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# TECHNIQUES OF CONTROL OF THE TRANSIT OF POWER BY FACTS-SERIES DEVICES

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**ABSTRACT**
Being given the increasing difficulties of realization of new electrical equipment to satisfy the large demand of energy, the specialists turned to the optimisation of the existing electrical equipments. The power electronics devices take part efficiently taking advantage of the enormous progress made in their control devices and their capabilities of energy transfer. This article is precisely based on the study of the control of the transit of power using FACTS-Series devices (TCSC, SSSC and UPFC). It shows the capacity of these devices to increase the power transit of the existing equipment, and in the same time improving the margins of exploitation without reaching the stability limit of the networks and this, by using equipment having an impact minimum on the environment, more rapids to be implemented and less expensive. All these proprieties of FACTS devices were analysed by digital simulations on simple circuits with a line, two lines then on a wider network.

**KEY WORDS**
FACTS-Series, SSSC, TCSC, UPFC, control, energy transit

## 1. Introduction

The concept of the flexible systems for energy system transport in AC current FACTS (Flexible Alternative Current Transmission System) is based on the technology of power electronics devices intended to reinforce the safety, the capability of transit and the flexibility of the net systems of energy.
FACTS solutions make it possible to the network operators to increase the power capacity of the existing equipment, by maintaining or by improving the essential trading margins to the network stability. One increases thus, the electric quantity of power conveyed until the centres of consumption with a minimum impact for the environment, with projects much faster to implement and capital expenditures reduced compared to the other solutions such as the construction of new lines of transport or new production equipments. The aim of this article is to show the contribution of FACTS-Series systems (TCSC, SSSC and UPFC), in the field of the power transits in the networks.

## 2. Concept of the control of the power transit in AC-current

### 2.1 Principle of the transfer of energy in AC [1]

If $\overline{A}$, $\overline{B}$, $\overline{C}$ and $\overline{D}$ are the linear parameters of a power line. They traduce the propagation of voltage and current waves in the line. They are given starting from the line characteristics. $\overline{V_S} = V_S \angle\theta_S$ , $\overline{V_R} = V_R \angle\theta_R$ are the potentials at its ends; the transported active and reactive powers by this line are expressed by :

$$\begin{cases} P_R = \dfrac{3V_R V_S}{B}\cos(\beta-\theta) - \dfrac{3AV_R^2}{B}\cos(\beta-\alpha) \\ Q_R = \dfrac{3V_R V_S}{B}\sin(\beta-\theta) - \dfrac{3AV_R^2}{B}\sin(\beta-\alpha) \end{cases} \quad (1)$$

$\theta=\theta_S-\theta_R$ ; α and β are respectively the phases of $\overline{A}$ and $\overline{B}$.
These two expressions show that the circulation of active power depends on phase shifting between the voltages at the ends of the line and the limit is reached for a phase shifting equal to the argument of the line impedance, which also corresponds to the static limit of stability (in normal exploitation, this phase shifting does not exceed 30 to 40°). In addition, the reactive power is related to the difference of the modules of the tensions at the ends. Moreover, they also show that the actions to undertake to adjust the transported active power are:
- Increase in the tension (for example by injection of reactive power);
- Reduction in the impedance of the line (by series compensation);
- Modification of the angle θ (by phase-converter of angle of load).

### 2.2 Study of the various methods of control of the power transit [1]

The apparent powers, by phase, at the two ends of a line are expressed by:

$$\overline{S}_S = \frac{V_S^2}{Z}e^{j\beta} - \frac{V_S V_R}{Z}e^{j(\beta+\theta)} = P_S + jQ_S \quad (2)$$

$$\bar{S}_R = \frac{V_S V_R}{Z} e^{j(\beta-\theta)} - \frac{V_R^2}{Z} e^{j\beta} = P_R + jQ_R \qquad (3)$$

The corresponding places in a complex plan P-Q can be represented by two circles centred respectively in:

$$\frac{V_S^{\ 2}}{Z} e^{j\beta} \text{ and } - \frac{V_R^{\ 2}}{Z} e^{j\beta} \text{ and radius } \frac{V_S\ V_R}{Z}.$$

