A Combination between FACTS Devices for a Safe and an Economic Power System Operation

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***Abstract*— Owing to the rising need for power electronics for sustaining the high quality of electrical energy and the considerable cost of such a technology, we present in this paper a solution dealing with these problems. We propose to create a combination between SVC (Static VAR Compensator) and TCSC (Thyristor Controlled Series Compensator) to reach the performances of UPFC (Unified Power Flow Controller) in improving system stability. This combination guarantees both: economic investment and efficient functioning. The investigation of the proposed idea and the comparative studies are performed in the IEEE 14-Bus system under EUROSTAG environment.**

***Keywords* - EUROSTAG, cost-efficiency, stability, SVC, TCSC, UPFC.**

I. Introduction

In recent years, the ever growing demand of power has led power system to operate very close to its stability limits [1]. As a result, system stability becomes a very challenging problem that has to be considered. The expansion of the network and the construction of new transmission lines to satisfy the escalating electricity demand, are subject to financial limitations. Therefore, it is mandatory to look for an efficient and economical solution to assure rapid control and flexible operation of the system [2].

Over the last decades, Flexible AC Transmission Systems (FACTS) technology has continued to prosper as power electronics components are developing [3, 4]. These controllers not only are capable of regulating active and reactive power in power system but similarly they have the potential to rebalance and redistribute powers in different network points, in case of heavy loaded conditions. This actually led to guarantee the continuity of electric power supply and to reinforce power system stability. UPFC, SVC and TCSC have acquired a well-recognized term for higher and smoother controllability in electric networks.

In literature, numerous works focused on the study of these controllers. Reference [5] compared the capabilities of UPFC and TCSC in controlling active and reactive power flows. By implementing the steady-state models of these FACTS in the IEEE 14-Bus system, authors find out that TCSC is more efficient than UPFC in improving the active power transmitted in lines. Reference [6] deals with the comparison of various FACTS devices in enhancing power system stability. Comparative studies were carried out in the IEEE 5-Bus network and in a two-area power system. Compared to SSSC (Static Synchronous Series Compensator), SVC and TCSC, it was concluded that UPFC is the better in regulating bus voltage, controlling power flows in addition to reducing the losses in lines. B. Bhattacharyya *et al*. [7] were interested in their paper to the impact of installing UPFC along with SVC and TCSC, on the cost of operation and power loss. After determining the optimal emplacement and parameters of the FACTS using specific algorithms, authors have signaled the gain obtained when adding the hybrid compensator to the other FACTS. Likewise, authors in [8] discussed the use of SVC, TCSC and UPFC in the improvement of dynamic and transient system stability. They compared the three FACTS based on their mathematical models and operation modes. It was found that UPFC provided the most rapid control and the highest performances in stabilizing the system. In order to enhance the voltage profile of a grid connected distributed generation system, the authors in [9] studied the contribution of the SVC and UPFC. They demonstrated through simulations, the satisfactory operation of the two FACTS especially the hybrid device.

Different from previous works, in this paper we study the possibility of creating a device analog to UPFC, by combining the performances of SVC and TCSC. Keeping in mind that UPFC is the most versatile and pricey FACTS device, the benefits of this idea is to reduce the investment cost into FACTS, which becomes fundamental, while overcoming the instability problem.

For this purpose, we exploited EUROSTAG; a software performing an automatic simulation piloting, respecting a precision given by the user. The proposed idea and the models

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of the controllers are incorporated into the IEEE 14-Bus system.

First, in section 2 we present a deep insight into the position of FACTS in literature and in real power systems. Second, we focus on the mathematical models and structures of the three mentioned FACTS. And then, we are interested in the case study and the discussion of simulation results. Finally, we summarize the main points of this paper in the conclusion.

II. FACTS Overview

Since the development of power electronics, a great interest has been granted to FACTS devices. Researches consider this technology as a substantial and a timely topic. For this reason, an important number of studies discussing the application of FACTS to power systems has been published. In power system stability field, the publications related to FACTS are also numerous. It was found that the interest to the flexible controllers is more and more increased which reflects the efficiency of such a solution for instability problems. According to reference [10], when looking at the statistics for SVC, TCSC and UPFC publications, we noted that they are dominant compared to the other FACTS. Nonetheless, SVC is reaping the major concern in researches studies with 114 publications until 2004.

