USING FACTS DEVICES TO RESOLVE CONGESTIONS IN TRANSMISSION GRIDS

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Abstract **-** Increased electric power consumption causes transmission lines to be driven close to or even beyond their transfer capacities resulting in overloaded lines and congestions. Flexible AC Transmission Systems (FACTS) provide an opportunity to resolve congestions by controlling power flows and voltages. The focus in this paper lies on the Thyristor Controlled Series Compensator (TCSC) and the Static Var Compensator (SVC) as they are already in use.

In general, SVCs and TCSCs are controlled locally without any coordination. The resulting mutual influences may lead to a suboptimal control performance which may endanger the security of the system. In simulations where SVCs and TCSCs are controlled by local PI controllers with anti-windup, the interactions among the devices are demonstrated with TCSCs in parallel lines as well as in nonparallel lines, SVCs at different buses and a combination of TCSC and SVC in the same grid. It is shown how the controllers interact with each other, in the worst case ending up in an unsolvable conflict.

Finally, a supervisory control based on optimal power flow is developed coordinating the actions of the FACTS devices placed in the same grid such that conflicts among devices are prevented. The objective is to ensure secure transmission of electrical power and to avoid congestions resulting in overloaded and possibly disconnected lines. In a test grid, the improvements in active power losses, in line loadings and in voltage profile are demonstrated.

Keywords **-** FACTS - Congestion Management - Coordinated Control - Optimal Power Flow

I. INTRODUCTION

The electrical energy demand increases continuously leading to an augmented stress of the transmission lines and higher risks for faulted lines. The extension of the transmission grid needed to further guarantee secure transmission is difficult for environmental and political reasons. The blackouts in different parts of the world in the last two years have shown that the current situation is not satisfactory and a way to increase transfer capability and controllability in order to ensure secure power transmission has to be found.

An option to achieve this is the utilization of Flexible AC Transmission Systems (FACTS) [1], [2], [3]. The focus in this paper lies on the Static Var Compensator (SVC) and the Thyristor-Controlled Series Capacitor (TCSC). The SVC is a shunt-connected device and is already well-established and widely used. Conceptually, it is a variable shunt reactance injecting or absorbing reactive power in order to control the voltage. The TCSC is a series-connected

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device, which is already in use at a few places, but has not managed yet to become an established piece of equipment. As a variable reactance placed in series to the transmission line, a TCSC is able to modify the line impedance and thereby to control the power flow. This provides an opportunity to relieve heavily loaded lines and to prevent congestions.

In order to investigate the effects of these devices on the overall steady-state situation in a power grid, models are needed which accurately capture the influences of the devices on power flows and voltages. The models of the devices used in this paper are given in Sect. II.

FACTS devices determine the power flows on certain lines or voltages at given buses. This has also consequences for the remaining part of the grid including the lines and buses where other FACTS devices are placed. So far, the control of the FACTS devices is local, i.e. no supervisory control coordinates the actions of different devices. Thus, mutual influences among the devices can arise possibly resulting in adverse interactions [4], [5]. Assuming that a FACTS device is controlled by a PI controller with anti-windup, results of simulations showing such interactions are given in Section III.

In Section IV, a supervisory control based on optimal power flow [6] is developed. The objective is to prevent conflicts among the devices by coordinating their actions as well as to mitigate the danger of overloaded lines and congestions. The power flows, the voltage profile and the active power losses resulting from the optimal control are compared with the situation where no FACTS devices are in operation showing the achieved improvements.

II. MODELLING OF FACTS DEVICES

In literature, several ways of modelling FACTS devices are proposed. One approach is the injection method [7], where FACTS devices are modelled as power injections. As SVCs control the voltage by injecting reactive power, the corresponding model is a reactive power injection. The characteristics of a TCSC are reproduced by both reactive and active power injections.

