SVC Modelling and Simulation for Power System Flow Studies: Electrical Network in Over-Voltage

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Abstract: *Voltage stability has been a major concern for power system utilities because of several events of the changes in power systems such as increase in loading, generator reaching reactive power limits, action of tap changing transformers, load recovery dynamics and line or generator outages. They may cause a progressively uncontrolled fall of voltages leading to voltage instability or voltage collapse. This paper deals with power flow control in electric power systems by use of Flexible AC Transmission Systems (FACTS) devices such as the Static Var Compensator (SVC). To study the impact of insertion of the SVC in the electrical network, it is necessary to establish the state of the network (bus voltages and angles, powers injected and forwarded in the lines) before and after the introduction of FACTS devices. This brings to calculate the transit powers by using an iterative Newton-Raphson method. Undertaking a calculation without the introduction of FACTS devices followed by a calculation with the modifications induced by the FACTS devices integration in the network, it's possible in both cases, compare the results obtained and assess the interest of the use of FACTS devices.*

Keywords: *SVC device, Newton-Raphson method, power flow, voltage regulation, electrical network modelling.*

I. Introduction

In recent years, the fast progress in the field of power electronics has opened new opportunities for the power industry via utilization of the controllable Flexible AC Transmission Systems (FACTS) devices [1,2,3]. In order to assess the impact of FACTS devices on the steady state electric transmission system operation, it is necessary to develop their mathematical models and include them in a power flow program.

In this paper, the impact of the Static Var Compensator (SVC) insert in the electrical network and modification in admittance matrix and Jacobian matrix in Newton Raphson method are defined [4,5]. The SVC device injects reactive power into busbars to improve the voltage profiles and can control active power flow in the lines.

A modification of the power flow model incorporating busbar voltage magnitudes and angles and power flow on the lines as independent variables will prove advantageous in relating the SVC device variables with system operating conditions. Initially, the introduction of the SVC is carried out by modification of the admittances matrix, varying the control parameter of this device and observing the changes on the bus voltages and the transit powers in the lines. This allows deducing the best value which allows an ideal compensation of the network.

The modification of the FACTS placement [6,7,8] in the network makes it possible to choose the best place in which to introduce the device in the studied network. The second step consists in fixing a consign value (of voltage or of power) for which a simulation program will find the control size value. This requires modifications in the Jacobian matrix for introduce the parameter control as a variable. This way, it will check, if it is possible to regulate a size (voltage or power) to a value consign without deteriorating the static performances of the network.

II. Presence of the FACTS in the network

The SVC based on thyristors without the gate turn-off capability is considered as a shunt connected static Var generator or absorber, whose output is adjusted to exchange capacitive or inductive current. It is an important component for voltage control in power systems and is usually installed at the receiving busbar. In the power flow formulation, the SVC has been considered as a reactive power source within the reactive power limits set by available inductive and capacitive susceptances [3, 9].

II.1. Construction of the nodal admittance matrix

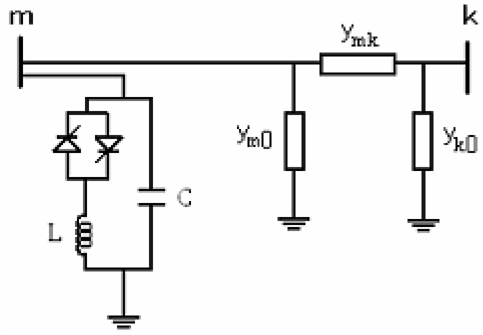

Fig 1: SVC inserting in a line

II.1.a SVC placed at the beginning of line

For an SVC connected at a busbar m of a line section represented by the quadruple (y_{m0}, y_{mk}, y_{k0}) as shown in figure 1, the contribution of the SVC [3,10,11] to the new admittance matrix relates to the element shunt. It results in the admittance matrix of the line.

$$Y_{new}^{line} = \begin{pmatrix} y_{mk} + y_{m0} + y_{svc} & -y_{mk} \\ -y_{mk} & y_{mk} + y_{k0} \end{pmatrix} \quad (1)$$

Such as : $$y_{svc} = \frac{1}{X_{svc}} \quad (2)$$

and

$$y_{svc} = j\frac{1}{X_L X_C}\left[X_L - \frac{X_C}{\pi}\left(2(\pi-\alpha)+\sin 2\alpha\right)\right] \quad (3)$$

The SVC reactance is given as the following expression:

$$X_{svc}(\alpha) = j\frac{\pi X_L}{2(\pi-\alpha)+\sin 2\alpha - \pi\frac{X_L}{X_C}} \quad (4)$$

II.1.b SVC placed at the middle of a line

When the static compensator is inserted into the middle of a line, the latter is divided into two identical sections. The SVC is connected to the additional bus "t" as illustrated by figure 2.