Thus, one can conclude that:

- The modification of the impedance of the line involves the variation of the radius of the circles and the displacement of their centres;
- The insertion of a pure phase-converter, in series with the line, corresponds to a displacement of the point of operation on the dials graduated into $\theta$.
- The introduction of a source of tension series in quadrature with the current of line $\bar{V}_i = jKI$ (fig.1) makes it possible to modify the places as follows:

$$\bar{S}_S' = \bar{S}_S \frac{\bar{Z}^*}{\bar{Z}^* + jK} \text{ and } \bar{S}_R' = \bar{S}_R \frac{\bar{Z}^*}{\bar{Z}^* + jK} \qquad (4)$$

What gives circles passing by the origin and respectively the points $\bar{S}_S$ and $\bar{S}_R$. It is also seen that there is an action broader than a simple modification of impedance.

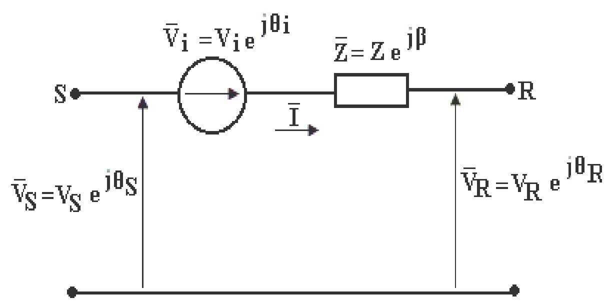


**Fig. 1:** Insertion of a series source of voltage

- Lastly, the concept of controller generalize with a source of arbitrary size and phase leads to interior fields with circles centred on $\bar{S}_S$ and $\bar{S}_R$ respectively:

$$\bar{S}_S' = \bar{S}_S + \frac{\bar{V}_S\ \dot{\bar{V}}_i^*}{\bar{Z}^*} \text{ and } \bar{S}_R' = \bar{S}_R + \frac{\bar{V}_R\ \bar{V}_i^*}{\bar{Z}^*} \qquad (5)$$

Also, the presence of two degrees of freedom increases the possibility of control.

If the impedance $\bar{Z}$ is purely inductive ($\bar{Z} = jX$) the active and reactive powers are expressed by the following relations:

$$\begin{cases} P_S' = P_S - \frac{V_S V_i}{X} \sin(\theta_S - \theta_i) \\ Q_S' = Q_S + \frac{V_S V_i}{X} \cos(\theta_S - \theta_i) \end{cases} \qquad (6)$$

$$\begin{cases} P_R' = P_R - \frac{V_R V_i}{X} \sin(\theta_R - \theta_i) \\ Q_R' = Q_R + \frac{V_R V_i}{X} \cos(\theta_R - \theta_i) \end{cases} \qquad (7)$$

**2.3 Concepts on the various techniques of compensation - Applications [2]**

**2.3.1 Ideal shunt compensator**

Figure 2 shows the model of a ideal shunt compensator connected to the point medium of a AC line with the source of tension $V_S$ controlled without interruption to control flows of power of this line.

The tensions $\bar{V}_S$ and $\bar{V}_R$ and are considered of the same amplitude and out of phase θ.

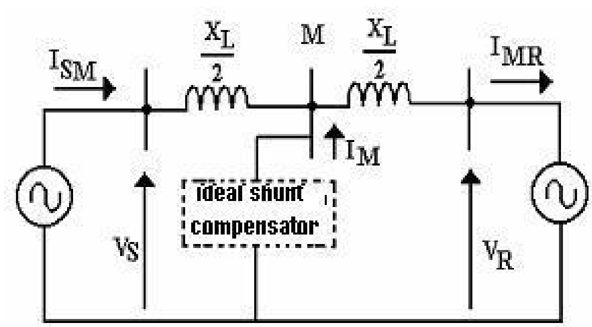


**Fig. 2 :** Shunt compensator connected to the medium of the line.

Figure 3 shows the vectorial diagram of the system for the case where the potential of compensation $\bar{V}_m$ has the same amplitude as those at the ends.

