

People's Democratic Republic of Algeria  
Ministry of Higher Education and Scientific Research  
Ibn Khaldoun University–Tiaret  
Electrical Engineering Department



GRADUATION MEMORY To obtain the Master's degree

Domain: Science and Technology

Field: Electrotechnics

Specialty: Electrical Networks

**INTRODUCTION OF A FACTS GUPFC  
SYSTEM FOR POWER TRANSIT CONTROL  
IN AN ELECTRICAL NETWORK**

THEME

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Academic year: 2022/2023

## **Dedication**

*I dedicate this humble work to my father who passed away, I wish he were present with us today, but I tell him that I have achieved what you wanted me succeed. I am very sure that he will be very proud of me.*

*I also dedicate this work to my loving mother for her sacrifices and moral backing throughout my career.*

*To my grandparents, brothers and all my family.*

*Sais Elbatoul Karima*

## **Dedication**

*I want like to dedicate this work To my dear father Abdelmalek, although no dedication in the world could express my eternal love, respect and devotion to him. I also dedicate this work to my dear mother for her sacrifices and support throughout my career, and to my brother Mohamed and my sisters.*

*A big thank you to all of you*

*Benaissa Norelhouda*

## **Acknowledgment**

Our first and utmost thanks and praises go to almighty الله for the will, the health and the patience bestowed on us during all these long years.

We would like to express our gratitude to our supervisor Prof. Smaili Atallah for having first proposed this topic and for his continuous support throughout the completion of this dissertation.

We sincerely thank Prof. Allaoui Tayeb for his technical guidance throughout the project.

Our sincere thanks go to the jury of examiners for the honor they have done us in providing constructive feedback and evaluating our work.

Our thanks also go to all the lecturers at the Electrical Engineering Department who have contributed to our academic development at the University.

Finally, we would like to express our gratitude to all those who have helped us, in different ways, to accomplish this work.

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## List of Abbreviations /acronyms

AC	Alternating Current
DC	Direct Current
FACTS	Flexible Alternating Current Transmission Systems
GTO	Gate Turn Off.
GUPFC	Generalized Unified Power Flow Controller
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor.
IPC	Interphase Power Controller
IPFC	Interlines Power Flow Controller
LTC	Load Tap Changer
PI	Proportional Integrator
PID	Proportional Integrator Derivative
PLL	Phase Lock Loop
RPI	Régulateur de Puissance Interphase
SMES	Superconducting Magnetic Energy Storage
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCPAR	Thyristor Controlled Phase Angle Regulator
TCSC	Thyristor Controlled Series Capacitor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified Power Flow Controller

# **GENERAL INTRODUCTION**

## General introduction

The primary factors driving electric energy consumption are industrialization and population growth. Therefore, in order to achieve a balance between production and consumption, it is first necessary to increase the number of electric power plants, transmission lines, transformers, and the like. This results in cost increases and environmental degradation. Therefore, it is now critical to have fractured networks and to work close to the stability limits .

The power flow in a transmission line is determined by three critical electrical parameters: the line tension, impedance, and the transport angle. When one of these electrical parameters is changed, the power flowing through the transmission line changes [1]. In fact, the power flow in an electrical network is difficult to control due to the complexity of controlling the line parameters that determine the flow of power in that line. The methods traditionally used to compensate and control power flow in networks include reversible transformers, dephasers, and compensators serially or paralleled commutated by circuit-breakers. Such methods appear to be too slow and insufficient to respond effectively to additional demands.

During an IEEE conference in 1988, Hingorani presented a new concept in a paper entitled "Flexible AC Transmission Systems (FACTS)", and showcased the new capabilities of power electronics in controlling the transport of alternating current (AC) [2]. According to IEEE, FACTS refers to electrical energy transport and distribution systems that use power electronics to improve operational flexibility and transit capacity.

FACTS systems are primarily composed of tension (or current) converters based on contemporary statically controlled interrupters, such as gate turn-off thyristors (GTO) and insulated-gate bipolar transistors (IGBT) that are controlled in opening and closing and are linked to condensators as continuous tension sources. These converters are grouped into three categories, shunt, series, or hybrid based on their network connection, such as STATCOM, SSSC, or UPFC [3].

In this work, we are interested in a type of FACTS called the Generalized Unified Power Flow Controller (GUPFC), which is greatly enhanced to regulate power flows of several lines or a sub-

network rather than a single line by a Unified Power Flow Controller (UPFC) or Static Synchronous Series Compensator (SSSC).

This dissertation is divided into four chapters. In the first chapter, FACTS were introduced in which some FACTS devices are highlighted, the significant role they play in the operation and management of electrical networks is discussed, their setup, operating principles and applications are presented.

The second chapter looks at the performance of the GUPFC using analogue control and mathematical modelling. First, the system will be modelled.

The second chapter discusses on the chosen GUPFC model. The GUPFC design, operational principles, mathematical model, reference identification, and fundamental control blocks are presented.

The third chapter examines advanced control strategies, such as fuzzy logic, to improve the control performance of the GUPFC, and fuzzy logic to improve the tuning performance of the GUPFC. The robustness of the control is also studied.

The fourth chapter presents the simulation results of control strategy used to control the GUPFC device.

Finally, a general conclusion is drawn and some recommendations for the future work are proposed.

# **CHAPTER 1:**

## **FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)**

## Chapter 1: Flexible AC Transmission Systems (FACTS)

### 1.1 Introduction

Given recent improvements in electrical transmission networks and power transit complications, it will become increasingly difficult to provide reliable regulation of energy transfers in densely interconnected networks using standard control devices with low switching frequency and the risk of accelerated aging in the future [4]. Some examples are phase-shifting transformers, transformers with changeable taps on load, and series and shunt-type compensators.

The FACTS concept encompasses all power electronic-based devices used to improve the operation of the power grid. The technology utilized in these systems (static switch) allows them to operate at a faster rate than standard electromechanical systems. They can also manage power flow through networks, increasing transmission capacity while preserving or even improving network stability.

### 1.2 Types of FACTS

There are three types of FACTS:

- Parallel compensators, also called reactive power compensators. By controlling the flow of reactive power in the line, they allow the network voltage at the connection point to be maintained within a well-defined range for the proper functioning of the network.
- Series compensators or impedance compensators. This type of compensator can control the active power flow in the line by adjusting the impedance of the line.
- Hybrid compensators. They modify the flow of active and reactive power on a line by only changing its electrical angle of energy transport.

#### 1.2.1 Parallel FACTS

Conventional compensation systems, such as capacitor banks and mechanically operated inductors have long been used to increase steady-state power flow by controlling the voltage

profile along transmission lines. It has been shown that the transient and the steady state stability of a power system can be improved if the compensation device can react quickly using thyristors as switches and electrical control and in particular the open and close controllable components such as GTO and IGBT.

**1.2.1.1 Principle of operation:**

The circuit in Figure 1-1 shows the shunt compensator upstream of a user.

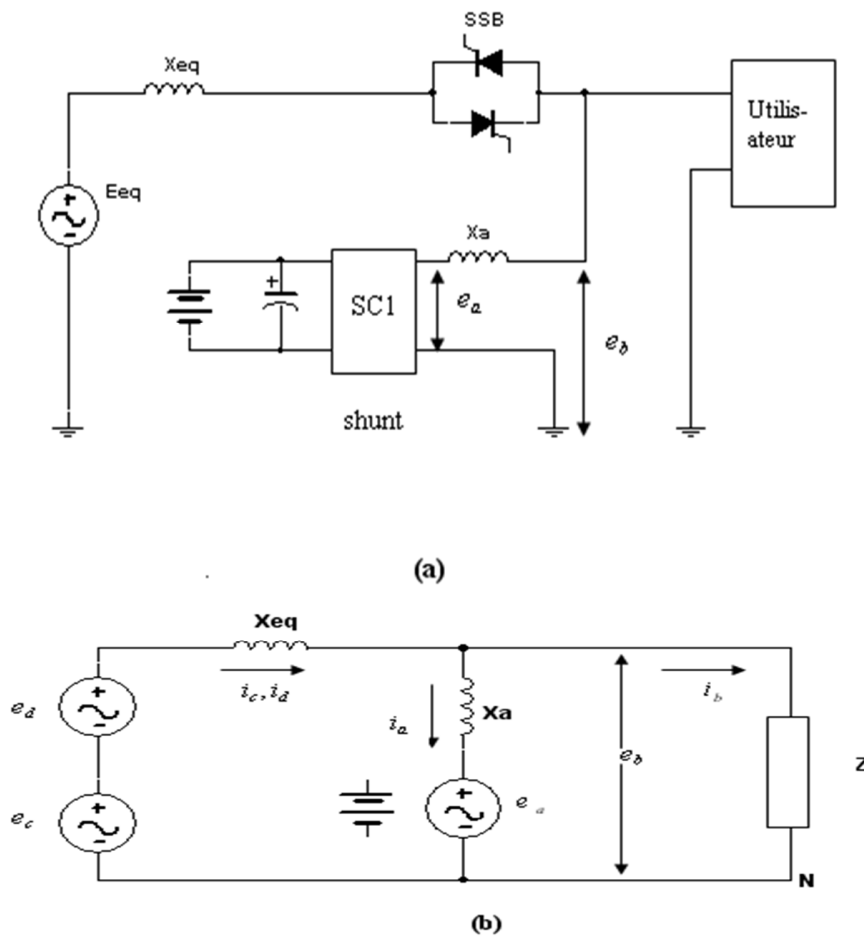


Figure 1-1. Equivalent circuit of the shunt compensator.



The network to the left of point (1) has been replaced by an equivalent reactance  $X_{eq}$  and an equivalent voltage  $E_{eq}$ . This simplification is possible thanks to Thevenin's theorem. The equivalent voltage  $E_{eq}$  comprises the fundamental component  $e_c$  at a frequency of e.g. 50 Hz and a voltage  $e_d$  which contains all random voltages and harmonic voltages.

### 1.2.1.2 Types of parallel compensators

#### 1.2.1.2.1 SVC

The Static Var Compensator (SVC) is a static reactive power compensator that makes fast voltage control possible. Figure 1-2 below shows the schematic of such a device.

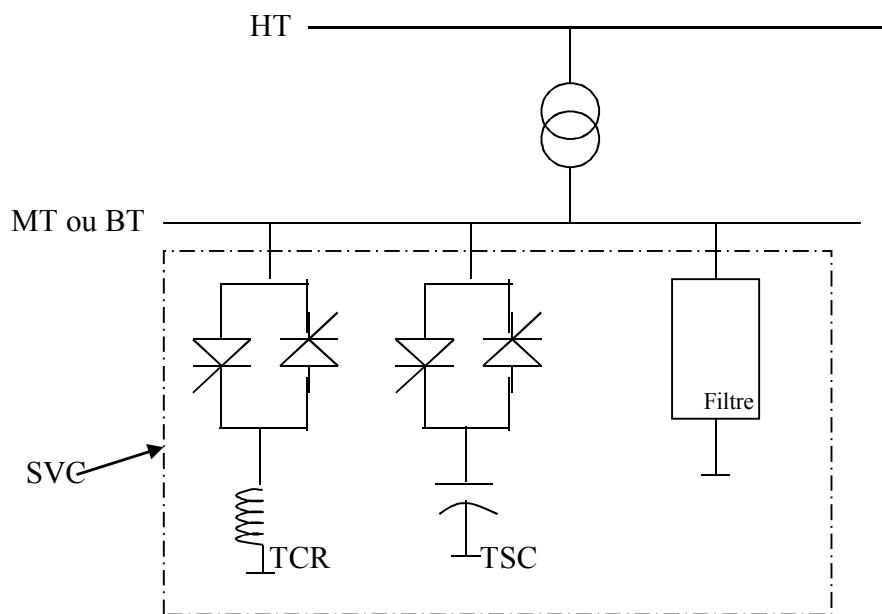


Figure 2-2. SVC diagram.

The SVC combines a Thyristor-Controlled Reactor (TCR), a Thyristor-Switched Capacitor (TSC) and a harmonic filter. The static characteristic of this type of FACTS is given in Figure 1-3.

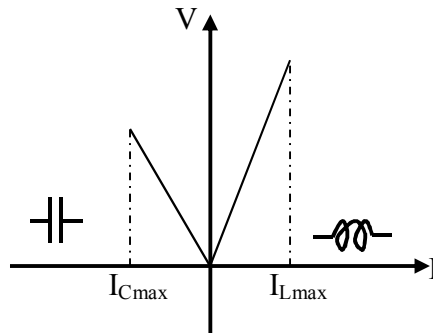


Figure 3-3. Characteristics of SVC

$I_{Cmax}$  and  $I_{Lmax}$  are the limiting currents that can be carried by the TCR and the TSC, respectively.

One example of implementing this type of FACTS in the power system is the Ross Substation in Australia. This installation is rated for  $\pm 230$  MVAR and connected to the 275 kV grid.

#### 1.2.1.2.2 STATCOM

The synchronous static compensator (STATCOM) consists of a voltage source converter, a coupling transformer and a control circuit. In this application, the DC power source can be replaced by a capacitor  $C$  so that the steady-state energy exchange between the static compensator and the grid is only reactive, as shown in Figure 1-4.  $I_q$  is the converter output current, perpendicular to the converter voltage  $V_i$ . The magnitude of the converter voltage and the reactive output of the converter are adjustable. If  $V_i$  is higher than the grid voltage  $V_t$ , the static compensator supplies reactive power to the system. However, if  $V_i$  is lower than  $V_t$ , the static compensator absorbs reactive power [5].

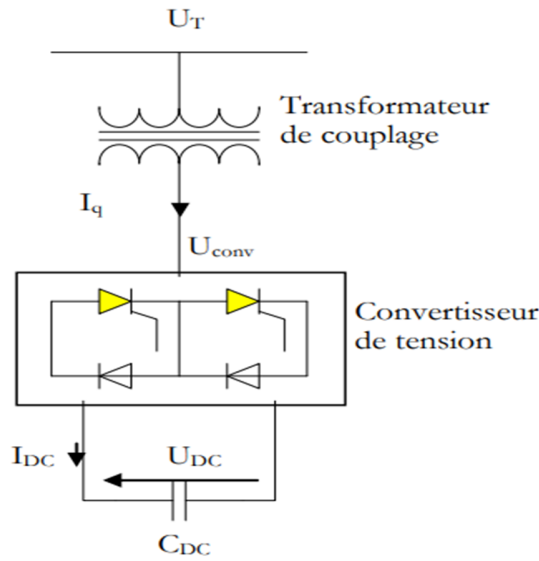


Figure 4-4. Basic STATCOM diagram [6].

#### 1.2.1.2.3 SMES

SMES stands for superconducting magnetic energy storage. This system stores energy in the form of a magnetic field created by the circulation of a direct current in a superconducting ring cooled below its "critical temperature". Figure 1-5 below shows a schematic diagram of such a device. The superconducting coil has no resistance; any current induced in it, for example by applying a voltage across it and then short-circuiting it, will continue until a voltage of opposite polarity is applied or a resistor is introduced into the circuit to discharge it. If the inductance of the coil is  $L_{sm}$ , it will accumulate energy  $W_{sm}$  and become charged, as shown in equations (1) and (2):

$$W_{sm} = \frac{1}{2} L_{sm} I_{sm}^2 \quad (1)$$

$$V_{sm} = L_{sm} \frac{dI_{sm}}{dt} \quad (2)$$

$I_{sm}$  and  $V_{sm}$  are the load current and the voltage across the coil, respectively. The combination of a superconducting coil used as superconducting magnetic energy storage and a high-power forced-switching converter constitutes the SMES. The exchange of active and reactive power between the superconducting coil and the electrical network through the appropriately controlled converter means that the SMES performs both control functions, i.e. speed control and voltage control [7].

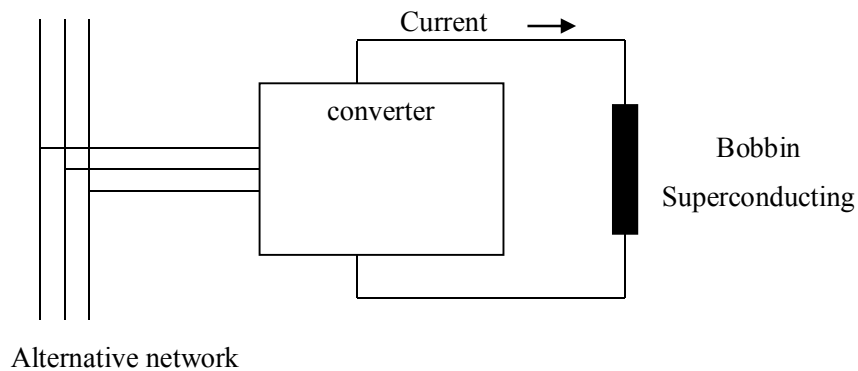


Figure 5-5. Diagram of the SMES [7].

There are currently several firms around the world interested in SMES and its realization. ACCEL, a German firm, is one of them. One of its research teams has developed a 2MJ SMES for power quality improvement at The Dortmunder Elektrizitäts und Wasserwerke in Germany [8].

Figure 1-6 gives an overview of this device.



Figure 1-6. Superconductivity bobbin for energy storage of 2MJ (With autorisation of « ACCEL Instruments ») [7].

This device is characterized as follows:

- SMES current: 1000 A
- Stored energy: 2.1 MJ
- Max power: 300 KW
- Device holding time: 8 s
- DC side voltage: > 800 V
- Generated magnetic field: 4.5 T

### **1.2.1.3 Advantages of parallel compensators**

The shunt compensator can serve multiple purposes:

- regulate voltage
- provide energy during a momentary failure
- eliminate voltage distortion

- eliminate voltage distortion
- correct the power factor
- act as an active filter

## 1.2.2 Series FACTS

A variable impedance (inductive, capacitive) or variable voltage source can be created by connecting FACTS in series with the grid. These compensators often alter the transmission lines' impedance by adding devices in series with them.

### 1.2.2.1 Principle of operation

The series compensator is similar to the shunt compensator; the main difference is that it is connected in series with the load instead of in parallel. considering the T transformer, the compensator is effectively interposed between the source and the receiver. Figure 1-7 shows the equivalent circuit for this part of the distribution network. The center is represented by the impedance  $Z$ , the compensator by the voltage and the transformer by the reactance.

This compensator type behaves as a voltage regulator and a device that eliminates distortion across the load. The principle is simple: the compensator only needs to generate a voltage so that the voltage across the load is constant and sinusoidal.

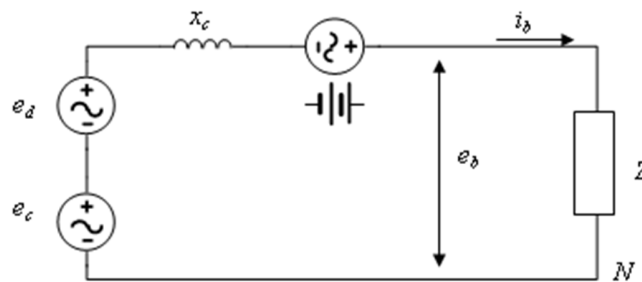


Figure 1-7. Simplified one phase circuit with series compensator.

### 1.2.2.2 Types of series compensators

The most common series compensators are as follows:

#### 1.2.2.2.1 TCSC

The Thyristor Controlled Series Capacitor (TCSC) is a series compensator that has been used successfully for many years to improve the stability and load capacities of high voltage transmission systems. Figure 1-8 shows the configuration of a TCSC. It inserts capacitive voltage to compensate for the inductive voltage drop on transmission lines [9].

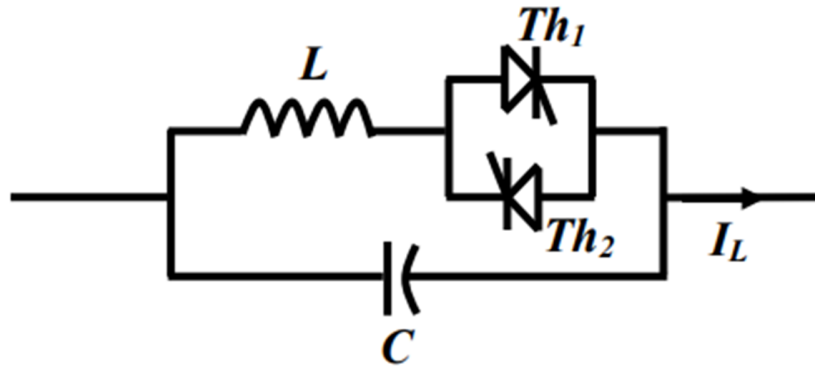


Figure 1-8. Schematic of the TCSC

#### 1.2.2.2.2 TCSR

The Thyristor Controlled Series Reactance (TCSR) is an inductive compensator consisting of an inductor in parallel with another thyristor-controlled inductor to provide a variable series inductive reactance. When the firing angle of the thyristor-controlled reactor is 180 degrees, it stops conducting, and the uncontrollable reactor  $X_1$  acts as a fault current limiter. As the firing angle decreases below 180 degrees and the equivalent reactance decreases to the 90 degree angle, there exists the parallel combination of two reactances exists.

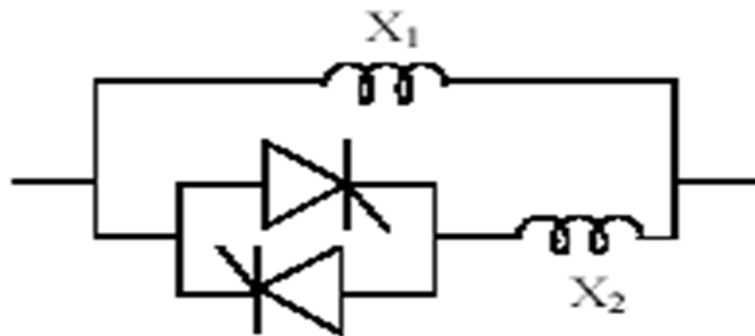


Figure 1-9. Schematic of the TCSR.

