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Power Transfer Capacity Enhancement using SVC

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***Abstract* -- This paper presents the results of a feasibility study for installing FACTS devices in the South-Eastern part of Romanian power grid (Dobrogea - a peninsular area), to increase the transfer capacity to the rest of the grid. This study assumed, on one hand, the scheduled increase in generated power in the area, mainly due to two new units in the Cernavodă nuclear power plant (1400 MW installed power) and wind generation with an estimated installed power of over 1600 MW. On the other hand, the scenarios considered the present topology and future developments of the transmission network. The increase in generated power in the S-E part of the power grid may lead to changes in the power market schedules, causing generation decrease or even shut down of other generators, leading to power flow changes and power system stability problems.**

***Index Terms* – available transfer capacity, static VAr compensator, voltage control**

I. Introduction

The power system loading caused by increase in both demand and generation is often leading to bottlenecks and reliability problems. To avoid such problems, advanced transmission technologies are essential to the system developments, providing more flexibility and better controllability features for the future grids.

HVDC and FACTS provide the necessary features to avoid technical problems in the more and more stressed power systems. As known, these technologies can increase the transmission capacity and improve the system stability very efficiently, contributing also to the prevention of cascading disturbances. They effectively support the access to grid of renewable energy sources and reduce the transmission losses by optimizing the voltage levels and power flows.

Specific problems are expected when additional generation sources, such as large wind farms, have to be integrated into the power grid, particularly when there is no sufficient available transfer capacity for power evacuation.

Furthermore, lots of generation units are being scheduled to be connected in the transmission and distribution grids (dispersed generation), leading to additional challenges for the power system planning and operation.

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The Romanian power grid is currently characterized by a dynamic increase in power generation in the S-E part of the Romanian power grid, in thermo and nuclear power plants, as well as in wind farms, which, on long term, may cause an energy surplus in this area.

Power evacuation from this area is mainly restricted by the impossibility to ensure an appropriate voltage level in case of contingencies. Therefore, the objectives of the work presented in this paper were to determine the maximum power that can be evacuated from the area under study to the main grid and the opportunity of installing SVC devices to control the voltage levels under steady-state and transient conditions.

In the first part of the paper, the static model of the SVC and the algorithm implemented in the Power Flow Analysis and Control (PFAC) software, are presented. In the second part, the results of the static and dynamic tests performed on the Romanian power system, are reported.

II. SVC Structure and Power Flow Model

A. SVC characteristic

As known, the two most popular configurations of the SVC device are:

– fixed capacitor combined with a thyristor-controlled reactor (TCR), and
– thyristor-switched capacitor (TSC) combined with a TCR (Fig. 1).

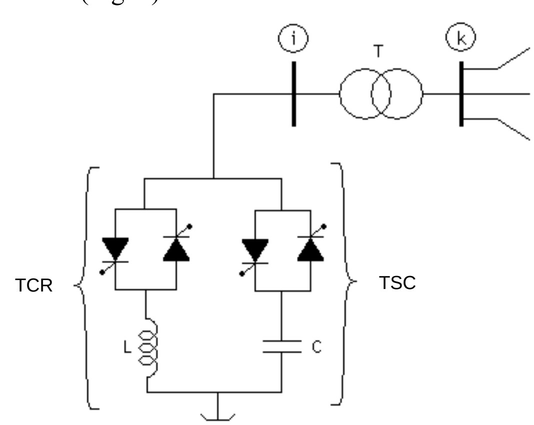

Fig. 1. One line diagram of a SVC device

The TCR consists of a fixed reactor and a bi-directional thyristor valve, fired symmetrically by a control angle α. The valves turn off automatically at the zero crossing of the a.c. current.

Note that, in Fig. 1, bus i is the connection node on the MV side, and bus k is the controlled node, on the HV side. The SVC device is a reactive power compensator, which, by absorbing or injecting reactive power (Q) controls the monitored voltage in the acceptable range around the reference voltage V_0.