Another way to model the devices are variable reactances. SVCs and TCSCs can both be built of modules consisting of a fixed capacitance in parallel to a thyristor controlled reactor. This results in a reactance with a value depending on the firing angle of the thyristors [8], [9]. For the following considerations this model is applied because it represents the structures of SVCs and TCSCs more closely and it is easier to incorporate existing device limitations into the optimal power flow calculations than with the power injection model.

A. Basic Circuit

The basic circuit from which SVC and TCSC are built in this paper is given in Fig. 1. In case of an SVC this circuit is shunt-connected to a bus, whereas for a TCSC it is connected in series to a transmission line. The firing angle α of the thyristor determines the equivalent reactance X_{eq} of the circuit and is defined as the delay angle measured from the peak of the capacitor voltage to the firing instant. The equivalent reactance X_{eq} is determined as [1]

$$X_{eq}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) + X_C} \tag{1}$$

where

$$X_C = -\frac{1}{\omega C}; \qquad X_L = \omega L \cdot \frac{\pi}{\pi - 2\alpha - \sin(2\alpha)} \tag{2}$$

The resulting graph for function (1) is given in Fig. 2(a). Apparently, this function has a discontinuity at the resonance angle α_{res} of the basic circuit. If the susceptance $B_{eq} = -\frac{1}{X_{eq}}$ is considered instead of the reactance, the resonance angle corresponds to the zero-crossing (Fig. 2(b)). Four different operating modes for this basic circuit can be identified [3]:

- **Bypass mode** ($\alpha = 0°$): The thyristor valve is triggered continuously. The basic circuit behaves like a parallel connection of the series capacitor and the inductor.
- **Inductive boost mode** ($0° < \alpha < \alpha_{res}$): For α below the resonance angle the equivalent reactance X_{eq} is positive corresponding to an inductance.

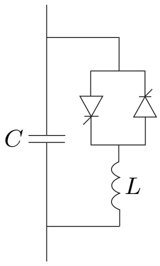
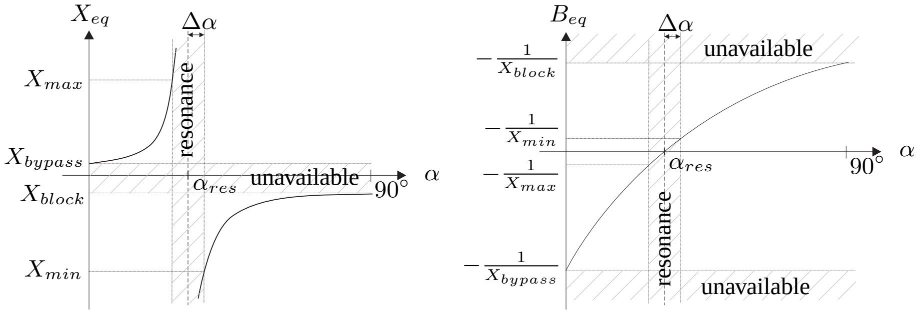


Fig. 1. Basic circuit for SVC and TCSC



(a) (b)

Fig. 2. (a) Equivalent reactance X_{eq} and (b) equivalent susceptance B_{eq} of basic circuit

- **Capacitive boost mode** ($\alpha_{res} < \alpha < 90°$): If the firing angle is larger than the resonance angle, the equivalent reactance is negative resulting in capacitive behavior.
- **Blocking mode** ($\alpha = 90°$): The thyristor is not triggered and therefore kept in nonconducting state. Simply the fixed capacitor contributes to the reactance.

B. Limitations

From the characteristics of the basic circuit, some limitations concerning the firing angle α give implicitly rise to constraints on the equivalent reactance X_{eq}. The minimal and maximal values for the firing angle are $0°$ and $90°$, respectively, resulting in an unavailable band between X_{block} and X_{bypass} [10]. As it is not acceptable to introduce an infinite reactance in series to a line, the firing angle in case of the TCSC must be kept at a certain distance $\Delta\alpha$ from the resonance angle α_{res}. This yields an upper bound X_{max} and a lower bound X_{min} for X_{eq} (Fig. 2(a)). The according limitations on the equivalent susceptance B_{eq} are given in Fig. 2(b).

