X SEPOPE

21 a 25 de maio de 2006

May – 21^{rst} to 25^{th} – 2006
FLORIANÓPOLIS (SC) – BRASIL

X SIMPÓSIO DE ESPECIALISTAS EM PLANEJAMENTO DA OPERAÇÃO
E EXPANSÃO ELÉTRICA

X SYMPOSIUM OF SPECIALISTS IN ELECTRIC OPERATIONAL
AND EXPANSION PLANNING

FACTS Control for Large Power Systems Incorporating Security Aspects

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SUMMARY

Flexible AC Transmission Systems (FACTS) are able to control power flows and/or voltages in a power grid providing opportunities to improve system security. In steady state, this corresponds as most important tasks to avoiding overloaded lines, enhancing voltage profile and increasing transfer capacities. In order to benefit from FACTS devices, an appropriate control is crucial. Especially, if the number of FACTS devices in a grid increases and the distances between them decrease, a local control might not be sufficient any more. Mutual influences among different devices may arise and render coordination indispensable.
In this paper, a control strategy based on Optimal Power Flow is proposed. The objective is to improve security in steady-state, which implies to avoid overloaded lines and to keep bus voltages close to a pre-defined reference value. As FACTS devices have only influence on a limited area in their vicinity, sensitivity analysis with respect to the settings of the device is used to identify the area of influence. Only buses and lines included in the area of influence are then taken into account in the process of determining the optimal settings for the FACTS device. Consequently, the proposed control is also applicable to large and therefore realistic grids.
When the number of devices in a grid increases, it becomes probable that the areas of influence of two or more devices overlap, which results in the mentioned mutual influences. In order to coordinate the devices, an iterative algorithm is applied, where the controllers sequentially determine the settings of the corresponding FACTS devices taking the effects of the other devices into account. Simulation results are given for the IEEE 57 bus grid for the limited control of a single FACTS device as well as for the multi-area control.

KEYWORDS

FACTS, sensitivity analysis, multi-area control, Optimal Power Flow, congestion management.

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1. Introduction

Caused by the liberalization of electricity markets, electric power trades across borders have increased and led to continuously changing load-flow patterns. Therefore, a transmission system is needed which is able to cope with daily modified generation and load distributions [1]. In several areas in Europe, the grid is not able to meet these demands any more, e.g. the lines between France/Switzerland and Italy are often driven very close to or even beyond their limits. The occurred blackouts (e.g. Italy 2003) have increased the importance of finding a solution to this problem. But building new lines is difficult for various reasons.

As FACTS devices are able to control power flows and voltages, they provide the possibility to alleviate overloaded lines and to influence the voltage profile [2, 3] meeting the demands of a liberalized market. Nowadays, FACTS devices are mostly controlled locally by P- or PI-controllers. The reference values for the FACTS devices are generally kept constant or adapted in large time steps and the determination of these references is normally based on local objectives [4]. The effects of the FACTS devices on the rest of the power system are not taken into account and furthermore, there is no coordination among devices placed in the same grid. This may lead to mutual influences among different FACTS devices and to a suboptimal control performance. As the number of installed FACTS increases, controllers are needed which consider not only local data but also the device's influences on the rest of the grid implicating a coordination among the controllers.

In this paper, a control for FACTS devices is proposed which has the above mentioned features, thus, on one side coordinates the actions of different devices if required and on the other side takes the part of the grid into account which is influenced by the device.

The FACTS devices considered are the Static Var Compensator (SVC) and the Thyristor Controlled Series Compensator (TCSC) [2, 5]. The models for these devices are given in the second section. In the third section, the proposed control based on Optimal Power Flow [6] is described. The equality and inequality constraints as well as the objective function which includes to relieve overloaded lines, to improve voltage profile and to minimize active power losses are defined. But in large grids, it is most often not possible to take the entire grid into account in the optimization process. Therefore, in Sect. 4, sensitivity analysis [7] is carried out in order to determine the area of influence of a device, i.e. which lines and buses are sensitive to the settings of the FACTS devices and should be included in the Optimal Power Flow calculations. How the optimization is reduced to this limited area is explained in Sect. 5. When areas of influence of several FACTS devices overlap, mutual influences among the devices may arise and therefore the controllers of the different devices have to be coordinated. The iterative method applied and corresponding simulation results are given in Sect. 6. Finally, the last section concludes the paper.

2. Modelling

As the investigations concentrate on the steady state situation, the models are also confined to steady state. The choice of model depends on the intended use. One option is to use the injection method where virtual power injections are placed at the buses connected to the device reproducing the characteristics of the device [8]. Another method is to model SVC and TCSC as variable reactances whose values depend on the firing angle of the thyristors. This second method is applied in this paper in order to simplify the integration into OPF formulation.

