CONGESTION MANAGEMENT USING COORDINATED CONTROL OF FACTS DEVICES AND LOAD SHEDDING

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Abstract – The development of a control system and control strategies capable of governing multiple flexible AC transmission system (FACTS) devices in coordination with a load shedding is described here. The main purpose of the presented coordinated control system is to remove overloads caused by unplanned line outages in transmission network. A sensitivity analysis was used to find out an intercoupling between a variation of set points of different FACTS devices and a volume of load shedding with a variation of active power flow in transmission lines. The proposed control system is based on linearized expressions in steady state. Therefore, a coordinated control process does not require intensive computations. A prototype of the coordinated control system is suitable for a real time implementation. It constantly monitors power flows in a test transmission network and generates appropriate control signals to each load and FACTS device in order to maintain an admissible power flow level. It has been interfaced with load flow software to test its effectiveness through non-linear simulations using the IEEE 30 bus test power system as the study case. The results obtained are discussed.

Keywords: Power system automation, FACTS devices, Load shedding, Congestion management, Power flow control, Sensitivity analysis.

1 INTRODUCTION

At present there is no doubt about the economical justification of the parallel operation of power plants as component parts of electric power systems and the parallel operation of power systems as component parts of power interconnections. However, the growing size and the electric industry deregulation complicate an operation of power systems. At the same time the risk of occurrence and avalanche-like development of emergencies also increases. That is why the congestion management plays a more and more important part in power system control [1]–[4]. Taking into account the high speed of emergency processes, such a control must be largely automatic.

Recently, a new suppleness in power system control appeared with the advent of flexible ac transmission systems (FACTS) technology. FACTS technology allows practically complete utilization of the capacity of transmission elements up to their limits and provides different kinds of devices permitting to redirect power in real-time and providing virtually instantaneous responses to transmission system disturbances [5].

There are many publications considering applications of FACTS devices in power systems, and particularly the application of FACTS devices to congestion management problem [4], [6]–[8]. However, a coordination and combined application of conventional emergency control actions (ex. load shedding) and FACTS devices has not been fully investigated.

In this paper, a new power flow control method based on a coordination of load shedding and FACTS devices is presented. Two types of FACTS devices, a Thyristor Controlled Series Capacitor (TCSC) [7] and a Thyristor Controlled Phase Shifting Transformer (TCPST) [8], are considered in this study.

2 METODOLOGY

2.1 The concept of sensitivity analysis

The methodology based on the sensitivity analysis for FACTS devices [6] was extended here to find out an intercoupling between a variation of load shedding volume and a variation of active power flow in transmission lines. A simple (linearized) but sufficiently accurate relationship could be derived for a computation of control actions (volume of load shedding and set points of FACTS devices) in order to meet the requirements for power flow in a post-emergency state of power system.

The control variables are the volume of load shedding and the setpoints of FACTS devices. The controlled quantities are the active power flows in transmission lines. For each pair FACTS–line or Load–line a direct effect of control action on power flow can be expressed as following:

$$P_{line} = f\left(Setting_{FACTS}\right) \text{ and } P_{line} = f\left(\Delta P_{load}\right)$$

where $Setting_{FACTS}$ is a direct control variable of FACTS device (e.g. line reactance, phase shift angle, etc.) and ΔP_{load} is a volume of load shedding. Below, the application of sensitivity analysis is illustrated with an example of FACTS devices.

For any pair FACTS-line the above mentioned non-linear relationships can be decomposed in two parts. The first part is the linear coefficient of influence k_{inf} and the second part is the non-linear regulation characteristic of FACTS device [6].

It means that at first, the level of violation of the controlled quantity (power flow) is initialized and required changing of the indirect control variable of the FACTS (the power flow through a FACTS device) is found to remove that violation. Then, for a known level of power flow through the FACTS device the value of direct control variable of FACTS device (line reactance for TCSC and phase shift angle for TCPST devices) is computed to provide a required indirect control variable.

2.2 *Coefficients of influence of FACTS*

The coefficient of influence of FACTS $k^{j}_{FACTS_i}$ estimates a relationship between the variation of active power flow in the controlled transmission line *j* – $\Delta P_{line\,j}$ and the variation of active power flow through the FACTS device *i* – $\Delta P_{FACTS\,i}$ [6].

$$k^{j}_{FACTS_i} = \frac{\Delta P_{line\,j}}{\Delta P_{FACTS\,i}} = \frac{P^{0}_{line\,j} - P^{new}_{line\ j}}{P^{0}_{FACTS\,i} - P^{new}_{FACTS\,i}}\ , \qquad (1)$$

where $P^{0}_{line\,j}$ is the value of active power flow in the controlled line *j* before changing the setpoint of FACTS *i*, $P^{new}_{line\ j}$ is the value of active power flow in the same line after changing the setpoint of FACTS *i*, $P^{0}_{FACTS\,i}$ is the value of active power flow in the line with FACTS *i* before changing its setpoint, and $P^{new}_{FACTS\,i}$ is the value of active power flow in the line with FACTS *i* after changing its setpoint.

