A new modeling and placement of shunt FACTS devices in the secondary voltage regulation environment

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1 Introduction

In the recent years, the load increased both due to the fast industry development and geographical evolution and dereg-ulation. Therefore, all around the world, power systems are operated closer and closer to their loadability limits; this leads to an increasingly difficult control of power system voltage and reactive power. Furthermore, the conventional approaches used in the voltage and reactive power control like switching the banks of shunt capacitors and reactors, set-ting the voltage set points of generators, OLTC, and FACTS devices are sometimes considered unsatisfactory because of the lack of a real coordination between the different volt-age/reactive controllers [1]. To face this technical challenge, the Hierarchical Voltage Control (HVC) has been proposed and implemented in several countries such as: France [2–5], Italy [1,6–10], Belgium [11,12], and Spain [13–15].

The HVC is based on the subdivision of the power system into several independent control areas and on the automatic coordination of reactive power resources in each area [1,16–18].The HVC is mainly made by three voltage control levels. The primary voltage regulation (PVR) is performed by the Automatic Voltage Regulations (AVRs) of the generators; its role is the local voltage control by means of the generator excitation. The SVR is based on the voltage control of the areas by the coordination of reactive power resources belonging to the same area. Each control area is represented by a pilot bus and various control generators. The pilot bus is a load bus where the voltage is controlled by the coordinated action of the voltage set points of area control generators'

AVR. The Tertiary Voltage Regulation (TVR) consists of optimizing the voltage set point of the pilot buses, according to a pre-defined technical-economical criterion.

On the other hand, the use of FACTS controllers for network voltage support, mainly SVC and STATCOM, has been seriously considered in the last years [22–24]. However, these FACTS are typically used on the local voltage control, without any coordination with other reactive power resources in the system. In this paper, a new power flow model of SVC and STATCOM is integrated with the SVR, so that their voltage control capability is coordinated with the area control generators to maintain the pilot bus voltage at its set point.

The paper is organized as follows: the HVC principles and structure are presented in Section 2; Section 3 presents the power flow modeling of SVR; the conventional and the proposed models of SVC and STATCOM for SVR are presented in Section 4. In Section 5, a sensitivity analysis for the location of SVC and STATCOM is proposed. The main simulation and preliminary results are presented in Section 6, and finally the conclusions are presented in Section 7.

2 HVC structure and principle

The basic HVC structure is presented in Fig. 1. From this figure, we can see that the HVC is basically made by three voltage control levels hierarchically organized. The details of each level are presented in the following.

2.1 Primary voltage regulation (PVR)

The primary voltage regulation (PVR) is the local level of HVC; its purpose is to regulate the output voltage of the generators via an AVR.

2.2 Secondary voltage regulation (SVR)

The SVR is the second voltage control level. It is based on the subdivision of the network into electric areas (or subdivisions). In order to guarantee an efficient control, these areas should be decoupled from the voltage point of view. This results in limiting the reactive power transits in the interconnections by controlling the pilot bus voltages [21]. The pilot bus is a load bus that represents the voltage profile of the area. Its voltage is controlled by the area controlling generators. These latter are chosen according to the analysis of the sensitivities of the pilot node voltages with respect to the generator reactive power: the largest entries in the sensitivity matrix define the generators most suitable for the control of each pilot node [2,16–18]. The reactive power output of each control generator is regulated according to the area reactive level q presented in (1) [3,16–18]. In this way, the control generators of an area are characterized by the same p.u. reactive power loading.

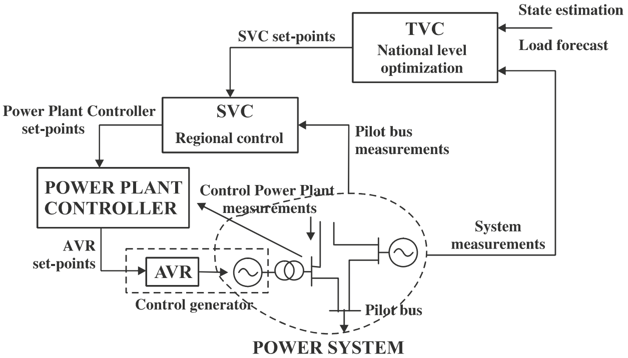

Fig. 1 Structure of Hierarchical Voltage Control

$$q_i = \frac{\sum_{j=1}^{NC_i} Q_{gj}}{\sum_{j=1}^{NC_i} Q_{g\,\max\,j}} = \frac{Q_{ai}}{Q_{a\,\max\,i}} \qquad (1)$$

where,

q_i is the reactive power level of the area i;
NC_i is the number of control generators of area i;
Q_{gi} is the reactive production of the control generator j;
$Q_{g\,\max\,j}$ is the maximum reactive production of the control generator j;
Q_{ai} is the reactive production of area i; and
$Q_{a\,\max\,i}$ is the maximum reactive production of area i;

