IJCTA, 9(38), 2016, pp. 189-201

Assessment of SVC in Improving Power System Stability

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ABSTRACT

Instability phenomenon is a main threat to the safety of power system operation. The application of technologies for the improvement of system stability particularly during fault conditions is a major concern in the field of power system operation and control. SVC has been widely proposed for this purpose. Its primary function is to sustain voltage through reactive power control and it is also integrated for enhancing angular stability and damping oscillations. However, to which extent the operation of this device is efficient, remains an axis of many problematic studies. This paper is concerned with the evaluation of the performance of SVC in improving network stability proceeding by numerical simulation method. The implementation of the dynamic model of SVC was applied to the IEEE 14-bus system and the simulations were performed via EUROSTAG.

Keywords: Angle stability, EUROSTAG, performance evaluation, SVC, voltage stability.

1. INTRODUCTION

The robustness of power system is evaluated by its ability to maintain an equilibrium state under normal circumstances as well as after being disturbed. Therefore, the concept of stability is concerned with the study of the behavior of the system subject to disturbances often happening as a short circuit or a sudden increase in load. Note that such disturbances can affect the equilibrium between production and consumption which is considered as a necessary condition for satisfactory operation [1]. Furthermore, the equilibrium between supply and demand particularly of the reactive power may not be met because of Joule effect losses generated by long-distance transmission.

To ensure the continuity of electric power supply and to remedy the various problems related to stability, the power flow through lines must be controlled and the production of reactive power must be close to consuming areas as much as possible. Consequently, it is necessary to equip the network with reactive power control devices with high response speed. The progress of power electronics has contributed to the development of a technology known as FACTS (Flexible AC Transmission System). The widespread use of these devices is due to their flexibility, rapidity and their ability to control one or more electrical parameters as phase, voltage, and power for enhancing electrical system stability [2]. Among various FACTS controllers, SVC (Static VAR Compensator) is the most widely used device to improve system stability. According to [3], more than 700 SVC are in operation around the world in power systems.

Reference [4] studied the maximum load capacity of the Bangladesh power system network, which once reached can lead to voltage collapse. In this case, injection of necessary reactive energy can be a support to the network. It improves voltage profile at various buses. Therefore, power system is away from the point of voltage collapse. It was for this reason that authors inserted an SVC in the most vulnerable bus. The application of FACTS devices to enhance voltage stability has been proposed also in [5]. This work focused on the assessment of voltage stability. To do this, authors proceeded by a gradual increase in system load which led to a progressive increase in voltage but still always conform to EN50160 [6]. This

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standard specifies the interval [0.94pu; 1.06pu] for HV networks as an allowable range. Nevertheless, they were talking about voltage collapse situation while voltage level has a permissible value.

The contribution of SVC to enhance stability performance of Henan power system was considered in [7]. Simulations results showed the effectiveness of this shunt device in reducing the impact of disturbances on system characteristics and in improving transient stability. A shunt FACTS was applied to IEEE 30-bus system for the improvement of voltage stability. By varying the number and the location, they proved the capability of such devices to increase voltage profile at the almost system buses [8].

Due to the harmful impact of the transfer of reactive power, the integration of SVC into the electrical grid is of great importance. However, the questioning over the limits of its effectiveness in improving stability is still a subject of controversy. Note that the installation of this device in a real network is costly, we will opt for a theoretical study followed by numerical simulations on the standard network IEEE 14-bus. Inasmuch, as the behavior of the machine following a disturbance affects the electrical characteristics of the network such as frequency, voltage, power transmitted etc. Likewise, even any variation in the voltage level can cause the loss of synchronism of the machine; our study focuses on the evaluation of the dynamic of rotor angles of the machines as well as the evolution of buses voltage with and without the intervention of SVC. Some recent control methods are discussed in [13-18].

This paper is organized as follows: firstly, we focus on the stability of power grid and on the relationship between angular stability and voltage stability. Secondly, we present the modeling of the synchronous machine and SVC regulator. Lastly, we discuss the simulations results carried out within the software EUROSTAG. The main items of this work are summarized in the conclusion.