#### 1.2.2.2.3 SSSC

The Synchronous series static compensator (SSSC) consists of a static converter with a power source connected in series with the transmission line through a voltage transformer, as shown in Figure 1-10. In early days, while using simple series capacitive compensation technique, capacitor doesn't sense the fault and hence gives the fixed amount of reactive power to the system. Due to this behavior of series capacitive compensation torsional effect may occur on the generator side. Therefore SSSC device is used to overcome the above-mentioned phenomenon [10]

The SSSC injects in series an AC voltage with adjustable amplitude and phase angle into the transmission line using a series transformer. The SSSC can generate or absorb reactive power depending on the static converter control.



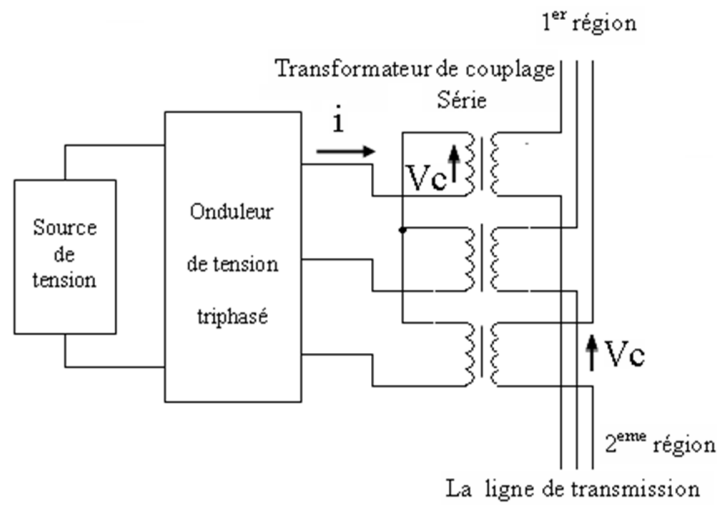


Figure 1-10. Schematic of SSSC.

The SSSC consists of a static converter with a power source connected in series with the transmission line through a voltage transformer as shown in Figure 1-10.

### 1.2.2.3 Advantages of serial compensators

The series compensator can serve multiple purposes:

- Voltage regulation
- Short-circuit current limitation.

## 1.2.3 Hybrid FACTS

These compensators modify the power flow active and reactive on an electrical transmission line.

### 1.2.3.1 Types of hybrid compensators

The most common hybrid compensators are the following:

### 1.2.3.1.1 TCPAR

The Thyristor Controlled Phase Angle Regulator (TCPAR) is a thyristor-based phase-shifting transformer. This device was created to replace the mechanically controlled Load Tap Changer (LTC) phase shifters. It consists of two transformers, one connected in series with the line and the other in parallel. The latter has different transformation ratios ( $n_1$ ,  $n_2$ ,  $n_3$ ). These two transformers are connected via thyristors. Their operating principle is to inject, on the three phases of the transmission line, a voltage in quadrature with the voltage to be dephased. It has the advantage of not generating harmonics because the thyristors are controlled as switches in full conduction. On the other hand, as the phase shift does not have a continuous variation, it is necessary to add a shunt compensator, which leads to additional installation costs. The amplitude of the injected voltage is a combination of the secondary parallel transformer whose transformation ratios are  $n_1$ ,  $n_2$ ,  $n_3$ . Figure 1-11 shows the schematic of the TCPAR [11]

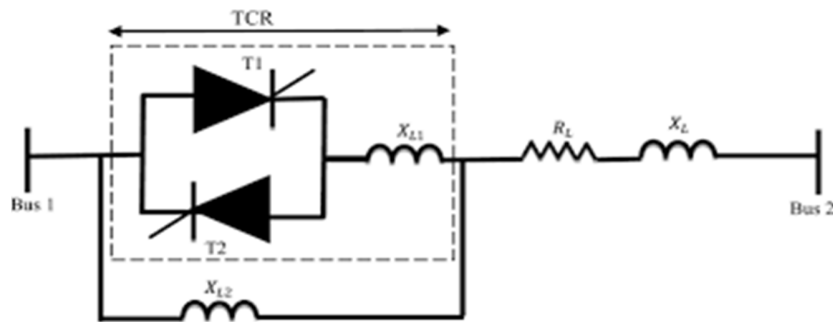


Figure 1-11. Schematic of the TCPAR [11].

### 1.2.3.1.2 IPFC

The Interline Power Flow Controller (IPFC) combines two or more serial static compensators that are coupled through a common direct current link. The IPFC uses DC-DC converters, connected in series with the line to be compensated. The IPFC structure may also include a STATCOM, coupled with the IPFC common DC link, to provide shunt compensation. The CFPI is intended to offset several transmission lines from a given substation [4].

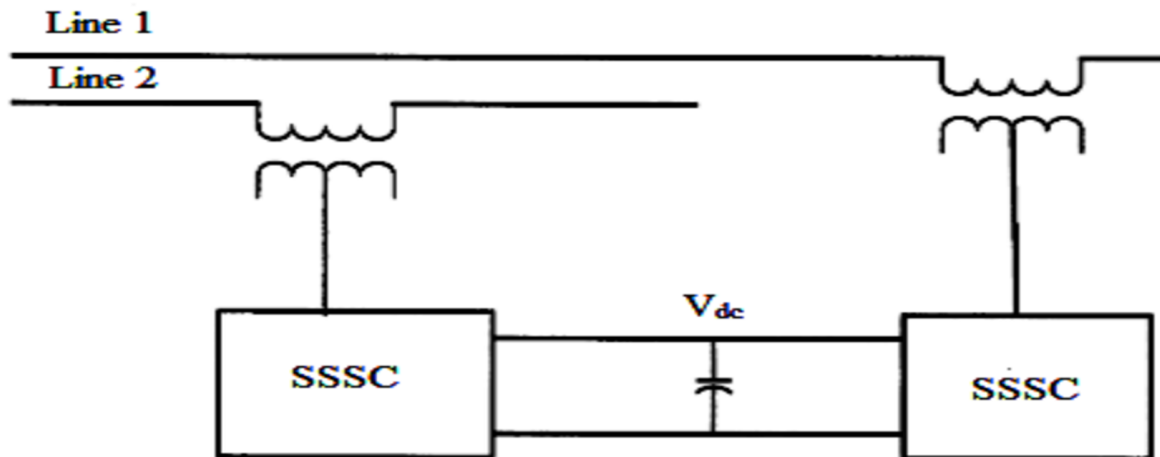


Figure 1-12. Diagram of the IPFC[4].

#### 1.2.3.1.3 UPFC

The unified power flow controller (UPFC) configuration given in Figure 1-13 below can vary the active and reactive power flowing on a high voltage line. The inverter (1), a parallel inverter, connected to the line through the transformer ( $T_p$ ) operating as a four quadrant rectifier maintains the voltage  $V_{dc}$  fixed on the buffer capacitor ( $C$ ). A second inverter (2), a series inverter, connected to the grid via the transformer ( $T_s$ ) and supplied with a D.C voltage ( $V_{dc}$ ), allows a series voltage ( $V_s$ ) to be injected into the grid. This additional voltage  $V_s$  is variable in modulus and in phase, so it is possible to vary the voltage  $V'$ . Thus the flow of active and reactive power transmitted on the line can be statically modified.

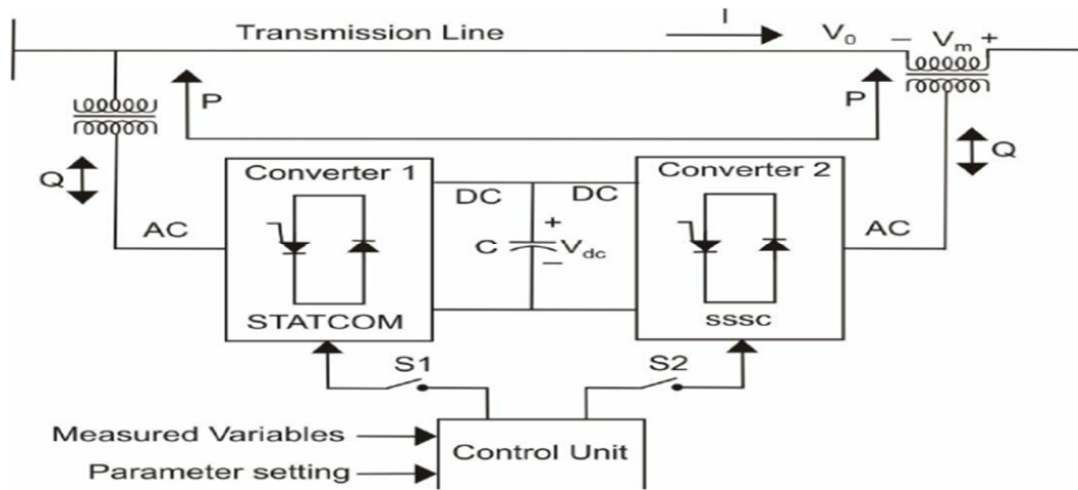


Figure 1-13. Diagram of a universal load inverter.

### 1.3 Conclusion

FACTS systems can enhance power flow control when the proper control is employed. Additionally, they have two options for controlling the line's transmissible power: series compensation and parallel compensation.

To improve the stability limit of the power system, FACTS devices provide quick and effective control over the various parameters. The most adaptable FACTS device, the GUPFC provides voltage independent regulation of both active and reactive power. The GUPFC will be discussed in detail in the next chapter.

## **Chapter 2:**

# **MODELING AND CLASSICAL CONTROL PI OF THE GUPFC**

## **Chapter 2: Modeling and classical control PI of the GUPFC**

### **2.1 Introduction**

The concept of GUPFC can be extended for more lines, if necessary. By using GUPFC devices, the transfer capability of transmission lines can be increased significantly. Furthermore, using the multi-line management capability of GUPFC, active power flow on lines can not only be increased, but also be decreased with respect to operating and market transaction requirement [1]. From the careful review of the literature, it is identified that, in the GUPFC modeling, the switching converter losses are not considered.

### **2.2 Operating principle of GUPFC**

Various operating configurations are possible by flexibly mixing two or more converter blocks. The GUPFC combines three or more three-phase switching converters coupled and connected back-to-back. The converter's primary job is to transform a DC input voltage into a symmetrical AC output voltage with the desired amplitude, frequency, and phase shift relative to the chosen reference. Coupling transformers' roles include isolating the GUPFC from the transmission line and balancing the voltage levels between the line and the converters' output voltage. By connecting a series connected transformer to the transmission line, a series converter inserts voltage with a configurable magnitude and phase angle, controlling the actual and reactive power flow in the transmission line [12].

### **2.3 Structure of the GUPFC**

Contrary to conventional notions of power transmission, GUPFC can simultaneously control every variable that affects power distribution in line transmission, such as voltage, impedance, and phase angle; this is how GUPFC defines the term "unified." Furthermore, the power flow of two active and reactive powers in the control line can be independently controlled by the GUPFC. The changes in the reactive power are similar to those in active power in

all prior controllers [13]. The simplest type of this compensator is a three-converter controller that contains one shunt converter and two series converters for two transmission lines [14].

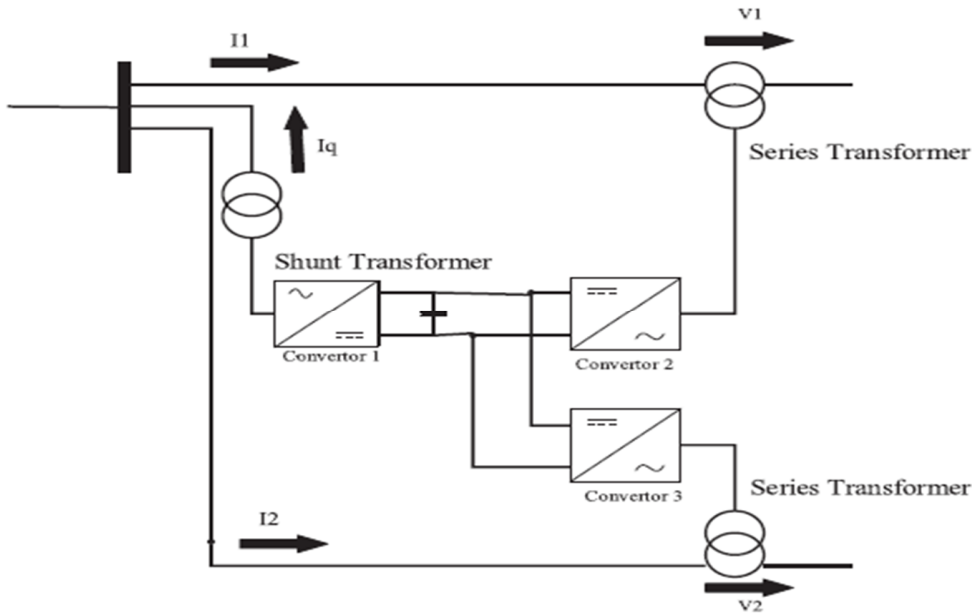


Figure 2-14. Principal configuration of GUPFC [14].

## 2.4 GUPFC Controller Design

### 2.4.1 Control scheme for STATCOM

The control scheme for GUPFC is divided into three parts: (1) Control scheme for STATCOM, (2) Control scheme for SSSC1, and (3) Control scheme for SSSC2. The objective of the control scheme for STATCOM is to generate the firing pulse to operate the shunt converter as shown in Figure 2-15. The shunt converter injects or converts the reactive power to control the connecting point voltage to the desired value  $V_{ref}$ . The three phase voltage  $V_{abc}$  at the connecting point are fed to the phase-lock-loop (PLL) to evaluate the desired angle  $\omega t$ , which must be synchronized with phase A voltage.

The current  $I_{abc}$  of the shunt converter into their real parts  $I_d$  and reactive part  $I_q$  is achieved via the  $abc\_dq0$  transformation using reference angle  $\omega t$  in its two-dimensional signal form

( $\sin\_cos$ ). The value of the positive sequence component of the voltage at the connecting point  $V_{mes}$  is compared with  $V_{ref}$ . If the error is generated, it is provided to a PI controller to generate the reference reactive current  $I_{qref}$ . The  $I_{qref}$  is again matched with the reactive part of the shunt current  $I_q$ , if the error generated is provided to the PI controller to generate the relative phase angle  $\alpha$  of the inverter voltage with respect to phase A voltage. The delay angle ( $D\_alpha$ ) is the angle between the voltage at d.c. link,  $V_{dc}$ , and the average reactive part current,  $I_{qavg}$ . The  $D\_alpha$  is generated by feeding  $V_{dc}$  and  $I_{qavg}$  to a PI controller. The desired firing pulse for the shunt converter is generated by feeding these calculated angles (phase angle  $\alpha$ , constant value angle  $\sigma$  signal  $\omega t$  and delay angle  $D\_alpha$ ) to the STATCOM firing pulse generator [15].

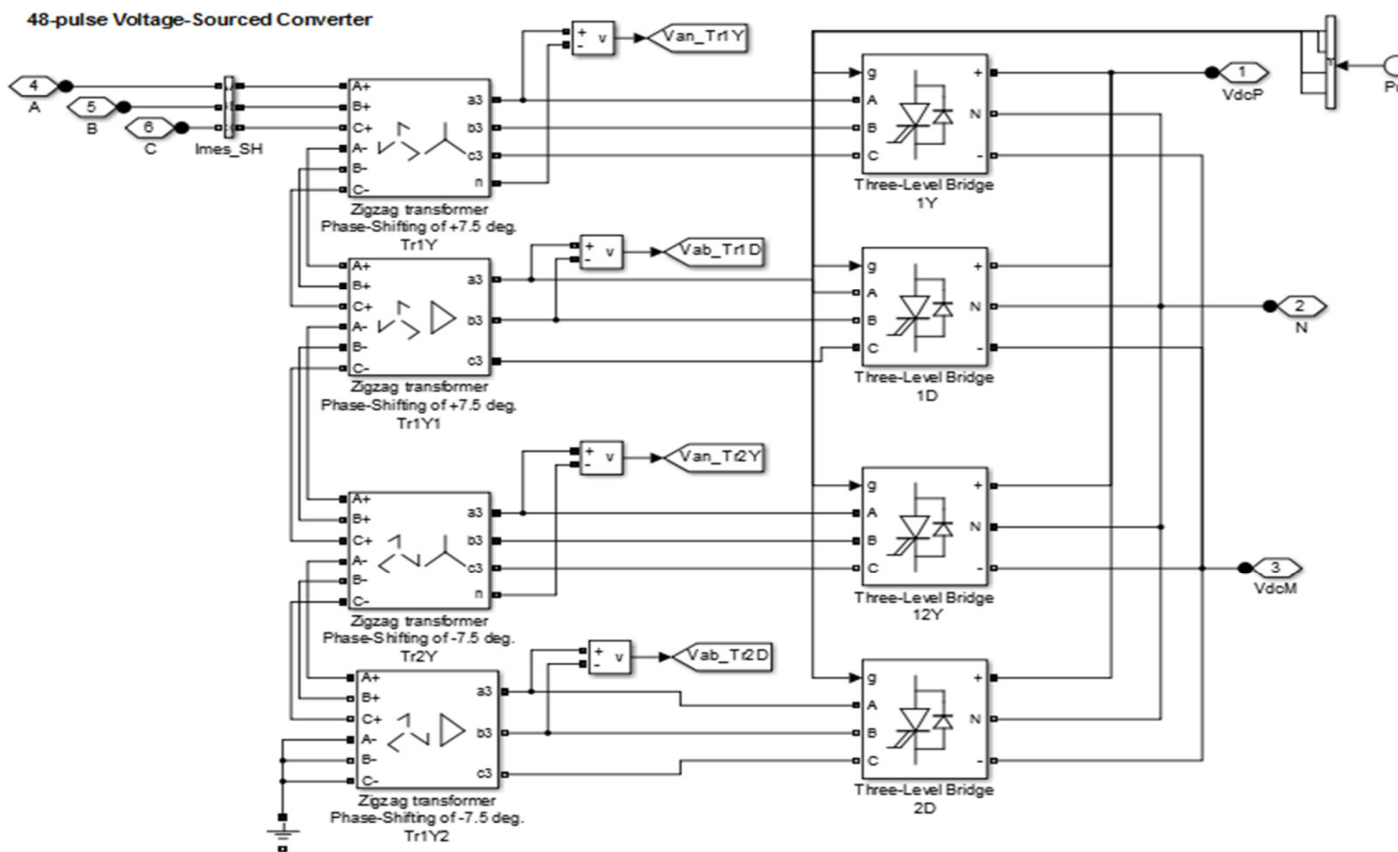


Figure 2-15. Control model of statcom [15].



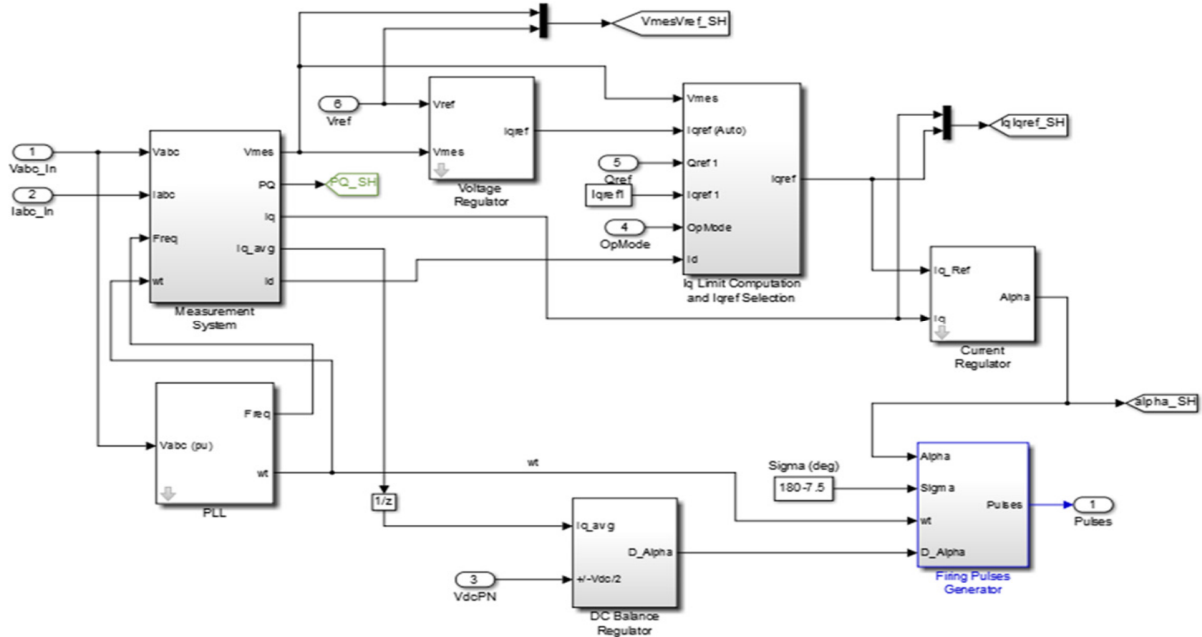


Figure 2-16. Control model of statcom

### 2.4.2 Control scheme for SSSC1

Voltage control is the foundation of the SSSC1 control strategy, which aims to provide the firing pulse needed to run the series converter 1 as shown in Figure 2-17. For the shunt converter to function, the voltage must be supplied in series with the transmission line, which raises both the voltage and the power flow in the line. In order to obtain the frequency and angle  $\omega t$  that must be synchronized with phase A voltage, the phase-lock-loop (PLL) is fed the three phase voltage. To get the decomposed signal, the discrete three-phase PLL-driven positive sequencer is fed these two PLL output signals along with the three-phase voltage  $V_{3abc}$  of bus 3. The PLL signal  $\omega t$  in its two-dimensional signal form ( $\sin\_cos$ ) and the three-phase current  $I_{3abc}$  are put into the  $abc\_dqo$  transformation to produce the decomposed signals of the three phase current as real portion  $I_d$  and reactive component  $I_q$ . The real reference part current  $I_d$  and the reactive part current  $I_q$  are calculated using the active reference power  $P_{ref}$ , the reactive power  $Q_{ref}$ , the real part voltage  $V_d$ , and the reactive part voltage  $V_q$ . The  $I_{dref}$  and  $I_{qref}$  are compared to  $I_d$  and  $I_q$ , respectively, and the error is sent to the PID controller to obtain the reference  $V_d$ . The calculation of the limit for  $V_d$  and  $V_q$  is done using  $opmode$ .  $\sigma$  and  $\alpha$  are calculated

using  $V_d$ ,  $V_q$ , and the voltage at the d.c. link ( $V_{dc}$ ). To determine their corresponding magnitude and angle,  $V_d$  and  $V_q$  are transformed. The angle  $\alpha$  is calculated using both this magnitude and angle. The angle  $\sigma$  is calculated using the magnitude and  $V_{dc}$ . These estimated angles  $\sigma$ , constant value delay  $\alpha$ ,  $\alpha$ , and PLL output angle  $\omega t$  are sent collectively to the SSSC1 firing pulse generator to provide the necessary firing signal for the series converter 1 [15].