The typical steady-state control law of a SVC used here is depicted in Fig. 2, and may be represented by the following voltage-current characteristic:

$$V_k = V_0 + X_{SL} \cdot I_{SVC} \tag{1}$$

where V_k and I_{SVC} stand for controlled bus voltage and SVC device current. Typical values for the slope X_{SL} are in the range of 0.02 to 0.05 pu, depending on the SVC device rated parameters; an appropriate slope is required to avoid reaching the capability limits in case of small variations of the bus voltage.

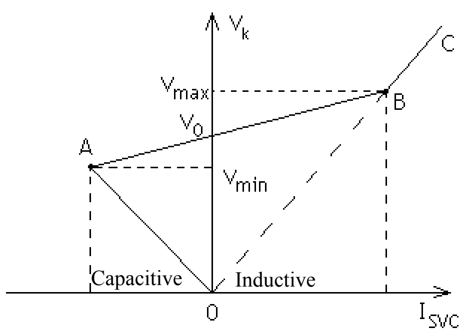

Fig. 2. SVC $V-I$ characteristic

The control law corresponding to the SVC characteristic (Fig. 2) is the following:

- if the monitored voltage is larger than the reference voltage, $V_k > V_0$, then the SVC device is absorbing reactive power;
- if the monitored voltage is smaller than the reference voltage, $V_k < V_0$, then reactive power injection into bus k is required.

B. SVC steady-state model

The equivalent reactance of the SVC device is given by:

$$X_e = \frac{X_L(\alpha) \cdot X_C}{X_L(\alpha) + X_C} \tag{2}$$

with

$$X_L(\alpha) = X_{L0} \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \tag{3}$$

where X_{L0} is the fundamental frequency reactance of the reactor without thyristor control, and α is the firing angle of the valves with respect to the zero crossing instant of the controller voltage. Replacing (3) in (2), the equivalent reactance can be written as:

$$X_e = X_C \frac{\pi k_X}{\sin 2\alpha - 2\alpha + a} \tag{4}$$

where $k_X = X_C / X_L$ and $a = \pi(2 + k_X)$. The capability limits of the controller are given by the firing angle limits, which are fixed by design. Theoretically, α can be chosen in the interval $\left[\frac{\pi}{2}, \pi\right]$, but in practice $\frac{\pi}{2} < \alpha_{\min} \le \alpha \le \alpha_{\max} < \pi$.

The steady-state model of the SVC device is described by the following equations:

- equivalent susceptance

$$B_e = -\frac{1}{X_e(\alpha)} = \frac{2\alpha - a - \sin 2\alpha}{\pi X_{L0}} \tag{5}$$

- current magnitude

$$I_{SVC} = -B_e(\alpha) V_i \tag{6}$$

- reactive power absorbed or injected by the SVC

$$Q_{SVC} = -B_e(\alpha) V_i^2 \tag{7}$$

- static characteristic of the SVC device

$$V_k = V_0 - X_{SL} \cdot B_e(\alpha) \cdot V_i \tag{8}$$

Note that, the equivalent susceptance is a function of α with $\alpha \in [\alpha_{\min}, \alpha_{\max}]$, and since the first derivative of this function is positive on the interval $\left[\frac{\pi}{2}, \pi\right]$, which is the maximum variation interval for α, it can be written that $B_{e,\min} \le B_e(\alpha) \le B_{e,\max}$.

In the load flow computation, the SVC equations can be solved simultaneously with the powers balance equations or sequentially. The latter approach has the advantage of keeping the Jacobian matrix structure unchanged in the case of Netwon-Raphson method. This approach can be also applied within the fast-decoupled method without major modifications. The proposed approach is shown in the sequel.