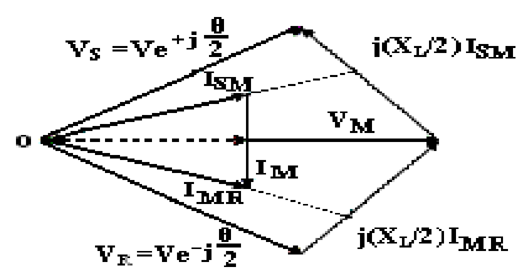


**Fig. 3:** Vectorial diagram of the considered system with the reactive power compensator.

If no compensation is envisaged, the transmitted power is given by the expression (9).

$$P_S = \frac{V^2}{X_L} \sin\theta \qquad (9)$$

By comparing the two preceding relations, one notes that the reactive shunt compensator increases the capability of active power transmission for the AC line, mainly, if $\theta$>30°. In addition, according to figure 3, one can conclude that with a current of compensation in quadrature with the tension $V_M$ only a reactive power flow is exchanged by the compensation source $V_M$ with the network.

### 2.3.2 Ideal series compensator

The figure 4 shows an ideal series compensator represented by a source of controlled voltage $V_C$ connected to the medium point of a short line of transmission. The current which circulates in the line is given by the following relation:

$$\overline{I_L} = \frac{\overline{V}_{SR} - \overline{V}_C}{jX_L} \tag{10}$$

where $\overline{V}_{SR} = V_S - V_R$

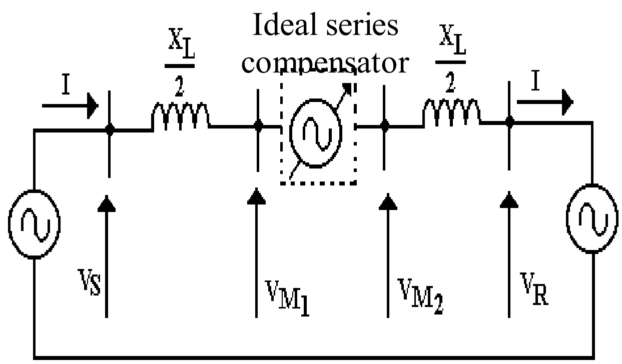


**Fig. 4:** Ideal series compensator connected to the medium point of a short line.

If the voltage $V_C$ is in quadrature with the current of line injected by this compensator, the power will be only reactive. Thus the source of voltage $V_C$ could be seen of its terminals like equivalent to a capacitive or inductive reactance. The active power flow in the line is given by relation (11).

$$P_S = \frac{V^2}{X_L(1-s)} \sin\theta \tag{11}$$

Where: $s = \frac{X_C}{X_L}$

$s$ is the parameter of serial compensation that must lie between 0 and 1 for the increase of the transmitted active power.

The Figure 5 shows the vectorial diagram of the system represented on figure 4. If one assumes that the source of voltage $V_C$ ensures the property of capacitive reactive power source, the current vector of line I has a lead 90° over the voltage vector $V_C$.

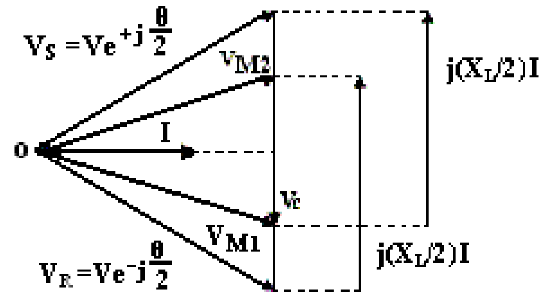


**Fig. 5:** Vectorial diagram of the considered system with a capacitive serial compensator.

### 2.3.3 Ideal phase-shifting compensator

Figure 6 shows an AC system with ideal compensator which makes it possible to shift the angle of load. This compensator controls the phase difference between the tensions of two AC systems " S and R " and can act thus directly on the flow of the exchanged active power between these two systems.

