Comparing Secondary Voltage Regulation and Shunt Compensation for Improving Voltage Stability and Transfer Capability in the Italian Power System

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Abstract

This paper concentrates on comparing the advantages and disadvantages, including costs, of using Secondary Voltage Regulation (SVR) versus using shunt-connected controllers, in particular Mechanical Switched Capacitors (MSC), Static var Compensators (SVC) and Static Synchronous Compensators (STATCOM), to improve voltage stability (VS) and the external transfer capability (TC) of the Italian power network. Basic VS and TC concepts and tools, as well as the models of the various controllers, particularly SVR, used to obtain the results presented are described in detail. The model of the Italian system used and the assumptions made for these studies are also discussed. The paper demonstrates that SVR is an option that should be seriously considered in practice when trying to improve VS and TC of power systems.

Key words: Secondary voltage control, FACTS, shunt compensation, mechanical switched capacitors, SVC, STATCOM, voltage stability, transfer capability.

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1 Introduction

Secondary Voltage Regulation (SVR), also known as secondary voltage control, has been developed and implemented in various European power networks, particularly in France [1] and Italy [2,3], with the objective of improving system voltage stability (VS). On the other hand, Flexible AC Transmission Systems (FACTS), particularly shunt-connected controllers, are also being considered and used as possible solutions to VS problems and to increase the Transfer Capability (TC) of power systems [4,5]. Hence, Italian researchers, at ENEL and CESI, were interested in carrying out a comparative study of the effects of SVR and shunt controllers on the VS and external TC of the Italian system, given the current interest in increasing the import/export capacity of the network so that Italy and its European neighbors can actively participate on the new electricity markets in the region. This paper presents and discusses the tools, models and results associated with these particular studies to give a general idea of the various issues that were considered during these studies, and the comparative advantages and disadvantages of SVR versus various shunt controllers from both VS and TC points of view for the Italian network.

The effects of SVR in the VS of power systems have been studied and documented (e.g. [6,7]), demonstrating that systems operating under SVR schemes show an increase in TC due to improvements in VS. On the other hand, there are several publications on the use of shunt compensation to improve VS and TC of power networks. For example, in [5], the effects of series and shunt-connected FACTS controllers in VS and TC are studied demonstrating the benefits of introducing these controllers in the system. On the other hand, in [8], Shunt Mechanically-Switched Capacitors (SMSC) are studied from the point of view of improving the VS of a particular power system. All these studies were basically based on loadability margins and PV curves computations, which nowadays are considered standard analysis methodologies for VS and TC studies [9,10], especially when care is taken to properly model all controllers, in particular their control limits [5]. Thus, in the current paper, similar analysis tools and models are used and/or proposed to directly compare the effects on system VS and TC for a detailed power-flow model of the Italian network operating under SVR, versus the use of SMSC, Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM).

Although SVC and STATCOM controllers, as opposed to SMSC, are used to improve the stability of HVDC converters due to their fast response, their practical application in ac transmission systems has been mostly for VS improvement [4], where the voltage control requirements do not demand fast acting controllers. This is the main reason why utilities with that do not face overvoltage problems in their networks, and hence do not require of the inductive support provided by SVC and STATCOM, typically choose SMSC as the solution to their VS problems (e.g. [8]). For these reasons, the studies and comparisons presented here are all based on typical steady-state VS stability analysis techniques. (In various publications such as [11], it is shown that the fast voltage control characteristics of SVC and STACOM controllers may be used to damp power/frequency oscillations, i.e. improve the angle stability of ac networks, by introducing additional controls; however, this particular issue is beyond the scope of the present paper.)

The current paper is structured as follows: In Section 2, the basic concepts and tools used to evaluate the effect on VS and TC of the various controllers are briefly dicussed. The models used for the SVR and the different shunt controllers used in the studies are described in detail in this section. Section 3 compares the results of using the various controllers to improve VS and TC in the Italian system; a brief description of the system model used to obtain these results is also presented here. Finally, Section 4 summarizes the main contributions of this paper.

2 Basic Concepts, Tools and Models

2.1 VS and TC Analysis Tools

All VS studies carried out for the proposed studies consist on obtaining the maximum loadability margin and the voltage profiles for the given system considering critical contingencies, which is a typical procedure for VS and TC studies in power systems [9,10]. The necessary computations are carried out based on an "improved" power flow model, where special care is taken in accurately modeling the steady state behavior and associated control limits of the various controllers used in the system, especially for the generator voltage regulators and their SVR controls, as well as the various shunt controllers used in the studies reported in this paper. Thus, assuming that the proper steady state model of the system is represented by

$$F(x, p, \lambda) = 0 \tag{1}$$

where $x \in \Re^n$ stands for all the system steady state variables, such as load voltage magnitudes V and angles δ; $p \in \Re^m$ represents the various control settings in the system, such as AVR, SVR and shunt controller voltage references; and $\lambda \in \Re^\ell$ stands for uncontrolled parameters that may change during the system operation, such as loading levels. For the purposes of the classical VS studies performed in the present paper, a scalar parameter λ, i.e. $\lambda \in \Re$, is used to simulate load changes in the system as follows:

$$\begin{aligned} P_l &= P_{lo} + \lambda \Delta P_l \\ Q_l &= Q_{lo} + \lambda \Delta Q_l \end{aligned} \tag{2}$$

where P_{lo} and Q_{lo} stand for the base active and reactive power load in the system, respectively, and ΔP_l and ΔQ_l are used to represent a “direction” of active and reactive load change in the system.