- **SVC:** The SVC injects or absorbs reactive power in order to control the voltage at a given bus. This corresponds to a shunt-connected variable susceptance [9] as shown in Fig. 1a). The variable susceptance B_{SVC} has a minimal and a maximal value caused by the limited firing angle. Therefore, the equations modeling the SVC are

$$Q_{SVC} = -V_k^2 \cdot B_{SVC} \tag{1}$$

$$\underline{B}_{SVC} \le B_{SVC} \le \overline{B}_{SVC} \tag{2}$$

- **TCSC:** The TCSC is placed in series with a line in order to control the active power flow on this line by increasing or decreasing the line reactance. Therefore, the TCSC corresponds to a series-connected variable reactance X_{TCSC} (Fig. 1b)) [10]. The value of the reactance is limited by the firing angle of the thyristors to an upper and a lower value. As there is also a limited allowed compensation range which is set here to 20% inductive and 80% capacitive, the TCSC is modelled by

$$X_{tot} = X + X_{TCSC} \tag{3}$$

$$\max\left(\underline{X}_{TCSC}, -0.8\cdot X\right) \le X_{TCSC} \le \min\left(\overline{X}_{TCSC}, 0.2\cdot X\right) \tag{4}$$

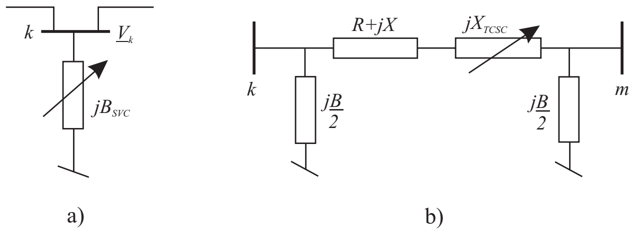

Figure 1: Models of a) SVC and b) TCSC

3. Control based on OPF

The control proposed in this paper is based on Optimal Power Flow [6] with the objective to improve system security [11]. Therefore, an objective function, equality and inequality constraints have to be defined. The general problem description is given as

$$\min \quad f(\mathbf{x},\mathbf{u}) \tag{5}$$

$$\text{subject to} \quad \mathbf{g}(\mathbf{x},\mathbf{u}) = 0 \tag{6}$$

$$\mathbf{h}(\mathbf{x},\mathbf{u}) \le 0 \tag{7}$$

where **x** contains the voltage magnitudes and angles and **u** the control parameters of the FACTS devices.

g(**x**,**u**): The equality constraints are composed of the power flow equations with incorporated FACTS devices.

h(**x**,**u**): Three different types of inequality constraints have to be defined in the considered problem. They concern the set values of the FACTS devices, bus voltages and line loadings.

- *FACTS:* As described in Sect. 2, SVC as well as TCSC have upper and lower limits on their susceptance and reactance value, respectively. Thus, (2) and (4) are included in the inequality constraints.
- *Bus voltages:* In order to improve voltage stability, the bus voltages V_j should be hold within acceptable limits. To avoid that the problem turns infeasible, these constraints are defined as soft constraints using slack variables ν_j which results in

$$\left|V_j - V_j^{ref}\right| \le V^{lim} + \nu_j, \quad 0 \le \nu_j \tag{8}$$

  where V_j^{ref} is the reference voltage for bus j and V^{lim} the maximal allowed deviation from this reference value. The slack variables are penalized heavily in the objective function such that there is a strong incentive to hold the original constraints.
- *Line loadings:* A way to improve security in a system is to prevent lines from high loadings. This is taken into account by defining soft constraints on the line loadings. The most important

is to keep line loadings below 100% but if possible to not exceed 90%. Therefore, for each line i two soft constraints are defined

$$S_i / S_i^{\max} \le 0.9 + \varepsilon_i, \quad 0 \le \varepsilon_i \tag{9}$$

$$S_i / S_i^{\max} \le 1 + \eta_i, \quad 0 \le \eta_i \tag{10}$$

where S_i is the apparent power flow on line i, $S_i^{\max}$ the corresponding thermal limit and ε_i and η_i the slack variables. Again, the slack variables are heavily penalized in the objective function.

$f(\mathbf{x},\mathbf{u})$: The objective function includes three different components:

1. to minimize active power losses,
2. to keep line loadings below 90% or if not possible at least below 100% and
3. to keep bus voltages as close as possible to the given reference values and within acceptable limits.

The sum of these objectives each weighted with an appropriate factor form the objective function given as

$$f(\mathbf{x},\mathbf{u}) = \sum_i \left(\underbrace{a \cdot P_i^{loss}}_{1} + \underbrace{b \cdot \varepsilon_i + c \cdot \eta_i}_{2} \right) + \sum_j \left(\underbrace{d \cdot \left(V_j - V_j^{ref}\right)^2 + e \cdot \nu_j}_{3} \right). \tag{11}$$

4. Sensitivity Analysis

In the described control, the entire grid is taken into account in the optimization process. For a realistic transmission grid, this is not possible due to the size of the resulting optimization problem. In addition, it is usually not necessary as the area where the FACTS devices have considerable influence is limited. In order to find out how far-ranging the influences of FACTS devices are, sensitivity analysis is performed and then only this area of influence is taken into account in the optimization process.