Usually both SVC and TCSC consist of several basic modules shown in Fig. 1, each controlled separately. For the TCSC, these modules are connected in series. Thus, the equivalent reactances whose characteristics are given in Fig. 2(a) can be added such that the gap around zero is covered [10]. Therefore, the constraints on the total TCSC reactance X_{TCSC} are reduced to an upper limit $\overline{X}_{TCSC}$ and a lower limit $\underline{X}_{TCSC}$.

In case of the SVC, the resonance point is not a problem. As the basic modules are shunt-connected in parallel, this simply corresponds to a disconnected module. Therefore, the unavailable band around zero for the equivalent susceptance B_{eq} is dissolved. In the sum, an upper bound $\overline{B}_{SVC}$ and a lower bound $\underline{B}_{SVC}$ result for the total susceptance.

For the TCSC, the allowed degree of compensation of the line reactance gives rise to additional limitations. In accordance with [11], the compensation range is set to 20% inductive and 80% capacitive.

C. Application

The SVC is a variable shunt reactance as shown in Fig. 3(a). In the power flow equations this is accounted for by including the reactive power

$$Q_{SVC} = -U_k^2 \cdot B_{SVC} \tag{3}$$

into the reactive power balance at bus k subject to

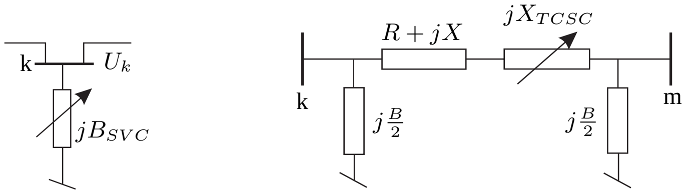
$$\underline{B}_{SVC} < B_{SVC} < \overline{B}_{SVC}. \tag{4}$$

According to Fig. 3(b), the TCSC is incorporated into the transmission line model by simply adding the variable reactance X_{TCSC} to the line reactance X [11]

$$X_{tot} = X + X_{TCSC} \tag{5}$$

and accounting for the limitations by

$$\max(\underline{X}_{TCSC}, -0.8 \cdot X) < X_{TCSC} < \min(\overline{X}_{TCSC}, 0.2 \cdot X) \tag{6}$$



(a) (b)

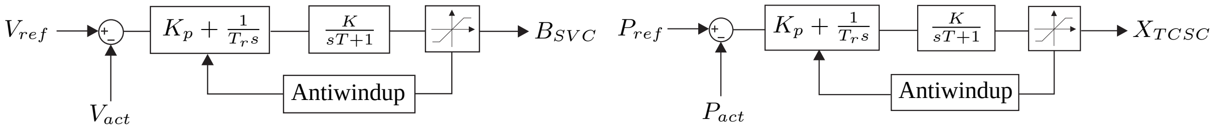
Fig. 3. (a) SVC modelled as shunt-connected susceptance and (b) TCSC modelled as series-connected reactance

III. MUTUAL INFLUENCES

The idea of SVC and TCSC devices is to control the power flow and voltages by adapting the reactances. The influence of a device is not confined to the line or the bus where it is placed at. On the contrary, the impacts could be far-ranging influencing power flows and voltages at distant lines and buses. As a consequence, interactions among FACTS devices placed in the same grid arise. If the controllers of the installed devices are not coordinated, these interactions may lead to undesirable effects such as conflicts between devices with different intentions. Especially when the number of FACTS devices increases and the distance among them decreases, this can become a considerable problem.

A. Test System Setup

The reactance values of SVCs and TCSCs are determined by PI controllers as shown in Fig. 4. The controlled value for the SVC is the voltage at the bus where it is placed and for the TCSC it is the active power flow through the device. The characteristics of the firing angle delay control are approximated by a transfer function of first order [1]. The limitations on SVC susceptance and TCSC reactance are modelled by saturation elements. To avoid that the integrator part of the PI controller continuously increases when the actuator has reached a limit, an anti-windup is applied in order to turn off the I-part in such cases.