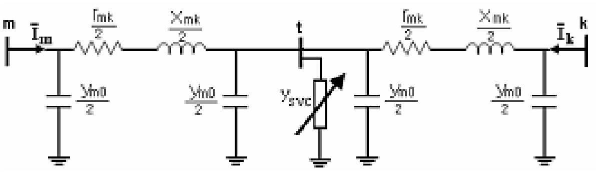

Fig 2 : SVC placed at the middle of a line

In order to take into account this new bus, an additional line and a column should be added to the nodal admittance matrix. To avoid having to change the number of buses of the network and thus the admittance matrix size, a transformation star-delta makes it possible to reduce the system by removing the bus "t" and by calculating the parameters of an equivalent line.

The figure 3 illustrates the steps to obtain this equivalent line.

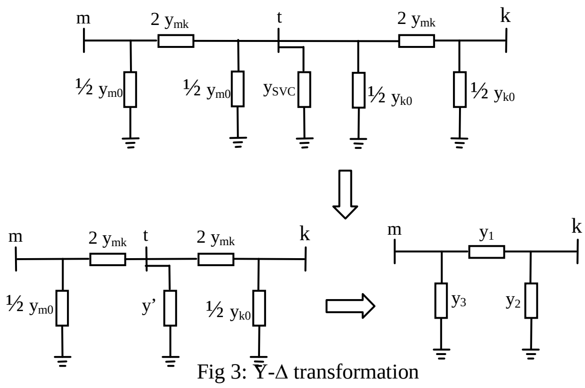

Fig 3: Y-Δ transformation

Such as:

$$\begin{cases} y_1 = \dfrac{4y_{mk}^2}{4y_{mk}+y_{svc}+\frac{1}{2}y_{m0}+\frac{1}{2}y_{k0}} \\ y_2 = \dfrac{y_{mk}\left(2y_{svc}+y_{m0}+y_{k0}\right)}{4y_{mk}+y_{svc}+\frac{1}{2}y_{m0}+\frac{1}{2}y_{k0}} + \dfrac{1}{2}y_{m0} \\ y_3 = \dfrac{y_{mk}\left(2y_{svc}+y_{m0}+y_{k0}\right)}{4y_{mk}+y_{svc}+\frac{1}{2}y_{m0}+\frac{1}{2}y_{k0}} + \dfrac{1}{2}y_{k0} \end{cases} \quad (5)$$

All the admittance matrix elements of a line with an SVC in its middle are modified, such as :

$$Y_{new}^{line} = \begin{pmatrix} Y_{mm} & Y_{mk} \\ Y_{km} & Y_{kk} \end{pmatrix} \quad (6)$$

With, , $Y_{km} = Y_{mk}$ and :

$$\begin{cases} Y_{mm} = \dfrac{4y_{mk}^2 + y_{mk}\left(2y_{svc}+y_{m0}+y_{k0}\right)}{4y_{mk}+y_{svc}+\frac{1}{2}y_{m0}+\frac{1}{2}y_{k0}} + \dfrac{1}{2}y_{m0} \\ Y_{kk} = \dfrac{4y_{mk}^2 + y_{mk}\left(2y_{svc}+y_{m0}+y_{k0}\right)}{4y_{mk}+y_{svc}+\frac{1}{2}y_{m0}+\frac{1}{2}y_{k0}} + \dfrac{1}{2}y_{k0} \\ Y_{mk} = -\dfrac{4y_{mk}^2}{4y_{mk}+y_{svc}+\frac{1}{2}y_{m0}+\frac{1}{2}y_{k0}} \end{cases} \quad (7)$$

II.2. influence of the SVC on the network (power flow calculation)

*II.2. a. Insertion of an SVC at the beginning of a line***:**

It results from these modifications on the nodal admittances matrix and from the Jacobian [11,12]. These modifications are detailed in what follows.

