Application of the Three-Phase STATCOM in Voltage Stability

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Abstract — This paper is aimed to the analysis of voltage stability margin by means of the P-V curves for different power systems' operation points, using three-phase power flows and modal analysis. It includes a three-phase steady state model of the static synchronous compensator (STATCOM), with the objective of analyzing its behavior in the improvement of voltage stability margin. The study is made in a three-phase reference frame taking into account balanced and unbalanced conditions. The test system is the 39 buses and 10 machines New England power system.

Keywords - Contingency, Load Increment, Power Flow, Voltage Stability, Voltage Stability Margin, STATCOM.

1. INTRODUCTION

In the last decades, due to the increment in load demand, the power systems have experienced continuous changes in their configuration. These have come about in different ways, as the increment of the existent interconnections or the use of faster controls. While the addition of these new elements to the system results in a more economic and reliable operation, they have also contributed to increase the complexity of the stability problems, as voltage stability [11].

Voltage stability is one of the biggest problems in power systems. Engineers and researchers have met with the purpose of discussing and trying to consolidate a definition regarding to voltage stability, besides proposing techniques and methodologies for their analysis, some of them reported in [1]. Most of these techniques are based on the search of the point in which the system's Jacobian becomes singular; this point is referred as the point of voltage collapse or maximum loadability point [8].

The series and shunt compensation are able to increase the maximum transfer capabilities of power network [8]. Concerning to voltage stability, such compensation has the purpose of injecting reactive power to maintain the voltage magnitude in the nodes close to the nominal values, besides, to reduce line currents and therefore the total system losses [4]. At the present time, thanks to the development in the power electronics devices, the voltage magnitude in some node of the system can be adjusted through sophisticated and versatile devices named FACTS, being the static synchronous compensator (STATCOM) one of them.

There are diverse publications regarding to model the STATCOM, for example, steady state studies [6], or transient stability ones [9]. There are other ones applied to voltage control problem using novel technical [13]. The focus in the present work is the analysis of the STATCOM model in a three-phase reference frame applied to the improvement of voltage stability margin. The intention of this analysis is to prove the device in severe conditions of load, to observe its behavior and range of its control parameters in such circumstances, besides, checking that it is able to increases voltage stability margin.

Among the tools used for the power systems analysis, three-phase power flow is so important, in order to simulate realistic conditions. There are three-phase transmission lines unbalanced in high-voltage transmission network and, there are one-phase or two-phase lines in some distribution network [12]. In this paper three-phase power flows analysis is carried out by means Newton's algorithm.

2. STATCOM MODELLING

A. Basic operation principles, (one-phase, STATCOM).

A schematic representation of the one-phase STATCOM is shown in Figure 1. It is composed by a voltage source converter (VSC), and its associated shunt connected transformer [6]. The transformer is used as a link between the VSC and the system.

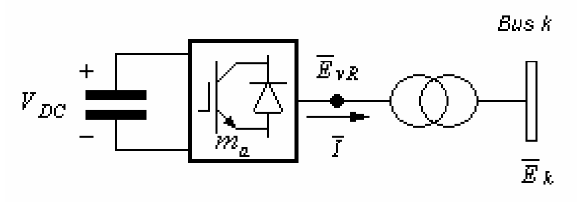


Fig. 1. STATCOM's schematic representation.

To explain the basic STATCOM's operation principles, it is considered that the coupling transformer is lossless; this way, its equivalent one-phase circuit is depicted in Figure 2, where $\boldsymbol{E_{vR}}$ represents the voltage in the STATCOM's terminals and $\boldsymbol{E_k}$ is the voltage in the power system bus.

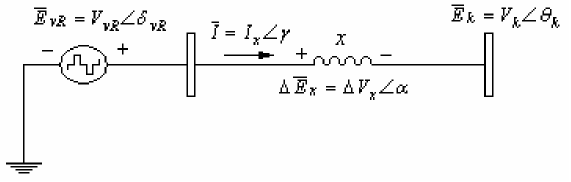


Fig. 2. equivalent one-phase circuit of the STATCOM.