4.1. Analytical Derivation

In general, the sensitivities K_{Sens} of variables $\mathbf{y}(\mathbf{x},\mathbf{u})$ with respect to changes in variables $\mathbf{u}$ and subject to the equation system $\mathbf{g}(\mathbf{x},\mathbf{u})$ are calculated from [7]

$$\begin{aligned} K_{Sens} &= \frac{d\mathbf{y}}{d\mathbf{u}} = \frac{\partial \mathbf{y}}{\partial \mathbf{u}} + \frac{\partial \mathbf{y}}{\partial \mathbf{x}} \cdot \frac{\partial \mathbf{x}}{\partial \mathbf{u}} \\ &= \frac{\partial \mathbf{y}}{\partial \mathbf{u}} - \frac{\partial \mathbf{y}}{\partial \mathbf{x}} \cdot \left(\frac{\partial \mathbf{g}}{\partial \mathbf{x}} \right)^{-1} \cdot \frac{\partial \mathbf{g}}{\partial \mathbf{u}} \end{aligned} \tag{12}$$

where the term $\frac{\partial \mathbf{x}}{\partial \mathbf{u}}$ is determined from the Taylor approximation of the equality constraints, i.e.

$$\begin{aligned} \mathbf{g}(\mathbf{x_0} + \Delta\mathbf{x}, \mathbf{u_0} + \Delta\mathbf{u}) &\approx \mathbf{g}(\mathbf{x_0}, \mathbf{u_0}) + \frac{\partial \mathbf{g}}{\partial \mathbf{u}} \Delta\mathbf{u} + \frac{\partial \mathbf{g}}{\partial \mathbf{x}} \Delta\mathbf{x} = 0 \\ \frac{\partial \mathbf{x}}{\partial \mathbf{u}} \approx \frac{\Delta\mathbf{x}}{\Delta\mathbf{u}} &= -\left(\frac{\partial \mathbf{g}}{\partial \mathbf{x}} \right)^{-1} \cdot \frac{\partial \mathbf{g}}{\partial \mathbf{u}} \end{aligned} \tag{13}$$

In the case considered, the equality constraints $\mathbf{g}(\mathbf{x},\mathbf{u})$ correspond to the power flow equations defined in Sect. 3, where $\mathbf{x}$ is the vector of voltage magnitudes and angles at the buses and $\mathbf{u}$ the settings of the FACTS devices. The variables in $\mathbf{y}(\mathbf{x},\mathbf{u})$ for which the sensitivities are to be calculated are the active, reactive and apparent power flows through the lines and the voltage magnitudes and angles at the buses.

4.2. Test system

The grid used as a test system in this paper is the IEEE 57 bus system, slightly modified in order to have a grid for which interesting results can be shown. Compared with the original grid, the total load is equally distributed among the loads in the grid, an additional generator is added at bus 31 and line resistances and reactances are multiplied by a factor of 0.3. The structure of this system and the numbering of buses and lines are given in Fig. 2.

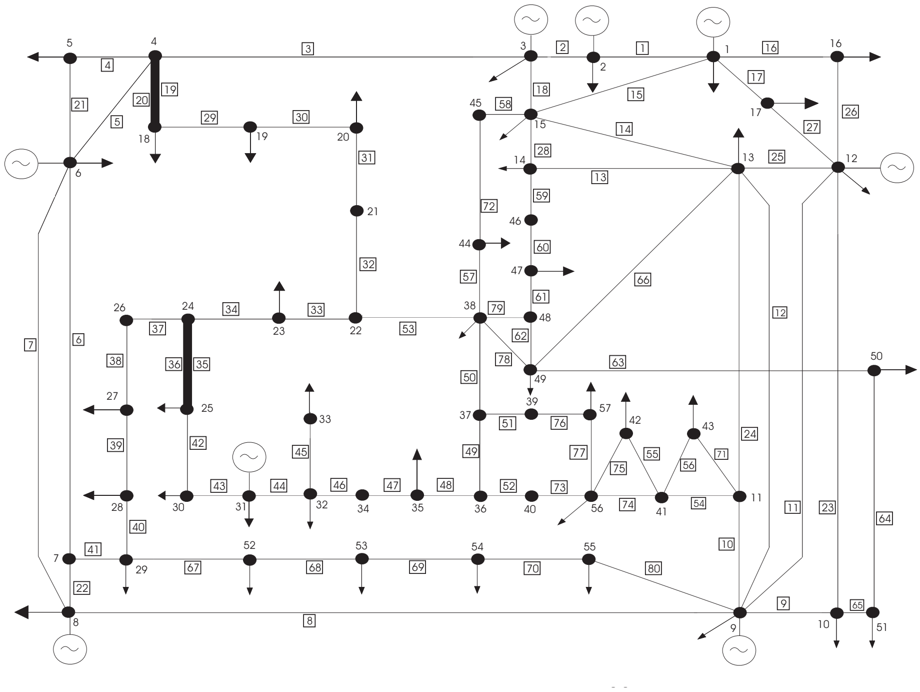

Figure 2: Modified IEEE 57 bus grid used as test system

4.3. Sensitivities for SVC

In case of an SVC, the sensitivities of power flows and voltages can be determined either with respect to the equivalent susceptance of the device B_{SVC} or with respect to the voltage at the corresponding bus V_{SVC} . As the sensitivities with respect to the voltage are less dependent on the operating point of the SVC than with respect to the susceptance [10], **u** is chosen as the SVC voltage. This results in