Modification of the admittances matrix:

We modelled the SVC as being a variable transverse admittance which is connected to a bus m of the network. Thus, the effect of this is based only on the modification of the element y in the admittances matrix. The new modified matrix is written as follows:

$$Y_{new} = \begin{bmatrix} Y_{11} & \cdots & Y_{1m} & \cdots & Y_{1n} \\ \vdots & \ddots & \vdots & & \vdots \\ Y_{m1} & \cdots & Y_{mm}^{old} + y_{svc} & \cdots & Y_{mn} \\ \vdots & & \vdots & \ddots & \vdots \\ Y_{n1} & \cdots & Y_{nm} & \cdots & Y_{nn} \end{bmatrix} \quad (8)$$

This new matrix is used to calculate the new power transit. By varying the firing angle of the SVC "α", it is possible to plot the curves of voltages variation at the buses. They allow to locate the best point of compensation of the network (all voltage drops within the limits =+0.05). The variation curves of the powers losses in the lines can be obtained according to "α" which makes it possible to measure the impact of the SVC device on these lines. These curves will be studied for the compensation of a network in the over-voltage.

The impact of the nature of the load and its importance will be observed by studying two loading cases purely active and reactivate respectively. While varying the load at the bus to which the SVC is connected and by maintaining "α" constant, the curves of voltages variation as well as those of the power losses will be plotted.

Modification of the Jacobian matrix:

To take into account the introduction of the SVC as a voltage regulator and thus to allow the program to calculate the ideal firing angle to maintain the bus voltage where it is inserted to a consign value, it is necessary to introduce modifications into the Jacobian matrix.

When the SVC is inserted in a bus, this is controlled, and thus its voltage is maintained in magnitude with a fixed value (value consigns); this makes it possible to eliminate the term $\Delta V_k = 0$ (such as k is the controlled bus index). This term is substituted the difference "α" which will allows to have, after convergence, the firing angle of the thrusters which allows the maintenance of the consign voltage.

The matrix system becomes then as follows:

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_k \\ \vdots \\ \Delta P_n \\ \vdots \\ \Delta Q_1 \\ \vdots \\ \Delta Q_k \\ \vdots \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} \cdots \frac{\partial P_1}{\partial \delta_k} \cdots \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial V_1} & \cdots 0 \cdots & \frac{\partial P_1}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_k}{\partial \delta_1} \cdots \frac{\partial P_k}{\partial \delta_k} \cdots \frac{\partial P_k}{\partial \delta_n} & \frac{\partial P_k}{\partial V_1} & \cdots 0 \cdots & \frac{\partial P_k}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} \cdots \frac{\partial P_n}{\partial \delta_k} \cdots \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial V_1} & \cdots 0 \cdots & \frac{\partial P_n}{\partial V_n} \\ \frac{\partial Q_1}{\partial \delta_1} \cdots \frac{\partial Q_1}{\partial \delta_k} \cdots \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial V_1} & \cdots 0 \cdots & \frac{\partial Q_1}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial Q_k}{\partial \delta_1} \cdots \frac{\partial Q_k}{\partial \delta_k} \cdots \frac{\partial Q_k}{\partial \delta_n} & \frac{\partial Q_k}{\partial V_1} & \cdots \frac{\partial Q_k}{\partial \alpha} \cdots & \frac{\partial Q_k}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial Q_n}{\partial \delta_1} \cdots \frac{\partial Q_n}{\partial \delta_k} \cdots \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial V_1} & \cdots 0 \cdots & \frac{\partial Q_n}{\partial V_n} \end{bmatrix} \begin{bmatrix} \Delta \delta_1 \\ \vdots \\ \Delta \delta_k \\ \vdots \\ \Delta \delta_n \\ \vdots \\ \Delta V_1 \\ \vdots \\ \Delta \alpha \\ \vdots \\ \Delta V_n \end{bmatrix} \quad (9)$$

But knowing that :

$$Q_k = Q_k^{old} + Q_{svc} \quad (10)$$

Then :

$$\frac{\partial Q_k}{\partial \alpha} = \frac{\partial Q_k^{old}}{\partial \alpha} + \frac{\partial Q_{svc}}{\partial \alpha} \quad (11)$$

and as Q_k depends only on the firing angle "α", it results :

$$\frac{\partial Q_k}{\partial \alpha} = \frac{\partial Q_{svc}}{\partial \alpha} \quad (12)$$