2.3 Tertiary voltage regulation (TVR)

The TVR exploits the output of the state estimation and load forecasting programs to compute the optimal voltage set points of the pilot buses, according to a defined objective function, for example, total losses minimization, congestion minimization, or voltage stability enhancement.

3 Power flow modeling of SVR

The implementation of SVR in the power flow program leads to the definition of new types of buses and variables.

3.1 PVQ-bus

The PVQ type bus represents the pilot bus, where the active power, reactive power Q, and magnitude voltage V are known and the voltage angle δ is unknown. For N_a areas in the system, $2N_a$ equations (P and Q) can be written and N_a variables (δ) appear.

3.2 P-bus

This type of buses represents the control generators participating in the SVR. For this reason, the reactive power produced by this generator will be used in the control of the pilot bus voltage. Thus, the P-bus has one known variable, i.e., the real power P, and two unknowns, represented by the voltage magnitude and angle. Therefore, for N_p control generators, we have N_p equations and $2N_p$ unknowns. The reactive power output of the control generators is defined according to the area reactive level.

The first equation used for the P-bus is the real power equilibrium equation:

$$P_{gj} - P_{Lj} - \sum_{i=1}^{n} V_j Y_{ji} V_i \cos\left(\delta_j - \delta_i - \theta_{ji}\right) = 0 \qquad (2)$$

where, j is the bus the control generator is connected to, P_{gj} is the real power generation of control generator j, and P_{Lj} is the load real power at bus j. δ_j and δ_i are the voltage phase angles at buses i and j, respectively, and θ_{ji} denotes the angle of admittance Y_{ji}.

Since the reactive power of the P-bus is unknown, a novel equation based on (1) and on the reactive power balance (3) at the P-bus can be written as follows:

$$Q_{gj} - Q_{Lj} - \sum_{i=1}^{n} V_j Y_{ij} V_i \sin\left(\delta_j - \delta_i - \theta_{ji}\right) = 0 \qquad (3)$$

By substituting Q_{gj} from (3) in (1) we obtain:

$$\frac{Q_{Lj} + \sum_{i=1}^{n} V_j Y_{ji} V_i \sin\left(\delta_j - \delta_i - \theta_{ji}\right)}{Q_{g\max j}} - q_a = 0, a \in N_a \qquad (4)$$

For each control area a, N_p reactive level equations with N_a variables can be written. Thus, as it can be seen in Table 1 the number of equations and unknowns is now balanced.

Finally, it should be specified that during the power flow program execution q_a must be limited as follows:

$$-1 \leq q_a \leq 1 \qquad (5)$$

Table 1 Equations and unknowns for the new bus types

	PVQ	P	q-eq	Total
Equations	2Na	Np	Np	2Na + 2Np
Unknowns	Na	2Np	Na	2Na + 2Np

3.3 Constraint violation handling of SVR

3.3.1 Reactive level constraint of the area

If the reactive level limits presented in (5) are violated, the PQV-bus and P-buses of the considered area become PQ-buses. Therefore, this area is no more controlled by the SVR.

3.3.2 Voltage constraint of the P-bus

If the voltage limits of P-bus are violated, the P-bus is switched to PV-bus and does not participate anymore in the SVR (its voltage set point is the upper or lower voltage limit).

4 Power flow models SVC and STATCOM

In this section, the proposed models of the SVC and STATCOM are presented.

4.1 Conventional power flow model of SVC and STATCOM

4.1.1 SVC model

Figure 2 presents the SVC model. It consists of a variable susceptance B_{svc} in order to keep a given voltage at the connection bus, where the real power P, the reactive power Q, and the voltage V are known, and the only unknown variable is the SVC susceptance, B_{svc} [19]. Since the SVC voltage is kept constant, in the Jacobian, the column corresponding to the voltage is substituted by the SVC susceptance variable B_{svc}.