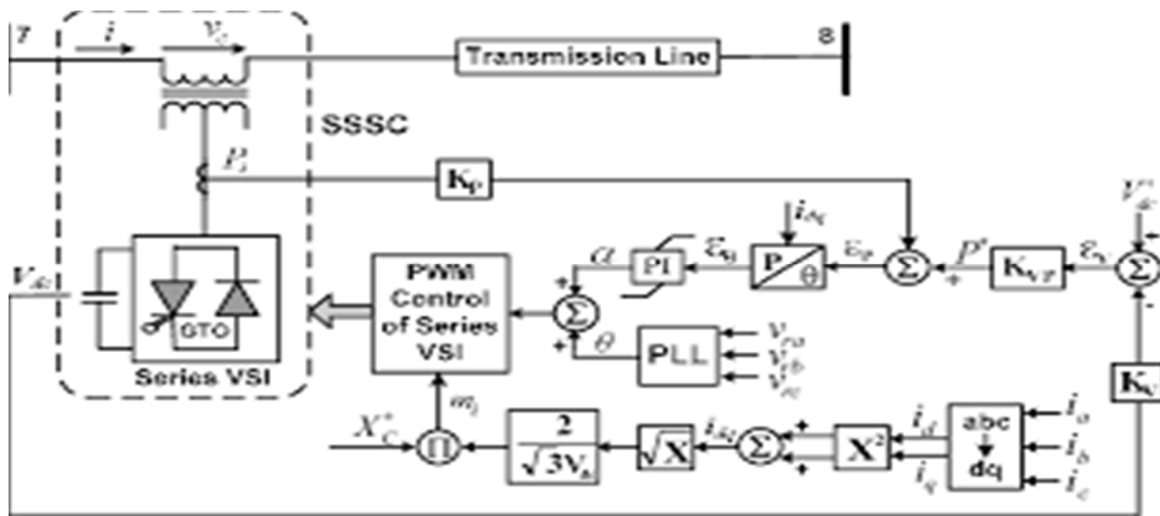


Figure 2-17. Control model of SSSC1 [15].

### 2.4.3 Control scheme for SSSC2

Injected voltage control is the foundation of the SSSC2 control strategy. This control strategy provides the firing pulse required to run the series converter 1a as seen in Figure 2-18. The operation of the transmission line's voltage and power flow levels are improved by the shunt converter's addition of a voltage supply in series with it. To obtain the frequency and angle that must be synchronized with phase A voltage, the PLL is fed the three-phase voltage. To get the decomposed signals, these two PLL output signals are given to the discrete three-phase PLL-driven positive sequencer along with the three-phase voltage  $V_{5abc}$  from bus 5 voltage signals in the actual component  $V_d$  and the reactive part  $V_q$ . The PLL signal  $\omega t$  in its two-dimensional signal form ( $\sin\_cos$ ) and the three-phase current  $I_{5abc}$  are put into the  $abc\_dqo$  transformation to produce the decomposed signals of the three-phase current as real portion  $I_d$  and reactive part

as  $I_q$ . The reference real part current  $I_d$  and reactive part current  $I_q$  are calculated using the active reference power  $P_{ref}$ , the reactive power  $Q_{ref}$ , the real part voltage  $V_d$ , and the reactive part voltage  $V_q$ . The  $I_{dref}$  and  $I_{qref}$  are compared to  $I_d$  and  $I_q$ , respectively, and the error is sent to the PID controller in order to obtain the reference  $V_d$  and  $V_q$ . The calculation of the limits for  $V_d$  and  $V_q$  is done using  $p_{omade}$ .  $\sigma$  and  $\alpha$  are calculated using  $V_d$ ,  $V_q$ , and the voltage at the D.C. link, or  $V_{dc}$ . To determine their corresponding magnitude and angle,  $V_d$  and  $V_q$  are transformed. The angle  $\alpha$  is calculated using both this magnitude and angle. The angle  $\sigma$  is calculated using the magnitude and  $V_{dc}$ . These estimated angles  $\sigma$  constant value delay  $\alpha$  angle  $D\_alpha$ ,  $\alpha$ , and PLL output angle  $\omega t$  are all sent together to the SSSC1 firing pulse generator to produce the desired firing signal for the series converter 2. [15]

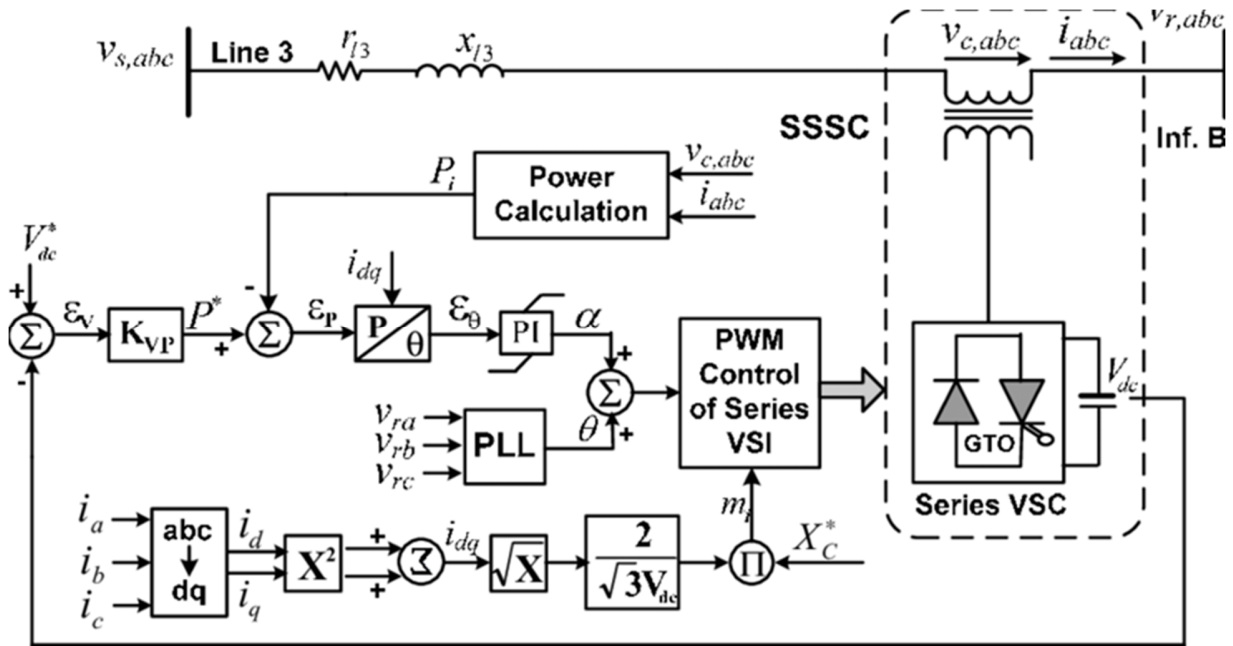


Figure 2-18. Control model of SSSC2.

## 2.5 The injection model of GUPFC

This section presents a model of the GUPFC power injection. Figure 2-19 shows a GUPFC device connected between three EPS buses (i, j and k).

The three voltage source converters (SSSC) are based on GTOs (Gate Turn-Off Thyristors) and have identical configurations and operating principles, However, their functions differ in connecting to the EPS [16]. SSSC are connected to the AC system via coupling transformers connected via a common DC link [17].

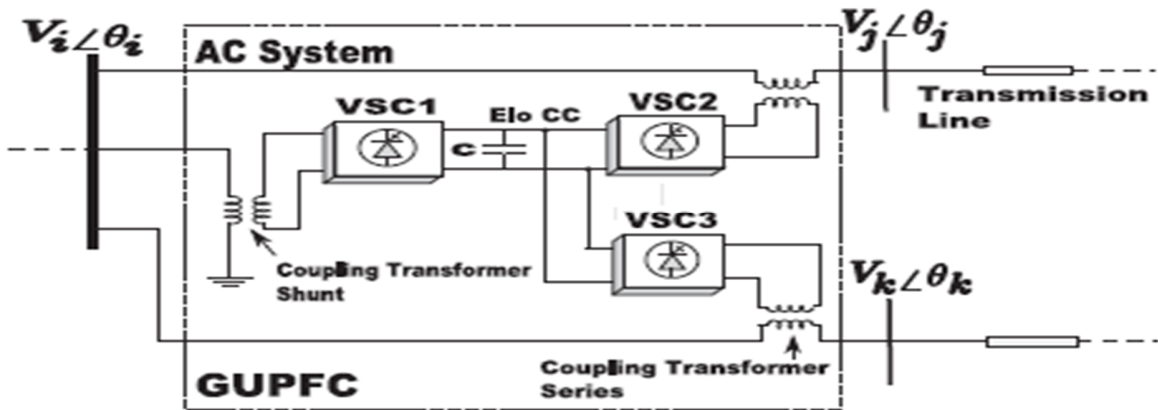


Figure 2-19. Diagram of the GUPFC device with three converters. [17].

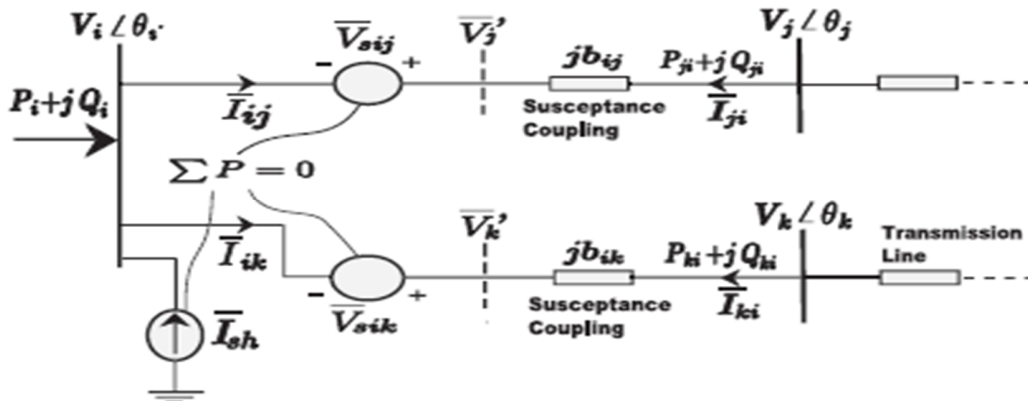


Figure 6-20. Schematic representation of a three converter GUPFC [17].

As shown in Figure 2-19, the converters in series, SSSC1 and SSSC2, are represented by two controllable synchronous voltage sources  $V \sin$  (with  $n = j, k$ ) in series with their respective susceptances ( $jb_{in}$ ) representing the coupling transformers. The converter VSC1 is electrically represented by an ideal current source, which is connected in shunt to the common bus  $i$  of the

GUPFC installation. As depicted in Figure 2-19,  $V_0$  in are two fictitious buses used to reduce of the model.  $P_i$  and  $Q_i$  are the active and reactive power injections at bus  $i$  of the installation.  $P_{nj}$  and  $Q_{nj}$  are conventional active and reactive power flows that circulate in the  $i$ - $n$  branches, leaving the  $n$  buses (with  $n = j, k$ ), respectively. The control of the active and reactive power flows in transmission lines by the GUPFC device is achieved by controlling the magnitudes ( $r_{in}$ ) and angles ( $\gamma_n$ ) of the serial voltage sources ( $V_{sin}$ ), as given by Eq (3):

$$V_{sin} = r_{in} e^{j\gamma_n} V_i \quad (3)$$

In Eq.(3), the controllable range of relative magnitude ( $r_{in}$ ) and angle ( $\gamma_n$ ) of  $V_{sin}$  with the respective voltage of the common installation bus ( $V_i$ ) is  $0 < r_{in} < r_{inmax}$  and  $0 < \gamma_n < 2\pi$ , respectively, where  $n = j, k$  [18]. Based on the phasor diagram of the Unified Power Flow Controller (UPFC) presented in [19] and reproduced in Figure 2-20, the voltage two sources  $V_{sin}$  (Eq(3)) can be decomposed into two components; one component in quadrature ( $V_{pn}$ ) and the other component in series ( $V_{qn}$ ) with the currents  $I_{in}$  crossing branches  $i$ - $n$  (with  $n = j, k$ ). These two components are represented by Eqs.(4) and (5).

$$V_{pn} = r_{in} V_i \sin(\gamma_n) \quad (4)$$

$$V_{qn} = r_{in} V_i \cos(\gamma_n) \quad (5)$$

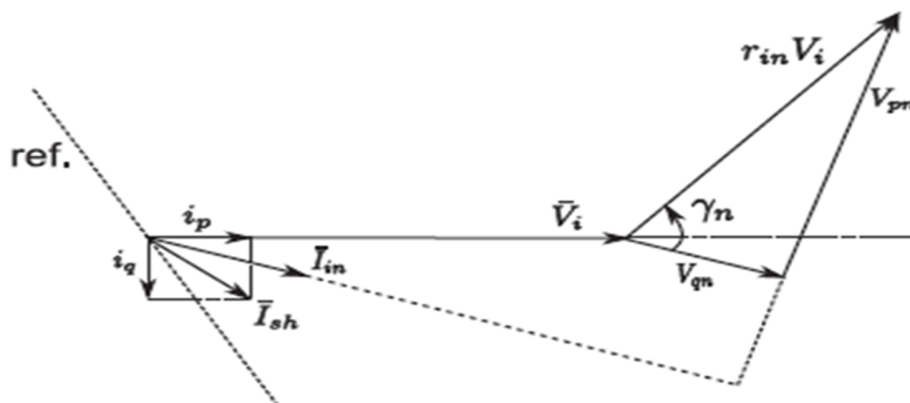


Figure 2-21. Phasor diagram of GUPFC.

For the GUPFC power injection model, the ideal current shunt source ( $I_{sh}$ ) shown in Figure 2-21 is also decomposed into two components; one being in-phase ( $i_p$ ) and the other in quadrature ( $i_q$ ) with the common installation voltage ( $V_i$ ) being described by Eq.(6) and shown in Figure 2-21.

$$i_{sh} = (i_p - ji_q)e^{j\theta_i} \quad (6)$$

As illustrated in Figure 2-21, a constraint that must be satisfied for the correct operation of the GUPFC in the EPS is related to the exchange of active power between converters [20].

This restriction (called the GUPFC invariance active power) establishes that when losses are disregarded, all the active power supplied by the shunt converter ( $P_{sh}$ ) must be exactly equal to the power delivered to the AC system by the serial converters ( $P_{se}$ ) of the GUPFC, that is:

$$P_{sh} = -\sum_{m=i,j,k} P_{se,m} \quad (7)$$

From the circuit equivalent to the GUPFC, depicted in Figure 2-21, and considering the restriction shown in Eq (7) together with Eqs(4-6), one arrives at the power injection model of this device (Eqs(8-11)). This represents the contributions of both the controllable synchronous voltage sources (serial converters) and the ideal current source (shunt converter) of the GUPFC.

$$P_{s,i} = -\sum_{n=j,k} v_n b_{in} (v_{pn} \cos(\theta_{in}) + v_{qn} \sin(\theta_{in})) \quad (8)$$

$$Q_{s,i} = -v_i \sum_{n=j,k} b_{in} v_n - v_i i_q \quad (9)$$

$$P_{s,n} = v_n b_{in} [v_{pn} \cos(\theta_{in}) + v_{qn} \sin(\theta_{in})] \quad (10)$$

$$Q_{s,n} = v_n b_{in} [v_{pn} \cos(\theta_{in}) - v_{qn} \sin(\theta_{in})] \quad (11)$$

In Eqs(8-11),  $n = j, k$ ,  $\theta_{in} = (\theta_i - \theta_n)$  and  $b_{in} = (1/X_{in})$ , with  $X_{in}$  being the reactance of the coupling transformer.  $P_{s,i}$  and  $Q_{s,i}$  are the active and reactive power injections at common bus  $i$  of the installation.  $P_{s,n}$  and  $Q_{s,n}$  are the installation's active and reactive power injections in

buses . Although the GUPFC power injection model presented in Eqs (8-11) is based on the model presented in [20] [21], the model described herein has an added advantage because it is independent of the  $r_{in}$  and  $c_n$  parameters, thereby eliminating a need for them to be calculated.

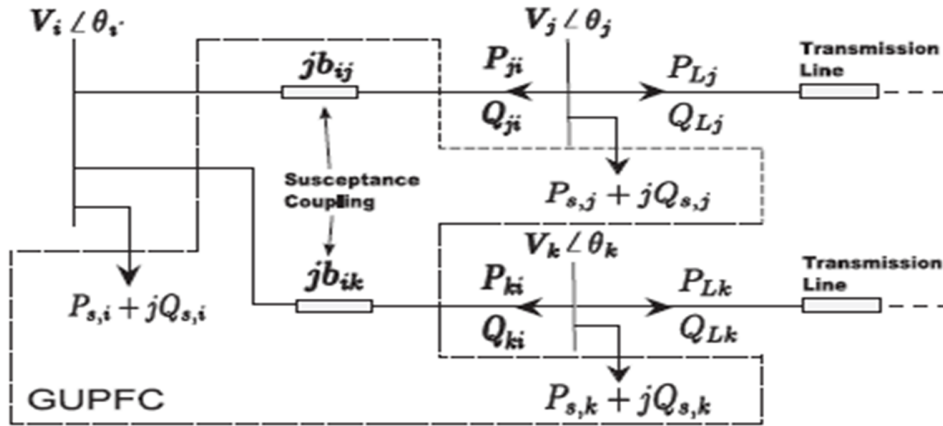


Figure 2-22. Flow control by the GUPFC.

Figure 2-22 illustrates the GUPFC device represented by its power injection model ( $P_{s,i}$ ,  $Q_{s,i}$ ,  $P_{s,n}$ ,  $Q_{s,n}$ ) and also the active and reactive power flows which will be controlled by the device ( $P_{Ln}$ ,  $Q_{Ln}$ , with  $n = j, k$ ) in the two transmission lines where it is installed.

As shown in Figure 2-22, this model facilitates the inclusion of the GUPFC device in load flow and optimal load flow programs, as the controller starts to be treated as power injections at the buses in which it is i

nstalled. The following mismatches of active power and reactive power must be guaranteed at buses  $i, j$  and  $k$ , where the GUPFC device is connected:

$$P_{gm} - P_{calc,m} - P_{lm} - P_{s,m} = 0 \quad (12)$$

$$Q_{gm} - Q_{calc,m} - Q_{lm} - Q_{s,m} = 0 \quad (13)$$

In Eqs (12) and (13),  $m = i, j$  and  $k$ .  $P_{gm}$  and  $Q_{gm}$  generate active and reactive powers entering bus  $m$ , respectively.  $P_{calc,m}$  and  $Q_{calc,m}$  are the active and reactive powers transmitted by lines from bus  $m$ .  $P_{lm}$  and  $Q_{lm}$  are the possible active and reactive loads leaving bus  $m$ , respectively and  $P_{s,m}$  and  $Q_{s,m}$  are the active and reactive powers related to power injections of the voltage and current sources of the GUPFC. By performing the balance of active and reactive powers at bus  $n$  (with  $n = j$  and  $k$ ) of Figure 2-22, the flows controlled by the GUPFC are expressed as shown in Eqs (14) and (15):

$$P_{1n} = -P_{ni} - P_{s,m} \quad (14)$$

$$Q_{1n} = -Q_{ni} - Q_{s,m} \quad (15)$$

In Eqs (14) and (15),  $P_{1n}$  and  $Q_{1n}$  are flows controlled by the device under study and that serve as inputs to the structure of the GUPFC control system as presented in the next section.  $P_{ni}$  and  $Q_{ni}$  are the conventional load flow's active and reactive power flows.

## 2.6 GUPFC mathematical modeling

GUPFC mathematical modeling refers to using mathematical equations and algorithms to describe, analyze, and predict the behavior of complex systems in the context of power flow control. This modeling technique is used to optimize the performance of power systems by predicting the effects of different control strategies and system configurations. The models used in GUPFC mathematical modeling include linear and nonlinear equations, differential equations, and optimization algorithms. These models are used to simulate the behavior of power systems under different conditions and to evaluate the effectiveness of different control strategies. The mathematical model of the GUPFC consists of one shunt converter and two or more series converters. In contrast to the practical applications of the GUPFC in power systems, very few publications have focused on the mathematical modeling of this new FACTS controller in power system analysis or power system dynamics and stability. A GUPFC can be represented by three voltage sources, which are controllable in both magnitude and phase angle and represent fundamental components of output voltages of three converters & impedances being leakage



reactance of three coupling transformers. Let three GUPFC buses i, j and k be defined as shown in Figure 2-23. The following considerations are taken for analysis purpose:

1. Voltage at bus-i is taken as  $V_i = V_i \angle \delta_i$ .
2. The two controllable series injected voltage sources are identical.
3. The leakage reactance of the two series coupling transformers is equal.