C. Proposed Algorithm

Given the voltage values for the current iteration (p), $U_i^{(p)}$ and $U_k^{(p)}$, the following steps have to be performed:

1. Use Eq. (8) to compute the equivalent susceptance
$$B_e^{(p)} = \frac{V_0 - V_k^{(p)}}{X_{SL} V_i^{(p)}}$$
2. Check if the value is within the capability limits
$$B_{e,\min} \le B_e^{(p)} \le B_{e,\max}$$
   2.1. If $B_e^{(p)} < B_{e,\min}$, then set $B_e^{(p)} = B_{e,\min}$;
   2.2. If $B_e^{(p)} > B_{e,\max}$, then set $B_e^{(p)} = B_{e,\max}$;
3. Compute the reactive power absorbed/injected by the SVC
$$Q_{SVC}^{(p)} = -B_e^{(p)} \left(V_i^{(p)}\right)^2$$
4. Compute the reactive power mismatch
$$\Delta Q_i^{(p)} = Q_{g,i} - Q_{c,i} - Q_{SVC,i}^{(p)} - Q_{calc,i}^{(p)}$$
5. Perform the $Q-V$ iteration.

The proposed algorithm was implemented in the PFAC software, which is provided with a power flow computation tool, including FACTS devices models. This software was used to determine the impact of the SVC device on the voltage levels in the whole system, and determine the maximum power that can be evacuated from the area under study, characterized by a power surplus, to the rest of the system.

III. CASE STUDY

A. Test system

Simulations were performed on the 220 kV and 400 kV Romanian transmission grid (estimated for the year 2013) consisting of 1084 buses, 173 generators, 1233 transmission lines and 212 transformers. A simplified representation is given in Fig. 3, in which, Zone 1 represents the S-E part of the Romanian power grid, where new generating facilities are installed, Zone 2 is the N-E part of the transmission power grid, where disconnection of generation facilities is assumed, while Zone 3 represents the remaining system. The interconnection lines with the neighboring power systems are represented by arrows, while the HVDC interconnection with Turkey (assumed for the year 2018) is represented by a dashed arrow in the same figure.

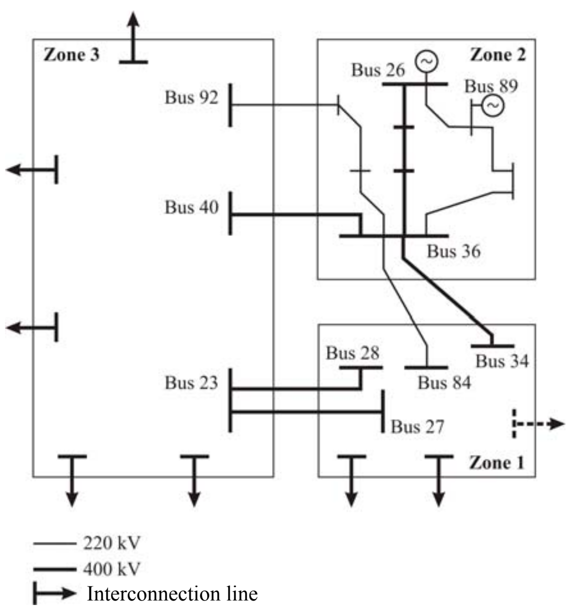

Fig. 3. Simplified representation of the Romanian transmission grid

Peculiar to the Zone 1 under study is that the main limitations in evacuating the generated power are given by voltage constraints and not by transmission lines loading capability.

B. Simulation tools and criteria

Steady-state computations were performed using the PFAC software, while dynamic simulations were performed under Eurostag software. In the dynamic simulations, the SVC device was represented using the standard models available in the Eurostag's library. The wind generators were modeled as double fed induction generators (DFIG) using also the Eurostag library, with the rotor connected to a voltage supply and controlled by a regulator [6].

The N-1 security criterion for all possible contingencies of the 400 kV and 220 kV transmission lines and the N-2 security criteria for a set of 400 kV line combinations were assumed in stability studies performed on the scenario of power evacuation from the nuclear power plant situated in Zone 1.

