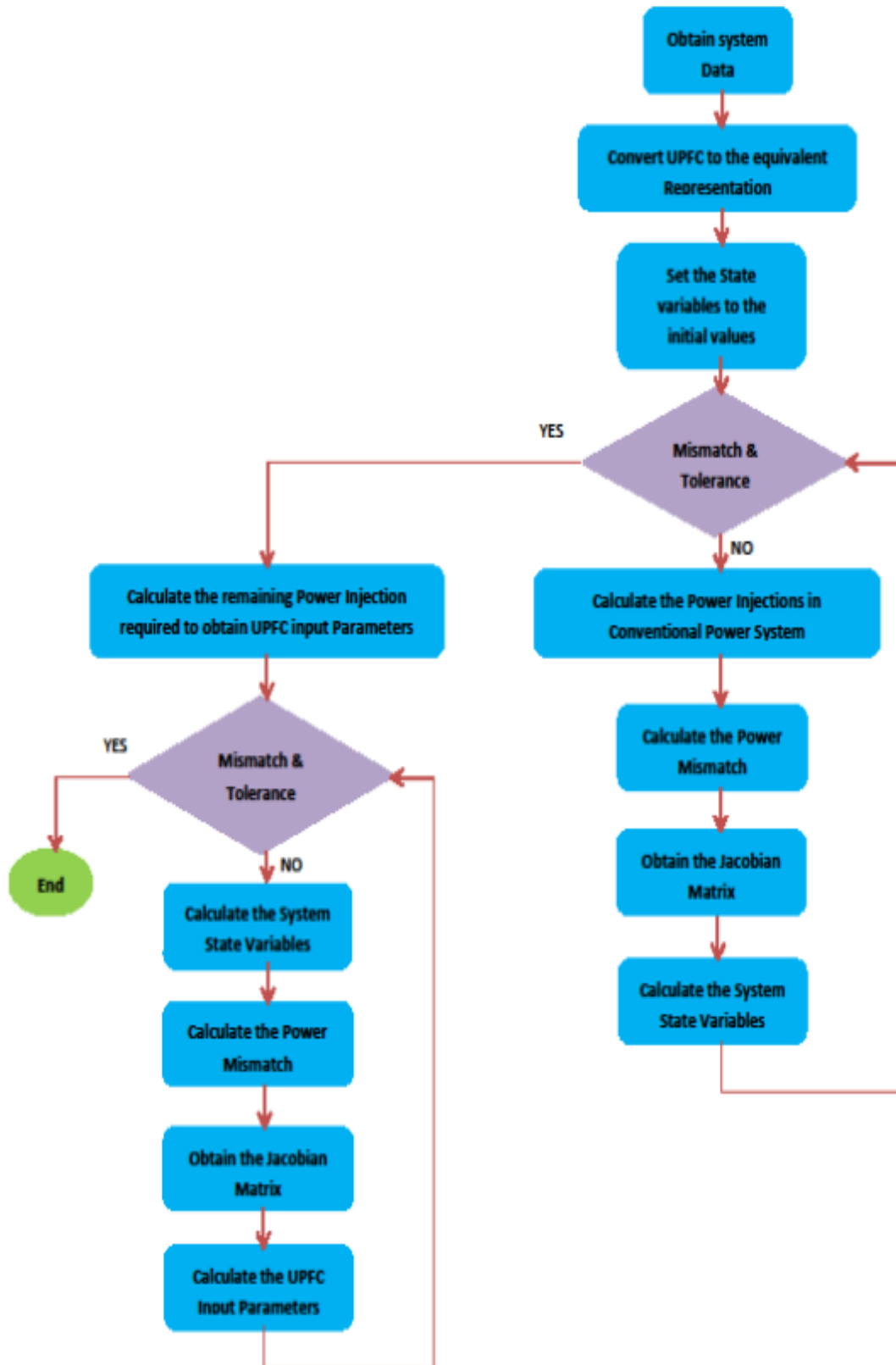


Figure (3.8)

Flow Chart of Newton Raphson Algorithm for UPFC Decouple Load Flow Model

The UPFC and the system equations which will be used are shown below from 3.8 till 3.89, based on Nabavi-Niaki, A., & Iravani, M. (1996) , Abido M. (2005) and Alqallaf S. A.(2015):

$$P_{Etc} = \frac{V_{Et}V_E}{X_E} \sin(\delta_{Et} - \delta_E) + \frac{V_{Et}V_{Bt}}{X_B} \sin(\delta_{Et} - \delta_{Bt}) - \frac{V_{Et}V_B}{X_B} \sin(\delta_{Et} - \delta_B) \quad (3.8)$$

$$Q_{Etc} = \left( \frac{X_E + X_B}{X_E X_B} \right) V_{Et}^2 - \frac{V_{Et}V_E}{X_E} \cos(\delta_{Et} - \delta_E) - \frac{V_{Et}V_{Bt}}{X_B} \cos(\delta_{Et} - \delta_{Bt}) + \frac{V_{Et}V_B}{X_B} \cos(\delta_{Et} - \delta_B) \quad (3.9)$$

$$P_{Bt} = \frac{V_{Bt}V_{Et}}{X_B} \sin(\delta_{Bt} - \delta_{Et}) + \frac{V_{Bt}V_B}{X_B} \sin(\delta_{Bt} - \delta_B) \quad (3.10)$$

$$Q_{Bt} = \frac{V_{Bt}^2}{X_B} - \frac{V_{Bt}V_{Et}}{X_B} \cos(\delta_{Bt} - \delta_{Et}) - \frac{V_{Bt}V_B}{X_B} \cos(\delta_{Bt} - \delta_B) \quad (3.11)$$

The details of the above equations with related illustrations are shown in Appendix (A). Since, the above equations are non-linear equations, Netwon-Raphson method is required to be used to solve the system. The Jacobian matrix for the above system equations is shown below:

$$J = \begin{vmatrix} \frac{\partial P_{Et}}{\partial \delta_E} & \frac{\partial P_{Et}}{\partial V_E} & \frac{\partial P_{Et}}{\partial \delta_B} & \frac{\partial P_{Et}}{\partial V_B} \\ \frac{\partial Q_{Et}}{\partial \delta_E} & \frac{\partial Q_{Et}}{\partial V_E} & \frac{\partial Q_{Et}}{\partial \delta_B} & \frac{\partial Q_{Et}}{\partial V_B} \\ \frac{\partial P_{Bt}}{\partial \delta_E} & \frac{\partial P_{Bt}}{\partial V_E} & \frac{\partial P_{Bt}}{\partial \delta_B} & \frac{\partial P_{Bt}}{\partial V_B} \\ \frac{\partial Q_{Bt}}{\partial \delta_E} & \frac{\partial Q_{Bt}}{\partial V_E} & \frac{\partial Q_{Bt}}{\partial \delta_B} & \frac{\partial Q_{Bt}}{\partial V_B} \end{vmatrix} \quad (3.12)$$

### 3.4.3 UPFC Dynamic Modelling

#### 3.4.3.1 Dynamic Modelling Literature Review

Padiyar, K. R., & Kulkarni, A. (1998, Oct) introduced a detailed dynamic model for the UPFC. The dynamic modelling for the series converter, shunt converter and the DC link are all taken in consideration. The VSCs of the UPFC were replaced by a controllable fundamental frequency voltage sources. The UPFC model need to be reconsidered if the model of the series and shunt transformers represented by its resistance and leakage reactance.

K.S. Smith, L.Ran, J. Penman, (1997) introduced the UPFC dynamic model but the dynamics of the DC link was not taken in consideration, which may result in unforeseen consequence during transients.

Nabavi-Niaki, A., & Iravani, M. (1996, Nov) replaced the UPFC by equivalent bus representation (Decoupled Model) and depends on the pulse width modulation (PWM) technique to control the converters.

Compared with the two approaches from Padiyar, K. R., & Kulkarni, A. (1998, Oct) and K.S. Smith, L.Ran, J. Penman, (1997), the Nabavi-Niaki, approach will be considered in this study.

### 3.4.3.2 Nabavi-Niaki, A., and Iravani, M. Dynamic Model

Reference to the Nabavi-Niaki, A., & Iravani, M. (1996,Nov) model, the UPFC dynamic model depends on the pulse width modulation (PWM) technique to control the converters as shown Figure (3.9).

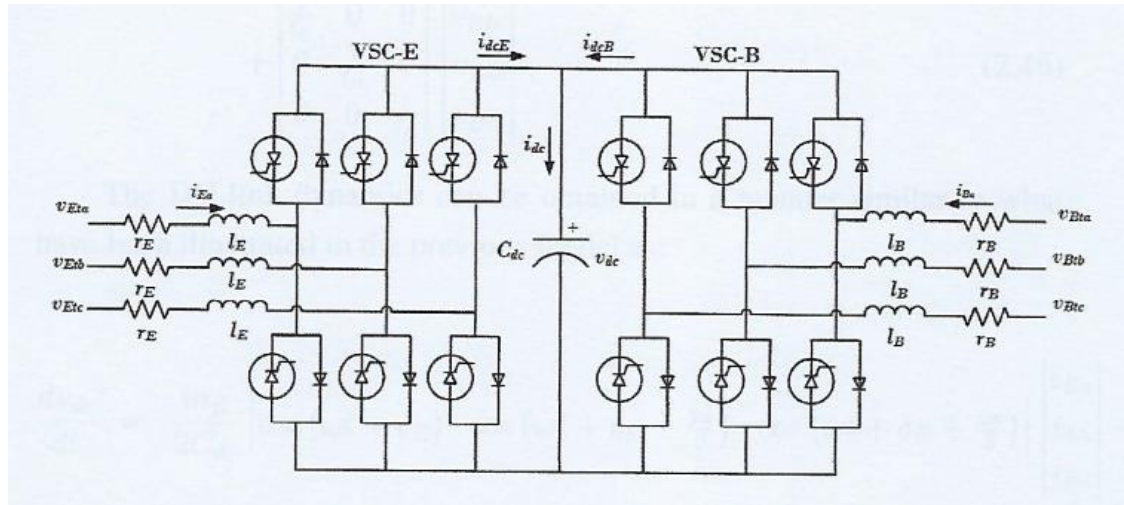


Figure (3.9)

UPFC Three Phase Schematic Diagram

The injected voltage to the converters assumed to be a pure sin wave signals by neglecting the higher order frequency components formed due to switching. The UPFC dynamic model can be represented by the DC link dynamic model which compose of the series current, shunt current, modulation indexes and angles of both converters. The DC link dynamic model will be determined as shown below.

$$\nu_{Eabc} = \frac{m_E \nu dc}{2} \cos \left( \omega t + \delta_E \pm \frac{2\pi}{3} \right) \quad (3.13)$$

$$\nu_{Babc} = \frac{m_B \nu dc}{2} \cos \left( \omega t + \delta_B \pm \frac{2\pi}{3} \right) \quad (3.14)$$

$$\begin{aligned} \frac{1}{\omega_B} \left| \begin{array}{c} \frac{di_{Ea}}{dt} \\ \frac{di_{Eb}}{dt} \\ \frac{di_{Ec}}{dt} \end{array} \right| &= \left| \begin{array}{ccc} -\frac{r_E}{l_E} & 0 & 0 \\ 0 & -\frac{r_E}{l_E} & 0 \\ 0 & 0 & -\frac{r_E}{l_E} \end{array} \right| \left| \begin{array}{c} i_{Ea} \\ i_{Eb} \\ i_{Ec} \end{array} \right| - \frac{m_E \nu dc}{2l_E} \left| \begin{array}{c} \cos(\omega t + \delta_E) \\ \cos\left(\omega t + \delta_E + \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \delta_E + \frac{4\pi}{3}\right) \end{array} \right| \\ + \left| \begin{array}{ccc} \frac{1}{l_E} & 0 & 0 \\ 0 & \frac{1}{l_E} & 0 \\ 0 & 0 & \frac{1}{l_E} \end{array} \right| \left| \begin{array}{c} \nu_{Eta} \\ \nu_{Etb} \\ \nu_{Etc} \end{array} \right| & \end{aligned} \quad (3.15)$$

$$\begin{aligned}
\frac{1}{\omega_B} \left| \begin{array}{c} \frac{di_{Ba}}{dt} \\ \frac{di_{Bb}}{dt} \\ \frac{di_{Bc}}{dt} \end{array} \right| &= \left| \begin{array}{ccc} -\frac{r_B}{l_B} & 0 & 0 \\ 0 & -\frac{r_B}{l_B} & 0 \\ 0 & 0 & -\frac{r_B}{l_B} \end{array} \right| \left| \begin{array}{c} i_{Ba} \\ i_{Bb} \\ i_{Bc} \end{array} \right| - \frac{m_B \nu_{dc}}{2l_B} \left| \begin{array}{c} \cos(\omega t + \delta_B) \\ \cos\left(\omega t + \delta_B + \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \delta_B + \frac{4\pi}{3}\right) \end{array} \right| \\
+ \left| \begin{array}{ccc} \frac{1}{l_B} & 0 & 0 \\ 0 & \frac{1}{l_B} & 0 \\ 0 & 0 & \frac{1}{l_B} \end{array} \right| \left| \begin{array}{c} \nu_{Bta} \\ \nu_{Btb} \\ \nu_{Btb} \end{array} \right| & \\
\end{aligned} \tag{3.16}$$

$$\begin{aligned}
\frac{1}{\omega_B} \frac{d\nu_{dc}}{dt} &= \frac{m_E}{2C_{dc}} \left| \cos(\omega t + \delta_E) \cos\left(\omega t + \delta_E + \frac{2\pi}{3}\right) \cos\left(\omega t + \delta_E + \frac{4\pi}{3}\right) \right| \left| \begin{array}{c} i_{Ea} \\ i_{Eb} \\ i_{Ec} \end{array} \right| + \\
&\frac{m_B}{2C_{dc}} \left| \cos(\omega t + \delta_B) \cos\left(\omega t + \delta_B + \frac{2\pi}{3}\right) \cos\left(\omega t + \delta_B + \frac{4\pi}{3}\right) \right| \\
&\left| \begin{array}{c} i_{Ba} \\ i_{Bb} \\ i_{Bc} \end{array} \right| \\
\end{aligned} \tag{3.17}$$

$$\begin{aligned}
\frac{1}{\omega_B} \begin{vmatrix} \frac{di_{Ed}}{dt} \\ \frac{di_{Eq}}{dt} \\ \frac{di_{E0}}{dt} \end{vmatrix} &= \begin{vmatrix} 0 & -\omega_O & 0 \\ \omega_O & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix} \begin{vmatrix} i_{Ed} \\ i_{Eq} \\ i_{E0} \end{vmatrix} + \begin{vmatrix} -\frac{r_E}{l_E} & 0 & 0 \\ 0 & -\frac{r_E}{l_E} & 0 \\ 0 & 0 & -\frac{r_E}{l_E} \end{vmatrix} \begin{vmatrix} i_{Ed} \\ i_{Eq} \\ i_{E0} \end{vmatrix} - \\
\frac{m_E \nu_{dc}}{2l_E} \begin{vmatrix} \cos \delta_E \\ \sin \delta_E \\ 0 \end{vmatrix} &+ \begin{vmatrix} \frac{1}{l_E} & 0 & 0 \\ 0 & \frac{1}{l_E} & 0 \\ 0 & 0 & \frac{1}{l_E} \end{vmatrix} \begin{vmatrix} \nu_{Etd} \\ \nu_{Etq} \\ \nu_{Et0} \end{vmatrix}
\end{aligned} \tag{3.18}$$

$$\begin{aligned}
\frac{1}{\omega_B} \begin{vmatrix} \frac{di_{Bd}}{dt} \\ \frac{di_{Bq}}{dt} \\ \frac{di_{B0}}{dt} \end{vmatrix} &= \begin{vmatrix} 0 & -\omega_O & 0 \\ \omega_O & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix} \begin{vmatrix} i_{Bd} \\ i_{Bq} \\ i_{B0} \end{vmatrix} + \begin{vmatrix} -\frac{r_B}{l_B} & 0 & 0 \\ 0 & -\frac{r_B}{l_B} & 0 \\ 0 & 0 & -\frac{r_B}{l_B} \end{vmatrix} \begin{vmatrix} i_{Bd} \\ i_{Bq} \\ i_{B0} \end{vmatrix} - \\
\frac{m_B \nu_{dc}}{2l_B} \begin{vmatrix} \cos \delta_B \\ \sin \delta_B \\ 0 \end{vmatrix} &+ \begin{vmatrix} \frac{1}{l_B} & 0 & 0 \\ 0 & \frac{1}{l_B} & 0 \\ 0 & 0 & \frac{1}{l_B} \end{vmatrix} \begin{vmatrix} \nu_{Btd} \\ \nu_{Btq} \\ \nu_{Bt0} \end{vmatrix}
\end{aligned} \tag{3.19}$$

$$\begin{aligned}
\frac{1}{\omega_B} \frac{d\nu_{dc}}{dt} = \frac{3m_E}{4C_{dc}} \left| \begin{array}{ccc} \cos \delta_E & \sin \delta_E & 0 \end{array} \right| \left| \begin{array}{c} i_{Ed} \\ i_{Eq} \\ i_{E0} \end{array} \right| + \\
\frac{3m_B}{4C_{dc}} \left| \begin{array}{ccc} \cos \delta_B & \sin \delta_B & 0 \end{array} \right| \left| \begin{array}{c} i_{Bd} \\ i_{Bq} \\ i_{B0} \end{array} \right|
\end{aligned} \tag{3.20}$$

$$\begin{aligned}
\left| \begin{array}{c} \nu_{Etd} \\ \nu_{Etq} \end{array} \right| = \left| \begin{array}{cc} 0 & x_E \\ -x_E & 0 \end{array} \right| \left| \begin{array}{c} i_{Ed} \\ i_{Eq} \end{array} \right| + \frac{m_E \nu_{dc}}{2} \left| \begin{array}{c} \cos \delta_E \\ \sin \delta_E \end{array} \right|
\end{aligned} \tag{3.21}$$

$$\begin{aligned}
\left| \begin{array}{c} \nu_{Btd} \\ \nu_{Btq} \end{array} \right| = \left| \begin{array}{cc} 0 & x_B \\ -x_B & 0 \end{array} \right| \left| \begin{array}{c} i_{Bd} \\ i_{Bq} \end{array} \right| + \frac{m_B \nu_{dc}}{2} \left| \begin{array}{c} \cos \delta_B \\ \sin \delta_B \end{array} \right|
\end{aligned} \tag{3.22}$$

$$\begin{aligned}
\frac{1}{\omega_B} \frac{d\nu_{dc}}{dt} = \frac{3m_E}{4C_{dc}} \left| \begin{array}{cc} \cos \delta_E & \sin \delta_E \end{array} \right| \left| \begin{array}{c} i_{Ed} \\ i_{Eq} \end{array} \right| + \frac{3m_B}{4C_{dc}} \left| \begin{array}{cc} \cos \delta_B & \sin \delta_B \end{array} \right| \left| \begin{array}{c} i_{Bd} \\ i_{Bq} \end{array} \right|
\end{aligned} \tag{3.23}$$

### 3.4.4 Modelling of the SMIB with UPFC

The UPFC is incorporated in a Single machine to infinite bus (SMIB) system to test and analyse the entire system performance as shown in Figure (3.10). Model number 1.0 of a synchronous generator with IEEE ST1A excitation system will be adopted as it is used in most of the dynamic studies of power system such as the studied performed by Abido M. (2005) and Alqallaf S. A.(2015).

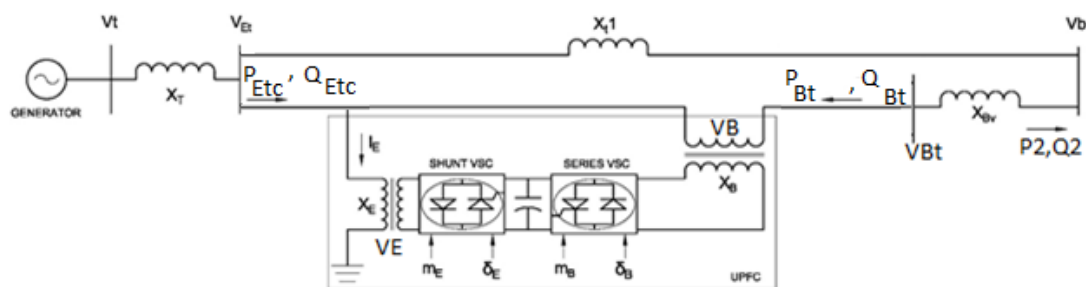


Figure (3.10)

SMIB system with UPFC

The non-linear model of the SMIB is shown below:

$$\frac{d\delta}{dt} = \omega_B \omega_r \quad (3.24)$$

$$\frac{d\omega_r}{dt} = \frac{1}{M} \left( -D\omega_r + P_m - P_e \right) \quad (3.25)$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}} \left( -E'_q + E_{fd} - (x_d - x'_d) i_d \right) \quad (3.26)$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A} \left( -E_{fd} + K_A (V_{ref} - V_t) \right) \quad (3.27)$$

$$P_e = v_d i_d + v_q i_q \quad (3.28)$$

$$V_t = \sqrt{v_q^2 + v_d^2} \quad (3.29)$$

$$v_q = E'_q - x'_d i_d \quad (3.30)$$

$$v_d = x_q i_q \quad (3.31)$$

Where,  $M$  is the generator moment of inertia,  $D$  is the friction and winding torque constant,  $\omega_B$  is the base synchronous speed,  $\delta$  is the generator rotor angle,  $\omega_r$  generator relative angular speed,  $E'_q$  internal transient generator voltage,  $E_{fd}$  generator field voltage,  $V_t$  generator terminal voltage,  $T'_{d0}$  open circuit transient time constant,  $T_A$  time constant,  $K_A$  gain of the excitation system and  $V_{ref}$  is the generator reference voltage.

So, in order to analysis the single machine to infinite bus (SMIB) along with the incorporated UPFC, the network currents in term of the system states and input variables to be extracted from figure (3.10).

$$I_t = \frac{V_t - V_{Et}}{j x_t} \quad (3.32)$$

$$j x_t I_t = V_t - V_{Et} \quad (3.33)$$

Using D-Q Transformation

$$j x_t \begin{pmatrix} i_q - j i_d \end{pmatrix} e^{j\delta} = \begin{pmatrix} v_q - j v_d \end{pmatrix} e^{j\delta} - \begin{pmatrix} v_{Etq} - j v_{Etd} \end{pmatrix} e^{j\delta} \quad (3.34)$$

$$v_{Etq} = v_q - x_t i_d \quad (3.35)$$

$$v_{Etd} = v_d + x_t i_q \quad (3.36)$$

From equation (3.30) and (3.31)

$$v_{Etq} = E' q - x_{dt} i_d \quad (3.37)$$

$$v_{Etd} = x_{qt} i_q \quad (3.38)$$

Where,

$$x_{dt} = x'_d + x_t \quad (3.39)$$

$$x_{qt} = x_q + x_t \quad (3.40)$$

From the upper uncompensated transmission line

$$I_1 = \frac{V_{Et} - V_b}{j x_{t1}} \quad (3.41)$$

Using D-Q Transformation

$$\left( i_{1q} - j i_{1d} \right) = \frac{1}{j x_{t1}} \left( v_{Etq} - j v_{Etd} - V_b \cos \delta + j V_b \sin \delta \right) \quad (3.42)$$

Hence,

$$i_{1q} = -\frac{1}{x_{t1}} \left( v_{Etd} - V_b \sin \delta \right) \quad (3.43)$$

$$i_{1d} = \frac{1}{x_{t1}} \left( v_{Etq} - V_b \cos \delta \right) \quad (3.44)$$

From the lower compensated transmission line

$$I_B = \frac{V_{ET} - V_B - V_b}{j x_{BB}} \quad (3.45)$$

Where,

$$x_{BB} = x_{Bv} + x_B \quad (3.46)$$

D-Q Transformation

$$\left( i_{Bq} - j i_{Bd} \right) = \frac{1}{j x_{BB}} \left( v_{Etq} - j v_{Etd} - \frac{m_B v_{dc}}{2} (\sin \delta_B - j \cos \delta_B) - V_b (\cos \delta - j \sin \delta) \right) \quad (3.47)$$

So, the D-Q currents of the lower compensated transmission line are:

$$i_{Bq} = -\frac{1}{x_{BB}} \left( v_{Etd} - \frac{m_B v_{dc}}{2} \cos \delta_B - V_b \sin \delta \right) \quad (3.48)$$

$$i_{Bd} = \frac{1}{x_{BB}} \left( v_{Etq} - \frac{m_B v_{dc}}{2} \sin \delta_B - V_b \cos \delta \right) \quad (3.49)$$

From the lower compensated transmission line/shunt branch:

$$I_E = \frac{V_{ET} - V_E}{jX_E} \quad (3.50)$$

D-Q Transformation

$$\begin{pmatrix} i_{Eq} - ji_{Ed} \end{pmatrix} = \frac{1}{jX_E} \left( v_{Etq} - j v_{Etd} - \frac{m_E v_{dc}}{2} (\sin \delta_E - j \cos \delta_E) \right) \quad (3.51)$$

So, the D-Q voltages of the shunt branch of the lower compensated transmission line are:

$$v_{Etq} = X_E i_{Ed} + \frac{m_E v_{dc}}{2} \sin \delta_E \quad (3.52)$$

$$v_{Etd} = -X_E i_{Eq} + \frac{m_E v_{dc}}{2} \cos \delta_E \quad (3.53)$$

Applying K.C.L at UPFC Sending bus to get the following equations:

$$i_d = i_{Ed} + i_{1d} + i_{Bd} \quad (3.54)$$

$$i_q = i_{Eq} + i_{1q} + i_{Bq} \quad (3.55)$$

Substituting the Value of  $v_{Etq}$  and  $v_{Etd}$  to reformulate the current components in term of  $i_{Ed}$  and  $i_{Eq}$

$$i_{1d} = \frac{1}{x_{t1}} \left( x_E i_{Ed} + \frac{m_E v_{dc}}{2} \sin \delta_E - V_b \cos \delta \right) \quad (3.56)$$

$$i_{1q} = -\frac{1}{x_{t1}} \left( -x_E i_{Eq} + \frac{m_E^v dc}{2} \cos \delta_E - V_b \sin \delta \right) \quad (3.57)$$

$$i_{Bd} = \frac{1}{x_{BB}} \left( x_E i_{Ed} + \frac{m_E^v dc}{2} \sin \delta_E - \frac{m_B^v dc}{2} \sin \delta_B - V_b \cos \delta \right) \quad (3.58)$$

$$i_{Bq} = -\frac{1}{x_{BB}} \left( -x_E i_{Eq} + \frac{m_E^v dc}{2} \cos \delta_E - \frac{m_B^v dc}{2} \cos \delta_B - V_b \sin \delta \right) \quad (3.59)$$

Substituting the currents in the  $i_d$  and  $i_q$  :

$$i_d = C_1 i_{Ed} + C_2 \frac{m_E^v dc}{2} \sin \delta_E - C_3 \frac{m_B^v dc}{2} \sin \delta_B - C_2 V_b \cos \delta \quad (3.60)$$

$$i_q = C_1 i_{Eq} - C_2 \frac{m_E^v dc}{2} \cos \delta_E + C_3 \frac{m_B^v dc}{2} \cos \delta_B + C_2 V_b \sin \delta \quad (3.61)$$

Since,

$$C_1 = 1 + \frac{x_E}{x_{BB}} + \frac{x_E}{x_{t1}} \quad (3.62)$$

$$C_2 = \frac{x_{BB} + x_{t1}}{x_{BB} x_{t1}} \quad (3.63)$$

$$C_3 = \frac{x_{t1}}{x_{BB} x_{t1}} \quad (3.64)$$

Substituting  $i_d$  and  $i_q$  in (3.37) and (3.38) :

$$v_{Eq} = E'_q - x_{dt} C_1 i_{Ed} - x_{dt} C_2 \frac{m_E^v dc}{2} \sin \delta_E + x_{dt} C_3 \frac{m_B^v dc}{2} \sin \delta_B + x_{dt} C_2 V_b \cos \delta \quad (3.65)$$

$$\nu_{Etd} = x_{qt} C_1 i_{Eq} - x_{qt} C_2 \frac{m_E \nu_{dc}}{2} \cos \delta_E + x_{qt} C_3 \frac{m_B \nu_{dc}}{2} \cos \delta_B + x_{qt} C_2 V_b \sin \delta \quad (3.66)$$

$$\therefore i_{Ed} = \frac{1}{x_E} \left( \nu_{Etq} - \frac{m_E \nu_{dc}}{2} \sin \delta_E \right) \quad (3.67)$$

$$i_{Eq} = -\frac{1}{x_E} \left( \nu_{Etd} - \frac{m_E \nu_{dc}}{2} \cos \delta_E \right) \quad (3.68)$$

By substituting the values of  $\nu_{Etq}$  and  $\nu_{Etd}$  in  $i_{Ed}$  and  $i_{Eq}$ , this result in:

$$i_{Ed} = \frac{x_{Bt}}{x_{d\Sigma}} E' - \frac{x_{d1}}{x_{d\Sigma}} \frac{m_E \nu_{dc}}{2} \sin \delta_E + \frac{x_{d2}}{x_{d\Sigma}} \frac{m_B \nu_{dc}}{2} \sin \delta_B + \frac{x_{d3}}{x_{d\Sigma}} V_b \cos \delta \quad (3.69)$$

$$i_{Eq} = \frac{x_{q1}}{x_{q\Sigma}} \frac{m_E \nu_{dc}}{2} \cos \delta_E - \frac{x_{q2}}{x_{q\Sigma}} \frac{m_B \nu_{dc}}{2} \cos \delta_B - \frac{x_{q3}}{x_{q\Sigma}} V_b \sin \delta \quad (3.70)$$

Where,

$$x_{Bt} = x_{BB} x_{t1} \quad (3.71)$$

$$x_{d\Sigma} = x_{BB} x_{t1} (x_E + x_{dt}) + x_{dt} x_E (x_{BB} + x_{t1}) \quad (3.72)$$

$$x_{d1} = x_{BB} x_{t1} + x_{dt} (x_{BB} + x_{t1}) \quad (3.73)$$

$$x_{d2} = x_{dt} x_{t1} \quad (3.74)$$

$$x_{d3} = x_{dt} (x_{BB} + x_{t1}) \quad (3.75)$$

$$x_{q\Sigma} = x_{BB} x_{t1} (x_E + x_{qt}) + x_{qt} x_E (x_{BB} + x_{t1}) \quad (3.76)$$

$$x_{q1} = x_{BB}x_{t1} + x_{qt} (x_{BB} + x_{t1}) \quad (3.77)$$

$$x_{q2} = x_{qt}x_{t1} \quad (3.78)$$

$$x_{q3} = x_{qt} (x_{BB} + x_{t1}) \quad (3.79)$$

By substituting the obtained expression of  $i_{Ed}$  and  $i_{Eq}$  into equations (3.58) to (3.61):

$$i_{Bd} = \frac{x_{Et}}{x_{d\Sigma}} E' q + \frac{x_{d2}}{x_{d\Sigma}} \frac{m_E \nu_{dc}}{2} \sin \delta_E - \frac{x_{d4}}{x_{d\Sigma}} \frac{m_B \nu_{dc}}{2} \sin \delta_B - \frac{x_{d5}}{x_{d\Sigma}} V_b \cos \delta \quad (3.80)$$

$$i_{Bq} = \frac{x_{q2}}{x_{q\Sigma}} \frac{m_E \nu_{dc}}{2} \cos \delta_E - \frac{x_{q4}}{x_{q\Sigma}} \frac{m_B \nu_{dc}}{2} \cos \delta_B - \frac{x_{q5}}{x_{q\Sigma}} V_b \sin \delta \quad (3.81)$$

$$i_d = \frac{x_{c1}}{x_{d\Sigma}} E' q - \frac{x_{Bt}}{x_{d\Sigma}} \frac{m_E \nu_{dc}}{2} \sin \delta_E + \frac{x_{Et}}{x_{d\Sigma}} \frac{m_B \nu_{dc}}{2} \sin \delta_B - \frac{x_{c2}}{x_{d\Sigma}} V_b \cos \delta \quad (3.82)$$

$$i_q = \frac{x_{Bt}}{x_{q\Sigma}} \frac{m_E \nu_{dc}}{2} \cos \delta_E - \frac{x_{Et}}{x_{q\Sigma}} \frac{m_B \nu_{dc}}{2} \cos \delta_B + \frac{x_{c2}}{x_{q\Sigma}} V_b \sin \delta \quad (3.83)$$

Where,

$$x_{Et} = x_E x_{t1} \quad (3.84)$$

$$x_{d4} = x_{t1} (x_E + x_{dt}) + x_{dt} x_E \quad (3.85)$$

$$x_{d5} = x_{t1} (x_E + x_{dt}) \quad (3.86)$$

$$x_{q4} = x_{t1} (x_E + x_{qt}) \quad (3.87)$$

$$x_{q5} = x_{t1} (x_E + x_{qt}) \quad (3.88)$$

$$x_{c1} = x_{BB}x_{t1} + x_E(x_{BB} + x_{t1}) \quad (3.89)$$

The complete model of the UPFC and system can be described by using the equations of the UPFC state-state model, the equation of the  $\frac{dv_{dc}}{dt}$  from the UPFC dynamic model and the current equations (3.69), (3.70), (3.80), (3.81), (3.82) and (3.83).