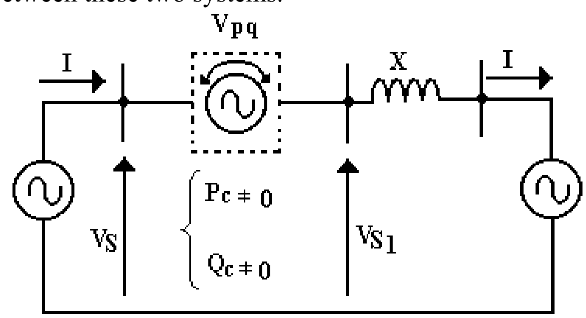


**Fig. 6:** Ideal compensator of the phase angle.

The figure 7 shows the vectorial diagram of an AC system with an ideal compensator of the angle of load. It indicates that the voltage vector $V_{pq}$ of the phase-shifting compensator can assume any imbalance in the relation of the current of line I and the mode of maximum operation of compensation which is described by a circle of radius equal to the voltage value $V_{pq}$. This means that this compensator can provide or absorb the active power as well as the reactive power; this one is a significant characteristic to take into account in the analysis of an angle compensator.

In the case of an operation of phase-shifting, the position of the vector $V_{pq}$ is more restricted as is shown in what follows. For this case of the phase equalizer, the transiting power in the transmission line (fig. 6) is given by the relation 12 where $\psi$ is the angle of the phase control.

$$P_{S1} = \frac{V^2}{X_L} \sin(\theta - \psi) \tag{12}$$

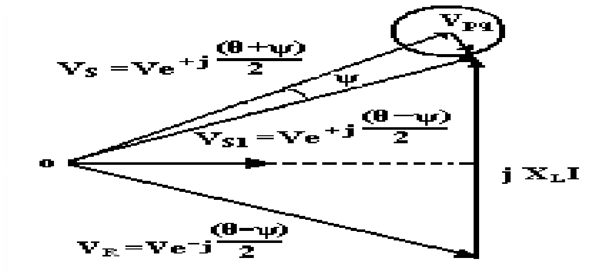


**Fig. 7**: Vectorial diagram of the considered system with an ideal series compensator of phase.

It is noted that more $(\theta - \psi)$ will be nearer to 90° the transmitted active power will be larger.

## 3. Simulation and results

The aim of the digital simulations carried out using software MATLAB 6.5 is to study, in a qualitative and quantitative form, the contribution of the insertion of the three FACTS-Series, (TCSC, SSSC and the UPFC), as regards transit of power in three types of networks such :

1st Case: Network made up of two sets of bars bounded by a line and at the boundaries of which one imposes potentials such as the transiting power there before insertion of the one of FACTS devices is 120 MW;

2nd case: Network made up of two sets of bars bounded by two parallel lines and at the boundaries of which one imposes two potentials such as the transiting powers there are 77 and 180 MW before insertion of the one of FACTS devices in the less charged line;

3rd case: Standard IEEE network of 14 nodes (including 3 generating nodes and 9 nodes of load) equipped or not with a serial - FACTS device established on the less charged line.

