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# Improving the power system performance using FACTS devices

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***Abstract:*** *This paper presents the performances of the three types of FACTS devices in controlling voltage, improve the voltage profile and reduce the power losses in transmission power system. Simulations were performed on the test network called TEST 2 using the Matlab software and Neplan package. The result shows that adding the FACTS devices to the power system led to improve the voltage level to the desired value and decrease the real power losses.*

***Keywords:*** *Flexible AC Transmission System (FACTS), Static VAr Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Unified power flow controller (UPFC), voltage profile, power losses.*

## I. Introduction

Increased demands on transmission, absence of long-term planning and the need to provide open access to generating companies and customers have created tendencies toward less security and reduced quality of supply. The FACTS technology is essential to alleviate these difficulties. The FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of the present, as well as new and upgraded, lines. The possibility that current and therefore power through a line can be controlled enables a large potential of increasing the capacity of existing lines. These opportunities arise through the ability of FACTS controllers. To control the interrelated parameters that govern the operation of transmission systems, including series impedance, shunt impedance, current, voltage, phase angle and the damping of oscillations [1].

The basic idea of FACTs is installing the power electronic devices at the high-voltage side of the power grid to make the whole system electronically controllable. The advances achieved in high power semiconductor devices and control technology make the foundation of the development of FACTs. The FACTs devices are able to provide active and. Reactive power to the power grid rapidly. The power compensation achieved by FACTs devices could adjust the voltage of the whole system and the power flow could be satisfactorily controlled.

## II. Classification of FACTS devices

FACTS devices can be traditionally classified according to their connection, as [2]:

- Shunt Compensators
- Series Compensators
- Combined Compensators

### 2.1 Shunt Compensator

Shunt compensation is used to influence the natural electrical characteristics of the transmission line to increase the steady-state transmittable power and to control the voltage profile along the line. As static shunt compensators are known Static VAr Compensators (SVC) and Static Synchronous Compensators (STATCOM). In our work we use Static VAr Compensator (SVC) [3] .

#### 2.1.1 Modelling of SVC device in steady-state

The SVC is modeled by a shunt variable admittance and can be placed either at the terminal bus of a transmission line or in the middle of a long line. SVC is basically a shunt connected static VAr generator that can exchange capacitive or inductive current with the power system so as to maintain or control specific power variables; typically, the control variable is the system bus voltage.

SVC is a shunt devices that consists typically of one thyristors controlled reactor and several thyristor switched capacitors. Filters should be also considered because they can produce reactive power. The simplified one line diagram of an SVC is presented in Figure 1.

The capacitors can be switched ON or OFF only, whereas the current through the reactors can be varied from zero to the rated current. Depending on the demand for reactive current/power, there can be a large number combinations between the reactor and the capacitors. When inductive reactive power is demanded in order to decrease the bus voltage, the capacitors are switched off, while the current through the thyristors is varied to achieve the exact reactive power to be absorbed. When capacitive power is required to increase the bus voltage, the necessary number of capacitors are switched on, and the surplus of reactive power is absorb by the reactor.

