DISEÑO DE UPFC CON CONTROLADOR DIFUSO PARA MEJORAR EL FLUJO DE POTENCIA

Development of a Fuzzy methodology for Unified Power Flow Controller

RESUMEN
Hasta hace algún tiempo inductores y capacitores eran introducidos de manera mecánica a un sistema eléctrico con el fin de controlar el flujo de potencia y proporcionar estabilidad de voltaje en los sistemas de trasmisión. Hoy en día la electrónica de potencia ha hecho posible la introducción de dispositivos FACTS que permiten controlar de una manera óptima el flujo de potencia. El objetivo de este trabajo es mostrar el control sobre un UPFC para la inyección de voltaje en una barra de referencia. Un controlador difuso que emplea el nivel de voltaje en la barra de referencia es implementado sobre el inversor con el fin de controlar la potencia reactiva que es inyectada al sistema y así ampliar los límites de estabilidad.

PALABRAS CLAVES: Controlador difuso, electrónica de potencia, dispositivos FACTS.

ABSTRACT
In the past, mechanically switched capacitors, inductors and synchronous condensers were used to control the power flow and provide voltage stability in transmission systems. With the development of power electronics and semiconductor devices, power electronics are becoming increasingly prevalent in different applications. These include ships, aircraft, motor drives, and power systems. In power systems, power electronics have been implemented more and more in order to inject or absorb reactive power and replace large synchronous condensers. FACTS devices are power electronics based and have many advantages in power systems. The focus of this paper is to analyze the advantages of installing a three-phase UPFC on a transmission system.

KEYWORDS: *FACT devices, fuzzy controllers, power electronics.*

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1. INTRODUCTION

Flexible AC Transmissions Systems (FACTS) integrate power electronic controllers to increase the power transfer capability and enhance the controllability of transmission systems [1]-[4]. They are mainly used to control the dynamical and transient response of a power system injecting or absorbing reactive power by using high power electronics. FACTS devices are versatile, reliable and flexible and have the following advantages [3]:

- Increase the amount of power transfer capacity of existing transmission systems
- Control active and reactive power flow in transmission lines
- Provide voltage support and control improving system stability
- Delay the construction of new transmission systems

Figure 1 lists the configurations of FACT devices in transmission systems. Conventional devices, such as resistors, capacitors and reactors, are switched mechanically and introduce to the system to control the voltage or power flow. FACTS devices perform the same functions but they use power electronics valves or converters in conjunction with or instead of passive components.

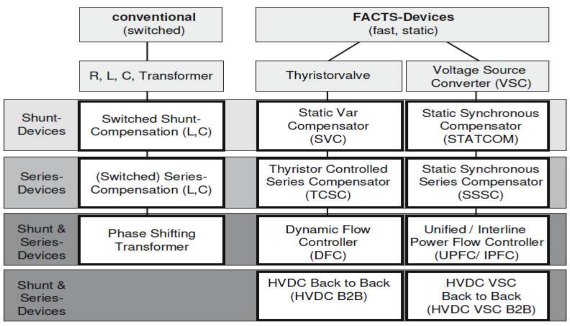

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Figure 1. Overview of FACT devices [5].

The use of semiconductor devices as switches is highly efficient and robust but adds complexity to the power system. FACTS thyristor-based devices have low losses because they operate at low frequency. On the other hand, voltage source converters (VSC) are less efficient and more complex than thysistor-based devices but offer additional capabilities such as controlling the voltage in magnitude and phase due to the PWM action [7]. These are known as second-generation devices and are GTO-based. However, most FACTS controllers in use are thyristor-based because they can be used at high voltage levels and are available at high power ratings [6].

Reactive power compensation and voltage control are achieved with shunt devices, whereas series devices are used to compensate reactive power, improve stability and power flow. At high voltage levels the most commonly used devices are the STATCOM and the UPFC. At low voltage level (distribution level), the D-STATCOM, dynamic voltage restorer (DVR), harmonic filter, and power factor corrector (PFC) are most commonly implemented [6].

Although FACTS offer many advantages on transmission systems, their growth has been reduced because new concepts have emerged, such as using distributed generation or microgrids to control power quality and power flow [6, 10]. Table 1 shows the number of FACTS devices installed around the word and their estimated total installed power in 2006 [6].

Table 1. Estimated installed FACTS.

TYPE	NUMBER	TOTAL INSTALLED (MVA)
SVC	600	90.000
STATCOM	15	1.200
SERIES COMPENSATION	700	350.000
TCSC	10	2.000
UPFC[1]	2-3	250

However, companies like SIEMENS, ABB, and KEPCO among others are still building and implementing FACTS devices as an alternative to enhance the capacity and reliability of transmission systems. At the same time, a variety of environmental regulations that restrict the expansion of electric power transmission facilities in the United States and right-of-way problems could increase FACTS implementations by using them delay new transmission line construction [8].