2.3 *Regulation characteristics of FACTS*

The regulation characteristic numerically links together the effect of FACTS control variable on the controlled parameters (power flows) in the transmission lines where the FACTS is located. Thus, it helps to transform the required amount of power flow through the FACTS device, for a modification of power flow in the controlled line, into a real setpoint of the FACTS device such as a reactance or a phase shift angle.

2.3.1 *TCSC*

The regulation characteristic of the TCSC for active power flow represents the effect of the variation of the control variable of the TCSC Δx_{TCSC} on the active power in the line with that TCSC ΔP_{TCSC}. Fig. 1 shows an example of the typical regulation characteristics of the TCSC. The best approximation of this characteristic is provided by a quadratic function [7], but as we could see in the most analyzed cases the quadratic term was relatively small. Therefore, it is possible to linearize the regulation characteristic of the TCSC. Fig. 2 presents the regulation characteristic of the TCSC for different power system operation conditions (different power flow patterns). The gradient of regulation characteristic of TCSC depends on operation conditions of power system (Fig. 2) and it could be calculated as:

$$\beta_{TCSC\,i} = \frac{\Delta P_{TCSC\,i}}{\Delta x_{TCSC\,i}} \qquad (2)$$

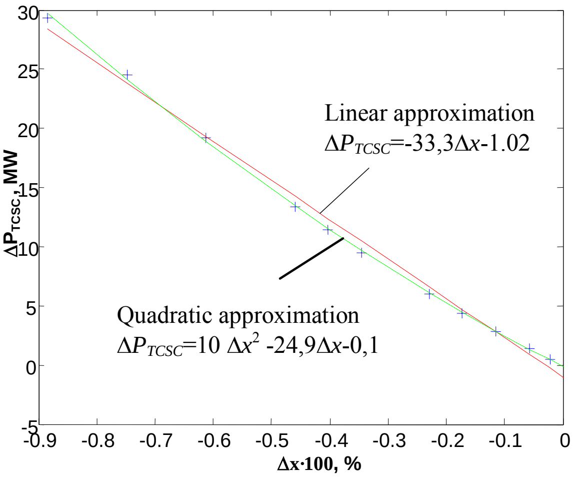

Figure 1: Regulation characteristic of the TCSC for active power flow.

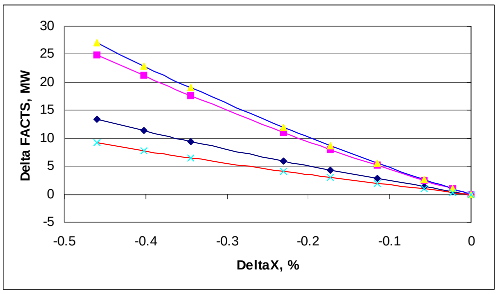

Figure 2: Regulation characteristic of the TCSC for different operation conditions.

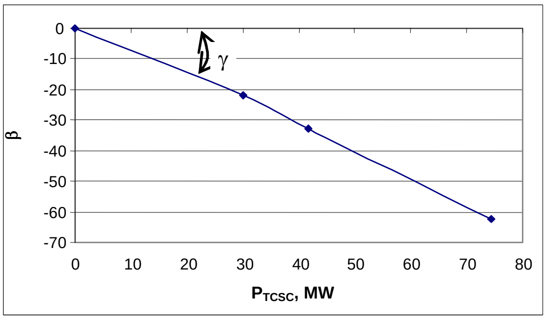

Figure 3: Relationship between the gradient of regulation characteristic and initial active power flow in the TCSC.

However, there is a linear relationship between the gradient of the regulation characteristic and the initial active power flow in the TCSC $P^{0}_{TCSC\,i}$ (Fig. 3).

Therefore we can formulate the following relationship:

$$\Delta x_i = \frac{1}{\gamma_{TCSC\,i}} \frac{\Delta P_{TCSC\,i}}{P^{0}_{TCSC\,i}}\ , \qquad (3)$$

where $\gamma_{TCSC\,i} = \dfrac{\beta_{TCSC\,i}}{P^{0}_{TCSC\,i}}$.

2.3.2 *TCPST*

The regulation characteristic of the TCPST for active power flow is a relationship between the variation of active power flow in that TCPST ΔP_{TCPST} and the variation of its control variable $\Delta\alpha_{TCPST}$ (Fig. 4). The gradient of the regulation characteristic of TCPST for active power flow unlike TCSC does not depend on operation conditions of power system (initial power flow through a TCPST device) and it can be calculated as:

$$\beta_{TCPST\,i} = \frac{\Delta P_{TCPST\,i}}{\Delta\alpha_{TCPST\,i}} \qquad (4)$$

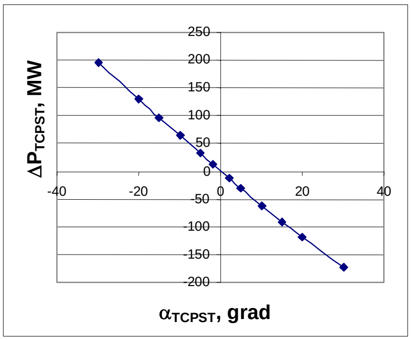

Figure 4: Regulation characteristic of the TCPST for active power flow.