(a) (b)

Fig. 4. (a) PI controller for SVC and (b) for TCSC

In the following simulations, the grid in Fig. 5 is used. This grid consists of a generation area in the left part and a load area in the right part. It is assumed that no generation rescheduling takes place, i.e. the power production of the generators is kept unchanged.

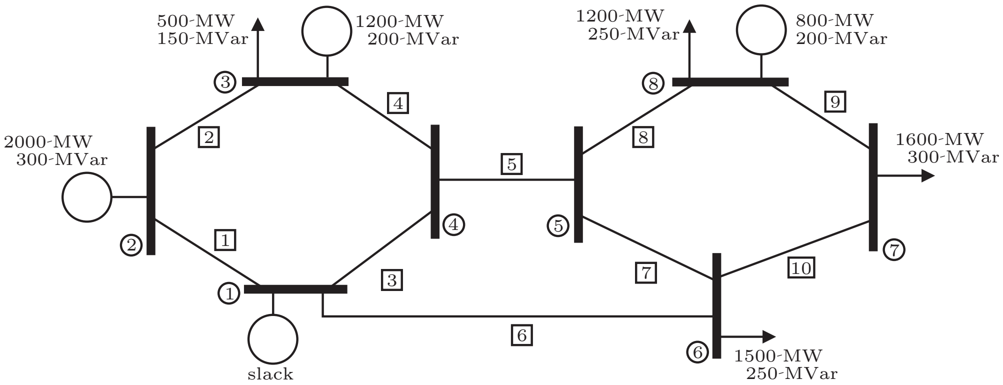
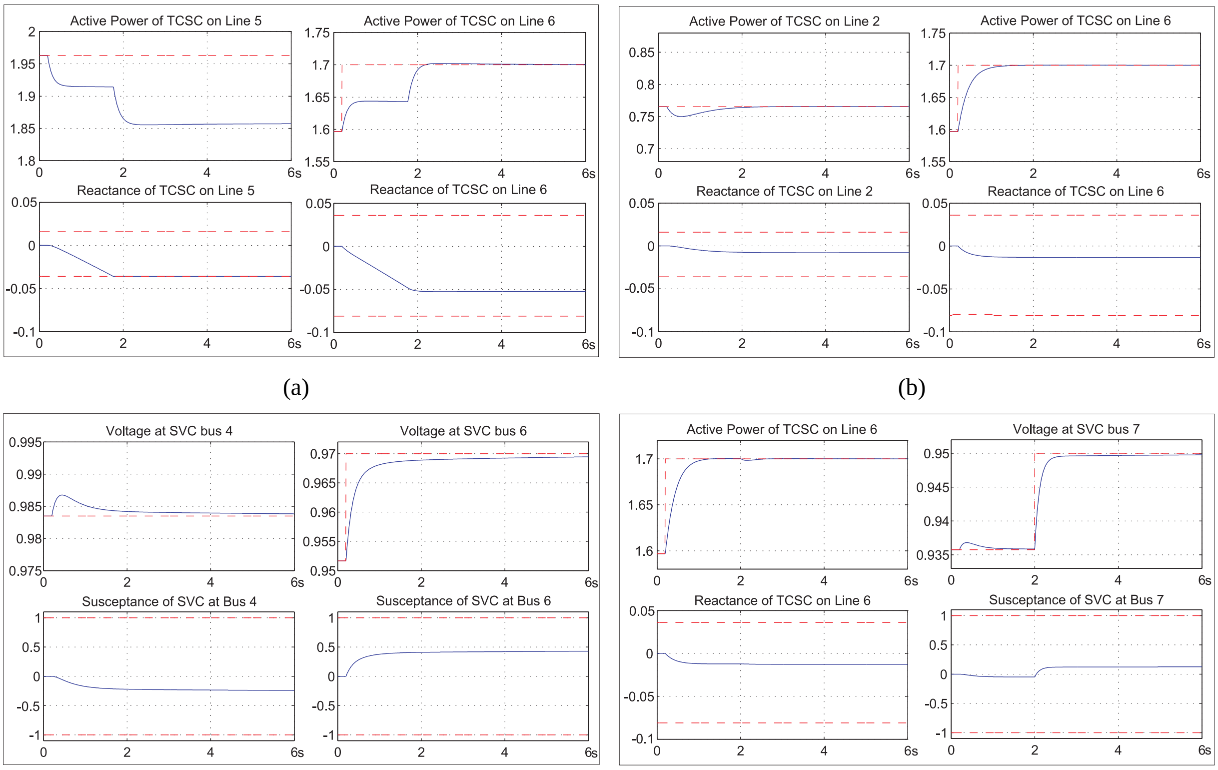