With, $Q_{svc} = -y_{svc} V_k^2$, then :

$$Q_{svc} = \frac{-V_k^2}{X_L X_C}\left[X_L - \frac{X_C}{\pi}\left(2(\pi - \alpha) + \sin 2\alpha\right)\right] \quad (13)$$

Finally, the expression (11) becomes:

$$\frac{\partial Q_k}{\partial \alpha} = \frac{2V_k^2}{\pi X_L}\left(\cos(2\alpha) - 1\right) \quad (14)$$

*II.2.b. Insertion of an SVC in the middle of a line***:**

An SVC inserted in the middle of a line of the network, conducts to modifications of the admittances nodal matrix and Jacobian matrix which are detailed as follows.

Modification of the admittances Matrix:

According to the equation (7), the elements $Y_{mm}, Y_{kk}, Y_{mk}, Y_{km}$ will be modified in such a way as to produce the new following matrix of admittances:

$$Y_{new} = \begin{bmatrix} Y_{11} & \cdots & Y_{1m} & \cdots & Y_{1k} & \cdots & Y_{1n} \\ \vdots & & \vdots & & \vdots & & \vdots \\ Y_{m1} & \cdots & Y_{mm}^{old} + Y_{mm}^{add} & \cdots & Y_{mk}^{old} + Y_{mk}^{add} & \cdots & Y_{mn} \\ \vdots & & \vdots & & \vdots & & \vdots \\ Y_{k1} & \cdots & Y_{km}^{oldc} + Y_{km}^{add} & \cdots & Y_{kk}^{old} + Y_{kk}^{add} & \cdots & Y_{kn} \\ \vdots & & \vdots & & \vdots & & \vdots \\ Y_{n1} & \cdots & Y_{nm} & \cdots & Y_{nk} & \cdots & Y_{nn} \end{bmatrix} \quad (15)$$

With, $Y_{mm}^{old}, Y_{kk}^{old}, Y_{mk}^{old}, Y_{km}^{old}$ being the elements of the matrix before the introduction of the SVC.

$$\begin{cases} Y_{mm}^{add} = \dfrac{4y_{mk}^2 + y_{mk}\left(2y_{svc} + y_{m0} + y_{k0}\right)}{4y_{mk} + y_{svc} + \frac{1}{2}y_{m0} + \frac{1}{2}y_{k0}} - y_{mk} - \dfrac{1}{2}y_{m0} \\ Y_{kk}^{add} = \dfrac{4y_{mk}^2 + y_{mk}\left(2y_{svc} + y_{m0} + y_{k0}\right)}{4y_{mk} + y_{svc} + \frac{1}{2}y_{m0} + \frac{1}{2}y_{k0}} - y_{km} - \dfrac{1}{2}y_{k0} \\ Y_{mk}^{add} = \dfrac{-4y_{mk}^2}{4y_{mk} + y_{svc} + \frac{1}{2}y_{m0} + \frac{1}{2}y_{k0}} + y_{mk} \\ Y_{km}^{add} = \dfrac{-4y_{mk}^2}{4y_{mk} + y_{svc} + \frac{1}{2}y_{m0} + \frac{1}{2}y_{k0}} + y_{km} \end{cases} \quad (16)$$

The same case studies will be carried out as for an SVC at the beginning of line. The results obtained will be compared for the two cases of placements; and conclude if an SVC in middle of a line can ensure the compensation with the same effectiveness as two SVC placed in ends of line.

II. The studied network structure

The simulation results are obtained for a network test shown in figure 4 whose buses are numbered from 1 to 5, and the lines are numbered from 1 to 7.

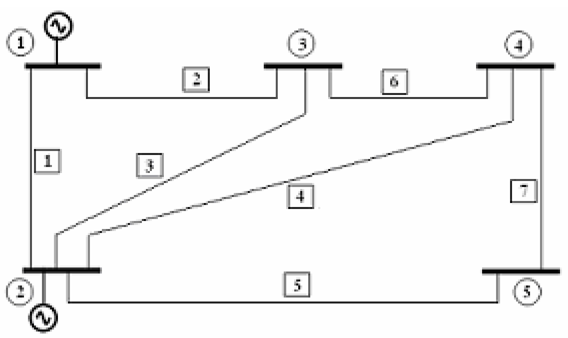

Fig 4 : The studied network structure

The network data

Data at buses: They are grouped in table 1:

