Study of a STATCOM Application for Voltage Stability Evaluated by Dynamic PV Curves and Time Simulations

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Abstract: *In this paper, voltage stability is evaluated by both dynamic PV curves and time-domain simulations, considering the combined dynamic control effects of a static compensator (STATCOM) and transformer on-load-taps (OLT). The studied system is heavily loaded at two locations and an 80 Mvar STATCOM is connected to improve the voltage stability of entire system for a contingency of a three-terminal line outage. The results presented in this paper: (a) show that a STATCOM can greatly improve the voltage stability of a heavily loaded system, (b) quantify the combined impacts of STATCOM and OLT control; (c) illustrate that the margin of stability can be easily and effectively evaluated by PV curves; (d) correlate time-domain simulations and PV curves for a system with a STATCOM and OLT dynamic control.*

Keywords: FACTS, STATCOM, Voltage Stability, PV Curve, Stability Margin, Voltage/Var Control

1. INTRODUCTION

With the ongoing deregulation of the electric utility industry, numerous changes are continuously being introduced to a once predictable business. With electricity increasingly being considered as a commodity, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. In addition, dynamic reactive power support is becoming more important, especially in urban areas where local (i.e., at the load) generation is being reduced or eliminated. In the deregulated utility environment, financial and market forces will demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. Power electronic based equipment, such as FACTS controllers, with their capability to rapidly respond to system events, increase power transfer limits, and improve the quality of power delivered, constitute one of the most-promising technical advancements to address the new operating challenges being presented today [1, 2, 12].

This paper focuses on one such FACTS controller for voltage support as a dynamic reactive power (var) source, namely the static compensator (STATCOM). Typically, the first step in providing voltage/var support in a power system is with the application of shunt capacitors, shunt reactors, and transformer on-load-taps (OLT). Therefore, combined control of this discrete-acting existing equipment with a continuously controlled dynamic device, such as a STATCOM, becomes important for the overall technical and economic operation of the system [11].

Typically, time-domain simulations are employed to analyze the performance of power systems containing both conventional equipment and FACTS controllers for voltage/var support. This approach, however, usually requires a large number of study cases at different system operating conditions and contingencies to evaluate the relationship between system and control parameters and voltage stability.

The application of PV curves also provides a means to evaluate the voltage stability of a power system for various conditions and contingencies [3, 4, 5]. Evaluations of voltage stability for an AC/DC hybrid system and for a system with FACTS controllers were reported in [6, 7, 8]. However, performance of conventional equipment for voltage regulation, (e.g., shunt capacitors, shunt reactors, OLTs) has not always been considered. Furthermore, combined control of conventional equipment and FACTS controllers should be considered for various operation conditions from light load to heavy load, not just around peak point of PV curve.

In this paper, power system performance is evaluated considering both OLT and STATCOM applications for voltage/var support. Both PV curves and time-domain simulations are carried out and compared to verify the agreement between two study methods. In addition, an index value, namely "Margin of Stability," is applied. It is shown that this index value is an effective means in which to evaluate the impacts of the system and control parameters on voltage stability.

2. MODELING AND TEST SYSTEM FOR ANALYSIS

2.1 Modeling of the STATCOM

Figure 1 shows a stability model for a STATCOM. For the simulations contained in this paper, the STATCOM is applied for voltage regulation with a slope reactance (i.e., droop) of 3%. The time constant of the STATCOM control is 50 milliseconds. The STATCOM is modeled as a current source, based on its inherent characteristics [12].

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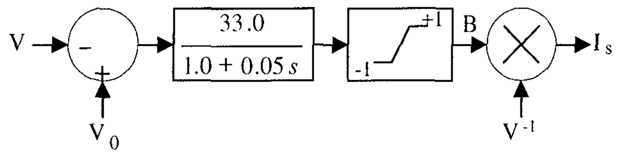
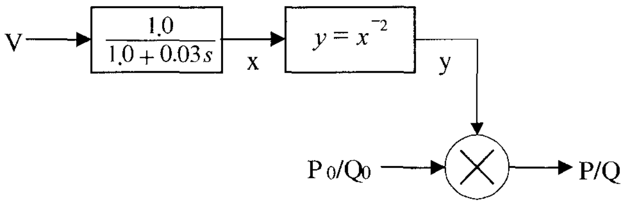


(V: Voltage, B: Susceptance, Is: STATCOM Current)

Figure 1. Modeling of the STATCOM

2.2 Modeling of the Load

The load model, shown in Figure 2, is applied considering its dynamic characteristics. For the time-domain simulations, the load is modeled by constant impedance characteristics for the fast (transient) portion and by constant MVA for the slow (steady-state) portion. For the PV curve simulations, the load is modeled as constant MVA.