2.4 Coefficients of influence of load

By analogy with coefficients of influence of the FACTS devices we can formulate the following equation for coefficients of influence of the load shedding at bus i on the power flow in the line j:

$$k^{j}_{load_i} = \frac{\Delta P_{line\,j}}{\Delta P_{load\,i}} = \frac{P^{0}_{line\,j} - P^{new}_{line\,j}}{P^{0}_{load\,i} - P^{new}_{load\,i}}, \qquad (5)$$

where $P^{0}_{line\,j}$ is the initial value of active power flow in the controlled line j; $P^{new}_{line\,j}$ is the value of active power flow in the controlled line j after load i shedding (changing); $P^{0}_{load\,i}$ is the initial value of active power of the load i; $P^{new}_{load\,i}$ is the value of active power of the load i after its changing.

3 CONTROL STRATEGY

3.1 Control strategy for the TCPST

In case of the overload of the line j ($\Delta P_{line\,j} = P^{0}_{line\,j} - P_{line\max}$), the control action for the TCPST device i can be calculated as:

$$\Delta\alpha_{TCPST\,i} = \frac{\Delta P_{line\,j}}{k^{j}_{TCPST_i}\cdot\beta_i} = \frac{P^{0}_{line\,j} - P_{line\max j}}{k^{j}_{TCPST_i}\cdot\beta_i} \qquad (6)$$

This equation does not observe the appearance of congestions in other transmission lines after the control action. Therefore we wrote the following system of inequalities on the basis of (6):

$$P^{0}_{line\,j} - P_{line\max j} \le k^{j}_{TCPST_i}\cdot\beta_i\cdot\Delta\alpha_{TCPST\,i}, \qquad (7)$$
$$j = 1\ldots M$$

where M is a number of controlled lines, $P_{line\max j}$ is the maximal admissible value of active power flow in the controlled line j.

Using the principle of superposition of control actions of several controllers we can deduce an equation (7) for a more general case with several TCPST devices:

$$P^{0}_{line\,j} - P_{line\max j} \le \sum_{i=1}^{N_{TCPST}} k^{j}_{TCPST_i}\cdot\beta_i\cdot\Delta\alpha_{TCPST\,i}, \qquad (8)$$
$$j = 1\ldots M$$

Moreover, there are as well the following regulation constraints:

$$\alpha_{TCPST\,i\min} \le \alpha_{TCPST\,i} + \Delta\alpha_{TCPST\,i} \le \alpha_{TCPST\,i\max}, \qquad (9)$$
$$i = 1\ldots N_{TCPST}$$

where N_{TCPST} is a number of TCPST devices, $\alpha_{TCPST\,i\min}$ and $\alpha_{TCPST\,i\max}$ are the minimal and maximal values of phase shift angle of ith TCPST.

3.2 Control strategy for the TCSC

We can formulate the system of inequalities for TCSC devices by analogy with (8) and (9).

$$P^{0}_{line\,j} - P_{line\max j} \le \sum_{i=1}^{N_{TCSC}} k^{j}_{TCSC_i}\cdot\gamma_i\cdot P^{0}_{TCSC\,i}\cdot\Delta x_{TCSC\,i}, \quad (10)$$
$$j = 1\ldots M$$

$$x_{TCSC\,i\min} \le x_{TCSC\,i} + \Delta x_{TCSC\,i} \le x_{TCSC\,i\max}, \qquad (11)$$
$$i = 1\ldots N_{TCSC}$$

where N_{TCSC} is a number of TCSC devices, $x_{TCSC\,i\min}$ and $x_{TCSC\,i\max}$ are the maximal and minimal values of reactance compensation of ith TCPST.

3.3 Control strategy for the load shedding

If we have overload $\Delta P_{line\,j}$ on the line j, the volume of load i that must be shed can be calculated as:

$$\Delta P_{load\,i} = \frac{P^{0}_{line\,j} - P_{line\max j}}{k^{j}_{load_i}} = \frac{\Delta P_{line\,j}}{k^{j}_{load_i}} \qquad (12)$$

A minimization of the total outage cost caused by the Load Shedding is chosen as objective function:

$$\min_{\Delta P_{Load_i}} Cost_{\Sigma}\left(\Delta P_{load\,i}\right) = \sum_{i=1}^{N_{load}} \Delta P_{load\,i}\cdot Cost_i, \qquad (13)$$

where $Cost_i$ is the outage cost of the load i, \$/MW, N_{load} is a number of the loads available to shed.