$$\mathbf{y}(\mathbf{x},\mathbf{u}) = \left(P_i(\mathbf{x},\mathbf{u}) \quad Q_i(\mathbf{x},\mathbf{u}) \quad S_i(\mathbf{x},\mathbf{u}) \quad V_j \quad \theta_j\right)^T, \qquad \mathbf{u} = V_{SVC}, \qquad \mathbf{x} = \left(V_j \quad \theta_j\right)^T. \tag{14}$$

As an example, an SVC is placed at bus 19 in the test grid and the sensitivities to the setting of this device are calculated. The obtained sensitivity values for power flows on lines 20 and 53 and for voltages at buses 21 and 38 are given in Table I for various operating points of the SVC. It can be stated that the sensitivities of the reactive power flow and the voltage magnitude are only slightly dependent on the operating point whereas the other variables vary much more. As expected from the fact that SVC injects or absorbs reactive power, the reactive power flows are more sensitive with respect to voltage changes than active power flows and voltage magnitudes more than angles.

Table I: Sensitivities with respect to V_{SVC} for SVC at bus 19

B_{SVC}		-0.8	-0.4	0	0.4	0.8
Line 20	*P*	-0.308	-0.232	-0.144	-0.040	0.085
	Q	-1.816	-1.843	-1.871	-1.901	-1.931
	S	-1.222	-0.862	-0.255	0.554	1.236
Line 53	*P*	0.055	-0.035	-0.140	-0.263	-0.409
	Q	1.935	1.959	1.986	2.015	2.044
	S	-1.695	-1.576	-1.343	-0.869	-0.003

B_{SVC} *(p.u.)*		-0.8	-0.4	0	0.4	0.8
Bus 21	*V*	0.159	0.155	0.151	0.147	0.142
	θ	-0.064	-0.072	-0.082	-0.094	-0.107
Bus 38	*V*	0.057	0.056	0.055	0.054	0.053
	θ	-0.006	-0.011	-0.017	-0.024	-0.032

4.4. Sensitivities for TCSC

If the considered device is a TCSC, the sensitivities can be taken either with respect to the equivalent reactance X_{TCSC} or the active power flow through the device P_{TCSC}. The dependency of the sensitivities on the operating point is lower if they are determined with respect to the active power flow [10]. Therefore, (12) is applied with

$$\mathbf{y}(\mathbf{x},\mathbf{u}) = \begin{pmatrix} P_i(\mathbf{x},\mathbf{u}) & Q_i(\mathbf{x},\mathbf{u}) & S_i(\mathbf{x},\mathbf{u}) & V_j & \theta_j \end{pmatrix}^T, \qquad \mathbf{u} = P_{TCSC}, \qquad \mathbf{x} = \begin{pmatrix} V_j & \theta_j \end{pmatrix}^T. \tag{15}$$

In Table II, the results are shown when a TCSC is placed in line 8 of the test system. Again, the sensitivities for various operating points of the TCSC are considered and the sensitivity values for lines 7 and 34 and buses 29 and 51 are given. Here, active power flows and voltage angles are more sensitive than reactive power flows and voltage magnitudes.

Table II: Sensitivities with respect to P_{TCSC} for TCSC in line 8

X_{TCSC}		-0.8	-0.5	-0.2	0	0.2
Line 7	P	0.415	0.405	0.403	0.402	0.402
	Q	-0.090	-0.090	-0.091	-0.092	-0.092
	S	-0.247	-0.285	-0.300	-0.308	-0.314
Line 34	P	0.124	0.125	0.125	0.125	0.124
	Q	-0.063	-0.064	-0.065	-0.065	-0.066
	S	-0.128	-0.134	-0.135	-0.135	-0.136

X_{TCSC} (p.u./X_{line})		-0.8	-0.5	-0.2	0	0.2
Bus 29	V	-0.004	-0.004	-0.004	-0.004	-0.004
	θ	-0.047	-0.041	-0.040	-0.039	-0.039
Bus 51	V	0.001	0.001	0.001	0.001	0.001
	θ	-0.001	0.009	0.011	0.011	0.011

5. Limited Area Control

Even though the influence of a FACTS device is not confined to the bus or line where it is placed, its impact on distant lines and buses is limited. Using sensitivity analysis, an area can be defined which includes lines and buses on which the influence is significant. This provides the possibility to limit the Optimal Power Flow control described in Sect. 3 to a reduced area. In the following, the proposed control for the limited area is described for SVC and TCSC and then simulation results are given.