For a given set of parameters p, as the load levels typically increase, i.e. as the parameter λ increases, the dynamical system associated with the steady state model (1) may reach a “voltage collapse” point at a “maximum” value λ_*, which is either associated with a singularity of the Jacobian of (1) (a saddle-node bifurcation of the dynamical model) or a particular controller limit (a saddle-node limit-induced bifurcation) [9]. This collapse point is characterized by the system not presenting any more local solutions for its associated power flow equations for $\lambda > \lambda_*$. This point is also referred to as a maximum loadability point, with λ_* representing the maximum loadability margin. Thus, the TC of the system can be expressed in total MW as [10]:

$$\mathrm{TC} = \lambda_* \sum_l \Delta P_l \tag{3}$$

with λ_* corresponding to the maximum loadability of the system for the worst, realistic system contingencies (N-1 contingency criteria). This classical approach for analyzing VS and TC in power networks is applied to the Italian power network when both SVR and FACTS controllers are considered. The tool used to determine the TC of the system under various operating conditions and controllers is UWPFLOW [9,12], which is a freeware continuation power flow that includes detailed steady state models of generators, SVR and several FACTS controllers.

The optimal location and size for the shunt FACTS controllers is determined using the techniques described in [5], which can be summarized as follows:

(1) The best location is decided by using sensitivity information at the maximum loading conditions. Thus, the maximum values of the entries associated with load voltage magnitudes in

$$t_* = \left.\frac{\mathrm{d}x}{\mathrm{d}\lambda}\right|_* = -D_xF|_*^{-1} \left.\frac{\partial F}{\partial \lambda}\right|_* \tag{4}$$

define the candidate buses for shunt compensation. If the Jacobian $D_xF|_*$ is singular, the right-eigenvector associated with the zero eigenvalue, i.e. the vector v defined by $D_xF|_*v = 0$, is used instead of t_* ($t \rightarrow v$ as D_xF approaches the singularity point [13])

(2) The optimal size is determined by computing the maximum amount of reactive power placed at the optimal location that maximizes the value

of TC in (3).

Critical lines for TC computations are identified using a similar sensitivity criteria to the one used to identify the critical buses (the best location for shunt compensation). Hence, the lines with the heaviest load at the maximum loading conditions λ_*, and with the maximum change in transmitted power with respect to changes in system loading, i.e. the maximum $\mathrm{d}P_{line}/\mathrm{d}\lambda|_*$, are chosen as the critical contingencies in the system.

The fact that the shunt FACTS controllers considered here, i.e. SVC and STATCOM, are being used in most practical applications in ac transmission systems for bus voltage control to improve system VS rather than for applications that require the fast response of these controllers, justify the use of typical VS analysis tools for comparison purposes in these paper. However, proper steady state models obtained from detailed dynamic models should be utilized to avoid significant errors in these types of studies [9].

The models discussed here, with the exception of the SVR model, come from the technical literature and are presented here for completeness, and to highlight their features and limitations for the benefit of the reader.

2.2 Models

All the controller models briefly described in this section were originally developed to properly represent the corresponding steady state behavior for VS studies and thus adequately compute TC, with particular attention put in modeling the controller limits, especially the mechanisms to recover from these limits.

2.2.1 Shunt Mechanically-Switched Capacitors (SMSC)

An SMSC typically consist of a set of capacitor banks that control the voltage magnitude at a “remote” bus or at the bus at which they are connected. The capacitor banks, which are defined in terms of their nominal reactive power, are switched on one at a time when the controlled-bus voltage magnitude reaches a minimum value, and they are switched off when the voltage reaches a maximum value. Hence, these controllers can be readily modeled in steady state as depicted in Fig. 1, i.e. as a set of shunt susceptances that are connected or disconnected as the controlled bus voltage reaches a given minimum or maximum value, respectively. Since there is a limited number of capacitor banks, voltage control is lost once all the available capacitance has been added to the system; voltage control is regained once the voltage recovers to its given minimum value.

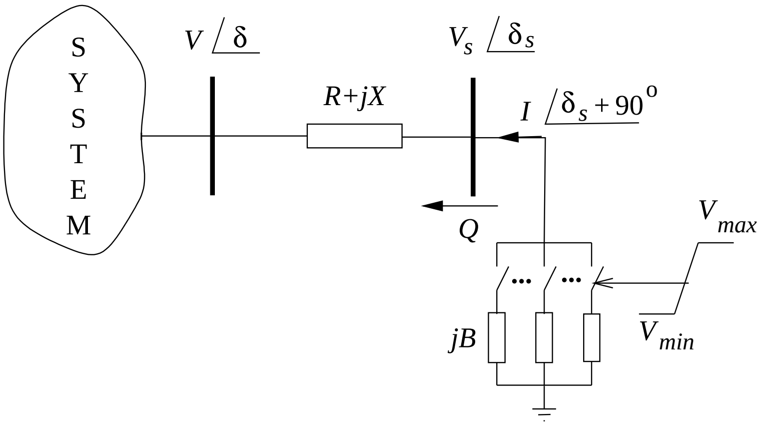


Fig. 1. SMSC steady state model.