The optimizing variables $\Delta P_{load\,i}$ are subjected to the following inequalities constraints:

$$P^{0}_{line\,j} - P_{line\max j} - \sum_{i=1}^{N_{load}} k^{j}_{load_i}\cdot\Delta P_{load\,i} \le 0,\; j = 1\ldots M \quad (14)$$

$$\Delta P_{load\,i} \le \Delta P_{load\max i},\; i = 1\ldots N_{load} \qquad (15)$$

where M is a number of controlled lines; $\Delta P_{load\max i}$ is the maximal volume of the load i shedding.

3.4 Coordinated control strategy for the load shedding and FACTS devises.

Finally we can formulate the optimization problem to finding coordinated control actions on the basis of equations (8–15).

$$\min_{\Delta P_{Load_i}} Cost_{\Sigma}\left(\Delta P_{load\,i}\right) = \sum_{i=1}^{N_{load}} \Delta P_{load\,i} \cdot Cost_i$$

subject to

$$P^0_{line\,j} - P_{line\max j} \le \Delta P^j_{loadshedding\,\Sigma} + \Delta P^j_{TCPST\,\Sigma} + \Delta P^j_{TCSC\,\Sigma}, \quad (16)$$

$$j = 1 \ldots M$$

where

$$\Delta P_{loadshedding\,\Sigma} = \sum_{l=1}^{N_{load}} k^j_{load_l} \cdot \Delta P_{load\,l}$$

$$\Delta P_{TCPST\,\Sigma} = \sum_{m=1}^{N_{TCPST}} k^j_{TCPST_m} \cdot \beta_m \cdot \Delta\alpha_{TCPST\,m}$$

$$\Delta P_{TCSC\,\Sigma} = \sum_{n=1}^{N_{TCSC}} k^j_{TCSC_n} \cdot \gamma_n \cdot P^0_{TCSC\,n} \cdot \Delta x_{TCPST\,n}$$

subject to following engineering constraints:

$$\left.\begin{aligned} \Delta P_{load\,l} &\le \Delta P_{load\max l} \\ \alpha_{TCPST\,m\min} \le \alpha_{TCPST\,m} + \Delta\alpha_{TCPST\,m} &\le \alpha_{TCPST\,m\max} \\ x_{TCSC\,n\min} \le x_{TCSC\,n} + \Delta x_{TCSC\,n} &\le x_{TCSC\,n\max} \\ l = 1 \ldots N_{load},\ m = 1 \ldots N_{TCPST},\ n &= 1 \ldots N_{TCSC} \end{aligned}\right\} (17)$$

Obviously the cost of control actions of FACTS devices equals to zero. Therefore, the algorithm first tries to remove the overloads by coordinated actions of FACTS devices. In the case of insufficiency of FACTS devices the algorithm involves the load shedding. The proposed technique allows finding the optimal volume of load shedding (with minimal total outage cost) taking into account the effect of FACTS devices.

4 TEST RESULTS

4.1 Description of the test power system

The Matpower package for Matlab™ has been used for load flow computations [9]. A special procedure was created to calculate the values of coefficients of influence and parameters of regulation characteristics. Also, a calculation program for the coordinated emergency control actions was developed on the basis of the proposed technique by using Matlab Optimization Toolbox.

The studies were carried out on the IEEE 30 bus test power system (Fig. 5).

It contains two distinct areas: the first one with a lack of production is in vicinity of the buses 3–7 and the second one with a surplus production is in vicinity of the buses 1 and 2.

The transmission lines, which connect these areas, are intensively loaded in the peak load period. Therefore, tripping one of these lines is a strong disturbance, which can result in a large overload in the network and even leads to the system instability.

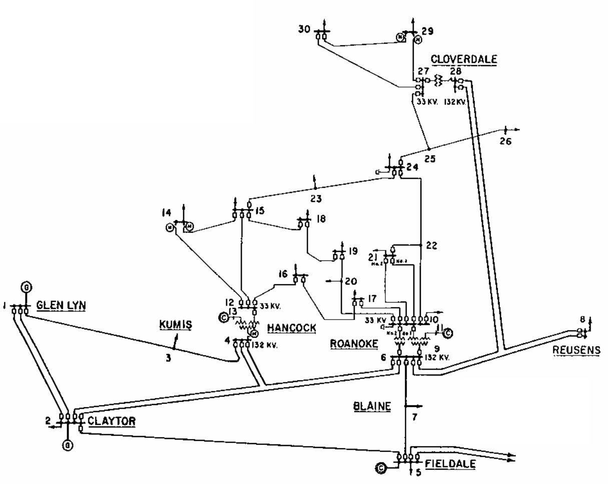

Figure 5: IEEE 30 bus test power system.

Different power system operation conditions (scenarios) were considered in this study. Parameters of some of them are presented in Table I. We supposed that FACTS devices (TCPST or TCSC) are installed in the lines 2–4 and 2–6 and the load at buses 2, 5, 7, 8 and 21 is available for shedding.