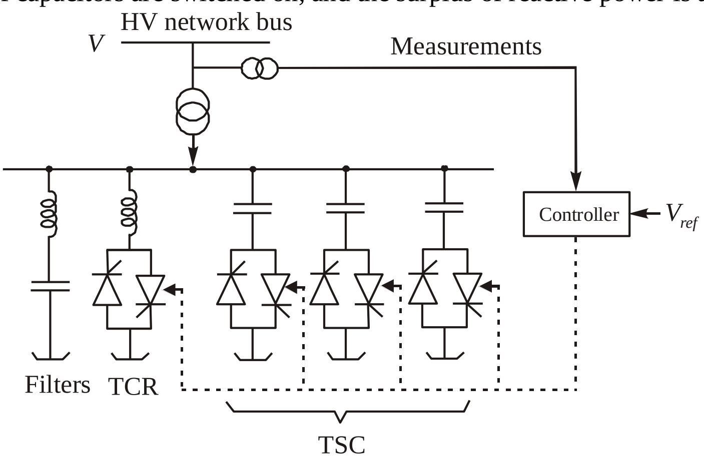


**Fig.1** Static VAr Compensator (SVC).

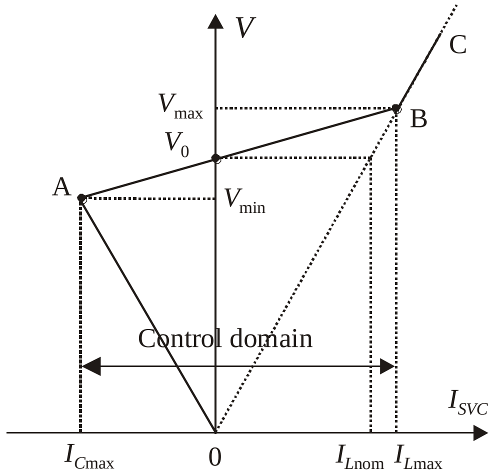


**Fig.2** Steady State V-I characteristics.

The steady-state operating domain of the SVC can be split into three sub-domains:

i) The *linear control* domain, in which the voltage control system is provided with appropriate reactive power resources, and the set-point can be defined anywhere on the AB characteristic. This domain is bounded by the reactive current $Q_{C\max}$, supplied by the capacitors, and by the reactive current $Q_{L\max}$ absorbed by the reactor, that is

$$Q_{C\max} \leq Q \leq Q_{L\max}$$

In practice, a SVC uses droop control of the voltage at the regulated bus, with a slope of about 5%. The droop control means that the voltage at the regulated bus is controlled within a certain interval [$V_{\min}$, $V_{\max}$], instead of a constant voltage value $V_{ref}$.

ii) The high voltages domain (BC), resulted from the limitation in the inductive reactive power, i.e. $Q > Q_{L\max}$. The SVC is, in this case, is out of the control area and it behaves like a fixed inductive susceptance.

iii) The low voltages domain (OA), resulted from the limitation in the capacitive reactive power, i.e. $Q < Q_{C\max}$. The SVC is, in this case, is out of the control area and it behaves like a fixed capacitive susceptance.

The typical steady-state control law of a SVC used here is depicted in Figure.2, and may be represented by the following voltage-current characteristic [4]:

$$V_k = V_{ref} + X_{SL} \cdot I_{SVC} \quad (1)$$

Where $V_k$ and $I_{SVC}$ stand for controlling bus voltage and SVC current

### 2.1.2 Series compensation

The variable series compensation is highly effective in both controlling power flow in the line and in improving stability. With series compensation the overall effective series transmission impedance from the sending end of the receiving end can be arbitrarily decreased thereby influencing the power flow There are many types of Series Compensator in our work we use the Thyristor-Controlled Series Capacitor (TCSC) [5].

### 2.2. Thyristor-controlled series capacitor (TCSC)

Thyristor-controlled series capacitors (TCSC) is a type of series compensator, can provide many benefits for a power system, including controlling power flow in the line, damping power oscillations, and mitigating subsynchronous resonance. The TCSC is a capacitive reactance compensator consisting of a series capacitor bank shunted by a Thyristor-Controlled Reactor (TCR) in order to provide a continuously variable series capacitive reactance. It can play various roles in the operation and control of power systems, such as scheduling power flow, damping of power oscillations, decreasing unsymmetrical components, providing voltage support, limiting, short-circuit currents, mitigating sub-synchronous resonance (SSR) and enhancing transient stability [6].