### 3.1 Power contribution of various FACTS devices inserted in the 1st network

#### 3.1.1 Curves of power variations in the line

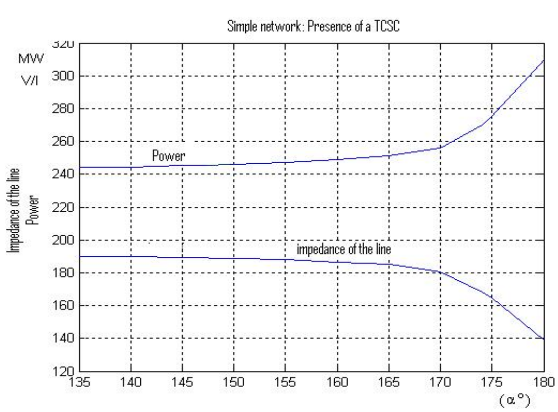


**Fig. 8:** Power contribution of a TCSC according to the firing angle of the thyristors

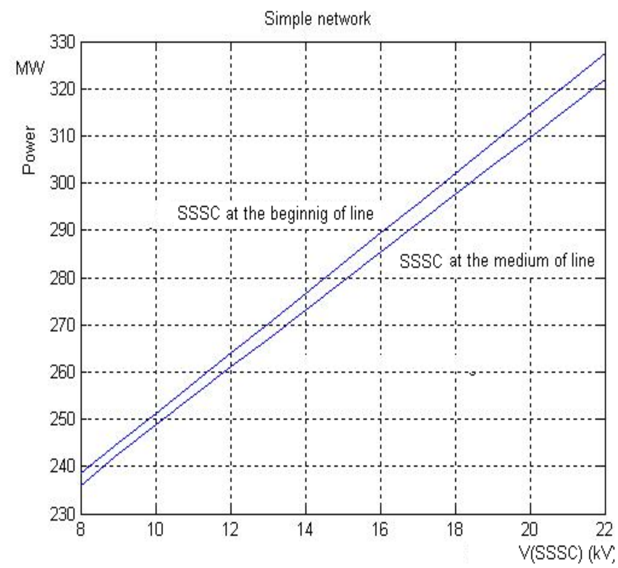


**Fig. 9:** Power contribution of a SSSC according to its output voltage.

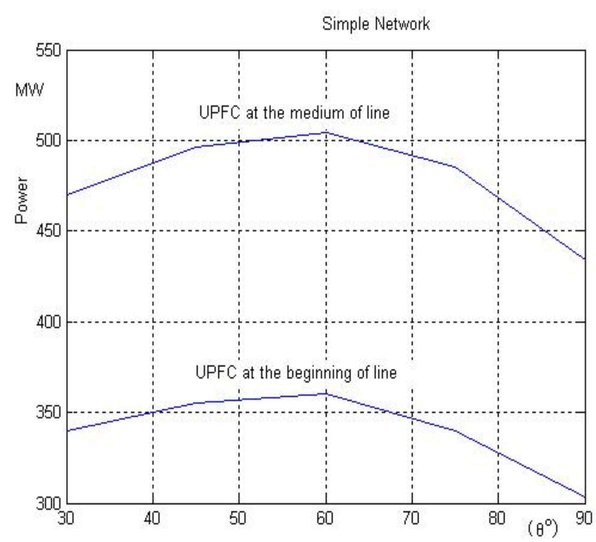


**Fig. 10:** Power contribution of an UPFC according to the imposed angle of load

#### 3.1.2 Interpretations of the results

The three pairs of characteristic curves highlight the contribution of each FACTS device of the active power transit in the line at witch ends we impose the potential vectors. The imposed power limits depend simultaneously from: parameters of the devices, characteristics of the line then levels and variations of phases of the potentials. In addition, in the case of the UPFC, the increase in the transmitted power is more significant when this one is established in the medium of the line.

