Coordinated Control of FACTS Devices based on Optimal Power Flow

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Abstract—**Flexible AC Transmission Systems (FACTS) are an option to mitigate the problem of overloaded lines due to increased electric power transmission by controlling power flows and voltages. To avoid mutual influences among several devices placed in the same grid, a coordinated control is indispensable. In this paper, a supervisory controller based on Optimal Power Flow (OPF) with multiple objectives is derived in order to avoid congestion, provide secure transmission and minimize active power losses. The contributions of SVC, TCSC and TCPST in this coordinated control and the achieved improvements compared with the case where no FACTS devices are in operation are demonstrated.**

Index Terms— **Congestion Management, Coordinated Control, FACTS, Optimal Power Flow, Power Systems**

I. Introduction

TRANSMISSION lines in congested areas are often driven close to or even beyond their limits in order to satisfy the increased electric power consumption and trades. Thus, secure operation and reliable supply is endangered by the higher risks for faulted lines. But the construction of additional power lines is often difficult for environmental, economical and political reasons. This is where the technology of FACTS provides a significant opportunity [1-3].

The numerous publications in the field of FACTS in the last few years show the growing interest and need for these devices. Topics are the optimal placement, the value of FACTS in the liberalized power market, the development of new devices and the control strategy.

FACTS devices are able to influence power flows and voltages to different degrees depending on the type of the device. The focus in this paper lies on the Static Var Compensator (SVC), the Thyristor-Controlled Series Compensator (TCSC) and the Thyristor-Controlled Phase Shifting Transformer (TCPST).

Typically, the devices are divided into three categories: shunt-connected, series-connected and a combination of both. The SVC belongs to the shunt-connected devices and is since long in operation in various places. Conceptually, it is a variable shunt reactance which injects or absorbs reactive power in order to control the voltage at a given bus. Both TCSC and TCPST are series-connected devices. The TCSC mainly controls the active power in a line by adapting the line reactance. This type of device is in operation at a few places but is still in the stage of development. The principle of a TCPST is very similar to a conventional phase angle regulator (PAR). A voltage in quadrature to the primary bus voltage is incorporated introducing a phase shift to control the transmission angle. The difference compared with the PAR is that the mechanical tap changer is replaced by a thyristor-controlled equivalent allowing for faster control [4].

In order to investigate the effects of FACTS devices in steady-state, appropriate models are needed capturing the influences of the devices on power flows and voltages. Various models for SVC, TCSC and TCPST are conceivable and applied in different studies. In Sect. II, the modeling of FACTS devices used in this paper and how they are incorporated into the power flow calculations are described.

The influences of FACTS devices are not confined to one bus or line. Changing the voltage at a certain bus or the power flow on a line also modifies the power flow in the surrounding grid. If a FACTS device is placed in the vicinity of another, mutual influences may arise which could vitiate the positive impacts of a single device. Coordination is needed to determine the variables such that detrimental actions are prevented. Additionally, measures in other parts of the grid have to be taken into account such that it is avoided that distant lines become overloaded or that voltages at other buses are driven to unacceptable values. Both can be achieved by a supervisory controller based on Optimal Power Flow (OPF) [5] with multiple objectives which determines the optimal steady-state settings of the FACTS devices. Thus, in Sect. III, the applied OPF problem formulation is derived.

The resulting objective function includes several components such as minimizing active power losses, avoiding overloaded lines and keeping bus voltages within an acceptable range and close to their reference values. A specific type of FACTS device is able to influence a certain parameter in the grid which is related to a particular part of the objective function. For instance, the SVC injects or absorbs reactive power which is strongly coupled to the voltage. TCSC and TCPST on the other hand control active power flow. Therefore, Sect. IV investigates the relations between devices and their effects on the different parts of the objective function.

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Section V illustrates the improvements of the derived coordinated control. In simulations, the performance of the controller with an SVC plus a TCSC and with an SVC plus a TCPST is compared with the case where no FACTS devices are in operation. It is shown that overloaded lines are relieved, the voltage profile is improved and the power losses are decreased, leading to the conclusions given in Sect. VI.

II. Modeling of FACTS Devices

Several ways of modeling FACTS devices are proposed in the literature. In [6], the power injection method is presented where the characteristics of the devices are reproduced by power injections. Another option is to model SVC and TCSC as variable reactances, whose values depend on the firing angle of the thyristors, [7], [8] and TCPST as a variable voltage source [9]. This second possibility is applied in this paper in order to simplify the integration into the OPF formulation.