(V: Voltage, P: Active Power, Q: Reactive Power)

Figure 2. Modeling of the load

2.3 Modeling of the OLT

The OLT adjusts the tap position of the transformer to maintain the secondary winding voltage at 1.0 p.u. The tap position changes when a volt-seconds quantity becomes larger than a set value. Figure 3 illustrates the volt-seconds quantity, which is an integral that initiates when the voltage exceeds a set deadband as shown by the area highlighted with the oblique-lines in the figure. After the tap position changes, the volt-seconds quantity is reset.

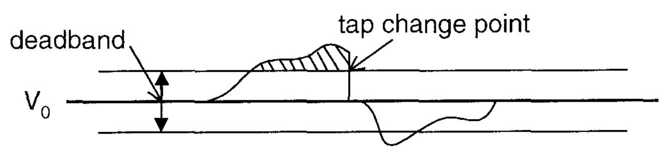


Figure 3 Measured quantity to change tap position

The tap position range is from 0.96 p.u. to 1.15 p.u., with a tap step of 0.01 p.u. When the controlled (secondary) voltage becomes higher than the setpoint+deadband, the tap position moves in steps of 0.01 p.u. to decrease the load voltage. When the controlled (secondary) winding voltage of the transformer becomes lower than the setpoint-deadband, the tap position moves in steps of 0.01 p.u. to increase the load voltage. The maximum and minimum levels are defined according to actual data of a transformer OLT and so variations of the tap position interval were not considered in this study.

2.4 The Studied System

The system studied in this paper has a radial configuration and is heavily loaded at two buses, as shown in Figure 4. Each of these buses is connected to two transformers with OLTs, for a total of four OLT transformers. Each OLT controls the load bus voltage to 1.0 p.u. by changing its tap position. The STATCOM is installed at bus N5. Table 1 shows the power line and transformer data. Table 2 shows the load data at buses N4 and N5.

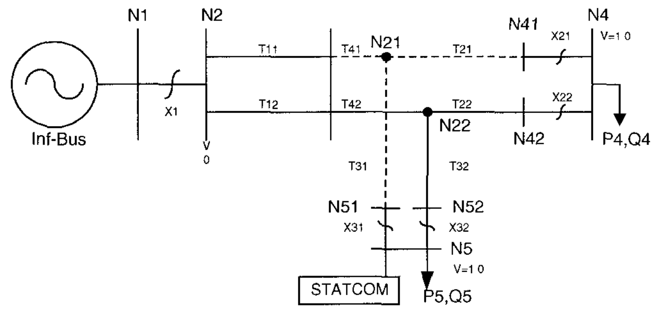


Figure 4. Study system

Table 1
Power Line Impedance Data

Line	R (%)	X (%)	B (Y/2) (%)
T11,T12	3.1	43.3	0.074
T21,T22	1.4	13.5	1.2
T31,T32	0.22	3.1	0.85
T41,T42	0.64	9.0	0.024

Table 2
Load Data

	N4	N5
P	234 MW	363 MW
Q	53.3 Mvar	82.6 Mvar

* *Operating point for the time-domain simulations shown in this paper*

2.5 Definition of Margin of Stability

The "Margin of Stability" applied in this paper is simply the difference in active power between operating point and the peak value (i.e., nose point) for a specific contingency, as illustrated in Figure 5. This difference is defined as "Loading Margin" in some papers [4, 9]. When this margin is relatively large for a particular operating point and contingency, there need not be an urgent concern with respect to voltage instability. In the next section, this Margin of Stability will be used as an index value.