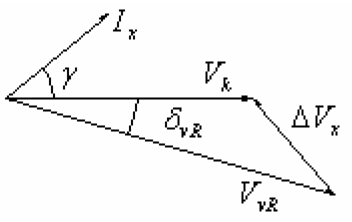
The basics of the STATCOM's operation is that the amplitude and phase angle of the voltage drop $\boldsymbol{\Delta E_x}$, Figure 2, can be controlled, defining the amount and direction of active and reactive power flows through the reactance [6]. If we take $\theta_k = 0$ as the reference to simplify the formulation, the following equations (1)-(3), are the voltage and power equations applied to the circuit.

$$\overline{E}_k = \overline{E}_{vR} - \Delta\overline{E}_x \qquad (1)$$

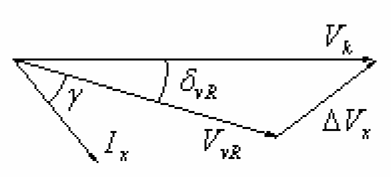
$$P = \frac{V_{vR}V_k}{x}\sin\delta_{vR} \qquad (2)$$

$$Q = \frac{V_{vR}^2}{x} - \frac{V_{vR}V_k}{x}\cos\delta_{vR} \qquad (3)$$

Under normal operation conditions, a small amount of active power must flows into the VSC to compensate for the power losses that exist in its interior, and in reference to Figure 2, δ_{vR} is kept slightly different that θ_k.. In Figure 3(a) and 3(b) are drawn the space vector representation of the STATCOM.



(a)



(b)

Figure 3. Lagging and leading currents.

Figure 3(a) represents a operation condition where $V_{vR} > V_k$, with a lagging power factor, in such circumstances, the STATCOM is absorbing active power from the system and giving reactive power to the same one. On the other hand, Figure 3(b) represents a operation condition where ($V_{vR} < V_k$), with leading power factor; now, the STATCOM absorbs active and reactive power from the system.

In summary, in reference to the equations (1)-(3) and observing Figure 3, if V_k is assumed constant, we take the conclusion that through the variation of V_{vR}, it can be achieved that the STATCOM absorbs or delivers reactive power to the system with compensation purposes. Therefore, a more flexible model of the STATCOM is represented as a variable voltage source $\boldsymbol{E_{vR}}$, for which the magnitude and phase angle can be adjusted with the object of satisfying a specific voltage magnitude at the point of connection. The voltage magnitude V_{vR} is conditioned by some maximum and minimum limits, which are a function of the STATCOM's capacitor rating. In this paper, the simulations include the limits on STATCOM's voltage magnitude within (0.9–1.1) p.u. However, the phase angle δ_{vR} can vary between 0 and 2π radians [6].

B. Three-phase STATCOM's equivalent circuit and steady-state equations.

With the help of the previous one-phase STATCOM formulation, it is easy to deduce the three-phase model. The shunt voltage source of the three-phase STATCOM may be represented by:

$$E_{vR}^{\rho} = V_{vR}^{\rho}(\cos\delta_{vR}^{\rho} + jsen\delta_{vR}^{\rho}) \qquad (4)$$

where ρ indicates phase quantities, *a, b* and *c*.

The equivalent circuit of the three-phase STATCOM is shown in Figure 4 in a wye configuration. This model is used to derive the steady state equations included into the three-phase power flow formulation.

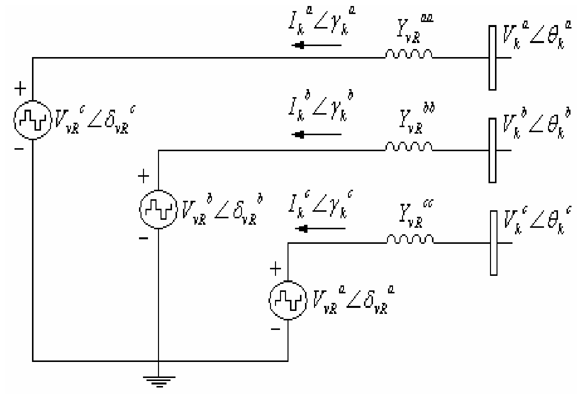


Fig. 4. Three-phase STATCOM´s equivalent circuit.