2. POWER SYSTEM STABILITY

Power system is considered stable if it is able, on the one hand, to ensure a state of operating equilibrium in steady state, and on the other hand to restore an acceptable state of equilibrium following a disturbance 9.The loss of stability in an electrical network can appear in various forms depending on the network configuration and operating conditions.

After a disturbance, if the network may lose the synchronism between its electrical machines, we speak about angular stability. Maintaining the synchronism is considered as a necessary condition for a satisfactory operation of the system. This aspect of stability is related to the dynamic of rotor angles of machines and is said transient in the case of a severe disturbance. However, instability can also be experienced at the buses of the network when it becomes unable to keep voltages close to nominal values and sometimes to prevent voltage collapse after being subjected to a disturbance. In this case, the problem is not to maintain synchronism but to control the voltage.

Note that the classification of stability under different aspects facilitates the study of various problems related to instability. However, the distinction between stability forms may not be explicit. Generally, voltage instability and angular instability are closely linked; the one can cause the other one 7.

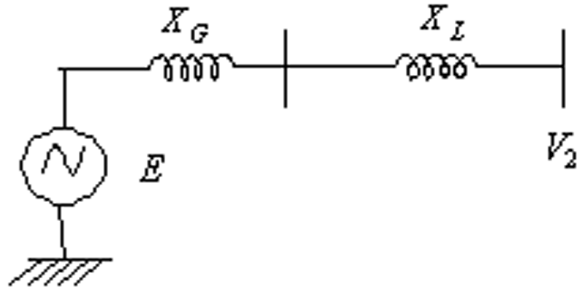

Figure 1: Equivalent model of a 2-bus system.

To understand the relationship between these two types of instability, we consider the system of Figure 1, consists of a generator connected to an infinite network.

The power output of the generator is expressed by the relationships (1) and (2)[9]:

$$P = \frac{EV_2 \sin(\delta)}{X_T} = P_{\max} \sin(\delta) \tag{1}$$

$$X_T = X_G + X_L \tag{2}$$

Where:

E : Generator electromotive voltage

V_2 : Busbar voltage

δ : Generator internal angle

X_G : Generator impedance

X_L : Line impedance

The relation (1) is an important characteristic that expresses the phenomenon of stability because it connects all network parameters: power, voltage, and angle. From this equation, we can assimilate the relationship between voltage stability and angular stability.

3. MODELING

3.1. Synchronous Machine

As mentioned previously, power system stability is highly related to the fact of sustaining the synchronism between interconnected synchronous machines. Thereby, the understanding of the structure and the precise mathematical model of the synchronous machine is of great importance in the analysis of the stability.

The model of the synchronous machine consists of electrical and mechanical equations described by the block diagram of Figure 2.

In the study of angular stability, the focus attention is accorded to the behavior of the machine angles. Thus, we express the variation of rotor angle in the relations (3) and (4)[10]. These mechanical equations relate the balance between mechanical and electrical powers to the temporal evolution of the angle. In the stable state, the term $P_m - P_e$ is equal to zero so the rotor is turning with a constant angle.

$$P_m - P_e = \frac{H}{\pi f_o} \frac{d\omega}{dt} + D\omega \tag{3}$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \tag{4}$$

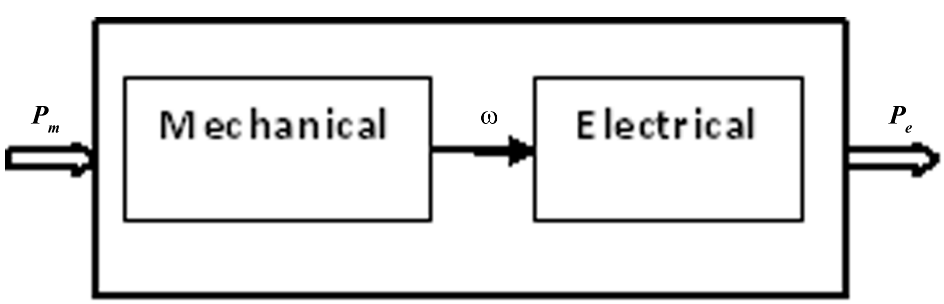

Figure 2: Block diagram of synchronousmachine.