An N-1 or N-2 contingency scenario was considered unsecure if the steady-state voltage of any of the EHV power system buses below 380 kV was observed.

C. Simulation results

The maximum transferrable active power from Zone 1 and the location and size of the SVC devices were determined under the most restrictive scenarios. These scenarios assume also a power supply from the wind farms located in Zone 1 to the preponderant load situated in Zone 2, leading to a power flow increase in the transmission corridor 34-36-26.

The worst scenario observed was the case in which all generating units (≅ 550 MW generated power) from Zone 2 are tripped. In this case, the most restrictive contingencies (N-1 or N-2 criteria) are the ones involving one of the 400 kV transmission lines situated between Bus 36 and Bus 26. The loss of any of these lines leads to unacceptable low values of the bus voltages, the lowest being observed in Bus 26 (see the heavy line in Fig. 4).

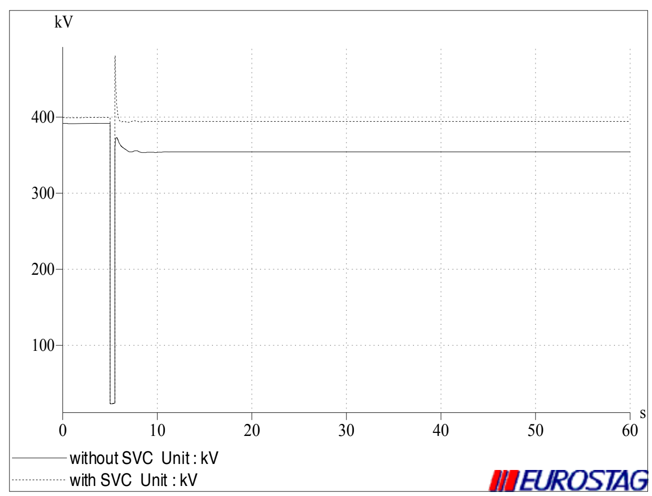

Fig. 4. Voltage evolution with and without SVC in Bus 26

This case could be solved by avoiding disconnection of one of the generating units connected to Bus 26 or Bus 89, as depicted in Fig. 3. However, this scenario is realistic, since these two groups are of cogeneration type and during summer time they might be disconnected.

In this context, it results a reactive power support necessary to be provided in the Northern part of Zone 2. Simulations were therefore performed on the mentioned test system with an SVC device installed at Bus 26.

In order to determine the ratings of the SVC device, the following assumptions were adopted:

- in normal operation, the voltage of the controlled bus, Bus26, has to be kept around the rated voltage of 400 kV;
- in case of the worst contingency, the voltage in the

controlled bus has to be kept above the minimum acceptable value of 380 kV by reactive power injection;

- the rated power in inductive operation is equal to 40% of the rated power in capacitive operation.

The operational parameters of the SVC identified using the PFAC software under the above presented assumptions are given in Table 1.

TABLE 1. BUS 26 SVC DEVICE PARAMETERS

Controlled bus	Voltage reference U_o	Slope X_{SL}	Rated power	
			Capacitive	Inductive
Bus 26	400 kV	5%	100 MVAr	40 MVAr

The influence of the proposed SVC device on the controlled bus voltage (Bus 26) in the worst scenario is illustrated in Fig. 4. The dynamic simulation reveals successful restoration of the bus voltage inside the acceptable limits. This is achieved by additional reactive power injection by the SVC into the controlled bus, as shown in Fig. 5.