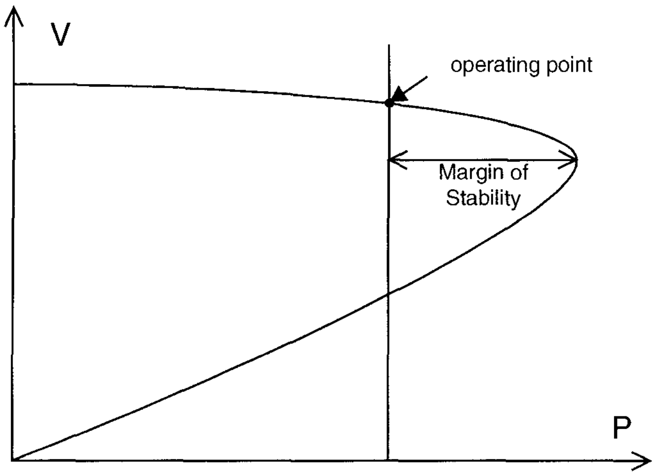


Figure 5. Definition for the Margin of Stability

3. SIMULATION RESULTS

For the system shown in Figure 4, two cases are simulated by two methods each, as explained in the following subsections (i.e., time domain and PV curves). One case is with an 80 Mvar STATCOM installed at bus N5 (labeled in the plots as "With STATCOM") and the other case is with no STATCOM installed in the system (labeled "Base Case" in the plots). The voltage of infinite generator bus (N1) is set as 1.05 p.u.

3.1 Time-Domain Simulation Results

Time-domain simulations were performed for a three-terminal line outage (shown by the dotted line in Figure 4) for both the system with the STATCOM and without STATCOM. For this outage, the steady-state load level at bus N4 and bus N5 is as shown in Table 2.

The time-domain simulation results for these two cases are shown in the comparison plots in Figures 5 to 9, where the dashed line is the "Base Case" and the solid line is the system "With STATCOM". Although voltage collapse occurs in the base case, it does not occur with the STATCOM in-service. Note that even with STATCOM in-service, this line outage results in some voltage drop at the load buses, with the deviation at bus N4 larger than that at bus N5, which is because the STATCOM is installed at bus N5. The STATCOM is able to rapidly regulate voltage and reaches its maximum leading reactive power limit following this line outage. Then, a short time later, the tap positions of the OLTs are gradually changed to their maximum level thus reducing the STATCOM output toward a lower value. This has the benefit of partially resetting the STATCOM output so that it is, at least partially, ready for the next system event. The remaining OLT connected to bus N4 initiates its action earlier than the remaining OLT at bus N5 because the STATCOM is located at bus N5.

At the end of the 1200-second (20 minute) simulation for this specific operating condition and contingency, the system reaches a new steady-state value. In this steady-state condition, the voltage deviation at bus N4 is 0.038 p.u. and the voltage deviation at bus N5 is only 0.017 p.u., with the leading reactive power of the STATCOM at -44 Mvar (-0.044 p.u.), which is only 55% of its rated capacity.