### 2.2.1 Operation of Thyristor- controlled series capacitor (TCSC)

The basic operation of TCSC can be easily explained from circuit analysis. It consists of a series compensating capacitor shunted by a Thyristor controlled reactor (TCR). TCR is a variable inductive reactor XL shown in figure .3, controlled by firing angle α . Here variation of XL with respect to α is given by ;

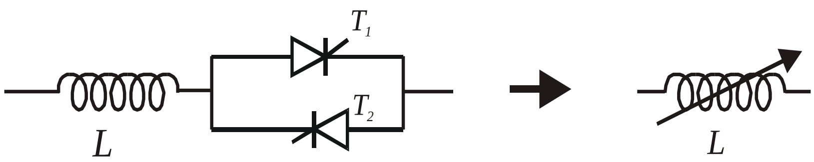


**Fig. 3** equivalent circuit of TCR

For the range of 0 to $90^0$ of α, $X_L$ (α) start vary from actual reactance $X_L$ to infinity. This controlled reactor is connected across the series capacitor, so that the variable capacitive reactance shown in figure .4 is possible across the TCSC to modify the transmission line impedance . Effective TCSC reactance $X_{TCSC}$ with respect to firing angle alpha (α) is [7],[ 8].

$$X_{TCSC}(\alpha) = -X_C + C1[2(\pi-\alpha)+\sin 2(\pi-\alpha)] - C2[\cos^2(\pi-\alpha)\overline{W}\tan\{\overline{W}(\pi-\alpha)\}] - \tan(\pi-\alpha) \quad (2)$$

where,

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}, \qquad C1 = \frac{X_C + X_L}{\pi}, \qquad C2 = X^2 LC / \pi X_L, \qquad \overline{W} = \sqrt{X_C / X_L}$$

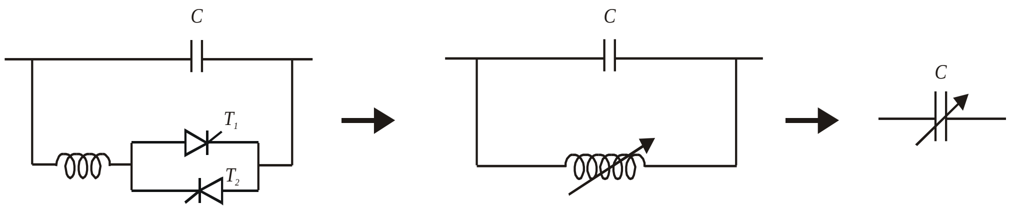


**Fig. 4** equivalent circit of a TCSC

### 2.2.2 Modeling of Thyristor-controlled series capacitor (TCSC)

The model of a transmission line with a TCSC installed between buses *I* and *j* is shown in figure 5. In steady state, the TCSC can be considered as additional reactance ( $-jx_c$ ). The real and reactive power flow from bus-*i* to bus-*j* and from bus-*j* to bus-*i* of the line having TCSC can be given by:

$$P_{ij} = V_i^2 G_{ij} - V_i V_j / (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \quad (3)$$

$$Q_{ij} = V_i^2 (B_{ij} + B_{sh}) - V_i V_j / (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \quad (4)$$

$$P_{ji} = V_i^2 G_{ij} - V_i V_j / (G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}) \quad (5)$$

$$Q_{iji} = V_j^2 (B_{ij} + B_{sh}) - V_i V_j /(G_{ij} \sin\delta_{ij} + B_{ij} \cos\delta_{ij}) \quad (6)$$

Where , $\delta_{ij} = \delta_i - \delta_j$ , $G_{ij} = \frac{r_{ij}}{r_{ij}^2 + (X_{ij} - X_C)^2}$ and $B_{ij} = \frac{-(X_{ij} - X_C)}{r_{ij}^2 + (X_{ij} - X_C)^2}$

The active and reactive power loss in the line with TCSC device can be expressed as:

$$P_L = P_{ij} + P_{ji} = G_{ij} (V_i^2 + V_j^2) - 2V_i V_j G_{ij} \cos\delta_{ij} \quad (7)$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2)(B_{ij} + B_{sh}) + 2V_i V_j B_{ij} \cos\delta_{ij} \quad (8)$$