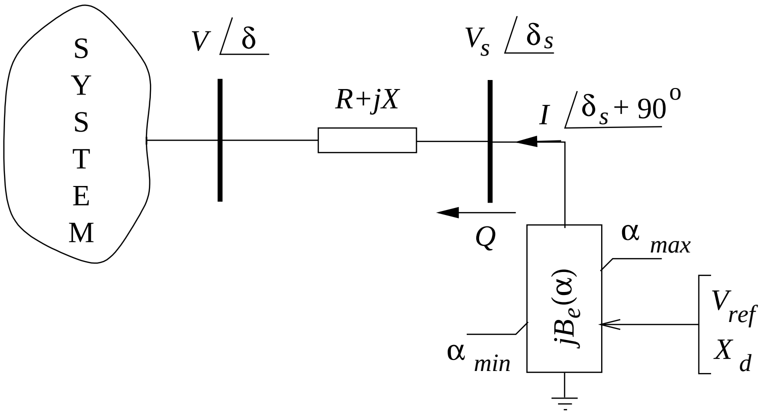


Fig. 2. SVC steady state model.

If, for simplicity, one assumes continuous voltage control, SMSCs can be approximately simulated as a "purely capacitive" SVCs, as explained below.

2.2.2 Static var Compensator (SVC)

The model used here for the SVC is the one proposed in [5], where the controller is modeled as a variable susceptance controlled by the firing angle α of the thyristor-controlled reactor of the SVC. Hence, control limits in this case are directly represented in the firing angle α; however, given the one-to-one correspondence between this firing angle and the corresponding equivalent susceptance value, one could assume that these limits directly correspond to limits on this susceptance, as it is typically done in most power system analysis tools.

The model used throughout this work is depicted in Fig. 2, and is based on the following equations, which assume capacitive behavior, i.e. the controller is delivering reactive power:

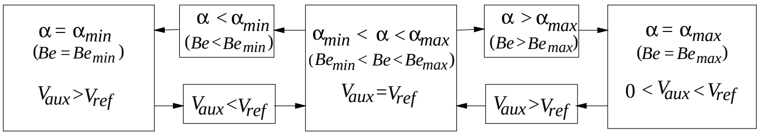


Fig. 3. SVC steady state representation of control limits.

$$
\begin{aligned}
V &= V_{ref} - X_d\, I \\
I &= B_e(\alpha)\, V_s \\
B_e(\alpha) &= \frac{1}{\pi X_L}\left[2\alpha - \sin 2\alpha - \pi\left(2 - \frac{X_L}{X_C}\right)\right]
\end{aligned}
\tag{5}
$$

where V is the voltage magnitude at the bus being controlled; V_{ref} is the desired voltage setting; I is the capacitive current of the SVC, which becomes negative when the controller is operating in inductive mode; X_d stands for the controller droop; B_e represents the equivalent susceptance of the SVC controller which is a function of the firing angle α; and X_C and X_L are the SVC's capacitor and inductor reactances.

The controller can also be modeled in steady state solely by the equivalent susceptance B_e, which is the more "classical" model used in typical stability studies. In this case, the last equation in (5) is not explicitly considered in the solution process; this equation is only used to determine the control limits $B_{e_{max}} = B_e(\alpha_{max})$ and $B_{e_{min}} = B_e(\alpha_{min})$. The limits on α are typically independent on the dimensions of the controller, whereas the limits in B_e are not, and hence have to be determined for the specific controller under study. Observe that this particular model can also be used to approximately model a SMSC operating in "continuous" voltage control by making $B_{e_{min}} = 0$; this model is used here to study the approximate effect of a SMSC on the system.

Limit recovery has to be implemented to properly represent the controller dynamic behavior, so that one can reliably compute the TC associated with these limits. The latter is implemented using the logic depicted in Fig. 3, where, as the voltage increase or decreases, either the limits become active or the controller recovers, depending on the operating conditions, as specified in this figure. The additional variable V_{aux}, where

$$
V_{aux} = V + X_d\, I \tag{6}
$$

is used to keep track of the controlled voltage value at the point where a limit is reached to allow recovery.

2.2.3 Static Synchronous Compensator (STATCOM)

The STATCOM model used here is the one proposed in [14], i.e. a model based on an active power balance between the ac side and dc side of the

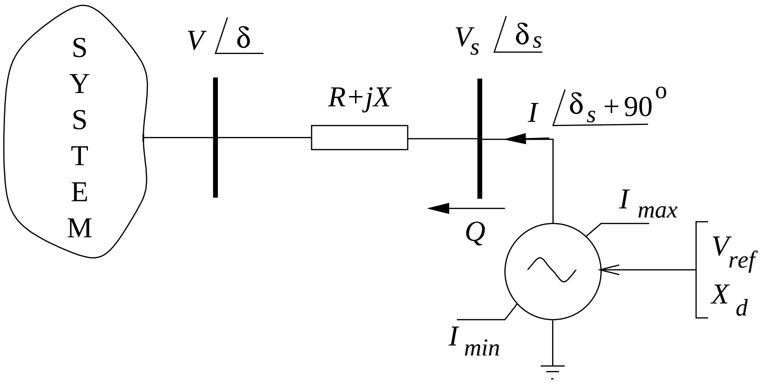


Fig. 4. STATCOM steady state model.