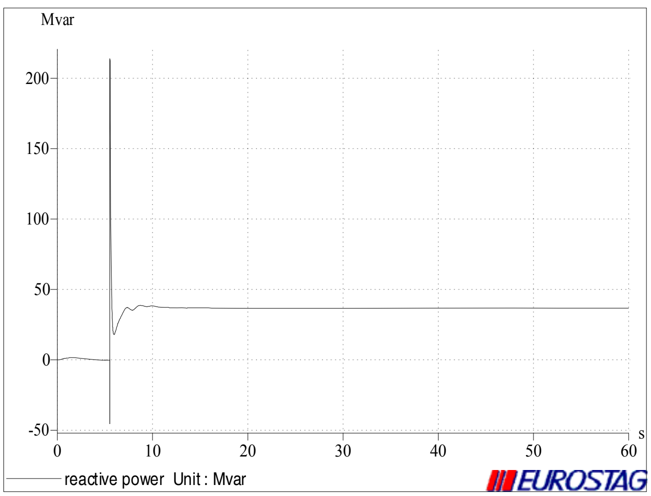

Fig. 5. SVC reactive power injection in Bus 26

Besides successful voltage restoration to acceptable values, reactive power injection at Bus 26 allows an additional active power evacuation from Zone 1 of 450 MW wind power (total amount of 900 MW to both Zone 2 and Zone 3).

Furthermore, the loading of the transmission lines situated on the 400 kV corridors, 34-36-26 and 34-36-40 (Fig. 3), is less than 60% of the net transfer capacity. Further increase of the power evacuated from Zone 1 towards the other zones through the above mentioned corridors is limited by the voltage levels experienced during different contingencies.

The worst scenario is represented by the loss of the line between Bus 34 and Bus 36, where, after an increase in wind generation up to 1075 MW (with classic generating units disconnected in both Zone 2 and Zone 3) the voltage in Bus 36 reaches an unacceptable low value of 372 kV (see the heavy line in Fig. 6).

For better use of the transmission lines, a second SVC device would be necessary to support the voltage in the above mentioned corridors. After system analysis, the second SVC device is proposed to be installed in Bus 36. Table 2 gives the parameters of the second SVC, determined using the same assumptions as for the previous case.

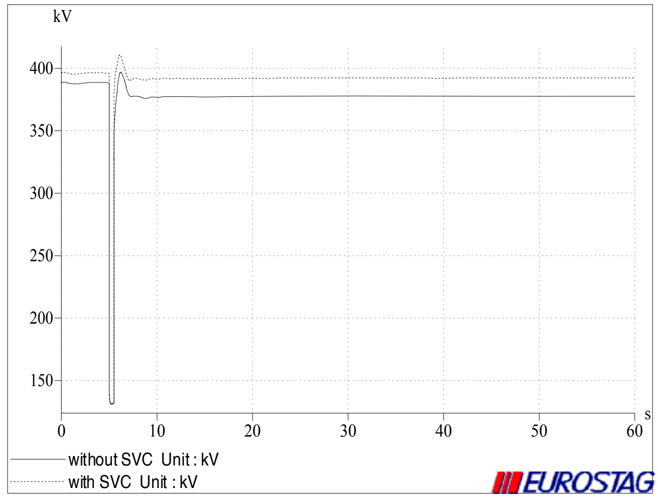

Fig. 6. Voltage evolution with and without SVC in Bus 36

TABLE 2. BUS 36 SVC DEVICE PARAMETERS

Controlled bus	Voltage reference U_o	Slope X_{SL}	Rated power	
			Capacitive	Inductive
Bus 36	400 kV	5%	150 MVAr	60 MVAr

The influence of the SVC device on the Bus 36 voltage in the worst scenario is illustrated in Fig. 6. It can be seen that the SVC successfully restore the voltage to an acceptable level. The reactive power injected by both SVC devices in order to achieve the desired objectives is shown in Fig. 7.