The two controllable series voltage sources  $V_{se1}$  and  $V_{se2}$  are defined as:

$$V_{se1} = V_{se2} = V = r v_i e^{j\gamma} \quad (16)$$

where 'r' and 'γ' are respective per unit magnitude and phase angles of series voltages, which are operating in the following specified limits:  $0 \leq r \leq r_{max}$  and  $0 \leq \gamma \leq \gamma_{max}$ .

The GUPFC device is incorporated in between three GUPFC buses, out of which one is a common bus for the remaining two buses. Briefly, one of the series converters is connected between bus-i and bus-j. Similarly, another series converter is connected between bus-i and bus-k. The GUPFC power injection model is developed in two stages : series connected voltage source model and the other is shunt connected voltage source model. The voltages behind the series reactance's can be calculated as:

$$v_{ij} = v_i + v_{se1} \quad \text{and} \quad v_{ik} = v_i + v_{se2} \quad (17)$$

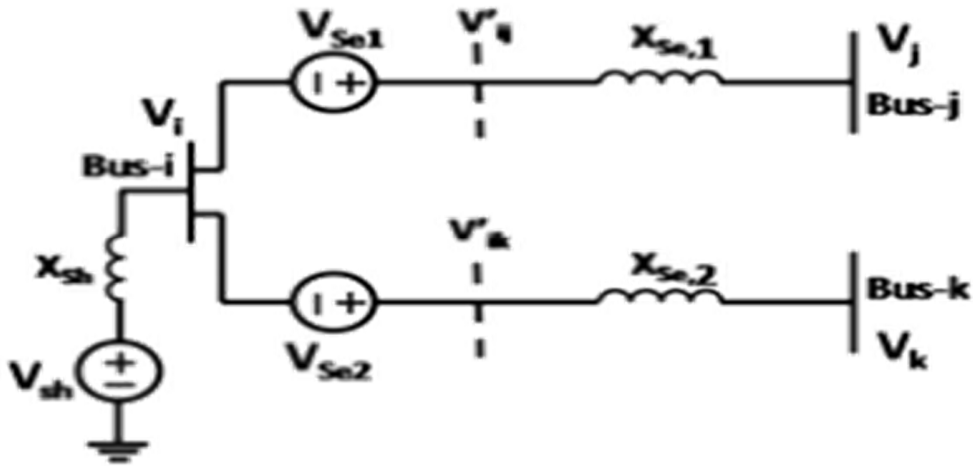


Figure 2-23. Voltage source model of GUPFC.

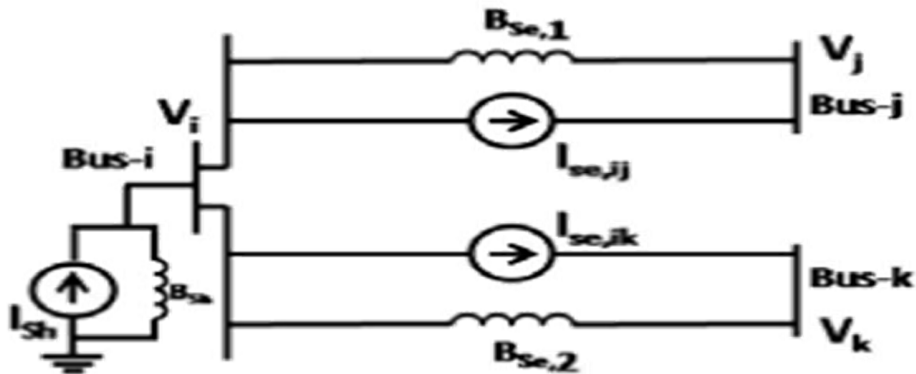


Figure 2-24. Equivalent current source model of GUPFC.

### 2.6.1 Series connected voltage source mode

According to Norton's theorem, the series connected voltage source can be modeled by replacing the voltage source ' $V_{se}$ ' with an equivalent current source ' $I_{se}$ ' in parallel with a transmission line susceptance ' $B_{se}$ ' as shown in Figure 2-24, where:

$$B_{se} = \frac{1}{x_{se}} \quad (18)$$

$X_{se}$  is the series transformer equivalent reactance.

The amount of current flowing from the source is given as

$$I_{se} = \frac{v_{se}}{jX_{se}} = -jB_{se}V_{se} \quad (19)$$

Substituting Eq (19) in eq (16):

$$I_{se} = -jrV_iB_{se}e^{j(\delta i + \gamma)} = rV_iB_{se}e^{j(90^\circ + \delta i + \gamma)} \quad (20)$$

Hence:

$$(I_{se})^* = -rV_iB_{se}e^{-j(90^\circ + \delta i + \gamma)} \quad (21)$$

This current source can be modeled by injecting equivalent powers at the respective buses to which the device is connected. The corresponding power injections.

This model can be seen as the three independent complex powers injections at the GUPFC buses and can be written as:

$$S_{ise} = -2V_i(I_{se}) \quad (22)$$

$$S_{jse} = V_j(I_{se}) \quad (23)$$

$$S_{kse} = -2V_k(I_{se}) \quad (24)$$

The detailed expressions for these injections can be deduced by substituting Eq. (21) in Eqs.

(22)-(24)

$$S_{ise} = 2rv_i^2B_{se}e^{-j(90^\circ + \gamma)} \quad (25)$$

$$S_{jse} = -r v_i v_j B_{se} e^{-j(\omega t + \delta_i - \delta_j + \gamma)} \quad (26)$$

$$S_{kse} = -r v_i v_k B_{se} e^{-j(\omega t + \delta_i - \delta_k + \gamma)} \quad (27)$$

Using trigonometric identities in Eqs (25)-(27), the active and reactive power injections at i, j, k are:

$$P_{ise} = -2 r v_i^2 B_{se} \sin(\gamma) \quad (28)$$

$$Q_{ise} = -2 r v_i^2 B_{se} \cos(\gamma) \quad (29)$$

$$P_{jse} = r v_i v_j B_{se} \sin(\delta_{ij} + \gamma) \quad (30)$$

$$Q_{jse} = r v_i v_j B_{se} \cos(\delta_{ij} + \gamma) \quad (31)$$

$$P_{kse} = r v_i v_k B_{se} \sin(\delta_{ik} + \gamma) \quad (32)$$

$$Q_{kse} = r v_i v_k B_{se} \cos(\delta_{ik} + \gamma) \quad (33)$$

The equivalent series connected voltage source model with the corresponding power injections are represented in Figure 2-26.

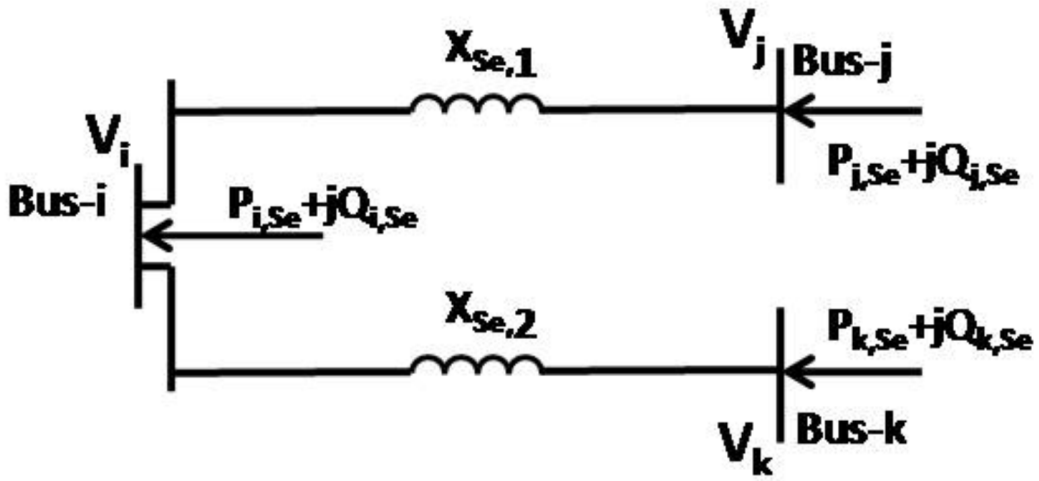


Figure 2-25. Equivalent series connected voltage source model.

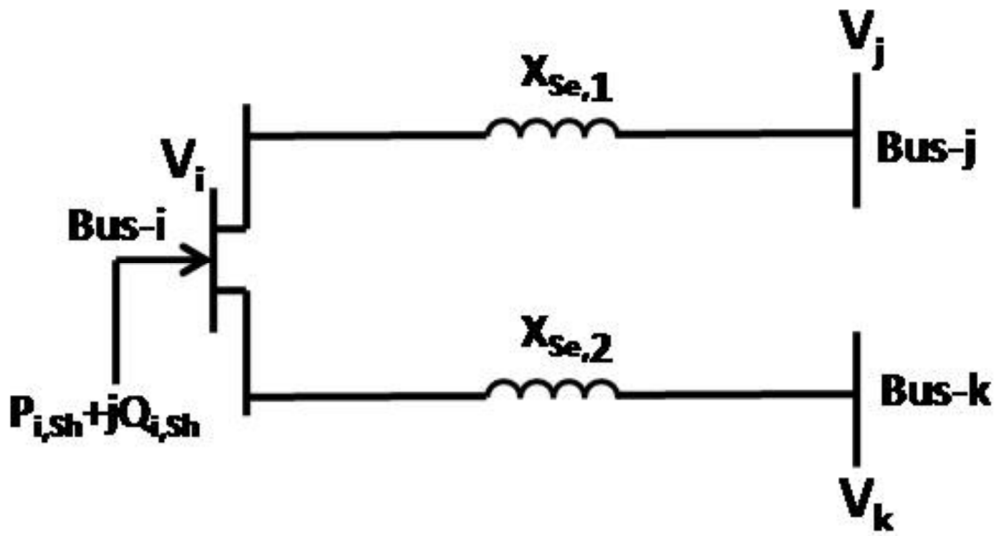


Figure 2-26. Equivalent series connected voltage source model.

The amount of apparent power supplied by the two series converters is derived as:

$$S_{se1} = P_{se1} + jQ_{se1} = V_{se}(I_{ij})^* = jrV_iB_{se}e^{j(\delta_i+\gamma)}(V'_{ij} + V_j)^* \quad (34)$$

By substituting Eq.(17) in Eq.(33) and simplifying:

$$P_{se1} + jQ_{se1} = jrV_i B_{se} e^{j(\delta_i + \gamma)} (rV_i e^{-j(\delta_i + \gamma)} + V_i e^{-j\delta_i} - V_j e^{-j\delta_j}) = jr^2 v_i^2 B_{se} + jr v_i^2 B_{se} (\cos\gamma + jsin\gamma) - jrV_i V_j B_{se} (\cos(\delta_{ij} + \gamma) + jsin(\delta_{ij} + \gamma)) \quad (35)$$

The real and imaginary parts, then:

$$P_{se1} = -rV_i V_j B_{se} (\cos(\delta_{ij} + \gamma) + r v_i^2 B_{se} \cos\gamma + r^2 v_i^2 B_{se}) \quad (36)$$

$$Q_{se1} = -rV_i V_j B_{se} (\sin(\delta_{ij} + \gamma) + r v_i^2 B_{se} \sin\gamma + r^2 v_i^2 B_{se}) \quad (37)$$

Similarly,

$$P_{se2} = rV_i V_k B_{se} \sin(\delta_{ik} + \gamma) - r v_i^2 B_{se} \sin\gamma \quad (38)$$

$$Q_{se2} = -rV_i V_k B_{se} \cos(\delta_{ik} + \gamma) + r v_i^2 B_{se} \cos\gamma + r^2 v_i^2 B_{se} \quad (39)$$

### 2.6.2 Shunt connected voltage source model

The shunt connected voltage source can be modeled as an equivalent power injection from the GUPFC shunt branch to the series branches through converters 1 and 2. This model is also used to provide the converter switching losses. The reactive power injection at the shunt converter is used to control/maintain the voltage level at the sending end within limits. The equivalent shunt connected voltage source model with the corresponding power injections is shown in Figure2-26. The total switching loss of each converter is about 0.8-1% [22] [23] of the power transferred through the converter. If these losses are considered, then the real power

$$P_{sh} = -1,03(P_{se1} + P_{se2}) \quad (40)$$

From Eqs (36) and (38)

$$P_{sh} = 2.06r v_i^2 B_{se} \sin\gamma - 1,03rV_i V_j B_{se} \sin(\delta_{ij} + \gamma) - 1,03rV_i V_k B_{se} \sin(\delta_{ik} + \gamma) \quad (41)$$

Assuming a constant  $Q_{sh}$  is injected at bus- $i$ . The apparent power injection at the shunt branch is:

$$S_{sh} = P_{sh} + jQ_{sh} \quad (42)$$

### 2.6.3 GUPFC mathematical model

The final steady state model of the GUPFC power injection model is obtained by combining series connected voltage and shunt connected voltage source models. The equivalent GUPFC model is shown in Figure 2-27. The resultant power injections are given as follows:

$$P_{i\ gupfc} = P_{i\ se} + P_{sh} \quad (43)$$

$$P_{i\ gupfc} = 0.06V_i^2 B_{se} \sin \gamma - 1.03rV_iV_jB_{se} \sin(\delta_{ij} + \gamma) - 1.03rV_iV_RB_{se} \sin(\delta_{ik} + \gamma)$$

$$Q_{i\ gupfc} = Q_{i\ se} + Q_{sh} = -2rV_i^2B_{se} \cos \gamma + Q_{sh} \quad (44)$$

$$P_{j\ gupfc} = P_{j\ se} = rV_iV_jB_{se} \sin(\delta_{ij} + \gamma) \quad (45)$$

$$Q_{j\ gupfc} = Q_{j\ se} = rV_iV_jB_{se} \cos(\delta_{ij} + \gamma) \quad (46)$$

$$P_{k\ gupfc} = P_{k\ se} = rV_iV_kB_{se} \sin(\delta_{ik} + \gamma) \quad (47)$$

$$Q_{k\ gupfc} = Q_{k\ se} = rV_iV_kB_{se} \cos(\delta_{ik} + \gamma) \quad (48)$$

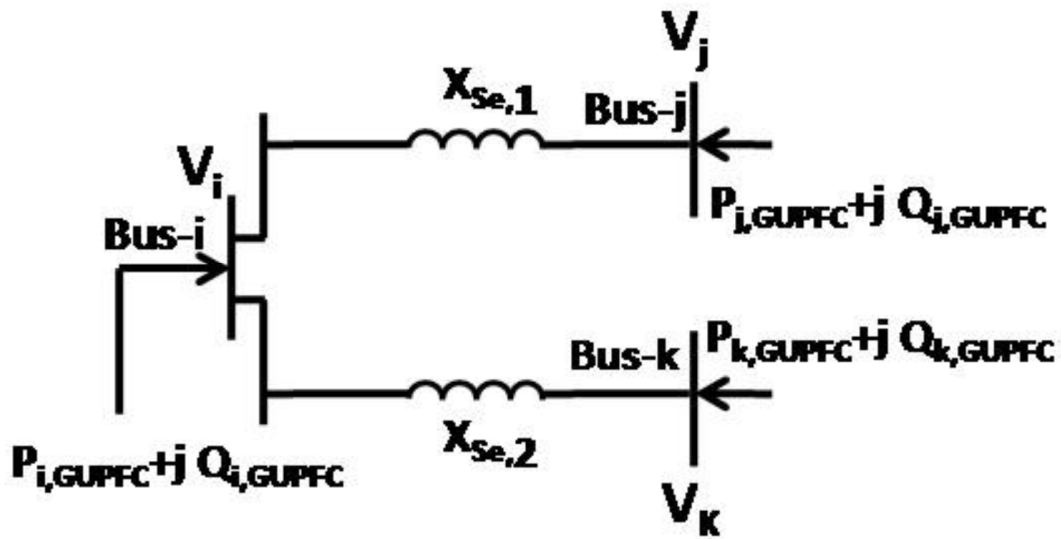


Figure 2-27. GUPFC mathematical model.

## 2.7 Design of PI Controller for GUPFC

The PI controller is a classical control method commonly used in industrial applications. a feedback control system adjusts the output based on the difference between the desired set-point and the actual output. The PI controller uses proportional and integral terms to calculate the output. The proportional term responds to the current error, while the integral term responds to the accumulated error over time.

In the case of the GUPFC, the PI controller is used to regulate the voltage and current at the point of connection. The controller compares the measured and desired values and adjusts the output accordingly. The PI controller uses a tuning method that optimizes the controller parameters for stability and performance. The most commonly used tuning method is the Ziegler-Nichols method, which involves step testing the system and using the resulting data to determine the controller parameters.



## 2.8 Conclusion

One of the most cutting-edge and adaptable FACTS instruments is the GUPFC. Instead of regulating the power flow of a single line, this equipment enables control of the power flow of many lines or a sub network. The GUPFC expands the idea of voltage and power-flow management beyond what is possible with the existing two-converter UPFC by combining three or more shunt and series converters. The transfer capacity of transmission lines can also be greatly boosted by deploying GUPFC devices to relieve congestion flexibly.

**CHAPTER 3:**  
**FUZZY LOGIC**

## Chapter 3: Fuzzy logic

### 3.1 Introduction

Fuzzy control has grown in popularity during the last two decades. One of the primary benefits of fuzzy logic-based control is that it is relatively simple to transfer process expertise to the controller using linguistic rules from the controller to the process. This makes it possible to transform the expert's into simple rules that the controller can implement. Ease of implementation solutions for complex problems is then combined with robustness in the face of and the possibility of integrating the expert's knowledge. From a historical point of view, the premises of fuzzy logic, aimed at dealing with the notion of uncertainty, date back to the 1930s. However, it was not until Zadeh introduced the concept of fuzzy subsets in 1965, to witness the first major advances in the field [24]. This was followed in 1974, in which Mamdani introduced fuzzy control for industrial process control. Finally, in the 1980s, fuzzy control underwent considerable development in Japan, notably the work of Sugeno, and then spread throughout the world [24].

Fuzzy logic can be found in electrical system parameter determination, where the precise command is never guaranteed. Utilizing fuzzy logic is therefore inappropriate. It is recommended for complicated and strongly non-linear processes. By controlling an electrical network, a device like the GUPFC can appear quite complicated. This prompts us to use faulty logic while using such a device to get around the complexity of the adjusting problem. This chapter provides a general overview of the fuzzy logic theory that will be applied to the GUPFC command procedure.

The process is not mathematically represented in a "fuzzy logic" method. However, a human operator considers the unregulated well-known, even though the goal is to automate it. This is known as knowledge by an "expert" who understands exactly what to do to make it work in all circumstances. For example, If the temperature is very low, the operator heats "full" to a certain value, then reduces it by 50% if the kiln is full or by 75% if the kiln is half full. The operator does so because he/she has noticed that this is a good choice; it is "expertise".

## 3.2 Fuzzy logic theory

### 3.2.1 Background

A continual manipulation of information, many arbitrary and subjective, characterizes the design and implementation of advanced information systems, decision-support software, and positions overseeing industrial processes. In general, we are faced with the need to model knowledge, which conflicts with the tradition of the so-called objective sciences, primarily concerned with modeling of the physical universe. The problems of knowledge representation and application are at the heart of the scientific field known as artificial intelligence, which is still relatively new and largely debated. This subject has had a limited impact on industrial applications up until recently since it has focused mostly on the symbolic manipulation of data [25] [26].

With the use of neural networks and fuzzy logic, artificial intelligence problems are witnessing a return to the digital age. Although networks neuron-mimetic systems implicitly advocate a "boite noire" approach to knowledge representation, very similar to the process of automatically identifying systems, fuzzy logic is more in line with artificial symbolic intelligence, which emphasizes reasoning and/or explicitly codifies knowledge. Fuzzy logic enables the link to be made between numerical modelling and symbolic modeling. This has led to industrial developments based on simple algorithms for translating symbolic knowledge into a digital entity [27].

The foundational ideas of fuzzy logic appeared prior to the year 1940 with the first approach to of uncertainty. It took until 1965 for L. A. Zadeh, an internationally renowned automatic, to propose the idea of fuzzy logic. A professor at the University of California, Berkeley, who helped model the phenomenon using a distorted form in order to overcome the shortcomings of traditional equation-based models. M. Mamdani tested the theory introduced by Zadeh on a steam boiler in 1974, introducing the fuzzy logic command into the regulation of an industrial operation symbolic knowledge into digital entities. A novel approach to dealing with uncertainty based on the concept of order has also emerged from the theory of collapsed ensembles.

### 3.2.2 Fuzzy set Theory

#### 3.2.2.1 Principles of fuzzy logic

The classification of people into the three groups "young," "between two ages," and "elderly" serves as a straightforward example of the fundamental concept of fuzzy logic. Boole's logic stipulates that just two values can be used, 0 and 1, as illustrated in Figure 3-28, where all individuals under 25 are categorized as young and all individuals above 50 are old.

#### Fonction d'appartenance

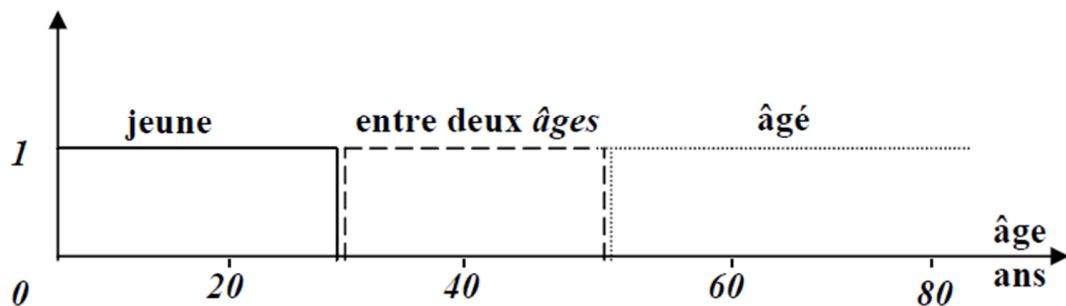


Figure 3-28. Classification of people according to Boolean logic.

