Bulk Power Systems Dynamics and Control IV–Restructuring, August 24-28, 1998, Santorini, Greece.

Using FACTS Controllers to Maximize Available Transfer Capability

Claudio A. Cañizares
University of Waterloo
E&CE Department
Waterloo, ON, Canada, N2L 3G1
claudio@iliniza.uwaterloo.ca

Alberto Berizzi
Politecnico di Milano
Dipartimento di Elettrotecnica
20133 Milano, Italy
berizzi@etec.polimi.it

Paolo Marannino
Universita di Pavia
Dipartimento di Ing. Elettrica
27100 Pavia, Italy
mara210@ipv36.unipv.it

***Abstract*—This paper concentrates on studying the effect of SVC and TCSC controllers on the Available Transfer Capability (ATC). Standard voltage collapse techniques are used to determine the ATC of a test system, considering a variety of system limits. Then, based on second-order sensitivity analysis, optimal locations for these particular FACTS controllers are determined; these techniques are compared to eigenvector analysis methodologies that have been successfully used for optimal placement of FACTS controllers. Finally, using proper models of SVC and TCSC controllers, the effects of these FACTS controllers on the system ATC are studied. The Italian system is used as a test bed, computing the system ATC for a given generation and loading pattern. All realistic control limits, as well as voltage dependent loads, are used in the ATC computation, with and without FACTS controllers.**

Keywords: FACTS, SVC, TCSC, ATC, bifurcations, modeling

I. Introduction

With the deregulation of electricity markets around the world, there is a clear need for adequate computations of the Available Transfer Capability (ATC) in power systems, as this quantity has a direct effect on production and transmission cost signals. Realistic computations of ATC require considering various system limitations such as maximum loadability, bus voltage and transmission current limits as well as reactive and active power generator limits, as indicated in [1, 2, 3]. The current paper presents the computation of the ATC for the Italian system for a given loading and generation pattern which is of particular interest, using similar computational strategies as those used in [1], i.e., techniques based on determining voltage stability limits directly associated to voltage collapse conditions (saddle-node bifurcations), while considering most realistic system limits.

It is a well known fact that transmission system power capabilities, and hence the system ATC, can be directly influenced by shunt and series compensation [4]. In [5], the author demonstrates the existence of optimal compensation levels and proposes new techniques to compute these values based on bifurcation theory. The concepts proposed in this paper are used here to determine compensation levels that maximize the ATC of the Italian system.

The appearance of Flexible AC Transmission System (FACTS) controllers, which are power-electronics-based devices designed for the direct control of ac transmission lines, is completely changing the way transmission systems are controlled and operated [6, 7]. Most FACTS controllers are basically based on variable shunt and/or series compensation of transmission systems; hence, it is important to study the effect of these controllers on ATC, so that design techniques can be developed to maximize ATC at minimum costs. The optimal location of these controllers is determined in this paper using first and second order sensitivity analysis, as described in [8] and [9], respectively. The techniques proposed in [8] are then used to design "optimal size" shunt and series FACTS controllers, specifically, Static Var Compensators (SVCs) and Thyristor Controlled Series Capacitors (TCSCs) [10], that maximize ATC.

Finally, based on the effect of load modeling in voltage collapse phenomena, as demonstrated in [11], the influence of voltage dependent loads on ATC and the proposed FACTS controller design techniques are also studied on the Italian system.

Section II briefly presents all the basic concepts on which the analysis techniques presented here are based; this section also describes the basic structure and operation of SVCs and TCSCs. In Section III, the techniques used for the "optimal" design of the controllers are presented. Finally, Section IV presents the results of applying the proposed design techniques to the Italian system.

II. Basic Concepts

The design techniques proposed in this paper are based on basic voltage stability concepts. A brief discussion of these concepts follows, together with a basic description of the operation, control and modeling of the two FACTS controllers, namely, SVC and TCSC, used throughout the paper.

A. Voltage Collapse

Voltage collapse studies and their related tools are typically based on the following general mathematical description of the system:

$$\begin{aligned} \dot{x} &= f(x, y, \lambda, p) \\ 0 &= g(x, y, \lambda, p) \end{aligned} \quad (1)$$

where $x \in \Re^n$ represents the system state variables, corresponding to dynamical states of generators, loads, and any other time varying element in the system, such as FACTS controllers; $y \in \Re^n$ corresponds to the algebraic variables, usually associated to the transmission system and steady-state element models, such as some generating sources and loads in the network. The parameters $\lambda \in \Re^l$ stand for a set of "non-controllable" parameters that drive the system to collapse, and typically represent the somewhat random changes in system demand. On the other hand, the parameters $p \in \Re^k$ are used here to represent system parameters that are directly controllable, such as shunt and series compensation levels.

Based on (1), the collapse point may be defined, under certain assumptions, as the equilibrium point where the related system Jacobian is singular, i.e., the point $(x_o, y_o, \lambda_o, p_o)$ where

$$\begin{bmatrix} f(x_o, y_o, \lambda_o, p_o) \\ g(x_o, y_o, \lambda_o, p_o) \end{bmatrix} = F(z_o, \lambda_o, p_o) = 0 \quad (2)$$

and its Jacobian $D_zF|_o$ has a zero eigenvalue (or zero singular value) [12]. This equilibrium is typically associated to a saddle-node bifurcation point [13].

For a given set of controllable parameters p_o, voltage collapse studies usually concentrate on determining the collapse or bifurcation point (x_o, y_o, λ_o), where λ_o typically corresponds to the maximum loading level or loadability margin in p.u., %, MW, Mvar or MVA, depending on how the load variations are modeled and defined. The objective of this paper is to find the "optimal" values of p that maximizes a given cost function directly associated with the value of λ at the collapse point, as proposed in [5, 8]. Based on bifurcation theory, two basic tools are typically applied to the computation of the collapse point, namely, direct and continuation methods [14]; the current paper makes extensive use of continuation methods to determine the desired collapse point.

Since one is mostly interested in the collapse point and its related zero eigenvalues and eigenvectors (or zero singular values and vectors), it has been shown in [15] that not all dynamical equations are of interest; precise results may be obtained if the set of equations used in the computation of the collapse point adequately represents the equilibrium equations of the full dynamical system. Control limits are of great importance in this case, as these have a significant effect on the values of $(x_o, y_o, \lambda_o, p_o)$; this has been clearly illustrated for generators in [16, 17]. Hence, an adequate subset of equations of (2) is used here, where all steady state device models and related control limits are properly represented, particularly those associated with FACTS controllers.

The ATC is typically defined as the maximum power that can be transmitted from one system area into another while the system remains "secure." This definition hinges on the loose word secure, which may have different meanings. This may mean that transmission voltages should be kept within somewhat arbitrary limits, e.g., in the 0.9-1.1 p.u. range; or that transmission system device currents should be below certain thresholds, which are typically defined in terms of the thermal ratings of these devices. Hence, transmission system operators can take action when monitored voltages and/or currents approach an "undesirable" limit. However, an ATC definition based on these types of limits is overly conservative, restricting the types of transactions that can take place in the system based on somewhat arbitrary limits that do not accurately represent the actual system ability to deliver the desired power, resulting in loss revenue.