The line flow change due to series capacitance can be represented as a line without series capacitance with additional injected power at receiving and sending ends as shown in figure 6. The real power injections at buses iand j can be written as follows,

$$P_i^C = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}) \quad (9)$$

$$P_i^C = V_j^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos\delta_{ij} - \Delta B_{ij} \sin\delta_{ij}) \quad (10)$$

Where , $\Delta G_{ij} = \frac{X_C r_{ij} (X_C - 2X_{ij})}{(r_{ij}^2 + X_{ij}^2)(r_{ij}^2 + (X_{ij} - X_C)^2)}$ and $\Delta B_{ij} = \frac{-X_C (r_{ij}^2 X_C - 2X_{ij}^2 + X_C X_{ij})}{(r_{ij}^2 + X_{ij}^2)(r_{ij}^2 + (X_{ij} - X_C)^2)}$

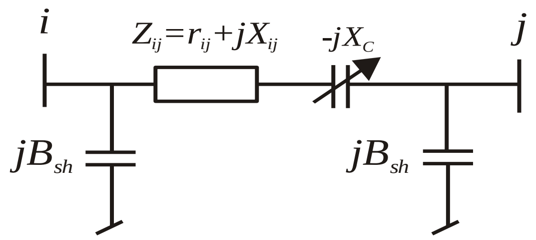


Fig.5. model with transmission line with TCSC

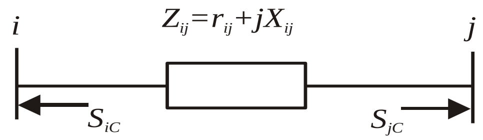


Fig.6. Injection model of TCSC

### 2.2.3 Combined compensators

The combined shunt and series devices have the big advantage of being able to simultaneously use the features of shunt and series devices. They are able to improve reactive power compensation and voltage control like the shunt devices.

Among combined controllers, a key function of UPFC is voltage regulation with continuously variable in-phase/anti-phase voltage injection**.**

### 2.2.4 Unified power flow controller (UPFC)

A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common DC link, to allow bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent active and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the active and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.

Figure.7 shows that there are two transformers that is shunted & series transformer & both the transformers are connected by two Gate-Turn-Off (GTO) converters and a DC circuit having a capacitor. The common DC link between both the converter works as a channel for the flow of power. The shunt converter is primarily used to provide the real power demand of the series converter via a common DC link terminal of the AC power system. Shunt converter can also generate and absorb reactive power at its AC terminal. Therefore with proper control it can also act as an independent advanced static VAR compensator providing reactive power compensation for the line and thus executing indirect voltage regulation at the input terminal of the UPFC. A series converter is used to generate voltage source at fundamental frequency with variable amplitude and phase angle, which are added to the AC transmission line by series connected boosting transformer. The converter output voltage, injected in series with the line, can be used for direct voltage control, series compensation, phase shifter and their combinations. This voltage source can internally generate or absorb all the reactive power required by different type of controls applied and transfers active power at its DC terminal [9],[10].