Why should a person be regarded as being in the elderly category when they are 50 years old? In reality, such a passage occurs gradually and individually. The fuzzy logic, wherein there are these realities considered by variables ability to take a value from 0 to 1. The limits do not shift abruptly but rather gradually.

Figure 3-28 illustrates a categorization that could be made for the previous example using illogical reasoning. Therefore, a person aged 25 belongs to the "entre deux âges" group with a value of  $=0.25$  and the "jeune" group with a value of  $=0.75$ . In contrast, a person over 65 has a value of 1 for their belonging to the entire elderly category.

### Fonction d'appartenance

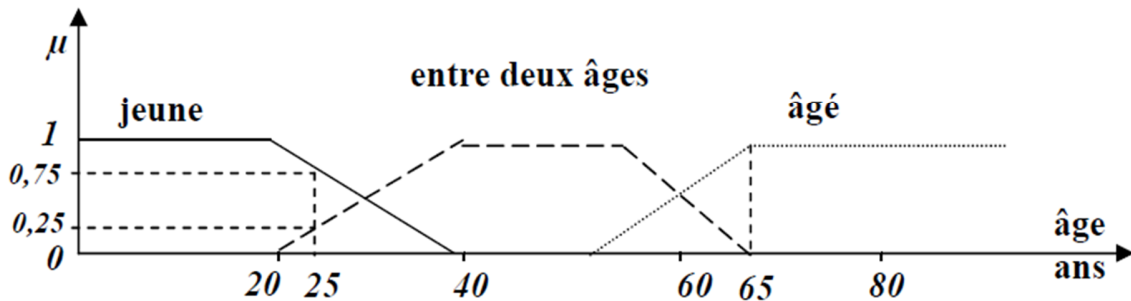


Figure 3-29. Classification of people according to fuzzy logic.

The fuzzy set is the fundamental building block of fuzzy logic; it is so named because its boundaries are ill-defined. Contrarily, the boundaries of traditional sets are well defined. Typically, fuzzy sub-sets represent some fuzzy logic variables [27].

Describing a particular circumstance, phenomenon, or procedure typically uses ambiguous qualifiers like: little, a lot, enormously, rarely, frequently, cold, warm, slow, quick, small, medium, large, etc. Such statements form the so-called fuzzy sets, which are the groups to which linguistic variables may belong.

A membership function characterizes a fuzzy subset of a reference frame  $T$  is defined as follows, where  $T$  is the time in the real interval  $[0, 1]$  referred to as the degree of membership.

$$:T \rightarrow [0,1]$$

$$t \rightarrow (t)$$

A fuzzy set consists of three parts:

- A horizontal axis representing the elements of the set
- A vertical axis where the membership values are represented
- A curve connecting the different coordinate points (element, membership value)

- Degree 1 corresponds to total membership or certainty
- Degree 0 corresponds to absolute exclusion or impossibility
- Intermediate values express more or less strong possibilities, represented by a continuous curve as opposed to a set which is formed by a discontinuous 'true/false' curve.

### 3.3 Fuzzy logic control

Before any development, the construction of a controller can be based on a classical structure of the Proportional - Integral (PI) corrector described by the transfer function  $C(z)$  such that:

$$C(z) = \frac{a+b(1-z^{-1})}{1-z^{-1}} \quad (49)$$

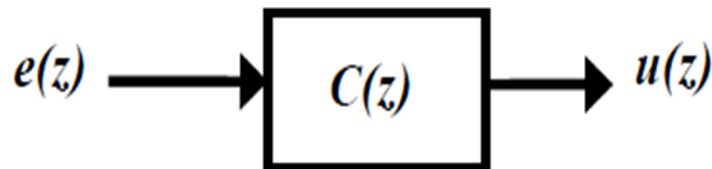


Figure 3-30. Transfer function of the corrector.

This controller lacks a series structure and has two gains—one for the original error and the other for the derived term (digital overflow or saturation). Regarding the latter, in the event of a significant fluctuation in the specification, a digital overshoot or saturation may appear. This overshoot may cause a temporary loss of control over the procedure. Additionally, it is preferable to continuously apply the derived function to the regulating variable rather than the error to monitor its evolution, as shown in Figure 3-31. We must ensure symmetries around the zero-error boundary to use a floating control device under ideal circumstances. This method therefore results in the integration function outputted by the regulator. The error and its derivative will

therefore be eliminated in a permanent system, and the integrator will output data continuously [28] [29] [30].

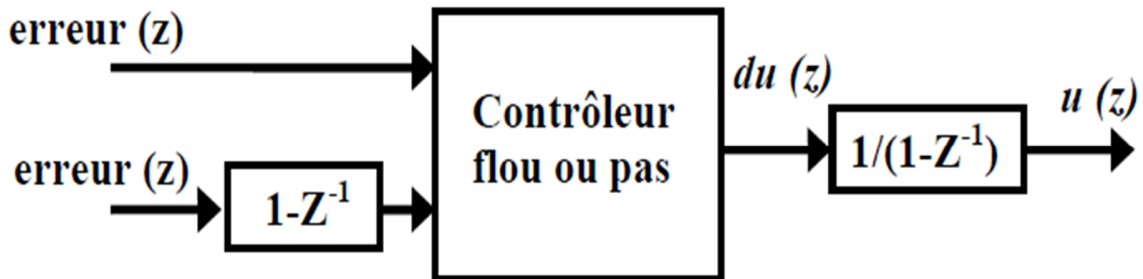


Figure 3-31. Structure of controller.

The goal of fuzzy control is to manage a process according to a set of instructions by acting on the variables that describe the process, However, its approach is different from that of classical automation. Fuzzy control is used to deal with problems of process control involving machines, networks, industrial processes, unmanned vehicles, and other similar devices [31]. The fuzzy logic regulator employs inferences with several rules based on symbolic factors instead of a well-defined mathematical relationship known as an "algorithm of adjusting" [28] [32] [33].

Figure 3-32 depicts the layout of a fuzzy controller with two inputs and one exit. It is divided into three main floors, namely:

- The evaluation of the variables' functions of membership in the entries in the fuzzification of the inputs.
- The inference engine; evaluates output functions using the rules table.
- The defuzzification; calculating the center of gravity to assess the controller's fuzzy output.



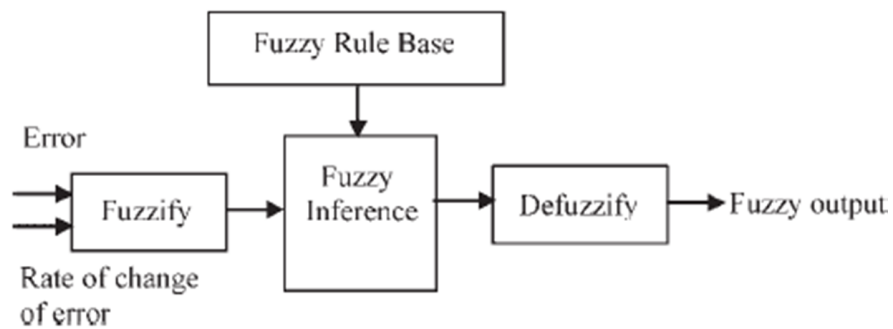


Figure 3-32. Configuration of Fuzzy system.

### 3.3.1 Making use of the "FUZZY LOGIC" toolbox

The Matlab fuzzy logic toolbox includes an editor for creating fuzzy inference systems called Fuzzy Inference System (FIS). This toolkit allows users to create ".fis" files, which relate to fuzzy inference systems and contain RLFs. This toolkit includes three editors (of fis, rules, and membership functions) for entering all FIS data, and two graphical interfaces for visualizing conclusions directly on the basis of rules and control surfaces.

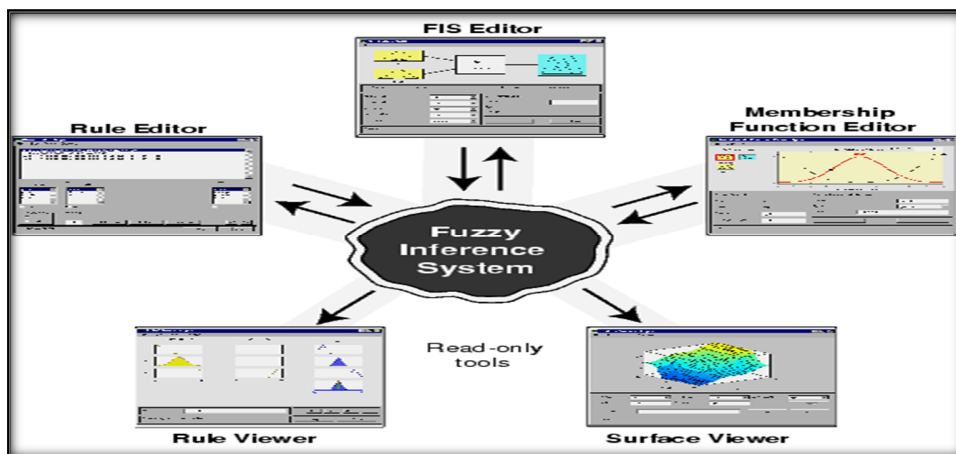


Figure 3-33. The Matlab fuzzy logic toolbox.

### 3.3.2 Fuzzification

The operators used in fuzzy control act on fuzzy sub-sets. Therefore, it is necessary to convert the non-fuzzy external variables into fuzzy external sub-ensembles. To do this, one uses a fuzzification operator that associates a certain function of  $x_0(x)$  with a measure of the variable  $x_0$ . The decision regarding the fuzzification operator is based on how much trust is placed in the taken measurements. As a result, if the measurement  $x_0$  is precise, the understated ensemble  $x_0$  needs to be represented by a precise fact; thus, the singleton transformation is used as a fuzzification operator.

The function of belonging to the fuzzy subset is defined as:

$$\mu_{x_0}(x) = 1 \quad \text{if } x = x_0$$

$$\mu_{x_0}(x) = 0 \quad \text{if } x \neq x_0$$

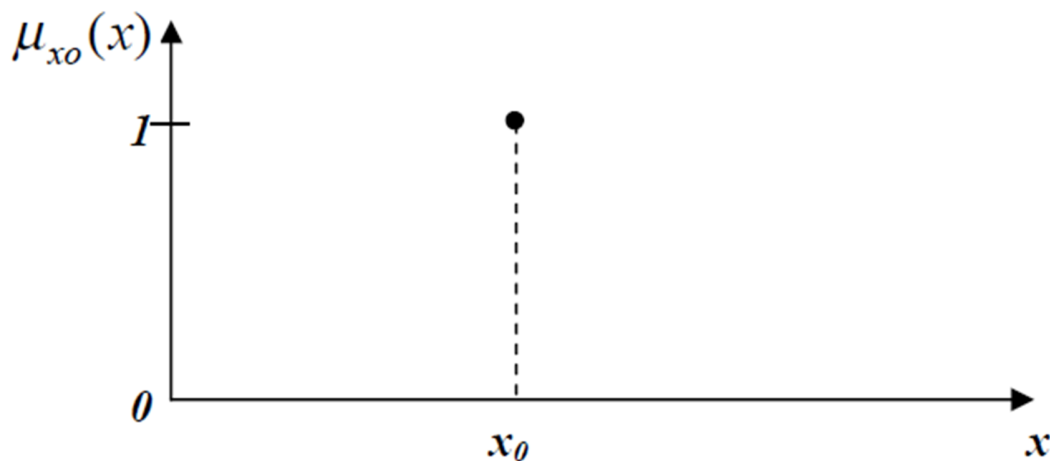


Figure 3-34. Fuzzification method for accurate measurement

#### 3.3.2.1 Fuzzification operations

In this example, we will fuzzify the error (noted e), the controller's input, as well as the variation of the error (noted e) and the output (noted s).

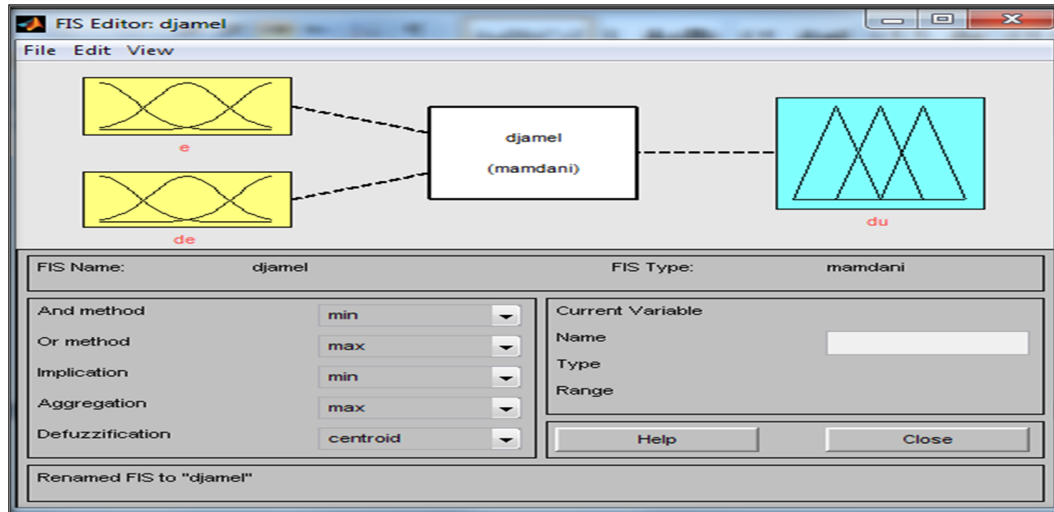


Figure 3-35. FIS Editor.

Step 1:

The Edit command allows to specify the number of inputs and outputs. In our case study, there were 2 inputs and 1 output. We can rename these variables as we see fit.

Step2:

To define the language values and the form of the membership functions, double-click on each input (e and de) or output (du) variable. To do so, go to the new Edit menu and select the Add MFs command, which means adding membership functions. Select two trapezoidal functions [trapmf] for each input and two trapezoidal functions combined with a triangular function for the output (du).

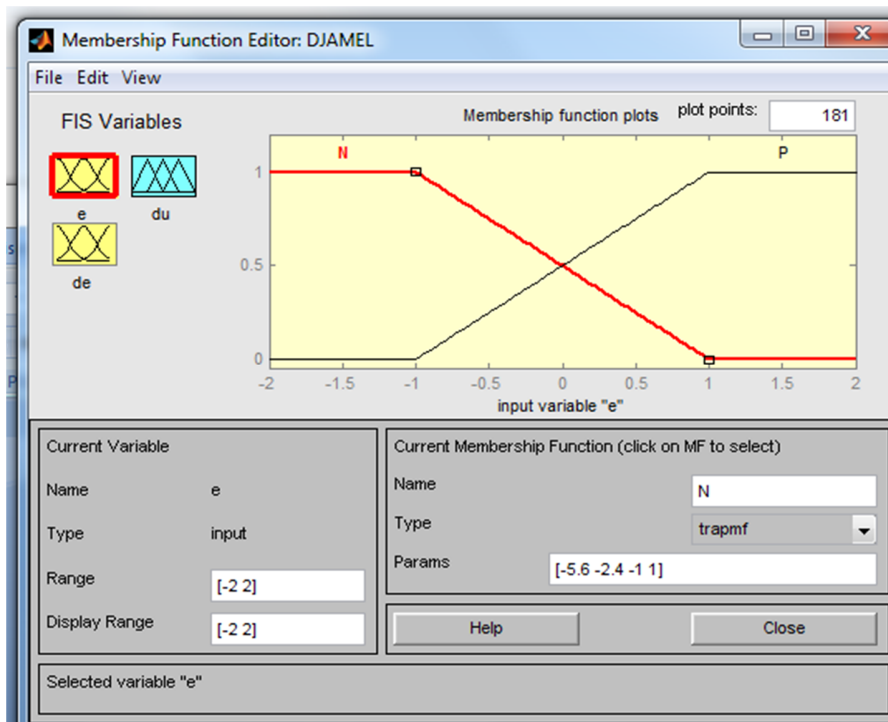


Figure 3-36. Depiction of the system error (e).

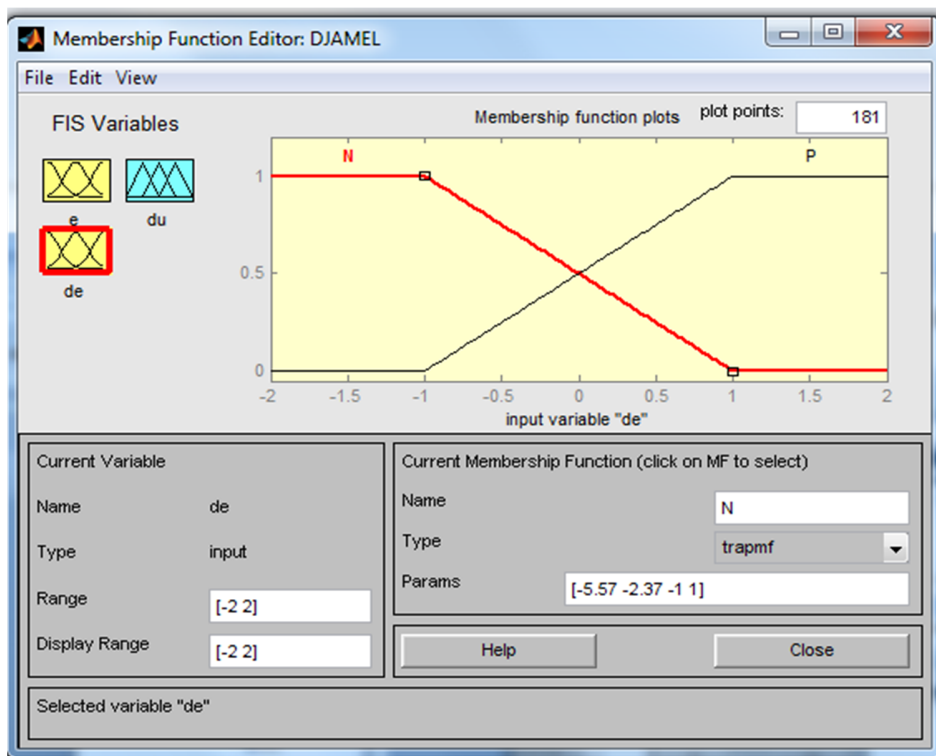


Figure 3-37. Depiction of the system error variation (de).

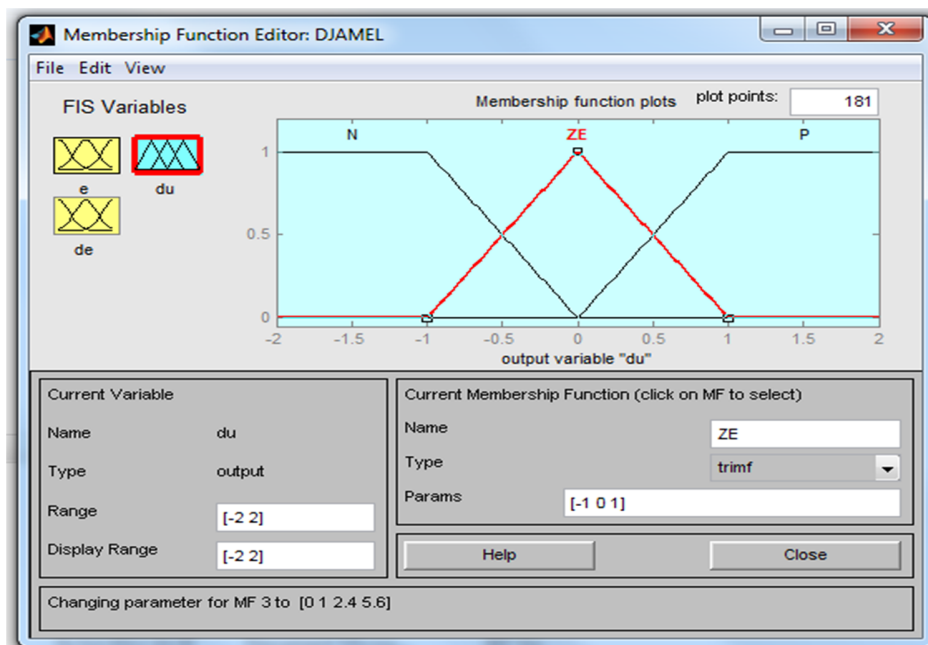


Figure 3-38. Depiction of the generated system output (du).

### 3.3.3 Defuzzification

Information that inference methods provide for the output variable  $z$  in the form of a  $RES(z)$  function of belonging. Given that the controlling system requires a signal upon entry, it is necessary to plan for a transformation of this data. Defuzzification is the term for this change.