voltage-sourced converter (VSC), which is the main element of a STATCOM. If dc losses in the STATCOM are neglected, as these are typically not very significant, this model can be viewed as a reactive power voltage source model depicted in Fig. 4. Thus, the STATCOM can be modeled in steady state by means of the following equations when delivering reactive power (operating in capacitive mode):

$$\begin{aligned} V &= V_{ref} - X_d \, I \\ I &= Q/V_s \\ 0 &= V_s^2 \, G - V_s \, V \, G \, \cos(\delta_s - \delta) - V_s \, V \, B \, \sin(\delta_s - \delta) \\ Q &= -V_s^2 \, B + V_s \, V \, B \, \cos(\delta_s - \delta) - V_s \, V \, G \, \sin(\delta_s - \delta) \end{aligned} \tag{7}$$

where $G + jB = (R + jX)^{-1}$ represents the step-down STATCOM transformer plus ac active and reactive power losses associated with the solid-state switches operation, which can be significant in PWM control; $V\angle\delta$ and $V_s\angle\delta_s$ are the voltage phasors at the bus being controlled and the VSC ac bus, respectively; V_{ref} is the desired voltage setting; I is the capacitive current of the STATCOM, which becomes negative when the controller is operating in inductive mode; and X_d stands for the controller droop. Observe that this model is similar to the “typical” voltage source (synchronous condenser) model used to represent STATCOMs in power flow analysis, since a transformer/line model can be used to represent the $R + jX$ impedance. The main differences between the typical model and the one used here are the more accurate representation of direct limits in the current I, as opposed to the use of reactive power limits in typical models, plus the direct representation of the droop X_d in the voltage control loop.

The I limits representation in the STATCOM model allows for the proper modeling of the steady state voltage control of this controller, including limit recovery, which, as previously mentioned, is important for the adequate computation of TC. Thus, the limit handling logic used in this model is illustrated in Fig. 5, where the same auxiliary variable V_{aux} defined in (6) is used to model

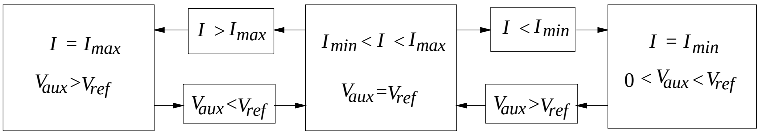


Fig. 5. STATCOM steady state representation of control limits.

the limit recovery in the STATCOM controller.

2.2.4 Secondary Voltage Regulation (SVR)

A generic scheme of the tertiary and secondary voltage regulation system currently under implementation in the Italian system is illustrated in Fig. 6. These are basically hierarchical controls added to a generator primary voltage regulator or AVR to improve the voltage stability characteristics of a power network. The National Voltage Regulator (NVR) determines the optimal voltage set points for the system pilot buses based on a given optimization criterion, such as maximizing voltage security. Regional Voltage Regulators (RVRs), of which there would be basically 3, for the northern, central and southern regions, are basically integral controls that set the reactive power levels of the different groups of generators associated with the pilot nodes to control their voltage magnitudes at the levels set by the NVR.

The main idea of these controls is that generators should deliver reactive power based on their own reactive power reserves at any loading conditions. Thus, from the steady-state point of view, these controls are designed so that groups of generators associated with a given pilot node move "together" to control the voltage at this bus, delivering a reactive power proportionally to their own available capability, which varies depending on the loading conditions of each generator, so that they all reach their limits at the same time.

The pilot nodes are chosen based on their short circuit capacity, i.e. those nodes with the largest short circuit level in a given region are chosen as the pilot nodes. The generators that control each pilot node are then chosen through a sensitivity analysis based on the sensitivity matrix $\partial V_p / \partial Q_g$, where V_p correspond to the pilot node voltages and Q_g are the system generator powers; the largest inputs on this matrix define the generators that should be associated with the pilot nodes.

The actual control blocks used to model these various regulators in stability studies are depicted in Fig. 7, where in terms of time constants it is assumed that AVR (ms) $<$ PQR ($T_{vsc} = 5$s) $<$ RVR ($T_{qsc} = 50$s), to clearly establish the hierarchical characteristics of these controllers. Observe that the limits on the PQR control block set the limits on the AVR input to 15% and -20%, which are typical voltage regulation limits used in AVRs throughout Italy.

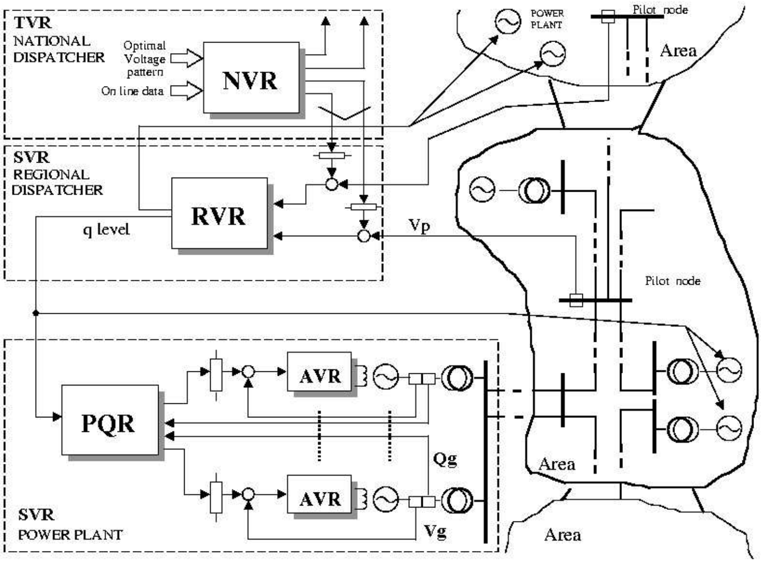
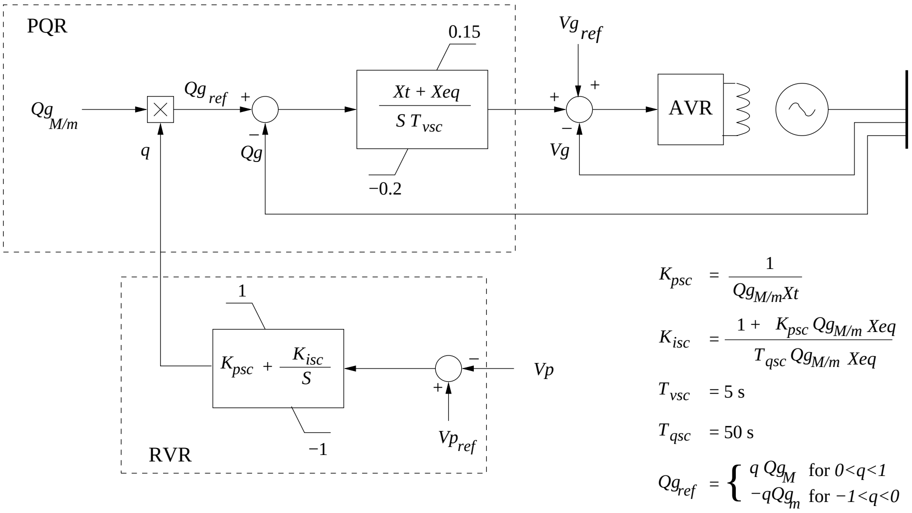