5.1. SVC

The main task of an SVC concerning the objective function (11) is to minimize active power losses and to bring the bus voltages close to their reference values. Therefore, the area of influence is determined by the sensitivities of active power losses and voltages with respect to the SVC voltage. The active power loss sensitivities are obtained by simply adding the sensitivities of active power flows at both ends of the corresponding line. First, all lines whose sensitivities for active power flow losses are greater than a certain value $\underline{K}_{Ploss}$ are included in the area of influence as well as the adjacent buses to these lines. Then, it is checked if there are any buses left out whose voltage sensitivities are considerable, i.e. greater than a certain limit $\underline{K}_V$. As a major part of the objective function concerns voltages, these buses cannot be neglected in the optimization process. In order to keep the problem as small as possible, they are not included in the area of influence but only taken into account in the objective function using a linear approximation of the voltage. Thus, the voltage magnitude V_{j1} at bus j after a change in the SVC voltage from V_{SVC0} to V_{SVC1} is approximated by

$$V_{j1} = V_{j0} + K_{jV} \cdot \left(V_{SVC1} - V_{SVC0}\right) \tag{16}$$

where V_{j0} is the bus voltage before the change and K_{jV} is the sensitivity value of the voltage at bus j.

In Fig. 3, the area of influence for an SVC at bus 21 is given. The active power loss sensitivity limit $\underline{K}_{Ploss}$ determining which lines are included in the area of influence is set to 0.02 and the voltage sensitivity limit $\underline{K}_V$ for the incorporation of additional buses into the objective function to 0.3. Therefore, buses 35, 36, 39, 40, and 44 are taken into account in the objective function but not considered in the power flow calculations in the area of influence. The buses at the border of the area of influence are turned into slack buses as the general power flow equations cannot be formulated. The voltage magnitude is approximated by (16) and the voltage angle θ_{j1} by

$$\theta_{j1} = \theta_{j0} + K_{j\theta} \cdot \left(V_{SVC1} - V_{SVC0} \right) \tag{17}$$

with corresponding meanings to (16).

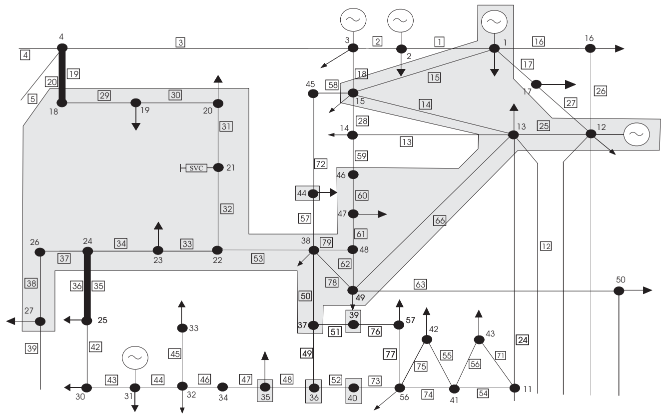

Figure 3: Area of influence for SVC at bus 21

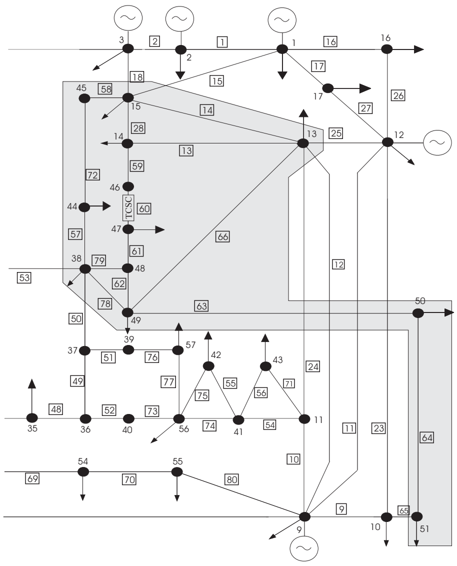

Figure 4: Area of influence for TCSC in line 60

5.2. TCSC

A TCSC mainly influences active power flows and in the context of the objective function given in (11) is used to avoid overloaded lines. Thus, the sensitivities for line loadings with respect to the active power flow through the TCSC are used to determine the area of influence. These sensitivities correspond to the apparent power flow sensitivities divided by the thermal limits. Therefore, all lines with line loading sensitivities greater than a certain value $\underline{K}_S$ and the adjacent buses are included in the area of influence. As a TCSC has only little influence on voltages, especially at buses which are not close by, considerations as in the case with the SVC are unnecessary.

In Fig. 4, the area of influence for a TCSC in line 60 is shown. The sensitivity limit $\underline{K}_S$ is set to 0.2. The buses at the border are turned into slack buses where voltage magnitudes and angles are set by

$$V_{j1} = V_{j0} + K_{jV} \cdot \left(P_{TCSC1} - P_{TCSC0} \right) \tag{18}$$

$$\theta_{j1} = \theta_{j0} + K_{j\theta} \cdot \left(P_{TCSC1} - P_{TCSC0} \right) \tag{19}$$

where P_{TCSC0} and P_{TCSC1} are the active power flows through the TCSCs before and after the determination of the optimal TCSC setting, respectively.