Actually, these statistics are reflecting the installed FACTS systems in the world. Reference [11] presented approximate results of a survey on worldwide integrated FACTS. It should be mentioned that SVC is the most exploited FACTS with a total power of 90.000MVA. While 2.000MVA are distributed on 10 incorporated TCSC into power systems, there are only 3 real networks equipped with UPFC with 250MVA of generated power.

To understand the reasons of the widespread use of SVC in comparison to the others FACTS particularly UPFC, we must look at system planners choices. Recognizing that the investment cost is always a considerable constraint, economical solutions for power system instability are generally preferred. The cost of a FACTS device is highly depending on the complexity of its model which is determined by the number of semiconductors used. Thereby, consisting of two voltage source converters, UPFC has the highest cost among the various FACTS [11]. According to reference [12], it is estimated by 0.33 million$ for 1MVAR generated power while the cost of SVC is approximately 0.19 million$ and the instrument and investement costs of TCSC are estimated by 0.22 million$ for 1MVAR generated power. So it is understandable why industrials are not opting for installing UPFC as introducing SVC in worldwide systems. Otherwise, the cost-efficiency is not always to install the least costly FACTS device but rather to choose the appropriate one based on the type of instability problem that we want to solve. As these problems are, on the one hand, unpredictable and on the other hand, closely linked, it is required to invest into an equipment which can assure the control of more than one network parameter. Currently, UPFC has the potential to act on three parameters namely: phase angle, line impedance, and bus voltage either simultaneously or separately. So, confronted with these constraints, we thought to find a solution for network instability, combining the economical side with wide application area and efficiency side. Hence, our idea is to create an equivalent of UPFC by joining the action of TCSC, as a series FACTS, to that of SVC which assure the shunt compensation. With this approach, we contribute in better enhancing the behavior of power system during distributed situations with fewer costs, especially because hundreds of power systems are equipped with SVC.

III. FACTS Models

When studying the application of FACTS devices to power system, it is required to describe their functionalities supported with mathematical models and equivalent schemes and that what we are going to present in this section.

A. UPFC

UPFC controller is consisting basically of two inverters, one connected in shunt while the other is coupled in series to the transmission line. A DC link capacitor ensures the connection of the two converters [13].

The shunt voltage source inverter plays a key role; by providing the reactive power, it boosts voltage at buses where UPFC is connected. Likewise, it maintains voltage of the DC capacitor at its reference value which is important for a good operation of the device. As for the series converter, it controls power flow in the transmission line by inserting voltage with adjustable phase angle and magnitude.

The equivalent circuit of UPFC is represented in Fig.1 [14]. From this scheme, we can extract the active and reactive power flows of the shunt and series converters which are expressed by the equations (1) - (4).

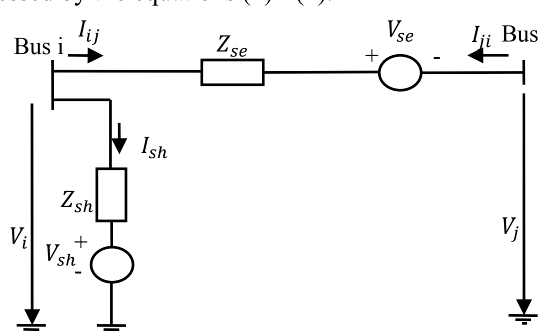

Fig. 1. Equivalent circuit of UPFC

$$P_{sh} = V_i^2 g_{sh} - V_i V_{sh} (g_{sh} \cos(\theta_i - \theta_{sh}) + b_{sh} \sin(\theta_i - \theta_{sh})) \tag{1}$$

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$$Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh}(g_{sh}\sin(\theta_i - \theta_{sh}) - b_{sh}\cos(\theta_i - \theta_{sh})) \quad (2)$$

$$P_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) - V_i V_{se}(g_{ij}\cos(\theta_i - \theta_{se}) + b_{ij}\sin(\theta_i - \theta_{se})) \quad (3)$$

$$Q_{ij} = -V_i^2 b_{ij} - V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}) - V_i V_{se}(g_{ij}\sin(\theta_i - \theta_{se}) - b_{ij}\cos(\theta_i - \theta_{se})) \quad (4)$$