Additionally, it is frequently necessary to plan for signal processing and a digital to analog conversion:

- To view all rules, select “view” and click on “view rules”.
- Apply the setpoint to each rule to obtain for each output (du)
- For data  $e=2$ ,  $de=0.5$  on a  $du = +0.92$

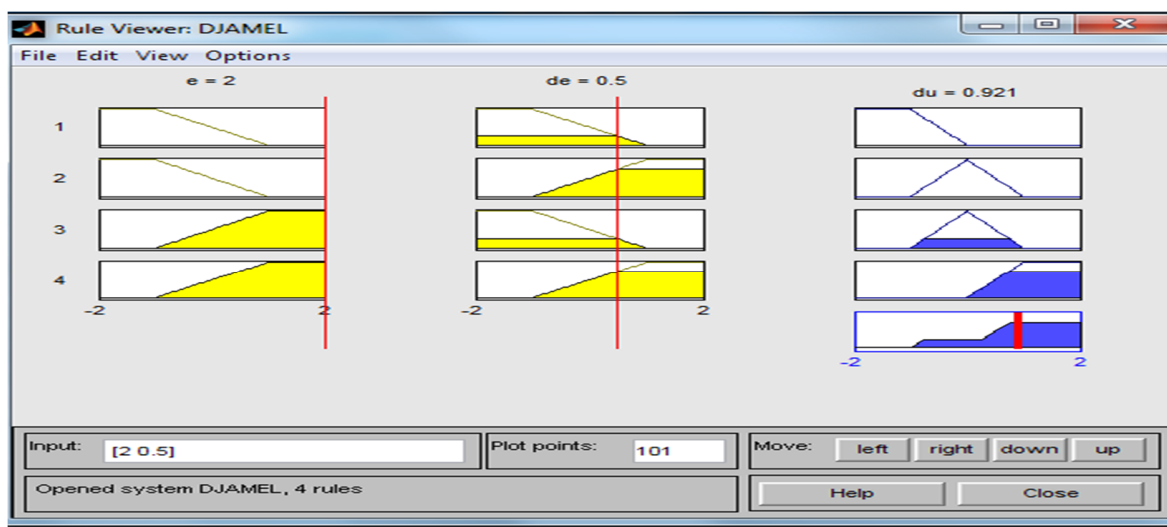


Figure 3-39. Output results for  $e=2, de=0.5$  we have  $du=+0.92$ .

- For data  $e= -2$ ,  $de=0.2$  on a  $du = -0.516$

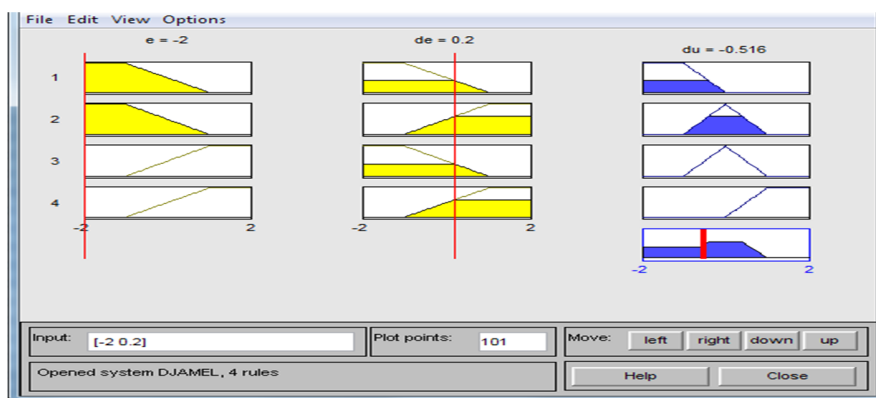


Figure 3-40. Output results for  $e = -2$ ,  $de = 0.2$  on a  $du = -0.516$ 

The input variables can then be set, the inference rules enabled and the relevant control voltage read. The system undergoes the following stages:

- Calculating the activation degree of each of the previously stated bases rules, then search for the membership function for each rule's output and finally return the resulting global membership function.

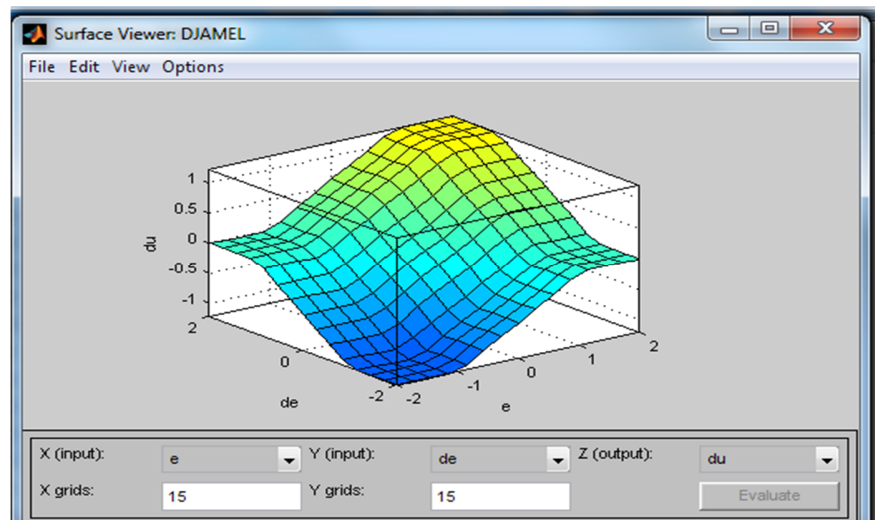


Figure 3-41. Surface area of entries and exits.

Figure 3-41 above defines the total surface area of the inputs  $e$  and  $de$  and the output in three dimensions (3d).

### 3.4 Application of fuzzy logic

Fuzzy logic is employed in processing and various intense Artificial Intelligence applications. It is often employed in current control systems like expert systems. Fuzzy logic replicates how

humans make decisions, but much faster. As a result, it can be used with Neural Networks. Fuzzy logic helps in solve a particular problem after considering all the suitable decisions.

### 3.4.1 Inferences rules

It is based on the applying an implication operator to assess the degree of truth of a rule R of the type "If X is A and X2 then Y is B." In other words, this operator quantifies the strength of the connection between the premise and the rule's conclusion. The most common operators in control are conjunctive:

- Mamdani's (1974) implication:

$$\mu_R(x, y) = \min(\mu_A(x), \mu_B(x)) \quad (50)$$

- Larsen's (1980) implication:

$$\mu_{R(x,y)} = \min(\mu_A(x), \mu_B(x)) \quad (51)$$

### 3.4.2 Inference rule base

The expert role is present here because he will determine the rules of the commands, which will be based solely on the values of the variables.



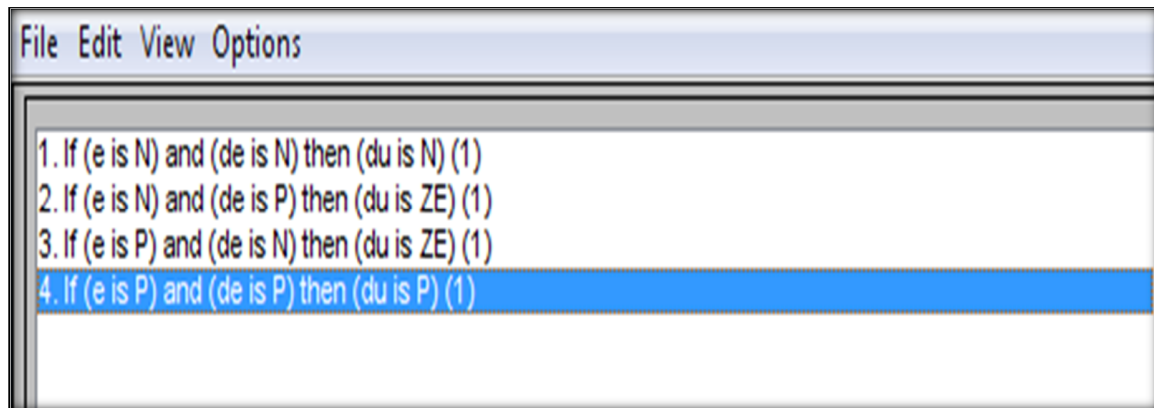


Figure 3-42. Model rule bases.

For example, consider the following list of rules:

- Rule1: If (e) is negative and ( $\Delta e$ ) is negative, (du) is negative.
- Rule 2: If (e) is negative and ( $\Delta e$ ) is positive, (du) is zero.
- Rule 3: If (e) is positive and ( $\Delta e$ ) is negative, (du) is zero.
- Rule4: If (e) is positive and ( $\Delta e$ ) is positive, (du) is average.

### 3.5 Conclusion

In this chapter, the Mamdani method for applying fuzzy control was presented. The research and the setting in which many simulations were created were detailed.

From the study outcome, it can be concluded that this command is simpler than the others and offers the following advantages:

- Simple structure, low synthesis and implementation costs.
- Close to common language and simple to alter.

Finally, the fuzzy controller is utilized when the following conditions exist: - Difficulty (or incapacity) to model the process; for example complicated processes and non-linear processes, and high modeling costs in terms of time, resources, and so on.

# **CHAPTER 4:**

# **SIMULATION RESULTS**

## Chapter 4: Simulation results

### 4.1 Introduction

We have assisted in the fast growth of projects utilizing FACTS technology to improve tension and oscillation stability in electrical systems during the last few years. This is due to their efficiency and speed of response. Control of parameters of more than one line is required in such systems. Multiple unified power flow controllers (M-UPFCs) are employed in this case to meet the power system needs. The generalized unified power flow controller (GUPFC), a modified variant of UPFC, is also used to regulate the power system parameters for more than one bus or even a subsystem. This study describes a unique technique based on voltage source converters that is used to create a thorough model of a GUPFC in MATLAB/Simulink.

### 4.2 Simulation tools

#### 4.2.1 Matlab

MATLAB is a matrix calculation software with a straightforward syntax. MATLAB, with its specialized capabilities, can also be regarded as a programming language appropriate for scientific issues. MATLAB is an interpreter, which interprets and executes instructions line by line. MATLAB can be run on various systems, including X-Windows, Windows, and Macintosh. There are two types of operation [34].

1. **Interactive mode:** MATLAB executes instructions as the user gives them.
  2. **Executive mode:** MATLAB executes an "M file" (program in MATLAB language) line by line
- ✓ **Command window:** In this window, the user gives instructions and MATLAB returns the results
  - ✓ **graphics windows:** MATLAB plots graphics in these windows. M files: These are MATLAB language programs (written by the user).
  - ✓ **Toolboxes:** These are collections of M files developed for specific fields of application (Signal Processing Toolbox, System Identification Toolbox, Control System Toolbox, u-

Synthesis and Analysis Toolbox, Robust Control Toolbox, Optimization Toolbox, Neural Network Toolbox, Spline Toolbox, Chemometrics *Toolbox*, *Fuzzy Logic* Toolbox, etc.)

- ✓ **Simulink**: This is the graphical extension to MATLAB for working with block diagrams.
- ✓ **Blocksets**: These are collections of Simulink blocks developed for specific fields of application (DSP Block set, Power System Block set, etc.).

### 4.2.2 Simulink

The Simulink Toolbox is a function launched from Matlab that gives access to a graphical description of problems with applications to signal processing, classical automatic control, fuzzy logic, etc.

The basis is a hierarchical block diagram description, with each block being a function described in the Matlab language or from other blocks. For the user, the description and execution of Matlab is transparent in the usual problems. All they have to worry about is the graphical construction of their problem, with the possible creation of new blocks for advanced problems.

### 4.2.3 Other simulation tools

With Simulink, we can move beyond idealized linear models and investigate more realistic non-linear models that consider real-world occurrences.

Simulink turns your computer into a laboratory for modeling and analyzing systems that would otherwise be impossible or impractical, such as the behavior of a car clutch system, the flutter of an aircraft wing, the dynamics of a predator-prey model, or the effect of money supply on the economy.

Simulink has a large library of sinks, sources, linear and nonlinear components, and connections. You can also personalize and design your own blocks. See the separate S-Functions writing tutorial for more details on developing your own blocks.

Models are hierarchical, so you can create models using both top-down and bottom-up approaches.

You can view the system at a high level, then progress through the layers by double-clicking on the blocks to reveal increasing levels of model detail. This method provides an overview of how a model is structured and how its components interact.

After you've defined a model, you may simulate it using one of several integration methods, which you can access via the Simulink menus or by entering instructions into the MATLAB command window.

Menus are especially handy for interactive work, however the command line approach is quite beneficial for performing a batch of simulations (for example, if you are doing Monte Carlo simulations or want to sweep a parameter over a range of values). You may see the simulation results while the simulation is ongoing by utilizing ranges and other display blocks. Furthermore, for a 'what if' inquiry, you can alter parameters and watch what occurs immediately. The simulation results can be imported.

Model analysis tools include linearization and slicing tools, accessible from the MATLAB command line, and the many tools in MATLAB and its application toolboxes. And because MATLAB and Simulink are integrated, you can simulate, analyze and revise your models in either environment at any time.

### **4.3 Comparison between a PI controller and a fuzzy logic controller applied to a GUPFC system**

#### **4.3.1 Description of the GUPFC model:**

Modele de 48-Pulse, GTO unified power flow controller (500 kV,100MVA).

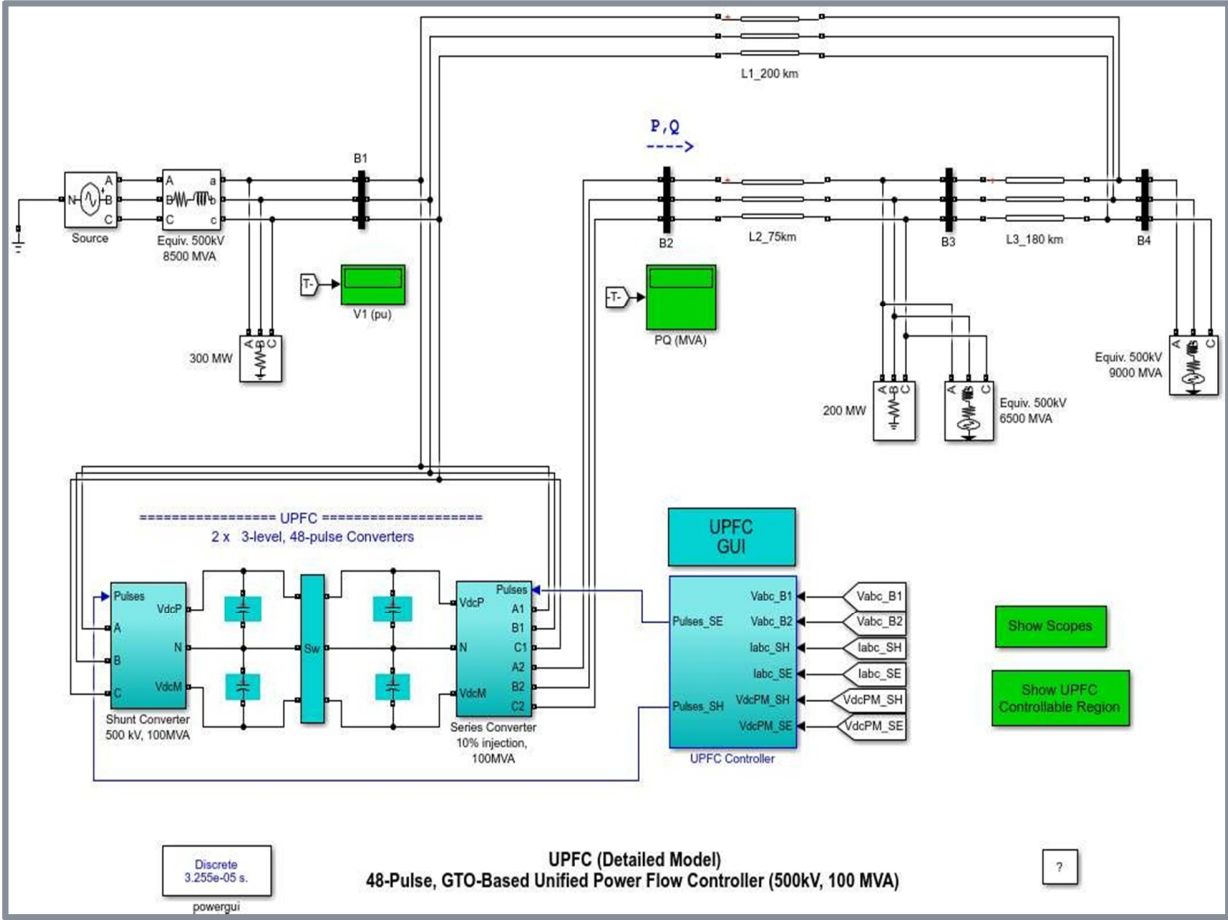


Figure 4-43. Model of 48-Pulse, GTO unified power flow controller (500 kV, 100MVA).

The UPFC controls the power flow in a 500 kv transmission system. The UPFC located at the left end of the 75 km L2 line, between the 500 kv B1 and B2 buses, controls the active and reactive power flowing on the B2 bus while controlling the voltage on the B1 bus. It consists of two 100 MVA, three-level, 48-pulse GTO converters, one connected in shunt to the B1 bus and the other connected in series between the B1 and B2 buses. The shunt and series converters can exchange energy via a DC bus. The series converter can inject a maximum of 10% of the nominal phase-to-earth voltage (28.87 kv) in series with the L2 line.

This pair of converters can operate in three modes:

- ✓ Unified Power Flow Controller (UPFC) mode, when the shunt and series converters are interconnected via the DC bus. When the isolating switches between the shunt and series converter DC buses are open, two additional modes are available:
- ✓ Shunt converter operating as a synchronous static compensator (STATCOM) controlling the voltage on the B1 bus
- ✓ The operating mode, reference voltage, and power values can be modified using the "UPFC GUI" block.

The operating principle of harmonic neutralised converters is explained in another example entitled "Three-phase 48-pulse GTO converter". This power\_48pulsegtoconverter model, can be found in the Power Electronics Models example library. When both converters operate in UPFC mode, the shunt converter functions as a STATCOM. It controls the B1 bus voltage by controlling the reactive power absorbed or generated, while also allowing active power to be transferred to the series converter via the DC bus. The reactive power is varied by varying the DC bus voltage. The four three-level shunt converters operate at a constant conduction angle ( $\sigma = 180 - 7.5 - 172.5$  degrees), generating a 48-step quasi-sinusoidal voltage waveform. The first significant harmonics are the 47th and 49th.

When operating in UPFC mode, the amplitude of the voltage injected in series is modified by varying the conduction angle  $\sigma$ , thus generating a higher harmonic content than the shunt converter. As illustrated in this example, when the series converter operates in SSSC mode, it generates a "true" 48-pulse waveform.

The natural power flows through the B2 bus when zero voltage is generated by the series converter (zero voltage on the converter side of the four converter transformers) is  $P = +870$  MW and  $Q = -70$  Mvar. In UPFC mode, the amplitude, phase angle, and voltage injected in series can be modified, enabling P and Q to be controlled. The GUPFC controllable region is obtained by holding the injected voltage at its maximum value (0.1 pu) and varying its phase angle from zero to 360 degrees. To see the resulting P-Q trajectory, double-click on 'Show GUPFC controllable region'. Any point within the elliptical PQ region can be obtained in GUPFC mode.



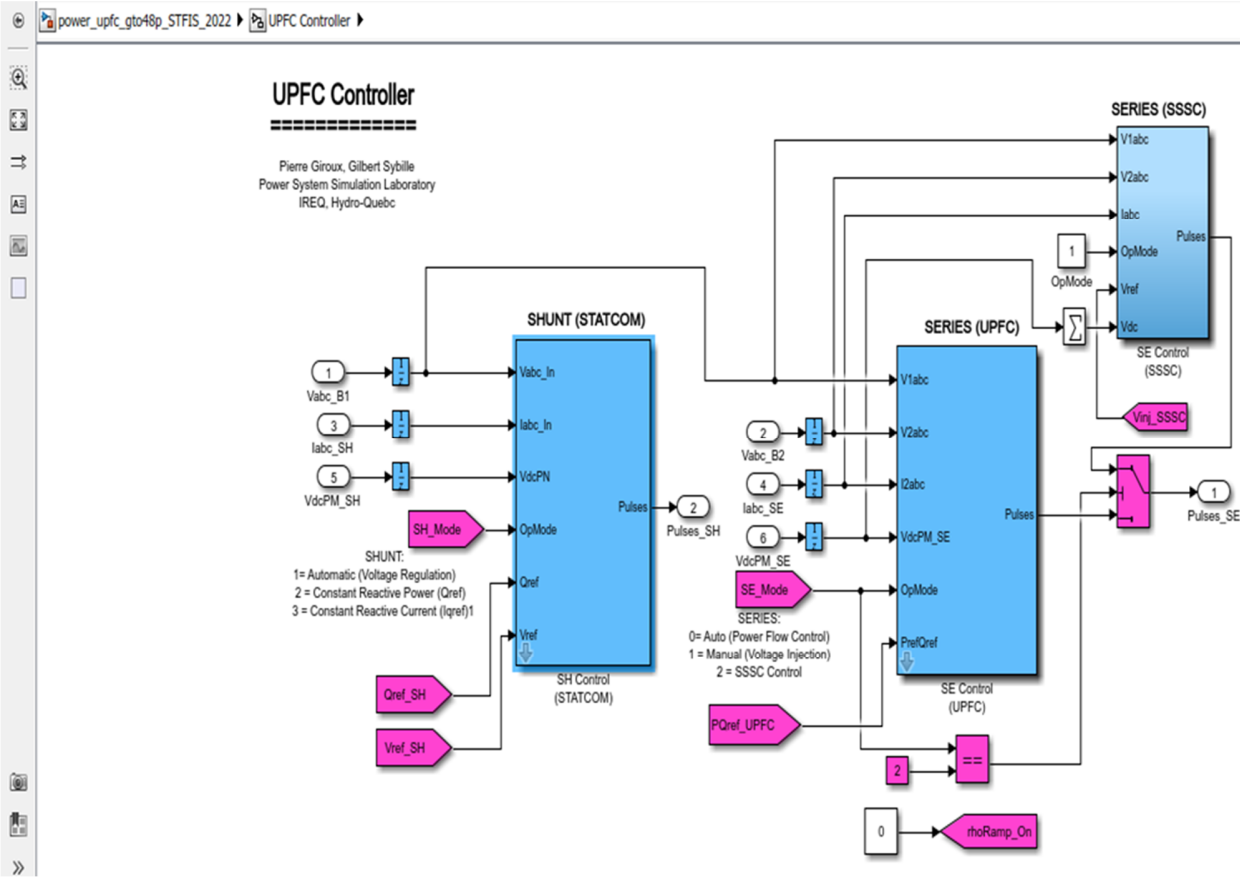


Figure 4-44. GUPFC controller.