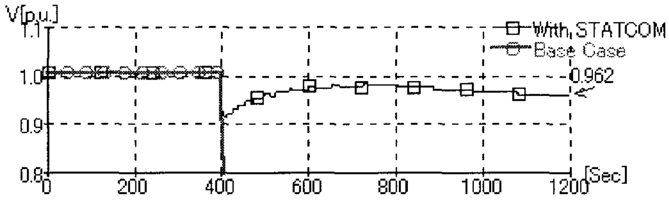


Figure 5. Voltage at N4

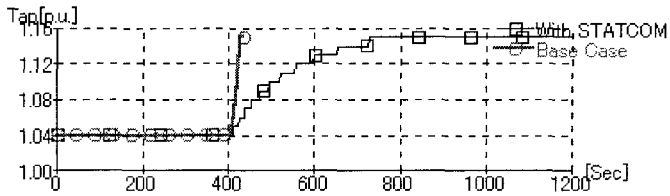


Figure 6. Tap ratio at N4

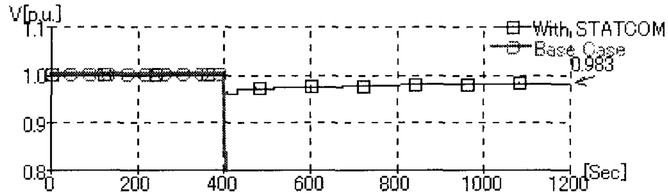


Figure 7. Voltage at N5

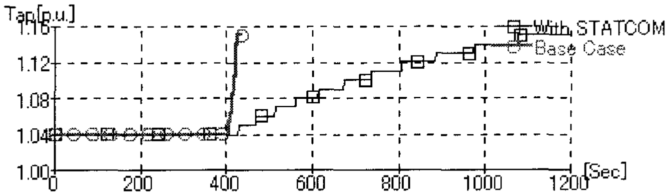
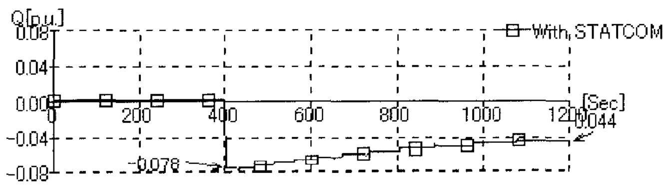


Figure 8. Tap ratio at N5



(lagging reactive power: +)

Figure 9. STATCOM output at N5

3.2 Dynamic PV Curve Simulation Results

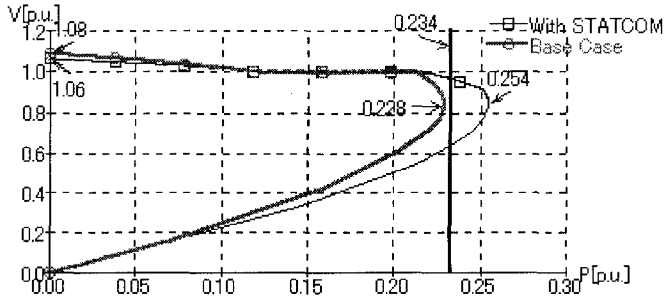
Dynamic PV curve simulations were also performed for the same contingency of the three-terminal line outage, shown by the dotted line in Figure 4, for both the case with STATCOM and without STATCOM. At the beginning of this PV curve simulation, the loads at bus N4 and bus N5 were set to 0. Then, the loads were gradually increased, keeping the same load power factor as shown in Table 2. The transformer OLTs were active during the load ramp.

The dynamic PV curve simulation results are shown in Figures 10 to 14, where the dashed line is the "Base Case" and the solid line is "With STATCOM". Figures 10 and 12 show the relationship between voltage and active power at bus N4 and bus N5, respectively (i.e., the PV curve). The vertical straight lines in Figures 10 and 12 indicate the active power of the load in the time-domain simulations, as listed in Table 2 and described in Section 3.1. Some basic observations based on these two figures are as follows:

1. The peak (i.e., nose point) of PV curve for the case "With STATCOM" is larger than for the "Base Case".
2. The voltage increases significantly over 1.0 p.u. for light load conditions for the "Base Case", but with the STATCOM in-service, the voltage is better regulated at light load conditions, particularly at bus N5, where the STATCOM is located.
3. On the stable operating side (i.e., upper side) of the PV curve with the STATCOM in-service, the voltage is relatively flat at 1.0 p.u. with respect to load active power at bus N5. This shows the effects of STATCOM operation for voltage regulation.

The tap response is shown in Figure 11 for bus N4 and Figure 13 for bus N5. Although the tap position remains at its lower limit for light load conditions, as the load is increased the tap position is adjusted to regulate the load bus voltage to near 1.0 p.u. With the STATCOM in-service, the load point at which the tap positions begin to adjust is higher than the base case with no STATCOM.

Figure 14 shows the relationship between the active power at bus N5 and the reactive power of the STATCOM. The STATCOM output is at a lagging reactive power operating point of +55 Mvar (+0.055 p.u.) for light load conditions but gradually moves toward a leading reactive power as the is load increased during the simulation, until it reaches its maximum leading reactive power output of -78 Mvar (-0.078 p.u.). When the OLT operation begins, at a load active power level near 250 MW (0.25 p.u. power in Figure 14), the STATCOM reacts to the changing tap positions as shown by the discrete changes in the curve of Figure 14. After the STATCOM outputs reaches its maximum leading reactive power of -78 Mvar (-0.078 p.u.), as the voltage decreases (due to voltage collapse), the STATCOM output is reduced accordingly because of its constant current characteristics (i.e., the STATCOM var output is a function of V*x*I). This can be seen in Figure 14.



(1000 MW=1.0 p.u.)