First, we calculated the coefficients of influence of loads and FACTSs and parameters of regulation characteristics for each FACTS device. Examples of relationships $k^j_{TCPST_i} = f(\alpha_{TSPST\,i})$ and $k^j_{load_i} = f(\Delta P_{load\,i})$ are represented in Figs. 6 and 7 respectively. These relationships are linear and do not depend on the value of setpoints of FACTS devices.

Node	Scenario 1 (base)		Scenario 2		Scenario 3	
	P	Q	P	Q	P	Q
Generators						
1	260.94	-16.79	389.28	-33.29	363.25	107.60
2	40.0	50.00	40.00	137.21	40.00	50.00
5	0	36.85	0.00	103.57	20.00	40.00
8	0	37.14	0.00	40.00	0.00	40.00
11	0	16.17	0.00	24.35	20.00	24.00
13	0	10.62	0.00	24.00	20.00	24.00
Loads						
2	21.70	12.70	50.04	39.24	32.55	19.05
3	2.40	1.20	2.88	1.44	3.60	1.80
4	7.60	1.60	9.12	1.92	11.40	2.40
5	94.20	19.00	113.04	58.80	141.30	28.50
7	22.80	10.90	39.36	25.08	34.20	16.35
8	30.00	30.00	54.00	36.00	45.00	45.00
10	5.80	2.00	6.96	2.40	8.70	3.00
12	11.20	7.50	13.44	9.00	16.80	11.25
14	6.20	1.60	7.44	1.92	9.30	2.40
15	8.20	2.50	9.84	3.00	12.30	3.75
16	3.50	1.80	4.20	2.16	5.25	2.70
17	9.00	5.80	10.80	6.96	13.50	8.70
18	3.20	0.90	3.84	1.08	4.80	1.35
19	9.50	3.40	11.40	4.08	14.25	5.10
20	2.20	0.70	2.64	0.84	3.30	1.05
21	17.50	11.20	21.00	13.44	26.25	16.80
23	3.20	1.60	3.84	1.92	4.80	2.40
24	8.70	6.70	10.44	8.04	13.05	10.05
26	3.50	2.30	4.20	2.76	5.25	3.45
29	2.40	0.90	2.88	1.08	3.60	1.35
30	10.60	1.90	12.72	2.28	15.90	2.85

Table 1: Parameters of considered power system operation scenarious.

Table 2 shows the values of coefficients of influence and gradient of regulation characteristic of TCPST 2–6, TCSC 2–6 and Load 5 on the transmission lines depending on the operation conditions of power system. The values of the coefficients of influence are practically constant and independent of the operation conditions. Therefore it is possible to use constant coefficients of influence of FACTS in most cases. Though obviously that if there are available measurements we can update all parameters on-line. Table 3 shows the calculated average values of coefficients of influence to the transmission network.

Then, the list of main disturbances (line outages) was formed on the basis of the analysis of the test power system. The coefficients of influence of loads and FACTS devices and the gradients of the regulation characteristics of FACTS devices were calculated for each emergency situation in the same way as for normal power system state. Table 4 presents the values of k_{inf} and β of the TCPST 2–6 for different line outages.

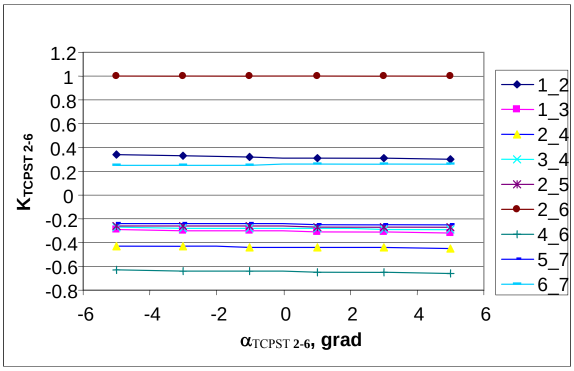

Figure 6: Influence of the TCPST 2-6 on the lines 1-2, 1-3, 2-4, 3-4, 2-5, 2-6, 4-6, 5-7, 6-7.

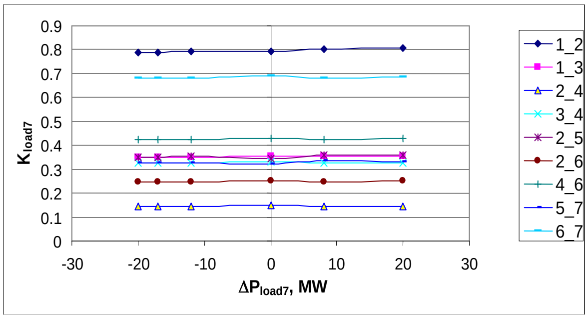

Figure 7: Influence of load at bus 7 on the lines 1-2, 1-3, 2-4, 3-4, 2-5, 2-6, 4-6, 5-7, 6-7.