Fig. 5. 8-bus network with a generation area on the left and a load area on the right

B. *Simulation Results*

Test Case 1 (TCSCs in parallel lines): TCSCs are placed in lines 5 and 6. These are the only connections between the generation and load area. Therefore, it is quite obvious that this has to result in a conflicting situation if the reference values for the active power flows through the TCSCs do not add up to the total power needed in the load area. At the beginning of the simulation, the reference values of the controllers are set such that they can be reached by setting the reactance values of both TCSCs to zero. Simulation results are given in Fig. 6(a).



(a) (b)

(c) (d)

Fig. 6. Interactions between PI controllers when changing set points. (a) TCSCs in lines 5 and 6, (b) TCSCs in lines 2 and 6, (c) SVCs at buses 4 and 6 and (d) an SVC at bus 7 and a TCSC in line 6; all values are given in p.u.

The graphs at the top show the active power through the TCSCs. The dashed lines are the corresponding reference values. The reference value for the active power flow through line 6 changes after 0.2s. In order to reach this reference value, the reactance of the TCSC on this line is decreased. But this also influences the power flow on line 5 and the TCSC reactance on that line is lowered, too. The controllers start to counteract and fight against each other. Both decrease their TCSC reactances in order to reach their reference values. At 1.8s the controller on line 5 arrives at its lower reactance limit and cannot react any more to the actions of the other controller. Therefore, the controller on line 6 is able to adapt the TCSC reactance such that the reference value for the active power flow on this line is reached.

Test Case 2 (TCSCs in nonparallel lines): In this test case, the TCSCs are placed in the nonparallel lines 2 and 6 for which the results are shown in Fig. 6(b). At 0.2s the reference value for the controller on line 6 is changed. The controller reacts and lowers the TCSC reactance which in turn has the effect that the active power flow on line 2 starts to deviate from its reference value. The controller on this line also decreases the reactance value of the TCSC. Changes in one line still influence the power flow on the other line but the reference values for the active power flows can independently be set without initiating unsolvable conflicts.

It is still possible that one controller reaches its limits before the active power flow attains the reference value but as opposed to the case with TCSCs in parallel lines this conflict could be solved by relaxing the constraints on the reactance value.

Test Case 3 (SVCs at different buses): The results for the simulation with SVCs at buses 4 and 6 are given in Fig. 6(c). The course of the voltages at these buses are shown in the graphs at the top. At 0.2s the reference value for the SVC at bus 6 is changed. As a consequence the susceptance value of the SVC at this bus is increased. Thereby the voltage at bus 4 deviates and in order to return to the reference value the SVC susceptance at this bus is lowered. As it is possible that the steady-state voltages at two buses are determined independently of each other both controllers reach their reference values.

Test Case 4 (TCSC and SVC): In transmission systems, active power flow is strongly coupled to voltage angles and reactive power flow to voltage magnitudes. As TCSCs control active power flow and SVCs voltage magnitude the mutual influences are expected to be minor.

In order to verify this, a TCSC is placed in line 6 and an SVC at bus 7. The results are given in Fig. 6(d). At 0.2s the reference value for the TCSC is changed. As expected, the deviations of the voltage at bus 4 from its reference value caused by the actions of the TCSC controller are marginal. This also holds for the active power flow deviations of the TCSC when the set point of the SVC is changed at 2s.