4.4. Simulink simulation

4.4.1 Power control in GUPFC mode

By opening the GUPFC graphical interface block menu. The GUI allows us to choose the operating mode (UPFC, STATCOM or SSSC) and the reference power Pref/Qref and/or reference voltage Vref parameters. In addition, the GUI is used to observe the control system’s dynamic response.

It is ensured that the operating mode is set to "GUPFC (Generalized Power Flow Control)". The reference active and reactive powers are specified in the last two lines of the GUI menu. Initially:

$P_{ref} = +8.7 \text{ pu} / 100\text{MVA} (+870 \text{ MW})$

And  $Q_{ref} = -0.6 \text{ pu} / 100\text{MVA} (-60 \text{ Mvar})$ .

At  $T = 0.25 \text{ sec}$ ,  $P_{ref}$  is changed to  $+10 \text{ pu} (+1000\text{MW})$ .

Then, at  $t = 0.5 \text{ sec}$ ,  $Q_{ref}$  is changed to  $+0.7 \text{ pu} (+70 \text{ Mvar})$ .

The shunt converter reference voltage (specified in the 2nd line of the graphical interface) will be kept constant at  $V_{ref} = 1 \text{ pu}$  throughout the simulation (Step Time =  $0.3 * 100 >$  Simulation stop time (0.8 sec). When the GUPFC is in power control mode, the variations in reference reactive power STATCOM and injected voltage SSSC (specified respectively on the 1st and 3rd lines of the GUI) are not used.

The simulation will be run for 0.8 sec. the powers P and Q will be traced, After a transient period steady state is reached ( $P = +8.7 \text{ pu}$ ;  $Q = -0.6 \text{ pu}$ ). P and Q are then returned to the new settings ( $P = +10 \text{ pu}$   $Q = +0.7 \text{ pu}$ ).

The resulting variations in P Q are also observed on the three transmission lines. The performance of the shunt and serial converters can be observed on the STATCOM and SSSC oscilloscopes respectively. If you zoom in on the first trace on the STATCOM oscilloscope, 0 you can see the 48-step voltage waveform  $V_s$  generated on the secondary side of the shunt converter transformers superimposed on the primary voltage  $V_p$  and primary current  $I_p$ .

#### **4.4.2 Var control in STATCOM mode**

In the GUI block menu, change the operating mode to "STATCOM (Var Control)". The STATCOM reference values (1st parameter line, [T1 T2 Q1 Q2]) are set to [0.3 0.5 +0.8 -0.8 ]. In this mode, the STATCOM operates as a variable source of reactive power. Initially, Q is set to zero, then at  $T1 = 0.3 \text{ sec}$  Q is increased to  $+0.8 \text{ pu}$  (STATCOM absorbing reactive power) and at  $T2 = 0.5 \text{ sec}$ , Q is inverted to  $-0.8 \text{ pu}$  (STATCOM generating reactive power).

When the simulation executes, we can see the dynamic response of the STATCOM on the STATCOM field. Zoom in on the first trace around  $t=0.5$  sec when  $Q$  goes from  $+0.8$  pu to  $-0.8$  pu. When  $Q = +0.8$  pu, the current flowing in the STATCOM lags behind the voltage, indicating that the STATCOM is absorbing reactive power. When  $Q_{ref}$  goes from  $+0.8$  to  $-0.8$ , the phase shift of the current with respect to the voltage goes from 90 degrees behind to 90 degrees ahead in one cycle. This reactive power control is achieved by varying the amplitude of the secondary voltage  $V_s$  generated by the shunt converter while keeping it in phase with the B1 bus voltage  $V_p$ . This change in amplitude  $V_s$  is achieved by controlling the DC bus voltage. When  $Q$  changes from  $+0.8$  pu to  $-0.8$  pu,  $V_{dc}$  changes from 17.5 kV to 21 kV.

**4.4.3 Serial voltage injection in SSSC mode**

In the GUI block menu, change the operating mode to "SSSC (voltage injection)". Make sure that the SSSC reference values (3rd line of parameters) [ $V_{inj}$   $V_{inj\_Final}$   $StepTime$ ] are set to [0.0 0.08 0.3]. The initial voltage is set to 0 pu, then at  $t = 0.3$  s, it is reduced to 0.8 pu.

**4.5 Simulation results with PI controller**

**4.5.1 Simulation results without GUPFC installed**

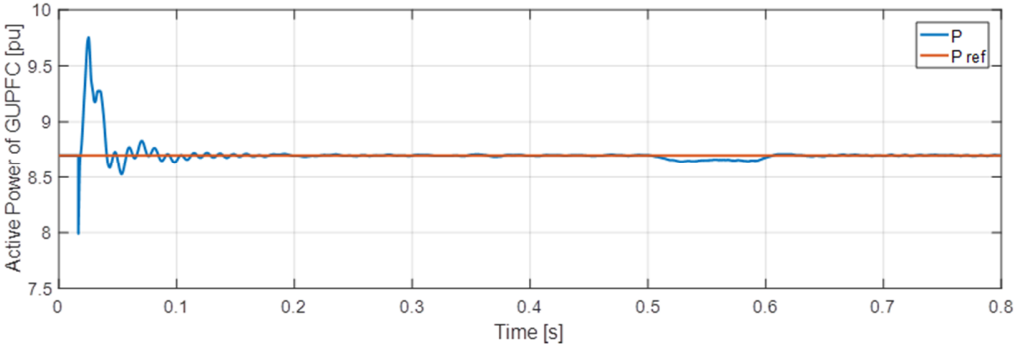


Figure 4-45. Simulation result of active power (Reference fixed and actual value).

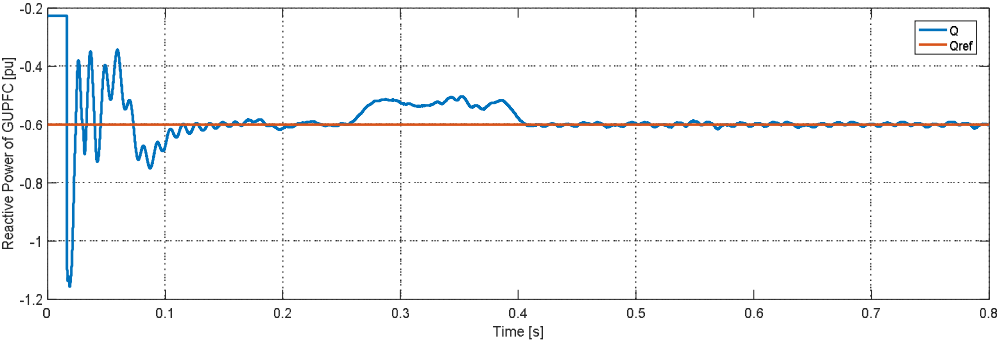


Figure 4-46. Simulation result of reactive power (Reference fixed and actual value).

4.5.2 Simulation results with GUPFC installed

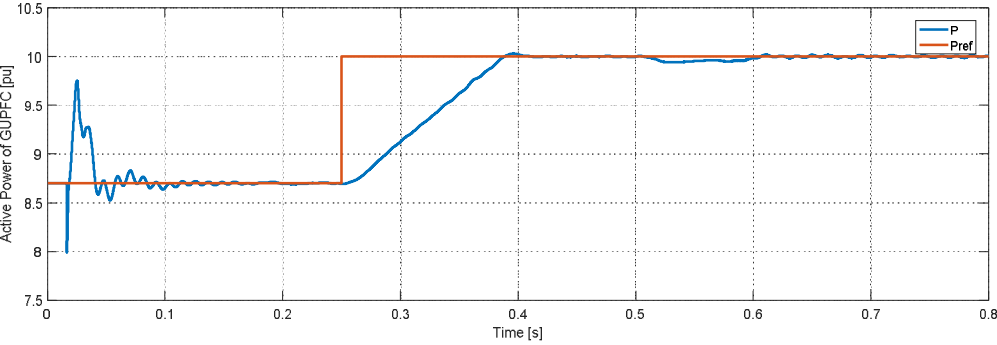


Figure 4-47. Simulation result of active power (Reference and actual value) with GUPFC installed.

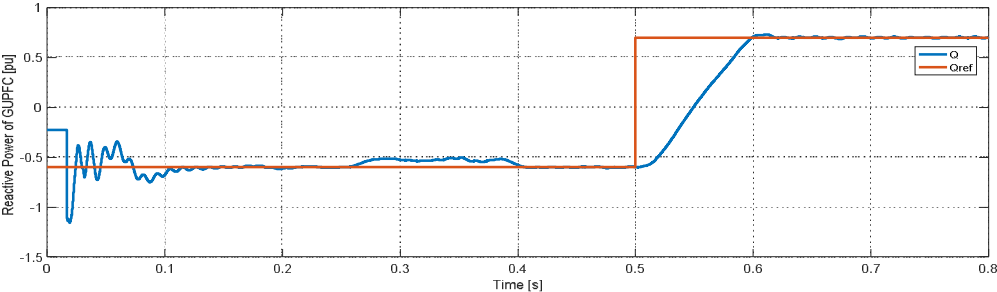


Figure 4-48. Simulation result of reactive power (Reference and actual value) with GUPFC installed.

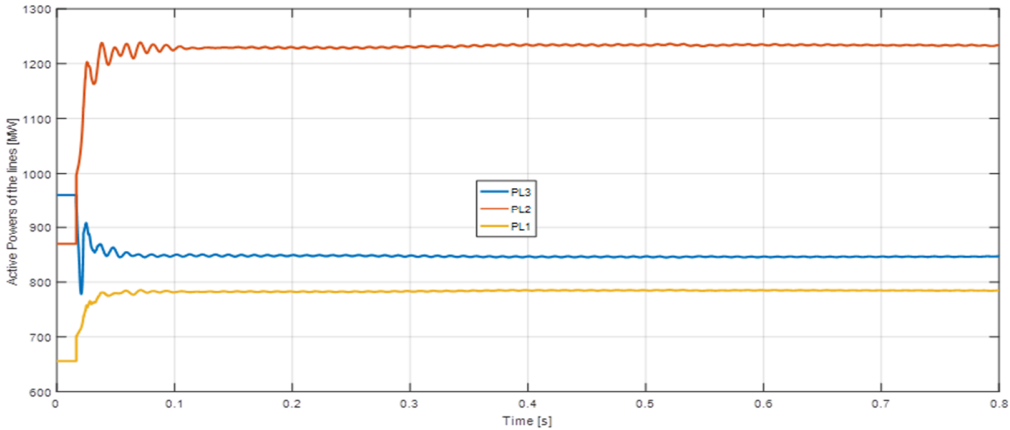


Figure 4-49. Simulation result of active power for L1, L2, L3 with GUPFC installed.

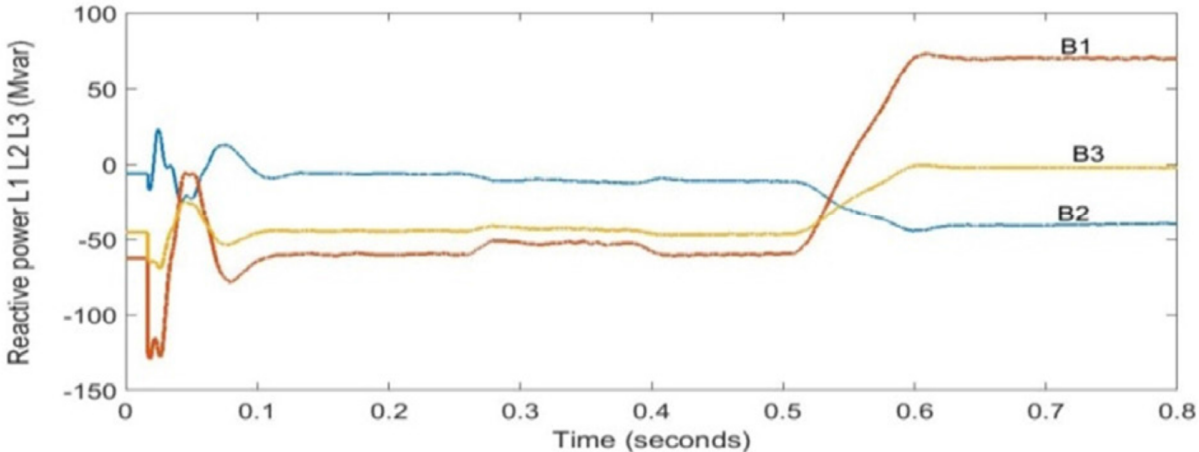


Figure 4-50. Simulation result of reactive power for L1, L2, L3 with GUPFC installed.

When the transmission system with GUPFC installed

- 1) In Figure 4-46, the active power value initially not tracking the reference value but finally overlaps with the reference active power values.
- 2) In Figure 4-47, the reactive power value is initially not tracking but finally overlaps the reference reactive power values.
- 3) The Figure 4-48 and Figure 4-49, shows the active power and reactive at bus L1, L2, and L3. The active and reactive power is steady state condition. No oscillation is detected in the result when GUPFC is installed.

Henceforth it is concluded that GUPFC is working in a better way

- 1) The GUPFC can track the reference active and reactive power value superior.
- 2) The GUPFC can regulate the active and reactive power better.

Here again, the authors would like to clarify that the simulation results should not lead to the conclusion that the use of other FACTS, such as the UPFC, should be avoided. The simulation clearly shows that both FACTS devices follow the reference values and regulate active and reactive power.

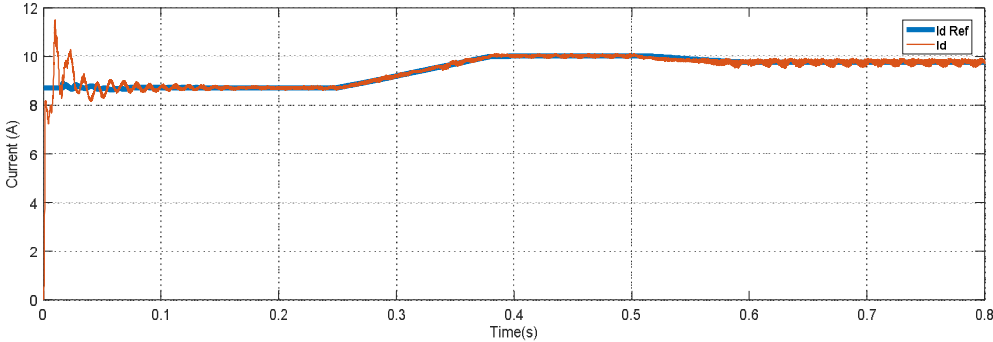


Figure 4-51. Current Id and Id ref.

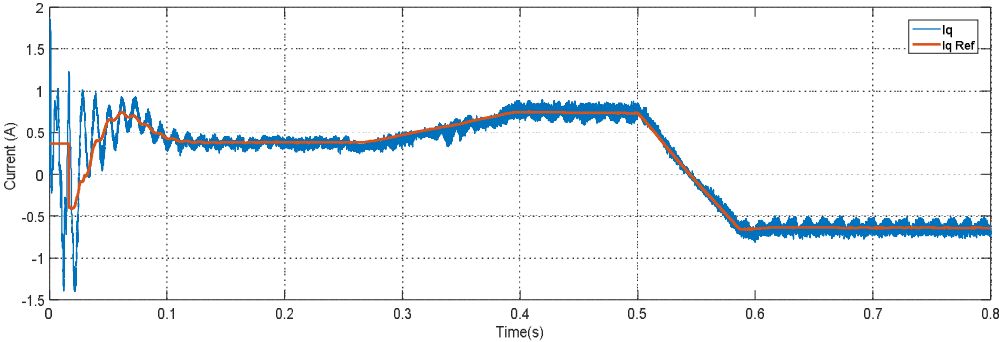


Figure 4-52. Current Iq and Iq ref.

4.6 Results of simulation with fuzzy logic control

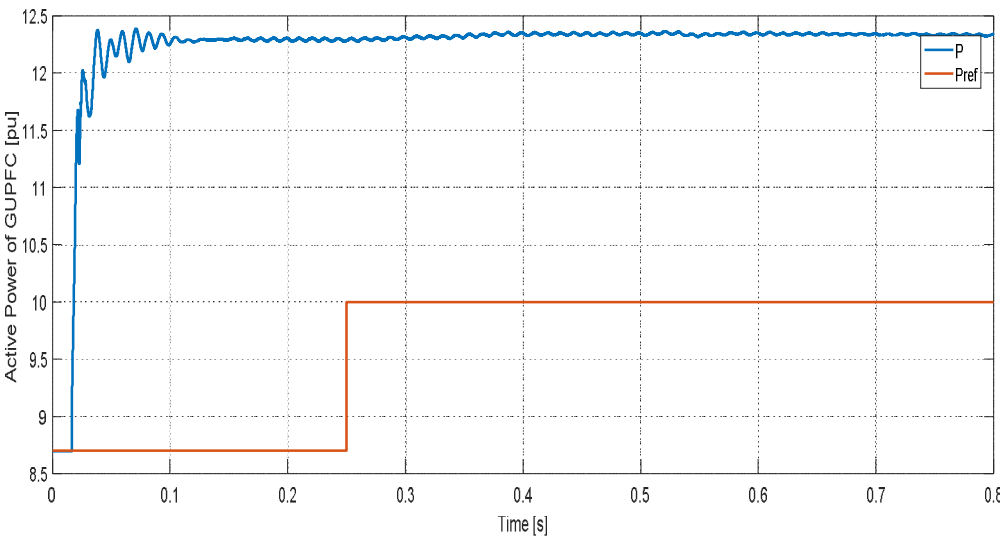


Figure 4-53. Active Power of GUPFC.

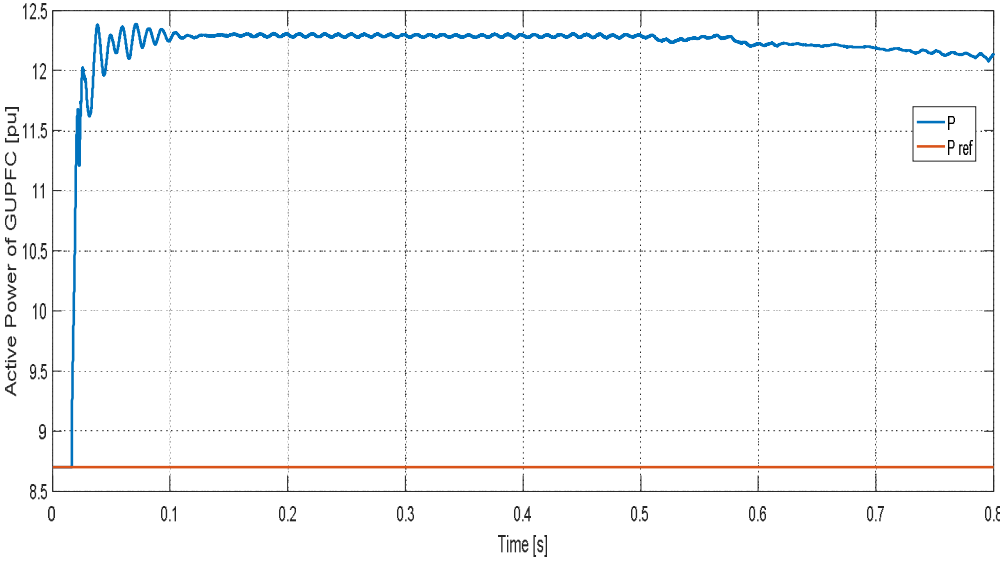


Figure 4-54. Active Power with fixed Pref.

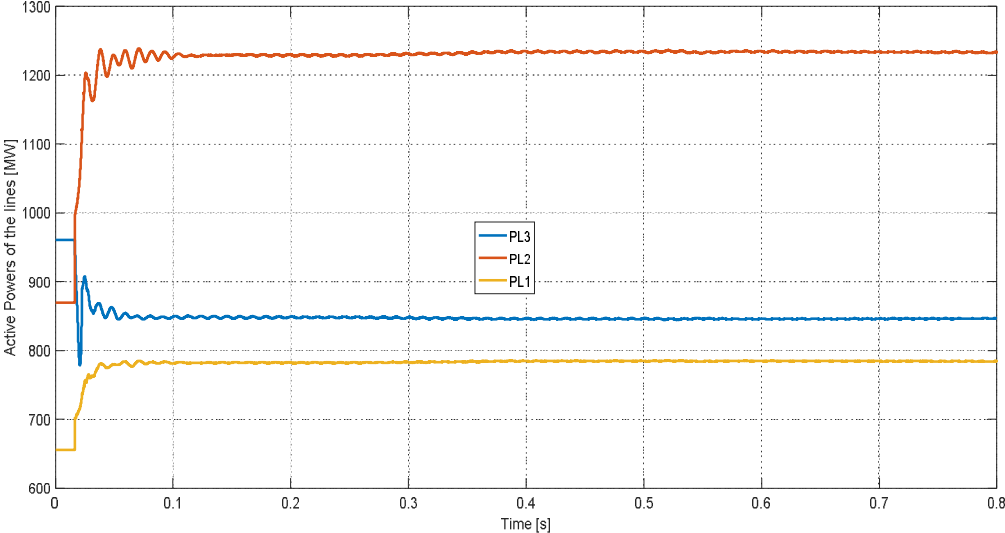


Figure 4-55. Active Power of lines for the GUPFC.