Based in the equivalent circuit of Figure 4, the following equation can be written

$$\bar{I}_k = \begin{bmatrix} Y_{vR} & -Y_{vR} \end{bmatrix} \begin{bmatrix} \bar{E}_k \\ \bar{E}_{vR} \end{bmatrix} \qquad (5)$$

where

$$\bar{I}_k = \left[I^a{}_k\angle\gamma^a{}_k \quad I^b{}_k\angle\gamma^b{}_k \quad I^c{}_k\angle\gamma^c{}_k \right]^t \qquad (6)$$

$$\bar{E}_k = \left[V^a{}_k\angle\theta^a{}_k \quad V^b{}_k\angle\theta^b{}_k \quad V^c{}_k\angle\theta^c{}_k \right]^t \qquad (7)$$

$$\bar{E}_{vR} = \left[V^a{}_{vRk}\angle\delta^a{}_{vRk} \quad V^b{}_{vRk}\angle\delta^b{}_{vRk} \quad V^c{}_{vRk}\angle\delta^c{}_{vRk} \right]^t \qquad (8)$$

$$Y_{vR} = \begin{bmatrix} Y_{vRk}^a & 0 & 0 \\ 0 & Y_{vRk}^b & 0 \\ 0 & 0 & Y_{vRk}^c \end{bmatrix} \qquad (9)$$

The equations that represent active and reactive power injection at the terminal system can be written as [6]

$$P_k = V_k^2 G_{vR} + V_k V_{vR}[G_{vR}\cos(\theta_k - \delta_{vR}) + B_{vR}\sin(\theta_k - \delta_{vR})] \qquad (10)$$

$$Q_k = -V_k^2 B_{vR} + V_k V_{vR}[G_{vR}\sin(\theta_k - \delta_{vR}) - B_{vR}\cos(\theta_k - \delta_{vR})] \qquad (11)$$

In the same way, the expressions at the STATCOM´s terminal become

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_k[G_{vR}\cos(\delta_{vR} - \theta_k) + B_{vR}\sin(\delta_{vR} - \theta_k)] \qquad (12)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR} V_k[G_{vR}\sin(\delta_{vR} - \theta_k) - B_{vR}\cos(\delta_{vR} - \theta_k)] \qquad (13)$$

To integrate the variables of the STATCOM into the three-phase power flow formulation, two variables are unknown by phase, V^{ρ}_{vR} y δ^{ρ}_{vR}, therefore, six additional equations are required. For the first equation, we will take account that the STATCOM can consume active power from the system or can be loss-less too, that is, it doesn't consume neither it generates active power. So the equation that models the active power in the STATCOM is given by the equation (12).

The second equation can be the k-th voltage magnitude. As the voltage magnitude in this node is specified, then V^{ρ}_{vR} substitutes V^{ρ}_k as state variable. Therefore, based on the equivalent circuit of Figure 4 and the equations (5) - (13), the following linearized equation can be obtained.

$$\begin{bmatrix} \Delta P_k^{\rho} \\ \Delta Q_k^{\rho} \\ \Delta P_{vR}^{\rho} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_k^{\rho}}{\partial \theta_k^{\rho}} & \dfrac{\partial P_k^{\rho}}{\partial V_{vR}^{\rho}} V_{vR}^{\rho} & \dfrac{\partial P_k^{\rho}}{\partial \delta_{vR}^{\rho}} \\ \dfrac{\partial Q_k^{\rho}}{\partial \theta_k^{\rho}} & \dfrac{\partial Q_k^{\rho}}{\partial V_{vR}^{\rho}} V_{vR}^{\rho} & \dfrac{\partial Q_k^{\rho}}{\partial \delta_{vR}^{\rho}} \\ \dfrac{\partial P_{vR}^{\rho}}{\partial \theta_k^{\rho}} & \dfrac{\partial P_{vR}^{\rho}}{\partial V_{vR}^{\rho}} V_{vR}^{\rho} & \dfrac{\partial P_{vR}^{\rho}}{\partial \delta_{vR}^{\rho}} \end{bmatrix} \begin{bmatrix} \Delta \theta_k^{\rho} \\ \dfrac{\Delta V_{vR}^{\rho}}{V_{vR}^{\rho}} \\ \Delta \delta_{vR}^{\rho} \end{bmatrix} \qquad (14)$$

Thus, the three-phase STATCOM model is integrated into the steady state formulation. In the simulations, the STATCOM´s node where is connected, is represented as a PV type node. This node can change to PQ type when, during the process, one of the limits in the device's voltage magnitude is violated.