Fig. 6. SVR overall structure.



$$K_{psc} = \frac{1}{Qg_{M/m}Xt}$$

$$K_{isc} = \frac{1 + K_{psc}\,Qg_{M/m}\,Xeq}{T_{qsc}\,Qg_{M/m}\,Xeq}$$

$$T_{vsc} = 5\text{ s}$$

$$T_{qsc} = 50\text{ s}$$

$$Qg_{ref} = \begin{cases} q\,Qg_M & \text{for } 0<q<1 \\ -qQg_m & \text{for } -1<q<0 \end{cases}$$

Fig. 7. Generator SVR controller. The X_t and X_{eq} parameters stand for the generator's transformer reactance and the equivalent reactance from the generator terminals to the pilot bus p, respectively; Q_g represents the generator g reactive power, $Q_{g_m} \leq Q_g \leq Q_{g_M}$; V corresponds to the bus voltage magnitudes; and K_{psc} and K_{isc} are the PI gains of the RVR controller.

The basic control characteristics of the SVR system were implemented into UWPFLOW using the remote voltage control feature already available in the program, as defined in [15]. Thus, generator buses directly associated with a remote voltage controlled bus are basically treated as PQ buses whose delivered reactive power changes in proportion to a K_g factor and the desired voltage magnitude at the remote bus, which in SVR corresponds to the pilot node. In standard remote voltage control, the K_g factor is a fixed value; in the case of SVR, however, K_g should change according to the available capability of the device, as explained in detail below.

As remote voltage control is a difficult numerical problem in power flow problems, particularly when the remote controlled bus is "weakly" coupled to the corresponding controlling generators (this is minimized in the case of SVR, as a pilot bus and its controlling generator buses are chosen so that there is "strong" coupling among them), only a first approximation of the SVR system was implemented in UWPFLOW. Thus, the K_g for each control generator is computed based on fixed maximum or minimum reactive power limits, depending on whether the generator is over or under excited, respectively, without regard for the loading level to diminish numerical problems during the solution process, especially for "poor" initial conditions. Hence,

$$K_g = \frac{Q_{g_{lim}}}{\sum_{G \in p} Q_{G_{lim}}} \;\Rightarrow\; Q_g = K_g \sum_{G \in p} Q_G$$

where $Q_{g_{lim}}$ stands for the maximum or minimum reactive power limits of the g^{th} generator controlling a pilot node p (this factor changes during the solution process depending on whether the generator is over or under excited); and $G \in p$ represents the set of generators controlling the bus voltage at the pilot node. This is only a first approximation of the actual SVR control, as the effect of generator loading levels on the corresponding reactive power limits is not modeled here, i.e. the generator limits are represented using fixed values.

3 Results

3.1 Italian System Model

All the results discussed in this section are based on a 1228 buses, 1903 lines/transformers model used in OPF studies of the Italian power system, which represents most of the 380 kV, 220kV, 150kV and 130 kV transmission system. This model also includes parts as well as equivalents of the networks of other European countries, especially of the systems directly connected to and supplying the Italian network, i.e. France, Switzerland, Austria and Slovenia, since one of the main objectives of the study is to determine the external TC of the Italian system and the influence of SVR and shunt FACTS controllers in this TC.

The data used corresponds to Saturday, March 3, 2001, at 10:00, with a total base load of about 30 GW for the Italian system (153 GW for the total system), which may be considered "light" as compared to the typical peak loading conditions of approximately 40 GW. The maximum loading levels registered on the Italian system have been in the order of 46 GW, with ENEL and IPPs supplying about 41.5 GW and exports of approximately 4.5 GW.

The Italian system has an installed capacity of about 73 GW, of which 20 GW come from hydro plants and 53 GW from thermal units; however, a number of aging units are not currently in use. For the case under study, the amount of generation in Italy directly represented in the data used corresponds to a maximum capacity of about 27.5 GW, with internal generators producing approximately 25 GW at base-load conditions; the additional 5 GW of base-load is being supplied in this case by generators outside Italy. This particular generation dispatch conditions, with internal generation in Italy assumed to be rather limited, is used to allow for analyses of the maximum amounts of power that can be imported from neighboring countries, since the maximum external capacity in the data used here is in the order of 270 GW.