### 3.4.5 Control Strategy

The UPFC will be controlled by manipulating the modulation indexes and phase angles of the injected voltages in the series VSC and shunt VSC. The active power, reactive power, bus voltage, DC link voltage will be controlled by phase angle  $\delta_B$ , modulation index  $m_B$ , modulation index  $m_E$  and phase angle  $\delta_E$  respectively as shown previously in figure (3.6). The following Controllers will be used to control the system:

- PI Controller
- MPC Controller
- NNPC Controller
- NARMA-L2 Controllers

The first controller is a traditional linear PI controller, and the other three are intelligent non-linear controllers based on using Predictive Scheme and Artificial Neural Networks. PI Controllers parameters  $K_p$  and  $K_i$  are selected based on the study made by S. A. Alqallaf (2015) to get the best values of PI parameters by using Biogeography-Based Optimization (BBO). The PI performance will be compared with Predictive controller (MPC) and ANN Controllers namely NNPC and NARMA-L2.

## 3.5 Initial Conditions of UPFC and SMIB

### 3.5.1 Initial Conditions

Matlab Program (.m) file was used to calculate the initial conditions of the UPFC in SMIB as shown in the block diagram Figure (3.8). The program details are maintained in Appendix (B) and the final result are shown below in table (3.1):

| Parameters | Value        |
|------------|--------------|
| Pes        | 1 p.u        |
| Qes        | 0.04 p.u     |
| VEt        | 1.05 p.u     |
| QBts       | 0.01 p.u     |
| PBts       | 0.5 p.u      |
| Pets       | 0.5 p.u      |
| tht        | 0.3806 rad.  |
| thEt       | 0.2898 rad.  |
| thBt       | 0.3193 rad.  |
| Vt         | 1.0495 p.u   |
| VBt        | 0.9557 p.u   |
| thE        | 0.2942 rad.  |
| thB        | -0.4126 rad. |
| VE         | 1.0696 p.u   |
| VB         | 0.1247 p.u   |
| Pe2s       | 0.5 p.u      |
| Qe2s       | 0.01 p.u     |

Table (3.1)

System Initial Conditions

### 3.5.2 Models Simulation

The obtained results from the initial conditions calculations of the UPFC and SMIB system models were used while modelling the entire

system by using the Simulink. The model details of the synchronous generator, UPFC Model, UPFC Controller, System Currents and System outputs were all shown thoroughly in Appendix (C).

### **3.6 Conclusion**

This chapter described the UPFC model and modes of operation in details. Several literatures related to the steady-state and dynamic model of UPFC were reviewed. The Nabavi-Niaki, A., & Iravani, M. (1996,Nov) model was adopted and the UPFC along with the SMIB system equations were drawn accordingly. The equations will be used in Chapter 5 to solve the load flow problem and then obtain all the system state variables and UPFC parameters.

# **Chapter 4**

## **UPFC Controller Design Using Predictive and Artificial Neural Network Schemes**

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## Chapter 4

# UPFC Controller Design Using Predictive and Artificial Neural Network Schemes

### 4.1 Introduction

Controller design of the UPFC is very important to stabilize the system and control the power flow parameters such as the voltage, impedance and the phase angle. In this chapter, various types of controllers will be introduced in order to evaluate their performance and recommend the most effective ones.

### 4.2 PI Controller

The PI control scheme is named after its two correcting terms, which are the proportional and integral terms, are 'e' weighted to calculate the output of the PI controller as shown in Figure (4.1).

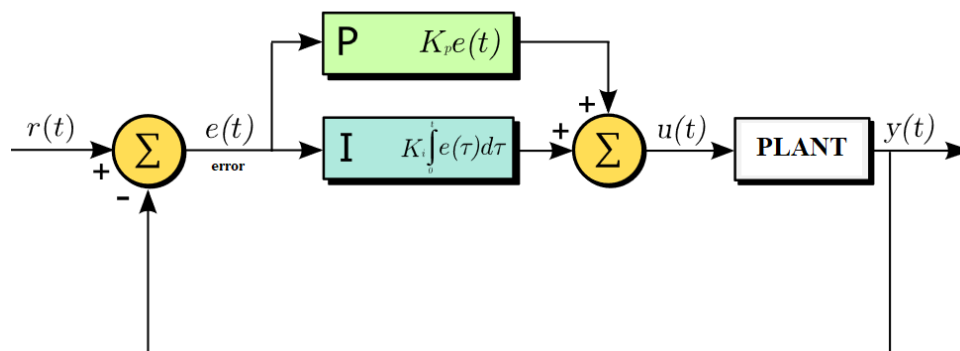


Figure (4.1)

PI Controller

The mathematical form of the PI controllers can be expressed as follows:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t) \cdot dt \quad (4.1)$$

The first term of the above equation can assist in reducing the steady state error, thus make the system more stable and also help in damping the system oscillation faster. While the second term help to return the controlled variable back to exact set point. PI Controller will be used in this study as a conventional controller to compare and test the outcome of new proposed adaptive controller.

In this research, PI controllers will be used to control the system controlled variable in the SMIB which is integrated with the UPFC. The system variables are the real power, reactive power, D.C link voltage, bus Voltage...etc. In general, the PI controllers coefficients can be tuned manually to obtain the desired output. In order to ensure that the system outputs are optimum, the PI coefficients are chosen to be the same as the ones obtained by using BBO which was performed and obtained in S. A. Alqalaf (2015) study as shown in Figure (4.2). These PI controllers results will be taken as a reference to compare and evaluate the output performance of the new proposed controllers which will be introduced in this chapter.

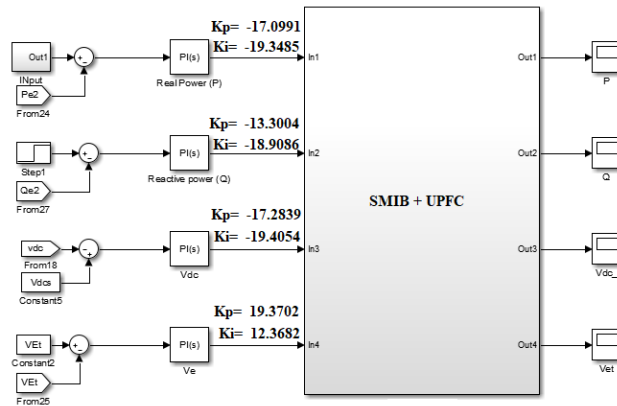


Figure (4.2)

### SMIB with UPFC and Controlled by PI Controllers

The PI controllers are placed in four loops in order to regulate the real power in line 2, reactive power in line 2, D.C voltage between the UPFC converters and finally the sending bus voltage as shown in figure (4.3). The PI controllers outputs will be fed to UPFC which is connected to line 2 in SMIB and the outputs will be checked accordingly.

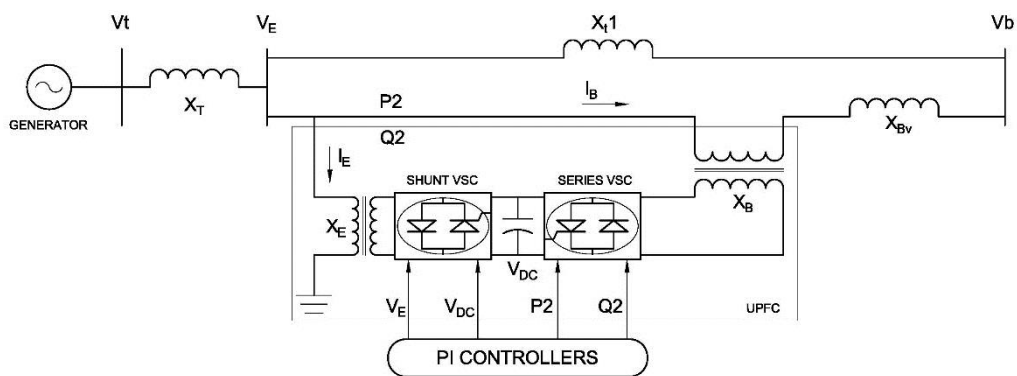


Figure (4.3)

### PI Controller variables

## 4.3 Model Predictive Controller

In 1970's, engineering at Shell Oil introduced their own MPC technology with an initial application in 1973 (Carlos E. et. al. 1989). A comprehensive study of self-adaptive long range predictive control methods was introduced by R.M.C.De Keyser et. al. (1988). For the selection of predication horizon, R. Scattolini and S. Bittanti (1990) provided some simple rules relevant to the plant step response or impulse response. Then, based on D.W. Clarke and R. Scattolini (1991), the constrained receding horizon predictive control optimizes cost function to stabilize the plant. Model Predictive Control concept has been extensively studied and widely accepted in industrial applications. The main reasons for such popularity of the predictive control strategies are the intuitiveness and the explicit constraint handling. The predictive controllers are used in many areas, where high-quality control is required (Thomas A. Badgwell 1997)

MPC concept was used at the beginning to meet the specialized control needs of power plants and petroleum refineries and the concept extended to include a wide variety of applications in different area including the chemical, food, processing, automotive and aerospace applications. MPC refer to a type of computer control algorithms that utilize an explicit process model to predict the future response of the plant (S. Qin & A. Badgwell 2002).

### 4.3.1 MPC Concept

The Model Predictive Controller used in Single Input Single Output (SISO), Muti Input Multi Output (MIMO), simple or complex processes. It is being used in a wide variety of industries and power applications.

The concept behind MPC controller is that it takes the reference signals and the plant outputs and generate control outputs just like any other controller except it is using the inboard model of the plant to predict the behaviour of the plant in future by any of the following method such as Kalman Predictor, BJ model, ARX, ARMAX or ...etc (Sachin C. Patwardhan, 2014). Future output predication is effected by the past state on future outputs, future inputs on future outputs and model mismatch.

The predicted behaviour of the plant will be fed to an optimizer to adjust of the value of the control outputs to make sure that the predicted plant outputs track the reference signals. MPC is considered as a popular controller in industrial applications because at every time step the process executed in the control algorithm, there is optimization involved to give better control outputs as shown below in the Figure (4.4) (P.E. Orukpe. 2005).

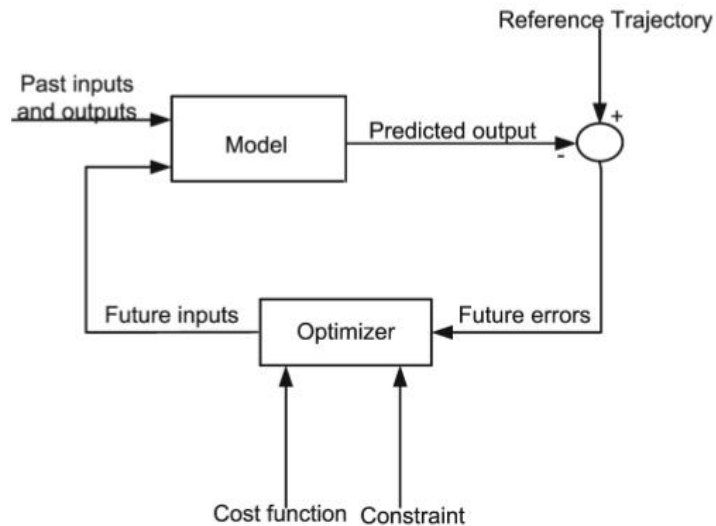


Figure (4.4)

Basic Structure of MPC

Model Predictive Control optimize future plant behaviour at each control interval by computing a sequence of future manipulated variable adjustments. MPC is an approach to control design but not considered as a specific algorithm. The user interprets the approach to define an algorithm suitable for their own requirements. Model Predictive controller, predict the future performance of the system by using the current inputs, outputs and future controller actions as shown in Figure (4.5) (Eduardo F. Camacho & Carlos Bordons. 2007).

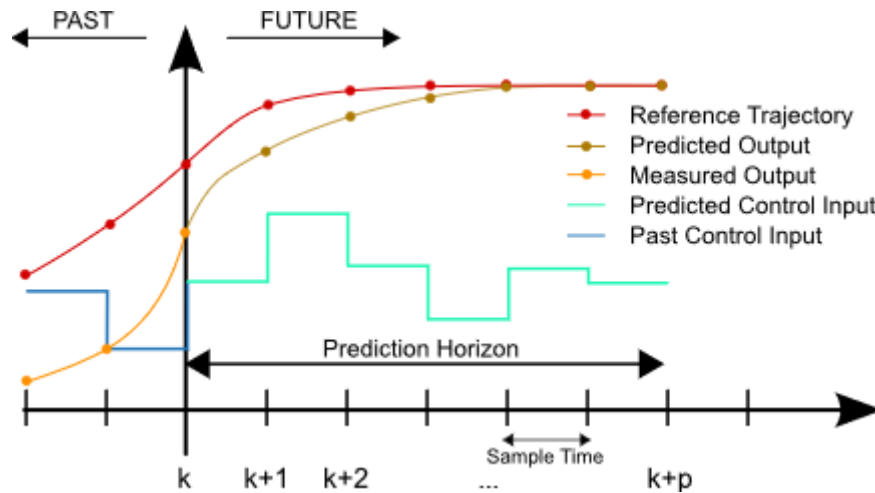


Figure (4.5)

Basic Philosophy of MPC

### 4.3.2 Prediction Horizon

The prediction horizon should be beyond the system key dynamics of a process in order to avoid system divergence. Receding Horizon Control (RHC) in MPC means that the controller shall continually update the predictions period to take in account of the most recent target and measurement data. So, the end point of the predication period moves away as the start point of the predication period is moving forward to keep the same horizon of the predication period (Sachin C. Patwardhan, 2014). The MPC main components are:

- i. Process model: to describe the process dynamics.
- ii. Objective function: can be referred as a cost function. Receding horizon method is considered to follow the predefined trajectory to predict future outputs taking into account the current and future constrains. The output calculated at each interval in horizon based on values at time  $t$ . Then, it will be sent to the controller. An example of a non-linear cost function for optimization is given by Eduardo F. Camacho & Carlos Bordons (2007).:

$$J = \sum_{i=1}^N w_{xi}(r_i - x_i)^2 + \sum_{i=1}^N w_{ui} \Delta u_i^2 \quad (4.2)$$

without violating constraints (low/high limits) with

$x_i:i^{th}$  Controlled variable

$r_i:i^{th}$  reference variable

$u_i:i^{th}$  manipulated variable

$w_{xi}$ : weighting coefficient reflecting the relative importance of  $x_i$

$w_{ui}$ : weighting coefficient penalizing relative big change in  $u_i$

- iii. Controller: At each step, the optimization problem is formulated over the predication horizon. The control signals will be applied to the plant and in the next step will be recomputed based on the new system states as shown below in Figure (4.6) (Gorinevsky, 2005).

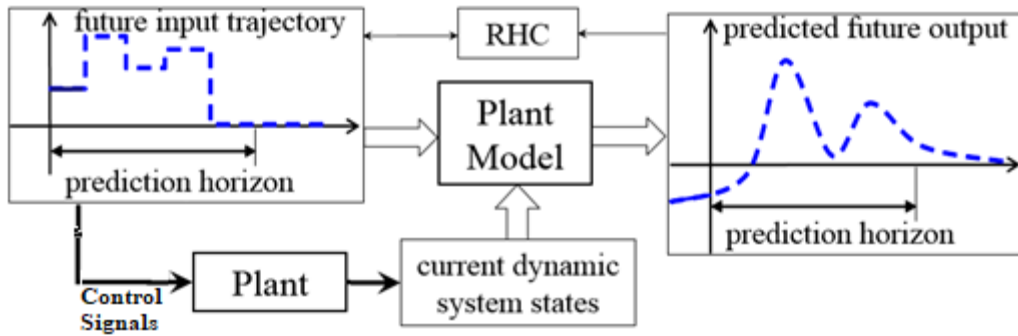


Figure (4.6).

MPC Control Scheme

### 4.3.3 MPC Design

The linear discrete model is logical basis for any predication and the common discrete state space model can be expressed as below:

$$x_{k+1} = Ax_k + Bu_k \quad (4.3)$$

$$y_k = Cx_k + d_k \quad (4.4)$$

Where 'x', 'y', 'u' and 'd' representing the State, Output, Control Input and Disturbance respectively. Discrete models are one step ahead predication model. So, at a sample 'k' the data can be determined for sample 'k+1'.

$$y_{k+1} = Cx_{k+1} + d_{k+1} \quad (4.5)$$

by substituting  $x_{k+1}$  from equation (4.3)

$$y_{k+1} = CAx_k + CBu_k + d_{k+1} \quad (4.6)$$

To simplify the equations, the disturbance could be assumed as follows:

$$d_{k+1} = d_k \quad (4.7)$$

The one-step ahead predication can be used recursively to find an n-step ahead predication as follows:

$$x_{k+1} = Ax_k + Bu_k \quad (4.8)$$

$$x_{k+2} = Ax_{k+1} + Bu_{k+1} = A \left[ Ax_k + Bu_k \right] + Bu_{k+1} \quad (4.9)$$

$$x_{k+3} = Ax_{k+2} + Bu_{k+2} = A \left[ \left[ Ax_k + Bu_k \right] + Bu_{k+1} \right] + Bu_{k+2} \quad (4.10)$$

$$x_{k+4} = Ax_{k+3} + Bu_{k+3} = A \left[ A \left[ \left[ Ax_k + Bu_k \right] + Bu_{k+1} \right] + Bu_{k+2} \right] + Bu_{k+3} \quad (4.11)$$

Rearranging the equation (4.9), (4.10) and (4.11) will be as follow:

$$x_{k+1} = Ax_k + Bu_k \quad (4.12)$$

$$x_{k+2} = A^2 x_k + ABu_k + Bu_{k+1} \quad (4.13)$$

$$x_{k+3} = A^3 x_k + A^2 Bu_k + ABu_{k+1} + Bu_{k+2} \quad (4.14)$$

$$x_{k+4} = A^4 x_k + A^3 Bu_k + A^2 Bu_{k+1} + ABu_{k+2} + ABu_k \quad (4.15)$$

So, the general expiration of the n-step ahead predications are shown below:

$$x_{k+n} = A^n x_k + A^{n-1} Bu_k + A^{n-2} Bu_{k+1} + \dots + ABu_{k+n-2} + Bu_{k+n-1} \quad (4.16)$$

$$y_{k+n} = Cx_{k+n} + d_{k+n} \quad (4.17)$$

$$y_{k+n} = CA^n x_k + C \left( A^{n-1} Bu_k + A^{n-2} Bu_{k+1} + \dots + ABu_{k+n-2} + Bu_{k+n-1} \right) + d_k \quad (4.18)$$

A double subscript will be used as a common notation to determine that the first term is identify the sample of the predication i.e. how many step ahead. The second term represent the sample at which the

predication was made like for example  $x_{k+4/k}$  and  $y_{k+6/k+2}$ . So, equation (4.16) and (4.18) can be written as follows:

$$x_{k+n/k} = A^n x_k + A^{n-1} Bu_{k/k} + A^{n-2} Bu_{k+1/k} + \dots + ABu_{k+n-2/k} + Bu_{k+n-1/k} \quad (4.19)$$

$$y_{k+n/k} = CA^n x_k + C \left( A^{n-1} Bu_{k/k} + A^{n-2} Bu_{k+1/k} + \dots + Bu_{k+n-1/k} \right) + d_k \quad (4.20)$$

It is convenient to spilt the equation into two parts. The first part is based on the current and past measurement and the second part is for future input that remain to be decided. This is for the purpose of choosing the unknown inputs to ensure that the overall predication is satisfactory.

$$y_{k+n/k} = \underbrace{CA^n x_k + d_k}_{\text{1st part}} + \underbrace{C \left( A^{n-1} Bu_{k/k} + A^{n-2} Bu_{k+1/k} + \dots + Bu_{k+n-1/k} \right)}_{\text{2nd part}} \quad (4.21)$$

Writing equation (4.19) in a vector form

$$\begin{bmatrix} X_{k+1/k} \\ X_{k+2/k} \\ \vdots \\ X_{k+n/k} \end{bmatrix} = \begin{bmatrix} Ax_k \\ A^2 x_k \\ \vdots \\ A^n x_k \end{bmatrix} + \begin{bmatrix} Bu_{k/k} \\ ABu_{k/k} + Bu_{k+1/k} \\ \vdots \\ A^{n-1} Bu_{k/k} + \dots + ABu_{k+n-2/k} + Bu_{k+n-1/k} \end{bmatrix} \quad (4.22)$$

$$\begin{array}{c}
\begin{bmatrix} X_{k+1/k} \\ X_{k+2/k} \\ \vdots \\ X_{k+n/k} \end{bmatrix} = \underbrace{\begin{bmatrix} A \\ A^2 \\ \vdots \\ A^n \end{bmatrix}}_{P_x} X_K + \underbrace{\begin{bmatrix} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{n-1}B & A^{n-2}B & \dots & B \end{bmatrix}}_{H_x} \underbrace{\begin{bmatrix} u_{k/k} \\ u_{k+1/k} \\ \vdots \\ u_{k+n-1/k} \end{bmatrix}}_{u_{\rightarrow k}}
\end{array} \quad (4.23)$$

$\underbrace{\hspace{10em}}_{x_{\rightarrow k+1}} \quad \underbrace{\hspace{10em}}_{P_x} \quad \underbrace{\hspace{10em}}_{H_x} \quad \underbrace{\hspace{10em}}_{u_{\rightarrow k}}$

$$\mathbf{x}_{\rightarrow k+1} = \begin{bmatrix} P_x \mathbf{x}_k \end{bmatrix} + \begin{bmatrix} H_x \mathbf{u}_{\rightarrow k} \end{bmatrix} \quad (4.24)$$

Also, writing equation (4.20) in a vector form

$$\begin{array}{c}
\begin{bmatrix} y_{k+1/k} \\ y_{k+2/k} \\ \vdots \\ y_{k+n/k} \end{bmatrix} = \underbrace{\begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^n \end{bmatrix}}_P y_k + \underbrace{\begin{bmatrix} CB & 0 & \dots & 0 \\ CAB & CB & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{n-1}B & CA^{n-2}B & \dots & CB \end{bmatrix}}_H \underbrace{\begin{bmatrix} u_{k/k} \\ u_{k+1/k} \\ \vdots \\ u_{k+n-1/k} \end{bmatrix}}_{u_{\rightarrow k}} + \underbrace{\begin{bmatrix} d_k \\ d_k \\ \vdots \\ d_k \end{bmatrix}}_{Ld}
\end{array} \quad (4.25)$$

$\underbrace{\hspace{10em}}_{y_{\rightarrow k+1}} \quad \underbrace{\hspace{10em}}_P \quad \underbrace{\hspace{10em}}_H \quad \underbrace{\hspace{10em}}_{u_{\rightarrow k}} \quad \underbrace{\hspace{10em}}_{Ld}$

$$\mathbf{y}_{\rightarrow k+1} = \begin{bmatrix} P \mathbf{y}_k + L \mathbf{d}_k \end{bmatrix} + H \mathbf{u}_{\rightarrow k} \quad (4.26)$$

So, it has been noticed from equation (4.24) and (4.26) that the second part of each equation contains of the control output ‘u’ which is only the unknown parameter and can be chosen in such way that the overall predication is desirable. This can be achieved by feeding the predicted behaviour of the plant to an optimizer to adjust of the value of the control outputs to make sure that the predicted plant outputs track the reference signals by minimizing the cost function in equation (4.2). At every time step the process executed in the control algorithm, there is optimization involved to give better control. Matlab toolbox for MPC will be used in order to train and design the controllers for UPFC control variables as shown in Appendix D.

## **4.4 Artificial Neural Network Controller**

### **4.4.1 Introduction**

An artificial neural network is considered as a model of how the human brain works. A biological neural network is an essential part of human brain. It is a highly complex network with the ability to process huge amounts of information simultaneously. A biological neural network consists of the central nervous system, which includes the brain and spinal cord. Moreover, composed of peripheral nervous which contain neurons and pathways associated with sensory inputs and motor response outputs as shown Figure (4.7) (Maad M. 2017).

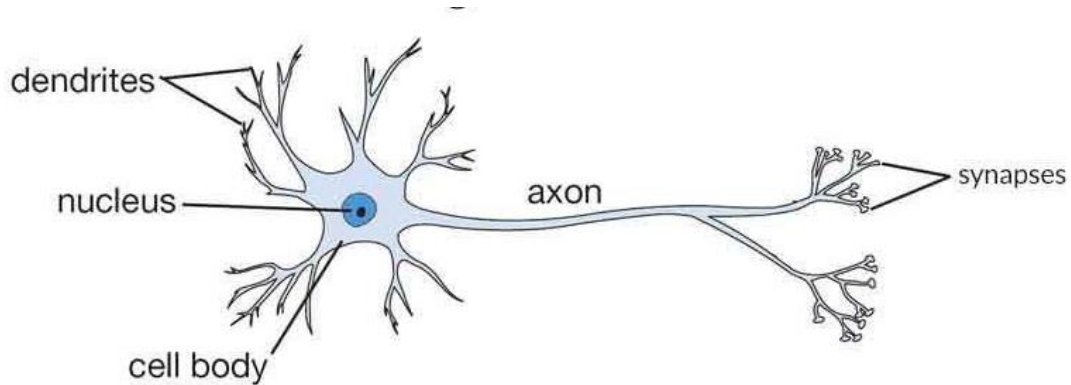


Figure (4.7)  
Biological neuron

The input impulses travel via the sensory portion of the peripheral nervous system to the central nervous system for higher level interpretation to response and convey the action through the peripheral nervous system to relevant part in the human body. So, human brain contains of an enormous number of nerve cells and neurons. The combination of these cells are together creating a very complex network of signal transmission. Each cell collects inputs from all other neural cells it is connected to and if the collected cell information reaches a certain threshold, then it will be conveyed to all the cells it is connected to. The biological neural network compositions can be summarized as below:

- Dendrites: receive electrical signals from other neurons
- cell body: structurally contains of nucleus and organelles, but functionally processes the incoming signal from the dendrites.
- axon: part of the neuron that takes the electrical signals from the cell body to the pre-synaptic terminals.
- presynaptic terminals: Pre-synaptic terminals form the end of the axon where it junctions with another neuron at a specialized

location called a synapse. A synapse is where the axon of one neuron communicates with the dendrites of another neuron.

So, the interconnection of the large number of neurons in the Biological neurons network architecture will allow a rapid communication spanning throughout all areas of the body. Although, Biological neural networks are complex, but Artificial Neural Network model will be the basic structure representation as shown in table (4.1) and Figure (4.8) (Hill R. et. al.2004)

| Structure              | Function    |
|------------------------|-------------|
| Dendrites              | Input       |
| Cell body              | Integration |
| Axon                   | Conduction  |
| Pre-synaptic terminals | Output      |

Table (4.1)

Basic Structure of Biological Neuron

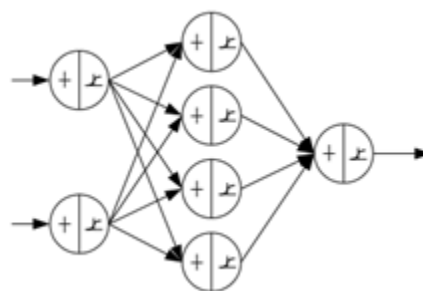


Figure (4.8)

ANN Structure

At outset, the neuro-physiologist Warren McCulloch and mathematician Walter Pitts made the ANN theory in 1943 and introduced

the artificial neurons with the threshold. In 1949, a psychologist Donald Hebb designed the first learning rule for artificial neural networks. His approach was to increase the strength of the connection between two neurons if they are active. Then, the ANN theory made significant progress in the following years and more of different types of ANN were proposed as the powerful computers were being introduced to facilitate such studies.