[1] Although UPFC has better performance on power systems than others, this topology is rarely used due to its complex topology [6, 9]

The proposed method does not focus on the mathematical model of the UPFC but instead contemplates the control strategy necessary to increase the power system rating.

Fuzzy logic controllers have presented their advantages over other methodologies to improve the performance of UPFC [18]. In this case the Mandani fuzzy logic controller is used to operate over the SSSC and compensate both voltage and power at a certain bus.

2. THE UPFC

The Unified Power Flow Controller (UPFC)[2] is one of the most versatile and complex power electronics-based equipment used for the control and optimization of power flow in transmission systems [8]. This is because it offers advantages in terms of static and dynamic operation of the power system. As shown in figure 2, this device consists of two fully controlled converters, shunt and series, which share a common dc-link [10, 11]. The converters control the voltage as well as the power in the transmission line.

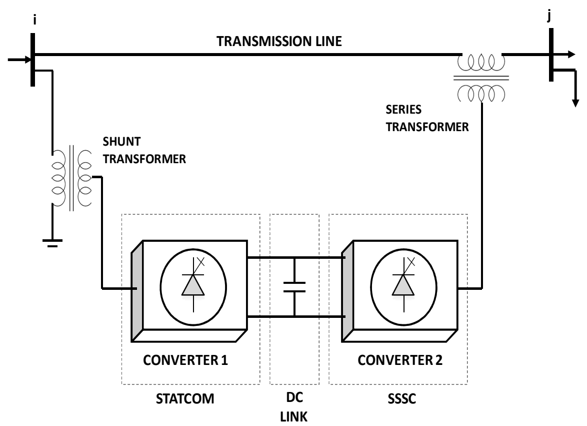

Figure 2. UPFC structure [16].

Converter 1 acts as a rectifier and is the shunt part which supplies or absorbs (bidirectional power flow) the active power required by the series controller at the dc link. Converter 2 acts as an inverter and is the series part. This inverter can operate in different ways but its main function is to inject ac series voltage into the line [6, 10, 11]. Real and reactive power flow on the transmission line are controlled by adjusting the magnitude of the series injected voltage and its phase angle. A UPFC can be represented as a combination between a STATCOM and a SSSC linked by a dc current source that allows active power flow between them.

The dc-link capacitor provides dc voltage support for the converters operation and works as an energy storage device. The active power flows from each bus through

[2] In the United States, American Electric Power installed the first UPFC unit in June 1998 at their Inez Substation in eastern Kentucky. This FACTS unit was a 160 MVA [8]

the UPFC dc-link. The reactive power is absorbed or generated by the UPFC converters.

3. POWER ELECTRONICS

Power electronics have changed the way in which power electric systems are analyzed. The application of semiconductor devices makes possible power flow control on transmission systems in an efficient way. They can be classified according to the manner they are controlled [7, 14]:

Uncontrolled: Diodes.

Semi-controlled: Thyristor or Silicon-Controlled Rectifier (SCR), TRIAC.

Fully-controlled: Gate Turn-off Thyristor (GTO), Bipolar Junction Transistor (BJT), Power MOSFET, Static Induction Transistor (SIT), Insulate Gate Bipolar Transistor (IGBT), Integrated Gate-Commutated Thyristor (IGCT).

Thyristor: These are triggered with a pulse at the gate. The on-stage is remained until the next current zero-crossing is reached. Because only one switching per half-cycle is possible, there is a controllability constraint. This semiconductor is can be implemented in high voltage-high power application since has a voltage operation range of 15kV up to 300kV and a power range from 100MVA to 1000MVA [6]. Thyristors have low losses during the on-stage.

GTO: These are a variation of thyristors and have been developed to increase controllability. GTOs can be turned off by applying a negative voltage to the gate.
IGCT: These have low switching losses. They are more common in small FACTS devices. They are available with voltage ratings from 2.3kV up to 15kV and power ratings from 5MVA to 100MVA [6].
IGBT: These can be switched on with positive voltage and off with zero or negative voltage. This approach simplifies gate driver design. Nowadays, IGBT capabilities cover the whole range of power system applications from 10MVA to 100MVA and from 7.2kV to 300kV.

4. SIMULATED SYSTEM

As was stated before, a UPFC is used to insert a controlled voltage (magnitude and angle) into the line. The two voltage source converters are connected by a common dc-bus [12, 13] and coupling transformers are used to connect the converters to the system. Because UPFC compensators are versatile and flexible, they can be operated in different modes [9]. In this case a Direct Voltage Injection Mode[3] is achieved and the main scope of this report involves the design of a three-phase UPFC using Matlab and Simulink™ software [15]. This has the capacity of simulating power semiconductors for a wide variety of topologies [13]. Figure 2 shows the UPFC used for the simulation. The system parameters are presented in Table 2.