According to Fig.2, the injected (absorbed) SVC current is as follows:

$$I_{svc} = jB_{svc}V_i \qquad (6)$$

Therefore, the real and reactive power injected by the SVC is as follows:

$$\begin{aligned} P_{svc} &= 0 \\ Q_{svc} &= -B_{svc}V_k^2 \end{aligned} \qquad (7)$$

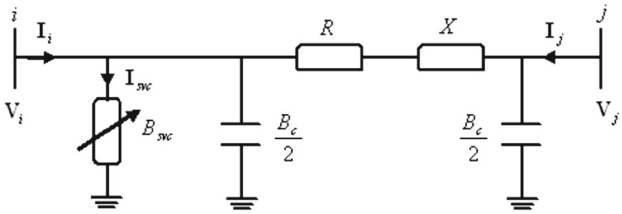

Fig. 2 Susceptance model of the SVC

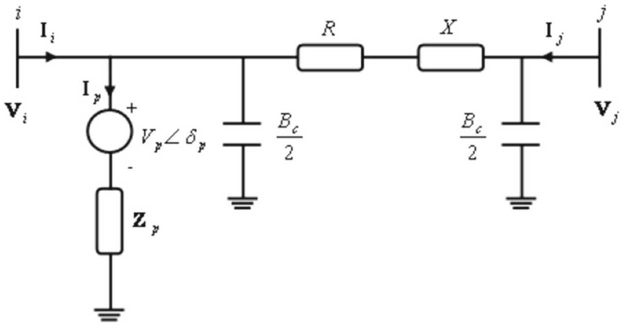

Fig. 3 STATCOM model

From (7), the linearized SVC model is derived:

$$\begin{bmatrix}\Delta P_i\\ \Delta Q_i\end{bmatrix}=\begin{bmatrix}0 & 0\\ 0 & -V_i^2\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta B_{svc}\end{bmatrix} \tag{8}$$

4.1.2 STATCOM model

Figure 3 presents the STATCOM model for local voltage control. The STATCOM is modeled as a complex voltage source $V_p = V_p\angle\delta_p$in series with the impedance Z_p. Its real part represents the real losses in the power electronics devices and transformer, and the imaginary part represents the magnetizing reactance of the transformer [20]. The real and reactive power injected by the STATCOM in the bus i is:

$$S_p = P_p + jQ_p = V_i\left[Y_p\left(V_i - V_p\right)\right]^* \tag{9}$$

where, $Y_p = 1/Z_p$.

The equation (9) can be expanded:

$$P_p{=}G_pV_i^2{-}V_iV_p\left(G_p\cos\left(\delta_i{-}\delta_p\right)+B_p\sin\left(\delta_i{-}\delta_p\right)\right) \tag{10}$$

$$Q_p{=}{-}B_pV_i^2{-}V_iV_p\left(G_p\sin\left(\delta_i{-}\delta_p\right)-B_p\cos\left(\delta_i{-}\delta_p\right)\right) \tag{11}$$

where G_p represents the real part of $1/Z_p$ and B_p represents the susceptance of $1/Z_p$. δ_i denotes the voltage phase angles at buses i and δ_p represents the phase angle of voltage V_p.

The STATCOM model adds two additional variables (V_p and δ_p) to the power flow program and the voltage V_i is kept constant. Therefore, one additional equation is required to solve the power flow problem. This equation is based on the fact that the STATCOM is assumed lossless.

The power towards the STATCOM is:

$$S_{Ep} = P_{Ep} + jQ_{Ep} = V_p\left[Y_p\left(V_i - V_p\right)\right]^* \tag{12}$$

According to (12), the real power withdrawn by the STATCOM is as follows:

$$\begin{aligned}P_{Ep} &= -G_pV_p^2\\ &\quad + V_iV_p\left(G_p\cos\left(\delta_p{-}\delta_i\right)+B_p\sin\left(\delta_p{-}\delta_i\right)\right){=}0\end{aligned} \tag{13}$$