B. ATC

In this paper, the ATC is more precisely defined as the maximum power that the system can transmit between areas of interest before the system collapses, while transmission system currents are kept within "realistic" limits, i.e., below thermal limits, at "reasonable" load voltage levels, as suggested by other authors, e.g., [2]. This ATC definition based on the voltage collapse point is certainly more adequate, since it is based on the fact that the stability region "shrinks" as the system approaches collapse [5], and hence this value represents better the system's ability to deliver power. From the operational point of view, however, this is not the most appropriate definition, as in practice the system should not be allowed to get to the collapse point, or too close to it for that matter, due to the reduction in system stability margins. In this case an index such as the one defined in [1] would be more appropriate so that operators can monitor this value and take early action when it falls below certain thresholds. However, for this paper, the ATC definition proposed here is sufficient, since this value will be used only to evaluate the effect of different FACTS devices on the system ability to deliver a given power.

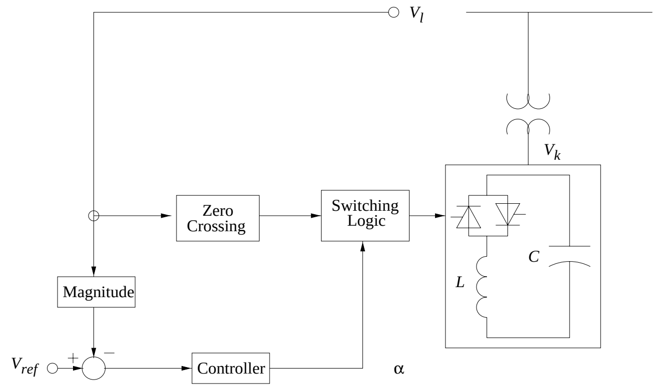


Fig. 1. Basic SVC structure.

C. SVC

Each phase of this FACTS controller is typically made up of a thyristor-controlled reactor (TCR) in parallel with a fixed capacitor bank; the system is then shunt connected to the bus through a step-up transformer bank to bring the voltages up to the required transmission levels, as depicted in Fig. 1 [10]. By controlling the firing angle α of the thyristors (the angle with respect to the zero crossing of the phase voltage), the device is able to control the bus voltage magnitude, as changes on α basically result on changes in the current and, hence, the amount of reactive power consumed by the inductor L; for $\alpha = 90°$ the inductor L is "fully on", whereas for $\alpha = 180°$ the inductor is "off." The continuous switching operations of the TCR generate certain harmonic pollution on the voltage waveforms that have to be taken into account for the design and operation of the controller.

The basic control strategy is typically to keep the transmission bus voltage within certain narrow limits defined by a controller droop and the firing angle α limits ($90° < \alpha < 180°$). However, more sophisticated control strategies may be implemented, such as reactive power control or oscillatory damping controls of various kinds.

For the studies carried out in this paper, which concentrate on steady state analyses of balanced, fundamental frequency phenomena, an adequate SVC controller model that captures the typical voltage control strategy and its related limits is all that is required. Thus, the equivalent reactance and control model proposed in [8] is used for all studies in this paper, which can be summarized in the following per-unit equations:

$$\begin{aligned} V_l - V_{REF} + X_{SL} V_k B_e &= 0 \qquad (3) \\ Q_{SVC} - V_k^2 B_e &= 0 \\ \pi X_C X_L B_e + \sin(2\alpha) - 2\alpha + \pi\left(2 - \frac{X_L}{X_C}\right) &= 0 \end{aligned}$$

where V_l stands for the controlled bus voltage magnitude; V_k represents the TCR and fixed capacitor voltage magnitude; V_{REF} is the controller set point and X_{SL} stands for the droop; Q_{SVC} is the controller reactive power; B_e is the equivalent susceptance of the TCR and fixed capacitor combination; and X_L and X_C correspond to the fundamental frequency reactance of L and C, respectively.

D. TCSC

This FACTS controller basically consists of the same TCR and fixed capacitor parallel combination used in the SVC but

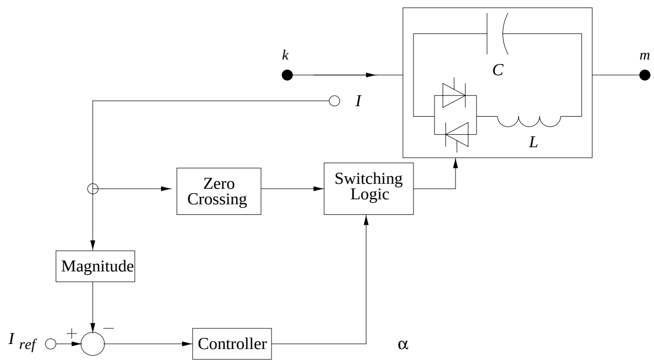


Fig. 2. Basic TCSC structure.

connected in series with a transmission line [10]. Due to the series connection, there is no need in this case for a transformer bank to change the controller voltages. Figure 2 depicts the typical basic structure and control strategy of this controller. The device is usually designed to directly control line currents, but various other strategies can be used to control line impedance or power flows, damp oscillations, etc.

The limits on the firing angle α for the TCSC controller are different than the ones used for the SVC, as there is a resonance region where the controller becomes an open circuit and, hence, it must be avoided in a series connection. Furthermore, the controller is designed to mainly operate in the capacitive region in steady state, to reduce harmonic pollution of the current waveforms. Thus, for this paper, $\alpha_r < \alpha < 180°$, where α_r corresponds to the resonant point (this value depends on the ratio X_C/X_L).

The following fundamental frequency, steady state model proposed in [8] is used here to model this controller:

$$
\begin{aligned}
P + V_k V_m B_e \sin(\theta_k - \theta_m) &= 0 \quad (4)\\
-V_k^2 B_e + V_k V_m B_e \cos(\theta_k - \theta_m) - Q_k &= 0\\
-V_m^2 B_e + V_k V_m B_e \cos(\theta_k - \theta_m) - Q_m &= 0\\
B_e - \pi \left(k_x^4 - 2k_x^2 + 1\right) \cos k_x(\pi - \alpha) / & \\
\Big[X_C \, \big(\pi \, k_x^4 \cos k_x(\pi - \alpha) & \\
-\pi \, \cos k_x(\pi - \alpha) - 2\, k_x^4 \alpha \, \cos k_x(\pi - \alpha) & \\
+2\, \alpha \, k_x^2 \cos k_x(\pi - \alpha) - k_x^4 \sin 2\alpha \cos k_x(\pi - \alpha) & \\
+k_x^2 \sin 2\alpha \cos k_x(\pi - \alpha) - 4\, k_x^3 \cos^2 \alpha \sin k_x(\pi - \alpha) & \\
-4\, k_x^2 \cos\alpha \, \sin\alpha \cos k_x(\pi - \alpha)\big)\Big] &= 0\\
\sqrt{P^2 + Q_k^2} - I\, V_k &= 0
\end{aligned}
$$

where $V_k\angle\theta_k$ and $V_m\angle\theta_m$ are the terminal phasor voltages of the controller; Q_k and Q_m are the reactive power injections at both controller terminals; P and I are the active power and current flowing through the controller, respectively; B_e is the equivalent susceptance of the TCR-fixed-capacitor combination; X_C and X_L are the fundamental frequency reactances of C and L; and $k_x = \sqrt{X_C/X_L}$. By fixing the value of one of the controller variables, one can model different types of controls; for example, by defining the value of I, equations (4) can be used to simulate a TCSC controller operating in current control (droop could be also included).