A. SVC

A possible structure of the SVC is given in Fig. 1. It is a shunt-connected device composed of several modules built of a fixed capacitance in parallel with a thyristor controlled reactor. Each of these modules corresponds to a variable susceptance. The equivalent susceptance B_{eq} is determined by the firing angle α of the thyristors which is defined as the delay angle measured from the peak of the capacitor voltage to the firing instant. The fundamental frequency equivalent neglecting the harmonics of the current results in [1]

$$B_{eq} = B_L(\alpha) + B_C \tag{1}$$

where

$$B_L(\alpha) = -\frac{1}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin(2\alpha)}{\pi}\right), \quad B_C = \omega C \tag{2}$$

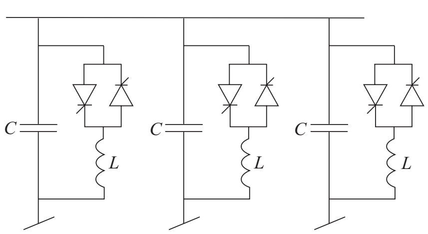

Fig. 1. Structure of an SVC

The graph for B_{eq} as a function of α is given in Fig. 2. The minimal and maximal values for the firing angle are 0° and 90°, respectively, resulting in a minimal value B_{min} and a maximal value B_{max} for the equivalent susceptance of each module. At the resonance angle where

$$B_L(\alpha_{res}) = -B_C \tag{3}$$

the equivalent susceptance is zero. But this resonance is not a problem here because this simply corresponds to a module which is not connected to the bus.

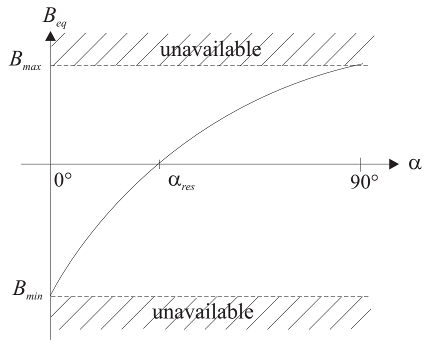

Fig. 2. Equivalent susceptance B_{eq} in function of the firing angle

The total susceptance of the SVC is composed of the parallel equivalent susceptances of the modules, each controlled separately. Thus, the SVC can be modeled as a shunt-connected variable susceptance B_{SVC} (Fig. 3) with a lower bound $\underline{B}_{SVC}$ and an upper bound $\overline{B}_{SVC}$ [7]. In the power flow equations this is accounted for by including the reactive power

$$Q_{SVC} = -V_k^2 \cdot B_{SVC} \tag{4}$$

into the reactive power balance at bus k subject to

$$\underline{B}_{SVC} \le B_{SVC} \le \overline{B}_{SVC}\,. \tag{5}$$

This range normally includes positive as well as negative values.

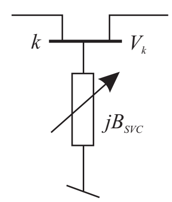

Fig. 3. Model of the SVC

B. TCSC

Similar to the SVC, the TCSC consists of several modules built of a fixed capacitance in parallel with a thyristor controlled inductor. But here, the modules are connected in series as shown in Fig. 4 [10].

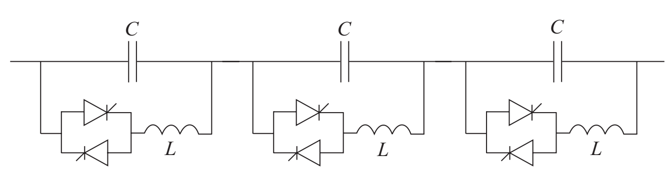

Fig. 4. Structure of a TCSC

Therefore, the equivalent reactance X_{eq} of each individual module is considered which is determined by the firing angle of the thyristors by

$$X_{eq}(\alpha) = \frac{-1}{B_L(\alpha) + B_C} \tag{6}$$

where $B_L(\alpha)$ and B_C are given in (2).

The graph of this function is shown in Fig. 5. Apparently, a discontinuity exists at the resonance angle determined by (3). As it is unacceptable to introduce an infinite reactance in series to the transmission line, the firing angle has to be kept a distance $\Delta\alpha$ from the resonance point. A minimal value X_{min} and a maximal value X_{max} result for the equivalent reactance. Additionally, the minimal and maximal values for the firing angle are again 0° and 90°. This yields an unavailable band between X_{lb} and X_{ub} [8].