ANN can be trained after implementation and needs a trainer designed in hardware or software to provide punishments or rewards for the adopted weights. A reward is used for the correct response and lead to no further changes in the weights are required. A punishment indicated the network gave an incorrect response and the connection weight of the affecting neurons need to be adjusted. Training after implementation is a continuous as long as the trainer is enabled. So, ANN is capable to learn and adapt in real time.

ANNs, like human, learn by example. ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurones.

#### **4.4.2 Classifications of ANN**

Neural networks may be classified according to their architecture, learning algorithm used to train the network or the applications.

##### **4.4.2.1 ANNs Architecture-Based Classification**

In general, there are two different classes of neural network architectures.

- a. Feed-forward networks

Feed-forward ANNs allow signals to travel one way only from input to output and the structure of this network it consists of one input layer, one or more hidden layers and an output layer. The input data is presented to the input layer and then are fed as weighted inputs to the first hidden layer, and subsequently the outputs from the first hidden layer are fed as weighted inputs to the second hidden layer as shown in Figure (4.9). This process continues until the output layer is reached. This network is termed a static network as the input signals are fed directly from network input to the network output with no feedback signal as shown below.

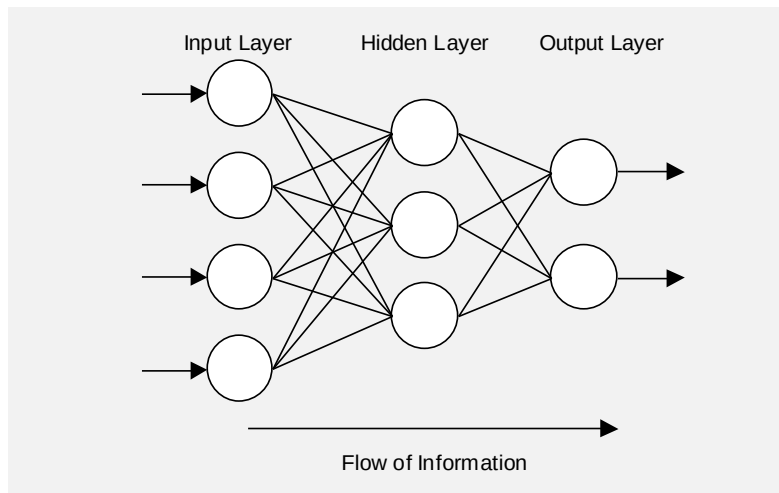


Figure (4.9)

#### Feed-forward Neural Networks

##### b. Feedback networks

The structure of the Feedback network has signals traveling in both directions by introducing loops in the network. So, this network can be distinguished from the static network by that as it has at least one feedback loop as shown below in Figure (4.10). Therefore, the current output of the network depends not only on the current input, but also on the previous outputs or states of the network. The presence of feedback

loops has profound impact on the learning capability of the network and on its performance.

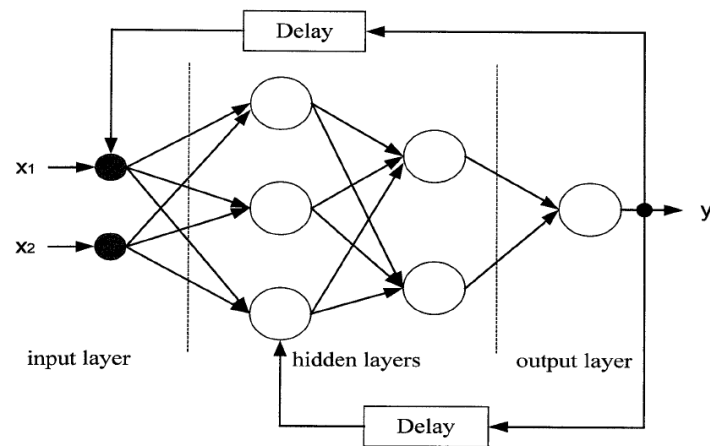


Figure (4.10)

Feedback Neural Networks

#### 4.4.2.2 ANNs Learning-based Classification

The second network classification is based on the learning strategy. There are three major learning algorithms for the neural network, supervised, unsupervised and reinforcement network.

##### a. Supervised learning network

In this network, a supervisor is assumed to be present during the learning process to teach the correct answer for each input pattern. A computation can be made between the network output and the correct desired output to determine the error. An important issue concerning supervised learning is the problem of error convergence, i.e. the minimization of error between the desired and computed unit values. The aim is to determine a set of weights which minimizes the error. One well-known method, which is common to many learning paradigms, is the least mean square (LMS) convergence. The error can be used by some

computation and then feed it back to change the network parameters. This results in an improvement in the performance.

b. Unsupervised learning network

In this learning algorithm, the network has no information regarding or correct output. It is also referred to as self-organization, in the sense that it self-organizes data presented to the network and detects their emergent collective properties. Therefore, the system must learn by discovering and adopting to structured features in the input patterns.

c. Reinforcement learning network

In this network, there is no supervisor to provide the exact answer. Instead, the network is only presented with an indication of whether the output answer it computes is right or wrong. The network must then use this information to improve its performance. Typically, the network is rewarded by reinforcing weights on units which give the right answer and punished by reducing the weight on units giving the wrong answer. Therefore, these networks are used to control physical system. Neural controllers are applied to do the same tasks as the conventional controllers.

### **4.4.3 ANN Concept**

ANN is modelled based on the biological neural networks structure and arrangement. The similarities are shown in Figure (4.11) (Jack N. Averitt, 2010).

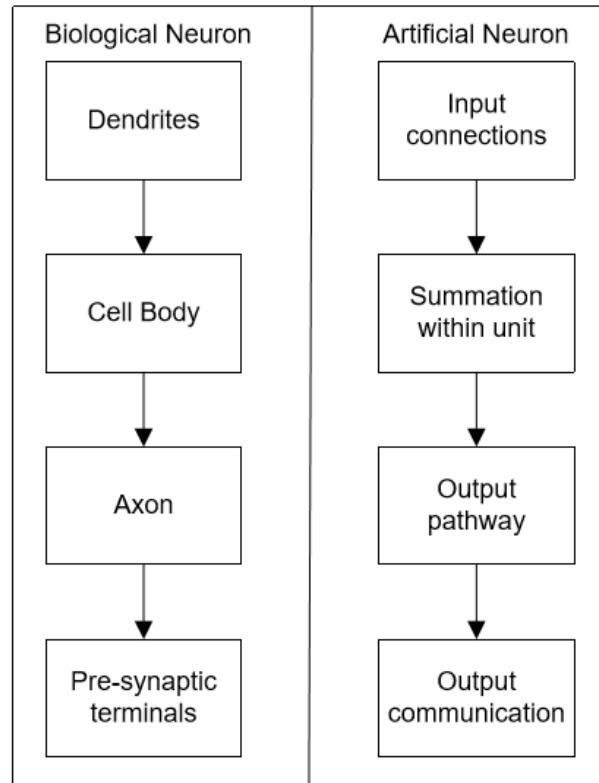


Figure (4.11)

Biological and Artificial Neuron similarities

Artificial Neural Networks (ANNs) and their learning capabilities have been examined for many decades. The most prominent feature of the neural networks their ability to learn from examples, using so called learning algorithms, they solve problems by processing a set of training data. basic computational element (model neuron) is often called a node or unit. It receives input from some other units, or perhaps from an external source. Each input has an associated weight ‘w’, which can be modified so as to model synaptic learning. The unit computes some function ‘f’ of the weighted sum of its inputs:

$$y_i = f(\sum_j w_{ij} y_j) \quad (4.27)$$

Its output, in turn, can serve as input to other units as shown in Figure (4.12).

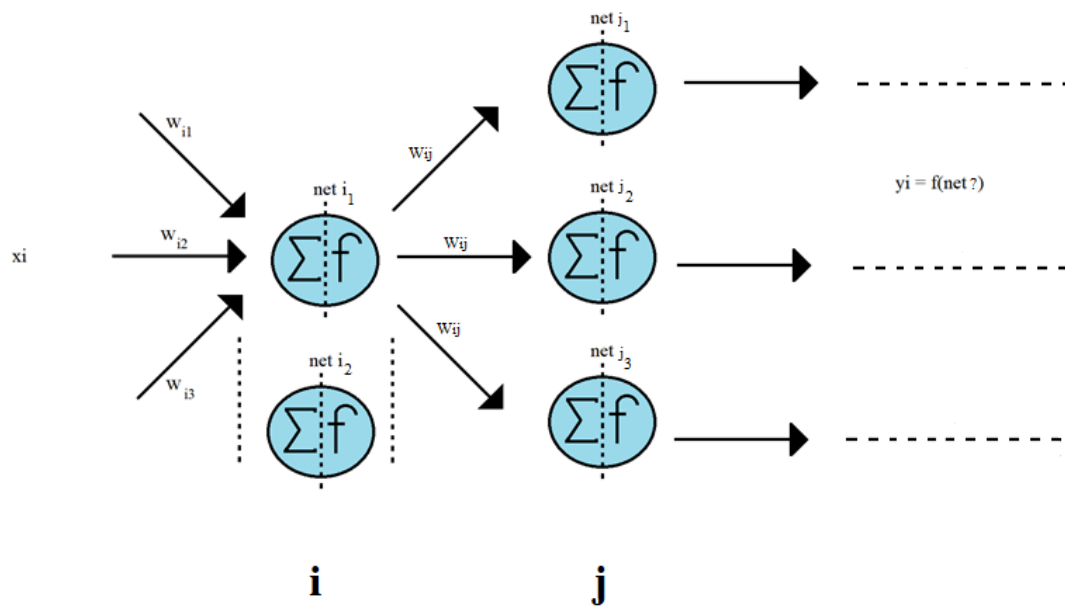


Figure (4.12)  
Artificial Neuron

The weighted sum  $\sum_j w_{ij} y_j$  is called the net input to the 'net'. Note that 'w<sub>ij</sub>' refers to the weight from unit j to unit 'i' (not the other way around). The function 'f' is the unit's activation function as could be as shown in table (4.2) (Larysa A. 2010).

| Function name      | Formula                                                                          | Values range        |
|--------------------|----------------------------------------------------------------------------------|---------------------|
| Linear             | $F(S) = kS, k \in \mathbb{R}_+$                                                  | $(-\infty, \infty)$ |
| Semi linear        | $F(S) = \begin{cases} kS, S > 0, k \in \mathbb{R}_+ \\ 0, S \leq 0 \end{cases}$  | $[0, \infty)$       |
| Sigmoid            | $F(S) = \frac{1}{1+e^{-\alpha S}}$                                               | $(0, 1)$            |
| Bipolar sigmoid    | $F(S) = \frac{2}{1+e^{-\alpha S}} - 1$                                           | $(-1, 1)$           |
| Hyperbolic tangent | $F(S) = \frac{e^{\alpha S} - e^{-\alpha S}}{e^{\alpha S} + e^{-\alpha S}}$       | $(-1, 1)$           |
| Exponential        | $F(S) = e^{-\alpha S}$                                                           | $(0, \infty)$       |
| Sinusoidal         | $F(S) = \sin(S)$                                                                 | $[-1, 1]$           |
| Fractional         | $F(S) = \frac{S}{\alpha +  S }$                                                  | $[-1, 1]$           |
| Step               | $F(S) = \begin{cases} 1, S \geq 0 \\ 0, S < 0 \end{cases}$                       | $[0, 1]$            |
| Signature          | $F(S) = \begin{cases} 1, S \geq 0 \\ -1, S < 0 \end{cases}$                      | $[-1, 1]$           |
| Binary step        | $F(S) = \begin{cases} -1, S \leq -1 \\ S, -1 < S < 1 \\ 1, S \geq 1 \end{cases}$ | $[-1, 1]$           |

Table (4.2)

#### Artificial Neuron Activation Function

So, in the feed forward neural network the inputs are multiplied by the weights then will be summed in the neural cell where the result of the summation will also pass through the activation function ‘f’. The outcome from the neural cell will be multiplied again with the next weights and the process will continue up until the final result is obtained. One the final result is obtained it will be compared with the actual result in order to determine the error and train the model. Back propagation will be used to train the network. An example will be extracted from figure

(4.12) in order to clarify the concept and the equation that will be used in the feed forward and back propagation method. So, for simplicity one string which is in green colour will be analysed as shown in figure (4.13).

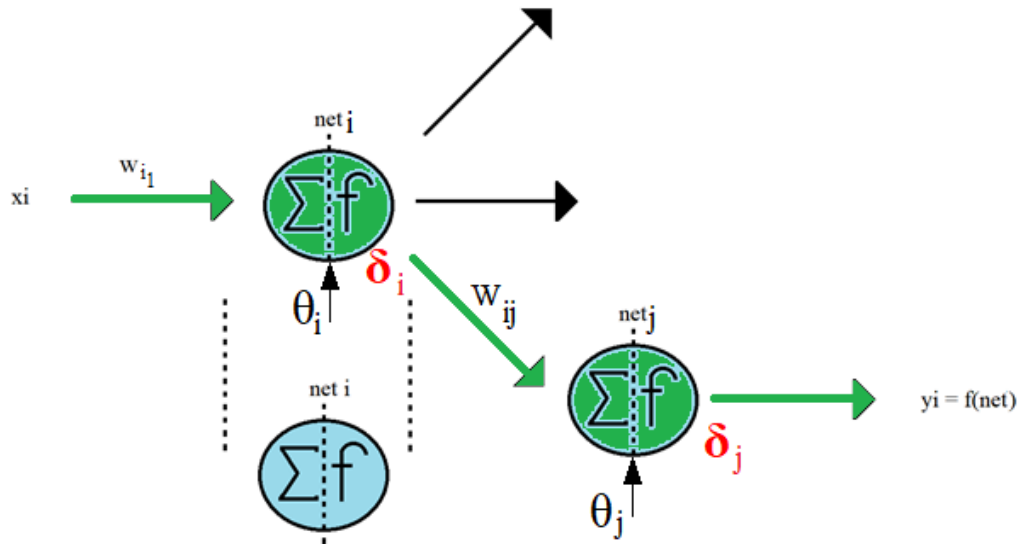


Figure (4.13)

Data flow in One String of Artificial Neuron

The calculation starts from the last output neuron all the way back to the input:

$$Y_j = f_j (f_i (X_i * W_{i1}) * W_{ij}) \quad (4.28)$$

$$\text{Error} = Y_{\text{desire}} - Y_j \quad (4.29)$$

$$\text{Gradient Error } (\delta_j) = \frac{\partial Y_j}{\partial X_i} * \text{Error} \quad (4.30)$$

The output from neuron 'i' is:

$$Y_i = f_i (X_i * W_{i1}) \quad (4.31)$$

$$\text{Gradient Error } (\delta_i) = \frac{\partial Y_i}{\partial X_i} * (W_{ij} * \delta_j) \quad (4.32)$$

After getting the gradient error 1 and 2 from equation (4.30) and (4.32) respectively, the  $\Delta W$  and  $\Delta \theta$  will be calculated in order to update the existing weights and biases.

$$\Delta W_{ij} = \text{learning Rate } (\alpha) * Y_i * \delta_j \quad (4.33)$$

$$\Delta W_{i1} = \text{learning Rate } (\alpha) * X_i * \delta_i \quad (4.34)$$

$$\Delta \theta_j = \text{learning Rate } (\alpha) * \theta_j * \delta_j \quad (4.35)$$

$$\Delta \theta_i = \text{learning Rate } (\alpha) * \theta_i * \delta_i \quad (4.36)$$

Hence the  $\Delta W$  and  $\Delta \theta$  are obtained, the weights and biases will be updated as follows:

$$W_{ij} \leftarrow W_{ij} + \Delta W_{ij} \quad (4.37)$$

$$W_{i1} \leftarrow W_{i1} + \Delta W_{i1} \quad (4.38)$$

$$\theta_j \leftarrow \theta_j + \Delta \theta_j \quad (4.39)$$

$$\theta_i \leftarrow \theta_i + \Delta \theta_i \quad (4.40)$$

The next input will be introduced to the network and same procedure will be followed to obtain the output and correct the weights and biases.

#### 4.4.4 ANN Controllers

ANN is useful in solving some power system control problems (e.g. non-linear, large scale, time variant parameters). It can solve algorithmic type problems and deals well with problems for which algorithms are not available but significant data is already at hand or can

be obtained during operation. There are many applications of ANNs in power system including load forecasting, fault classification, voltage stability and harmonics detection Rajesh N. et. al. (2013). ANNs are also used to enhance the power system stability thorough controlling the compensations installed in the system. In this study, the trained ANN controller expected to be like a tuned PI controller and has the same control performance on the trained operating conditions with better-interpolated output for the untrained operating conditions within the training range. There are several constructions of neural networks like the Multi-Layer Perceptron (MLP) trained by back propagation learning algorithm. Moreover, there are several tools serving this purpose and in this study the following Matlab® tools will be used in order to train the UPFC control variables.

- Neural Network Predictive Control tool.
- NARMA-L2 control tool.

#### **4.4.4.1 Neural Network Model Predictive Controller**

Although the MPC is widely used approach which relies on solving a numerical optimization problem on line, but due to the complexity of nonlinear control problems it is in general necessary to apply various computational or approximative procedures for the solution. The main drawback of the MPC is that the optimization problem may computationally quite demanding for nonlinear systems. So, in order to reduce the on-line computational requirements, another approach is applied as off-line function approximators to represent the optimal control law such as artificial neural network (Bernt M., Hannu T. 2006)

Neural networks have been applied very successfully in the identification and control of dynamic systems. The universal approximation capabilities of the multilayer perceptron make it a popular choice for modelling of nonlinear systems and for implementing of nonlinear controllers. Two-layer networks, with sigmoid transfer functions in the hidden layer and linear transfer functions in the output layer, are universal approximators (transfer function are shown previously in table (4.2)). The Neural Network Predictive Controller is based on the concept of the Artificial Neural Network that has been discussed previously in this chapter. NNMPC uses a neural network model of a nonlinear plant to predict future plant performance. Then the controller calculates the control input which will optimize plant performance over a specified future time horizon. The training data were obtained from the nonlinear model of the system. The used model predictive control method was based on the receding horizon technique. The neural network model predicted the plant response over a specified time horizon. The predictions were used by a numerical optimization program to determine the control signal that minimizes performance criterion over the specified horizon (Anna Vasičkaninová & Monika Bakošová. 2009). The controller block was implemented in by using Matlab Simulink.

The following steps will be followed to design the NNMPC:

- a. System identification: the model predictive control is used to determine the neural network plant model. The prediction error between the plant output and the neural network output is used as the neural network training signal as shown in Figure (4.14) (Mark Hudson et. al. 2014).

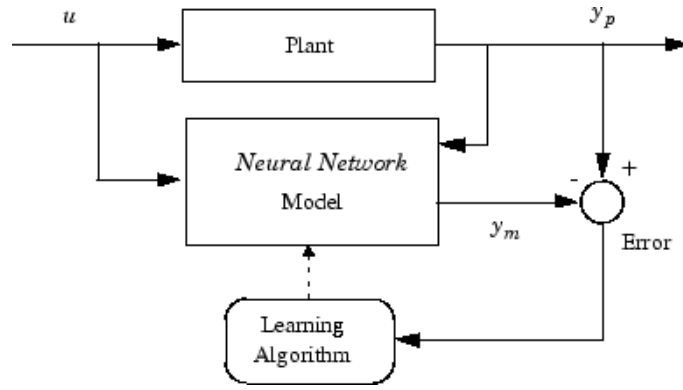


Figure (4.14)

#### NNMPC System Identification

- b. The neural network plant model to predict future performance: The past inputs and past plant outputs will be used to predict future values of the plant output as shown in structure Figure (4.15) (Anna Vasičkaninová & Monika Bakošová. 2009).  $u(t)$  is the system input,  $yp(t)$  is the plant output,  $ym(t)$  is the neural network model plant output, the blocks labelled TDL are tapped delay lines that store previous values of the input signal,  $IW_{i,j}$  is the weight matrix from the input  $j$  to the layer  $i$ .  $LW_{i,j}$  is the weight matrix from the layer  $j$  to the layer  $i$ .

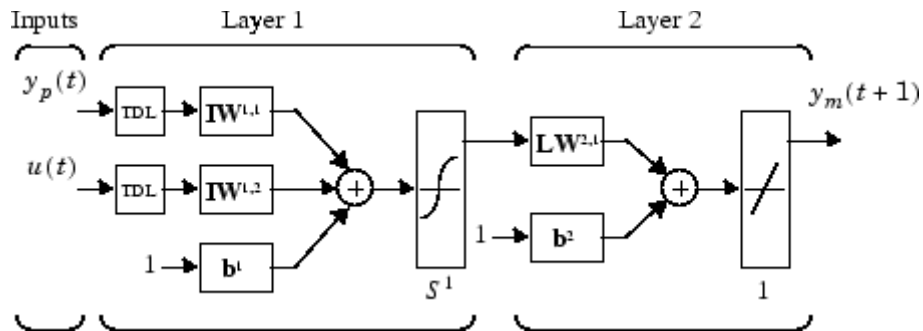


Figure (4.15)

#### NNMPC prediction

- c. Train the NN MPC by backpropagation method.
- d. Optimization algorithm will be used to determine the control signal that minimize the cost function in equation (4.41) over the specified horizon.

$$J = \sum_{j=N_1}^{N_2} (y_r(t+j) - y_m(t+j))^2 + \rho \sum_{j=1}^{N_u} (u'(t+j-1) - u'(t+j-2))^2 \quad (4.41)$$

Where,

- $N_1$ ,  $N_2$ , and  $N_u$  define the horizons over which the tracking error and the control increments are evaluated.
- $u'$  variable is the tentative control signal.
- $y_r$  is the desired response.
- $y_m$  is the network model response.
- $\rho$  value determines the contribution that the sum of the squares of the control increments has on the performance index.

- e. The block diagram in Figure (4.16) (Mark Hudson et. al. 2014) shows the model predictive control process. The controller consists of the neural network plant model and the optimization block, where the optimization block determines the values of  $u'$  that minimize  $J$  in equation (4.41), and then the optimal  $u$  is input to the plant.

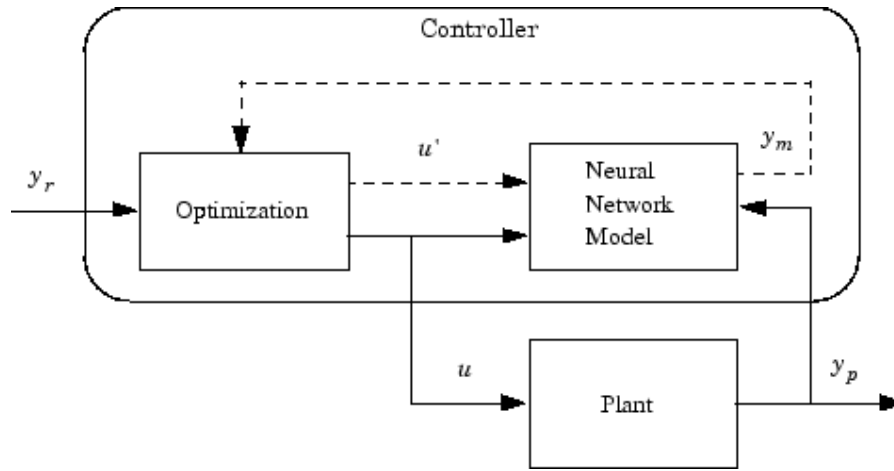


Figure (4.16)

#### NNMPC Model Predictive Control Process

So, in this study the real power in line 2 is considered as a reference signal which will be fed to the NNMPC. The output of real power in line 2 from the SMIB will be also fed to the NNMPC in order to simulate and give the proper control signal to the plant as shown below in figure (4.17).

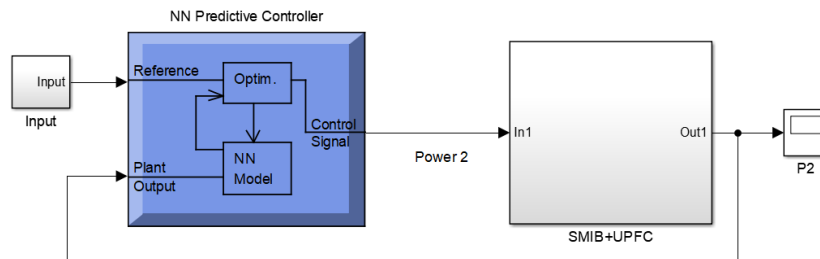


Figure (4.17)

#### NNMPC Matlab Model

Part of NNMPC actions is to perform the system identification to determine the neural network plant model in order send the output to the optimization program to generate the control signal. In order to get an acceptable performance, the number of the neural network hidden layer was selected to be 30 and 10000 numbers of training samples were used to train the neural network model.

#### **4.4.4.2 NARMA-L2 Controller**

NARMA-L2 is considered as one of the most appropriate architectures for prediction and control of time variant nonlinear systems. It has the advantage of fast and accurate output regulation due to its mapping capability. NARMA-L2 control technique is based on input output linearization (Garces, F. et. al 2003) This control strategy converts the dynamics of nonlinear process into linear process. The principle of NARMA-L2 controller is to apply the input-output linearization method where the output becomes a linear function of a new control input (Awwad, A. et. al. 2008) and (Wahyudi S. et. al. 2008). NARMA-L2 control technique can be used for power applications. It has good performance while using it for automatic generation control of two area system (Patel, H. et. al. 2016).

Basically, there are two steps involved when using NARMA L2 control (Mark Hudson Beal et. al. 2014) which are:

##### **a. System Identification**

a neural network of the plant that needs to be controlled is developed using two subnetworks for the model approximation as shown in Figure (4.18).

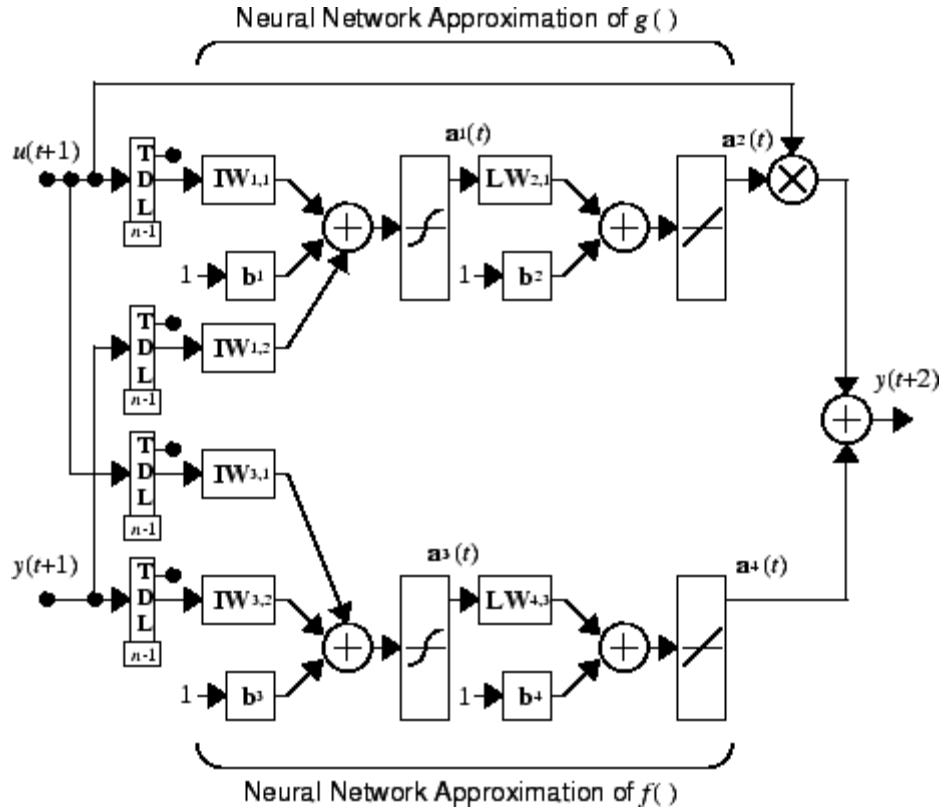


Figure (4.18)

### NARMA-L2 system Identification

The network is then trained offline in batch form using data collected from the operation of the plant. The discrete-time nonlinear system is represented by one standard model which is the Nonlinear Autoregressive Moving Average:

$$y(k+d) = N[y(k), y(k-1), \dots, y(k-n+1), u(k), u(k-1), \dots, u(k-n+1)] \quad (4.42)$$

where  $u(k)$  and  $y(k)$  are the system input output. 'm' and 'n' positive integers representing the number of measured delayed values of inputs and outputs respectively and 'd' is the relative degree. To maintain an acceptable performance, the number of the neural network hidden

layer was selected to be 30 and 10000 numbers of training samples were used to train the neural network model.

## b. Control System Design

The controller is simply the rearrangement of two subnetworks of the plant model which is 'g' and 'f' as shown in figure (4.21). The controller used is based on the NARMA-L2 approximate model. The solution proposed by Narendra and Mukhopadhyay (K. S. Narendra & S. Mukhopadhyay, 1997), is to use approximate models to represent the system.

$$\begin{aligned} \hat{y}(k+d) = & f[y(k), y(k-1), \dots, y(k-n+1), u(k-1), \dots, u(k-m \\ & + 1)] + g[y(k), y(k-1), \dots, y(k-n+1), u(k-1), \dots, u(k \\ & - m + 1)] \cdot u(k) \end{aligned} \quad (4.43)$$

This model is in companion form, where the next controller input  $u(k)$  is not contained inside the nonlinearity. The advantage of this form is that the control input that causes the system output to follow the reference  $y(k+d) = y_r(k+d)$  can be solved. The resulting controller is of the form:

$$\begin{aligned} y(k+d) = & f[y(k), y(k-1), \dots, y(k-n+1), u(k), u(k-1), \dots, u(k-n \\ & + 1)] + g[y(k), \dots, y(k-n+1), u(k), \dots, u(k-n+1)] \\ & \cdot u(k+1) \end{aligned} \quad (4.44)$$

Using the NARMA-L2 model, the controller can be obtained as follows

$$\begin{aligned} u(k+1) = & y_r(k+d) - f[y(k), \dots, y(k-n+1), u(k), \dots, u(k-n \\ & + 1)]g[y(k), \dots, y(k-n+1), u(k), \dots, u(k-n+1)] \end{aligned}$$

(4.45)

which is realizable for  $d \geq 2$ . The NARMA-L2 controller block diagram is shown in Figure (4.19).