Where:

$$g_{sh} + jb_{sh} = \frac{1}{Z_{sh}}$$

$$g_{ij} + jb_{ij} = \frac{1}{Z_{se}}$$

$$\theta_{ij} = \theta_i - \theta_j$$

V_i and V_j : voltages at buses i and j

P_{sh} and Q_{sh} : active and reactive power flows of the shunt inverter

P_{ij} and Q_{ij} : active and reactive power flows of the series inverter

V_{sh} and V_{se} : shunt and series voltage sources

Z_{sh} and Z_{se} : shunt and series coupling transformer impedances.

The modeling of the UPFC shunt part on EUROSTAG is simple; it is represented by a current injector. As for the modeling of the series part, we must open the line where we want to insert UPFC and place at its extremities two current injectors (Fig.2). The opening of the line is assured by a high reactance value.

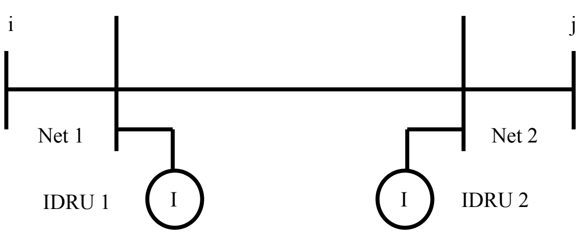

Fig. 2. UPFC model on EUROSTAG

B. SVC

SVC is a static reactive power compensator whose output is adjusted for exchanging a capacitive or inductive current with the network to typically control buses voltage [15]. In the steady state as well as in transient regime, this device is able to maintain voltage within the desired limits. Fig.3 shows the dynamic model of SVC. It can be modeled as variable shunt admittance with a thyristor controller. However, by neglecting the losses of SVC, we can consider it as ideal, so the admittance is purely imaginary and is described by the equations (5) and (6):

$$G_{SVC} = 0 \quad (5)$$

$$y_{SVC} = jB_{SVC} \quad (6)$$

The susceptance can be capacitive or inductive. Indeed, in the case of reactive power excess, SVC absorbs the increased amount through the inductor and in the opposite case; the capacitor cover the reactive demand.

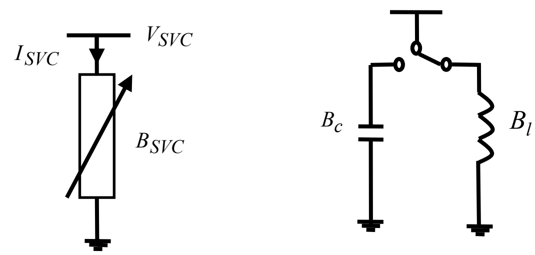

Fig. 3. SVC model

The capacitive power injection model of SVC at the rated voltage is given by equation (7) [16]:

$$Q_{SVC} = -V_N{}^2 B_{SVC} \quad (7)$$

Where B_{SVC} must be controlled according to relation (8):

$$B_{SVC}{}^{\min} \le B_{SVC} \le B_{SVC}{}^{\max} \quad (8)$$

$B_{SVC}{}^{\max}$ designates the capacitive limit state while $B_{SVC}{}^{\min}$ designates the inductive one. If SVC susceptance reaches its limits without maintaining the voltage of the bus where it is connected, it loses the capability of voltage control and it becomes similar to a fixed susceptance.

EUROSTAG adopts the model of Fig.4 and represents SVC as an impedance injector connected to a bus of the electrical network.

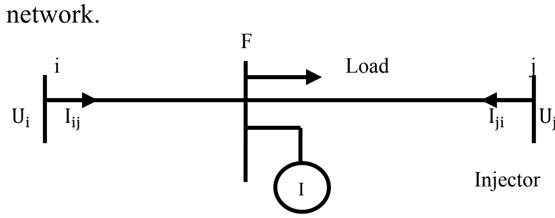

Fig. 4. SVC model on EUROSTAG

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C. TCSC

A typical TCSC is composed of a thyristor controlled reactor in parallel with a fixed capacitor, which is equivalent to an adjustable reactance as shown in Fig.5 [17]. It allows the control of the active flow on the transmission line by regulating its series reactance. The operation of the TCSC is similar to that of SVC but they differ in the connection mode.