For all VS and TC studies discussed here, the loads in the Italian system are assumed to have a constant power factor, and increase according to the typical regional load distribution depicted in Table 1. Although other load change patterns could be considered, the one chosen here corresponds to the typical weekday load increase in the Italian system, and hence should generate results that allow a reasonable comparison of the various controllers being considered, which is the main purpose of this paper. Thus, the values of ΔP_l and ΔQ_l in (2) are obtained from

$$\begin{aligned} \Delta P_l &= k_l \; P_{lo} \\ \Delta Q_l &= k_l \; Q_{lo} \end{aligned} \tag{8}$$

with k_l being defined from the regional load increases given in Table 1 as follows:

$$k_l = r_l \; \frac{\sum_{l \in R} P_{lo}}{\sum_{l \in R_{r_l}} P_{lo}} \tag{9}$$

where r_l is the factor in p.u. given in Table 1, R stands for the set the regions listed in this table, and R_{r_l} represents the region associated with the factor r_l. The rest of the system loads are assumed to remain fixed at their base-load values, i.e. $\Delta P_l = \Delta Q_l = 0$ for these loads.

The generation dispatch scenario considered for these studies consists on allowing the internal generators as well as all external generators present in the data base to deliver power up to their maximum values, in proportion to the powers being generated at base-load. A distributed slack bus model is used in all studies, i.e. all generators share the system losses proportionally to their base-load power levels.

The basic SVR structure of the Italian network used for the present studies, which is currently under implementation, is depicted in Fig. 8. Observe that the country is divided in 14 regions for voltage regulation that have been

Table 1
Regional load variations

Name	%
TORINO	20
MILANO	30
VENEZIA	20
FIRENZE	10
ROMA	20

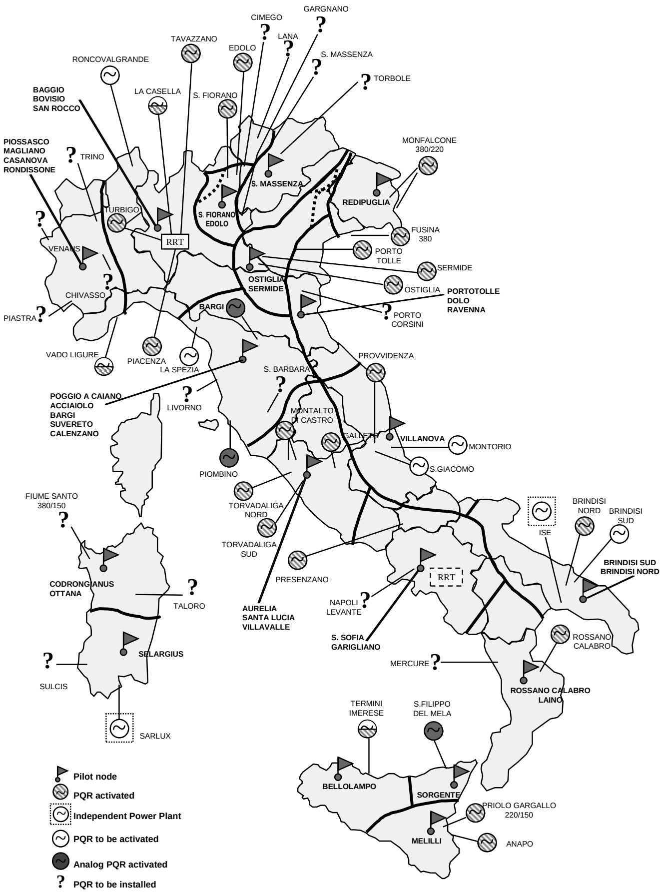


Fig. 8. Current state of the Italian SVR scheme.

chosen based on their geographical and system characteristics, i.e. location and network "density"; each one of them has a pilot node with its voltage controlled remotely by a set of regional generators, chosen based on the criteria previously explained. There are 3 regional regulators, North, Central and South, which coordinate the corresponding pilot node controls in each one of these regions.

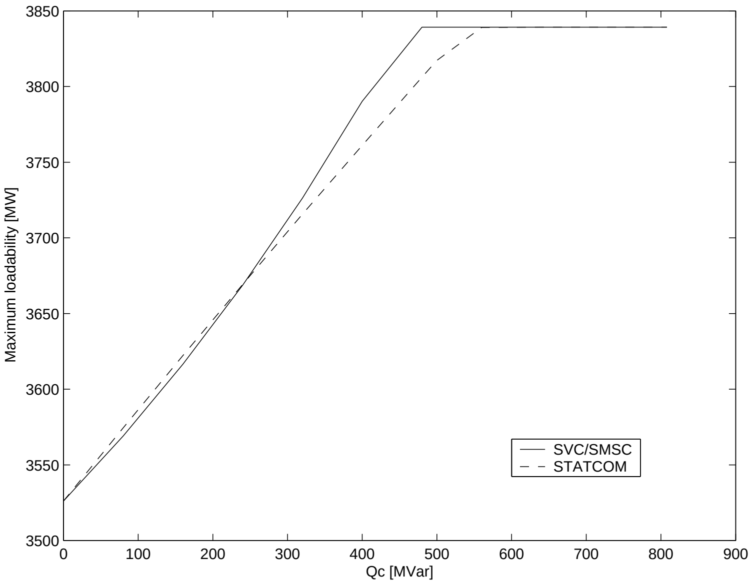


Fig. 9. Maximum loadability in Italy versus capacitive compensation for various types of compensators at the critical bus.

The given load and generator dispatch conditions are used to determine the optimal location and levels for shunt compensation, as previously explained, as well as to comparatively study the effect on the system's voltage profiles and TC of SVR, SMSC (assuming "continuous" voltage control), SVC and STATCOM.