III. Analysis Techniques

As previously discussed, the definition of ATC used in this paper, for the purpose of designing FACTS controllers to "maximize" system transfer capability, is based on basic voltage collapse concepts that are in turn grounded on bifurcation theory [13]. The ATC is then formally defined here as the difference on active power flowing into a system area between the base case and the voltage collapse (saddle-node bifurcation) point for a given generation and load pattern. Thus, to compute the ATC value, one has to first define the power transaction to be studied, i.e., the generation and load pattern, and then determine the voltage collapse point using any of the techniques developed to calculate this point; in this paper, the continuation method is used to determine this point, as described in detailed in [13]. If there is no bifurcation point for the system under analysis, as in the case of the Italian System with voltage dependent load model, the ATC will be defined as the maximum change in area power flow.

A detailed description of the techniques used to determine the optimal location and size of the FACTS controllers to maximize the ATC defined in this paper follows.

A. *Bifurcation-based Tools*

In [5], the author studies in detail the effect of the controllable parameters p on the bifurcation behavior of equations (1), proposing a series of numerical techniques to compute the optimal values of p that maximize the "distance" to a bifurcation point. The paper demonstrates the advantages of maximizing this distance from the point of view of system stability, since the system becomes generally "more stable" as the distance to a bifurcation point is increased. In [8], the authors use these basic concepts and some of the related numerical techniques to design FACTS controllers to maximize the system distance to collapse, and hence improve system stability.

The techniques used here to determine the optimal location and size of SVCs and TCSCs to increase ATC are based on the methodologies proposed in [8], and are summarized below. The original techniques are based on determining a saddle-node bifurcation point; however, in the current paper these are modified to consider systems that do not present a bifurcation point and only have a maximum area power transfer point, which is defined here as the ATC point.

1. For the given generation and load pattern, determine the collapse or bifurcation point. If there is no bifurcation point, determine the maximum area power transfer equilibrium point. Either one of these equilibrium points yields the desired ATC value, and is referred to as the ATC point in this paper.

2. The largest entries corresponding to bus voltage magnitudes in the "zero" right eigenvector at the collapse point can then be used to pinpoint the buses or area where SVCs may be located to have the most effect on distance to collapse. For systems without bifurcation, use the maximum voltage entries in the tangent vector, i.e., $\mathrm{d}x/\mathrm{d}\lambda|_o$ in equations (2), at the corresponding ATC point.

3. The lines that present the largest change in power flow between the base case and the ATC point are considered to be the best candidates for placing TCSC controllers.

4. Determine the manifold of ATC points with respect to the controllable parameters p. The simplest way of obtaining this manifold is to continuously vary p and compute the corresponding collapse or ATC points; however, more efficient continuation techniques may be used here as proposed in [5].

5. To determine the "optimal" controller size from the ATC point of view, one should define a cost function that takes

into account the change on the ATC (ΔATC) due to the controller and the cost of this controller. In the case of the SVC, the controller size (the size of the TCR and capacitor bank), and hence its cost, is defined in terms of its reactive power rating, whereas for the TCSC the size is defined by the impedance of the corresponding transmission line and the desired compensation levels. Thus, the controller cost functions used in this paper are defined as

$$f_{SVC} = \frac{\Delta ATC\ [\text{MW}]}{Q_{SVC}\ [\text{Mvar}]} \quad (5)$$

$$f_{TCSC} = \frac{\Delta ATC\ [\text{MW}]}{X_e\ [\%]} \quad (6)$$

The optimal SVC and TCSC controllers would be the ones that maximize functions (5) and (6), respectively.

6. The SVC and TCSC X_C/X_L ratio and control set points, droops and limits are defined based on stability studies; for this paper, typical values are used. Thus, for the SVC, a 1 pu set point and a 2 % voltage droop are used here, i.e., $V_{REF} = 1$, and $X_{SL} = 0.02$ in equations (3); and $X_L = 0.52 X_C$, so that $Q_{SVC_{\max}} \approx -Q_{SVC_{\min}}$. For the TCSC, typical values of $X_C/X_L = 10$ and a 100 % impedance compensation at the minimum firing angle $\alpha_{\min}$ are assumed here; the value of $\alpha_{\min}$ is chosen based on equations (4), so that $X_e(\alpha_{\min}) = X_{line} \approx -5X_C$

B. *Second Order Sensitivity Analysis*

Alternatively to the methods described above for determining most suitable buses for the installation of SVCs and the most appropriate branches for placing TCSCs, one may use second order sensitivities as proposed here.

Since the ATC definition used in this paper is related to the maximum power exchange between areas before voltage collapse occurs, it is reasonable to assess the quality of a candidate bus/branch by means of voltage collapse related indices or sensitivities. Thus, using the ideas proposed in [9, 18], one can readily determine the sensitivities of a voltage collapse index based on singular values with respect to various system parameters, which in this case are the reactive power injections (SVC) and the branch admittances (TCSC). This voltage collapse index is specifically defined as the minimum singular value of the Jacobian $J = D_z F|_o$ of equations (2), or of an appropriate subset of equations like the load flow equations; the corresponding sensitivities contain second order information, as these are determined based on the system Hessian, as described below.

As it is well known, the Singular Value Decomposition (SVD) of a matrix J is given by

$$J = U \Sigma V^T = \sum_{i=1}^{n} \sigma_i u_i v_i^T$$

where U and V are orthonormal matrices (u and v are the left and right singular vectors respectively), and Σ is a diagonal matrix whose elements σ_i are the singular values of J, ordered in ascending order.

Based on the concepts presented in [18], it is possible to determine the influence of any control parameter p on the minimum singular value $\sigma_{\min}$ of J (or on the maximum singular value $\sigma_{\max}$ of J^{-1}). Thus, following a change Δz about a given equilibrium point z_o, the new Jacobian J' may be approximated by

$$J' = J(z_o + \Delta z) \approx J + H \Delta z$$

where the three dimensional array H is the Hessian of equations (2) evaluated at z_o, i.e., $H = D_z^2 F|_o$, or of an appropriate subset of equations. A change in the r^{th} singular value of J following a change Δp on the controllable system parameters p may be determined by

$$\Delta \sigma_r = -\left[U^T\ H\ J^{-1} \Delta p\ V \right]_{rr}$$

In particular, for the minimum singular value,

$$\Delta \sigma_{\min} = c^T \Delta p$$

where

$$c^T = -v_1^T \left(u_1^T\ H\ J^{-1} \right) J_p$$

and $J_p = D_p F|_o$ in (2). To evaluate the sensitivities of the minimum singular value with respect to power injections in the load flow equations, J_p becomes the unit matrix. On the other hand, if p corresponds to a branch admittance used to evaluate the effect of series compensation in the load flow equations, J_p presents four nonzero elements corresponding to the P and Q mismatch equations at the two buses i and j connected by the branch.