IV. COORDINATED CONTROL OF FACTS

In order to avoid adverse mutual influences, the control of FACTS devices has to be coordinated. In [11], fuzzy logic is used to control multiple series FACTS devices. A two step optimization is applied in [12] where in the first step the deviations of the bus voltages from their reference values and in the second step the sum of squared active line loads are minimized. In [4], a remote feedback control scheme is compared with a control based on optimal power flow optimizing loadability also taking N-1 security considerations into account.

Optimal power flow (OPF) with different objective functions has been applied in several works to design controllers in order to coordinate FACTS devices. Common objective functions are minimizing operating costs, active power losses, deviations from given reference values or minimizing or maximizing power transfer to an area [8], [13], [14]. The advantage of a control law based on OPF is not only that the defined objective is achieved, but also that the mutual influences of FACTS devices are negligible because reactances and not power flows or voltages are set and these are independent of each other. In this paper, the objective is to guarantee a secure operation of the transmission grid and to resolve possible congestions.

A. Problem Formulation

The formulation of an OPF consists of an objective function as well as linear and nonlinear equality and inequality constraints [6]

$$\min \quad f(\mathbf{x}, \mathbf{u}) \tag{7}$$

$$\text{subject to} \quad \mathbf{g}(\mathbf{x}, \mathbf{u}) = \mathbf{0} \tag{8}$$

$$\mathbf{h}(\mathbf{x}, \mathbf{u}) \leq \mathbf{0} \tag{9}$$

where the state vector x in this case contains the voltage magnitudes and angles at all buses and the vector u the control variables of FACTS devices and possible auxiliary variables.

$\mathbf{g}(\mathbf{x}, \mathbf{u})$: The equality constraints correspond to the power flow equations including the power injections by SVCs and the modification of the line reactances by TCSCs.

$\mathbf{h}(\mathbf{x}, \mathbf{u})$: The limitations on SVCs and TCSCs (4) and (6) belong to the inequality constraints. Additionally, the aim is to keep the power flow on each transmission line below its transfer capacity. These limitations are formulated as soft constraints in order to avoid that the defined problem results in an unsolvable system. In a first step, the power flows should not exceed 90% of the corresponding transfer capacities. If this is not achievable, the lines at least should not be overloaded. For each line i the inequalities

$$\begin{aligned} S_i &\leq 0.9 \cdot S_i^{max} + \varepsilon_i, & 0 &\leq \varepsilon_i & (10)\\ S_i &\leq S_i^{max} + \eta_i, & 0 &\leq \eta_i & (11) \end{aligned}$$

are defined where S_i is the apparent power on line i and S_i^{max} the corresponding capacity limit. The slack variables ε_i and η_i are only non-zero if the original constraints are violated. Their values are heavily penalized in the cost function such that the solver has a strong incentive to set them to zero whereas the penalization of η_i is much severer than of ε_i.

Soft constrains are also applied to bus voltages V_j which are supposed to lie within $\pm V^{lim}$ from their reference value V_j^{ref}

$$|V_j - V_j^{ref}| \leq V^{lim} + \nu_j, \qquad 0 \leq \nu_j. \tag{12}$$

Again, the slack variable ν_j is heavily penalized in the objective function.

$f(\mathbf{x}, \mathbf{u})$: The objective function is the core of the optimization and is not given a priori by the system. The objective in this paper is on one side to lower the risk for congestions and failures of lines, and on the other side to reduce power losses. The former is achieved by holding the inequality constraints (10)-(12) with slacks variables equal to zero. Thus, the slack variables ε_i, η_i and ν_j are penalized heavily. Keeping the voltages close to predefined reference values contributes to the same objective. The active power losses are minimized by simply incorporating them into the objective function. Therefore, the objective function results in

$$f(x) = \sum_i (a \cdot P_i^{loss} + b \cdot \varepsilon_i + c \cdot \eta_i) + \sum_j (d \cdot (V_j - V_j^{ref})^2 + e \cdot \nu_j). \tag{13}$$

The parameters to be adjusted are the weighting factors a, b, c, d and e. Their values are dependent on the importance of the individual objectives.