3. APPLIED METHOD

Based in [10], a voltage stability study applied to any system should contain the following six steps:

1.- Establishment of a base case operation (BCO).

2.- Selection of a list of contingencies to prove voltage stability of the tested system.

3.- Definition of a Key System Parameter (KSP) for the calculation of voltage stability margin.

4.- Specification of a voltage stability criterion.

5.- Calculation of voltage stability margin for the BCO and all the contingencies.

6.- Design and validation of remedial measured for cases which do not satisfy the specified criterion.

A. Definition of the BCO

The chosen test system to carry out voltage stability studies is the equivalent New England power system, shown in Figure 5, which consists of 39 nodes and 10 generators [5].

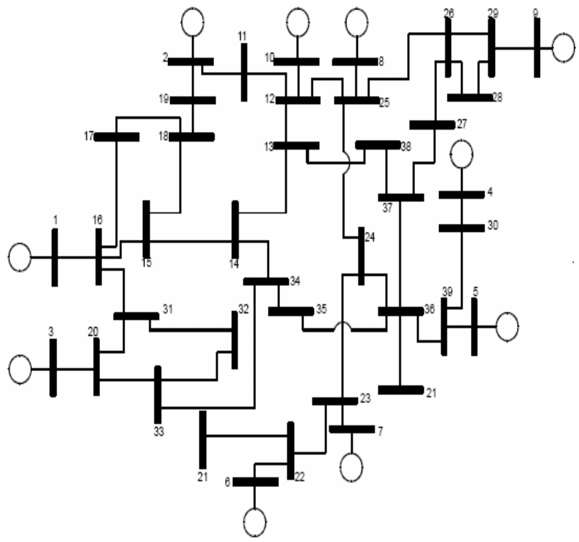


Figure 5. 10 machines power system.

The chosen BCO, considering the system operating under a three-phase balanced condition, correspond to a total active and reactive power demand equal to 6124.5 MW/phase and 1593.4 MVAr/phase [5].

When applying the power flows method to voltage stability study, the following assumption are made:

1).- Loads are modeled as constant power in all the nodes.

2).- Active power in all the generators is specified.

3).- There are reactive power limits in all the generators.

4).- The tap position is nominal in all transformer.

5).- The commutation of the STATCOM to the system is instantaneous.

B. Selection of contingencies

The contingencies applied to the 39-buses power system shown in the Fig. 5 are the following:

a). – tripping the line 2-19

b). – tripping the generating unit 6.

The approach for selecting these contingencies is explained in section 3.4.

C.Key System Parameter (KSP) determination

The voltage stability margin is a measure of what so close it is the system to the voltage instability. The voltage stability margin is generally defined as the difference between the KSP value in the point of the CBO and the voltage stability critical point [10]. In the analysis that is carried out, the total increment of load is chosen as the KSP.

D. Voltage stability approach specification

In this paper a previous calculation of the voltage stability margin using single-phase load flows is carried out. Thus, the approach for selecting the contingencies was the line and the generator that had the smallest voltage stability margin in this single-phase study, see section 3.2. The CBO's stability margin becomes 2511.05 MW. The margin of the line's contingency is 2204.82 MW and that of the generator becomes 1714.86 MW.

E. Voltage stability margin calculation

This analysis is carried out through the calculation of the P-V curves. P-V curves are sometimes called V-P, but taking into account the terminology conventionally used in the curves of the type *x-y*, it is better to name them P-V, since P denotes the independent variable [3]. They are a graphic of the total power active demand versus the voltage magnitude in some of the nodes. The procedure for obtaining such curves is described in the following.