Figure 10. PV curve at N4

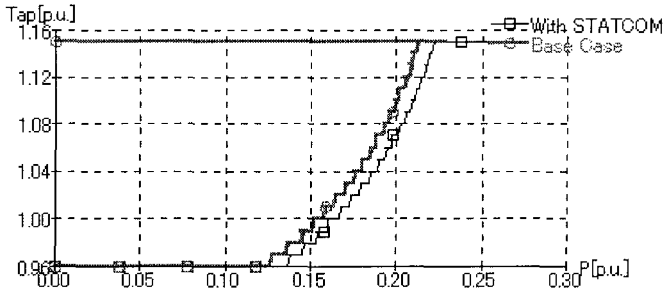


Figure 11. Tap ratio at N4

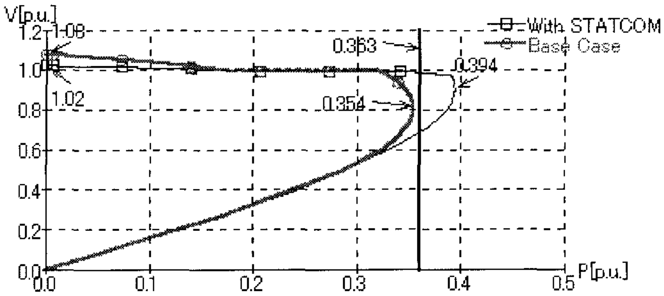


Figure 12. PV curve at N5

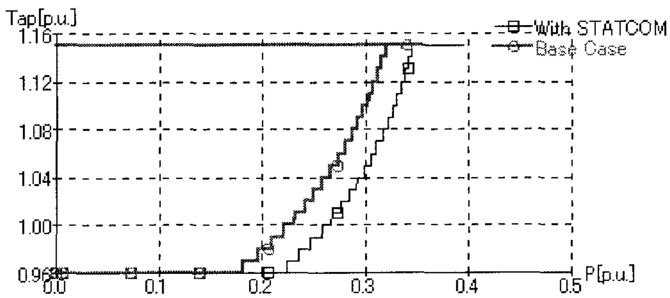
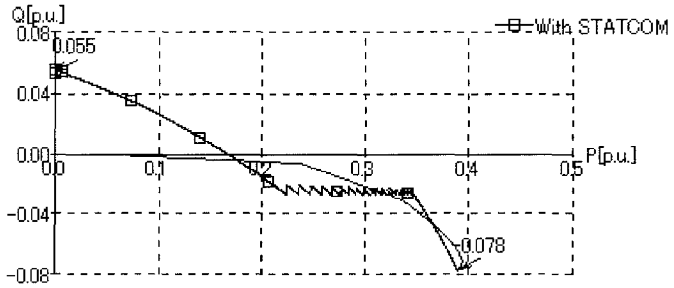


Figure 13. Tap ratio at N5



(lagging reactive power: + , 1000 Mvar=1.0 p.u.)

Figure 14. STATCOM output at N5

3.3 Comparison Simulation Results

The results presented in Sections 3.1 and 3.2 are compared in this section. For the time-domain simulations it was observed that voltage collapse occurred in the base case without the STATCOM, but was avoided with the STATCOM in-service. For the dynamic PV curve simulations the operating point simulated in the time domain was illustrated by a vertical line in the PV curves in Figures 10 and 12, where it was shown that the load was beyond the maximum power transfer in the base case without STATCOM (unstable), but intersects the PV curve with the STATCOM in-service (stable).

For the specific operating point simulated in the time-domain simulation plots shown in Section 3.1, the active power and the voltage at bus N4 was 234 MW (0.234 p.u.) and 0.962 p.u., respectively, and at bus N5 they were 363 MW (0.363 p.u.) and 0.983 p.u. The reactive power of the STATCOM was -44 Mvar (-0.044 p.u.) in the steady state following the line outage.

For the dynamic PV curve simulation, the vertical load line at 234 MW (0.234 p.u.) intersects the PV curve at a voltage of 0.962 p.u. in Figure 10 for bus N4. The vertical load line at 363 MW (0.363 p.u.) intersects the PV curve at a voltage of 0.983 p.u. in Figure 12 for bus N5. Figure 14 shows the reactive power of the STATCOM as -44 Mvar (-0.044 p.u.) at the point where active power is 363 MW (0.363 p.u.) for bus N5. This confirms that the two different methods of simulation, namely time domain and PV curve, lead to the same results. However, the PV curves are much more illustrative because they cover a wide range of system operating conditions, whereas the time-domain simulations are for only one operating point.