The equivalent reactance x_{TCSC} varies depending on the firing angle α and is given in equation (9) [18].

$$x_{TCSC}(\alpha) = \frac{jL\omega}{\frac{2}{\pi}(\pi - \alpha + \frac{\sin(2\alpha)}{2}) - LC\omega^2} \quad (9)$$

The TCSC control action is expressed as a compensation percentage given by the following equation:

$$K_C = \frac{x_C}{x_L} \times 100 \quad (10)$$

Where:

x_C : line reactance

x_L : effective capacitive reactance given by TCSC

On EUROSTAG, to model a series and variable admittance, we must create two fictive buses in a transmission line and insert a current injector to each bus, as described in Fig.6. The two fictive buses must be connected to the network by lines with high reactance value to avoid injector shutdown in case of opening line.

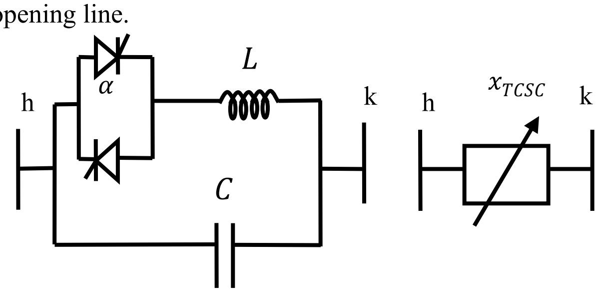

Fig. 5. TCSC model

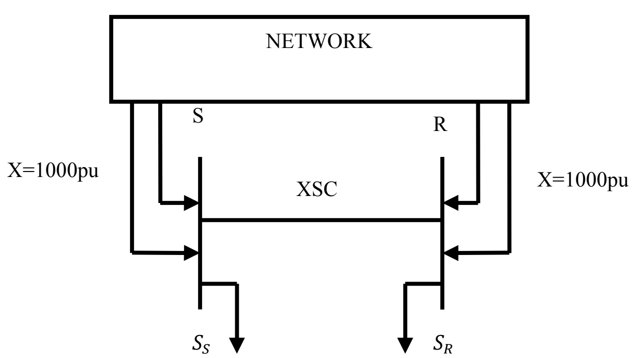

Fig. 6. TCSC model on EUROSTAG

IV. Simulation

A. Case study

IEEE 14-bus network is a classical system consisting of two generator buses and eleven load buses with a total power of 259MW and 81,3 MVAR. It has fifteen transmission lines, a three-winding transformer and two step-up transformers with two windings, to elevate the voltage from 13,8KV to 69KV. For purpose of reactive power support, it got three synchronous compensators connected to buses 3, 6 and 8. All data relating to this test network are extracted from reference [14] and we used EUROSTAG software package [19] for the simulations.

B. Simulation results

1) Step change in load: To conduct the comparative studies between UPFC and the combination SVC-TCSC, first of all we need to investigate the behavior of the test network. Therefore, we plan a step change in load at time t= 200s from 5% of the initial load by a step of 5%. The procedure continues until reaching the maximum loading capability of the system.

For the evaluation of network stability, we choose to follow the voltage level at the weakest busbar. The results of the base state signaled that bus 14 has got the lowest voltage amplitude; hence we summarized the voltage levels of bus 14 during various step changes in Table 1.

TABLE 1. NETWORK BEHAVIOR UNDER INCREMENTAL LOAD INCREASE.

Network Settings	**Load Increase in %**					
	5%	**10%**	**20%**	**25%**	**30%**	**33%**
U14 (pu)	0.966	0.962	0.952	0.948	0.946	Voltage collapse
State System	Stable					

We note the occurrence of a voltage dip in bus 14, which is increased as more the loads are augmented. Until 32% of load increase, voltage level is still acceptable and the network is maintaining its stability. When reaching the case of 33%, EUROSTAG fails to execute the simulation, indicating the collapse of the system. In addition, we verified that the collapse is not local by examining the voltage waveform of the slack node, bus1, the most stable bus in the network. As shown in Fig.7, similarly bus1 experienced a sudden and an uncontrollable voltage drop which augments the potential of blackout phenomena.