It is important to mention that, although the currents on the external tie lines of the Italian system are monitored for the studies discussed here, the thermal limits are not actively enforced, as these lines are relatively short and are already loaded near their thermal limits at base-load conditions; hence, enforcing thermal limits on these lines will not allow to carry out any meaningful VS and TC studies. It is widely recognized that before any significant power exchanges take place between Italy and other European countries, the thermal capacity of these lines must be upgraded.

3.2 TC Results

The critical bus was first identified for the generation dispatch under consideration, determining that a bus near the Swiss border is the best location for shunt compensation. Thus, Fig. 9 depicts the maximum loadability in the Italian system versus the shunt compensation level of SMSC, SVC and STATCOM located at the critical bus. Observe that for an approximate compensation level below 500 Mvar, the maximum loadability increases quasi linearly with the injected reactive power in all cases.

Table 2
TC for critical contingency

Controller	TC [MW]
None	2762
SVC/SMSC	2986
STATCOM	2982
SVR	3005

Introducing SVR in the system yields a max loadability value of 3832 MW. Hence, a somewhat similar maximum loadability value in Fig. 9 results in approximately a 500 Mvar capacitive compensation level for the shunt controllers, which corresponds also to the "saturation" point, i.e. the optimum compensation level from the maximum loadability point of view. The TC values for this compensation level, which is assumed equal for all controllers to allow for proper comparisons, are depicted in Table 2. These values are computed considering the critical contingencies for the different voltage control strategies, which correspond to the tripping of the main lines connecting Switzerland and the Milan region, which is consistent with previous VS studies in the Italian systems (these lines are associated with the September 2003 blackout of the Italian system). Observe that all controllers yield an approximately 10% increase in the system TC, with SVR yielding a slightly larger value.

3.3 Voltage Profiles

The voltage profiles at the critical bus and pilot buses in the north, the central region and the south are depicted in Figs. 10 through 13, for the internal-external generation dispatch option; minimum and maximum allowable voltage levels can also be seen in these figures (360-430 kV for 380 kV; 197-250 kV for 220 kV; 115-145 kV for 130 kV). Similar profiles were obtained for the case of external generation dispatch. Observe that the further away from the critical bus/area in the north, the "flatter" the profiles are, as expected. Also, notice that the SVR control option presents the best voltage profiles throughout the system; however, the best voltage control at the critical bus is obtained with SVC/SMSC and STATCOM, as expected.

3.4 Cost-benefit Analysis

Table 3 shows the costs provided directly by equipment manufactures of the kind of controllers being considered here (e.g. ABB, SIEMENS). These costs

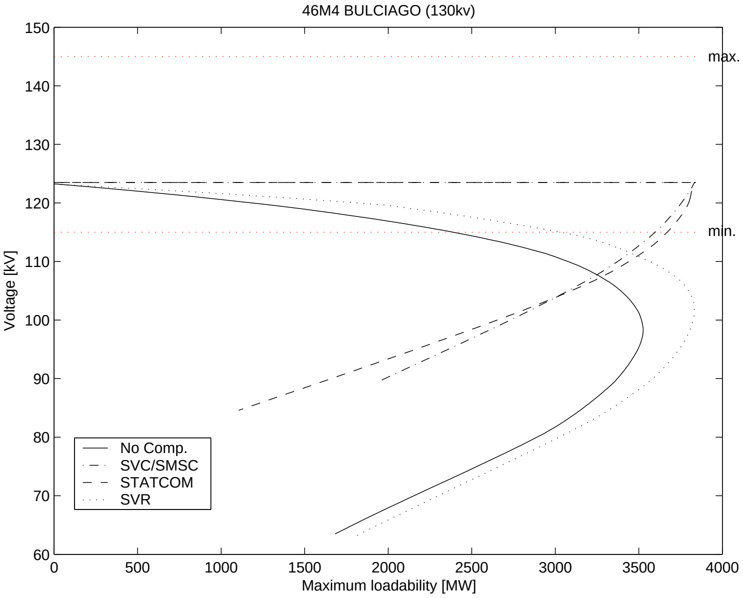


Fig. 10. Voltage profile at the critical bus in the Milan region (North, near Switzerland).

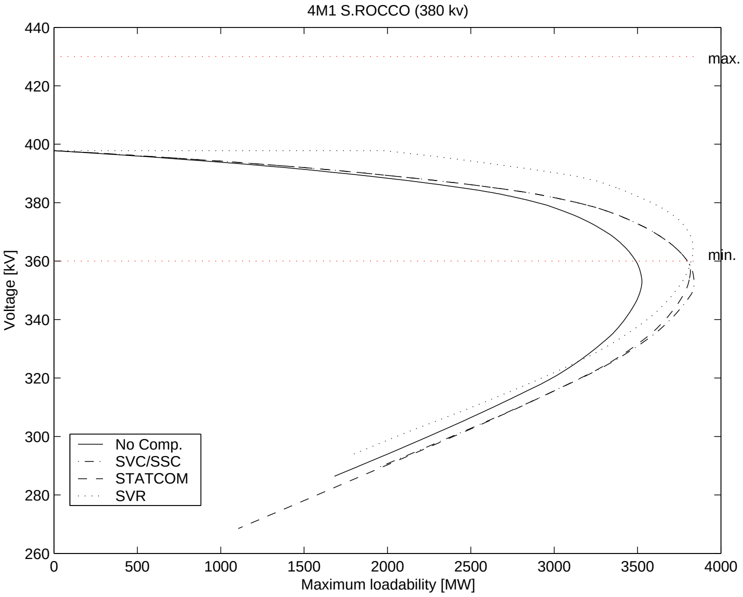


Fig. 11. Voltage profile at a pilot bus in the Milan region (North).

consider all equipment costs, which is the most significant part of SVR, and does not include installation costs. In the case of the STATCOM, these values correspond to a GTO-based controller (IGBT-based STATCOMs for distribution system applications are reported to be about 50% more expensive than equivalent SVCs). As expected, the SVR is the cheapest option, as it only requires additional controls and monitoring devices at the generator stations, national/regional control centers and pilot buses.