TABLE 1
BUSES DATA

Bus	V (pu)	δ (°)	Generation P (pu)	Generation Q (pu)	Load P (pu)	Load Q (pu)
1	1.000	0.000	0.000	0.000	0.000	0.000
2	1.020	0.000	0.400	0.000	0.200	0.100
3	1.000	0.000	0.000	0.000	0.450	0.150
4	1.000	0.000	0.000	0.000	0.400	0.050
5	1.000	0.000	0.000	0.000	0.600	0.100

Lines data : they are grouped in table 2 :

TABLE 2
LINES DATA

Line	R (pu)	X (pu)	B (pu)
1-2	0.0200	0.0600	0.0600
1-3	0.0800	0.2400	0.0600
2-3	0.0600	0.1800	0.0400
2-4	0.0600	0.1800	0.0400
2-5	0.0400	0.1200	0.0300
3-4	0.0100	0.0300	0.0200
4-5	0.0800	0.2400	0.0600

The network state (voltages and powers) after convergence is given in tables 3, 4 and 5.

TABLE 3
VOLTAGE MAGNITUDES AT THE BUSES (PU)

1	2	3	4	5
1.0000	1.02000	0.9711	0.9712	0.9673

TABLE 4
VOLTAGE ANGLES AT THE BUSES (DEG)

1	2	3	4	5
0.0000	-3.3941	-5.7398	-6.1192	-7.0576

TABLE 5
TRANSIT POWERS IN LINES

N°	P (pu)	Q (pu)
1	0.8968	-0.2997
2	0.4064	-0.0199
3	0.2482	0.0622
4	0.2808	0.0527
5	0.5503	0.0908
6	0.1873	-0.0722
7	0.0626	-0.0281

IV. Insertion of the SVC in the network

To observe the impact of the presence of an SVC in the network, a study on the network in over-voltage. The localisation of the SVC in the network was changed to deduce the one which offers the best compensation, and to observe the voltages variation of at the buses according to the reactive power injected by the SVC, this will give the ideal firing angle for the network compensation.

The SVC parameters used in calculations are given in table 6.

TABLE 6
SVC PARAMETERS

X_c (pu)	X_L (pu)	α_{min} (°)	α_{max} (°)
1.0700	0.2880	90	180

The figure 5 shows the SVC admittance variation according to firing angle α.

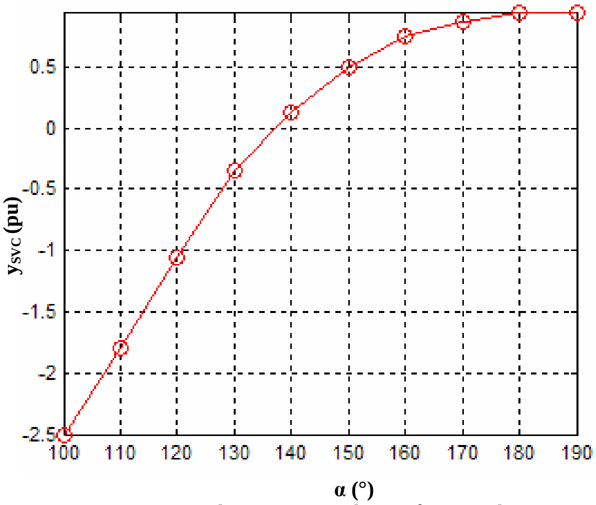

Fig 5: SVC admittance according to firing angle α.

V. Network in over-voltage

What follows here is devoted to the study of the SVC aptitudes to restore the busbars voltages of the network after an over-voltage. To do so, an over-voltage at busbar 4 was caused by modifying its load parameters (the active power of 0,40pu and the reactive power of -1,80 pu). Consequently, the state of the network is according to resulted given in tables 7.8 and 9:

TABLE 7
VOLTAGE MAGNITUDES AT THE BUSES (PU)

1	2	3	4	5
1.0000	1.02000	1.0703	1.0955	1.0233

TABLE 8
VOLTAGE ANGLES AT THE BUSES (DEG)

1	2	3	4	5
0.0000	-3.7980	-7.3571	-8.1290	-7.8017

TABLE 9
POWER LOSSES IN THE LINES (PU)

N°	ΔP (pu)	ΔQ (pu)
1	0.0244	0.0120
2	0.0282	0.0310
3	0.0112	-0.0100
4	0.0201	0.0156
5	0.0128	0.0070
6	0.0085	0.0021
7	0.0066	-0.0365

V.1. Insertion of the SVC at bus 4

The principle applied in this case is to vary "α" from 100° to 180° and to observe the SVC effect on the voltages at the busbars and on the powers losses in the lines.