### 3.2 Power contribution of various FACTS devices in the 2nd network

#### 3.2.1 Curves of power variations in the two lines

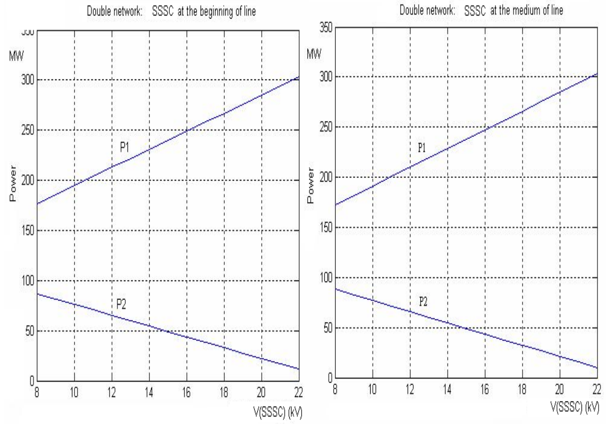


**Fig. 11 :** Power variations in the two lines according to the angle control of the TCSC.

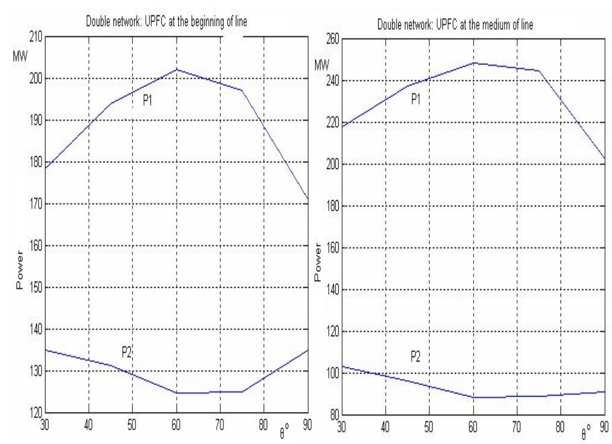


**Fig. 12:** Power variations in the two lines according to the output voltage of the STATCOM

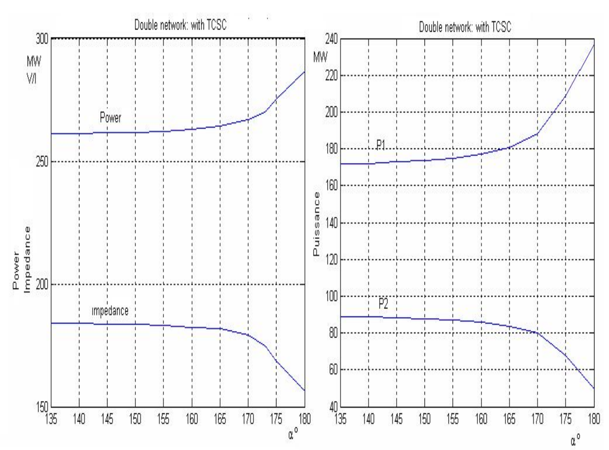


**Fig. 13 :** Power variations in the two lines according to the angle of load imposed from the UPFC.

#### 3.2.2 Interpretations of the results

We can easily notice the possibility of control of the powers to transit in each line when one of the FACTS devices is inserted there. This characteristic is very significant at the time where contingencies of lines or breakdowns of transformers occur. These devices thus enable us to increase or decrease, with wish, the transport capacities without any actuation nor additional expenditure and this, while respecting the allowed limits by each element of the branch: line, transformer, protection etc... In addition, these devices enable us to make function the networks very far from their limits of stabilities from where a less constraining exploitation.

### 3.3 Powers Variations in the various branches of the 3rd network

The aim of the simulations carried out in this case is to observe the power distributions in the inter-connected lines of the network and this, in absence of FACTS devices or in presence of one of the three above mentioned FACTS devices.

For various load levels of the complete network (homogeneous load variations in the whole system), simulations on the load distribution showed that nodes 1, 9, 10 were most critical. It was observed that these nodes are located in the same area that we then defined as a "fragile" zone. In addition, one can notice that the most critical nodes are those which are more "distant" from the nodes of production.

For the site of FACTS-Series systems, it is necessary to observe the distribution of the Power transits. On can also note that the network is composed of a "southern" area made up of the numbered lines from 1 to 10 and of a " northern" area made up of the numbered lines from 13 to 20. The load zone is included in the "northern" area. The inter-connection of these two areas is carried out by the lines 8, 11, 9 and 12 which in the beginning represented transformers with regulators in load.

One can notice that the generators are located in the "southern" zone. The transfers of active power of the "southern" zone towards the "northern" zone are distributed (according to simulations of load distribution) between the lines of interconnection in the following way:

- 50% of the power transits by line 12;
- 20% by line 9; and
- 30% by line 8.

We deduced that the FACTS–Series will have to be placed on the branch 9, which is the less overloaded line. Indeed, to place those in branches 11 or 12 would result in overloading them more still, which would destabilize a priori the networks. Moreover, their insertion in line 8 would be less effective than on line 9. For these simulations, one realise the same operations as those established for the two preceding networks.