For the total reactance value of the TCSC, the equivalent reactances of the modules are added. As each module is controlled separately, the unavailable band around zero can be covered [10]. Thus, the TCSC is modeled as variable reactance X_{TCSC} with a lower bound $\underline{X}_{TCSC}$ and an upper bound $\overline{X}_{TCSC}$ connected in series with a line.

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.

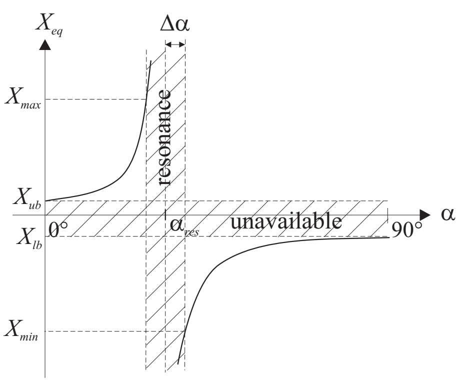

Fig. 5. Equivalent reactance X_{eq} in function of the firing angle

According to Fig. 6a), the TCSC is incorporated into the transmission line model by simply adding the variable reactance X_{TCSC} to the line reactance X [11]. As the TCSCs are normally placed close to a bus, it would be more accurate to add the reactance there (Fig. 6b)). But this complicates the situation by far and especially in cases of short lines, the differences in power flow calculations are marginal due to small shunt susceptances B. Therefore, this simplification is justified and the TCSC is incorporated into the load flow calculations by setting the total line reactance to

$$X_{tot} = X + X_{TCSC} \tag{7}$$

and accounting for the limitations by

$$\max\left(\underline{X}_{TCSC}, -0.8\cdot X\right) \le X_{TCSC} \le \min\left(\overline{X}_{TCSC}, 0.2\cdot X\right) \tag{8}$$

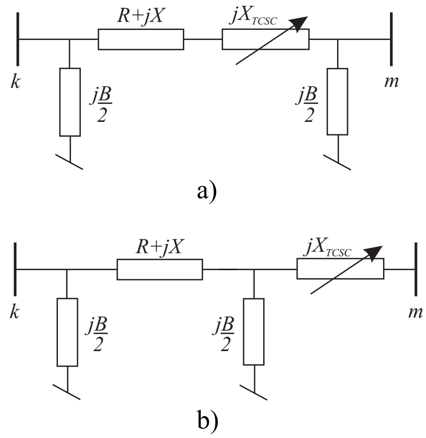

Fig. 6. TCSC modeled as series-connected reactance a) simplified b) exact

C. TCPST

The structure of a TCPST is given in Fig. 7. The shunt connected transformer draws power from the network and provides it to the series connected transformer in order to introduce a voltage $\underline{V}_T$ at the series branch. Compared to conventional phase shifting transformers, the mechanical tap changer is replaced by a thyristor controlled equivalent [9]. The purpose of the TCPST is to control the power flow by shifting the transmission angle.

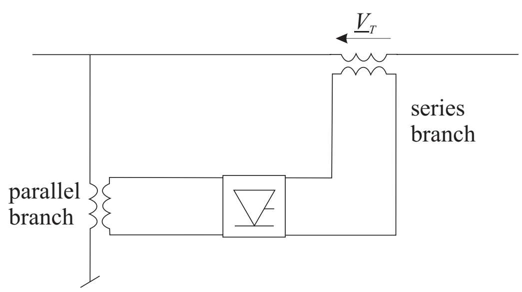

Fig. 7. Structure of a TCPST

The model used is given in Fig. 8 where the TCPST corresponds to a variable voltage source with a fixed angle of 90° with respect to the primary voltage. The manipulated variable is the phase shift δ which is determined by the magnitude of the inserted voltage $\underline{V}_T$.

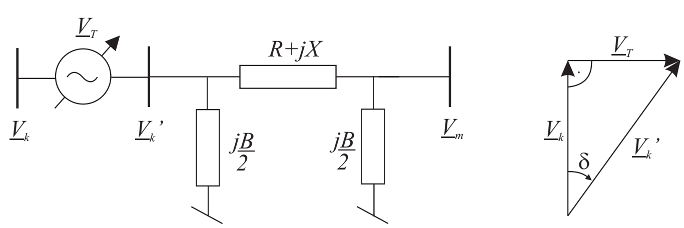

Fig. 8. Model of a TCPST

It is assumed that the device is lossless. Thus, the relationship between the primary and the secondary voltage is

$$\begin{aligned} \underline{V}_k' &= \underline{V}_k + \underline{V}_T \\ V_k' e^{j\theta_k'} &= V_k e^{j\theta_k} + V_T e^{j(\theta_k - 90°)} \end{aligned} \tag{9}$$

where the magnitude of the inserted voltage is determined from the phase shift by

$$V_T = V_k \tan\delta \ . \tag{10}$$

The range in which the angle δ may vary is dependent on the specific device and has to be taken into account by

$$\delta_{\min} \le \delta \le \delta_{\max} \tag{11}$$

in the process of determining the appropriate phase shift. Here, this range is set to ±20°.