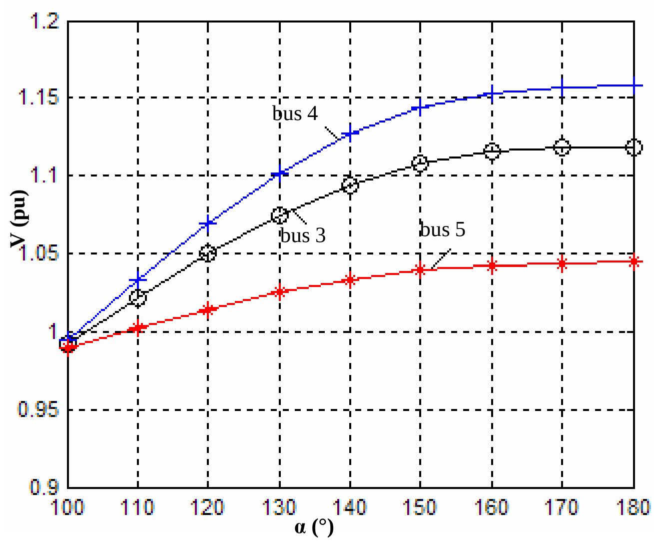

Fig 6: Voltage magnitudes variation at the buses according to α

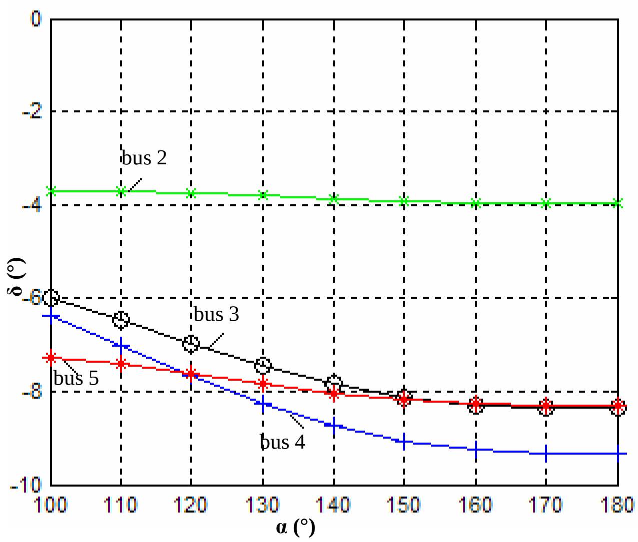

Fig 7: Voltage angles variation at the buses according to α

Interpretation

The figures 6 and 7 show the effect of the insertion of an SVC at busbar 4 on the voltage magnitudes and angles. The SVC makes it possible to consume the excess of reactive energy and thus reduce over-voltage. In an interval of "α" ranging from 100° to 115° (corresponding to Q_{SVC} ranging from 0,9243 pu to 0,8864 pu), the voltages in the network are maintained within the limits fixed for the quality of the voltage profile.

According to figures 8 and 9, the active and reactive powers losses in the lines are reduced thanks to the presence of the SVC, this is due to the reduction of the powers forwarded. Being proportional to the bus voltages, the active powers decrease with the reduction of these latter. For the reactive powers, the SVC consumes the power injected by the capacitive overload, and thus, reduces its transit through the lines.