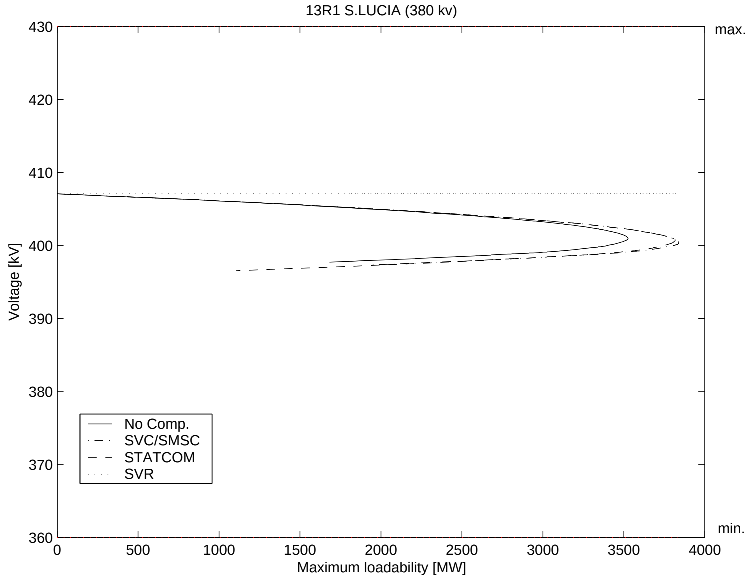


Fig. 12. Voltage profile at a pilot bus in the Rome region (Center).

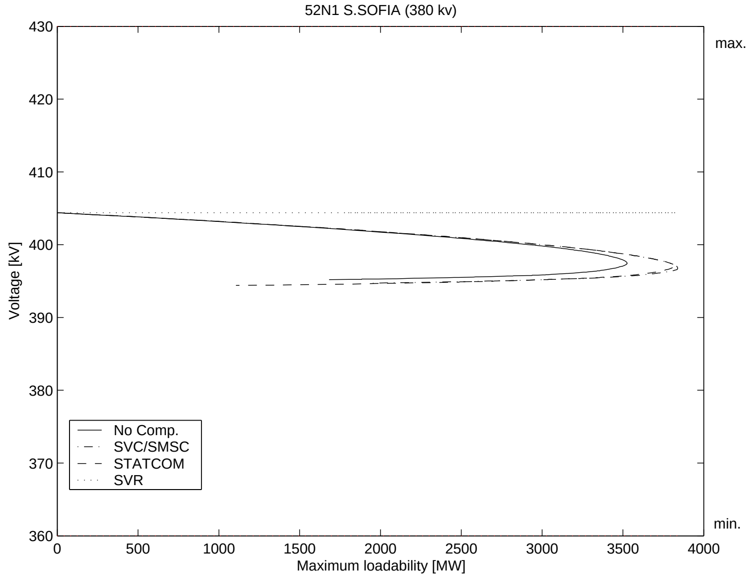


Fig. 13. Voltage profile at a pilot bus in the Naples region (South).

Based on the costs in Table 3, the 500 Mvar shunt controllers under consideration, which may be deemed large given the "typical" ratings for these types of controllers, would cost significantly more for a similar TC increase than introducing SVR in the system. It is important to highlight the fact that a shunt controller rated at 500 Mvar and located at the critical bus is more effective, from the TC level point of view, than 5×100 Mvar controllers scattered throughout the system, given the quasi linear profiles illustrated in Fig. 9 for reactive powers below 500 Mvar. Although for different load patterns and/or multiple contingencies this might not be necessarily the case, for the typical load increase and N-1 contingency criteria used here, this is certainly the best

Table 3
Installation costs

Controller	Cost [USD/Mvar]
SMSC	10k
SVC	50k-60k (100 Mvar) 35k-40k (200 Mvar)
STATCOM	1.2-1.3 SVC
SVR	1k

choice.

It could be argued that the voltage profiles depicted above show that the SVC/SMSC and STATCOM present the best solution to improve VS for the given study case, since no min./max. voltage levels are violated at any bus for the given TC increase. However, the costs associated to obtain this kind of performance would be difficult to justify in comparison to SVR. (It should be noted that if the alternative pilot buses near the critical area were in operation, the voltage profile in the critical bus would be flatter, as these pilot buses are closer to this bus.)

4 Conclusions

This paper presents and discusses the results of using shunt FACTS controllers versus SVR to improve the VS and increase the external TC of the Italian system, using standard steady state VS analysis techniques. Special care was taken in properly modeling the voltage controllers used. The results clearly show that SVR is a very competitive option for VS and TC improvement, and hence should be considered as a feasible alternative to shunt compensation for these purposes.

It is important to highlight the fact that from the classical VS and TC points of view, which are mostly based on steady state studies, the response speed of the controllers, particularly for the SVC and STATCOM, will not yield significantly different results as the ones discussed here. However, for angle stability analyses, this would certainly not be the case, as controller dynamic response does have a significant effect on these phenomena.

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