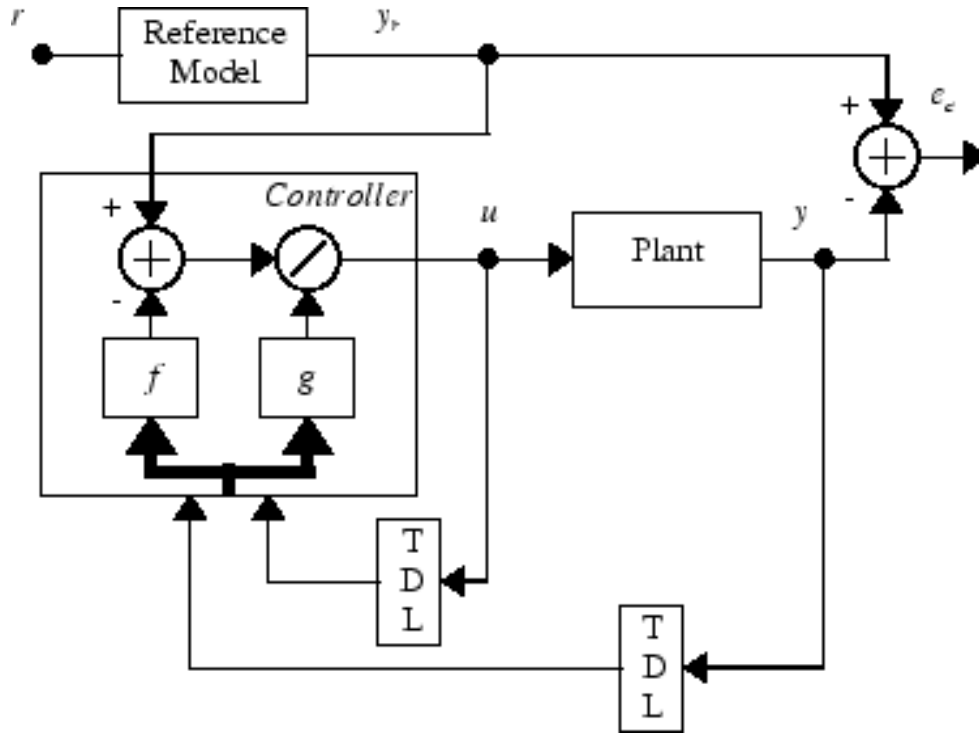


Figure (4.19)

NARMA-L2 Controller

The real power in line 2 is considered as a reference signal which will be fed to the NARAM-L2. The output of real power in line 2 from the SMIB will be also fed to the NARMA-L2 in order to simulate and give the proper control signal to the plant as shown below in figure (4.20).

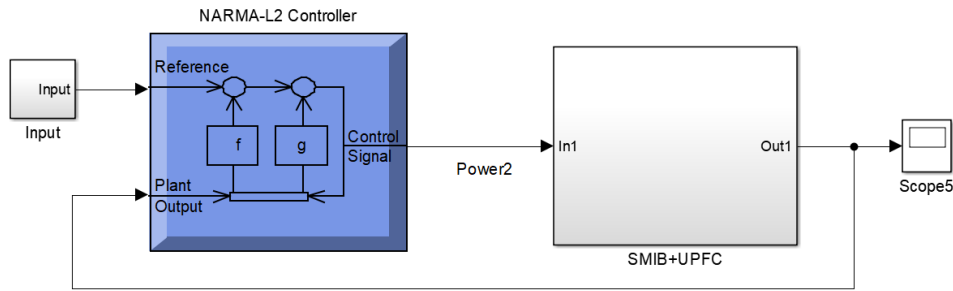


Figure (4.20)

NARMA Control Configuration

## 4.5 Conclusion

In this chapter, the concept of various type of controllers such as PI Controller, Model Predictive Controller, Neural Network Predictive Controller and NARMA-L2 controller, were thoroughly introduced and explained. The PI controller concept was discussed and it has been noticed that the controller coefficients  $K_p$  and  $K_i$  are influencing the performance of the PI Controller. These coefficients will be fixed once it has been determined i.e. it can't be changed automatically when its required to meet any change in the system. Moreover, the concept of the new proposed adaptive controller named as Model Predictive controller was elaborated in this chapter. This controller looks like the any conventional controllers but has the ability to tune the control output signals automatically to meet the new system condition by predicting and optimizing the control signals at each sample step. Finally, the controllers which are based on the Artificial Neural Network namely NNMPD and NARAM-L2 were discussed. These type of controllers need to be trained in order to get the desired outcome.

In next chapter, the conventional controller i.e. PI controller will be considered as a reference throughout the study to confirm the functionality and effectiveness of other new proposed controller schemes during normal and abnormal condition of the system.

# Chapter 5

## Dynamic Controllers Analysis

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# Chapter 5

## Dynamic Controllers Analysis

### 5.1 Introduction

The system contains of one synchronous machine connected to infinite bus through two parallel lines. The UPFC is connected to line 2 as shown below in figure (5.1).

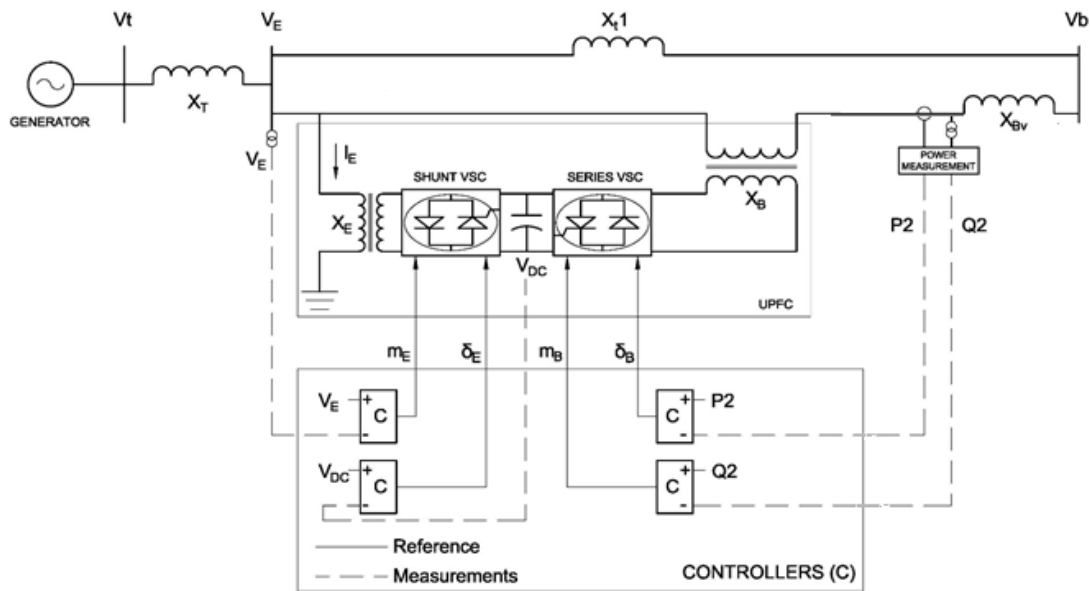


Figure (5.1)

#### UPFC Controllers

From Chapter 3, the equations number (3.24) till (3.31) will be used to model the synchronous machine. Equations number (3.69), (3.70) and number (3.80) till (3.83) will be used to model SMIB. Finally, the equations number (3.8) till (3.11) will be used to model the UPFC. Four PI controllers are connected to the UPFC to control P2, Q2, Vdc and VE. The PI controllers performance will be verified and then will be replaced by new proposed controller schemes to control P2 and the result will be compared accordingly. The raise time, settling time and the overshoot of

the controller will be investigated and observed during the step changes in the system and disturbance. System disturbance will be created at second 70 for a duration of one second. The disturbance involve  $\pm 10\%$  step change for one second in the internal mechanical torque.

## 5.2 Dynamic Response Performance of the PI Controller

The Dynamic response of the PI controllers during the sudden step change and system disturbance in line 2 will be investigated and analysed.

### 5.2.1 PI Controller Performance in Case of Sudden Step Change

The dynamic response waveform of the real power flow in line 2 with the UPFC installed on case of sudden step change is shown in Figure (5.2). It can be seen that, the reference signal which is equal to 0.5 p.u is reduced by 10% and the PI controller respond smoothly to this sudden change. In this case, the raise and settling time are 3.81 and 3.9 respectively without overshoot.

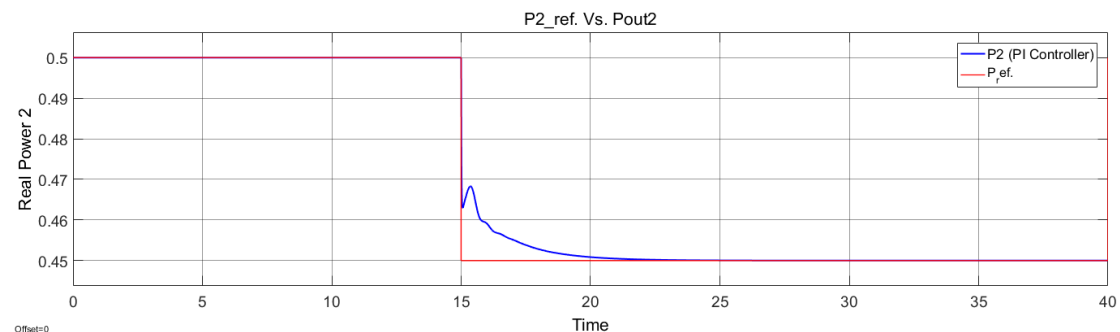


Figure (5.2)

Real Power flow in line 2 by using PI Controllers in case of sudden step change (-10%)

Moreover, it can be noticed from figure (5.3) that the 10% reduction in power flow in line 2 is compensated in line number 1 in order to meet the load required which is equal to 1 p.u. So, the power flow manoeuvre is achieved in this case satisfactorily. Also, it can be noticed that real power in line 2 has better performance than the real power flow in line 1 which has intentionally no controller for comparison purposes.

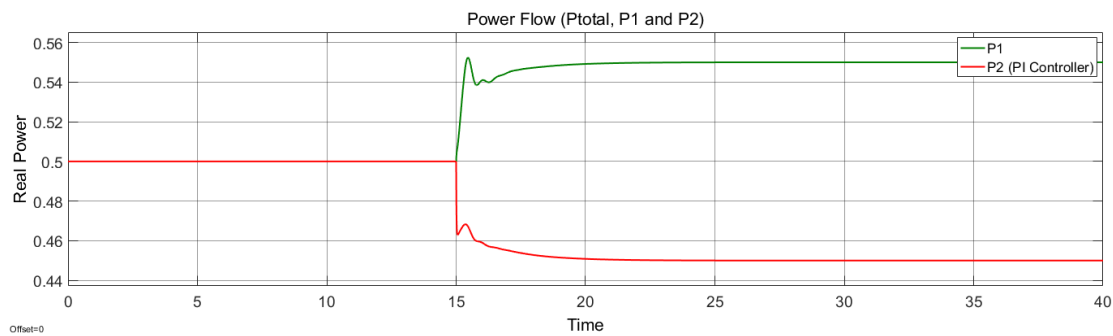


Figure (5.3)

Real Power flow in line 1 & 2 by using PI Controllers in case of sudden step change (-10%)

## 5.2.2 PI Controller Performance in Case of Sudden Step Change and System Disturbance

To investigate the controller robustness, the reference signal for the real power in line 2 will be changed frequently by  $\pm 10\%$ . Moreover,  $\pm 10\%$  step change created in the internal mechanical torque at 70 second and for one second duration as shown in figure (5.4). It is noticed that the PI Controller is responding to the frequent change in the reference signal but has a sluggish raise time response equal to 1.07 second and the settling time is equal to 0.6 second. Small overshoot is observed equal to 7.8% due to the disturbance.

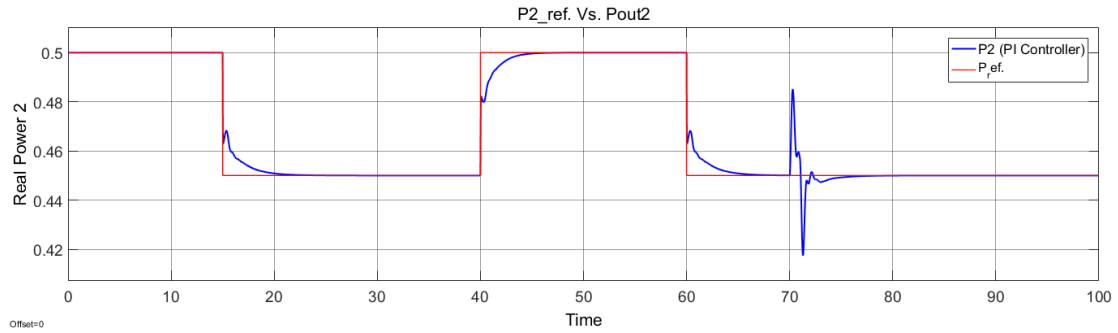


Figure (5.4)

Real Power flow in line 2 by using PI Controllers in case of sudden step change and sudden system disturbance

In addition, both real powers in parallel lines are investigated as shown in figure (5.5). It is clear that any increase or decrease in the power flow in line 2, will be compensated in line 1 in order to deliver the required total power which is equal to 1 p.u. Furthermore, the PI controller in line 2 control the disturbance within 0.6 second with small overshoot, while line number 1 has overshoot around 29.1% as there is no controller installed in line 1.

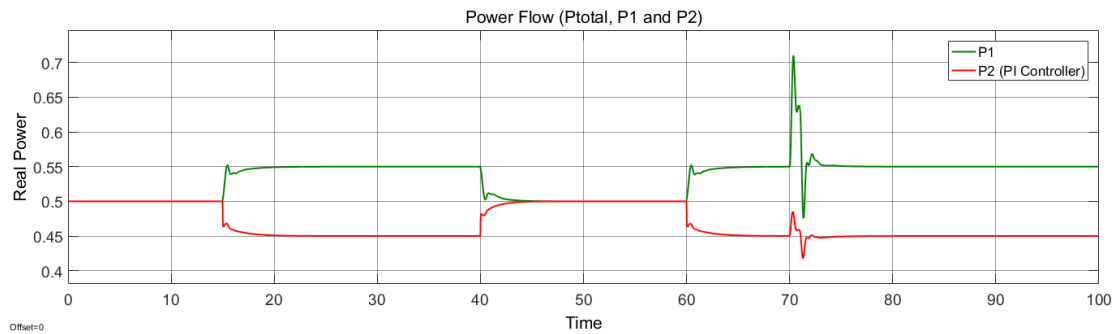


Figure (5.5)

Real Power flow in line 1 & 2 by using PI Controllers in case of sudden step change and sudden system disturbance

### 5.2.3 PI Controller Performance in Case of System Disturbance and 10% change in the impedance of line 2.

Figure (5.6) shows the performance of PI controller during  $\pm 10\%$  of a sudden change in the internal mechanical torque at 70 second and for a duration of 1 second. In addition, the figure shows the robustness of the PI controller in case if the reactance ( $X_{BV}$ ) of the transmission line number 2 is changed from 0.6 to 0.54 p.u.

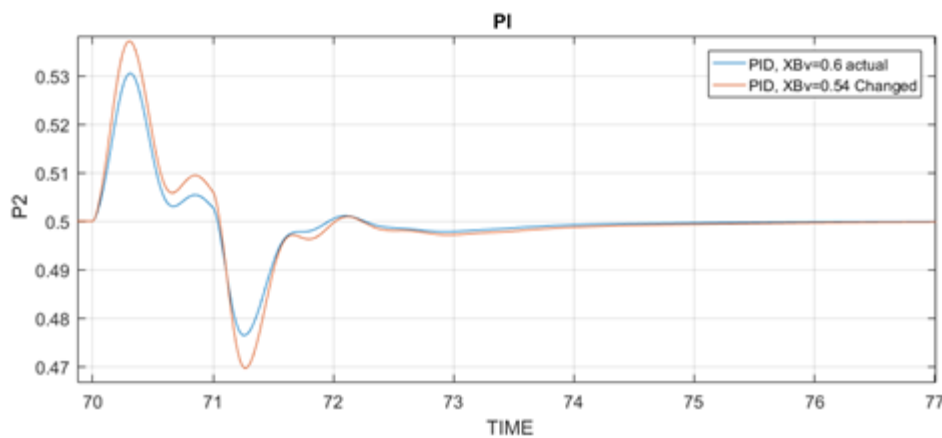


Figure (5.6)

Real Power flow in line 2 by using PI Controllers in case of changing  $X_{BV}$

The above figure shows that, the performance of PI controller will be decreased if the system parameters are changed because of aging, new system arrangements...etc. The overshoot percentage also increased due to this change.

## 5.3 Model Predictive Controller

The PI controller of the real power flow in line 2 (P2) will be replace by MPC. The performance of the MPC controller will be examined in case of sudden step change and sudden system disturbance.

### 5.3.1 MPC Performance in Case of Sudden Step Change

The conventional PI controller used to control the real power in line 2 will be replaced by MPC as shown in figure (5.7). It clear that the MPC controller is much faster than PI controller and stabilize the system in less than 1.4 second with negligible overshoot equal to 0.18%. This is because the optimization process of controller take place in each time sample and indicate that the predicted system behaviour is well accepted.

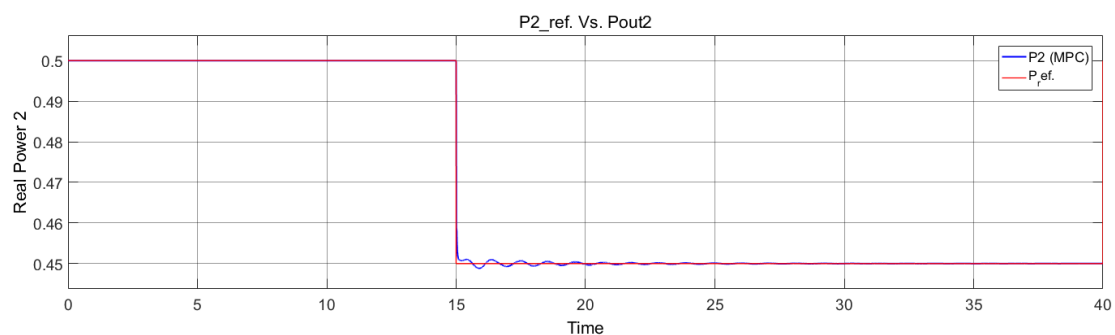


Figure (5.7)

Real Power flow in line 2 by using MPC Controllers in case of sudden step change (-10%)

Figure (5.8) shows the difference between the real power in line 1 which has no controller in place and the real power in line 2 with MPC controller. The real power in line 1 is oscillating and settled approximately after 10 second, while line 2 respond to the step change effectively. The reference power in 2 decreased and the balance is transferred to line 1 as expected.

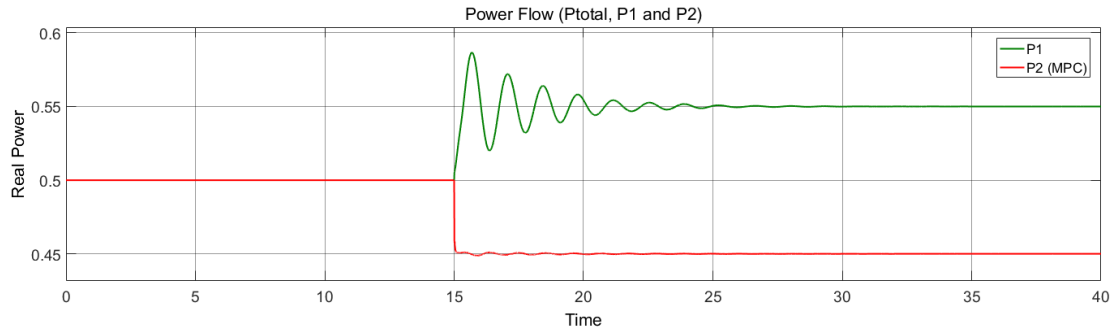


Figure (5.8)

Real Power flow in line 1 & 2 by using MPC Controllers in case of sudden step change (-10%)

### 5.3.2 MPC Performance in Case of Sudden Step Change and Sudden System Disturbance

Several step changes  $\pm 10\%$  in the reference signal of the real power in line 2 are introduced to the system to examine the MPC controller. Also 10% sudden increase in the mechanical torque at second 70 and removed after a second (at second 71) as shown in figure (5.9). The MPC controller proves its ability to stabilize the system and damp the oscillation better and faster than the conventional PI controller. The maximum overshoot is around 2.4% which much less than the PI controller output.

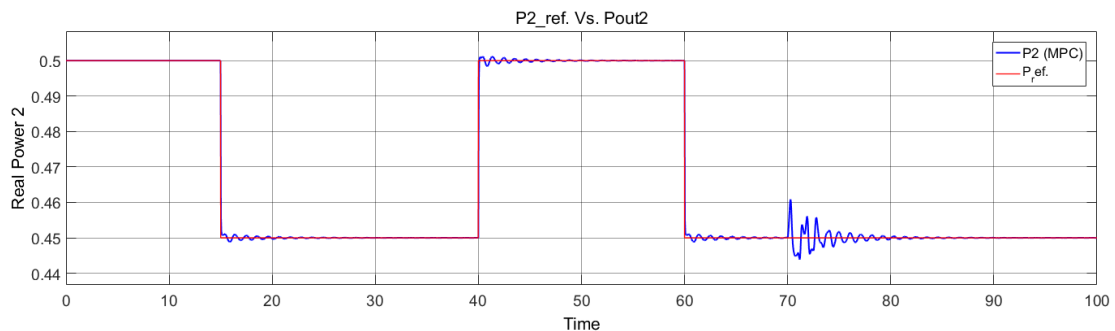


Figure (5.9)

Real Power flow in line 2 by using MPC Controllers in case of sudden step change and sudden system disturbance

The difference between the real power in line 1 which has no controller in place and the real power in line 2 with MPC controller is shown in figure (5.10). The real power in line 1 is oscillating and settled after 12 second, while line 2 respond to the step change effectively within 0.32 a second.

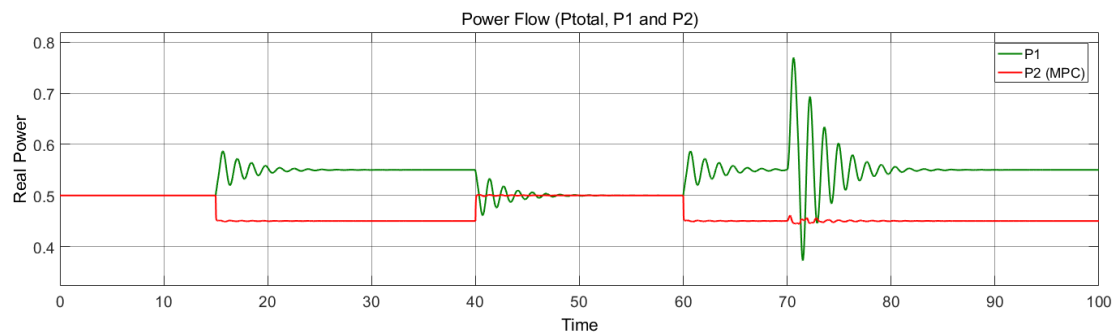


Figure (5.10)

Real Power flow in line 1 & 2 by using MPC Controllers in case of sudden step change and sudden system disturbance

### 5.3.3 MPC Performance in Case of System Disturbance and 10% change in the impedance of line 2.

Figure (5.11) shows the robustness of MPC controller during system disturbance and changing the reactance ( $X_{BV}$ ) of the transmission line number 2 from 0.6 to 0.54 p.u. The figure shows that, the performance of MPC controller will be decreased if system parameters are changed because of aging, new system arrangements...etc. The overshoot percentage also increased due to this change.

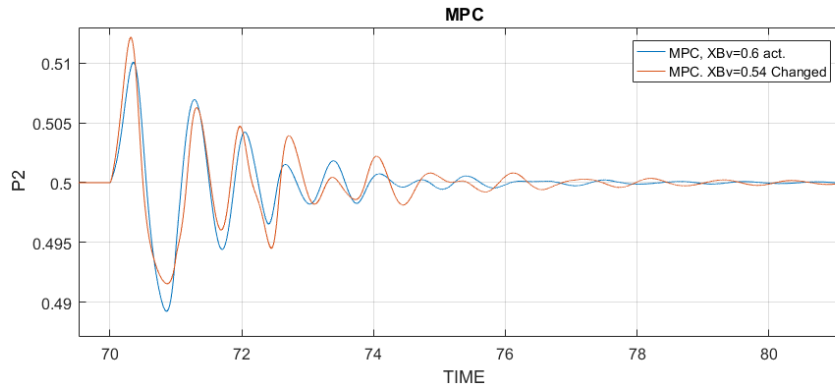


Figure (5.11)

Real Power flow in line 2 by using MPC Controllers in case of changing  $X_{BV}$

## 5.4 Artificial Neural Network based Controllers

NNMPC and NARMA controllers are based on ANN concept and depend on the number of layers and training samples. So, it is important to define the number of layers and training samples before performing the rest of NNMPC and NARMA controllers analysis. Figure (5.12) and Figure (5.13) show that, the best preferable combination between the number of layers and training samples for NNMPC and NARMA controllers is 30 layers and 10000 training samples. Accordingly, the NNMPC and NARMA controllers will be programmed based on 30 numbers of layers and 10000 training samples.

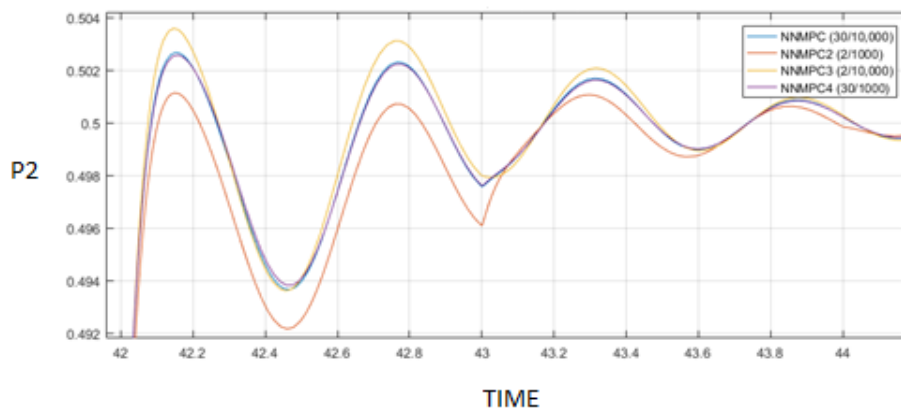


Figure (5.12)

Number of Layers Vs. Training Sample for NNMPC Controller

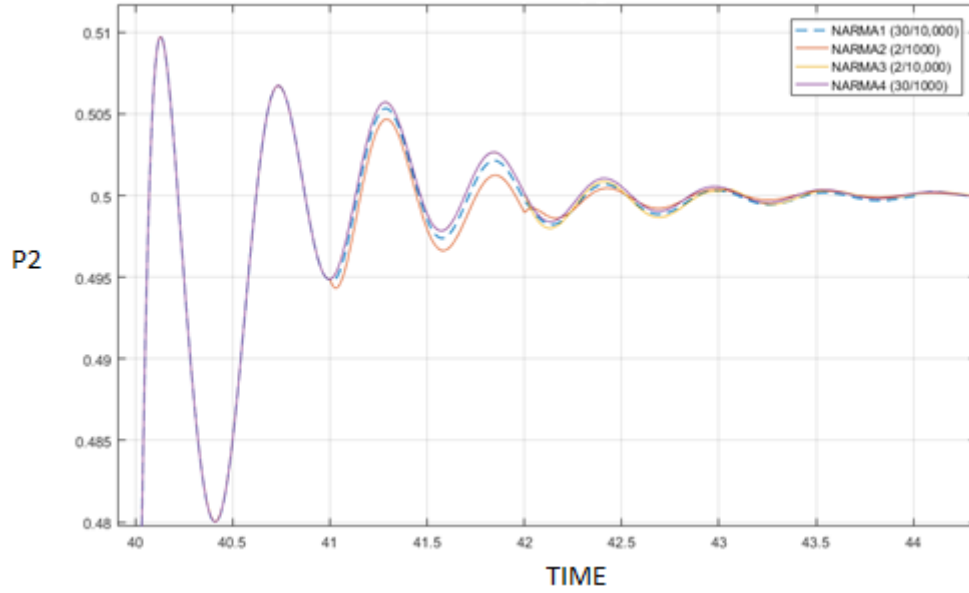


Figure (5.13)

Number of Layers Vs. Training Sample for NARMA Controller

### 5.4.1 Neural Network Model Predictive Controller

The conventional PI controller of the real power flow in line 2 (P2) will be replaced by NNMPC. The performance of the MPC controller will be verified in case of sudden step change, sudden system disturbance and change in the system parameters. The NNMPC configuration is shown below in Figure (5.14)

### Neural Network Predictive Control

|                                                                          |                                                                                       |
|--------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Cost Horizon (N2) <input style="width: 50px;" type="text" value="20"/>   | Control Weighting Factor ( \ ) <input style="width: 50px;" type="text" value="0.01"/> |
| Control Horizon (Nu) <input style="width: 50px;" type="text" value="2"/> | Search Parameter ( \ ) <input style="width: 50px;" type="text" value="0.05"/>         |

Minimization Routine csrchbac
Iterations Per Sample Time

---

### Plant Identification

#### Network Architecture

|                                                                             |                                                                               |
|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Size of Hidden Layer <input style="width: 50px;" type="text" value="30"/>   | No. Delayed Plant Inputs <input style="width: 50px;" type="text" value="2"/>  |
| Sampling Interval (sec) <input style="width: 50px;" type="text" value="1"/> | No. Delayed Plant Outputs <input style="width: 50px;" type="text" value="2"/> |

☐ Normalize Training Data

#### Training Data

|                                                                                   |                                                                                          |
|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Training Samples <input style="width: 50px;" type="text" value="10000"/>          | <input checked="" type="checkbox"/> Limit Output Data                                    |
| Maximum Plant Input <input style="width: 50px;" type="text" value="0.6"/>         | Maximum Plant Output <input style="width: 50px;" type="text" value="0.6"/>               |
| Minimum Plant Input <input style="width: 50px;" type="text" value="0"/>           | Minimum Plant Output <input style="width: 50px;" type="text" value="0"/>                 |
| Maximum Interval Value (sec) <input style="width: 50px;" type="text" value="10"/> | Simulink Plant Model: <span style="border: 1px solid black; padding: 2px;">Browse</span> |
| Minimum Interval Value (sec) <input style="width: 50px;" type="text" value="5"/>  | <span style="border: 1px solid black; padding: 2px;">NNPCModel</span>                    |

Generate Training Data
Import Data
Export Data

#### Training Parameters

|                                                                        |                                                                                       |
|------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Training Epochs <input style="width: 50px;" type="text" value="5000"/> | Training Function <span style="border: 1px solid black; padding: 2px;">trainlm</span> |
|------------------------------------------------------------------------|---------------------------------------------------------------------------------------|

☒ Use Current Weights
☒ Use Validation Data
☒ Use Testing Data

Figure (5.14)

NNMPC Configuration

#### 5.4.1.1 NNMPC Controller Performance in Case of Sudden Step Change

In Figure (5.15), the reference power signal which is equal to 0.5 p.u is reduced by 10% and the NNMPC controller respond with initial oscillation to this sudden change in power flow and the settling time is equal to 3.6 second. The NNMPC performance is almost similar to some

extent to the PI controller but with small oscillation at the beginning and overshoot equal to 0.54%. NNMPC performance is not better than MPC performance which is described previously.