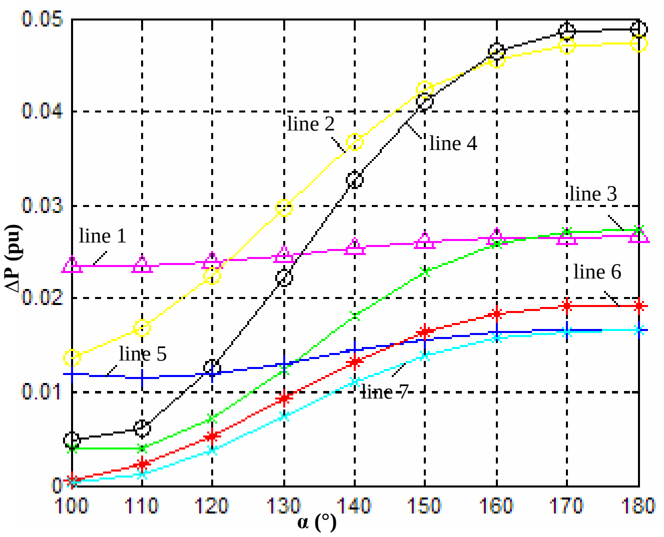

Fig 8: Active power losses in lines according to α

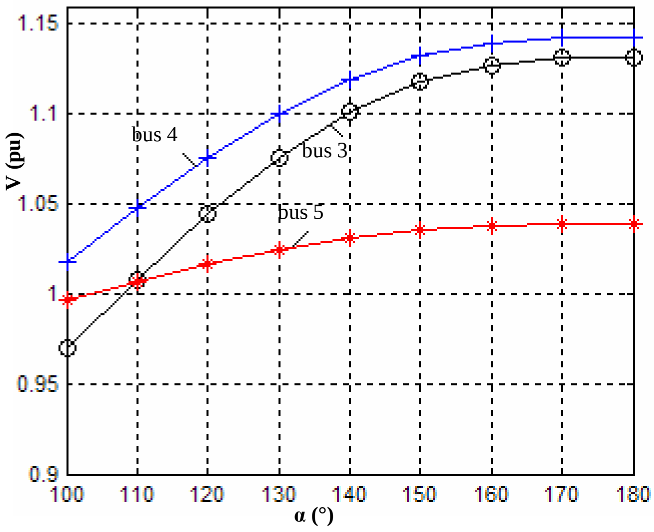

Fig 10: Voltage magnitudes variation at the buses according to α

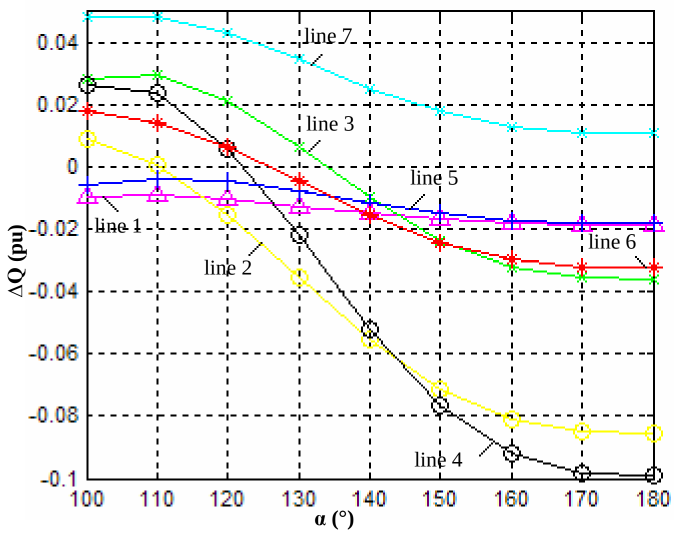

Fig 9: Reactive power losses in lines according to α

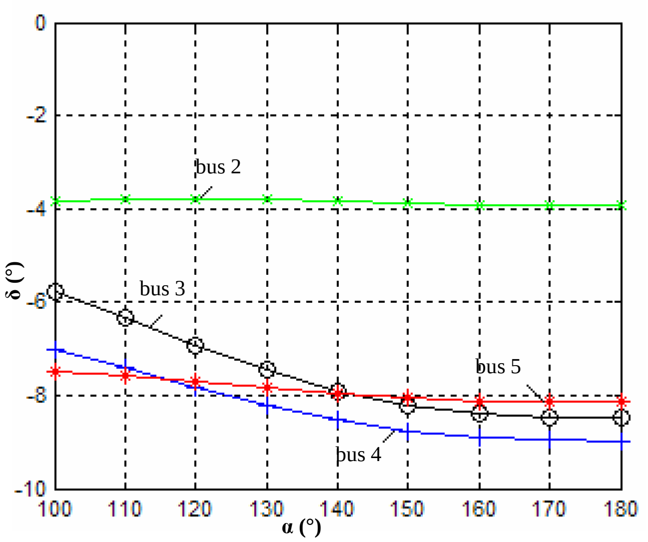

Fig 11: Voltage angles variation at the buses according to α

V.2. Insertion of the SVC at bus 3

The principle applied in this case is to vary "α" from 100° to 180° and to observe the effect of the SVC on the busbar voltages and the powers losses in the lines. Figures 10 and 11 show the influence of reactive power Q_{SVC} of the SVC on the voltage magnitudes as well as on the voltage angles.