Table 2. System main parameters.

Line to line voltage node i	25kV
Frequency	50Hz
Transmission rating	30MVA
DC link capacitor	4000μF
DC link voltage	5600V
Resistance of the line	0.01273Ohms/km
Inductance of the line	0.9337mH/km
Capacitance of the line	12.74pF/km
Shunt transformer rating	50kVA, 25kV/4kV
Series transformer rating	50kVA, 2kV/2kV
Load 1	670kVA
Load 2	1020kVA
Load 3	1020kVA
Solver algorithm	Discrete fixed-step

4.1 SHUNT COMPENSATOR

The shunt converter implemented is a universal three-phase power converter which has full-bridge rectifiers (See Figure 3). The types of power switch used are diodes (naturally commutated) and there is not a necessity for a voltage controller. It is desired set up the dc-link voltage Vd at 5600V dc. Thus the input voltage V_{LL} of the rectifier should be [2]:

$$Vd = 1.35 \cdot Vll$$

$$(V_{LL})_{RMS} = 4148\ V.$$

Hence, the inverter ac side is connected in parallel with the source (at bus i) through a 50kVA, 25kV/4000V three-phase transformer.

4.2 SERIES COMPENSATOR

[3] In this case the series inverter generated the voltage vector with phase as per the reference [9]

The most important component for this compensator is a universal three-phase PWM force-commutated voltage source inverter. This consists of up to six power switches connected in a bridge configuration [16] as is shown in Figure 3 (the number indicates the turn-on order). It has six IGBT switches Q1-Q6, and six anti-parallel diodes.
The size of the capacitor is sufficiently large to guarantee a stiff dc voltage source for the inverter. Its initial voltage is 5600V.

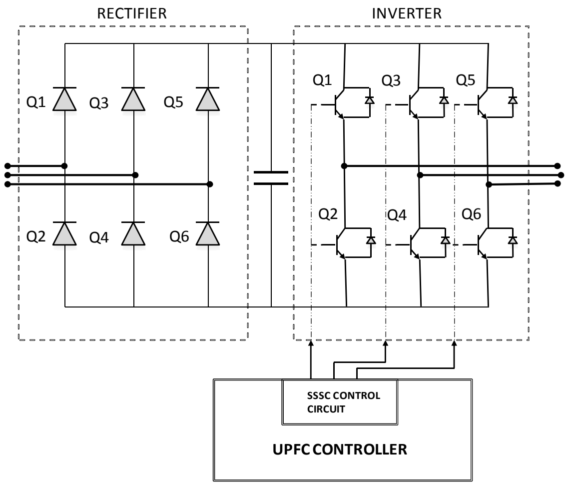

Figure 3. Shunt and series converter for the UPFC.

For a three-phase six-switch converter the PWM technique uses the PWM generator block available in [15]. The block uses three reference (sinusoidal) signals phase shifted by 120° at the fundamental frequency and one carrier signal (triangular) at a higher frequency.
Comparing the reference signals and the carrier signal generates square-wave signals which are used to trigger the six IGBT switches. These signals are shown in Figure 5. The rms value of the line-to-line voltage including all harmonics is:

$$(V_{LL})_{RMS} = 0.81 \cdot Vd$$

$$(V_{LL})_{RMS} = 4536V.$$

Similarly, the rms value of the fundamental component is:

$$(V_{LL1})_{RMS} = 0.78 \cdot Vd$$

$$(V_{LL1})_{RMS} = 4368V.$$

Figure 4 shows the control signals for three of the six switches.

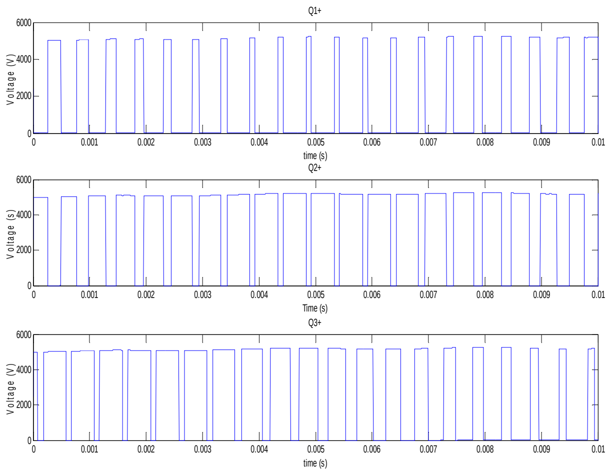

Figure 4. Signals to drive IGBTs Q1, Q2 and Q3.