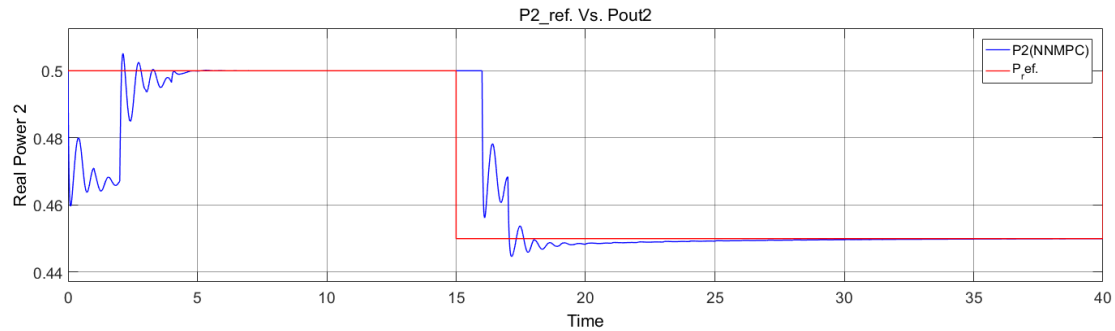


Figure (5.15)

Real Power flow in line 2 by using NNMPC Controllers in case of sudden step change (-10%)

It has been notice from figure (5.16) that the 10% reduction in power flow in line 2 is diverted to line number 1 in order to meet the total load required which is equal to 1 p.u. So, the power flow manoeuvre is achieved in this case satisfactorily.

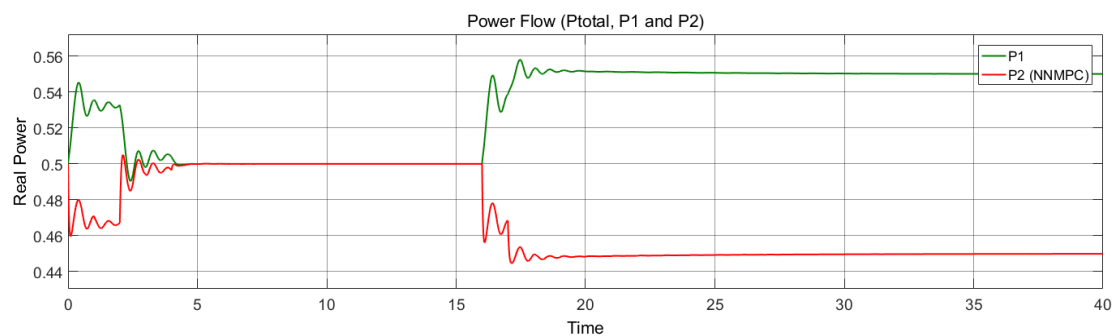


Figure (5.16)

Real Power flow in line 1 & 2 by using NNMPC Controllers in case of sudden step change (-10%)

### 5.4.1.2 NNMPC Controller Performance in Case of Sudden Step Change and Sudden System Disturbance

From figure (5.17), the NNMPC controller has undergone to several step change in real power reference in line 2. Moreover  $\pm 10\%$  of a sudden mechanical torque at second number 70 and disconnected immediately at one second later. The NNMPC performance show its capability to stabilize the system with overshoot equal to 19.2%. Although, the overshoot in both PI and NNMPC controllers are noticed, but PI controller is superior in this aspect and the MPC controller still better than PI and NNMPC controller.

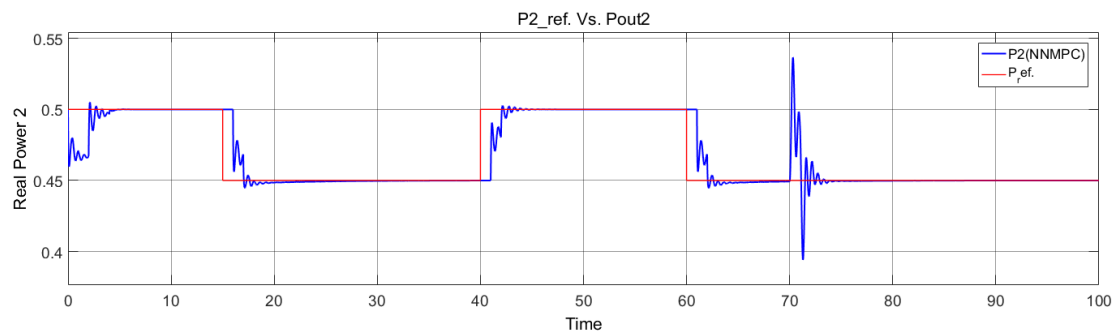


Figure (5.17)

Real Power flow in line 2 by using NNMPC Controllers in case of sudden step change and sudden system disturbance

The real powers in the parallel lines are also investigated as shown in figure (5.18). Any change in the power flow in line 2, will be compensated in line 1 in order to deliver the required total real power which is equal to 1 p.u. In addition to that, the NNMPC controller in line 2 control the disturbance within less than 2.36 second and 19.2% overshoot, while line number 1 has overshoot around 21.8% as purposely there is no controller installed.

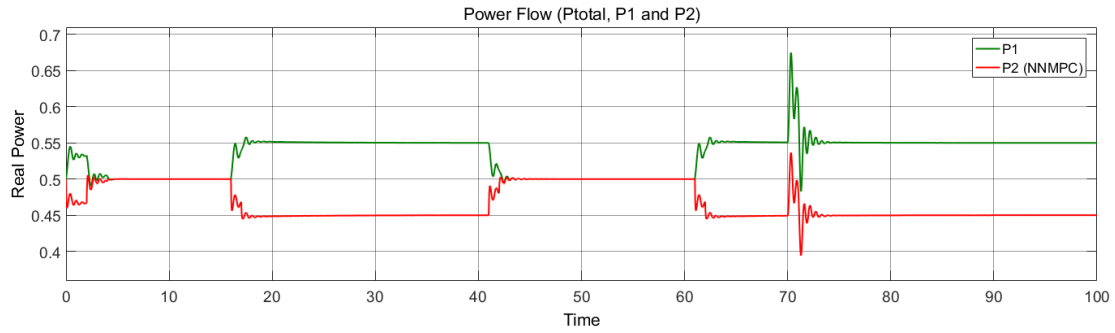


Figure (5.18)

Real Power flow in line 1 & 2 by using NNMPC Controllers in case of sudden step change and sudden system disturbance

### 5.4.1.3 NNMPC Controller Performance in Case of System Disturbance and 10% change in the impedance of line 2.

In order to test the robustness of NNMPC controller, the system has undergone to an internal mechanical torque disturbance ( $\pm 10\%$ ) at 70 second and for a duration of one second. Moreover, the reactance ( $X_{BV}$ ) of the transmission line number 2 is changed from 0.6 to 0.54 p.u.. Figure (5.19) shows that, the performance of NNMPC controller is acceptable and not being effected by changing the system parameters.

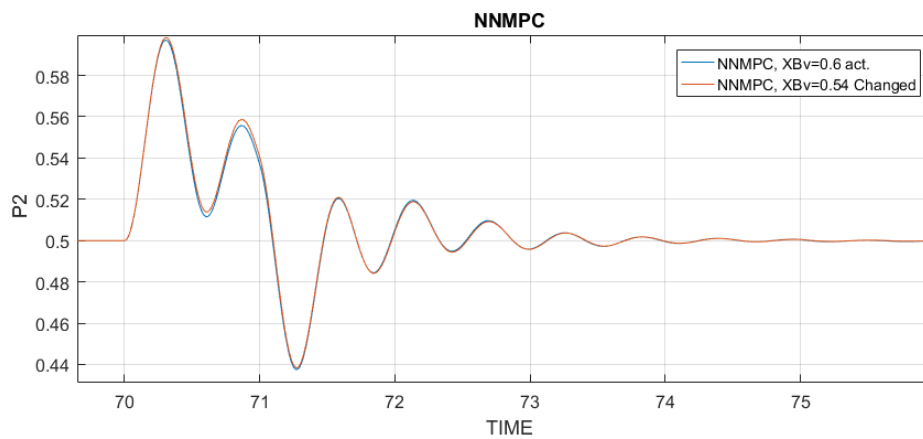


Figure (5.19)

Real Power flow in line 2 by using NNMPC Controllers in case of changing  $X_{BV}$

## 5.4.2 NARAM-L2 Controller

NARMA-L2 controller will be installed instead of the conventional PI controller of the real power flow in line 2 (P2). NARMA-L2 performance will be inspected in case of sudden step change and sudden system disturbance. The NARMA configuration is shown below in Figure (5.20).

**Plant Identification - NARMA-L2**

**Network Architecture**

Size of Hidden Layer: 30  
Sampling Interval (sec): 1  
No. Delayed Plant Inputs: 2  
No. Delayed Plant Outputs: 2  
☐ Normalize Training Data

**Training Data**

Training Samples: 10000  
Maximum Plant Input: 0.6  
Minimum Plant Input: 0  
Maximum Interval Value (sec): 10  
Minimum Interval Value (sec): 5  
☒ Limit Output Data  
Maximum Plant Output: 0.6  
Minimum Plant Output: 0  
Simulink Plant Model: Browse  
NARMAModel

**Training Parameters**

Training Epochs: 5000  
Training Function: trainlm  
☒ Use Current Weights  
☒ Use Validation Data  
☒ Use Testing Data

Generate Training Data Import Data Export Data

Figure (5.21)

NARMA Configuration

### 5.4.2.1 NARAM-L2 Controller Performance in Case of Sudden Step Change

It has been noticed from figure (5.22) that 10% reduction in the real power reference at second number 15, was tracked effectively by the

actual real power in line 2 through the NARAM-L2 Controller. The system becomes stable in less than 2.24 seconds and with less than 1.96% overshoot. The controller is faster than the PI and NNMPC controller, but not faster than the MPC control.

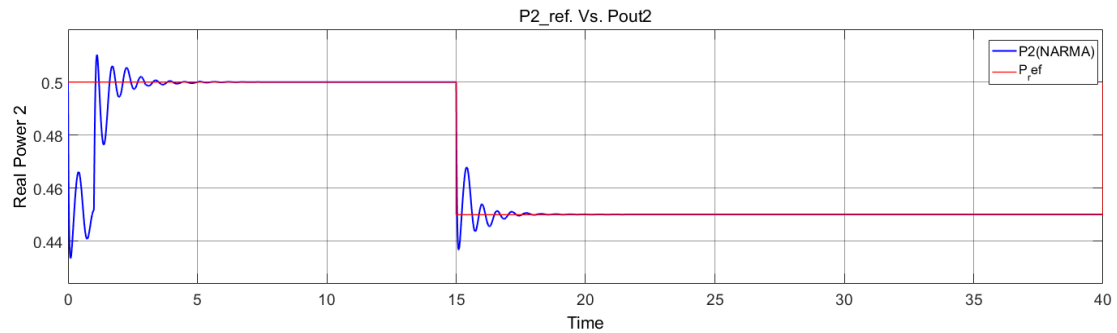


Figure (5.22)

Real Power flow in line 2 by using NARMA-L2 Controllers in case of sudden step change (-10%)

Figure (5.23) also shows good efficiency of the controller in controlling the power flow in both transmission lines.

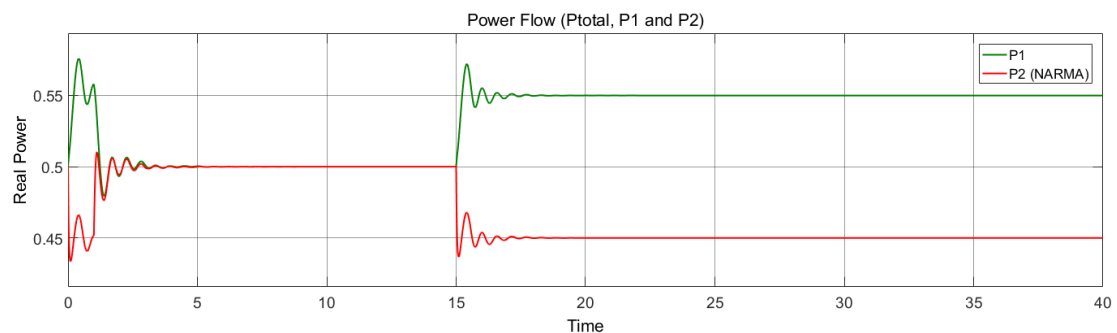


Figure (5.23)

Real Power flow in line 1 & 2 by using NARMA-L2 Controllers in case of sudden step change (-10%)

### 5.4.2.2 NARAM-L2 Controller Performance in Case of Sudden Step Change and Sudden System Disturbance

The NARAM-L2 Controller also examined by introducing several change in the reference real power signal and a disturbance equal to  $\pm 10\%$  at 70 second for a duration of one second as shown in figure (5.24). NARAM-L2 Controller has proven its ability to control the real power satisfactorily and stabilised the system within less than 2.31 second and 19.4% overshoot. NARAM-L2 in this case is almost similar to NNMPCC controller.

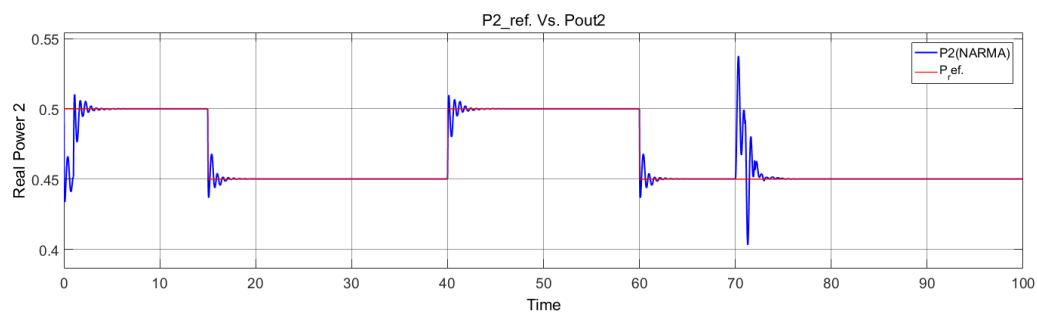


Figure (5.24)

Real Power flow in line 2 by using NARMA-L2 Controllers in case of sudden step change and sudden system disturbance

The power flow control shown in figure (5.25), prove the efficiency and the fast response of this controller as well.

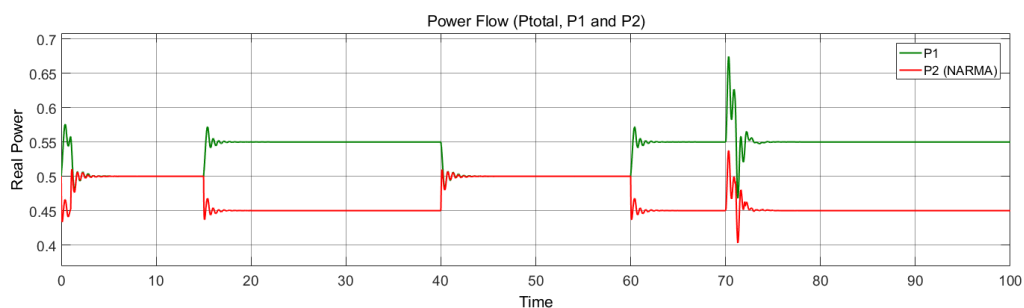


Figure (5.25)

Real Power flow in line 1 & 2 by using NARMA-L2 Controllers in case of sudden step change and sudden system disturbance

### 5.4.2.3 NARMA-L2 Controller Performance in Case of System Disturbance and 10% change in the impedance of line 2.

Figure (5.26) shows the performance of NARMA controller during  $\pm 10\%$  of a sudden change in the internal mechanical torque at 70 second and for a duration of 1 second. In addition, the figure shows the robustness of the NARMA controller in case if the reactance ( $X_{BV}$ ) of the transmission line number 2 is changed from 0.6 to 0.54 p.u. The figure shows that, the performance of NARMA controller is acceptable and not being effected by changing the system parameters.

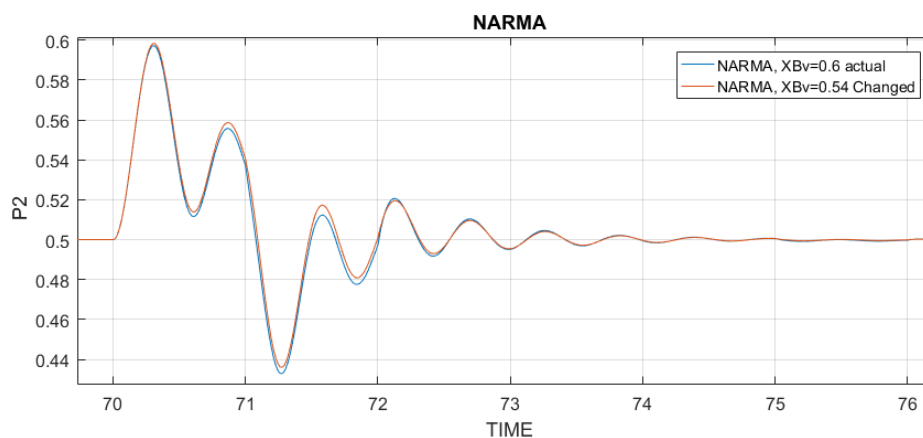


Figure (5.26)

Real Power flow in line 2 by using NARMA Controllers in case of changing  $X_{BV}$

## 5.6 Discussion and Conclusion

The performance of all controllers have been examined, verified and compared to have solid and accurate conclusion. The raise time, settling time and overshoot are the selected criteria to evaluate the controller's capabilities as shown below in table (5.1) and table (5.2). Figure (5.27) shows the dynamic performance of the different type of

controller in the system in case of step change ( $\pm 10\%$ ). This is in order to confirm that the power flow can be controlled whenever required. Although, all types of controller which are investigated in this study are efficient to stabilize the system, but the time response for each one of them is different. The better controller based on the rise time and settling time is MPC, NARMA, NNMPC then PI Controller. The overshoot can be noticed only in the adaptive controllers (less than 2%).

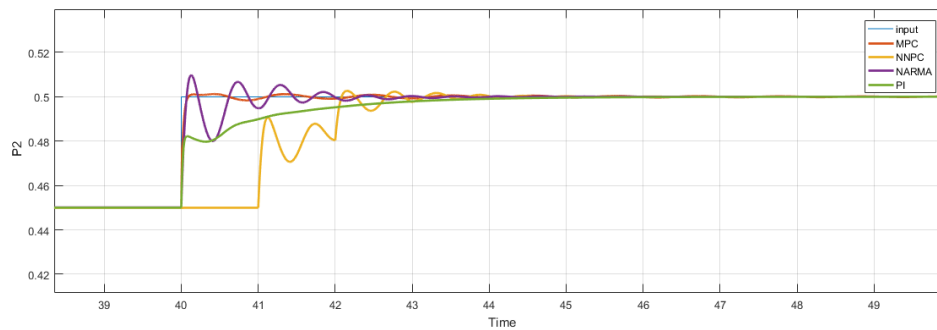


Figure (5.27)

Controllers output for step change

|        | Rise Time (Sec.) | Settling Time (Sec.)<br>(2%) | Overshoot (%) |
|--------|------------------|------------------------------|---------------|
| PI     | 3.81             | 3.9                          | 0             |
| MPC    | 0.09             | 1.4                          | 0.18          |
| NNMPC  | 2.09             | 3.6                          | 0.54          |
| NARAMA | 0.07             | 2.24                         | 1.96          |

Table (5.1)

Rating Score for each type of controller during step change

Figure (5.28) shows the dynamic performance of the different type of controller in the system in case of system disturbance. The system has also undergone to several change in the reference real power signal which equal to  $\pm 10\%$ . This is in order to confirm that the power flow can be controlled whenever required. Moreover,  $\pm 10\%$  of a sudden change in the

internal mechanical torque at time 70 second was introduced to the system for a duration of one second. This is to make a stress in the system to examine the functionality of the proposed controllers. The fastest controller based on the rise time and settling time is MPC, PI, NNMPC then NARMA. The better controller based on the settling time is MPC, PI, NARMA then NNMPC. The minimum overshoot noticed in the MPC controller, while NNMPC and NARMA have the highest overshoot.

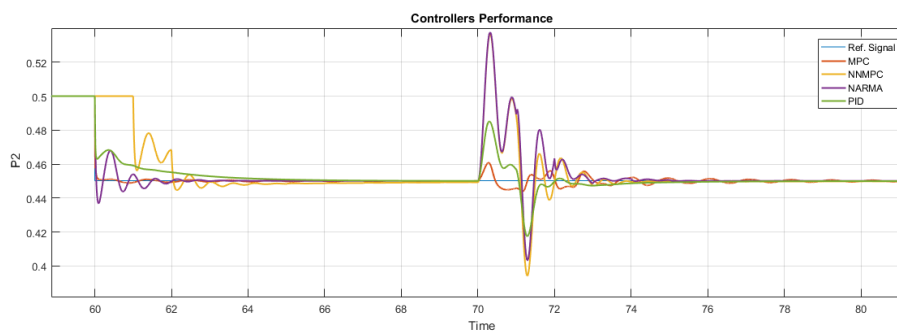


Figure (5.28)

Controllers output for step change and system disturbance

|        | Rise Time (Sec.) | Settling Time (Sec.)<br>(2%) | Overshoot (%) |
|--------|------------------|------------------------------|---------------|
| PI     | 1.07             | 0.6                          | 7.8           |
| MPC    | 0.46             | 0.32                         | 2.4           |
| NNMPC  | 1.11             | 2.26                         | 19.2          |
| NARAMA | 1.15             | 2.31                         | 19.4          |

Table (5.2)

Rating Score for each type of controller during disturbance

In addition, the reactance on transmission line number 2 also changed from 0.60 to 0.54 p.u. in order to evaluate the performance of the

proposed controllers for such change in the system parameters. The NNMPC and NARMA controllers are very robust in this regard and superior to MPC and PI controllers. The performance of all the system parameters, due to the effect of each controller, are extracted and shown in Appendix E.

# **Chapter 6**

## **Conclusion and Future Work**

### **Chapter contents**

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## **Chapter 6**

### **Conclusion and Future Work**

#### **6.1 Conclusion**

It is obvious that beside the importance of the electric power to the human life, various constraints and challenges are facing the electricity sector due to rapid load growth, scarcity of the natural and complexity of the generation, transmission and distribution systems. So, proper utilization of the existing transmission lines need to have more attention since the transmission network is considered as the back bone of the power system grid.

In this research, innovative solutions have been proposed to obtain better utilization and controlling of power over the transmission network in steady state and transient conditions by using FACTS technology. So, the most of versatile FACTS devices entitled as UPFC has been deployed to a SMIB system to test its performance, capability and ability to support the system operations during study-state and transient period. Moreover, several type of UPFC advanced controllers have been proposed such as an adaptive controllers (MPC) and controllers based on artificial neural network concept like NNMPC and NARAM-L2 respectively.

The capability of controlling real and reactive power flow in the transmission lines which consist of UPFC was verified and found that the behaviour of the power system was enhanced in presences of the UPFC and the adaptive controllers. The robustness, controllability and the effectiveness of the proposed adaptive controllers and the controllers which were based on the artificial neural network concept have been proven as well. So, the proposed controllers are superior to the PI

conventional controller which has sluggish response during normal step change in the system input. MPC can accommodate the system disturbance better than PI Controller. The only drawback of the adaptive controllers is the need of sufficient training in order to obtain the expected result with less overshoot. This matter can be tackled today with the presence of the high speed microprocessors.

## **6.2 Future Work**

Based on the findings from this research, the future work may focus on how the advanced controllers become even much better than now. Moreover, to perform an adequate training of the advanced controllers to overcome the overshoot and the small oscillations, although they are within the acceptable limit. Furthermore, to set-up a lab experiment to verify the controller design and performance. Finally, to expand the proposed system to become a multi machine system.