These models for SVC, TCSC and TCPST can now be applied in optimal power flow calculations in order to determine the optimal settings for the devices.

III. Coordinated Control

The controlled variable in case of TCSC and TCPST is the active power flow and in case of the SVC the corresponding bus voltage. As these devices are controlled locally so far, they do not take into account their influences on other lines or buses [12]. Thus, a control action which is reasonable for the line or bus where the device is located might cause another line to be overloaded or voltages to take unacceptable values. Additionally, if devices are located close to each other the action of one controller can lead to a counteraction of the other controller possibly resulting in a conflicting situation. For these reasons, coordination is necessary, especially when the number of devices increases and the distance among them decreases.

First, it has to be decided which control technique is applied. Investigations have been carried out on fuzzy control [11], remote feedback control [12] or different optimization strategies [8], [13], [14]. In this paper, a controller based on optimal power flow with multiple objectives is developed. The advantage of this approach is that not the reference values such as active power flow or voltages but directly the settings of the devices like firing angle or phase shift which fulfill best the objectives are determined. The power flows and the voltages follow accordingly from these settings. Thus, mutual influences like in the case with local control are not a problem any more.

For the formulation of an optimal power flow problem, three elements have to be defined: the objective function $f(\mathbf{x},\mathbf{u})$, the equality constraints $\mathbf{g}(\mathbf{x},\mathbf{u})$ and the inequality constraints $\mathbf{h}(\mathbf{x},\mathbf{u})$ yielding

$$\begin{aligned} \min \quad & f(\mathbf{x},\mathbf{u}) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{x},\mathbf{u}) = 0 \\ & \mathbf{h}(\mathbf{x},\mathbf{u}) \le 0 \end{aligned} \tag{12}$$

where the vector $\mathbf{x}$ contains the voltages and angles of all buses and $\mathbf{u}$ the set values for the devices and the slack variables used to define soft constraints:

$$\mathbf{x} = \begin{bmatrix} V_1 \\ \vdots \\ V_n \\ \theta_1 \\ \vdots \\ \theta_n \end{bmatrix}; \quad \mathbf{u} = \begin{bmatrix} \alpha_{SVC} \\ \alpha_{TCSC} \\ \delta_{PST} \\ u_{slack} \end{bmatrix} \tag{13}$$

As opposed to the equality and inequality constraints which are mostly determined by the system, the objective function is not given a priori but has to be specified such that it reflects the intended objectives. In the following, the equality and inequality constraints as well as the objective function are discussed.

$\mathbf{g}(\mathbf{x},\mathbf{u})$:

- *power flow*: The equality constraints result from the power flow equations including the power injections by SVCs, the modifications of the line reactances by TCSCs and the phase shifts of the TCPSTs.

$\mathbf{h}(\mathbf{x},\mathbf{u})$:

- *FACTS devices*: The equations (5), (8) and (11) which define the limitations for the settings of the FACTS have to be hold.
- *transmission lines:* Lines should not be loaded to more than 90% or, if this is not achievable, at least should not exceed the transfer capacities. This is defined using soft constraints in order to avoid an unfeasible system. For each line i, the inequalities

$$\begin{aligned} S_i &\le 0.9 \cdot S_i^{\max} + \varepsilon_i, \quad 0 \le \varepsilon_i \\ S_i &\le S_i^{\max} + \eta_i, \qquad 0 \le \eta_i \end{aligned} \tag{14}$$

  result, where S_i is the apparent power flow 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. They are penalized in the objective function such that the controller has a strong incentive to set them to zero whereas the penalization of η_i is much severer than on ε_i.
- *buses*: Unacceptable bus voltages should be avoided, i.e. their values should lie within a certain range. This is also defined as soft constraints

$$\left| V_j - V_j^{ref} \right| \le V^{lim} + \nu_j, \quad 0 \le \nu_j \tag{15}$$

  where V_j is the bus voltage at bus j, V_j^{ref} is the corresponding reference value and V^{lim} is the allowed range of acceptable voltage values.