The linearized STATCOM model is therefore:

$$\begin{bmatrix}\Delta P_i\\ \Delta Q_i\\ \Delta P_{Ep}\end{bmatrix}^i=\begin{bmatrix}\frac{\partial P_i}{\partial\delta_i} & \frac{\partial P_i}{\partial V_p} & \frac{\partial P_i}{\partial\delta_p}\\ \frac{\partial Q_i}{\partial\delta_i} & \frac{\partial Q_i}{\partial V_p} & \frac{\partial Q_i}{\partial\delta_p}\\ \frac{\partial P_{Ep}}{\partial\delta_i} & \frac{\partial P_{Ep}}{\partial V_p} & \frac{\partial P_{Ep}}{\partial\delta_p}\end{bmatrix}\begin{bmatrix}\Delta\delta_i\\ \Delta V_p\\ \Delta\delta_p\end{bmatrix} \tag{14}$$

4.2 New proposed models of SVC and STATCOM to participate in the SVR

In this section, new models of SVC and STATCOM are defined to be integrated in the SVR Power Flow. The reactive power output of SVC and STATCOM is coordinated with the control generators of the area, according to (1) in order to keep the voltage of the pilot bus at its set point.

4.2.1 New SVC model

The participation of the SVC in the SVR means that its reactive power is generated according to the reactive level of the area it belongs to. The voltage magnitude, the voltage angle, and the susceptance B_{svc} are considered as unknown variables in the power flow problem. Therefore, three equations must be defined as follows:

- The *first* equation represents the real power balance at the SVC-bus i,

$$P_{Gi} - P_{svc} - P_{Li} - \sum_{j=1}^{n} V_iY_{ij}V_j\cos\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{15}$$

- The *second* equation represents the reactive power balance at the SVC-bus i,

$$Q_{Gi} - Q_{svc} - Q_{Li} - \sum_{j=1}^{n} V_iY_{ij}V_j\sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{16}$$

- The *third* equation represents the reactive power alignment of the SVC. According to (1), we can write:

$$q_a = \frac{Q_{svc}}{Q_{svc\max}} \tag{17}$$

Writing $Q_{svc}$and $Q_{svc\max}$ according to (7), we get:

$$q_a = \frac{-B_{svc}V_i^2}{-B_{svc\max}V_i^2} \tag{18}$$

Simplifying (18), we get the new reactive power alignment of the SVC as the third equation needed.

$$q_a = \frac{B_{svc}}{B_{svc\max}} \tag{19}$$

Therefore, for n SVCs installed in the system, we have $3 \times n$ additional unknowns and $4 \times n$ additional equations.

4.2.2 *New STATCOM model*

As in the case of the SVC, the participation of the STATCOM in the SVR means that its reactive power is generated according to the reactive level of the area it belongs to. In this case, the voltage magnitude, the voltage angle, and the complex voltage $V_p = V_p \angle \delta_p$ injected by the STATCOM are considered as unknown variables in the power flow model. Therefore, for solving the power flow in the presence of STATCOM, four equations must be defined as follows:

- The *first* equation represents the real power balance at the STATCOM-bus i,

$$\begin{aligned} & P_{Gi} - P_{statcom} - P_{Li} \\ & \quad - \sum_{j=1}^{n} V_i Y_{ij} V_j \cos\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \end{aligned} \tag{20}$$

- The *second* equation represents the reactive power balance at the STATCOM-bus i,

$$Q_{Gi} - Q_{statcom} - Q_{Li} - \sum_{j=1}^{n} V_i Y_{ij} V_j \sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{21}$$

- The *third* equation is relevant to the assumption that the STATCOM is lossless (see (13)),
- The *fourth* equation is relevant to the reactive power alignment of the STATCOM. According to (1) the following holds:

$$q_a = \frac{Q_{statcom}}{Q_{statcommax}} \tag{22}$$

Therefore, for n STATCOMs installed in the system, we have $4 \times n$ additional unknowns and $4 \times n$ additional equations.

4.2.3 *Handling of the constraint violation of SVC and STATCOM*

Handling of the voltage limits constraints

If the voltage limits of the SVC-bus (STATCOM-bus) presented in (23) are violated, the SVC (STATCOM) will not participate in the SVR but will ensure only the local control of the voltage at the bus where it is installed, setting as voltage set point the violated voltage limit:

$$V_{\min} \le V \le V_{\max} \tag{23}$$

5 Placement of SVC and STATCOM using sensitivity analysis

In this section, a sensitivity-based method is adopted to select the most sensitive placements for the installation of shunt FACTS devices. This method aims at computing the sensitivities of the pilot bus voltages with respect to the reactive power injections in the load buses [1].