1)The CBO

Beginning with the CBO load conditions, the load and the generated active power are increased gradually. In each step a load flows solution is obtained, this way the P-V curve is built. The voltage stability critical point is obtained when, for a certain value of the KSP, solution doesn't exist for the load flows algorithm. The increment in the load from the point of the CBO until the voltage stability critical point (nose of the curve P-V) is the voltage stability margin for the CBO [1].

The index taken as the stop criterion within the load flows algorithm, is the smallest eigenvalue in the reduced Jacobian, which is calculated starting from the submatrices of the total Jacobian in the following way [2]:

$$J = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \qquad (15)$$

$$J_{RED} = J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \qquad (16)$$

While increasing the load, the smallest eigenvalue in J_{RED} tends toward zero.

2) Unbalanced system

Once established the CBO reference parameters, a mechanism is defined to produce an unbalanced condition in the three-phase power system; this is carried out so much in the same proportion for the active as well as the reactive power. This procedure is schematically shown in Fig. 6.

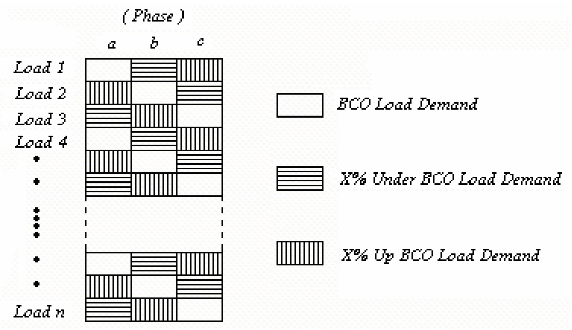


Figure 6. Unbalance applied in three-phase system.

In general, the voltage unbalance doesn't exceed 1% [7]. Thus, the settled down factors in the simulation are 1.7% below the demand of the CBO, and 3.2% for the case above the CBO. The unbalanced condition shown in Fig.

6 remains for the two operative states, without and with compensation by the STATCOM. For the unbalanced case, the P-V curve is calculated following the same steps described in section *1*

3) Applying a contingency to the unbalanced system

For each one of the load levels of the unbalanced case the contingency is applied; similarly to the precedent sections the corresponding load flows solutions are obtained. The last load level for which solution of load flows exists is the critical point of post-contingency, and the increment in the load pre-contingency of the system until the critical point of post-contingency it is the voltage stability margin for the applied contingency.

F. Design and validation of corrective measures

One of the main objectives of this work is to evaluate the STATCOM's operation for improving the voltage stability margin, so this is the elected device to compensate the system.

To know where the STATCOM should be connected, a short circuit capacity (SCC) study is carried out. In the analysis the following approach is elected; the nodes are enumerated in an upward way according to their SCC, from such a list the generating nodes are eliminated, in such a way that only in the load nodes it is feasible to connect the STATCOM, and of these ones that of smaller SCC is chosen. Based on this procedure the node 32, Fig. 5, is elected to connect the STATCOM to increase its voltage stability margin.

4. SIMULATIONS.

For the development of this stage all points mentioned in section 3 are taken into account. Fig. 7 depicts the flow chart representing the sequence of events for constructing the P-V curves by the aforementioned strategy.

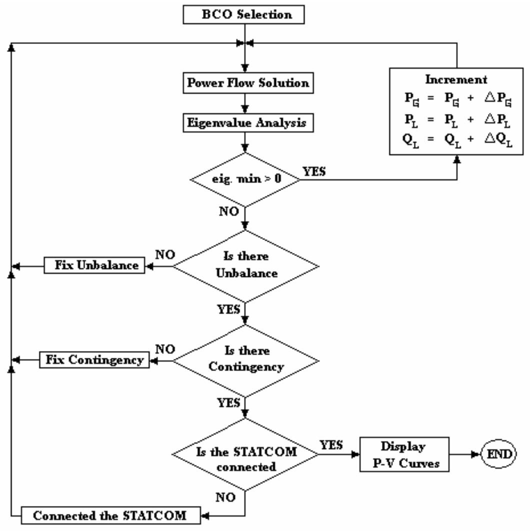


Figure 7. Flow chart for the P-V curves calculation.