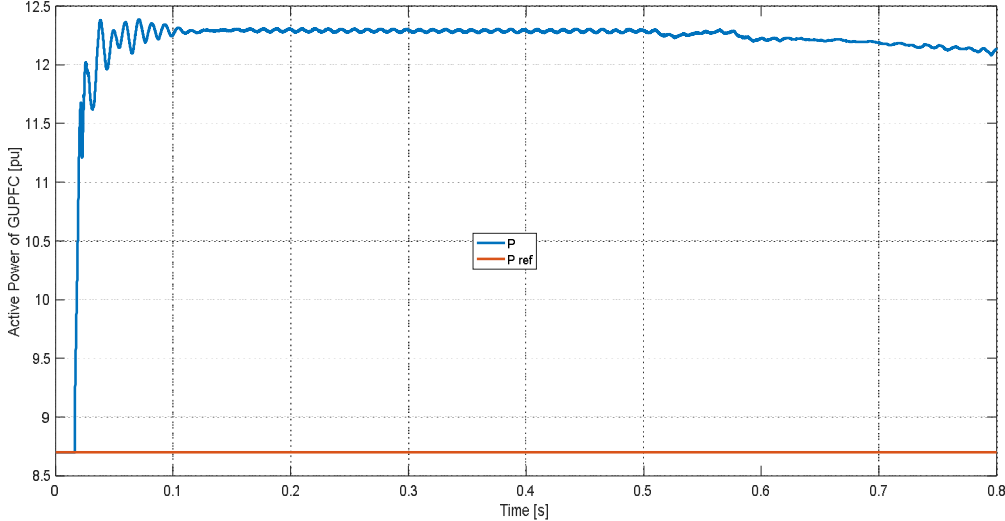


Figure 4-56. Active Power of GUPFC with fixed Pref.



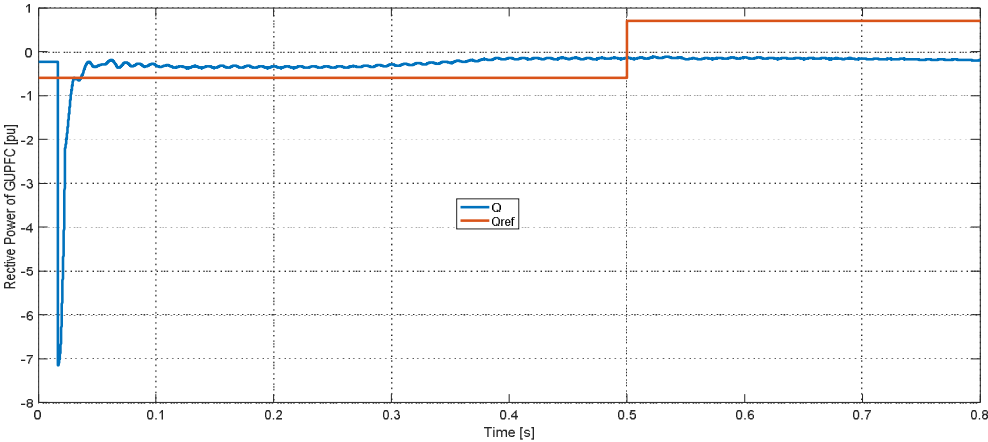


Figure 4-57. Reactive Power without changing parameters.

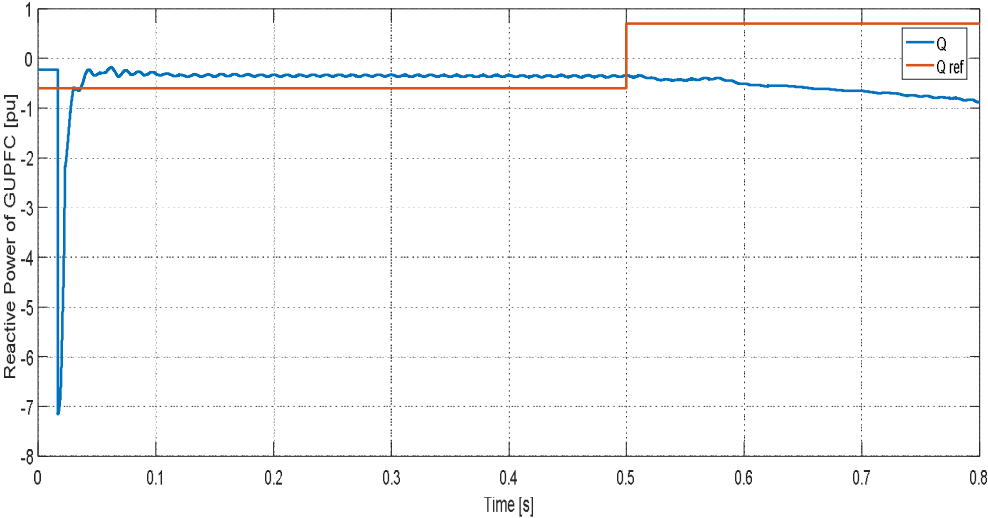


Figure 4-58. Reactive power with changing parameters

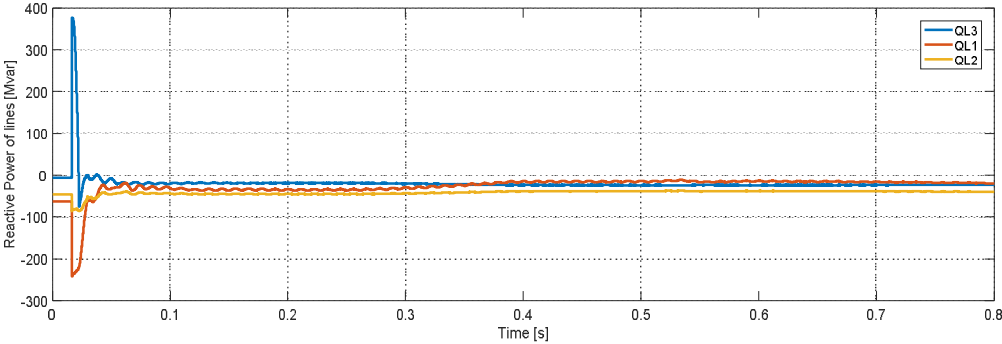


Figure 4-59. Reactive Power of lines

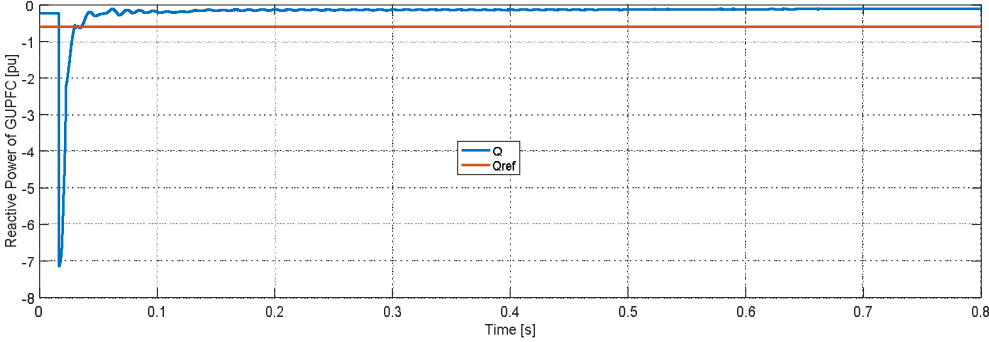


Figure 4-60. Reactive Power with fixed Qref.

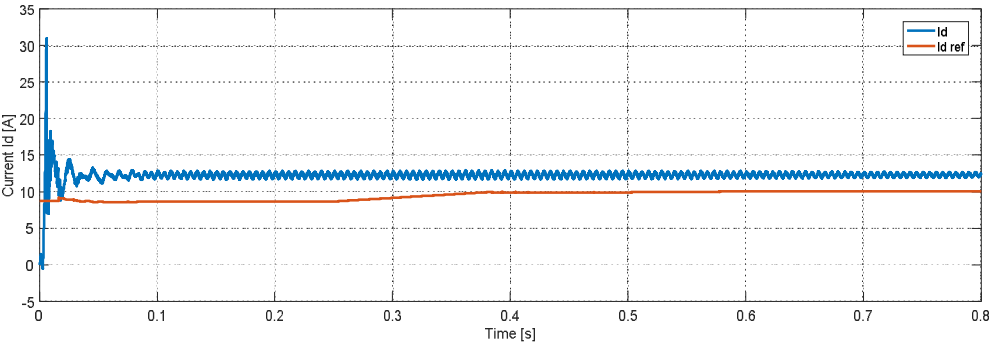


Figure 4-61. Id and Id ref current.

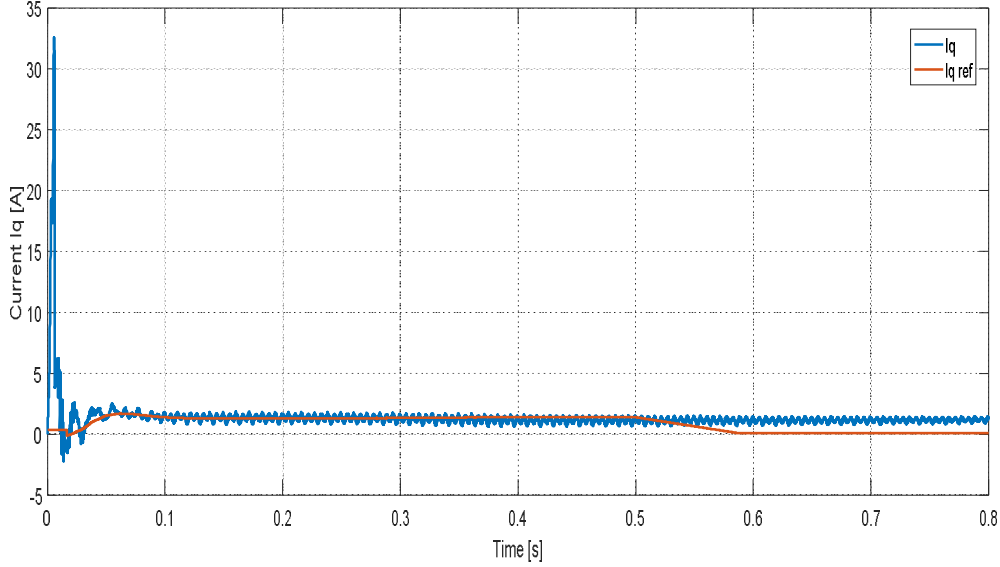


Figure 4-62. Iq and Iq ref current.

### 4.7 Conclusion

The simulation of GUPFC in this chapter concludes with the main points below and The GUPFC is tracking the reference active and reactive power levels well. We analyze the price factor, as it is obvious that GUPFC is a less expensive FACTS device. Then we can finally conclude that GUPFC can be used to replace the M-UPFC.

# **GENERAL CONCLUSION**

## General conclusion

The stability of electrical networks and the regulation of power flow are critical concerns for the planning and operating of constrained electricity networks. This means that quick control systems are crucial. These swift control systems include FACTS devices based on developments in power electronics. By developing the capacity of existing facilities, they make an essential contribution to the functioning of electrical networks in an increasingly constrained context.

In this dissertation we studied a control strategy for a GUPFC, one of the best performing FACTS tools used for optimizing the operation of electrical networks. We examined the possibilities for power transit control that GUPFC can offer. Our work focused on modeling, identifying references, and developing GUPFC control to enhance power flow transit. For this device, we also studied a “PI “and “Fuzzy Logic” control methods. We have used a classical PI controller but when the default reference values of active and reactive power were changed, transient faults occur, or a transmission line experiences an outage. Therefore the PI systems alone cannot control the GUPFC. Consequently, we have applied the Fuzzy Logic theory to the GUPFC command procedure. The obtained results have helped us to appreciate the contribution of the GUPFC employing fuzzy logic in network stabilization. i.e. helping the disturbed system to recover to equilibrium states extremely fast. This method also proved to be incredibly durable. The results revealed that the performance of a control system is determined by the objectives given to it, as well as the projected time for the system to return to a new state of equilibrium.

In this work, we have shown that the performance of a fuzzy logic-controlled GUPFC can be very high in controlling power transients, maintaining network voltage and improving network stability. The work carried out here suggests other research prospects. A real multi-machine network equipped with FACTS GUPFC, such as -the energy distribution organization network, - could be investigated. Another research can be on the contribution of FACTS GUPFC to the control of decentralized networks where electricity production from renewable sources is significant.

# **REFERENCES**

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## References

- [1] X. P. Zhang, "Robust modeling of the interline power flow controller and the generalized," vol. 1.89, 2006, pp. 1-9.
- [2] X. P. Zhang, «Robust modeling of the interline power flow controller and the generalized,» *Electrical Engineering(Spring Verlag)*, vol. 1.89, pp. 1-9, 2006.
- [3] X. P.Zhang, «modeling of the generalized unified power flow controller (GUPFC) in a nonlinear interior point OPFICA,» chez *International Conferemce on Power Industry Computer Application. Innovative Computing for Power*, 2001.
- [4] F.Messaoud, «:"A Novel and Robust Model of the GUPFC Controller System ",» *The International* , vol. VOL. 13 , p. 51, 2020.
- [5] K. Nassima, *gestion du flux de puissance dans une ligne HT en utilisant un SSSC*, 2013.
- [6] D.Chattarjee,«"Improvement of transient stability of power systems with STATCOM controller using sensitivity"Electrical power and Energy Systems,» *Electrical Power and Energy Systems* , vol. 48, p. 531, 2013.
- [7] B.Bekki, *contribution du SMES,dispositif FACTS a la stabilisation d'un Reseau Electrique Haute Tension*, Alger, 2006.
- [8] D.Krischel, *2MJ Supraconducting Magnetic Energy Storage System-SMES*, allemagne, 2005.
- [9] F.Cherbi, «"Dispatching Economique au moyen du Dispositif FACTS",» *ACTA*

- 
- Electrotechnica, Mediamira Science Publisher. All rights reserved., vol. 51, n° 11, 2010.*
- [10] U. Patil, «"SSSC Based Hybrid Scheme for damping sub-synchronous resonance",» chez *International Conference on Recent Trends on Electronics*, India, 2019.
- [11] E. Shahraki, "*Apport de l'UPFC à l'amélioration de la stabilité transitoire des réseaux électriques*", France: These de Doctorat, Université Henri Poincaré-Nancy, 2003.
- [12] C. V. S. a. S. S. Raju, *Mathematical modeling and analysis of a Generalized Unified Power Flow Controller with Device rating Methodology*, vol. 7, Kakinada, A.P., India, Department of Electrical & Electronics Engineering, 2015, p. 533-003..
- [13] P. Zhang, *Modeling of the generalized unified power flow controller (GUPFC) in a nonlinear interior point OPF* *PICA 2001*, (Cat.No.01CH37195) éd., I. C. o. P. I. C. Applications, Éd., Electric Energy Meets the Market: 22nd IEEE Power Engineering Society, 2001, p. 283–286.
- [14] B. Fardanesh, *Multi-converter FACTS devices: the generalized unified power flow controller (GUPFC)*, 2000, pp. 1020-1025..
- [15] S. V. Sandeep Sharma, *Development of generalized unified power flow controller (GUPFC)*, Haryana, New Delhi,, Bharati Vidyapeeth's Collge of Engineering, National Institute of Technology, Kurukshetra, 2019, p. 233–246.
- [16] C. D. Deckmann SM, *A power sensitivity model for electromechanical*, 965–71, 1994.
- [17] V. F. Vyakaranam B, *Dynamic modeling and analysis of generalized unified power flow controller* *Electr Power Syst Res*, 2014.
- [18] S. M. Kazemi A, *Extended supplementary controller of UPFC to improve damping inter-*



- 
- area oscillations considering inertia coefficient*, 2008, p. 1–8.
- [19] B. Huang Z, *Application of unified power flow controller in interconnected power systems-modeling, interface, control strategy, and case study*, 2000, p. 817–24..
- [20] S. T. Lubis RS, *Modeling of the generalized unified power flow controller for optimal power flow. In: Proc, international conference on electrical engineering and informatics (ICEEI), Bandung, 2011*, p. 1–6.
- [21] S. T. Lubis RS, *Using the upfc and gupfc controllers to maximize available transfer capability (atc).*, Int J Electr Eng Informatics, 2014.
- [22] P. Xiao-Ping Zhang, *Flexible AC Transmission Systems :Modelling and Control (Power Systems)*„, 2006.
- [23] X. P. Zhang, Zhang., “*Modelling of the interline power flow controller and the generalised unified power flow controller in Newton power flow*”, vol. 150, 2003, pp. 268-274.
- [24] N. DIZDARVIC, *Unified power flow controller in alleviation of voltage stabilityproblem*, 2001.
- [25] V.-H. G. Palacio, *Modélisation Et Commande Floues De Type Takagi-Sugeno Appliquées A Un Bioprocédé De*, 2007.
- [26] K. Sreenivasachar, *Unified power flow controller: Modeling, Stability analysis, Control strategy and Control system*, Waterloo, Ontario,, 2001.
- [27] L.Baghli, *Contribution à la commande de la machine asynchrone, utilisation de la logique floue, des*, 1999.

- 
- [28] K. Ram Chahran. B. Amarendra Reddy, *Control of Non-Linear Systems Using Parallel Structure of Fuzzy PI+PD Controller*, vol. 2(8), 2010, pp. 3422-3433.
- [29] M. Boudhraf, *Comparaison des performances d'un compensateur série statique synchrone réglée*, Ecole Militaire Polytechnique, Bordj El.
- [30] E. Lutfu Saribulut, *Performance Analysis of Fuzzy Logic Based Unified Power Flow Controller*, 2008, pp. 320- 325.
- [31] R. Orizondo, *IEEE, UPFC Simulation and Control Using the ATP/EMTP and MATLAB/Simulink Programs*, 2006, pp. 1-7..
- [32] T. Allaoui, *Fuzzy decoupling control of multi-level UPFC-based power flow compensation*, Université IBN KHLDOUN, 2004.
- [33] A.Gopala Rao, *Fuzzy Pi and Integrating Type Fuzzy PID Controllers of Linear, Nonlinear and Time -Delay*, vol. 1, 2010.
- [34] L. -H. Hong, Canada, 1989.
- [35] D. B. & A. P. B. Valle, «The influence of GUPFC FACTS device on small signal stability of the electrical power systems,» *International Journal of Electrical Power & Energy Systems*, vol. 65, pp. 209-306, 2015.
- [36] S. Raju, «Mathematical modeling and analysis of a Generalized Unified Power Flow Controller with rating Methodoly,» vol. 7, 2015.
- [37] M. Kamel, *contribution a l'amelioration des methodes evolutionnaires pour la repartition optimale des puissances :application dans un reseau d'energie electrique avec et sans FACTS*, 2017.

[38] J. tessier, *ligne de distribution et de transport*, université LAVAL Montréal, 2005.

[39] S. Raju, *Mathematical modeling and analysis of a Generalized Unified Power Flow*, vol. 7, India, Electrical & Electronics Engineering, Number 1, March 2015, p. 533 003.

[42]

[43] MathWorks.

## لملخص

وفي السنوات الأخيرة، ازداد الطلب على الكهرباء زيادة كبيرة، في حين أن تطوير توليد الطاقة الكهربائية ونقلها قد تقلص بشدة بسبب محدودية الموارد والقيود البيئية. ونتيجة لذلك، فإن بعض كابلات النقل مثقلة بالأعباء مما يعرض استقرار النظام للخطر. أحد الحلول هو تقنية أنظمة نقل التيار المتردد المرنة (FACTS). لذلك، يركز هذا العمل على مساهمة جهاز FACTS مثل GUPFC في إزالة تلك القيود والقيود. على شبكة متعددة الآلات، قمنا بتقييم أداء الأداة باستخدام تكوينات تحكم منطقية مشابهة وغامضة. بمقارنة طريقتي التحكم هاتين، تُظهر نتائجنا أن GUPFC تعمل بكفاءة عند التحكم بها باستخدام منطق غامض. في الواقع، ثبت أنه قوي للغاية. تبين أن مساهمة GUPFC في الحفاظ على الاستقرار ذات أهمية كبيرة عندما تكون ظروف الخطأ شديدة للغاية.

الكلمات المفتاحية: FACTS, GUPFC, Fuzzy Logic, PI controller, Matlab, Simulink

## **Abstract**

In recent years, electricity demand has significantly expanded whereas the development of power generation and transmission has been severely curtailed due to limited resources and environmental constraints. As a result, some transmission cables are overburdened putting system stability at risk. One of the solutions is Flexible AC Transmission Systems (FACTS) technology. Therefore, this work focuses on the contribution of a FACTS device such as the GUPFC in lifting those limitations and constraints. On a multi-machine network, we assessed the tool's performance using an analogical and a fuzzy logic control configurations. Comparing these two control methods, our results shows that the GUPFC performs efficiently when controlled using fuzzy logic. In fact it proved to be very robust. The contribution of the GUPFC in maintaining stability turns out to be of great interest when the fault conditions are very severe.

**Keywords** : FACTS, GUPFC, Fuzzy Logic, PI controller, Matlab, Simulink

## Résumé

Ces dernières années, la demande d'électricité a considérablement augmenté alors que le développement de la production et de la transmission d'électricité a été sévèrement freiné en raison de ressources limitées et de contraintes environnementales. En conséquence, certains câbles de transmission sont surchargés, ce qui met en péril la stabilité du système. L'une des solutions est la technologie des systèmes de transmission à courant alternatif flexible (FACTS). C'est pourquoi ce travail se concentre sur la contribution d'un dispositif FACTS tel que le GUPFC à la levée de ces limitations et contraintes. Sur un réseau multi-machines, nous avons évalué les performances de l'outil en utilisant une configuration de contrôle analogique et une configuration de contrôle à logique floue. En comparant ces deux méthodes de contrôle, nos résultats montrent que le GUPFC fonctionne efficacement lorsqu'il est contrôlé à l'aide de la logique floue. En fait, il s'est avéré très robuste. La contribution du GUPFC au maintien de la stabilité s'avère être d'un grand intérêt lorsque les conditions de défaut sont très sévères.

**Mots clé :** FACTS, GUPFC, Logique Floue, Contrôleur PI, Matlab, Simulink