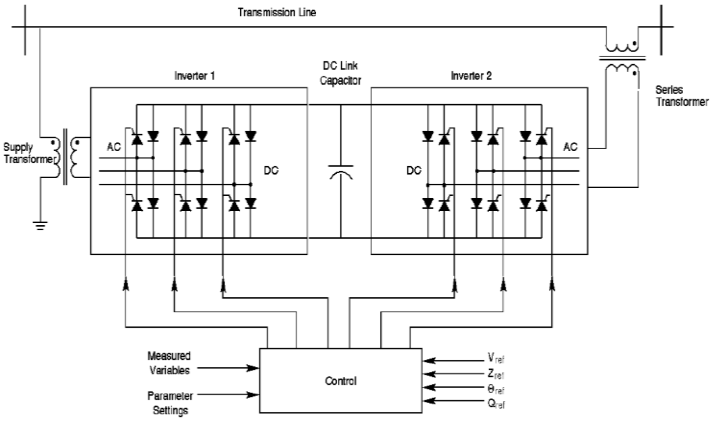


**Fig.7** Implementation of a UPFC.

### 2.2.1. Characteristics and operation Modes of UPFC

In the power system there are many major issues where the capability & utilization of FACTS are noticed. These issues are power system stability loss, Line outage, cascading, line tripping, and congestion. Representative of the last generation of FACTS devices is the Unified Power Flow Controller (UPFC). The UPFC can control simultaneously all three parameters of line power flow -line impedance, voltage and phase angle. Such "new" FACTS device combines the features of two "old" FACTS devices: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC). These two devices are two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer. Both the converters are connected to each other by a common DC link including a storage capacitor. Shunt inverter is used to balance the real power flow exchanged between the series inverter and the transmission line and for voltage regulation at the point of connection injecting an appropriate reactive power flow into the line. Series inverter is used to control the real and reactive line power flow inserting an appropriate voltage with controllable magnitude and phase in series with the transmission line. Thus, UPFC accomplishes the functions of active and reactive series compensation, reactive shunt compensation, and phase shifting. Instead of these functions, UPFC allows a secondary but important function such as stability control to suppress power system oscillations for improving the transient stability of the power system. Because of changes in the future electricity market scenario, there is a need for flexible and fast power flow controllers, such as the UPFC. To investigate the impact of UPFC on the performance of the power system, there is a corresponding need for reliable and realistic models of these controllers.

With the presence of the two converters, UPFC not only can supply reactive power but also active power. The equation for the Active and Reactive power is given as follows [11].

$$P_{12} = \frac{V_1 V_2}{X_{12}} \sin\delta \tag{11}$$

$$Q_{12} = \frac{V_1 V_2}{X_{12}} (1 + \cos\delta) \tag{12}$$

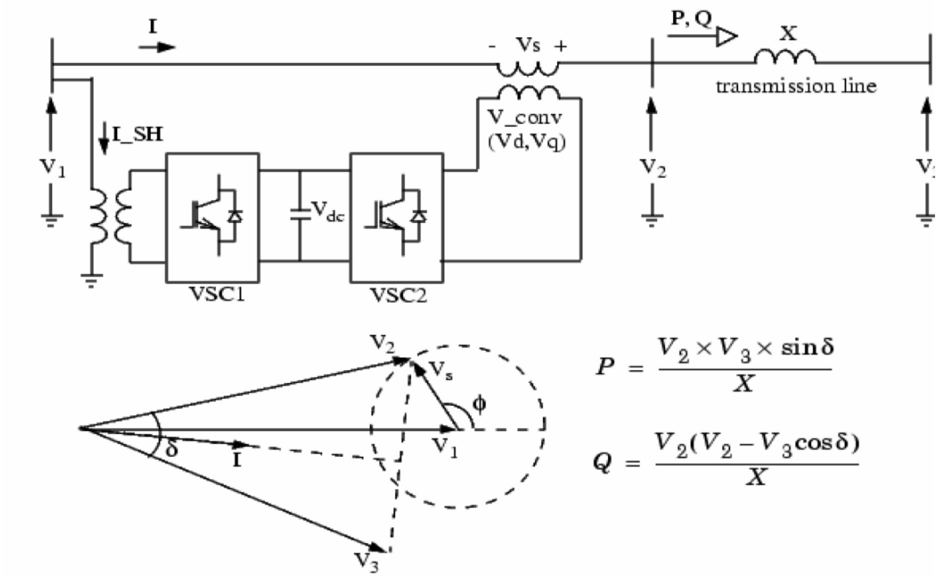


**Fig.8** Single line diagram of UPFC and Phasor diagram voltage and current

## III. Case studies

The case study is performed on the (TEST 2 network), which consists of 13 buses, 15 transmission lines (single and double circuit), 8 loads and 5 generating units. The slack bus is associated to bus 12, The one line diagram of the studied network is shown in Figure 9.