In summary, the operating conditions are:
Case 1: three-phase balanced (CBO).
Case 2: three-phase unbalanced.
Case 3: three-phase unbalanced with contingency.
Case 4: three-phase unbalanced with contingency and the STATCOM's compensation.

Since the STATCOM is installed at node 32, it is for this node that the P-V curve is evaluated. Fig. 8 exhibits the operating condition for case 1 and case 2.

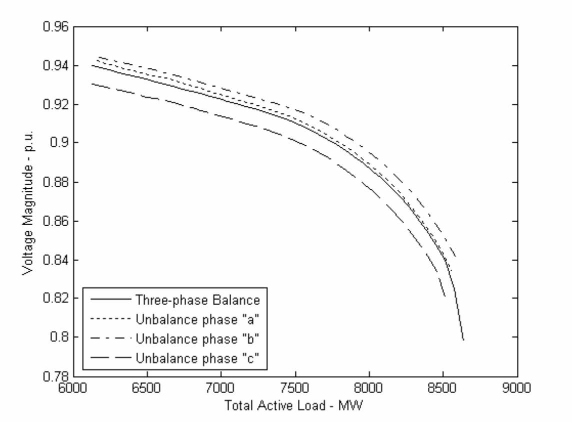


Figure 8. P-V curves at node 32.

Table I presents the voltage stability margin for each one of the four mentioned cases when both contingencies are applied.

TABLE I
VOLTAGE STABILITY MARGIN (MW).

CASE	LINE'S CONTINGENCY			GENERATOR'S CONTINGENCY		
	PHASE "A"	PHASE "B"	PHASE "C"	PHASE "A"	PHASE "B"	PHASE "C"
1	2511.1	2511.1	2511.1	2511.1	2511.1	2511.1
2	2402.1	2409.3	2390.2	2402.1	2409.3	2390.2
3	1847.8	1853.3	1838.6	1478.2	1482.6	1470.9
4	2278.2	2285.7	2267.8	1601.4	1606.2	1593.4

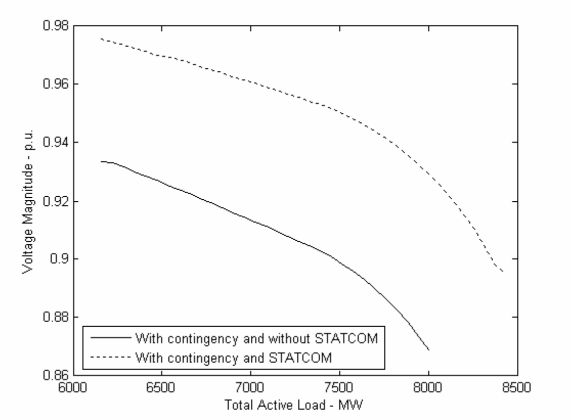


Figure 9. P-V curves at node 32, phase "a".

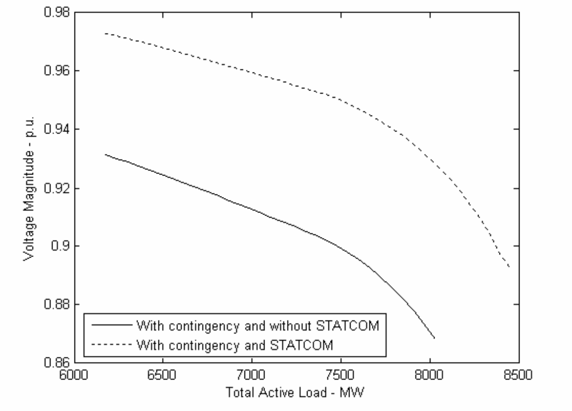


Figure 10P-V curves at node 32, phase "b".