### 3.3.1 Tables of the powers in the branches forgiven load mode

**Table 1** Case of the network without FACTS

| N° line | 8 | 9 | 10 | 11 | 12 | 13 | 17 |
|---|---|---|---|---|---|---|---|
| P(Mw) | 87.3 | -45.5 | 174.5 | 131 | -220 | 108 | 104 |

**Table 2** Case of the network with TCSC in the most loaded branch

| α (°) | P8 (Mw) | P9 (Mw) | P10 (Mw) | P11 (Mw) | P12 (Mw) | P13 (Mw) | P17 (Mw) |
|---|---|---|---|---|---|---|---|
| 135 | 72.7 | -186 | 115 | -288 | 223 | 118 | 105 |
| 145 | 59.5 | -187 | 115 | -290 | 195 | 117 | 106 |
| 150 | 46.5 | -223 | 145 | -360 | 78 | 106 | 116 |
| 160 | 33.4 | -227 | 143 | -366 | 57 | 105 | 116 |

**Table 3** Case of the network with SSSC in the most loaded branch

| V (KV) | P8 (Mw) | P9 (Mw) | P10 (Mw) | P11 (Mw) | P12 (Mw) | P13 (Mw) | P17 (Mw) |
|---|---|---|---|---|---|---|---|
| 12 | 77.7 | -121 | 180 | -315 | 72.7 | 118 | 114 |
| 14 | 75.7 | -137 | 180.5 | -337 | 59.5 | 120 | 116 |
| 16 | 73.7 | -153 | 181 | -360 | 46.5 | 122 | 119 |
| 18 | 72 | -170 | 181 | -380 | 33.4 | 124 | 121 |

Table 4 Case of the network with phase-shifting in the most loaded branch

| θ (°) | 05 | 10 | 15 | 20 |
|---|---|---|---|---|
| $V_c$ (Kv) | 27.7 | 38.3 | 57.4 | 108 |
| P9 (Mw) | 28.2 | 97 | 163 | 223 |
| P10 (Mw) | 188.6 | 207 | 224.2 | 242.4 |
| P11 (Mw) | 167.8 | 205.5 | 240 | 271 |
| P12 (Mw) | -167 | -126 | -90 | -60 |
| P13 (Mw) | 91.3 | 90 | 88.8 | 88.1 |
| P17 (Mw) | 103.1 | 100.5 | 98.8 | 96.5 |
| P6( Mw) | 119.6 | 106.5 | 89.2 | 77.5 |
| P7 (Mw) | 1.4 | 9.15 | 16.7 | 23.2 |
| P3 (Mw) | 26.6 | 20.5 | 14.4 | 9.3 |

### 3.3.2 Interpretations of the results

After a serial of simulations, we noticed that an improvement of the power stability is felt on the whole of the network by the presence of various FACTS-Series devices and this, because of the influence of the latter on the values of the reactance of the branches and on the values of the voltage drops in these same branches.
In addition, we confirmed that the increase in the transited power in each branch is the most important point of these devices, because they make it possible to increase the transmissible maximum power by a line in a significant way without affecting the critical tension. This increase can almost double according to the site of the TCSC and the line which one observes.
It should nevertheless be specified that, if one considers for example the lines 11 and 12 which are the only lines feeding node 9, the insertion of these devices on line 9 increases the transit of power on line 11 but it decreases it on line 12 (what is logical).
We have noticed that these devices support indeed better the voltage in the area where they are inserted (for example with nodes 4 and 7 mainly), but less effective on the remainder of the network.
At least, one can note that in spite of the good general behaviour of the compensator series inserted on line 9, there is a case where this one can destabilize the network, in particular at the time of the opening of line 12. The largest part of the power which transits by this line (50% of the feeding of the Northern zone of the network) pays then on line 9, this one becomes very overloaded then from where the interest of a studied choice of the site of FACTS device. In addition, if one carries out a release of line 16, one notes that the TCSC answers in a very satisfactory way

## 4. Conclusion

This study enabled us to analyze the operation of the series compensators according to their internal parameters and to show their influences on the power transit in the lines.
Various simulations carried out showed that these compensators, can make it possible to exploit the interconnections on their best level by optimizing the capacities of energy transfer and the sharing of the loads between the parallel circuits while preserving the network stability under various operating conditions..

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