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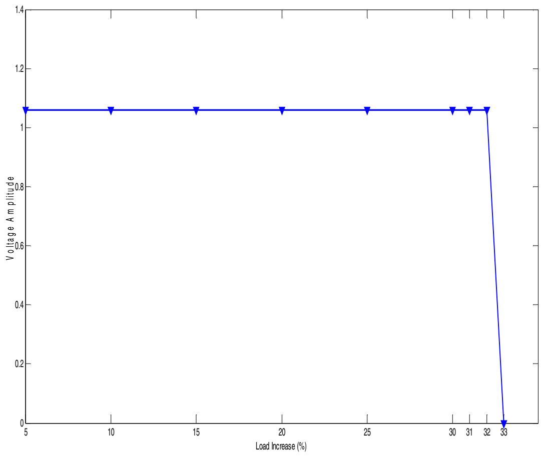

Fig. 7. Voltage collapse after 33% of load increase.

2) Comparative study:

Now, we connect UPFC and SVC-TCSC to the network, separately. Firstly, UPFC was integrated in the middle of line 9-14 with a capacity of 60MVAR for each one of its inverters, and then, with keeping the same dimensions, we inserted TCSC through the line 9-14 and SVC to bus9. The emplacement of the FACTS is not our main purpose, so we choose it based on the analyses of the power flow results. The weakest zone in the network is the nearest to system collapse, so it needs to be compensated.

According to the prior section, we consider the case of 30% to compare the performances of our FACTS. In this case, the test network is under heavy loaded conditions.

We are interested in the comparison, to the evolution of bus voltage as well as the active and reactive power flows in transmission lines.

Taking bus 14 as an example as shown in Fig.8, it can be seen that both UPFC and SVC-TCSC have a bearing on the voltage magnitude by increasing it significantly, while it was under the minimum acceptable value before compensation. However, UPFC showed a higher capability of enhancing voltage level, from 0.90pu to 0.96pu. In addition, we obtained a rapid damping of oscillations after only 7s either by UPFC or SVC-TCSC.

The impact of the FACTS on the oscillatory regime is clearer in the voltage curve of bus1, plotted in Fig.9. Nonetheless, we note that the damping action of SVC-TCSC is more considerable compared to that of UPFC, in fact, it reduced the highest oscillation from 1.08pu to 1.071pu and rapidly established the steady state with well amortized oscillations.

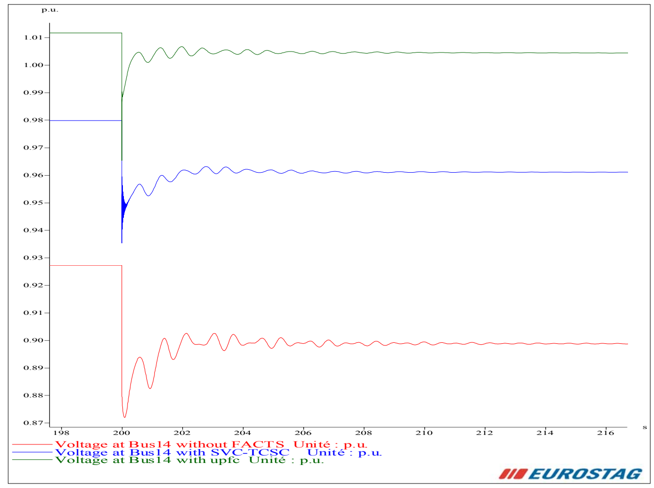

Fig. 8. Voltage of bus14 with and without FACTS.

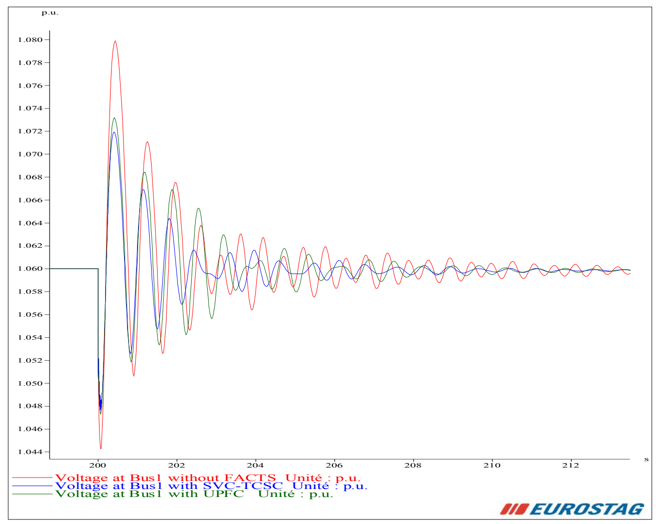

Fig. 9. Voltage of bus1 with and without FACTS.