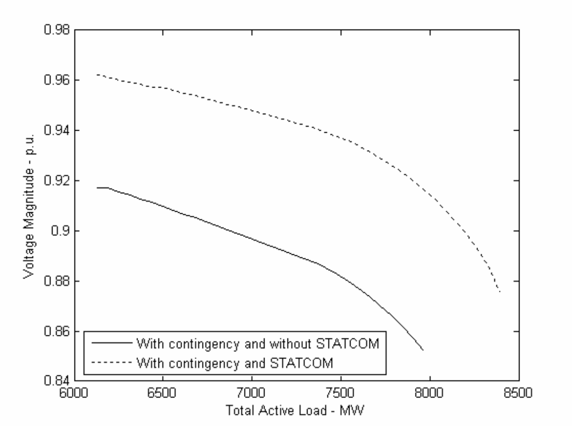


Figure 11. P-V curves at node 32, phase "c".

Analyzing the results of Table I, it is appreciated that the voltage stability margin for the three-phase unbalanced system diminishes around 4% per phase respect to the CBO, representing about 100 MW less margin in order to the system experiences problems of voltage instability.

Now, analyzing the cases 3 and 4 that correspond to the condition without and with compensation, respectively, when the contingency is implemented, it is proven that although the STATCOM doesn't help significantly to improve the existent unbalance in the system in face of such load conditions, it helps to increase in more than 10% the voltage stability margin.

Regarding the voltage level at node 32, Figs. 9-11 show the case when the line's contingency is implemented.

The Figs. 9-11, represent each one of the phases in the node 32. In these Figs. two operative states are exhibited, case 3 and case 4. The solid line represents the case with contingency and without compensation, where the maximum loadability point is reached around 8000 MW and the voltage magnitude decays below 0.85 p.u. The dotted line indicates that the STATCOM is connected to the system and it works so that it increases the voltage level in the node and therefore it increases the voltage stability margin. In such circumstances the maximum loadability point increases from 8000 MW to 8450 MW, thus increasing the voltage stability margin in 5% approximately; the voltage magnitude in the three phases is also around 0.9 p.u.

In Tables II-III the STATCOM's parameters are shown for the case 4 in face the two contingencies.

TABLE II

STATCOM PARAMETERS WITH LINE'S CONTINGENCY

Parameter	CBO Conditions		
	Phase a	Phase b	Phase c
Voltage Magnitude (p.u.)	1.1	1.1	1.1
Phase Angle (Deg.)	-5.88	-126.07	-248.95
Supply Reactive Power (MVar)	137.20	142.27	148.56

(a)

Parameter	Collapse Conditions		
	Phase a	Phase b	Phase c
Voltage Magnitude (p.u.)	1.1	1.1	1.1
Phase Angle (Deg.)	-33.29	-152.77	-273.88
Supply Reactive Power (MVar)	227.47	231.06	242.95

(b)

TABLE III

STATCOM PARAMETERS WITH GENERATOR´S CONTINGENCY

Parameter	CBO Conditions		
	Phase a	Phase b	Phase c
Voltage Magnitude (p.u.)	1.1	1.1	1.1
Phase Angle (Deg.)	-18.98	-138.22	-260.07
Supply Reactive Power (MVar)	146.58	146.72	154.12

(a)

Parameter	Collapse Conditions		
	Phase a	Phase b	Phase c
Voltage Magnitude (p.u.)	1.1	1.1	1.1
Phase Angle (Deg.)	-34.24	-153.54	-274.44
Supply Reactive Power (MVar)	211.56	210.35	218.61

(b)

The Tables II-III stand out the following points. If it is desired to maintain the voltage magnitude in the node 32 around 1 p.u. under the load conditions outlined in [5], that is the case analyzed in this paper, the STATCOM violates its operation limits beginning the CBO's conditions, and consequently for higher load levels.

5. CONCLUSIONS

It is concluded that the STATCOM improves the voltage magnitude considerably in the compensated node, around 5% in the three phases, achieving besides the fundamental objective aimed in this paper; that is, the improvement of the voltage stability margin. Also, the model of the STATCOM used under stronger load conditions that those used in [6], it doesn't help to correct the actual unbalance in the system, since once reached their voltage magnitude limits, it is no longer able to control the voltage magnitude in the node of the system, causing the continuation of the existing unbalance among the phases of the same one. Thus, deal with this inconvenience, the acting of the STATCOM is acceptable, since if voltage dependent loads are included, this helps to improve its performance and it gets around problems of voltage instability.

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