Mode	β	1–2	1–3	2–4	3–4	2–5
TCPST 2–6						
1	–6.076	0.321	–0.300	–0.435	–0.279	–0.262
2	–6.069	0.324	–0.300	–0.436	–0.274	–0.263
3	–6.055	0.327	–0.300	–0.438	–0.270	–0.264
TCSC 2–6						
1	–233.42	0.328	–0.297	–0.432	–0.277	–0.258
2	–233.41	0.327	–0.299	–0.432	–0.277	–0.258
3	–233.40	0.327	–0.230	–0.431	–0.277	–0.258
Load 5						
1	–	0.839	0.289	0.057	0.270	0.609
2	–	0.850	0.290	0.057	0.269	0.610
3	–	0.848	0.291	0.056	0.269	0.609

Table 2: The values of k_{inf} and β depending on operation conditions.

Line	TCPST 2–4	TCSC 2–4	TCPST 2–6	TCSC 2–6	Load 2	Load 5	Load 7	Load 8	Load 21
1–2	0.41	0.41	0.32	0.33	0.88	0.85	0.79	0.73	0.73
1–3	-0.39	-0.38	-0.30	-0.30	0.18	0.29	0.35	0.39	0.41
2–4	1	1	-0.44	-0.43	-0.08	0.06	0.15	0.21	0.24
3–4	-0.37	-0.37	-0.28	-0.28	0.17	0.27	0.33	0.37	0.38
2–5	-0.19	-0.20	-0.26	-0.26	-0.03	0.61	0.35	0.15	0.14
2–6	-0.42	-0.42	1	1	-0.06	0.13	0.25	0.33	0.30
4–6	0.55	0.54	-0.64	-0.64	0.08	0.30	0.42	0.52	0.27
5–7	-0.18	-0.18	-0.24	-0.24	-0.03	-0.43	0.33	0.14	0.13
6–7	0.18	0.18	0.25	0.25	0.03	0.44	0.68	-0.14	-0.14

Table 3: The values of coefficients of influence (no line outages).

After we have found all required numerical data a number of different simulations were carried out to evaluate the proposed emergency control algorithm. Coordinated control actions for different line outages in different power system operation conditions were calculated and analyzed.

These studies have shown the proper operation of the proposed technique. Let us present in detail an example of emergency control algorithm's operation.

4.2 Example of emergency control algorithm's operation (outage of the line 4–6, operation scenario 2 (Table 1))

In the case of the emergency outage of line 4–6 we have three heavy overloaded lines 1–2, 2–6 and 2–5 (Fig. 8). The values of coefficients of influence for this emergency state are presented in Table 5. Several possible cases are considered.

1. There are no FACTS devices, only load shedding is available.
    1.1. All loads have the same shedding cost, i.e. $Cost_2$=$Cost_5$=$Cost_7$=$Cost_8$=$Cost_{21}$=1 $/MW; We used "$" as a symbol of some conventional units.
    1.2. $Cost_5$=1 $/MW; $Cost_2$= =$Cost_7$=$Cost_8$=$Cost_{21}$=1,33 $/MW.
    1.3. $Cost_5$=1 $/MW; $Cost_2$= =$Cost_7$=$Cost_8$=$Cost_{21}$=1,66 $/MW.
    1.4. $Cost_5$=1 $/MW; $Cost_2$= =$Cost_7$=$Cost_8$=$Cost_{21}$=2 $/MW.
    1.5. $Cost_5$=1 $/MW; $Cost_2$=$Cost_7$=4 $/MW; $Cost_8$=3 $/MW; $Cost_{21}$=1 $/MW.
    1.6. $Cost_5$=$Cost_2$=$Cost_7$=1 $/MW; $Cost_8$=$Cost_{21}$=3 $/MW.
2. TCPST device is installed in the line 2–6. $Cost_3$=$Cost_4$=$Cost_9$=$Cost_{13}$=1 $/MW.
3. TCPST device is installed in the line 2–4. $Cost_3$=$Cost_4$=$Cost_9$=$Cost_{13}$=1 $/MW.
4. TCSC device is installed in the line 2–4. $Cost_3$=$Cost_4$=$Cost_9$=$Cost_{13}$=1 $/MW.
5. TCPST devices are installed in the lines 2–4 and 2–6. $Cost_3$=$Cost_4$=$Cost_9$=$Cost_{13}$=1 $/MW.