Since $\sigma_{\max} = 1/\sigma_{\min}$, the change $\Delta \sigma_{\max}$ in the maximum singular value $\sigma_{\max}$ of J^{-1} may be computed by

$$\begin{aligned} \Delta \sigma_{\max} &= c_{\max}^T \Delta p \\ &= -c^T \sigma_{\max}^2 \Delta p \end{aligned} \quad (7)$$

Equation (7) has been successfully used in [19] to rank contingencies, and is adopted here to evaluate, from the voltage collapse point of view, optimal locations of shunt and series compensation. It is important to mention that the procedure proposed here to determine the most suitable bus/branch for the insertion of SVCs/TCSCs needs neither the definition of the collapse point nor the definition of the system load change pattern; hence, this technique can be directly applied to the case where the system does not present a bifurcation. This is one of the main advantages of this technique, and has been confirmed in several studies by basically obtaining the same results when the sensitivities are computed at the initial loading conditions as when these are computed at the collapse point. The reason for this is that second order information regarding the system behavior is included in the analysis.

IV. Results

All results presented in this paper were obtained for the Italian power system depicted in Fig. 3. The network under examination corresponds to the ENEL transmission system in its interconnected operation with the European System, and is modeled with about 700 buses, 1100 branches, 123 hydro-units and 109 thermal-units. The system data used here corresponds to the scenario before the blackout that stroke southern Italy in August 1994, characterized by a low load level and a large number of 380 kV lines both in maintenance and out of service to avoid over-voltages. In particular, the interconnection between the northern and the southern (Naples Department) parts of the system was ensured by two of the four 380 kV lines available (Valmontone-Presenzano and Villanova-Larino-Foggia) and by a single 220 kV line (Popoli-Capriati), as illustrated in Fig. 4; the blackout took place when one of the two 380 kV line tripped out (line Valmontone-Presenzano). The total load on the system before the black out was 81700 MW (including the UCPTE equivalent); the load on the Italian system itself was 24000 MW/8200 Mvar.

The load for this system is modeled as follows:

$$\begin{aligned} P_L &= (P_o + \Delta P\ \lambda) V^a \\ Q_L &= (Q_o + \Delta Q\ \lambda) V^b \end{aligned} \quad (8)$$

Fig. 3. The Italian system.

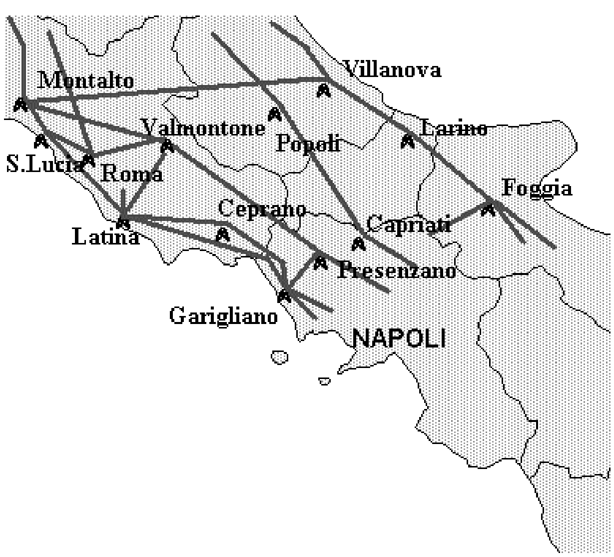


Fig. 4. Main transmission lines feeding the Naples Department.

where P_o and Q_o stand for the base system load; ΔP and ΔQ represent the load variation as defined by the non-controllable parameter λ (loading factor); and a and b define the voltage dependency of the load. Thus, $a = b = 0$ for constant PQ loads, whereas, for voltage dependent loads, the values $a = 1$ and $b = 2.5$ are chosen, as these values have been successfully used to represented the Italian system load in contingency studies. The ATC cases studied in this case correspond to the power transfer from the north and central parts of the Italian system to the southern part of the network, which corresponds to the main power corridor in this system. Thus, the following realistic load and generation patterns are assumed:

- All generators in the Milano, Torino, Venezia, Firenze and Roma areas (north and central Italy) are assumed to supply for the load changes; the European system does not supply power for these changes.
- The load is assumed to only increase in the Naples (70%) and Palermo (30 %) areas for constant PQ loads. For voltage dependent loads, only the loads in the Naples Department are increased.

All Q and S limits on generators as well as limits on the SVC and TCSC controllers were enforced for the ATC computations in all cases. On the other hand, bus voltage and current limits were only monitored and not strictly enforced, as some of these limits overly constrained the transmission system voltages and currents, yielding rather conservative results.

A. Constant PQ Loads

Figure 5 depicts the bifurcation diagram or PV curves for the test system using constant PQ loads. Three bus voltages are shown together with their corresponding voltage limits; these buses belong to the Naples and Rome areas, which undergo the largest voltage changes in the system. Observe that the voltages exceed their limits; however, as indicated before, these limits are not strictly enforced but only monitored. The system presents a collapse point at the maximum value of λ, which corresponds to a maximum total loading condition of 82225 MW and an ATC of 528 MW; for this kind of load model, the value of λ can be directly associated to the total MW loading. It is interesting to notice that the maximum power transfer to the Naples area, which does not correspond to the ATC in this case, does not occur at the collapse or maximum loading point, but on the lower ("unstable") side of the bifurcation diagram.

The collapse in this case is actually due to one of the generators in the Naples area reaching an $S_{\max}$ limit [16]. However, the eigenvectors and singular vectors associated to the smallest real eigenvalue and singular values can still be used in this case to determine the optimal location of the FACTS controllers, due to the proximity of this collapse point to a saddle-node bifurcation (the smallest eigenvalue and singular value is rather close to zero). Thus, Fig. 6 depicts the relative sensitivities of the most significant buses obtained from (a) the bus voltage entries in the "zero" right eigenvector, and (b) the singular value second order sensitivities to changes in the reactive power bus injections computed using (7). From these two graphs, one can first observe that both techniques point to similar system buses, all belonging to approximately the same geographical area, as possible candidates to place a SVC to have the most effect on the distance to collapse. Based on these sensitivity values and the voltage levels of the candidate buses, for both load models, the most adequate bus is determined to be Popoli (220 kV); placing an SVC on any