3.4 Investigation by the "Margin of Stability" Index Value

Voltage stability is affected by various parameters, including the following:

- Voltage of the generator bus
- Rating of STATCOM

The Margin of Stability will change whenever either one or both of these parameters are modified. By changing these parameters, the change in the "Margin of Stability" was investigated via PV curve simulations, with the results shown in Figures 15 and 16.

Figure 15 shows the change in the "Margin of Stability" in p.u. of active power (y-axis) when the generator bus voltage is changed from 1.0 p.u. to 1.05 p.u. to 1.1 p.u. (x-axis). For these simulations, the base operating point is taken as shown in Table 2, which is illustrated by the vertical lines in Figures 10 and 12 (i.e., at a load level of 234 MW at Bus N4 and 363 MW at bus N5). The rating of the STATCOM at bus N5 remained constant at 80 Mvar. Figure 15 shows that the generator bus voltage must remain at least slightly above 1.0 p.u. to maintain a positive margin of stability for both buses N4 and N5 with an 80 Mvar STATCOM at bus N5.

Figure 16 shows the change in the "Margin of Stability" in p.u. of active power (y-axis), for the same base operating point as shown in Table 2, as the STATCOM rating is changed from 0 Mvar to 80 Mvar to 160 Mvar (x-axis). Here, the generator bus voltage is kept constant at 1.05 p.u. in each of the simulations. Figure 16 shows that there is a negative margin of stability in Figure 16 with no STATCOM. In other words, a voltage collapse is to be expected for this condition, as confirmed in both the time-domain and PV curve simulations. Although it is difficult to see exactly, it should be noted that the lines in Figure 16 (and Figure 15) are not perfectly straight (i.e. linear), as observed in some papers [10]. Figure 16 indicates that the 0 MW Margin of Stability point occurs with a minimum STATCOM rating of about 20 Mvar. Therefore, it can be concluded that a minimum of 20 Mvar of STATCOM is needed to maintain voltage stability in this studied system for the loading conditions listed in Table 2 for the three-terminal line outage.

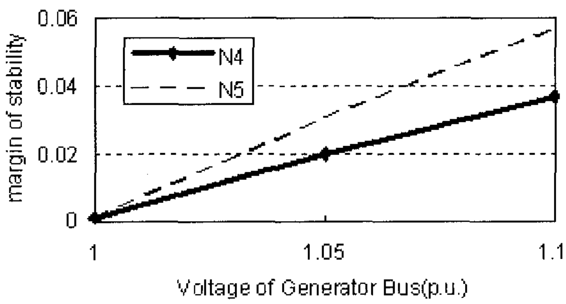


Figure 15. Relation between the generator voltage and margin of stability (with 80 Mvar STATCOM at bus N5)

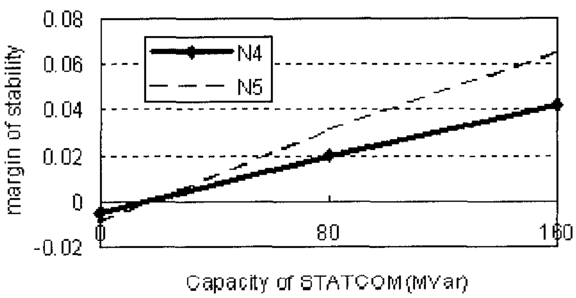


Figure 16. Relation between capacity of a STATCOM at bus N5 and the Margin of Stability (voltage of generator bus: 1.05 p.u.)

4. CONCLUSIONS

In this paper, PV curves and time-domain simulations were applied to evaluate voltage stability of a power system with a STATCOM and OLTs. Results from the PV curve simulations were verified by time-domain simulations. It should be noted that PV curves provide much more information on the relationship between system and control parameters and voltage stability, over a wide range of operating conditions. An index value, "Margin of Stability" was effectively used here to illustrate the impact on the voltage stability for changing system parameters.

It was also shown that a STATCOM can improve system voltage performance both for heavy load conditions and light load conditions. It is expected that detailed design studies for an actual power system including a STATCOM, OLTs, and shunt capacitors will be carried out using this study method and will reported on later.

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