The total active power generation is 1291 MW, and the total active power load is 1265 MW. The network nominal voltage is 220 kV Figure.7, illustrates the one-line diagram of the test network.

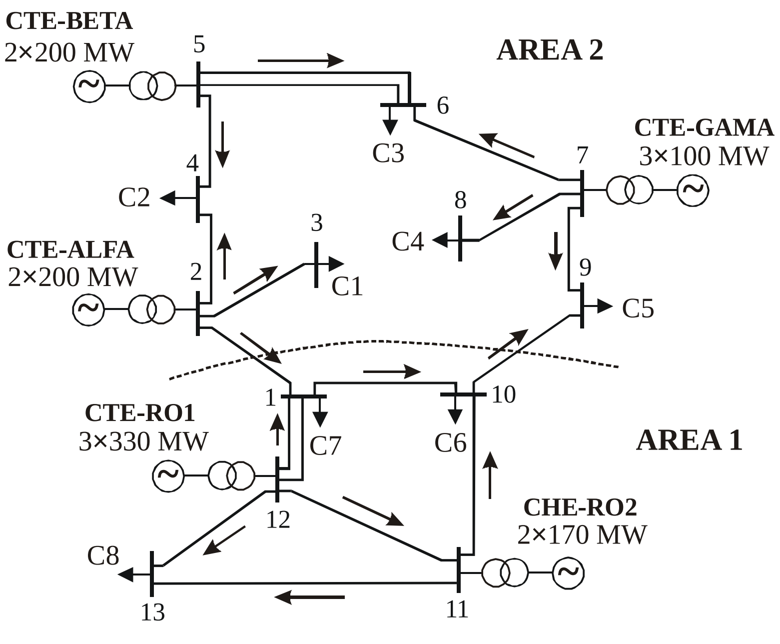


**Fig.9.**One line Diagram of the TEST 2 network.

### 3.1 Load flow calculation

Test system was performed using Newton-Raphson method based algorithm implemented in Matlab.

The active power losses ΔP = 26.187 MW. The load flow results shows that the voltage at bus No. 10 is less than the admissible limits (±5%).

**Table.2. Load flow calculation to the base case**

| BUS No. | Type | Voltage Amplitude (kV) | Voltage Angle (degree) | Generation | | Load | |
|---|---|---|---|---|---|---|---|
| | | | | MW | MVAr | MW | MVAr |
| 1 | PQ | 212.506 | -7.76 | 0.0 | 0.0 | 250 | 155 |
| 2 | PV | 230 | -3.05 | 255 | 121.53 | 0.0 | 0.0 |
| 3 | PQ | 224.2 | -5.03 | 0.0 | 0.0 | 60 | 35 |
| 4 | PQ | 216.11 | -8.71 | 0.0 | 0.0 | 190 | 130 |
| 5 | PV | 226.09 | -6.96 | 240 | 153.53 | 0.0 | 0.0 |
| 6 | PQ | 215.825 | -10.64 | 0.0 | 0.0 | 220 | 135 |
| 7 | PV | 224.99 | -8.32 | 240 | 168.4 | 0.0 | 0.0 |
| 8 | PQ | 219.59 | .3 -10 | 0.0 | 0.0 | 65 | 35 |
| 9 | PQ | 211.98 | -11.22 | 0.0 | 0.0 | 135 | 70 |
| 10 | PQ | 207.52 | -10.12 | 0.0 | 0.0 | 200 | 140 |
| 11 | PV | 223 | -1.37 | 165 | 116.02 | 0.0 | 0.0 |
| 12 | Slack | 235 | 0 | 396.181 | 172.9 | 0.0 | 0.0 |
| 13 | PQ | 226.25 | -3.11 | 0.0 | 0.0 | 150 | 90 |
| **Total** | | | | **1290.8** | **731.28** | **1265** | **790** |

Three types of FACTS devices (SVC, TCSC, UPFC) was used in this work to control the voltage in the buses, improve the system stability and decrease active power losses ΔP.