5.3. Results

In order to evaluate the performance of the limited area control, simulation results are presented for different sizes of the area of influence, i.e. different values for the sensitivity limits which determine the area of influence. First, an SVC is placed at bus 21 and then an SVC at bus 34. As the SVC is responsible for the objectives concerning active power losses and voltages, the thermal limits of the lines in the IEEE 57 bus grid are adapted such that no line is at risk to exceed 90% of the corresponding thermal limit. Therefore, the objective concerning line loadings will not play a role in these simulations. Thus, if the abbreviations

$$\begin{aligned} obj1 &= \sum_i \left(a \cdot P_i^{loss} \right) && \text{(active power losses)} \\ obj2 &= \sum_i \left(b \cdot \varepsilon_i + c \cdot \eta_i \right) && \text{(line loadings)} \\ obj3 &= \sum_j \left(d \cdot \left(V_j - V_j^{ref} \right)^2 + e \cdot \nu_j \right) && \text{(bus voltages)} \end{aligned} \tag{20}$$

are used for the components of the objective function, *obj2* will be zero for the simulations with the SVCs. In Table III, the results for the SVC at bus 21 are given for different values of $\underline{K}_{Ploss}$ and the same for the SVC at bus 34 in Table IV. The voltage sensitivity limit $\underline{K}_V$ is kept at 0.3. The column denoted by B_{SVC} contains the susceptance value of the SVC resulting from the optimization, *objtot* corresponds to the total value of the objective function (for the entire grid) and the last three columns contain the number of lines and buses in the area of influence, respectively, and the number of buses which are not in the area of influence but additionally incorporated into the objective function. The first row gives the values for the objective function if the SVC is out of operation, thus, the base case without SVC and the second row corresponds to the optimal case where the entire grid is taken into account.

Table III: Simulation results for SVC at bus 21

$\underline{K}_{Ploss}$	$\underline{K}_V$	B_{SVC}	*obj1*	*obj2*	*obj3*	*obj tot*	*#Lines*	*#Bus*	*#Bus+*
Base		0	4.669	0	3.541	8.210	80	57	0
0	0.3	0.489	4.617	0	3.330	7.947	80	57	0
0.005	0.3	0.418	4.614	0	3.340	7.953	46	38	3
0.01	0.3	0.429	4.614	0	3.338	7.952	30	27	5
0.02	0.3	0.337	4.615	0	3.359	7.974	19	19	5
0.03	0.3	0.308	4.616	0	3.368	7.985	16	16	6
0.04	0.3	0.388	4.614	0	3.346	7.959	8	8	8

Table IV: Simulation results for SVC at bus 34

$\underline{K}_{Ploss}$	$\underline{K}_V$	B_{SVC}	*obj1*	*obj2*	*obj3*	*obj tot*	*#Lines*	*#Bus*	*#Bus+*
Base		0	4.669	0	3.541	8.210	80	57	0
0	0.3	0.619	4.456	0	2.987	7.442	80	57	0
0.005	0.3	0.604	4.456	0	2.987	7.443	38	33	5
0.01	0.3	0.653	4.455	0	2.990	7.445	19	20	5
0.02	0.3	0.625	4.455	0	2.987	7.442	16	16	5
0.03	0.3	0.648	4.455	0	2.989	7.444	12	12	5
0.04	0.3	0.639	4.455	0	2.988	7.443	10	10	5

The results for both SVCs show that even if the area of influence is reduced to just a few lines and buses, the achieved performance is still remarkably good compared with the optimal case.

For the simulations with TCSCs, the thermal limits are adapted such that line 22 is overloaded and lines 72 and 24 are loaded to more than 90% in the base case in order to be able to show the effect of the TCSCs. First, a TCSC is placed in line 8 and then in line 60. The results for different values of $\underline{K}_S$ and therefore for different sizes of the area of influence are given in Tables V and VI.

Table V: Simulation results for TCSC in line 8

$\underline{K}_S$	X_{TCSC}	*obj1*	*obj2*	*obj3*	*obj tot*	*#Lines*	*#Bus*
Base	0	4.669	28.015	3.541	36.225	80	57
0	-0.00606	4.753	15.611	3.541	23.905	80	57
0.05	-0.00606	4.753	15.616	3.541	23.909	46	35
0.1	-0.00606	4.753	15.616	3.541	23.910	35	27
0.2	-0.00606	4.753	15.623	3.541	23.916	25	22
0.35	-0.00606	4.753	15.623	3.541	23.916	13	12
0.5	0.00303	4.658	40.926	3.542	49.125	8	9

Table VI: Simulation results for TCSC in line 60

$\underline{K}_S$	X_{TCSC}	*obj1*	*obj2*	*obj3*	*obj tot*	*#Lines*	*#Bus*
Base	0	4.669	28.015	3.541	36.225	80	57
0	-0.00949	4.693	16.661	3.510	24.863	80	57
0.05	-0.00949	4.693	16.665	3.510	24.868	54	40
0.1	-0.00954	4.693	16.705	3.510	24.908	25	20
0.2	-0.00943	4.693	16.702	3.510	24.905	15	12
0.35	-0.00943	4.693	16.702	3.510	24.905	13	10
0.5	-0.00942	4.693	16.714	3.510	24.917	10	9