$f(\mathbf{x},\mathbf{u})$:

- *resolve congestions*: This is done by keeping the loading of the lines below 90% or at least by avoiding overloading. Thus, the penalization of the slack variables used in (14) to define soft constraints on the apparent power flows contributes to this objective.

- *improve security*: If voltages exceed a certain range of acceptable values the security of the grid is endangered. Therefore, penalizing the slack variable used in (15) and keeping the voltage values as close as possible to their references improves security.
- *minimize power losses*: This simply is incorporated by summing the active power losses and penalizing them in the objective function.

Thus, the complete objective function is the sum of these objectives each weighted with an appropriate factor

$$f(\mathbf{x},\mathbf{u}) = \sum_i \Big(\underbrace{a \cdot P_i^{loss}}_{1} + \underbrace{b \cdot \varepsilon_i + c \cdot \eta_i}_{2} \Big) + \sum_j \Big(\underbrace{d \cdot \left(V_j - V_j^{ref}\right)^2 + e \cdot \nu_j}_{3} \Big) \quad (16)$$

The setting of the weights *a*, *b*, *c*, *d* and *e,* which are at the same time the control parameters, are dependent on the importance of each objective. A summary of the meaning of all weights is given in Table I. As the incentive to avoid overloaded lines consequentially is greater than to keep their loadings below 90%, the weight *c* will be larger than *b*. For the other parameters no general statement is applicable.

It is of course possible to include other objectives in the objective function. This will be the topic of future research.

With **g**(**x**,**u**), **h**(**x**,**u**) and *f*(**x**,**u**) the problem is formulated and can be given to an appropriate solver which is able to solve an optimization problem with a nonlinear objective function subject to nonlinear equality and inequality constraints. For the simulations in this paper, the MATLAB function `fmincon` is used.

IV. Analysis of the Objective Function

The objective function (16) consists of three components. The first is the minimization of active power losses, the second accounts for keeping the line loadings below the transfer capacities and the third concerns the bus voltages, i.e. keeping them close to their reference values and within an acceptable range. A given type of FACTS device is not able to influence all parts to the same extent. In simulations where only some control parameters in the objective function are non-zero, it can be evaluated which device is mainly responsible for which part of the objectives.

The test grid for the simulations is shown in Fig. 9. The left part of this grid is basically a generation area and the right part a load area. The considered combinations of FACTS devices are given in Table II. In the first three combinations, only one single device is placed in the grid whereas in combinations 4 and 5 two different devices are in operation at the same time. For these combinations the coordinated control derived in the preceding section with different parts of the objective function taken into account is applied.

TABLE I
OVERVIEW OF WEIGHTS IN THE OBJECTIVE FUNCTION

Weight	Objective
a	minimization of active power losses
b	keeping line loadings below 90%
c	keeping line loadings below 100%
d	minimization of voltage deviations from references
e	keeping bus voltages within acceptable limits

TABLE II
CONSIDERED COMBINATIONS OF FACTS DEVICES

Comb.	Devices
1	SVC at bus 7
2	TCSC in line 6
3	TCPST in line 6
4	SVC at bus 7, TCSC in line 6
5	SVC at bus 7, TCPST in line 6

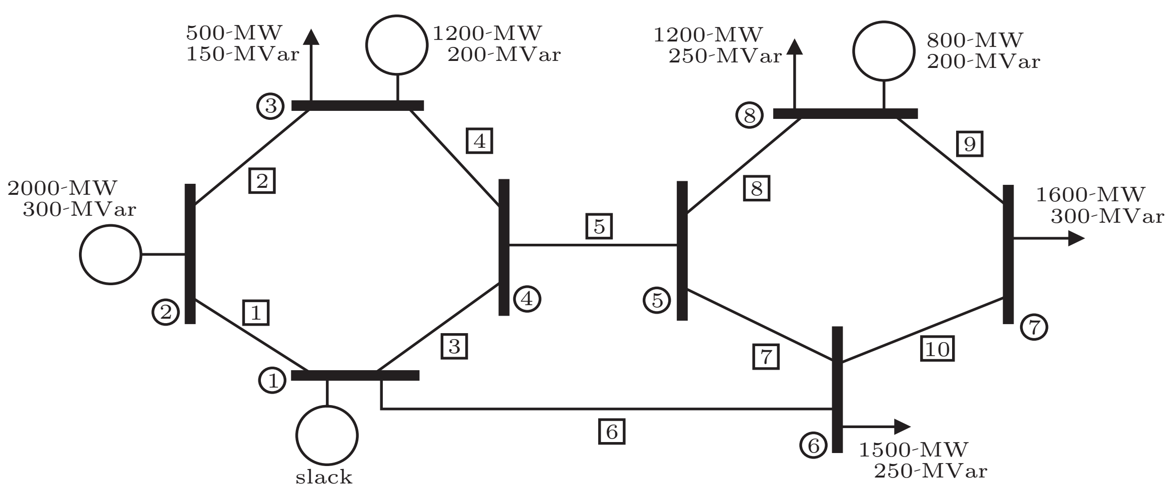

Fig. 9. 8-bus test grid with a generation area on the left and a load area on the right