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## Appendix (A)

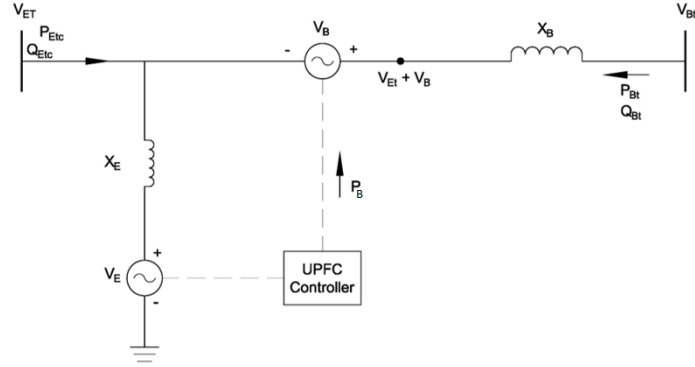


Figure (1)

$$S_{Bt}^* = \frac{1}{jX_B} \cdot V_{Bt}^* \cdot (V_{Bt} - V_{Et} - V_B) = P_{Bt} - jQ_{Bt}$$

$$S_{Bt}^* = -j \frac{1}{X_B} \left[ V_{Bt}^2 - V_{Bt} \cdot V_{Et} \sin(\delta_{Et} - \delta_{Bt}) - V_B \cdot V_{Bt} \angle \delta_B - \delta_{Bt} \right]$$

$$\therefore P_{Bt} = \frac{-V_{Bt} \cdot V_{Et}}{X_B} \sin(\delta_{Et} - \delta_{Bt}) - \frac{V_{Bt} \cdot V_B}{X_B} \sin(\delta_B - \delta_{Bt})$$

$$P_{Bt} = \frac{V_{Bt} \cdot V_{Et}}{X_B} \sin(\delta_{Bt} - \delta_{Et}) + \frac{V_{Bt} \cdot V_B}{X_B} \sin(\delta_{Bt} - \delta_B)$$

$$Q_{Bt} = \frac{V_{Bt}^2}{X_B} - \frac{V_{Bt} V_{Et}}{X_B} \cos(\delta_{Bt} - \delta_{Et}) - \frac{V_{Bt} \cdot V_B}{X_B} \cos(\delta_{Bt} - \delta_B)$$

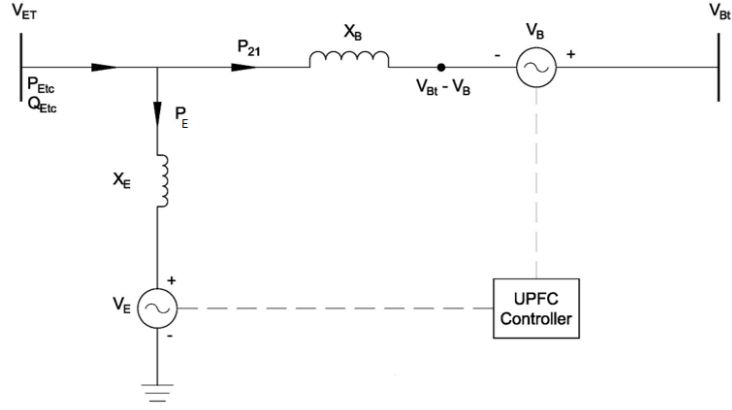


Figure (2)

$$S_{Etc}^* = V_{Et}^* \left( \frac{V_{Et} - V_E}{jX_E} \right) + V_{Et}^* \left( \frac{V_{Et} - (V_{Bt} - V_B)}{jX_B} \right)$$

$$S_{Etc}^* = -j \cdot \frac{1}{jX_E} \left[ V_{Et}^2 - V_{Et} V_E \angle \delta_E - \delta_{Et} \right] + \left( -j \cdot \frac{1}{X_B} \right) \left( V_{Et}^2 - V_{Et} V_{Bt} \angle \delta_{Bt} - \delta_{Et} + V_{Et} V_B \angle \delta_B - \delta_{Et} \right)$$

$$\therefore P_{Etc} = \frac{V_{Et} \cdot V_E}{X_E} \sin(\delta_{Et} - \delta_E) + \frac{V_{Et} \cdot V_{Bt}}{X_B} \sin(\delta_{Et} - \delta_{Bt}) - \frac{V_{Et} \cdot V_B}{X_B} \sin(\delta_E - \delta_B)$$

$$Q_{Etc} = \frac{V_{Et}^2}{X_E} + \frac{V_{Et}^2}{X_B} - \frac{V_{Et} \cdot V_E}{X_E} \cos(\delta_{Et} - \delta_E) - \frac{V_{Et} \cdot V_{Bt}}{X_B} \cos(\delta_{Et} - \delta_{Bt}) + \frac{V_{Et} \cdot V_B}{X_B} \cos(\delta_{Et} - \delta_B)$$

$$Q_{Etc} = \left( \frac{X_E + X_B}{X_E X_B} \right) V_{Et}^2 - \frac{V_{Et} \cdot V_E}{X_E} \cos(\delta_{Et} - \delta_E) - \frac{V_{Et} \cdot V_{Bt}}{X_B} \cos(\delta_{Et} - \delta_{Bt}) + \frac{V_{Et} \cdot V_B}{X_B} \cos(\delta_{Et} - \delta_B)$$

From figure (1)

$$P_{Etc} + P_{Bt} = 0$$

So,

$$\begin{aligned} & \frac{V_{Et} \cdot V_E}{X_E} \sin(\delta_{Et} - \delta_E) + \frac{V_{Et} \cdot V_{Bt}}{X_B} \sin(\delta_{Et} - \delta_{Bt}) - \frac{V_{Et} \cdot V_B}{X_B} \sin(\delta_{Et} - \delta_B) + \frac{V_{Et} \cdot V_{Bt}}{X_B} \sin(\delta_{Bt} - \delta_{Et}) \\ & + \frac{V_{Bt} \cdot V_B}{X_B} \sin(\delta_{Bt} - \delta_B) = 0 \end{aligned}$$

From above equation,

$$\begin{aligned} & \frac{V_{Et} \cdot V_E}{X_E} \sin(\delta_{Et} - \delta_E) = \frac{V_{Et} \cdot V_B}{X_B} \sin(\delta_{Et} - \delta_B) - \frac{V_{Bt} \cdot V_B}{X_B} \sin(\delta_{Bt} - \delta_B) \\ \therefore P_E &= \frac{V_{Et} \cdot V_B}{X_B} \sin(\delta_{Et} - \delta_B) - \frac{V_{Bt} \cdot V_B}{X_B} \sin(\delta_{Bt} - \delta_B) \end{aligned}$$

The Second term will be proved that it is equal to  $P_B$ ,

From figure (1)

$$\begin{aligned} P_B &= \text{Re al} \left[ V_B^* \left( \frac{(V_{Et} + V_B) - V_{Bt}}{jX_B} \right) \right] \\ P_B &= \text{Re al} \left[ -j \cdot \frac{1}{X_B} \cdot (V_{Et} V_B \angle \delta_{Et} - \delta_B + V_B^2 - V_{Bt} V_B \angle \delta_{Bt} - \delta_B) \right] \\ P_B &= \frac{V_{Et} V_B}{X_B} \sin(\delta_{Et} - \delta_B) - \frac{V_{Bt} V_B}{X_B} \sin(\delta_{Bt} - \delta_B) \end{aligned}$$

So, from  $P_E$  and  $P_B$  equations,

$$\therefore P_E + P_B = 0$$

## Appendix (B)

### Matlab Codes

- **System Data**

%This function defines the parameters for a SMIB system with double transmission line circuit and Generator Data:

```
M = 8;
D = 0;
wB = 2*pi*50;
Tdod = 5.044;
xdd = 0.3;
xd = 1;
xq = 0.6;
%Exciter Data:
Ta = 0.05;
Ka = 50;
Efdmin = -7.3;
Efdmax = 7.3;
% Transmission system:
xtE = 0.1;
xt1 = 0.6;
xBv = 0.6;
% Unified Power Flow Controller:
xE = 0.1;
xB = 0.1;
Vdcs = 2;
Cdc = 3;
Ts = 0.05;
Ks = 1;
mBmin = 0;
mBmax = 2;
mEmin = 0;
mEmax = 2;
% Infinite Bus:
Vb = 1;
thb = 0;
%Washout Circuit time constant:
Tw = 5;
%Calculate the reactances
xqE = xq + xtE;
```

```

xdE = xdd + xtE;
xBB = xBv + xB;
xd1 = xE*(1+(xdE*(xE+xt1)/(xE*xt1)));
xd2 = xBB*xd1+xE*xdE;
xd3 = (1/xd2)*((xE*xdE/xt1)-xd1);
xd4 = (1/xd2)*(xd1-xE-(xE*xdE/xt1));
xd5 = (1/xE)*(1+xBB*xd3);
xd6 = (1/xE)*(-1+xBB*xd4);
xd7 = (1/xE)*(1-xBB*(xd1/xd2));
xq1 = xE*(1+(xqE*(xE+xt1)/(xE*xt1)));
xq2 = xBB*xq1+xE*xqE;
xq3 = (1/xq2)*(-(xE*xqE/xt1)+xq1);
xq4 = (1/xq2)*(-xq1+xE+(xE*xqE/xt1));
xq5 = (1/xE)*(-1+xBB*xq3);
xq6 = (1/xE)*(1+xBB*xq4);
xq7 = (1/xE)*(-1+xBB*(xq1/xq2));

```

- **Calculate Initial Condition**

% the operating point of the generator:

```

Pes = 1.0;
Qes = 0.04;
VEt = 1.05;
QBts = 0.01;
PBts = Pes/2;
PEts = -PBts;

```

% Obtaining the initial conditions for the problem by applying the load  
% flow study:

```

x = [0;0;0;1;1];
u = [0;0;1;0.03];
% This function will calculate the state variables and the UPFC control
% parameters initial condition prior to system disturbance for a simple
% power network : SMIB with double transmission line circuit
%Pe = Generator input active power
%Qe = Generator input reactive power
%PEt = Second transmission line active power setpoint
%VEt = UPFC sending end bus voltage setpoint
%PBt = same as PEt but negated
%QBt = regulated reactive power for the second transmission line
%xtE = stepup transformer reactance

```

```

%xt1 = Uncompensated transmission line reactance
%xBv = Compensated transmission line reactance
%x = initial guess for system state variables
YtE = 1/xtE;
Yt1 = 1/xt1;
YBv = 1/xBv;
%System contain five state variables
tht = x(1);
thEt = x(2);
thBt = x(3);
Vt = x(4);
VBt = x(5);
for i = 1:50
    %First calculate the power injections at each bus where it is
    %prespecified
    Pe = Vt*VEt*YtE*sin(tht-thEt);
    Qe = (Vt^2)*YtE-Vt*VEt*YtE*cos(tht-thEt);
    PEt = YtE*VEt*Vt*sin(thEt-tht)+Yt1*VEt*Vb*sin(thEt-thb);
    QEt = (YtE+Yt1)*VEt^2-YtE*VEt*Vt*cos(thEt-tht)-
        Yt1*VEt*Vb*cos(thEt-thb);
    PBt = YBv*VBt*Vb*sin(thBt-thb);
    QBt = YBv*VBt^2-YBv*VBt*Vb*cos(thBt-thb);
    %Calculate the Mismatch:
    dS = [Pes-Pe;PEts-PEt;PBts-PBt;Qes-Qe;QBts-QBt];
    % Formulating the Jacobian Matrix:
    J = zeros(5,5);
    J(1,1) = Vt*VEt*YtE*cos(tht-thEt); %dPe/dtht
    J(1,2) = -Vt*VEt*YtE*cos(tht-thEt); %dPe/dthEt
    J(1,3) = 0; %dPe/dthBt
    J(1,4) = VEt*YtE*sin(tht-thEt); %dPe/dVt
    J(1,5) = 0;
    J(2,1) = -YtE*VEt*Vt*cos(thEt-tht); %dPEt/dtht
    J(2,2) = YtE*VEt*Vt*cos(thEt-tht)+Yt1*VEt*Vb*cos(thEt-
        thb);%dPEt/dthEt
    J(2,3) = 0;%dPEt/dthBt
    J(2,4) = YtE*Vt*sin(thEt-tht)+Yt1*Vb*sin(thEt-thb); %dPEt/dVt
    J(2,5) = 0; %dPEt/dVBt
    J(3,1) = 0; %dPBt/dtht
    J(3,2) = 0; %dPBt/dthEt
    J(3,3) = YBv*VBt*Vb*cos(thBt-thb); %dPBt/dthBt
    J(3,4) = 0; %dPBt/dVt
    J(3,5) = YBv*Vb*sin(thBt-thb); %dPBt/dVBt
    J(4,1) = YtE*Vt*VEt*sin(tht-thEt); %dQe/dtht

```

```

J(4,2) = -Vt*VEt*YtE*sin(tht-thEt); %dQe/dthEt
J(4,3) = 0; %dQe/dthBt
J(4,4) = 2*Vt*YtE - VEt*YtE*cos(tht-thEt); %dQe/dVt
J(4,5) = 0; %dQe/dVBt
J(5,1) = 0; %dQBt/dtht
J(5,2) = 0; %dQBt/dtEt
J(5,3) = YBv*VBt*Vb*sin(thBt-thb); %dQBt/dthBt
J(5,4) = 0; %dQBt/dVt
J(5,5) = 2*YBv*VBt-YBv*Vb*cos(thBt-thb); %dQBt/dVBt
x = x + inv(J)*dS;
tht = x(1);
thEt = x(2);
thBt = x(3);
Vt = x(4);
VBt = x(5);
end

```

```

% This function will calculate the UPFC initial parameters using the
% decoupled model introduced by Nabavi-Niaki and Iravani
thE = u(1);
thB = u(2);
VE = u(3);
VB = u(4);
YE = 1/xE;
YB = 1/xB;
for i = 1:35
    %Calculated power injection at the buses of the UPFC:
    PEtc = YB*VEt*VB*sin(thEt-thB)+YB*VEt*VBt*sin(thEt-
        thBt)+YE*VEt*VE*sin(thEt-thE);
    QETc = (YB+YE)*VEt^2-YB*VEt*VB*cos(thEt-thB)-
        YB*VEt*VBt*cos(thEt-thBt)-YE*VEt*VE*cos(thEt-thE);
    PBtc = YB*VBt*VEt*sin(thBt-thEt)-YB*VBt*VB*sin(thBt-thB);
    QBtc = YB*VBt^2+YB*VBt*VB*cos(thBt-thB)-
        YB*VBt*VEt*cos(thBt-thEt);
    % The Mismatch:
    dS = [PEt-PEtc;PBt-PBtc;QEt-QETc;QBt-QBtc];
    %Forming the Jacobian of the system:
    J = zeros(4,4);
    J(1,1) = -YE*VEt*VE*cos(thEt-thE);%dPEt/dthE
    J(1,2) = -YB*VEt*VB*cos(thEt-thB);%dPEt/dthB
    J(1,3) = YE*VEt*sin(thEt-thE);%dPEt/dVE
    J(1,4) = YB*VEt*sin(thEt-thB);%dPEt/dVB

```

```

J(2,1) = 0;%dPBt/dthE
J(2,2) = YB*VBt*VB*cos(thBt-thB);%dPBt/dthB
J(2,3) = 0;%dPBt/dVE
J(2,4) = -YB*VBt*sin(thBt-thB);%dPBt/dVB
J(3,1) = -YE*VEt*VE*sin(thEt-thE);%dQEt/dthE
J(3,2) = -YB*VEt*VB*sin(thEt-thB);%dQEt/dthB
J(3,3) = -YE*VEt*cos(thEt-thE);%dQEt/dVE
J(3,4) = -YB*VEt*cos(thEt-thB);%dQEt/dVB
J(4,1) = 0;%dQBt/dthE
J(4,2) = YB*VBt*VB*sin(thBt-thB);%dQBt/dthB
J(4,3) = 0;%dQBt/dVE
J(4,4) = YB*VBt*cos(thBt-thB);%dQBt/dVB
% To find the new estimate of the input variables:
u = u + inv(J)*dS;
thE = u(1);
thB = u(2);
VE = u(3);
VB = u(4);
end

```

```

% This function will calculate the initial conditions of the dq quantities
% of a SMIB
Vb = 1;
Vtp = Vt*exp(1i*tht);
VEtp = VEt*exp(1i*thEt);
VEp = VE*exp(1i*thE);
VBp = VB*exp(1i*thB);
Itp = (Pe-1i*Qe)/(Vtp');
It = abs(Itp);
phi = angle(Itp);
IEp = (VEtp-VEp)/(1i*xE);
IE = abs(IEp);
phiE = angle(IEp);
IBp = (VEtp-VBp-Vb)/(1i*(xB+xBv));
IB = abs(IBp);
phiB = angle(IBp);
It1p = (VEtp - Vb)/(1i*xt1);
It1 = abs(It1p);
phi1 = angle(It1p);
Eqp = Vtp + 1i*xq*Itp;
del0 = angle(Eqp);
id0 = It*sin(del0-phi);

```

```

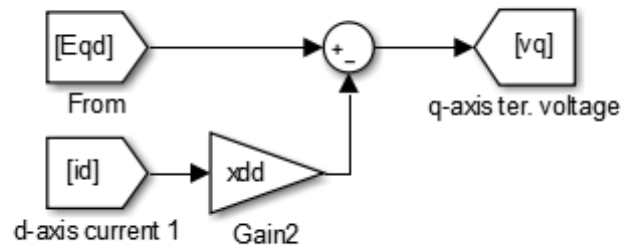
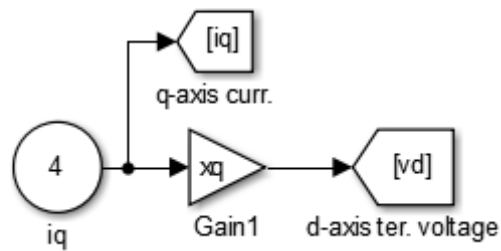
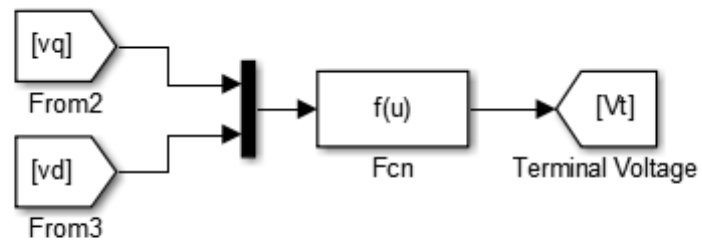
iq0 = It*cos(del0-phi);
iEd0 = IE*sin(del0-phiE);
iEq0 = IE*cos(del0-phiE);
iBd0 = IB*sin(del0-phiB);
iBq0 = IB*cos(del0-phiB);
itd0 = It1*sin(del0-phi1);
itq0 = It1*cos(del0-phi1);
vd0 = Vt*sin(del0-tht);
vq0 = Vt*cos(del0-tht);
Efd0 = abs(Eqp) +(xd-xq)*id0;
Eqd0 = Efd0 - (xd-xdd)*id0;
Pm0 = vq0*iq0+vd0*id0;
Vref0 = Efd0/Ka + Vt;
wr0 = 0;
mE0 = 2*VE/Vdc;
mB0 = 2*VB/Vdc;
delE0 = pi/2 - del0 + thE;
delB0 = pi/2 - del0 + thB;
Pe2s = PBts;
Qe2s = QBt;

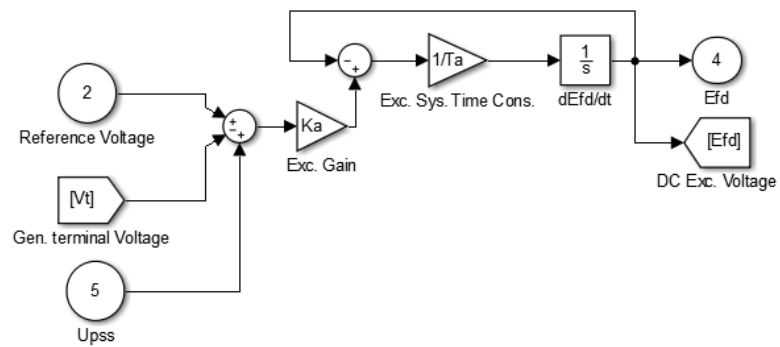
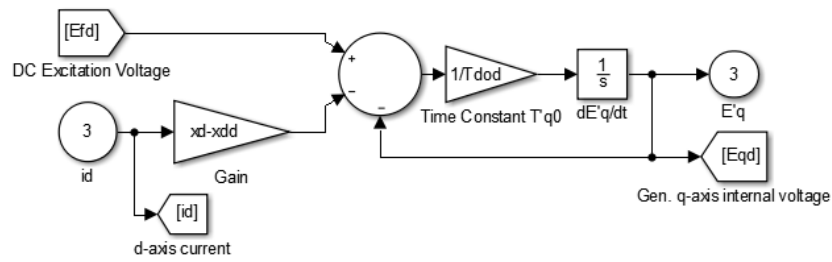
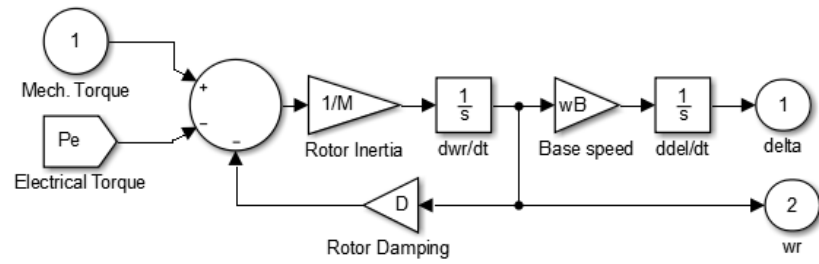
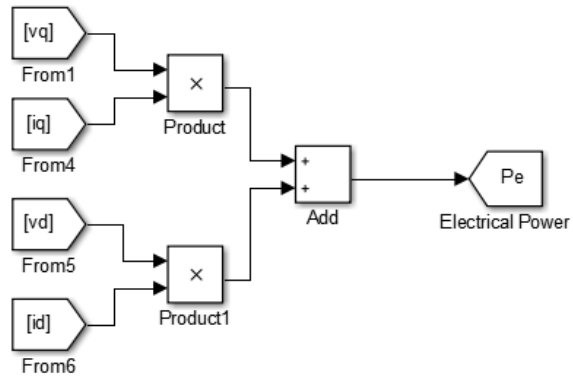
```

## Appendix (C)

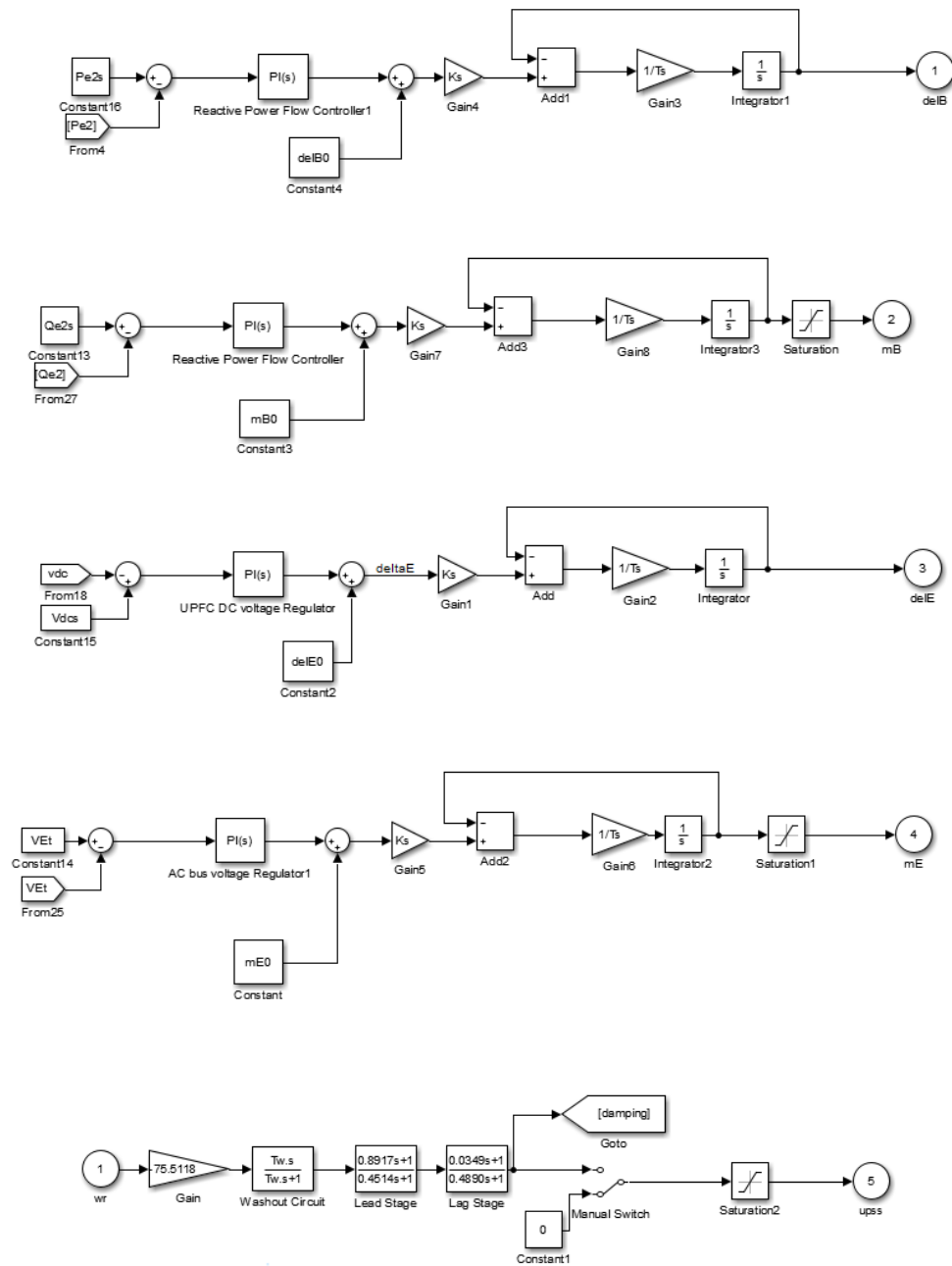
### Matlab Simulink

#### a. Generator and Excitation





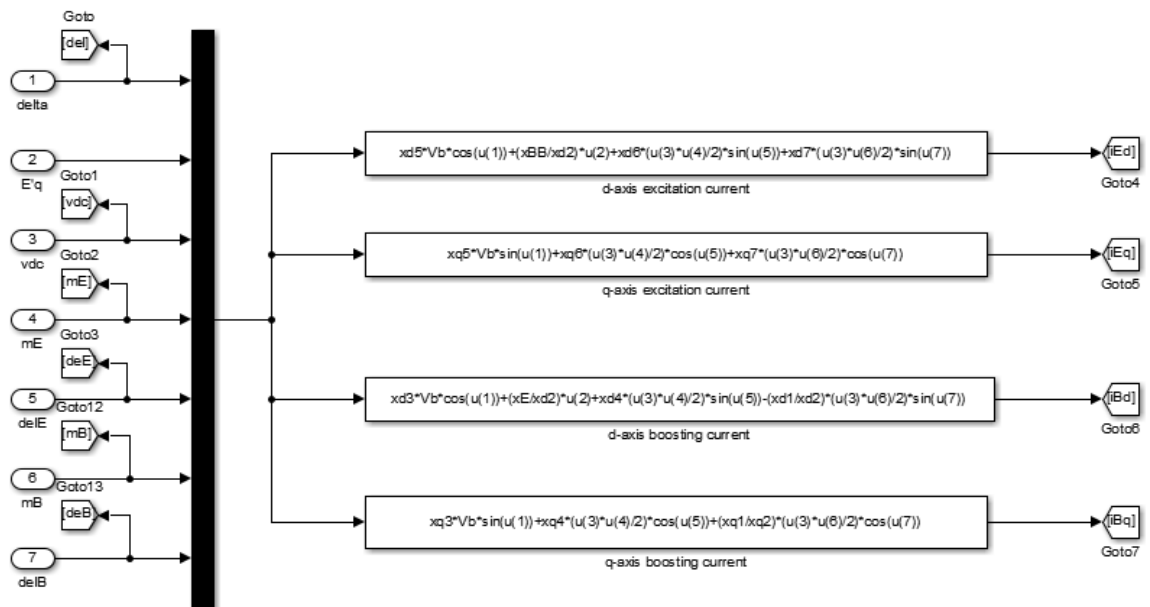
## b. UPFC Controller

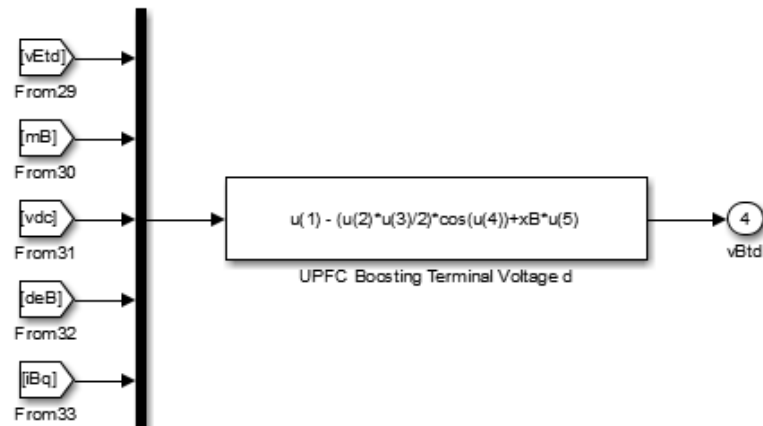
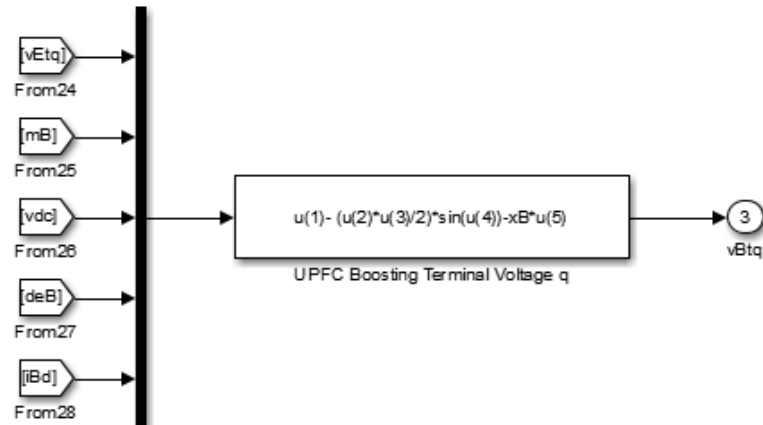
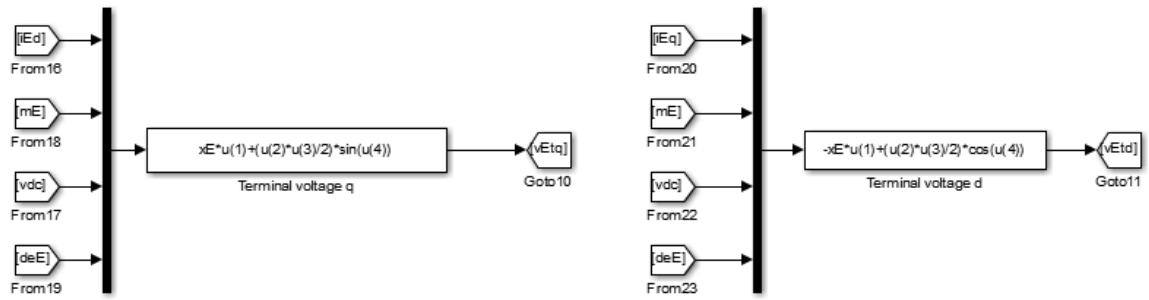


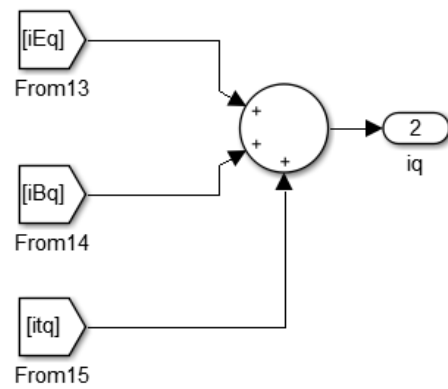
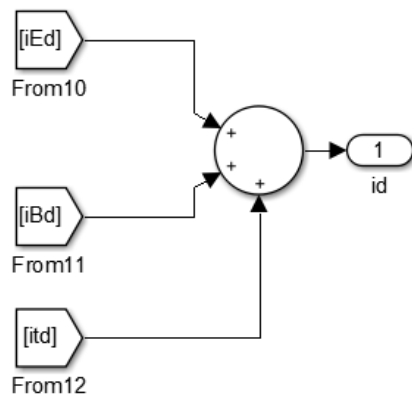
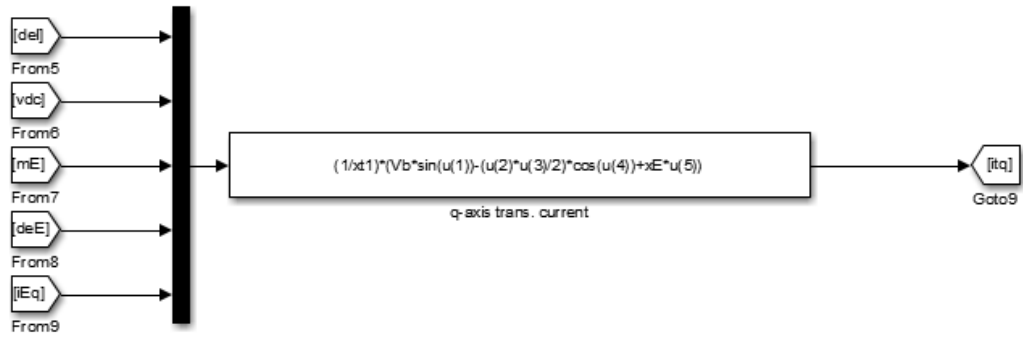
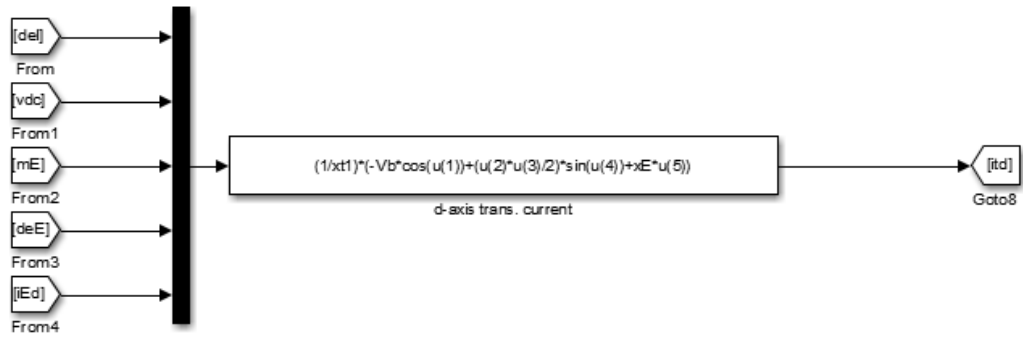
## c. UPFC Model