According to the results of Table 2, an excellent enhancement in the active power has been observed with the action of UPFC. However, we didn’t note any important change in its level when used SVC-TCSC. As for the reactive power flow, it encountered a considerable decrease by using UPFC; it was decremented from 5.7 MVAR to 2.5MVAR through the line 9-10 as an example. This was observable also when introducing the combination SVC-TCSC which reduced the amount of reactive power in line 6-12 with about 12% and in line 1-2, from 20MVAR to 19.2MVAR. Nevertheless, we recorded an increase of 10.5% in the transmitted MVARs across line 9-10.

Fig.10 shows the active power transmitted in line 1-2 with and without FACTS. When focusing on the transient regime, it must be mentioned that even in the temporal evolution of powers, the damping action of SVC-TCSC is more efficient; it

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gives more attenuated oscillations and joined the stable state in a shorter time.

TABLE 2. ACTIVE AND REACTIVE POWER FLOWS WITH AND WITHOUT FACTS.

Simulation case	Line 9-10		Line 1-2		Line 6-12	
	Active Power MW	React. Power MVAR	Active Power MW	React. Power MVAR	Active Power MW	React. Power MVAR
Without FACTS	8.3	5.7	209	20	9.8	3.4
With SVC-TCSC	8.3	6.3	209	19.2	10	3
With UPFC	9.2	2.5	216	18.1	10.8	1.5

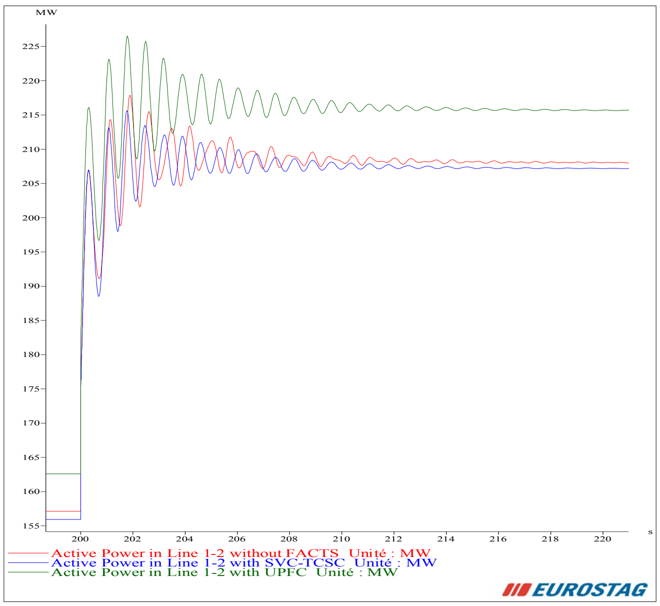

Fig. 10. Active power flow in line 1-2 with and without FACTS.

V. CONCLUSION

In this paper, we have presented a contribution to ensure a safe and an economical power system operation. By empathizing, on the one hand, the position of FACTS in stability field, and on the other hand, the importance of avoiding intensive cost, we proposed a coordination between the performances of TCSC and SVC, the most installed controller worldwide. Through this conjunction, we aimed to obtain a promoting combined action that can emulate UPFC, the multi-functional and the most expensive FACTS device. Using dynamic simulations, it was demonstrated that during heavy loaded conditions, the addition of a TCSC to an existing SVC leads to a significant improvement of voltage profiles of the whole system. Moreover the combination SVC-TCSC deals effectively with the problem of oscillations better than the action of UPFC. However, UPFC proves a satisfactory operation in controlling power flows in lines as opposed to the combined devices.

In conclusion, our proposal for reducing the network operation cost is benefic and simple to be applied. Further works are undergoing to ameliorate the idea of this paper and to study the introduction of another factor for the economization of network operation.

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