Again, even if the number of lines and buses in the area of influence decreases, the control performance is not majorly affected. An exception is the case with the TCSC in line 8 and $\underline{K}_S = 0.5$. The reason for this poor performance is that the overloaded line 22 falls out of the area of influence. Therefore, the controller does not realize that there is an overloaded line and optimizes for the other objectives. If the sensitivity of the overloaded line is small, the line falls out early, but this does not have a great effect on the control performance because the TCSC cannot influence this line loading noticeably anyhow. For example line 72 is excluded from the area of influence already for $\underline{K}_S = 0.05$. On the other hand, if the influence of the TCSC on the overloaded line is quite large, the performance is affected heavily. But as the sensitivity limit is chosen such that lines which could be influenced to some extent if overloaded are included in the area of influence, this problem will not arise.

6. Coordinated Control of FACTS

In the previous section, interactions between devices were not considered. But as soon as the distance between devices is reduced and the areas of influence overlap, mutual influences cannot be neglected. Here, an iterative concept is chosen to coordinate the devices [12].

6.1. Algorithm

In Fig. 5, a situation is shown where the areas of influence of two FACTS devices for a given sensitivity limit $\underline{K}_{Ploss}$ or $\underline{K}_S$ overlap. As described in Section 5, the voltage magnitudes and angles of the buses at the border are approximated by the linear functions (16)-(19). Therefore, if both controllers determine the set values of their FACTS devices independently of each other at the same time, they assume that no other device will influence the voltages at the borders. But this assumption may lead to a poor overall control performance.

On the other hand, if the controllers know that there is another device, they can take this into account by adapting V_{j0} in (16) and (18) and θ_{j0} in (17) and (19) to the values resulting from the control of the other device. Therefore, an iterative algorithm for the determination of the FACTS settings is applied:

1. Determine setting of FACTS device in area 1.
2. Detect influences on voltages of the buses at the border of area 2.
3. Based on these values determine setting of FACTS device in area 2.
4. If changes in set values are $< \varepsilon$, stop. Otherwise, detect influences on voltages of the buses at the border of area 1 and go to 1.

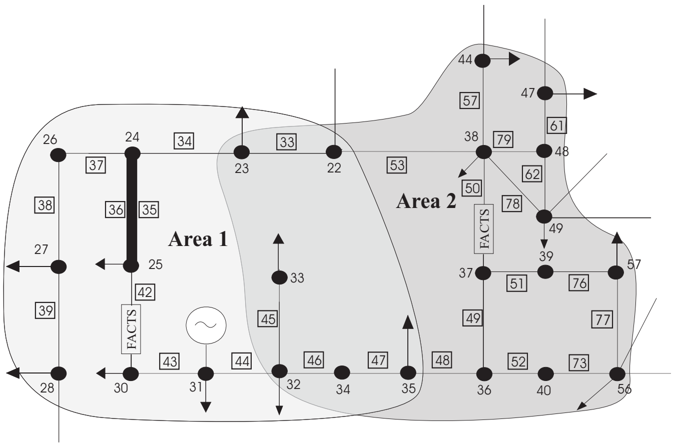

Figure 5: Overlapping areas of influence of two FACTS devices

This algorithm can easily be extended for three and more overlapping areas. In the following section results for two and three overlapping areas for SVCs and TCSCs are given.

6.2. Results

SVCs are placed at buses 21 and 34. As SVCs mainly affect voltage magnitudes and active power losses, the thermal limits of the lines are chosen such that no line is loaded to more than 80% in the base case in order to concentrate on the objectives concerning voltages and active power losses. The areas of influence are determined by $\underline{K}_{Ploss} = 0.015$ and $\underline{K}_V = 0.3$. Table VII shows the results for the simulations whereas the number of lines and buses in the areas of influence and also the buses whose voltages are incorporated into the objective function additionally are given in Table VIII.

The columns B_{SVC21} and B_{SVC34} show the settings for the FACTS devices determined by the controllers and the following columns the resulting values for the components of the objective function as described in (20). In the first row, the values for the base case, thus, without any FACTS devices in operation is given as a reference. The second row contains the values corresponding to the optimal case when the entire grid and both SVCs are taken into account at the same time in the optimization process. The results for the multi-area control as described in the preceding section are given in the last row.

Table VII: Results for SVCs at buses 21 and 34

Case	$B_{SVC\,21}$	$B_{SVC\,34}$	*obj 1*	*obj 2*	*obj 3*	*obj tot*
Base	0	0	4.669	0	3.541	8.210
Optimal	0.07485	0.59076	4.442	0	2.995	7.438
Limited	-0.02120	0.63020	4.460	0	2.985	7.445

Table VIII: # of lines and buses included

Area	bus SVC	# Bus	# Lines	# Bus+
1	21	22	22	5
2	34	16	16	5

The value of the objective function in the limited case is very close to the optimal value. The SVC susceptance values differ more but as the objective function is relatively flat in this case, this has only little influence on the objective function value.