The following volumes of maximum load shedding were specified: $\Delta P_{\text{loadmax2}}$=50 MW, $\Delta P_{\text{loadmax5}}$=80 MW, $\Delta P_{\text{loadmax7}}$=30 MW, $\Delta P_{\text{loadmax8}}$=50 MW, $\Delta P_{\text{loadmax21}}$=20 MW. And FACTS devices have the following working

Outage of line	β	Line								
		1–2	1–3	2–4	3–4	2–5	2–6	4–6	5–7	6–7
1–2 (1 circuit)	–5.96	0.29	–0.26	–0.46	–0.23	–0.27	1	–0.63	–0.26	0.27
1–2	–5.11	–	0.03	–0.64	0.02	–0.36	1	–0.61	–0.35	0.38
1–4	–5.49	0.02	–	–0.64	–	–0.34	1	–0.54	–0.32	0.32
2–4	–4.98	0.61	–0.57	–	–0.52	–0.42	1	–0.48	–0.39	0.40
2–6	–	–	–	–	–	–	–	–	–	–
2–5	–5.41	0.43	–0.40	–0.59	–0.37	–	1	–0.84	0	0
5–6	–5.32	0.43	–0.42	–0.60	–0.39	0	1	–0.90	–	–
4–6	–4.13	0.19	–0.14	–0.22	–0.13	–0.61	1	–	–0.56	0.56

Table 4: Values of k_{inf} and β of TCPST 2–6 for different outages.

Line	TCPST 2–4	TCSC 2–4	TCPST 2–6	TCSC 2–6	Load 2	Load 5	Load 7	Load 8	Load 21
1–2	0.79	0.78	0.20	0.19	0.95	0.99	1.02	1.01	0.94
1–3	–0.79	–0.78	–0.13	–0.13	0.16	0.20	0.24	0.25	0.33
2–4	1	1	–0.22	–0.22	–0.11	–0.08	–0.05	–0.02	0.11
3–4	–0.74	–0.74	–0.12	–0.13	0.15	0.19	0.22	0.23	0.31
2–5	–0.09	–0.10	–0.61	–0.61	–0.01	0.69	0.49	0.30	0.24
2–6	–0.20	–0.20	1	1	–0.02	0.29	0.50	0.64	0.50
4–6	–	–	–	–	–	–	–	–	–
5–7	–0.08	–0.08	–0.54	–0.54	–0.01	–0.37	0.44	0.26	0.21
6–7	0.08	0.08	0.54	0.54	0.01	0.36	0.58	–0.27	–0.21

Table 5: Values of coefficients of influence (outage of line 4–6).

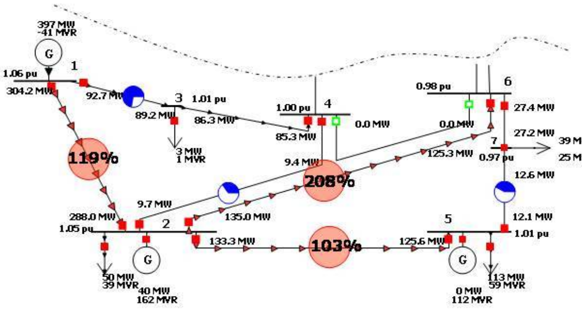

Figure 8: Fragment of test power system. Outage of the line 4–6.

range: $-10° < \alpha_{TCPST2-5} < +10°$; $-10° < \alpha_{TCPST3-4} < +10°$; $0\,\% < \Delta x_{TCSC2-5} < 50\,\%$

The calculated optimal solutions for all cases are shown in Table 6. Below, an analysis of the results is presented.

In the case 1.1 the following optimal solution was obtained: in order to unload lines 1–2, 2–5 and 2–6 it is necessary to shed the loads number 5, 7, 8 and 21 ($\Delta P_{load5} = 43$ MW, $\Delta P_{load7} = 30$ MW, $\Delta P_{load8} = 50$ MW, $\Delta P_{load21} = 20$ MW). The cost of load shedding is 143 $ and the total amount is 143 MW. This solution corresponds to a solution with a minimum total amount of load shedding. The load 2 is not involved in control action because it practically does not have influence on the overloaded lines 2–6 and 2–5.

In the case 1.2 we have the same solution as in the previous case. It could be explained by the fact that the load 5 has a small influence on the overloaded lines and this solution is economically feasible regardless the shedding cost of the load 5 is cheaper by a factor of 1.33.

In the case 1.3 the optimal solution is $\Delta P_{load5} = 59$ MW, $\Delta P_{load7} = 27$ MW, $\Delta P_{load8} = 50$ MW, $\Delta P_{load21} = 13$ MW. The total cost of load shedding is 208 $ and the total amount is 149 MW. As may be seen, the total amount of load shedding is higher than in the first case. This effect has the following explanation: the shedding of the load 5 (the load with a small influence on the overloaded lines) is cheaper by a factor of 1.66. Therefore, it is economically feasible to shed the load with smaller influence on the overloaded lines, but with lower cost.