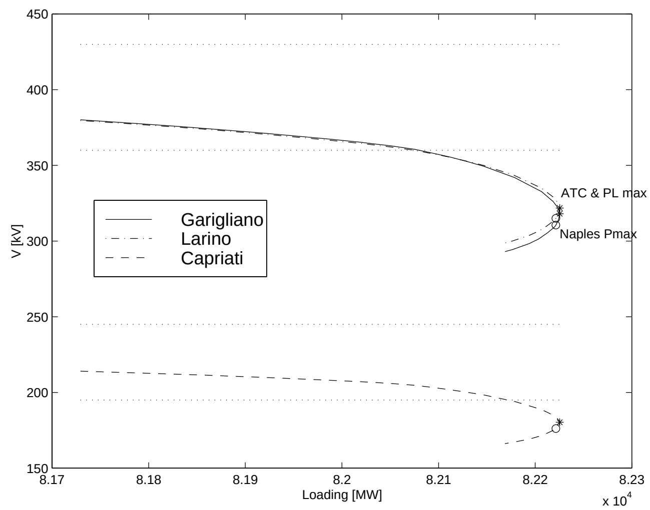
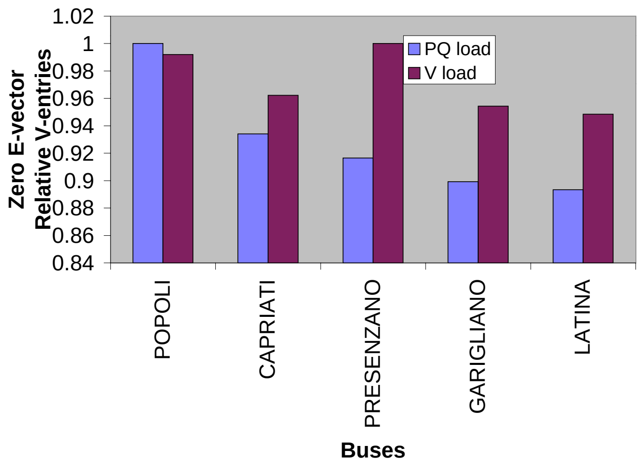
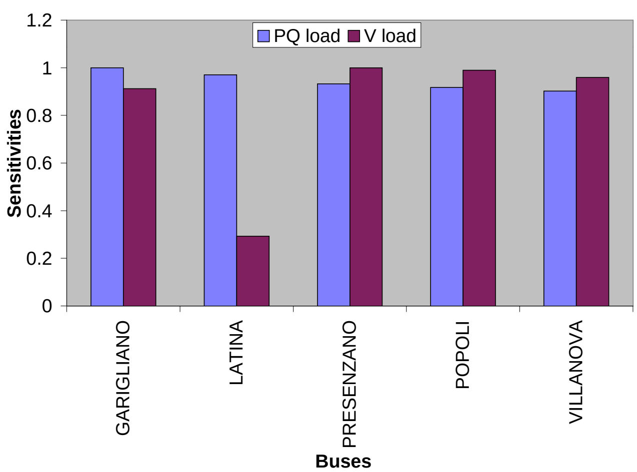


Fig. 5. Basic voltage profiles for constant PQ load model.

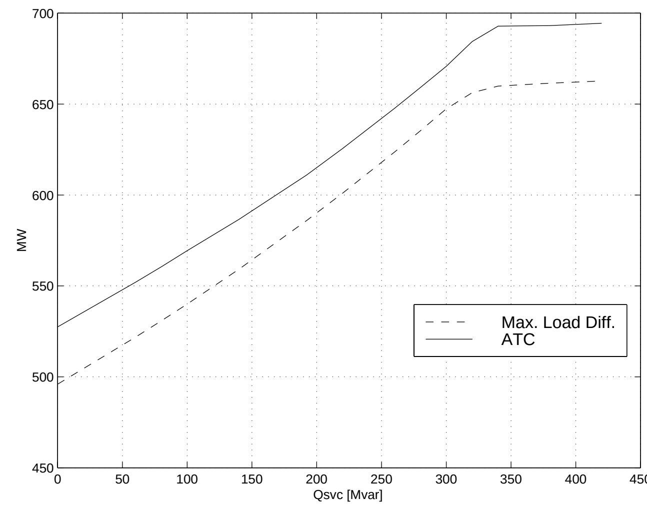


(a)

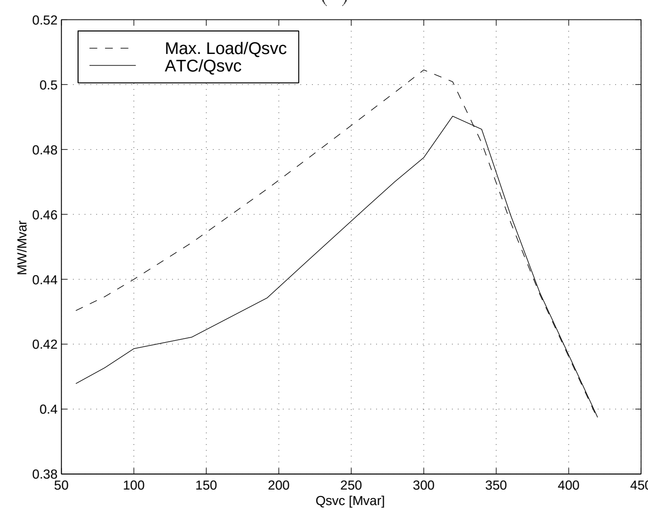


(b)

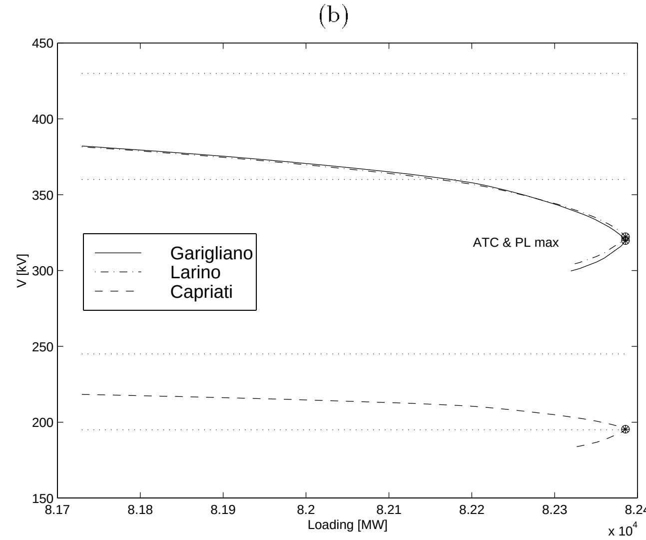
Fig. 6. Normalized bus sensitivities for SVC placement: (a) "zero" right eigenvector analysis; (b) second order sensitivity analysis of singular values at initial loading conditions.



(a)



(b)



(c)

Fig. 7. Results for constant PQ load and SVC at Popoli: (a) maximum loadability and ATC versus SVC rating; (b) optimal SVC rating computation; (c) voltage profiles for optimal SVC ($Q_{SVC} = \pm 320$ Mvar).