In Table III, the obtained steady-state values for the SVC susceptance B_{SVC} (p.u.), the TCSC reactance B_{TCSC} (p.u.) and the TCPST phase shift δ_{PST} are presented. In the second column, the components of the objective function which were taken into account in each case are listed according to the numbering in (16). The control parameters belonging to the other components are set to zero. The third column identifies the considered combination according to Table II. The columns *O*1, *O*2 and *O*3 indicate the values of the different objectives

$$\begin{aligned} O1 &= \sum_i \left(a \cdot P_i^{loss} \right) && \text{(active power losses)} \\ O2 &= \sum_i \left(b \cdot \varepsilon_i + c \cdot \eta_i \right) && \text{(line loadings)} \\ O3 &= \sum_j \left(d \cdot \left(V_j - V_j^{ref} \right)^2 + e \cdot \nu_j \right) && \text{(bus voltages)} \end{aligned} \tag{17}$$

in the considered case and combination. The sum of these values yields the total value of the objective function $f(\mathbf{x},\mathbf{u})$. In the first row, the corresponding values for the base case where no FACTS devices are in operation are given for comparison.

TABLE III
OPTIMAL SETTINGS OF SVC, TCSC AND TCPST FOR DIFFERENT OBJECTIVES

Case	Obj.	Com.	B_{SVC}	X_{TCSC}	δ_{PST}	*O1*	*O2*	*O3*
Base	-	-	-	-	-	84.03	84.31	111.67
A	1	1	0.754	-	-	78.29		
		2	-	-0.0148	-	83.64		
		3	-	-	-0.173°	84.02		
		4	0.750	-0.0021	-	78.28		
		5	0.754	-	-0.024°	78.29		
B	2	1	0.686	-	-		66.25	
		2	-	-0.0354	-		0.00	
		3	-	-	-3.918°		0.00	
		4	-0.003	-0.0353	-		0.00	
		5	0.214	-	-3.566°		0.00	
C	3	1	0.768	-	-			7.22
		2	-	-0.0720	-			44.34
		3	-	-	-1.378°			110.71
		4	0.788	0.0180	-			7.04
		5	0.858	-	5.677°			6.71
D	1,2	1	0.700	-	-	78.32	66.26	
		2	-	-0.0313	-	84.29	0.00	
		3	-	-	-3.918°	86.25	0.00	
		4	0.677	-0.0294	-	79.62	0.00	
		5	0.753	-	-3.142°	79.81	0.00	
E	1,3	1	0.767	-	-	78.29		7.22
		2	-	-0.0670	-	93.59		46.68
		3	-	-	-1.090°	84.16		110.74
		4	0.770	0.0024	-	78.31		7.19
		5	0.770	-	0.439°	78.33		7.16
F	2,3	1	0.753	-	-		66.45	7.27
		2	-	-0.0354	-		0.00	70.87
		3	-	-	-3.918°		0.00	113.98
		4	0.745	-0.0295	-		0.00	7.66
		5	0.770	-	-3.140°		0.00	7.77
G	1,2,3	1	0.754	-	-	78.29	66.45	7.26
		2	-	-0.0354	-	84.70	0.00	70.87
		3	-	-	-3.918°	86.25	0.00	113.98
		4	0.739	-0.0295	-	79.66	0.00	7.67
		5	0.769	-	-3.140°	79.81	0.00	7.77

In case A, the only objective is the minimization of active power losses. In all combinations, the SVC susceptance B_{SVC} takes similar values independent of if a TCSC or a TCPST is turned on or not and column *O*1 shows that where an SVC is in operation, the power losses are reduced by about 5.6% compared with the base case. TCSC and TCPST in single operation do not manage to decrease the power losses significantly. From this, it can be concluded that the improvements concerning power losses are mostly due to an SVC.

Case B only incorporates the objective to keep the line loadings below 90% or at least below 100%. Here, the situation is reversed to case A. Combinations where a TCSC or a TCPST is employed manage to bring all line loadings below 90% indicated by *O*2 equal to zero. The influence of the SVC on this objective is limited. In combinations 2 to 5, there exists more than one setting which brings all line loadings below 90%. Therefore, the shown settings are just possible values among others to reach the minimal value of zero for the objective function.