### 3.2 Adding the SVC in bus No. 10 for voltage control .

The capacitive reactive power of the SVC is set to 200 MVAr. Since the voltage is lower than the nominal value, the reactive power installed in the reactor is set to a value that allow the SVC to counterbalance the amount in excess of the capacitive reactive power, thus to 50 MVAr.

Figure10, represent the voltage profile in the base case and in case with SVC device and Figure11, represent the active power losses in the base case and in case with SVC device.

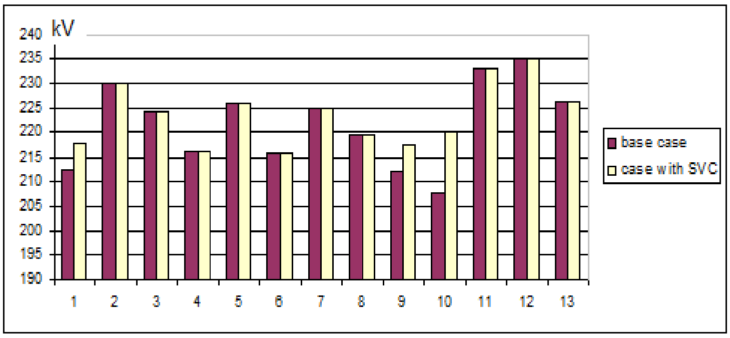


**Fig.10** Voltage profile in the base case and in case with SVC.

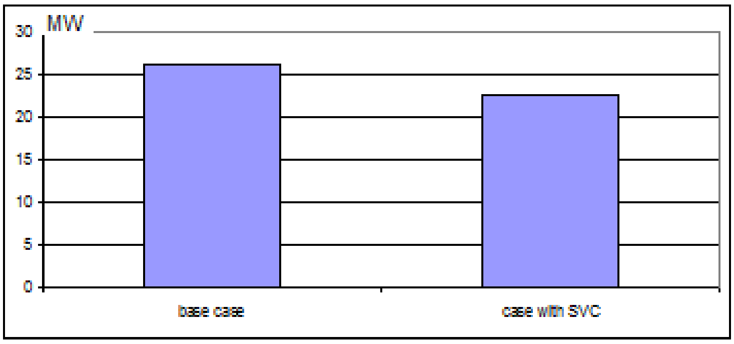


**Fig.11** Active power losses in the base case and in case with SVC.

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### 3.3 Adding the TCSC in the line 1-10 for Active Power control

The simulation shown that the value of $P_{set}$ that makes the system working conversion is (-52 to 245) MW. Figure12 represents the voltage profile in the base case and in case with TCSC device and Figure13 represent the active power losses in the base case and in case with TCSC device.