The main steps of the proposed procedure are:

- *Step1*: The power flow result with SVR is obtained to define the nominal operating point of the system;
- *Step2*: Shift the PVQ-bus and P-bus to PQ-bus, and set the reactive power generation of the P-bus to the value obtained at step1;
- *Step3*: Compute sensitivity matrix;
- *Step4*: For each pilot bus, select from the sensitivity matrix, the five load buses which have the greatest sensitivity coefficients.

The variation of the reactive power at load buses with respect to the voltage is as follows:

$$[\Delta Q] = \left[\frac{\partial Q}{\partial V}\right][\Delta V] \tag{24}$$

where, the matrix $\left[\frac{\partial Q}{\partial V}\right]$ is sub matrix in the Jacobian matrix of the power flow. Inverting (24):

$$[\Delta V] = \left[\frac{\partial V}{\partial Q}\right][\Delta Q] \tag{25}$$

From (25), the variation of pilot bus voltages is determined, with respect to the variation of the reactive power of load buses.

$$\left[\Delta V_{pvq}\right] = \left[\frac{\partial V_{pvq}}{\partial Q_{pq}}\right]\left[\Delta Q_{pq}\right] \tag{26}$$

where, the subscripts pvq and pq are relevant to the pilot and load buses, respectively. $\left[\frac{\partial V_{pvq}}{\partial Q_{pq}}\right]$ is the sensitivity matrix adopted for the FACTS location: the best placement of SVC and STATCOM is the load buses which have the largest sensitivity elements.

6 Simulation and preliminary results

Figure 4 presents the Italian transmission system used for the test. The system consists of around 650 buses, 772 branches and transformers, 64 non controlling generators, 13 SVR control areas, and 92 control generators. The real and reactive power of the load is about 25300 MW and 7900 Mvar, respectively.

The Power flow model including SVR solves the problem in 4 iterations, with a tolerance of 10-6 pu.

6.1 Validation of the proposed SVC and STATCOM models

In order to validate the proposed models of SVC and STACOM, an SVR and a STATCOM are installed separately in area 12 to participate in the SVR. The different parameters of SVC and STATCOM are presented in table 2.

Table 2 Installation parameters of SVC and STATCOM in the SVR

	SVC	STATCOM
Area	12	12
Pilot bus	505	505
Voltage reference of pilot bus (pu)	1.0054	1.0054
FACTS-Bus	501	501
$B_{svc\,\max}/B_{svc\,\min}$ (pu)	0.5/-0.5	-
$Q_{statcom\,\max}/B_{statcom\,\min}$ (pu)	-	0.5/-0.5
Z_p(pu)	-	$0.006 + j0.01$

Table 3 Obtained State variables solution of SVC and STATCOM

	SVC	STATCOM
Voltage of FACTS-bus	1.041	1.0407
Reactive power injection by the FACTS device (pu)	-0.15417	-0.1491
Number of iteration of the power flow program	04	05
Reactive level of area 12 (pu)	0.28451	0.2982
B_{svc}(pu)	0.14226	-
V_p(pu)	-	1.0421
δ_p(deg)	-	-6.6735

Table 3 presents the steady-state variables relevant to the SVC and STATCOM. The modified power flow converges in the same number of iterations as in the base case power flow, for the case of SVC, and requires only one more iteration for the case of STATCOM. The reactive level of the area 12 in the case of SVC is a little bit lower than for the case of STATCOM, because the reactive power injected by the SVC is higher than that injected by the STATCOM. This difference in the reactive power injected by the SVC and the STATCOM is because the maximum reactive power of SVC and STATCOM is not equal $\left(B_{svc\,\max}V^2 \neq Q_{statcom\,\max}\right)$ in the case the voltage in the bus 501 is different to 1pu (see Table 2).