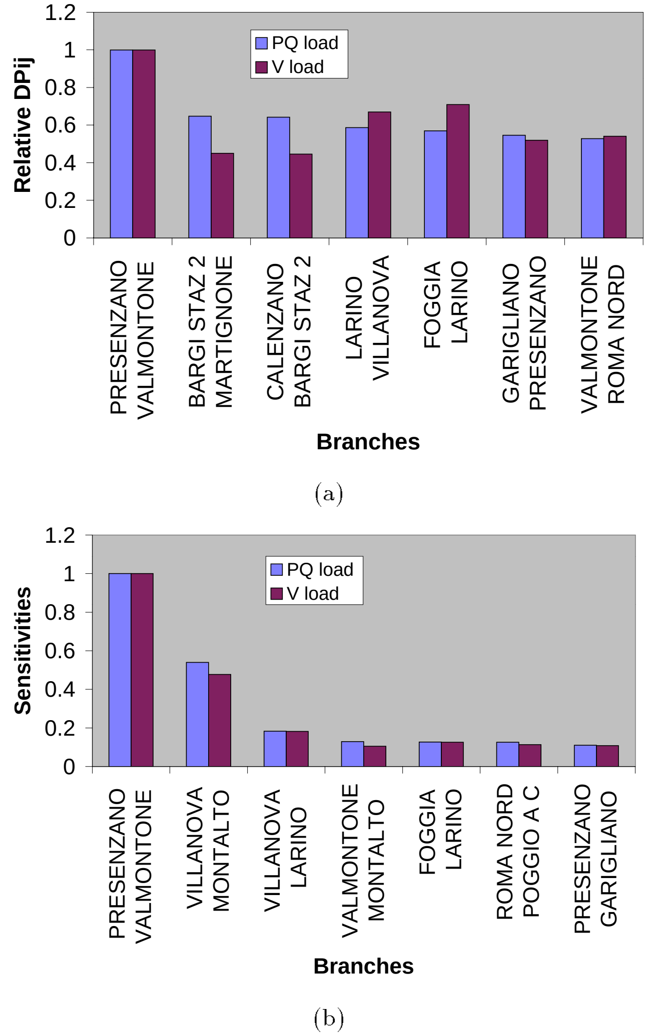


Fig. 8. Normalized branch sensitivities for TCSC placement: (a) relative power flow changes; (b) second order sensitivity analysis of singular values at initial loading conditions.

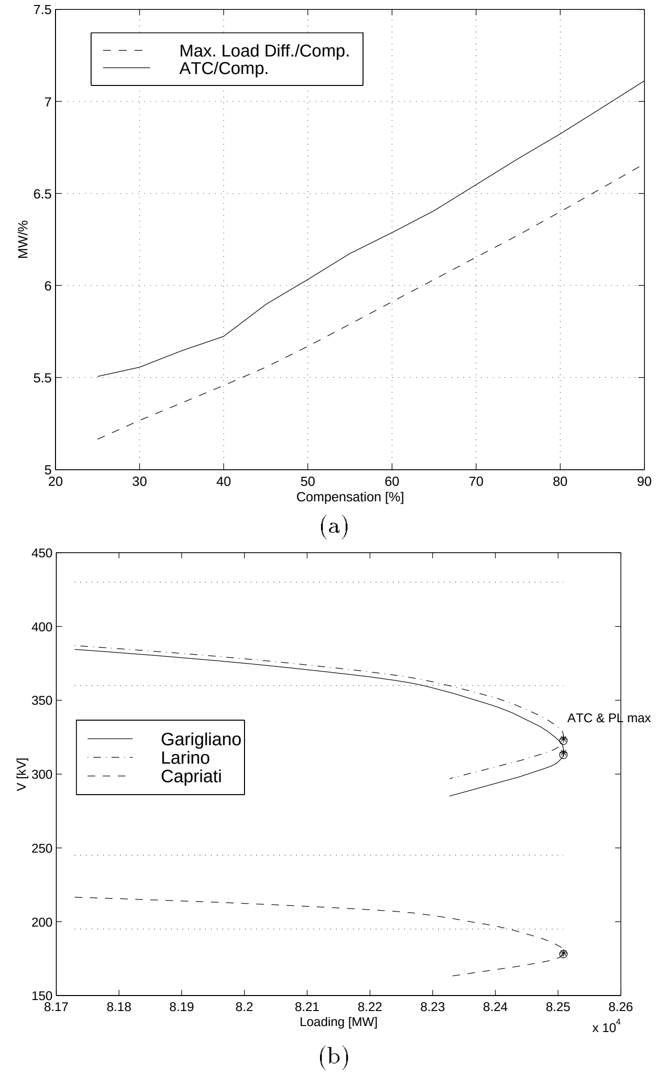


Fig. 9. Results for constant PQ load and TCSC at Valmontone-Presenzano: (a) optimal TCSC compensation computation; (b) voltage profiles for optimal compensation (50%).

other of the candidate buses has basically the same effect on the ATC as the one proposed here.

To obtain the "optimal" reactive power rating for the SVC, the ATC manifold with respect to the SVC Mvar rating is computed, as depicted in Fig. 7(a); the SVC cost function defined in (5) is then calculated and plotted in Fig. 7(b). From this analysis, is clear that a ± 320 Mvar SVC would be the best choice in this case to increase the system ATC; the new ATC value is 684 MW. The manifold corresponding to the maximum loading conditions is also depicted in both of these figures for comparison purposes only. Observe that there is a slight difference on the optimal SVC rating value if this criterion is used; this difference becomes much more significant in the case of voltage dependent load models, as discussed below. Figure 7(c) shows the new bifurcation diagrams or PV curves for the system with the optimal SVC; notice the improvement on the voltage profiles, which is expected due to the voltage control characteristics of the SVC.

To decide on the optimal TCSC controller compensation levels and placement, which define the TCSC size, first and second order sensitivity analyses are carried out, using the techniques previously discussed. The results of these studies are depicted in Fig. 8, and clearly indicate that the Valmontone-Presenzano 380 kV line is the best candidate for connecting the controller in series.

Based on results presented in [8] showing that, to increase distance to collapse, the best TCSC control strategy is to control the line impedance, the optimal impedance compensation level from the ATC point of view is determined using the cost function f_{TCSC} in (6). This cost function is plotted in Fig. 9(a), together with a similar cost function defined with respect to the maximum loading conditions; observe that there is no maximum in this case, leading to the conclusion that any compensation level would result in similarly adequate ATC increments. Hence, a typical 50 % compensation level is chosen in this case, based on stability and harmonic distortion criteria. The voltage profiles for the system with the optimal TCSC controller are depicted in Fig. 9(b); notice that the voltage profiles do not improve significantly with respect to the base case. The optimal TCSC increases the ATC to 829 MW, which is significantly larger than the ATC obtained for shunt compensation with the SVC, which is to be expected given the direct effect that series compensation has on the power capability of the main transmission line feeding the Naples area.