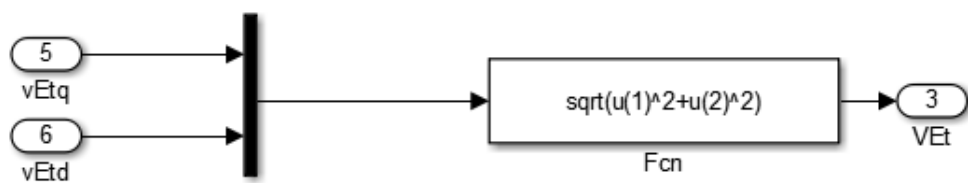
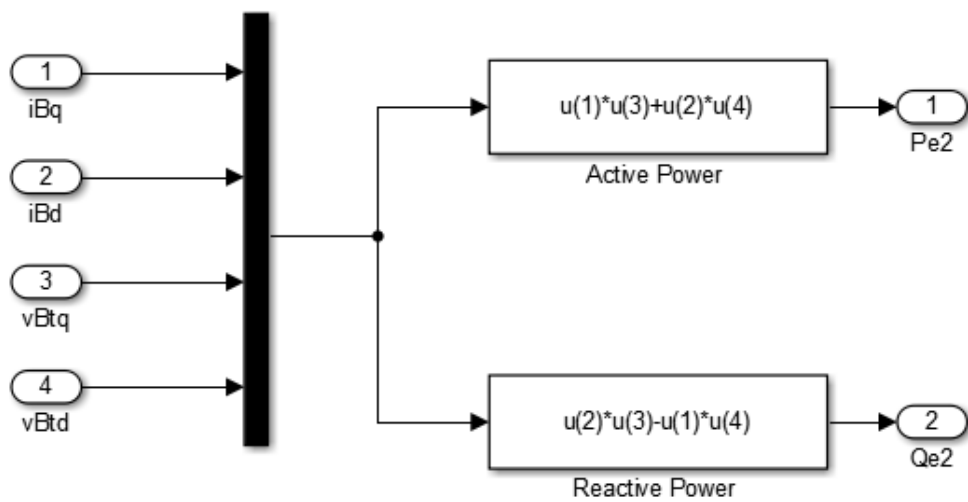
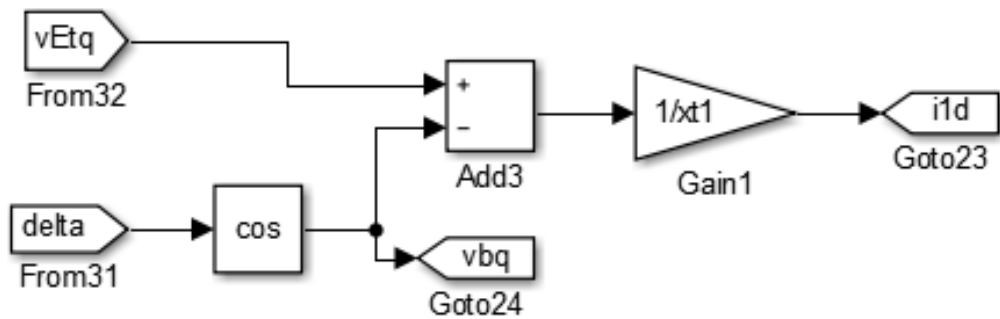
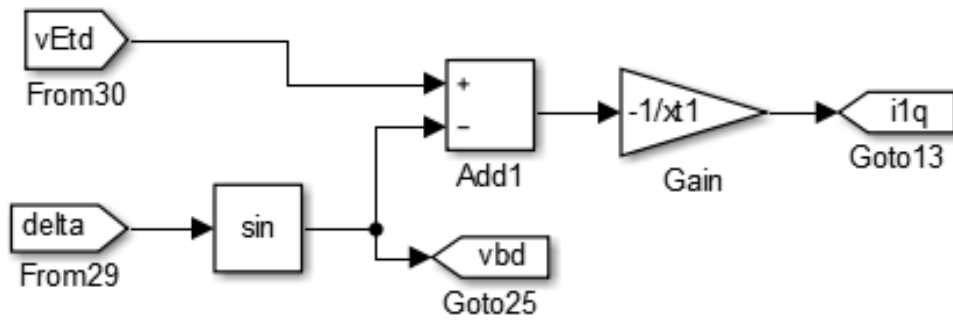
## d. System Currents

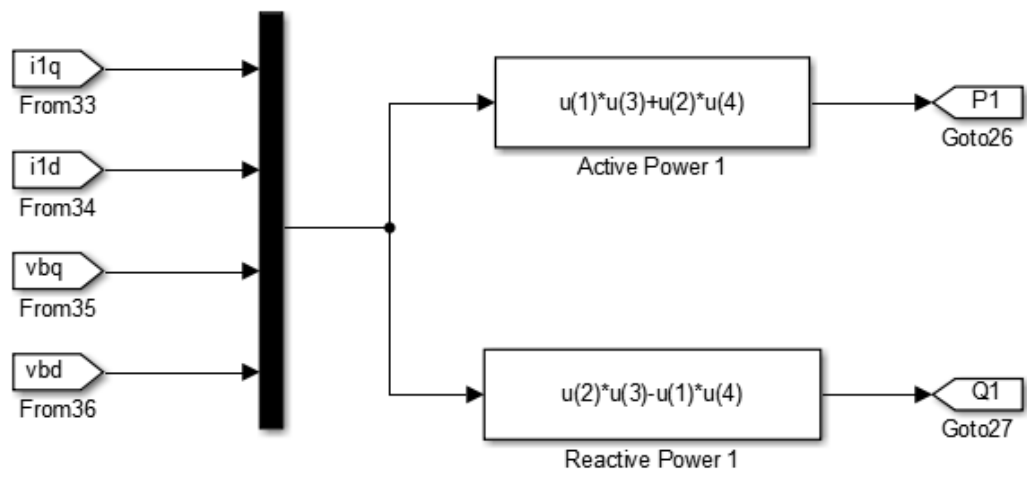






## e. System Outputs





## Appendix (D)

The input to the Model Predictive Controller is the reference signal and the plant output as shown in figure (A1). In this study, the conventional PI Controller which was used to control the real power flow in line 2 will be replaced by MPC.

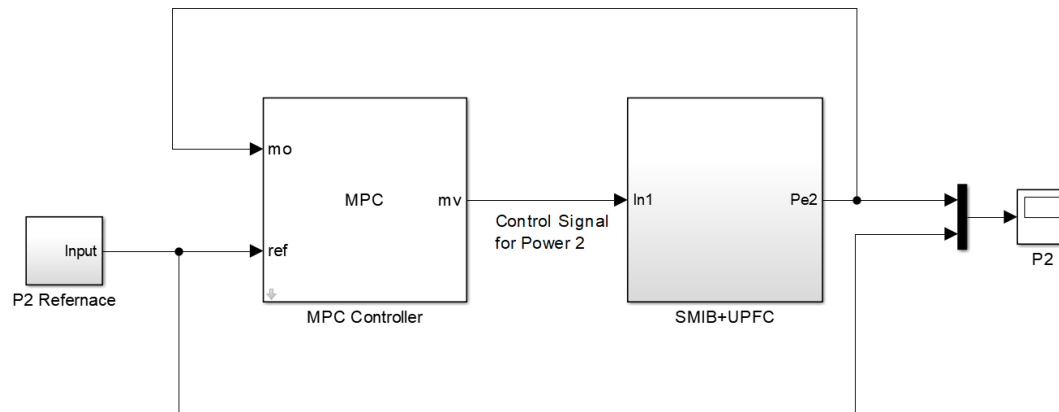


Figure (A1)

MPC in Matlab Simulink

The MPC need to be reconfigured as shown below in Figure (A2). The measured disturbance is considered inside the model.

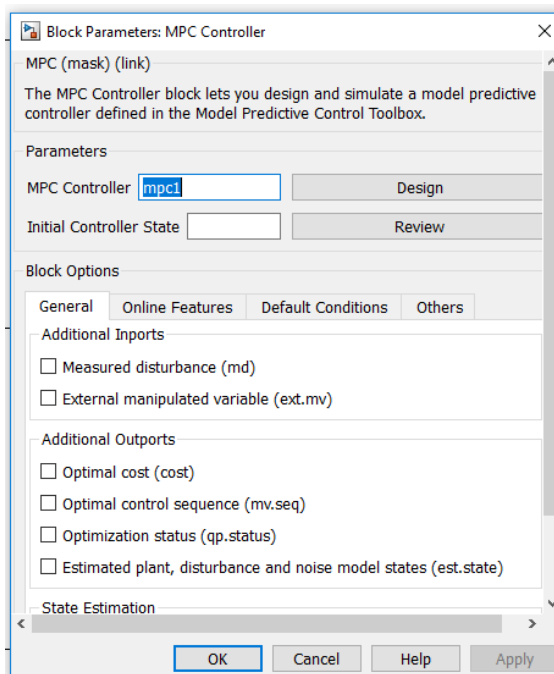


Figure (A2)

#### MPC Block Parameter

While designing the MPC, the number of the input and output parameters need to be identified with time step as mentioned below in figure (A3).

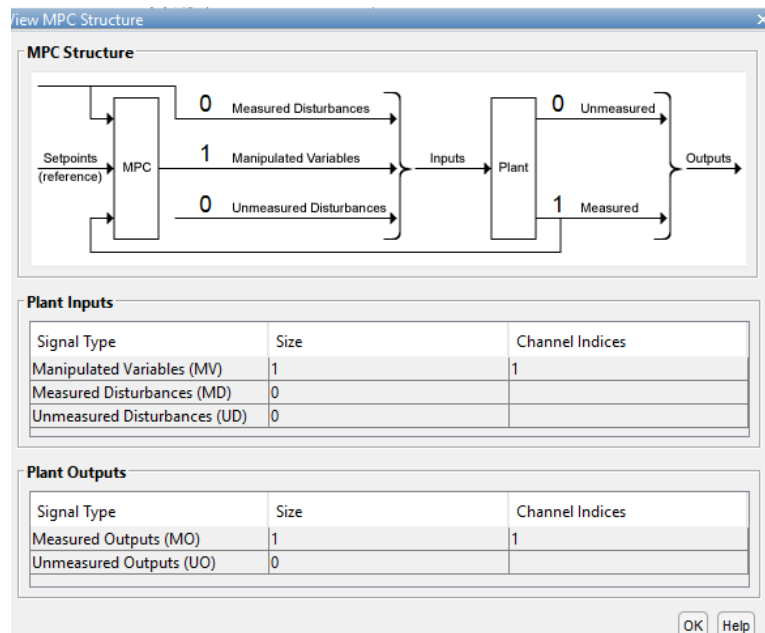


Figure (A3)

#### MPC Matlab Structure

The sample time, prediction horizon and control horizon need to be tuned to get the desired output response as shown in figure (A4) and finally export the controller to the Simulink file to perform its function.

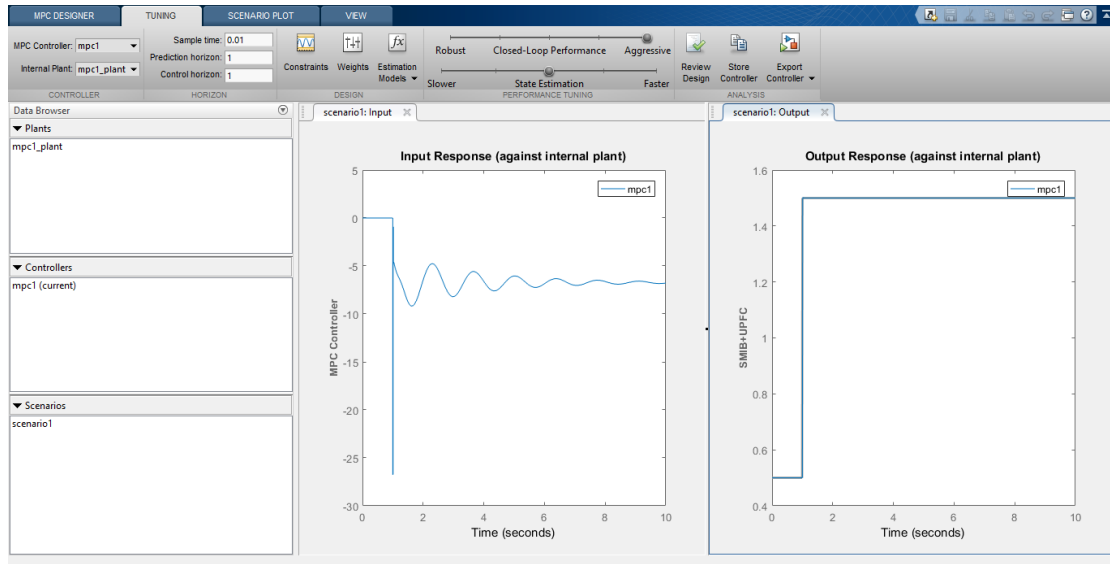
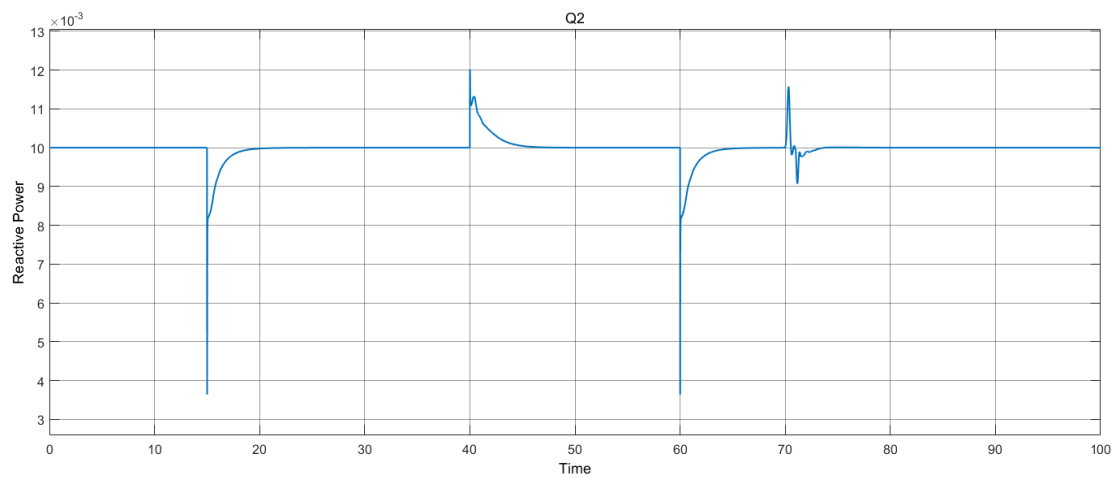
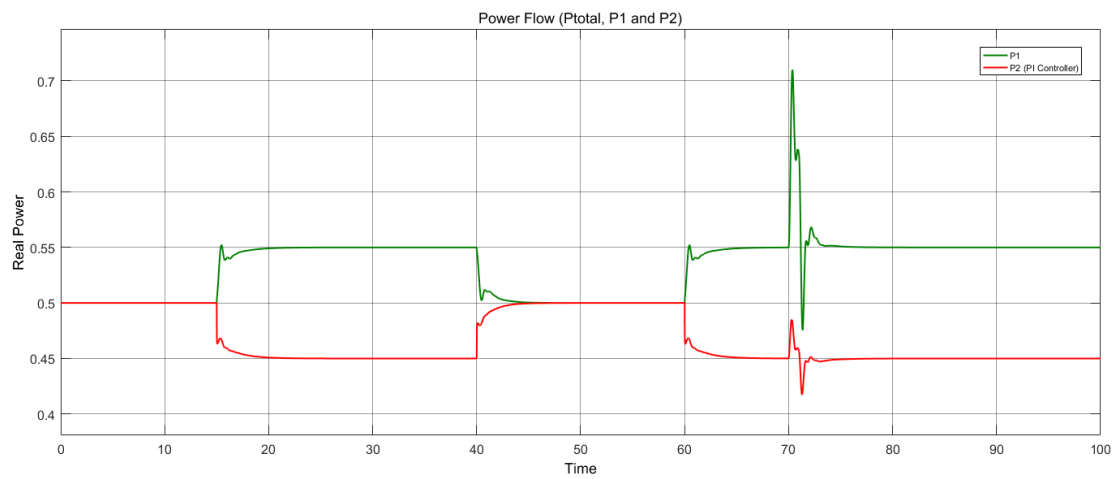
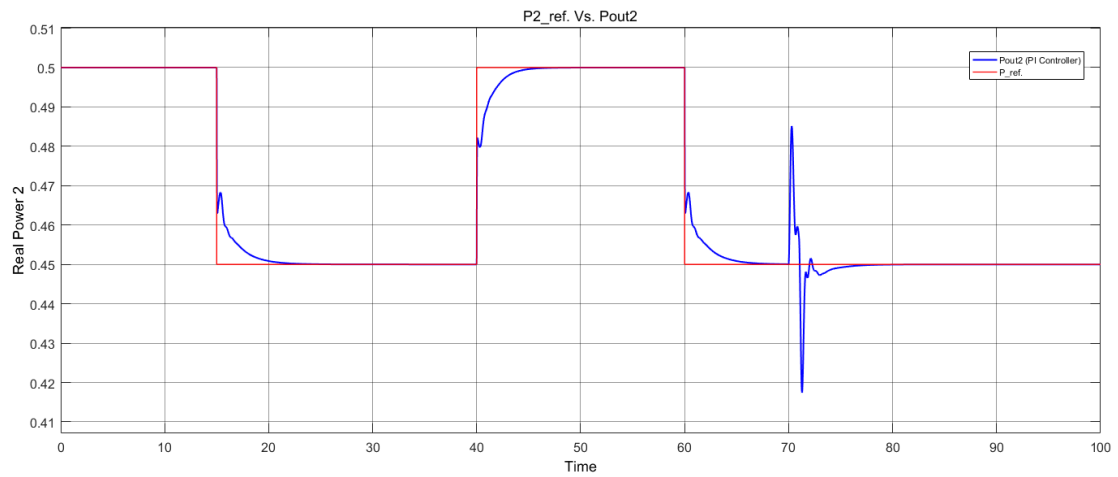
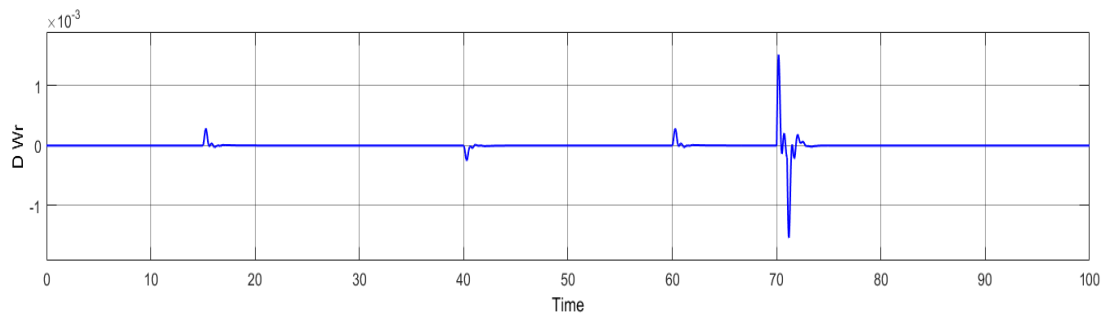
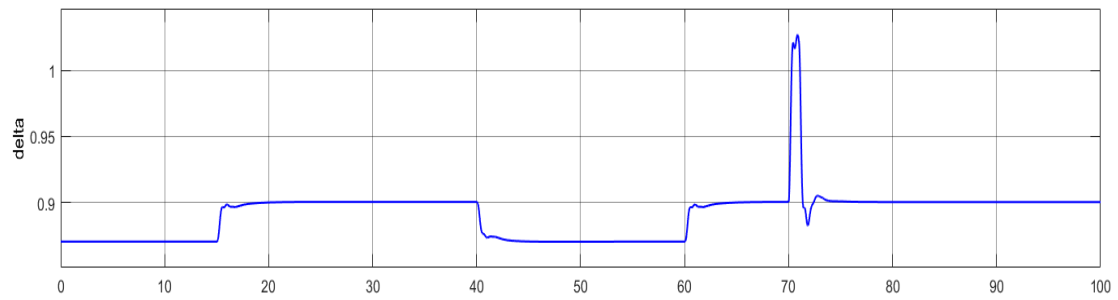
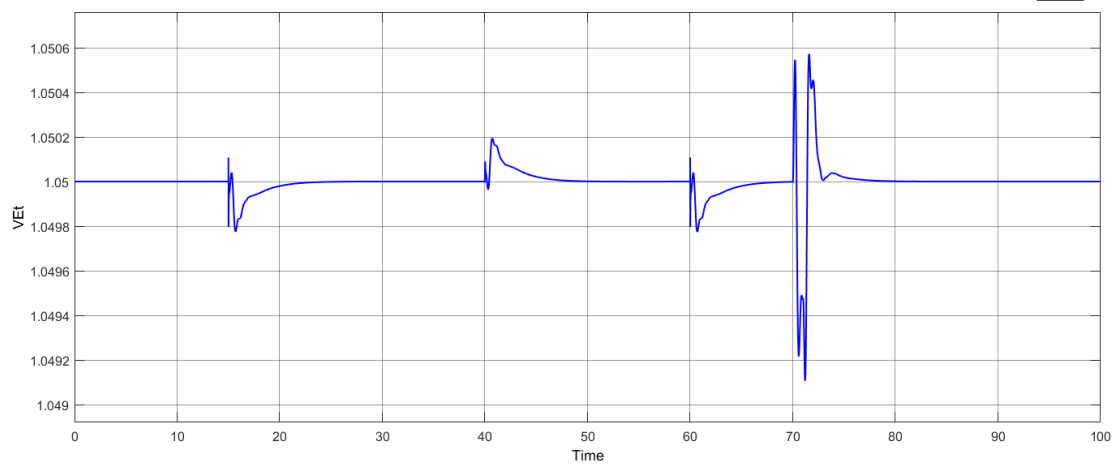
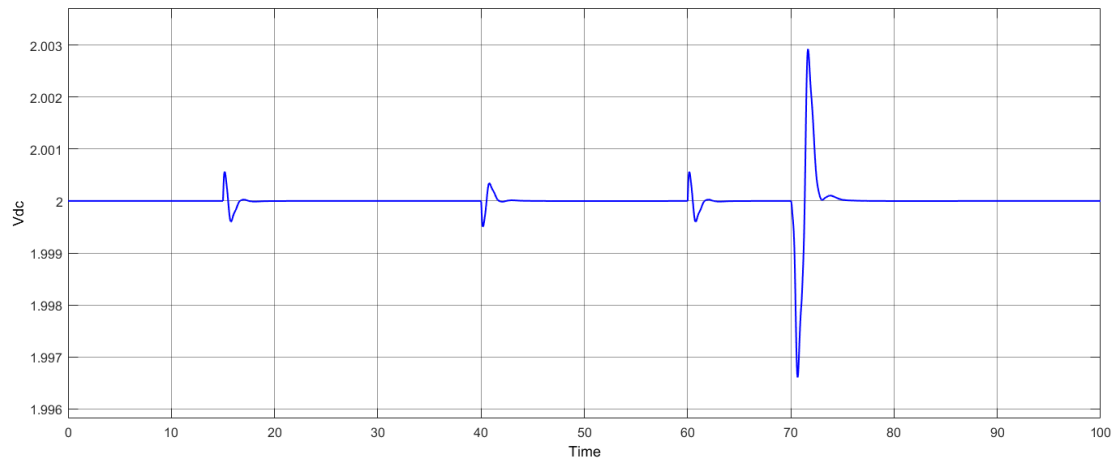


Figure (A4)  
Tuning MPC

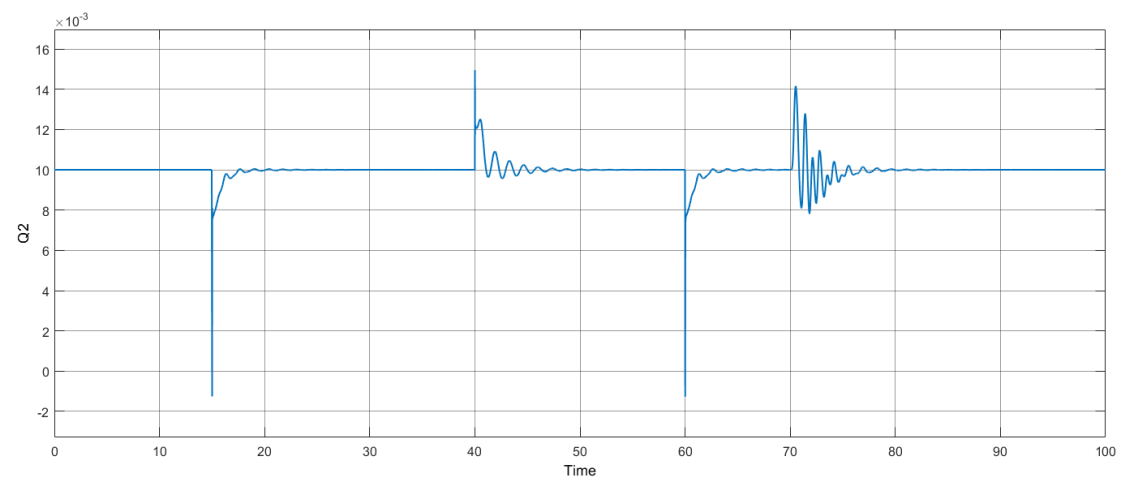
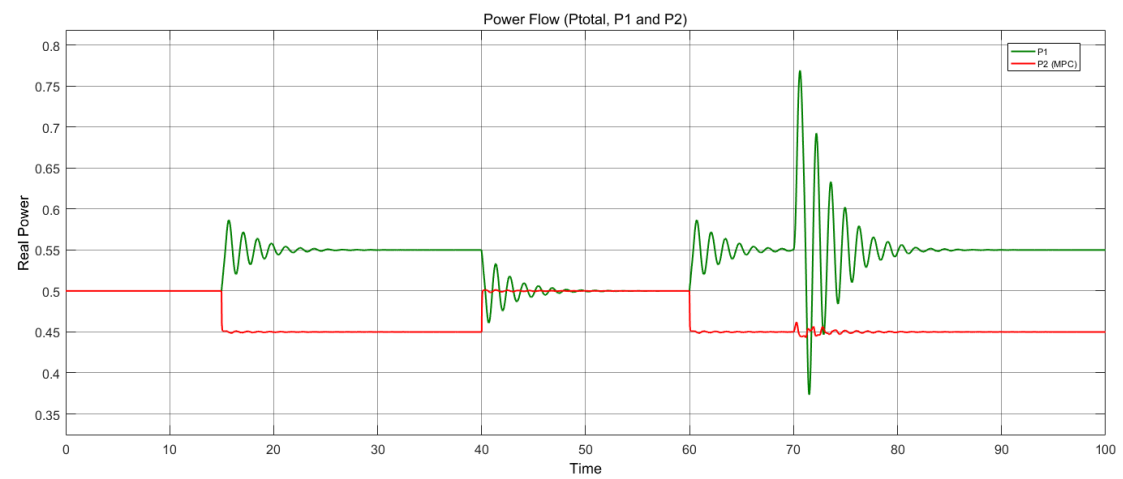
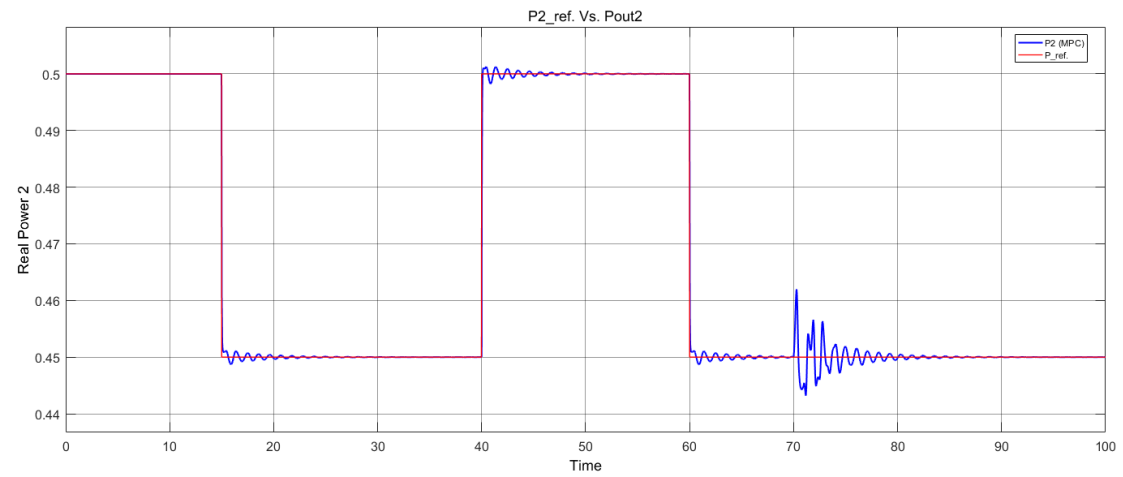
# Appendix (E)