Now, an additional SVC is placed at bus 51. Therefore, the control is extended to a three area control. The results for the simulations are given in Table IX and the description of the areas of influence in Table X.

Table IX: Results for SVCs at buses 21, 34 and 51

Case	$B_{SVC\ 21}$	$B_{SVC\ 34}$	$B_{SVC\ 51}$	*obj 1*	*obj 2*	*obj 3*	*obj tot*
Base	0	0	0	4.669	0	3.541	8.210
Optimal	0.09369	0.60998	-0.53746	4.476	0	2.826	7.302
Limited	0.01755	0.65004	-0.55193	4.490	0	2.817	7.307

Table X: # of lines and buses incl.

Area	bus SVC	# Bus	# Lines	# Bus+
1	21	22	22	5
2	34	16	16	5
3	51	13	16	0

Again, the SVC susceptances of the optimal and the limited case differ, but the value of the objective function is almost identical. Active power losses are reduced and the voltage magnitudes are brought closer to their reference values.

In another simulation, TCSCs are placed in lines 8 and 60. As TCSCs mainly influence line loadings and in order to show significant results, the thermal limits are adapted for the base case as in Sect. 5.3. The areas of influence are determined by $\underline{K}_S = 0.2$. The simulation results are given in Table XI and the number of buses and lines included in the areas of influence in Table XII.

In the first and the second row, again the values in the base case and the optimal case are given, respectively. In the last row, the settings for the FACTS devices resulting from the multi-area control described in the previous section are given.

Table XI: Results for TCSCs in lines 8 and 60

Case	$X_{TCSC\ 8}$	$X_{TCSC\ 60}$	*obj 1*	*obj 2*	*obj 3*	*obj tot*
Base	0	0	4.669	28.015	3.541	36.225
Optimal	-0.00605	-0.00530	4.765	10.269	3.523	18.556
Limited	-0.00605	-0.00532	4.765	10.286	3.523	18.573

Table XII: # of lines and buses included

Area	line TCSC	# Bus	# Lines
1	8	22	25
2	60	12	15

It can be seen that the total value of the objective function can be reduced significantly with the optimal control. But also the results for the multi-area control are remarkable. The settings for the FACTS devices are very close to the optimal values and the value for the objective function is only slightly larger.

In addition to the two TCSCs, an additional TCSC is placed in line 64 such that there are three overlapping areas which are again determined by $\underline{K}_S = 0.2$. In Tables XIII and XIV, the results of the simulation and the number of buses and lines included in the areas of influence are given, respectively.

Table XIII: Results for TCSCs in lines 8, 60 and 64

Case	$X_{TCSC\ 8}$	$X_{TCSC\ 60}$	$X_{TCSC\ 64}$	*obj 1*	*obj 2*	*obj 3*	*obj tot*
Base	0	0	0	4.669	28.015	3.541	36.225
Optimal	-0.00601	-0.00639	-0.04933	4.790	7.331	3.532	15.652
Limited	-0.00602	-0.00610	-0.04819	4.789	7.692	3.533	16.013

Table XIV: # of lines and buses incl.

Area	line TCSC	# Bus	# Lines
1	8	22	25
2	60	12	15
3	64	10	12

Again, the control performance for the multi-area control is very close to the optimal control. The settings of the FACTS devices and thus, also the value of the objective function differ only little from the optimal values. The loading of line 24 is brought to 90.8%, of line 72 to 90.5% and line 22 which was overloaded in the base case is brought to 94.8%. All other lines are still below 90%. The active power losses are slightly increased as seen in Table XIII in column *obj1* and the objective concerning voltage magnitudes *obj3* is hardly influenced.

Based on various simulations, it can be said that the order in which the areas are optimized has only influence on the convergence speed, especially when one device has considerably greater influence on the overall objective than the other one, but not on the result. If the setting for the device with the greatest influence is determined first, the simulation converges significantly faster than if the device with the lowest influence is considered first.

7. Conclusion

FACTS devices provide a great opportunity to improve security in a transmission grid. In order to take advantage of these opportunities, a control method has to be chosen which determines the set values of the devices. In this paper, a control based on Optimal Power Flow was presented. Sensitivity analysis has been carried out to determine the area of influence of a device to which the Optimal Power Flow calculation is constrained. The voltage magnitudes and angles at the border of the area of influence are approximated by a linear equation using sensitivity values. This limited area control makes the method also applicable to large grids.

As the number of devices in a grid increases, the problem of overlapping areas has to be solved. Here, an iterative procedure where the areas sequentially determine the values of the corresponding FACTS devices taking the effects of the other FACTS devices into account is used. The method has been applied to the IEEE 57 bus grid with two and with three SVCs as well as TCSCs. The results of the multi-area control are comparable to the results obtained from the centralized control.

In further studies, it has to be evaluated if there are situations where the performance of the multi-area control deviates considerably from the optimal case. As the sensitivities play an important role in this control, it is also necessary to check how much influence a change in the grid, such as a line outage or a load increase has on the sensitivity values and when they have to be adapted.

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