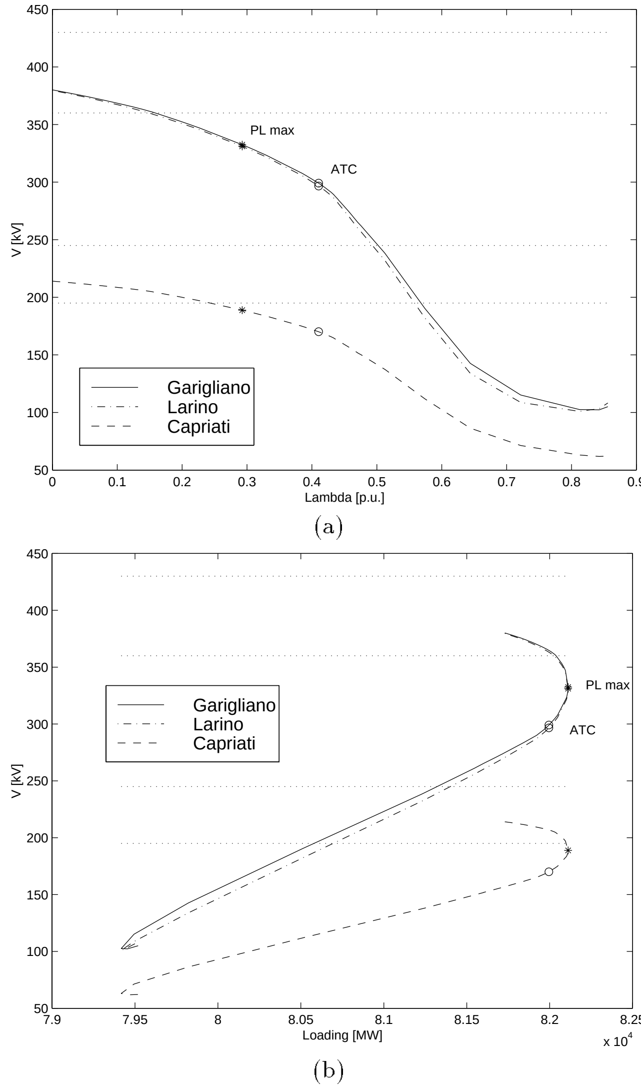


Fig. 10. Voltage profiles for voltage dependent load model: (a) bifurcation diagram; (b) maximum loading. The system does not present a voltage collapse due to bifurcation or control limits.

B. *Voltage Dependent Loads*

Similar studies are carried out for the Italian system using a voltage dependent load with $a = 1$ and $b = 2.5$ in (8), as previously discussed. Thus, Fig. 10 depicts the (a) bifurcation diagram and (b) PV curves obtained without FACTS controllers in the system. First, observe that the system does not present a bifurcation or generator limit (collapse) point, and hence the voltage does not collapse by any of these mechanisms in this case [11]. Second, the ATC (927 MW), defined as the maximum power transferred into the Naples Department, and the maximum loading (82111 MW) points do not coincide in this case, and hence one can expect significantly different results when using each of these criteria to select the optimal controllers, as illustrated below for the SVC controller.

Based on first and second order sensitivity analysis results depicted in Fig. 6, and the cost function f_{SVC} of equation (5) depicted in Fig. 11(a), the optimal SVC, from the ATC point of view, is determined to be a ± 400 Mvar controller located at the Popoli bus. In this case, the new ATC is 1080 MW, and the maximum loading is 82233 MW. Observe that a completely different SVC rating would be obtained if the maximum system loading is used to select the controller. Also, the plot of the f_{SVC} cost function seems to suggest that a low rating SVC (± 60 Mvar) would be more adequate; however, such a small SVC would produce very little change on the ATC (less than 30 MW), that it would not be justifiable in practice. Figure 11(b) shows the system bifurcation diagram for the optimal SVC; notice again the improvement on the voltage profiles and the slight increment on the value of λ at the ATC point.

Finally, following the same design path as before, the optimal TCSC is determined to be located at the same Valmontone-Presenzano 380 kV line, operating at a 50 % compensation level. The later is obtained based on stability and harmonic distortion criteria, as the cost function f_{TCSC} of equation (6) is also inconclusive in this case. The corresponding voltage profiles are depicted in Figure 12. The ATC and maximum loading in this case are 1318 MW and 82366 MW, respectively.

V. Conclusions

This paper discusses in detail proper techniques to locate and size SVC and TCSC controllers from the ATC point of view, and tests the proposed methodologies in a real system. These techniques can be also applied to other FACTS controllers used for shunt and series compensations, such as Shunt and Series Static Var Compensators (STATCOM and SSSC), provided that accurate steady state controller models that take into account control limits and droops are considered. The paper also demonstrates that both first and second order sensitivity information obtained from collapse studies yield basically the same results, which can then be used to determine optimal control parameters to improve system operation.

It is important to highlight the fact that all studies presented in this paper are based on steady state techniques, and no consideration is given here to the dynamic response of the system, which in some cases could also be a determinant factor on the design process of FACTS controllers. Also, the voltage dependent representation of loads in the Italian system require more study, as the operational knowledge of the system does not seem to match very well with some of the results presented in this paper. Nevertheless, the system presented a unique opportunity to develop and test new techniques for the integral design of FACTS controllers.

References

[1] R. P. Klump and T. J. Overbye, "A transmission-based voltage stability measure for available transfer capability (atc) calculations," *Proc. NAPS*, MIT, November 1996, pp. 351–357.

[2] C. A. Ayasum and R. Fischl, "On the region-wise analysis of available transfer capability (atc)," *Proc. NAPS*, Wyoming, October 1997, pp. 464–469.

[3] G. Gross, editor, *Proc. Workshop on ATC*, University of Illinois, Urbana-Champaign, IL, June 1997.

[4] A. R. Bergen, *Power Systems Analysis.* Prentice-Hall, New Jersey, 1986.

[5] C. A. Cañizares, "Calculating optimal system parameters to maximize the distance to saddle-node bifurcations," *IEEE Trans. Circuits and Systems–I*, vol. 45, no. 3, 1998, pp. 225–237.

[6] N. G. Hingorani, "Flexible ac transmission systems," *IEEE Spectrum*, April 1993, pp. 40–45.

[7] D. Maratukulam, editor, *Proc. FACTS Conference I—The Future in High-voltage Transmission*, TR-100504, EPRI, March 1992.