Concerning case C where the bus voltages are to be kept close to their reference values and within an acceptable range, again the SVC is the most effective device. The value for *O*3 is brought to a minimum. The TCSC is able to reduce this value, too, but the resulting reactance value hits the lower limit. Additionally, the SVC in all combinations has similar settings whereas for the TCSC and also for the TCPST the values differ considerably. Thus, SVC is the device which is responsible for controlling the bus voltages.

In cases D to F where always two different objectives are taken into account, the separation of the objectives becomes even more apparent. The power losses are only reduced when an SVC is in operation and also the voltage deviations take by far the best values in these combinations. On the other hand, the loadings are all brought below 90% only in combinations where a TCSC or a TCPST is employed.

Case G incorporates all objectives. When the SVC is the single device in operation, active power losses and voltage deviations are reduced but loadings are still quite high. On the other hand, when a TCSC or a TCPST is the only device, line loadings are optimally taken care of but power losses are even increased and the voltage deviations are still considerable. In combinations where an SVC as well as a TCSC or a TCPST are employed, a reduction in active power losses and in voltage deviations are achieved and all line loadings are brought below 90%.

The conclusion is that the objectives can be divided into a part which is mainly controlled by SVC namely active power losses and voltage deviations and a part corresponding to line loadings which is controlled by TCSC and TCPST. Combinations of an SVC and a TCSC or a TCPST therefore manage to improve all objectives.

V. SIMULATION RESULTS

For the following simulations, again the test grid in Fig. 9 is used. The coordinated control described in Sect. III is applied for the combinations 4 and 5 given in Table II.

In Fig. 10, the line loadings, the power losses and the voltage profile for combination 4, an SVC at bus 7 and a TCSC in line 6, is compared with the case where no FACTS devices are in operation. The loading is defined as apparent power flow in fraction of the transfer capacity. The voltages are given in p.u. and the reference value for all buses is chosen to 1 p.u. The settings of the devices correspond to the values in case G.

In the base case, line 6 is overloaded and lines 4 and 7 are loaded to more than 90%. The power losses add up to 84.03 MW and the voltage profile shows large deviations from the reference value in lines 5 to 8. This situation is not acceptable for any length of time.

As has been shown in the preceding section, the voltage profile can be influenced by an SVC and the active power flow by a TCSC or a TCPST. The combination of SVC and TCSC manages to bring all loadings below 90%, thus, to resolve the congestion on line 5. The voltages are all in the range of ±0.02 p.u. with respect to the reference value. Additionally, the power losses are decreased to 79.66 MW which is a reduction of approximately 5.2%.

The effects on power flow in the different lines can be observed in the first graph of Fig. 10. To relieve line 5 which was overloaded in the base case, the TCSC reactance is set such that power is shifted to line 6. Therefore, part of the power flowing from the generator at bus 2 through lines 2 and 4 and then through line 5 to the load area is redirected through lines 1 and 6. The power flow through line 3 is decreased, too, because part of the power coming from the slack generator and the generator at bus 2 flowing through lines 3 and 5 is now flowing through line 6. This shift of power flow from line 5 to line 6 has also influences on the load area. Power which before has flowed through line 7 to bus 6 is no directly arriving at bus 6 coming from line 6. The part of the power consumed by the load at bus 7 is coming now from line 6 and through line 10 instead of taking the way through lines 5, 8 and 9.

In the second simulation, the TCSC is replaced by a TCPST. The weights in the objective function stay unchanged. The obtained results are shown in Fig. 11. Apparently, power flow and voltages are very similar to the case with the TCSC. The congestion on line 5 is relieved by redirecting power from line 5 to line 6. This leads to the conclusion that TCSC and TCPST perform a similar task in this optimal control.

By changing the settings of the control parameters the importance of the objectives is adapted. This has influence on the obtained results in the sense that the power losses might be increased in favor of a smoother voltage profile or vice versa.