Scenario		Load 2	Load 5	Load 7	Load 8	Load 21	Cost	TCPST 2–4	TCSC 2–4	TCPST 2–6
1	1.1	0	43	30	50	20	143	–	–	–
	1.2	0	43	30	50	20	176	–	–	–
	1.3	0	59	27	50	13	208	–	–	–
	1.4	0	80	21	50	6	234	–	–	–
	1.5	0	80	8	50	20	321	–	–	–
	1.6	0	80	30	48	0	254	–	–	–
2		0	19	18	16	7	60	–	–	10°
3		0	18	30	50	20	118	–10°	–	–
4		0	40	30	50	20	140	–	50%	–
5		0	13	30	8	0	51	–4.8°	–	10°

Table 6: List of calculated control actions.

In the case 1.4 the optimal solution is $\Delta P_{load5} = 80$ MW, $\Delta P_{load7} = 21$ MW, $\Delta P_{load8} = 50$ MW, $\Delta P_{load21} = 6$ MW. Total cost of load shedding is 234 $ and the total amount is 157 MW. Hence, the volume of the load 5 shedding reached the maximum value since the shedding of the load 5 is two times cheaper.

Plots in Fig. 9 illustrate the efficiency of control actions. Fig. 9(a) shows a comparison of different control actions according to the total amount of load shedding. Fig. 9(b) presents a comparison of the economic feasibility of the calculated optimal control actions and the control action with the minimum amount of load shedding (obtained in the case 1.1).

In the case 2 the following solution was achieved: $\Delta P_{load5} = 19$ MW, $\Delta P_{load7} = 18$ MW, $\Delta P_{load8} = 16$ MW, $\Delta P_{load21} = 7$ MW, $\alpha_{TCPST2-6} = 10°$. The cost of the load shedding is 60 $ and the total amount is 60 MW. Thus, the amount of required load shedding is decreased by 58 % in comparison with the first scenario in the case of the application of the TCPST 2–6 (case 1.1).

In the third and the fourth cases the application of the TCPST 2–4 and TCSC 2–4 demonstrates smaller effi-

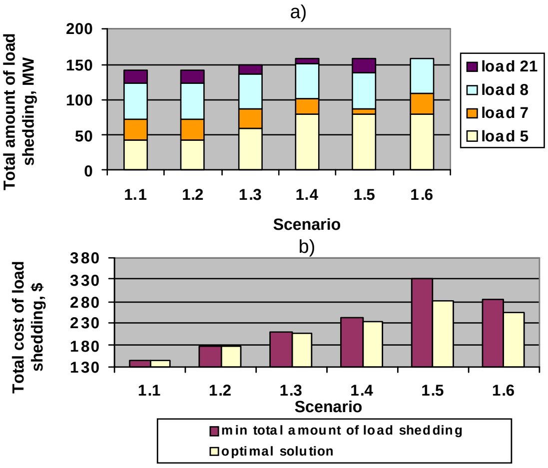

Figure 9: Comparison of different load shedding scenarios: according to a total amount (a) and a total cost (b).

ciency because they have a smaller influence on the overloaded lines. Moreover, the TCSC 2–4 has shown a worse performance compared to the TCPST 2–4 because of the low initial current through TCSC device.

In the fifth case the following solution was achieved: $\Delta P_{load5} = 13$ MW, $\Delta P_{load7} = 30$ MW, $\Delta P_{load8} = 8$ MW, $\alpha_{TCPST2\text{-}6} = 10°$.; $\alpha_{TCPST2\text{-}4} = -4.8°$. The cost of the load shedding is 51 $ and the total amount is 51 MW. Thus in the case of the application of the coordinated multiple FACTS devices the amount of required load shedding is reduced by 64 % in comparison with the first case.

The illustration of the efficiency of FACTS devices as congestion management means is shown in Fig.10. The combined application of the load shedding and FACTS devices allows to curtail a financial damage to consumers.

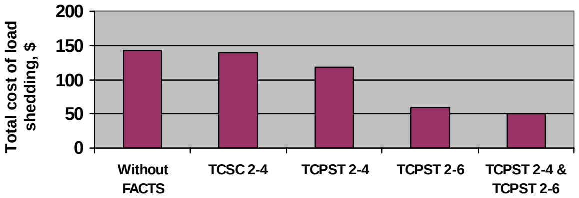

Figure 10: Economic benefits of FACTS applications.

5 CONCLUSIONS

This paper presents a coordinated control system for overload limitations in a transmission system using load shedding combined with multiple FACTS. The coordination algorithm is based on a sensitivity analysis and a linear optimization technique. The conclusions of the paper can be summarized as follows:

- The proposed coordinated control system and its control strategies can be successfully used for the coordination of the load shedding as well as for the load shedding combined with the control of multiple FACTS devices to limit line overloads and prevent power system instability caused by the outages of transmission lines.
- The proposed control strategy allows choosing optimal selection of load shedding to limit line overloads taking into account the cost of consumers' disconnection.
- Simulations have shown that FACTS devices are an effective tool for congestion management. The application of FACTS devices combined with a load shedding decreases the amount of required load shedding and so allows reducing a financial damage to customers.
- A performance of a TCPST device is usualy higher than a performance of a TCSC device in a meshed network topology (presence of many parallel paths).

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