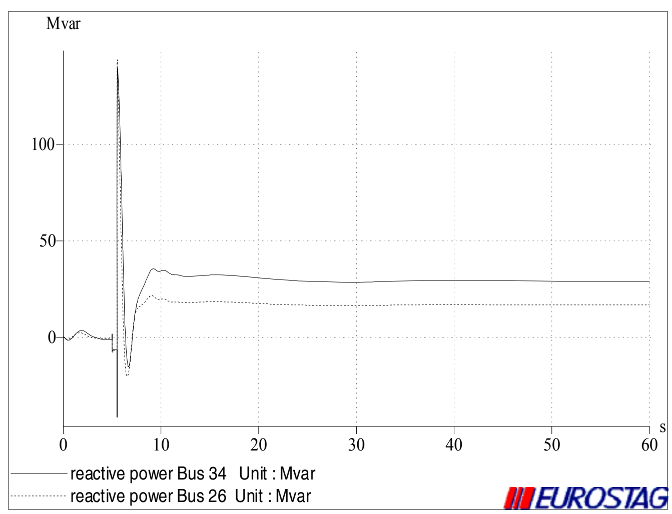

Fig. 7. SVC reactive power injection in Bus 36 and Bus 26

Extensive tests have shown that additional reactive power support by a SVC device installed at Bus 27 may allow additional 550 MW generated by wind farms to be evacuated from Zone 1, leading to a total amount of 2525 MW net transfer capacity.

IV. Conclusion

Operation of wind generation facilities is a great challenge for the power system operator, especially when transmission facilities are not capable to appropriately support the power transfer from generation sites to the load areas. Such issues are the great challenges in Romania, where the best sites for developing wind farms, with highest wind speed, are locates in the areas in which the power grid presents weak connections, just because of the geographical position. As experienced in the Dobrogea area, the S-E part of Romania, wind generation facilities added to scheduled nuclear and thermo power plants require advanced technologies. Therefore feasibility study on using SVC devices to control the voltages and to enhance the available transfer capacity in the transmission system was performed.

A static model of the SVC device was implemented in the PFAC software, developed by the authors, to analyze the power flows control possibilities into the power system. The static simulations performed with PFAC proved that SVC is a good solution for stressed conditions of the power systems. The installation location as well as the main rated parameters of the SVC were determined accordingly.

The static and dynamic analyses have shown that, by using SVC devices, the voltage levels have been improved, leading to a better use of the transmission grid. Furthermore, the SVC devices had shown an improvement in the dynamic performances of the power system.

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VI. Biographies

Constantin Bulac (M'02) graduated at the Polytechnic Institute of Bucharest in 1982 and has received the Ph.D. degree in electrical engineering from the University "Politehnica" of Bucharest in 1998; currently he is Professor in the Electric Power Engineering Department in the same University. His research interests are related to power systems stability, FACTS devices and artificial intelligence applications in power systems.

Mircea Eremia (M'98, SM'02) received the B.S. and Ph.D. degree in electrical engineering from the Polytechnic Institute of Bucharest in 1968 and 1977 respectively. He is currently Professor at the Electric Power Engineering Department from University "Politehnica" of Bucharest. His area of research includes planning and operation of transmission and distribution networks, power system stability and applications of FACTS devices and artificial intelligence applications in power systems.

Bogdan Otomega received the engineer degree and M.Sc. in power systems from University "Politehnica" of Bucharest in 2002 and 2003, respectively, and the PhD degree in 2008 from University of Liege, Belgium. He is employed as senior lecturer within the Electric Power Systems Department from University "Politehnica" of Bucharest. His main fields of interest are voltage stability, blackouts and cascading events, power system protection schemes, planning and operation of transmission and distribution networks and FACTS devices applications in power systems.

Lucian Toma (MS'04, M'09) was born in Romania in 1977. He received the engineer degree and M.Sc. in power systems from University "Politehnica" of Bucharest in 2002 and 2003, respectively. He is currently pursuing his Ph.D. degree in power systems. Mr. Toma is employed as senior lecturer within the Electric Power Systems Department from University "Politehnica" of Bucharest. His main fields of interest are electricity markets, planning and operation of transmission and distribution networks and FACTS devices applications in power systems.