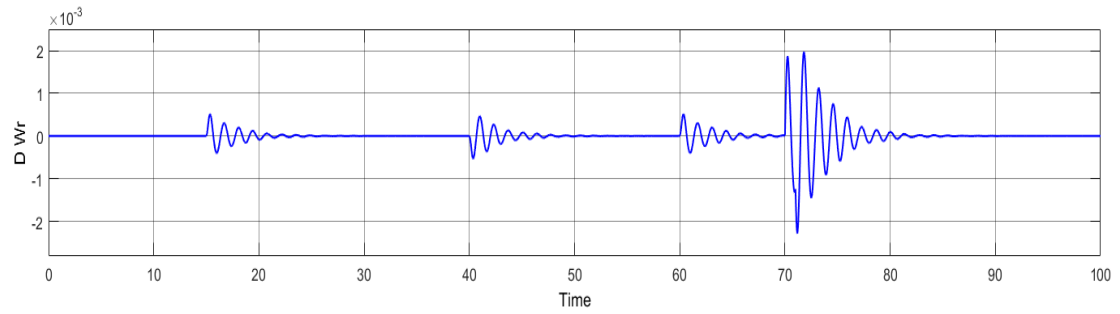
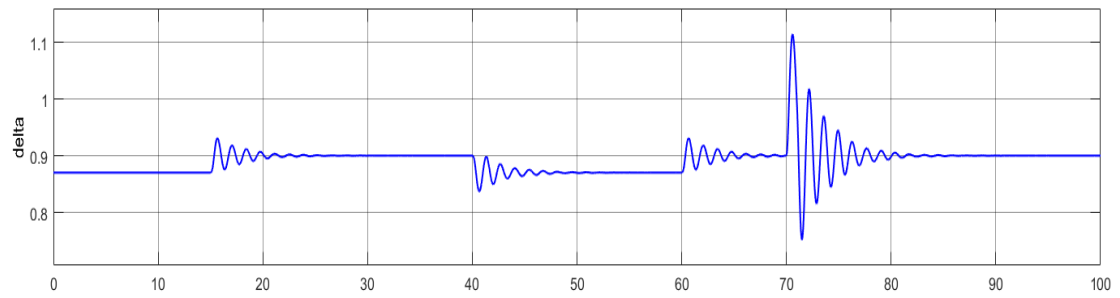
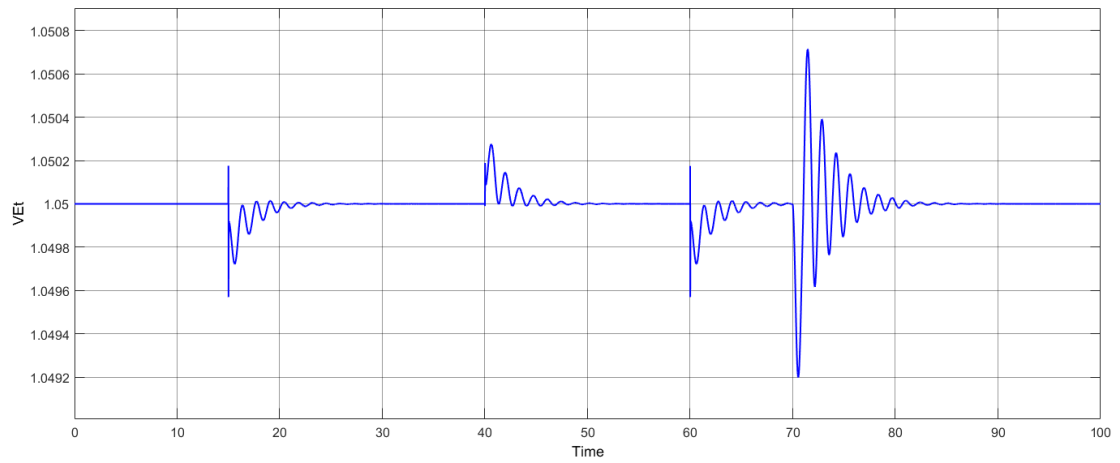
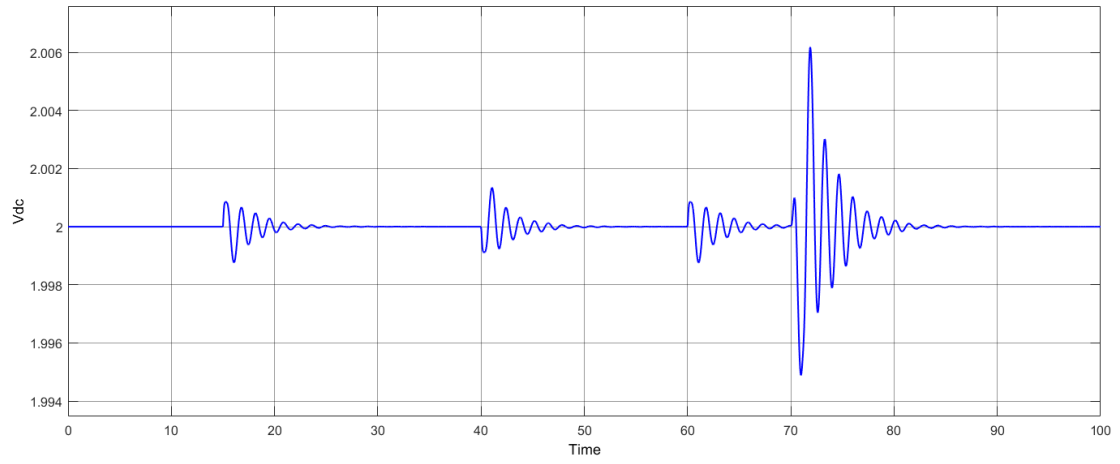
## PI Controllers



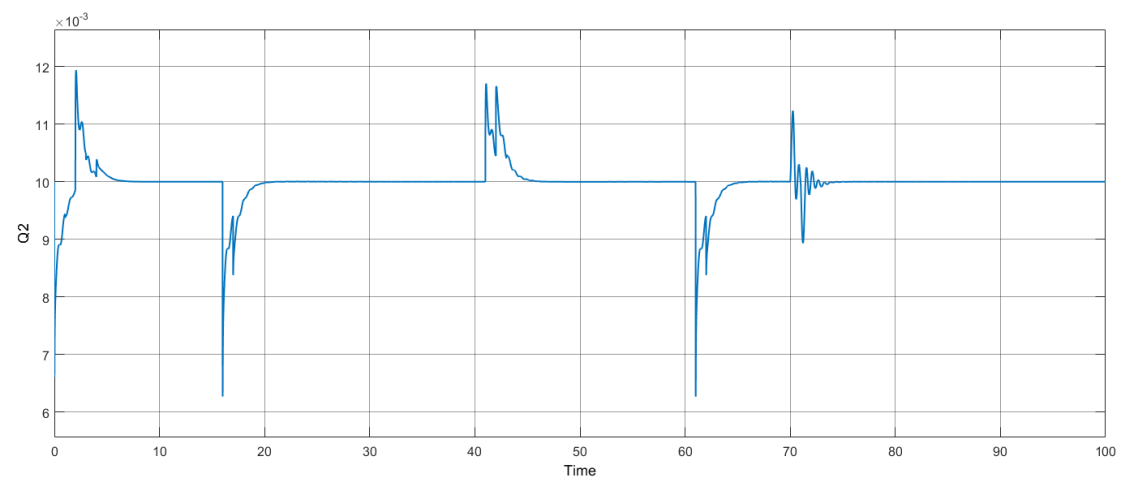
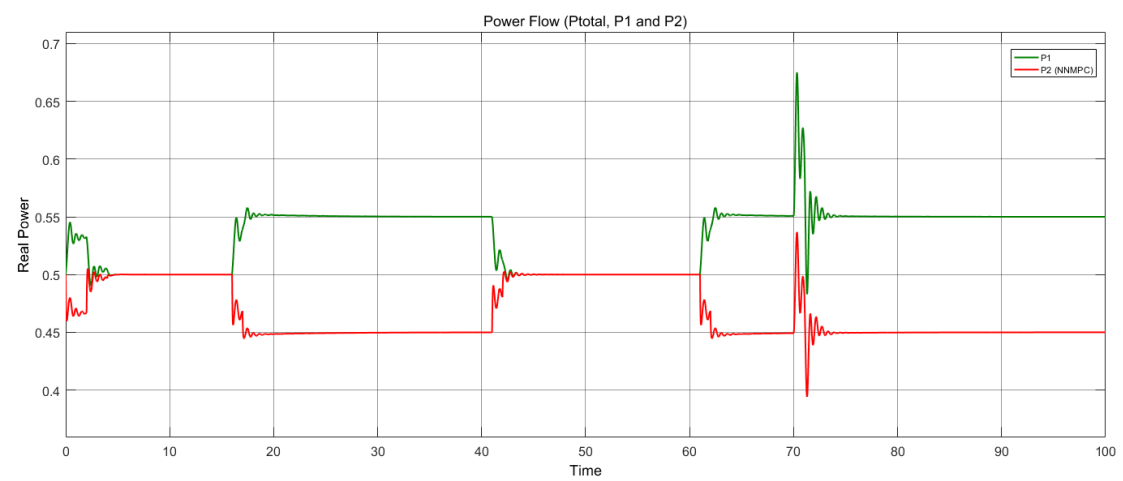
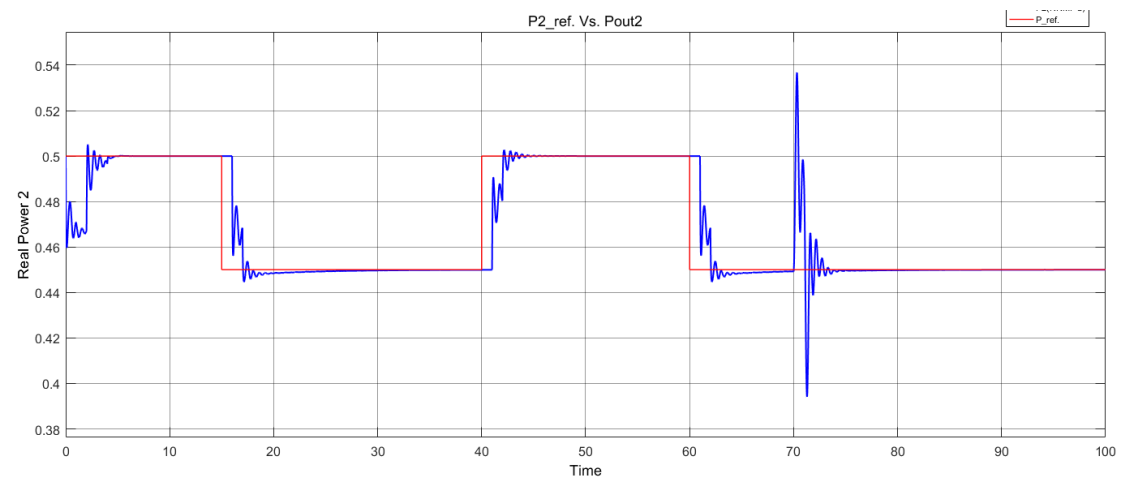


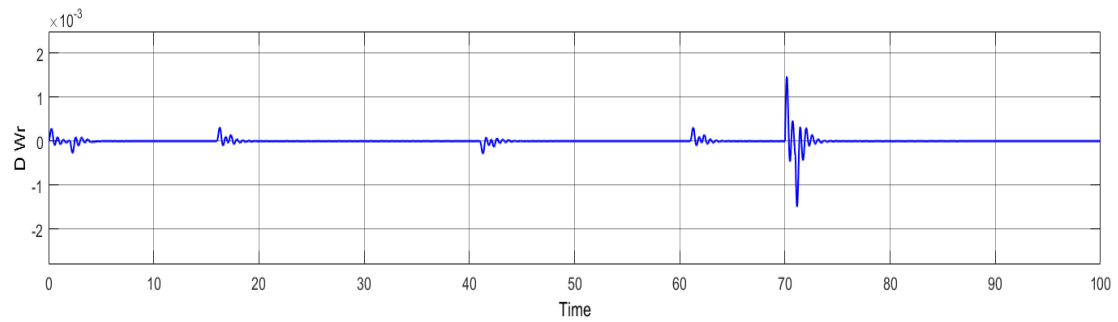
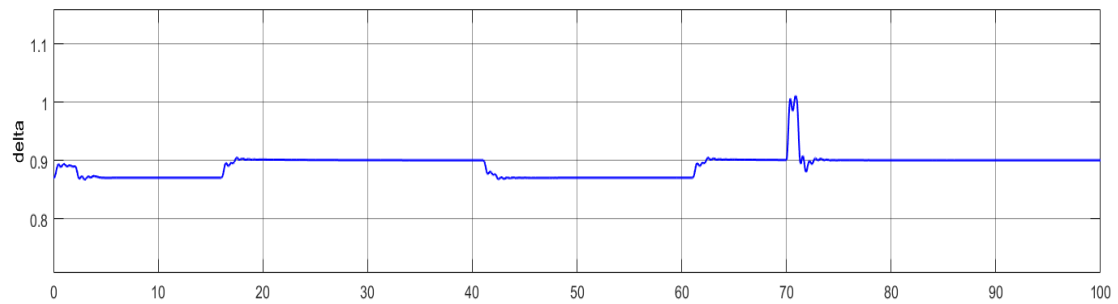
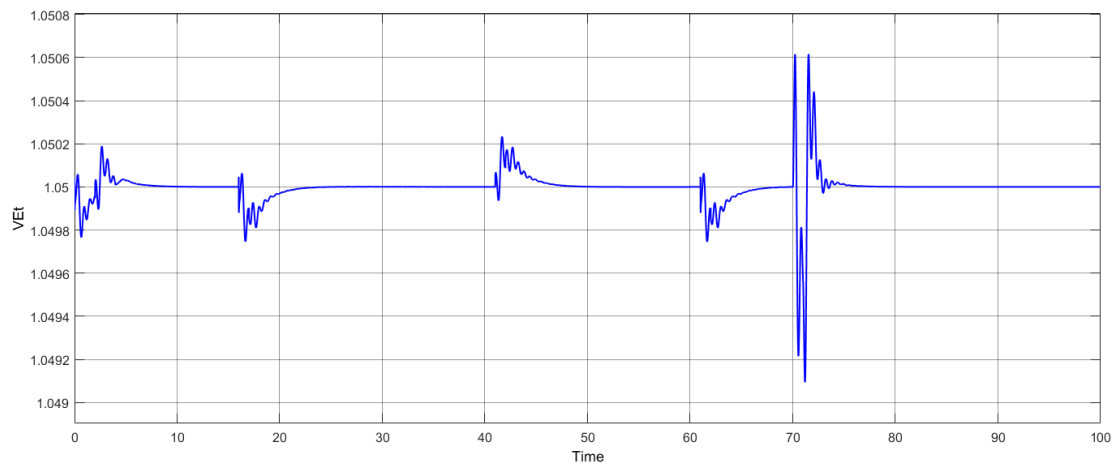
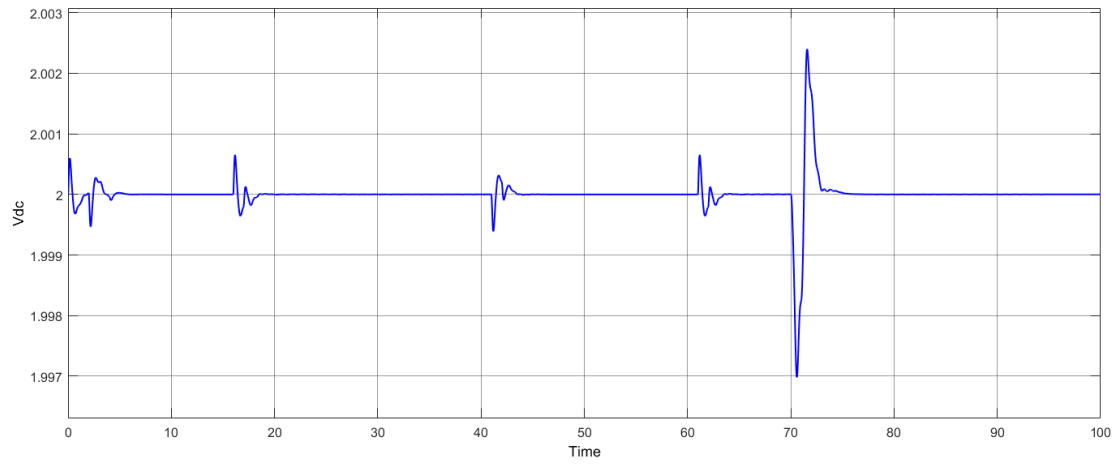
# MPC



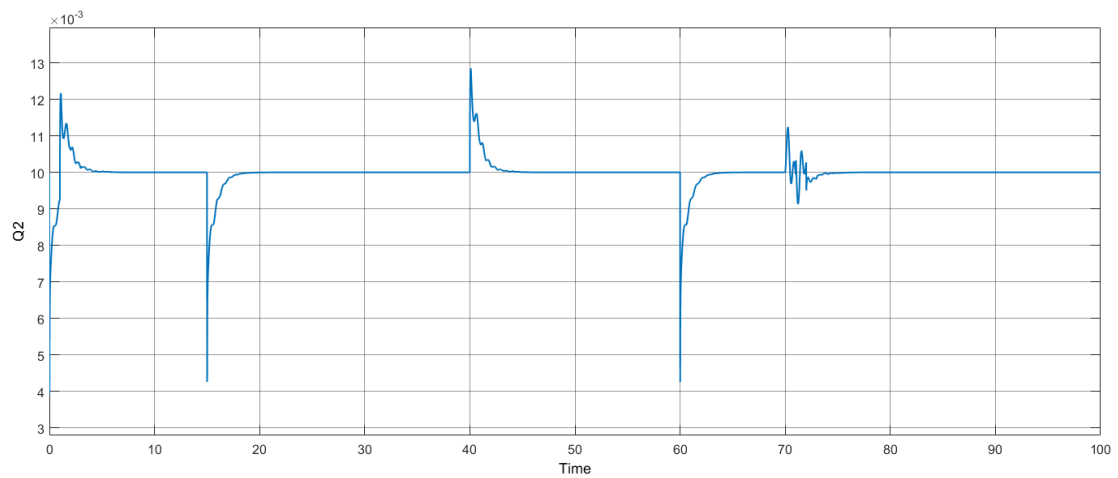
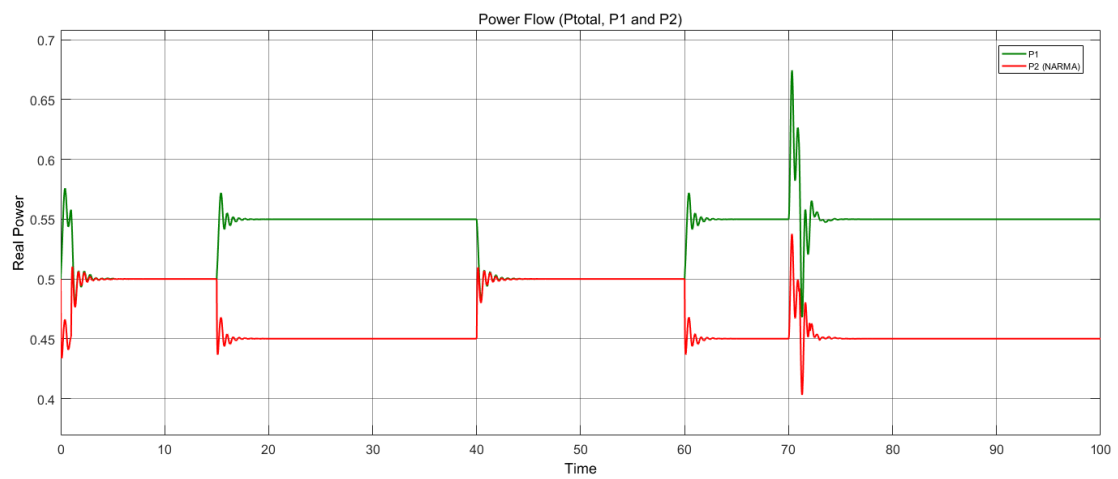
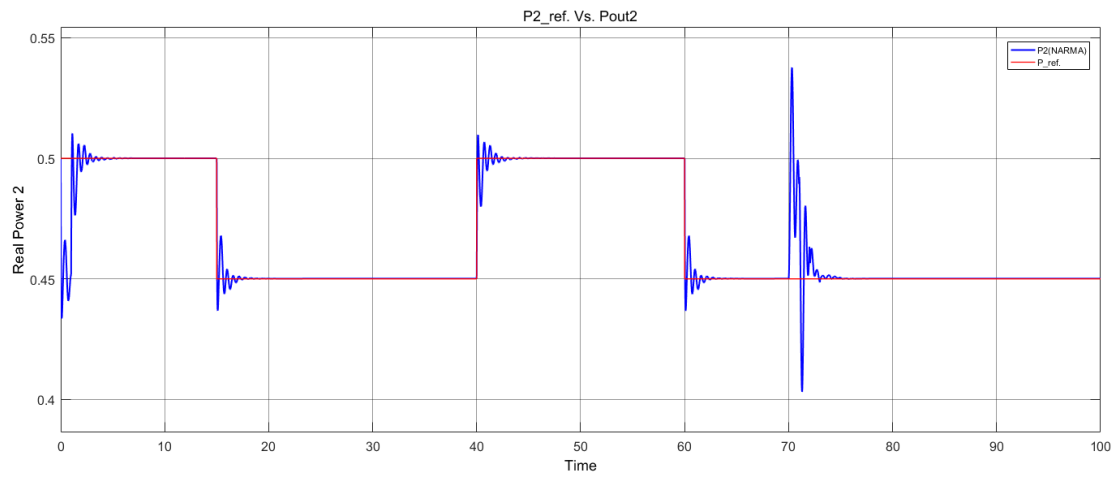


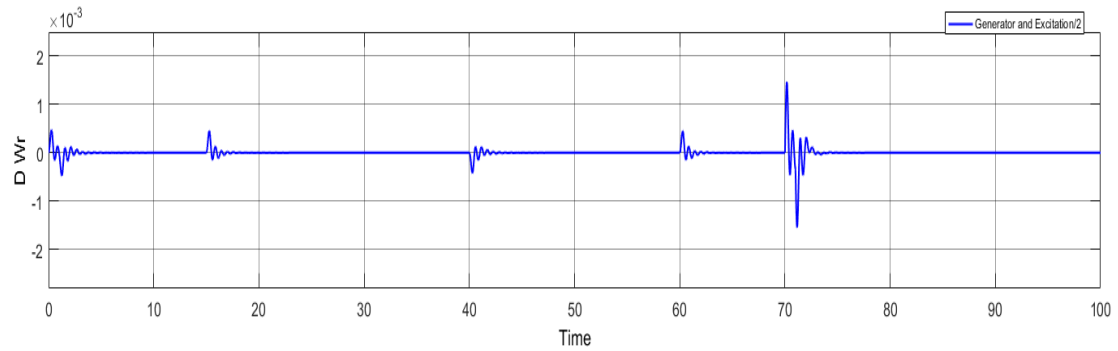
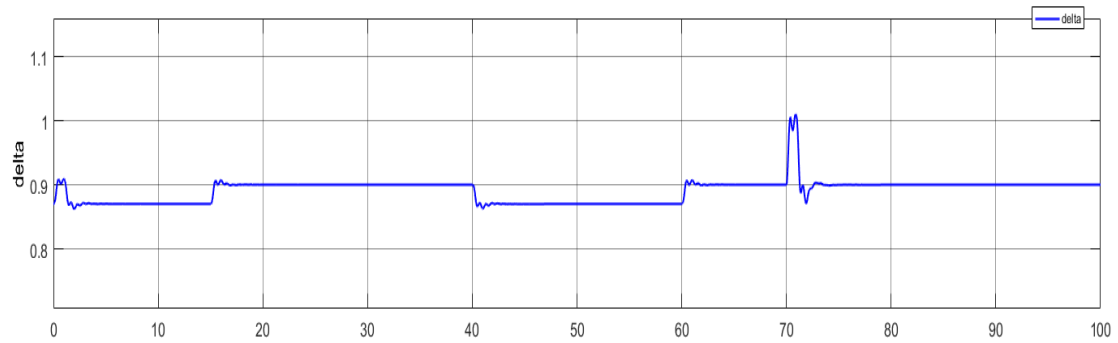
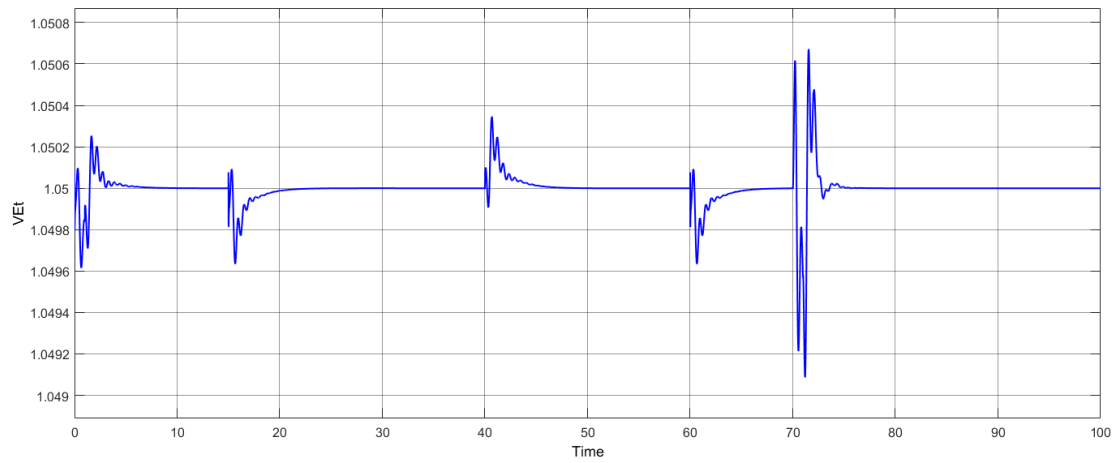
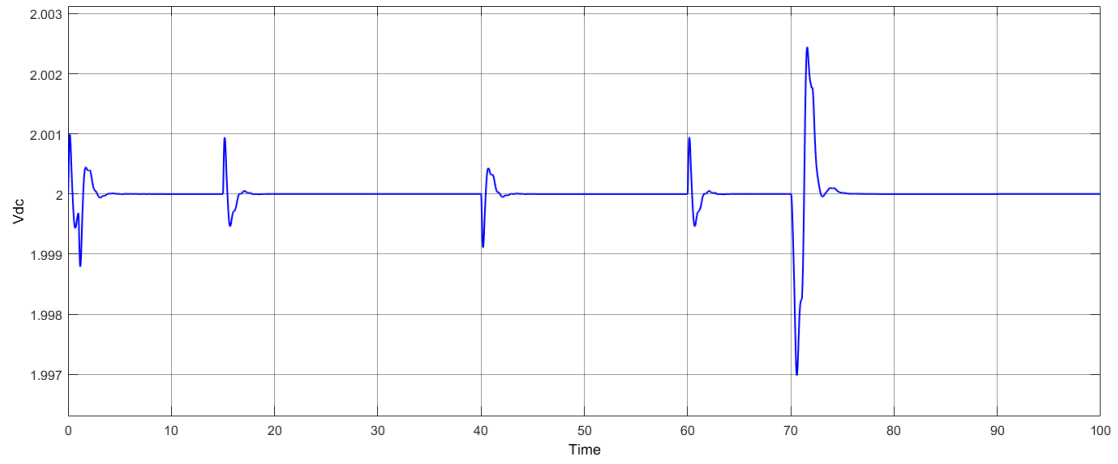
# NNMPC





# NARMA





## المخلص

على مدى السنوات الماضية، كان من الواضح أن الطلب على الطاقة قد شهد نموا سريعا في جميع أنحاء العالم بسبب الزيادة في معدل السكان والنمو الصناعي وبالتالي الحاجة إلى الطاقة الكهربائية. ونتيجة لذلك، تتعرض شبكات الكهرباء لتطور كبير في أنظمة التوليد والنقل والتوزيع، وأصبحت أكثر تعقيدا وتحديا.

وسيكون الاستخدام الأفضل لشبكات النقل الكهربائية الحالية إلى أقصى حد أكثر فعالية واقتصاديا طالما أن أمن النظام واستقراره وموثوقيته لا تتعرض للخطر. لذلك، تم اقتراح حل مبتكر للحصول على أفضل استخدام والسيطرة على تدفق الطاقة في شبكة نقل الكهرباء في حالات الاستقرار والحالات اللحظية باستخدام أجهزة نظام نقل التيار المتردد المرنة التي تعتبر كتقنية إلكترونيات الطاقة.

في هذا البحث، يتم دراسة وحدة تحكم تدفق الطاقة الموحدة لأنها تعتبر النموذج الأكثر قوة وتنوعا لمجموعة أجهزة نظام نقل التيار المتردد المرنة. وعلاوة على ذلك، فإن وحدات التحكم التي تستخدم في وحدة تحكم تدفق الطاقة الموحدة مهمة جدا للسيطرة على متغيرات عوامل خطوط النقل كما هو مطلوب ومن أحد وحدات التحكم التقليدية التي يتم استخدامها اليوم هو وحدات تحكم (PI) التقليدية.

في هذه الدراسة، سيتم استبدال وحدات تحكم (PI) التقليدية من قبل وحدات تحكم تكيفية ووحدات تحكم تعتمد على فكرة الشبكة العصبية الاصطناعية. هذا من أجل التحقيق في متانة وفعالية وقدرة وحدات التحكم هذه لاستيعاب أي تغيير مفاجئ في متغيرات عوامل خط النقل مثل حجم الجهد، والمقاومة وزاوية المرحلة.

جامعة البحرين

قسم الهندسة الكهربائية و الإلكترونية

كلية الهندسة



## تصميم وحدة تحكم تدفق الطاقة الموحدة بإستخدام نماذج متكيفة

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير في الهندسة الكهربائية والإلكترونية

إعداد

قحطان حسان الفارس

الرقم الجامعي: ١٩٩٩١٧٣٥

إشراف

الدكتور أنور حيدر

الدكتور سيد علي الموسوي

أستاذ مساعد

أستاذ مشارك

جامعة البحرين

مملكة البحرين

٢٠١٨/٠٥/٠٢