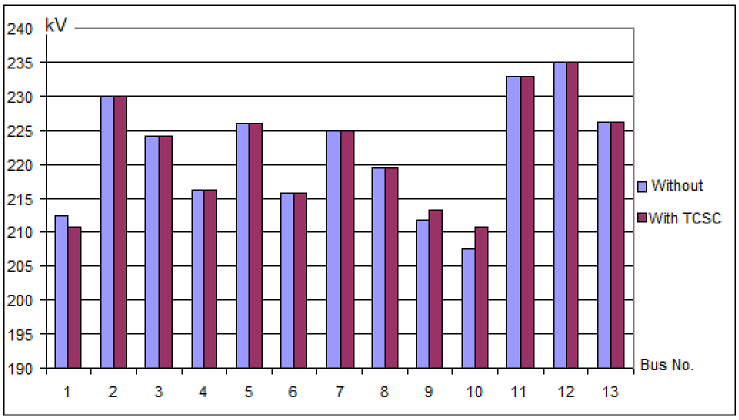


**Fig.12** Voltage profile in the base case and in case with TCSC.

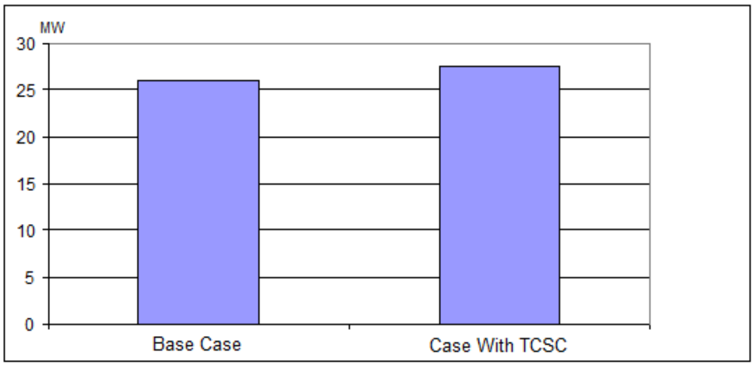


**Fig.13** Active power losses in the base case and in case with TCSC.

### 3.4 Adding theUPFC in the line 1-10 for Network control

The simulation shown that the value for line flow regulation that makes the system working conversion is ( P = -60MW , Q = -30 MVAr).

Figure 14 represents the voltage profile in the base case and in case with UPFC device and Figure15 represent the active power losses in the base case and in case with UPFC device.

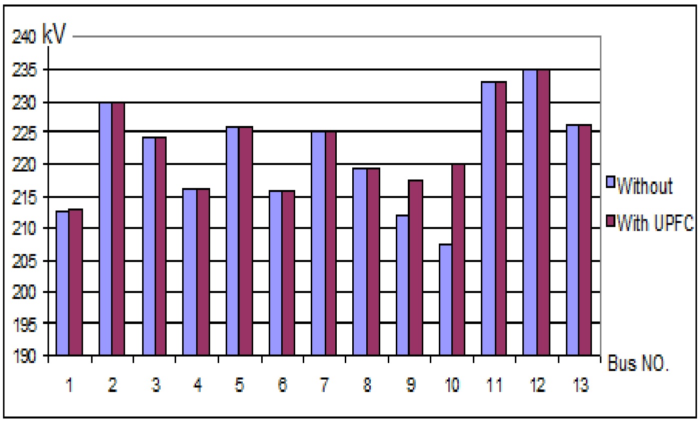


**Fig. 14** Voltage profile in the base case and in case With UPFC.

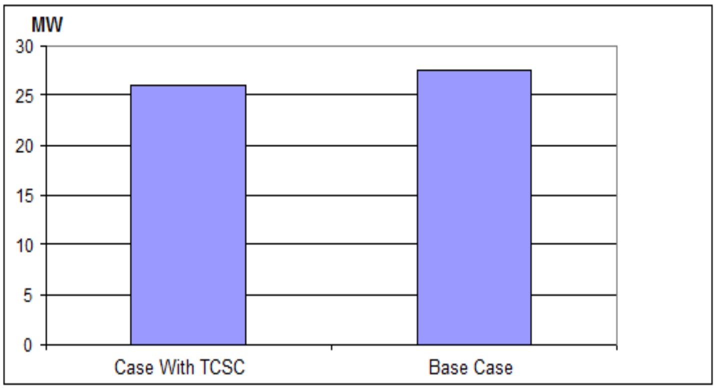


**Fig.15** Active power losses in the base case and in case with UPFC.

## IV. Conclusion

The simulations have revealed that:

- Adding the SVC device to the network leads to increase the voltage in Bus **10** to the desired value, improve the voltage profile and decrease the active power losses ΔP, because when we inject the reactive power the reactive current component from the source is reduced there for the active power losses in the line is reduced.

- Adding the TCSC device to the network leads to increase the voltage in Bus **10**, active power losses ΔP also increase, because the active power flow on the line and the direction of power is different depends on the value of the power that we control it.

- Adding the UPFC caused to increase the voltage Bus **10** to the desired value, improve the voltage profile and decrease the active power losses ΔP, because the UPFC is a complex device which is able to control several parameter (voltage, active and reactive power).

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