Interpretation

The figure 11 shows that for values of "α" between 100° and 110° (which corresponds to QSVC ranging between 0,9243 pu and 0,9157 pu), the SVC makes it possible to maintain the five voltages of the network within the limits of ±5% of variation around the value of one pu.

The SVC connected to busbar 3 allows to restore the voltage balance and to eliminate the over-voltage induced by the capacitive overload at busbar 4, even if its margin is less than an SVC connected at the point of overload.

The SVC also allows reducing the active and reactive losses in the lines as shown on figures 12 and 13. They show that for values of QSVC, it is possible to have acceptable voltages, the power losses in the lines decrease and approach to the zero value. When the firing angle (which vary the current of inductance) increases, its effect decreases and its contribution to the reactance of the SVC decreases too.

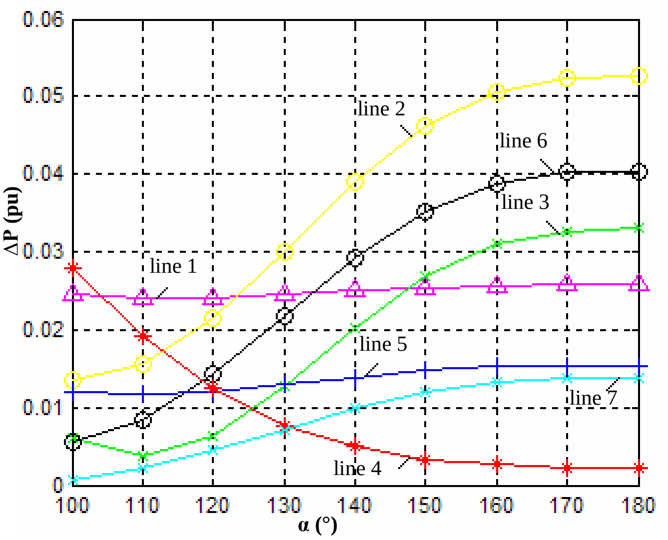

Fig 12 : Active power losses in lines according to α

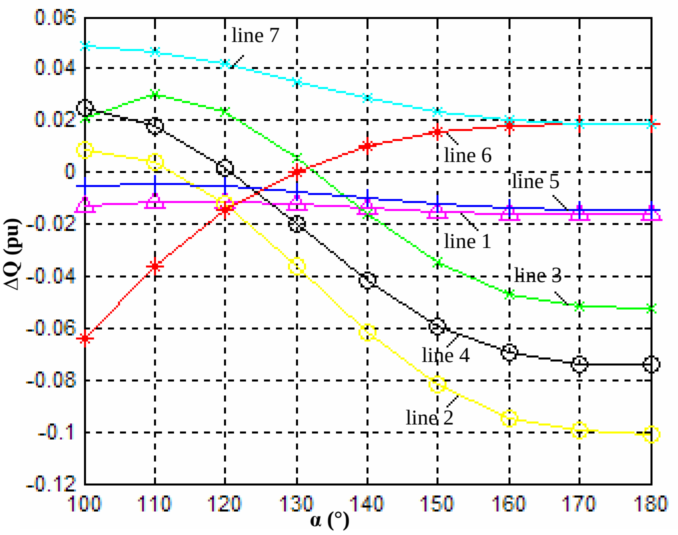

Fig 13 : Reactive power losses in lines according to α

VI. Conclusion

The study undertaken on case regarding the tested network state (over-voltage), show the influence of the SVC device insertion in the electrical network. The effectiveness of the SVC to compensate for an over-voltage which is due to a capacitive overload at one of the network busbars was checked.

An SVC device allows indeed restoring a good level of bus voltages after an imbalance even if it is not inserted into the overloaded bus. Indeed, we showed that if the SVC is connected to an adjacent bus to the overload, it has also good performances. The SVC allows also, even though it is not its first vocation, to reduce the powers losses in the lines for the compensated network and increase the power transit.

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