The PWM modulation ratio is used to control the amplitude of the fundamental component of the output voltage. In steady state it is desired to inject 2900Vrms to the transmission line in node j in order to compensate for voltage drop. The modulation ratio is selected as 0.65, so

$$M_A = \frac{\widehat{A_s}}{\widehat{A_c}} = \frac{2000}{4400}$$

$$M_A = 0.66.$$

Where $\widehat{A_s}$ is the amplitude of the sinusoidal signal and $\widehat{A_c}$ is the amplitude of the triangular signal. The carrier signal has a frequency of 2000Hz. Due to the square-wave generated by the converter, the output voltage waveform is rich in harmonics. Consequently, a LC filter is implemented in order to mitigate high order frequencies.

4.3 FUZZY CONTROLLER

In general, the controller is formed by rules based on "*if x and y then z*". Each rule has a membership function which is part of the function of the fuzzy logic controller. The more membership functions there are, the more sensitive the UPFC is in regards to compensating both voltage and power requirements [17].

For this case, the inputs of the fuzzy system are 5 membership functions and 25 rules. The voltage at the bus i is sensed and compared with the voltage reference. The error is then calculated as the difference between these two voltages and is transformed to linguistic variables: Large Negative (LN), Small Negative (SN), Very Small (VS), Small positive (SP) and Large Positive (LP).

In the fuzzyfication process the output is achieved using Takagy-Sugeno inference (which is optimized by comparing its output with the objective output data) [18]. The linguistic variables are named: Positive Big (PB), Positive Medium (PM), Positive Small (PS) and Zero (Z).

In the defuzzyfication process the fuzzy set is converted to real control signals. These signals are used to change both the carrier signal frequency and PWM modulation index.

5. SIMULATIONS

The results of the simulations are presented in the following figures.

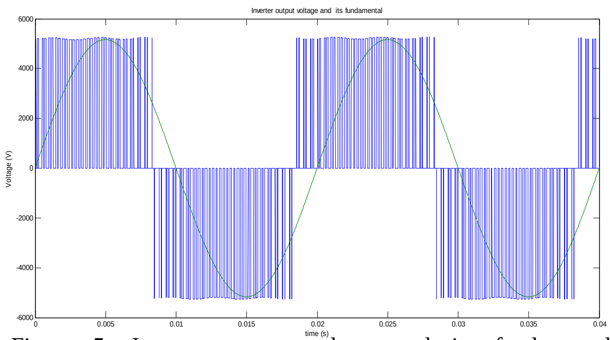

Figure 5. Inverter output voltage and its fundamental component (50Hz).

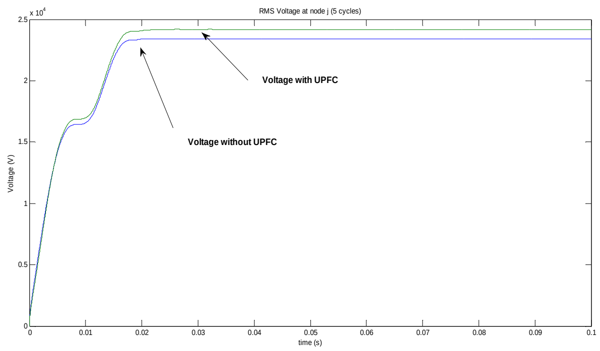

Figure 6. Voltage at reference node (j) with and without UPFC.

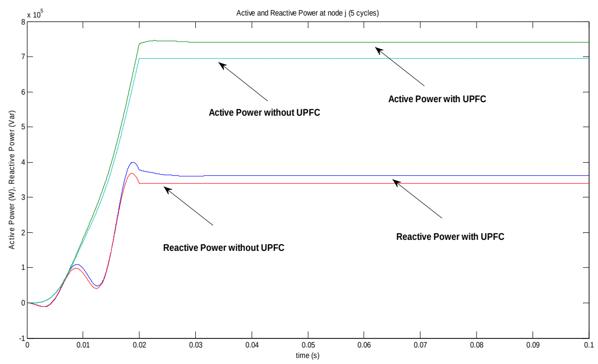

Figure 7. Active and reactive power flow at reference node (j) with and without UPFC.

6. CONCLUSIONS

The switching power conversion using semiconductor devices is highly efficient. However, due to the nonlinearity of switches, harmonics are generated and can be injected at the source and load side. This can be mitigated using filters.

The UPFC provides all functions that a SVC can offer. High modulation frequencies allow low harmonics in the output signal. However, increasing switching frequency increases the losses as well.

Although FACTS increase the reliability and capacity of ac grids improving the efficiency power transmission systems, its growing have been delayed because of attention to distributed generation (DG).

In order to improve the behavior of the STATCOM and the SSSC, a control circuit could be implemented. The idea with this controller is to generate the required modulation index to operate the converters. The advantage is that the UPFC can operate in a dynamic way.

In conclusion, the fuzzy logic controller operates as is expected and helps to compensate both voltage and power at the selected bus.

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