Fig. 4 Presentation of the SVR in the Italian Transmission system

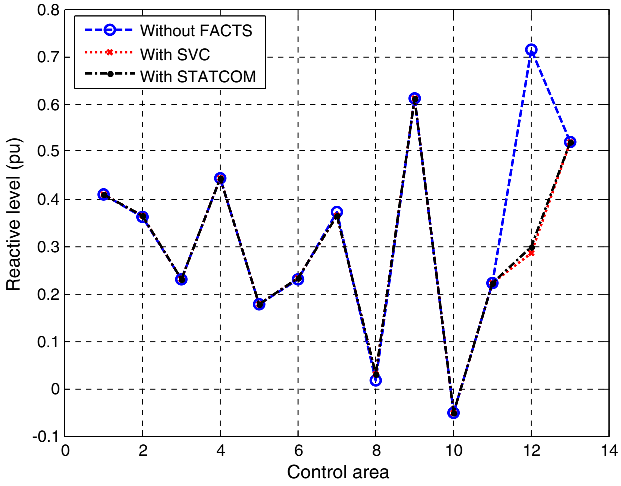

Fig. 5 Reactive level with and without FACTS devices

Figure 5 presents the reactive level of the 13 areas of the Italian power system with and without FACTS.

The impact of SVC and the STATCOM is observed only in the area 12 (where they are installed); moreover, this result

Table 4 The first and the fifth biggest sensitivity coefficients of each control area

Area number	Pilot buses	Sensitivity coefficient	Load bus
1	195	0.049885	616
		0.047198	516
2	206	0.35965	628
		0.35789	434
3	228	0.097988	309
		0.096924	536
4	264	0.086646	465
		0.080214	222
5	346	0.067502	348
		0.056938	407
6	370	0.12199	508
		0.11636	174
7	393	0.23202	276
		0.22143	296
8	413	0.18202	517
		0.17966	519
9	417	0.16797	339
		0.16463	246
10	454	0.28768	528
		0.22571	412
11	489	0.10995	324
		0.080705	381
12	505	0.18237	415
		0.17487	184
13	593	0.1203	556
		0.11448	237

confirms that the control areas of the system are independent from the point of view of the voltage/reactive power control. The installation of SVC and STATCOM in the area 12 decreases its reactive level. This is because, the installation of a new reactive power source increases the ratio of reduces the reactive power production ratio in (1).

6.2 Placement of SVC and STATCOM using sensitivity analysis

The sensitivity analysis proposed in this paper is applied on the Italian power system in order to find the most sensitive locations for the installation of SVC and STATCOM. Table 4 presents the first and the fifth biggest sensitivity coefficients of the 13 areas of the system. In order to validate these results, we install the SVC and the STATCOM in the first and in the fifth best placement and we compare the reactive levels obtained for each area. The results are presented in Table 5, where it can be seen that the reactive level for the first best placement is a little lower than for the fifth best placement in each area. This result shows that the first ranked location of each area is more sensitive for the installation of SVC and STATCOM than the fifth location. Therefore, the sensitivity analysis provides a good index to rank the buses for the placement of FACTS devices to be included in the SVR.

Table 5 Installation of SVC and STATCOM in the first and the fifth best placements of each control area

Area	Installation bus	Reactive level SVC	STATCOM
1	616	0.38498	0.3625
	516	0.39044	0.39045
2	628	0.32908	0.3328
	434	0.32921	0.3329
3	309	0.21563	0.21573
	536	0.21544	0.21575
4	465	0.39419	0.39504
	222	0.39823	0.40076
5	348	0.16005	0.1602
	407	0.16294	0.16313
6	508	0.2055	0.20589
	174	0.20595	0.20659
7	276	0.3452	0.3491
	296	0.34407	0.34515
8	517	0.015656	0.015692
	519	0.015683	0.015718
9	339	0.41128	0.4402
	246	0.4116	0.44195
10	528	−0.035069	−0.035743
	412	−0.038761	−0.038818
11	324	0.093107	0.094426
	381	0.10644	0.11208
12	415	0.51993	0.5224
	184	0.62167	0.62567
13	556	0.33194	0.32924
	237	0.33927	0.33695

7 Conclusion

In this paper, a new modeling of SVC and STATCOM for participating in the secondary voltage regulation is presented. The proposed models are implemented in the Newton–Raphson program and tested on the Italian power system showing a very good computational performance. The reactive power injected by the SVC and the STATCOM devices is coordinated with the other control generators according to the area reactive level. Furthermore, a method based on the sensitivity analysis is proposed to find the best locations for installing SVC and STATCOM devices. The results obtained demonstrate that the proposed method provides the best placement of FACTS devices in the SVR. In the future work, we propose the application of the Genetic Algorithms to find the optimal settings of the shunt FACTS in the SVR environment.

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