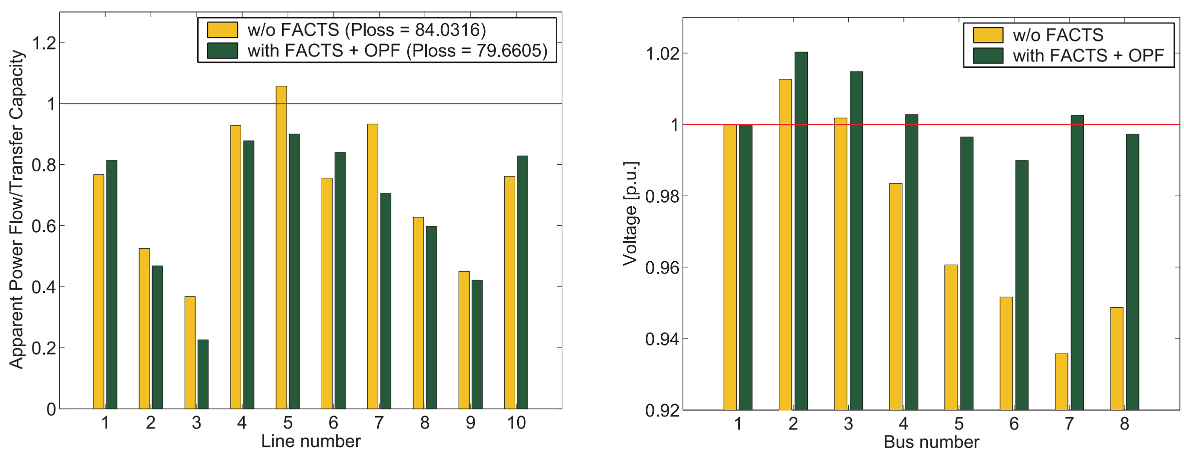

Fig. 10. Line loadings and bus voltages without FACTS devices and with SVC at bus 7 and TCSC in line 6

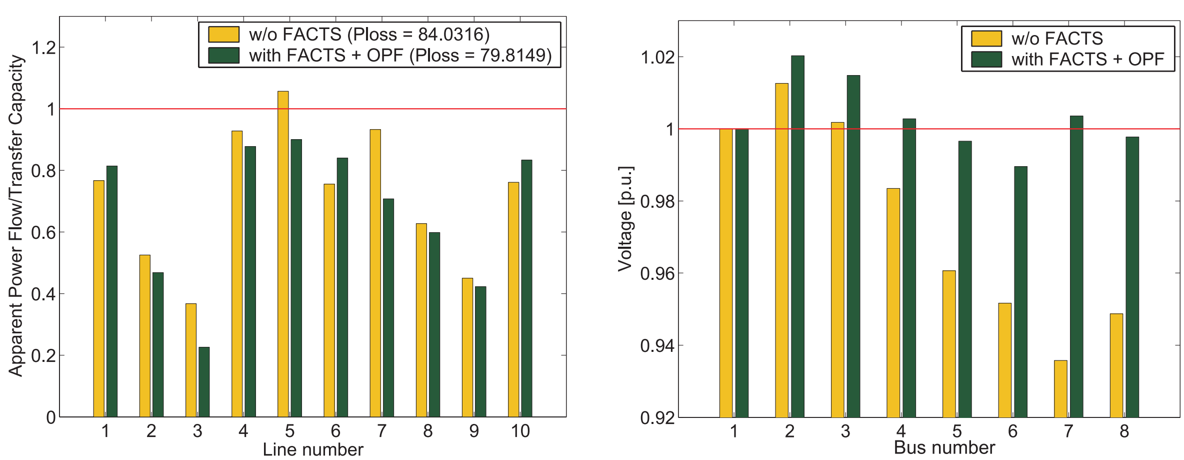

Fig. 11..Line loadings and bus voltages without FACTS devices and with SVC at bus 7 and TCPST in line 6

VI. Conclusion

FACTS devices are a powerful tool to resolve congestions and to improve security of the system. But an uncoordinated utilization of such devices may result in conflicting situations which can endanger secure operation of the transmission grid. Thus, a coordinated control based on optimal power flow has been developed in this paper. The objective was to resolve congestions, improve security and decrease active power losses.

The objective function was analyzed in simulations with different combinations of FACTS devices. It was demonstrated that each device is able to influence certain parts of the objective function. SVCs are responsible for the parts dealing with the voltage and the active power losses and TCSCs as well as TCPST account for the part concerning line loadings. Thus, a decoupling takes place which allows for a straightforward application of the various FACTS devices.

Finally, simulations showing the improvements of the derived control were presented: congestions were resolved, voltage profiles became more balanced and active power losses were reduced. Additionally, it was demonstrated that TCSC and TCPST have comparable effects concerning the considered objectives.

A more detailed comparison of TCSC and TCPST and their simultaneous use will be subject to future elaborations. Additionally, the derived control will be studied for larger transmission grids in order to investigate the performance in a more practical environment.

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