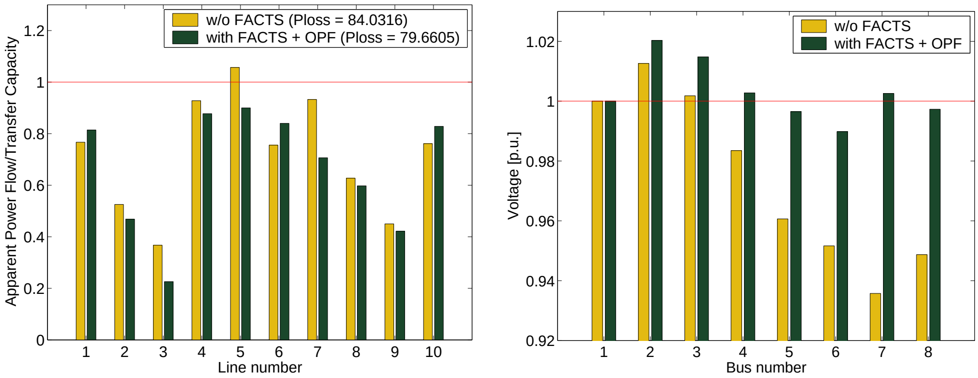
With $\mathbf{g}(\mathbf{x}, \mathbf{u})$, $\mathbf{h}(\mathbf{x}, \mathbf{u})$ and $f(\mathbf{x}, \mathbf{u})$ the optimal power flow problem is defined and can be solved by an appropriate solver. For the simulations in this paper, the Matlab function `fmincon` is used.

B. Simulation Results

In the following simulation, the configuration is the same as in the preceding section in test case 4: in the grid given in Fig. 5, a SVC is placed at bus 7 and a TCSC on line 6. In Fig. 7, the apparent power flows and voltages obtained with optimal power flow control employing the SVC and TCSC are compared with the base case where no FACTS devices are in use. The power flows are given in fractions of the corresponding transfer capacities and the voltages in p.u. The reference value for all bus voltages is chosen to be 1 p.u.

In the base case, line 5 is overloaded and lines 4 and 7 are loaded to more than 90%. The active power losses add up to 84.03 MW. The deviations of the bus voltages from the reference value are especially in lines 5 to 8 considerable. The heavily loaded lines in combination with the resulting voltage profile yield the transmission grid to be in a precarious situation.

Placing an SVC and a TCSC in the grid, gives the possibility to influence the voltage profile and the power flow. The apparent power flows in Fig. 7 for this case show that no line is loaded to more than 90%. Thus, the congestion in line 5 is resolved. The voltage profile is improved such that all bus voltages lie within ± 0.02 p.u. from the reference value. Since the SVC was placed at the bus with the lowest voltage, the reactive power injected at this point increases the voltages at all buses, except the slack bus, bringing them closer to their reference values. The overall voltage profile is considerably more balanced. But the improvements cannot only be seen in apparent power and voltage distribution but also in active power losses. Compared with the base case, losses are decreased by approximately 5.2%.



(a) (b)

Fig. 7. (a) Apparent power flows with respect to the corresponding transfer capacities and (b) bus voltages (p.u.)

V. CONCLUSION

FACTS devices are able to influence the power flow in a transmission grid. As the number of such devices increases, a careful consideration of mutual influences becomes necessary. It has been shown in this paper that adverse interactions between local controllers may arise possibly endangering the security of the system.

Therefore, a coordinated control based on optimal power flow was developed in order to relieve overloaded lines, resolve congestions and ensure security. It was shown in simulations that active power losses are reduced, the voltage profile improved and the power flow distributed such that no line is overloaded any more.

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