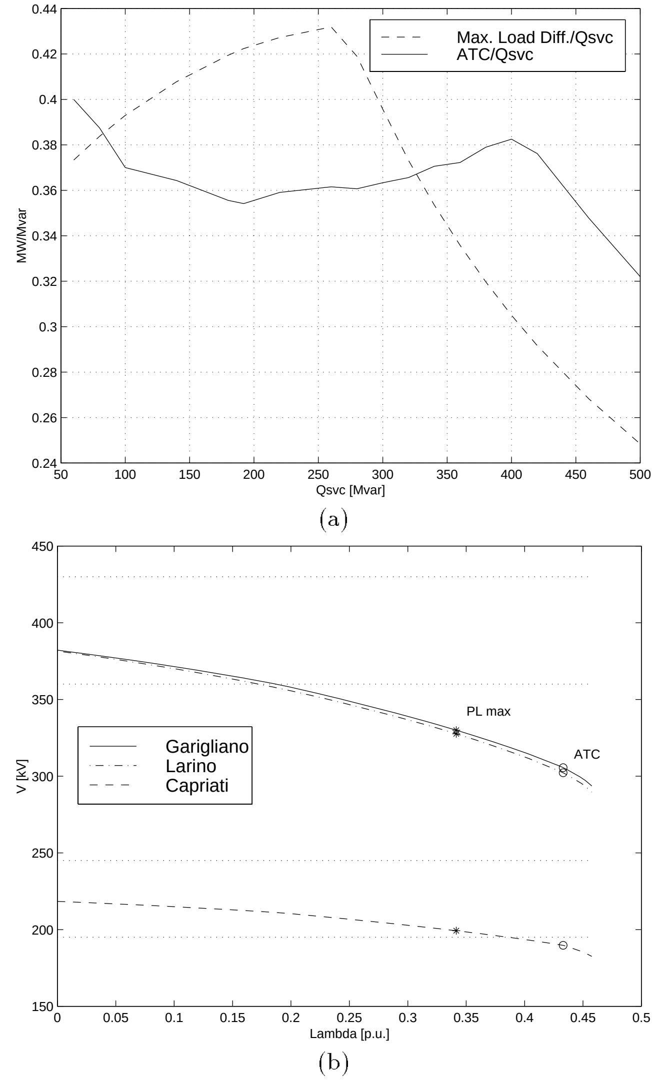


Fig. 11. Results for voltage dependent load and SVC: (a) optimal SVC rating computation; (b) voltage profiles for optimal SVC ($Q_{SVC} = \pm 400$ Mvar).

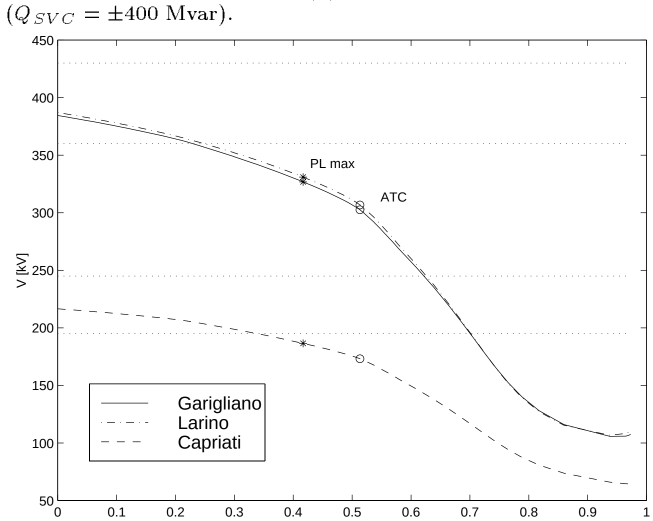


Fig. 12. Voltage profiles for optimal TCSC compensation (50%) with voltage dependent load model.

[8] C. A. Cañizares and Z. T. Faur, "Analysis of SVC and TCSC controllers in voltage collapse," IEEE/PES PE-200-PWRS-0-2-1998, accepted for publication in *IEEE Trans. Power Systems*, March 1998.

[9] A. Berizzi, P. Finazzi, D. Dosi, P. Marannino, and S. Corsi, "First and second order methods for voltage collapse assessment and security enhancement," *IEEE Trans. Power Systems*, vol. 13, no. 2, May 1998, pp. 543–551.

[10] L. Gyugyi, "Power electronics in electric utilities: Static var compensators," *Proceedings of the IEEE*, vol. 76, no. 4, April 1988, pp. 483–494.

[11] C. A. Cañizares, "On bifurcations, voltage collapse and load modeling," *IEEE Trans. Power Systems*, vol. 10, no. 1, February 1995, pp. 512–522.

[12] C. A. Cañizares, "Conditions for saddle-node bifurcations in ac/dc power systems," *Int. J. of Electric Power & Energy Systems*, vol. 17, no. 1, February 1995, pp. 61–68.

[13] P. Kundur, editor, "Voltage stability assessment, procedures and guides," technical report Final draft, IEEE/PES Power Systems Stability Subcommittee, 1998. Available at http://www.power.uwaterloo.ca.

[14] C. A. Cañizares and F. L. Alvarado, "Point of collapse and continuation methods for large ac/dc systems," *IEEE Trans. Power Systems*, vol. 8, no. 1, February 1993, pp. 1–8.

[15] I. Dobson, "The irrelevance of load dynamics for the loading margin to voltage collapse and its sensitivities," pp. 509–518 in [20].

[16] I. Dobson and L. Lu, "Voltage collapse precipitated by the immediate change in stability when generator reactive power limits are encountered," *IEEE Trans. Circuits and Systems—I*, vol. 39, no. 9, September 1992, pp. 762–766.

[17] P. A. Löf, G. Andersson, and D.J. Hill, "Voltage dependent reactive power limits for voltage stability studies," *IEEE Trans. Power Systems*, vol. 10, no. 1, February 1995, pp. 220–228.

[18] A. Tiranuchit and R. Thomas, "A posturing strategy against voltage instability in electric power systems," *IEEE Trans. Power Systems*, vol. 3, no. 1, February 1988, pp. 87–93.

[19] A. Berizzi, Y. G. Zeng, R. Abbruzzetti, M. Delfanti, P. Marannino, and P. A. Scarpellini, "Contingency screening and risk quantification related to voltage collapse in extended real time," *IEE International Conference on Advances in Power System Control, Operation & Management, Hong Kong*, November 1997, pp. 176–181.

[20] L. H. Fink, editor, *Proc. Bulk Power System Voltage Phenomena III—Voltage Stability and Security*, ECC Inc., Fairfax, VA, August 1994.

Claudio A. Cañizares (S'87, M'92) received the Electrical Engineer diploma (1984) from the Escuela Politécnica Nacional (EPN), Quito-Ecuador, where he held different positions from 1983 to 1993. His MS (1988) and PhD (1991) degrees in Electrical Engineering are from the University of Wisconsin-Madison. Dr. Cañizares is currently an Associate Professor at the University of Waterloo and his research activities are mostly concentrated in the study of computational, modeling, and stability issues in ac/dc/FACTS systems.

Alberto Berizzi (M'93) received his M.Sc. degree (1990) and his Ph.D. degree (1994) both in Electrical Engineering from the Politecnico di Milano. Since 1992 he is Assistant Professor at the Electrical Engineering Department of the Politecnico di Milano. His areas of research include power system analysis and voltage stability and control.

Paolo Marannino (M'86, SM'95) received his Dr. degree in Electrical Engineering from the University of Bari (Italy) in 1968. In 1970 he joined the Automation and Computation Research Center of ENEL in Milan, where he has been responsible for research activities in the field of power system analysis, optimization and control. Since 1994 he is a Professor of Electric Energy Systems at the University of Pavia.