While:

H : Inertia,

f_0 : Synchronous Frequency,

ω : Angular speed,

D : Damping factor,

P_e : Electrical power,

P_m : Mechanical power,

δ : Machine internal angle

3.2. 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. In the steady state as well as in transient regime, this device is able to maintain voltage within the desired limits.

Figure 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 (7) and (8):

$$G_{SVC} = 0 \tag{7}$$

$$y_{SVC} = jB_{SVC} \tag{8}$$

The susceptance B_{SVC} 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.

The capacitive power injection model of SVC at the rated voltage is given by equation (9):

$$Q_{SVC} = -V_N^{\,2} B_{SVC} \tag{9}$$

To control the voltage at the connection bus, SVC has to have an appropriate control system. One of the standard models recommended by CIGRE is that shown in Figure 4[11].

The transfer function of this control system is given by the equation (10):

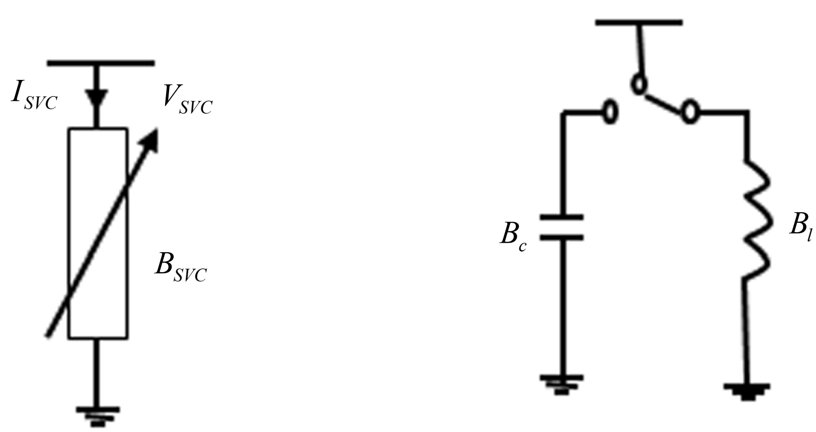

Figure 3: SVC Model.

$$H(s) = \frac{1+sT_1}{1+sT_2} \times \frac{K_R}{1+sT_R} \tag{10}$$

This system has a control module to command the voltage by comparing the measured voltage to the reference. In addition, if the network is subjected to a severe disturbance as a short circuit, the voltage level undergoes a significant drop. In this case, SVC is expected to produce a large amount of reactive power which results in a very high level of voltage after the elimination of the fault. For this reason, SVC has a control module of the susceptance according to equation (11). This module has a protective function to avoid overvoltage.

$$B_{SVC}^{\min} \le B_{SVC} \le B_{SVC}^{\max} \tag{11}$$

$B_{SVC}^{\max}$ 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.

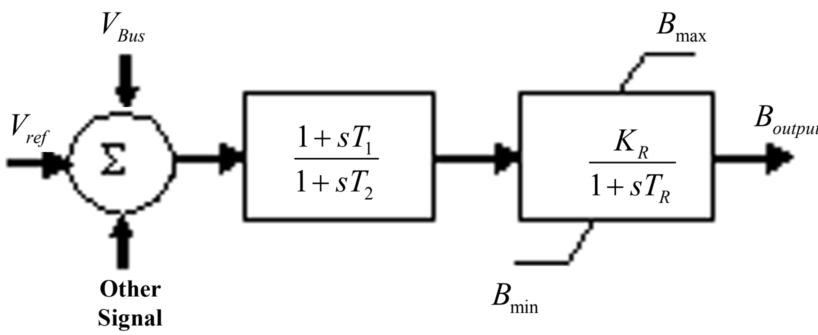

Figure 4: Voltage Regulator of SVC.

Eurostag adopts the model of Figure 4 and represents SVC as an impedance injector connected to a bus of the electrical network as shown in Figure 5.

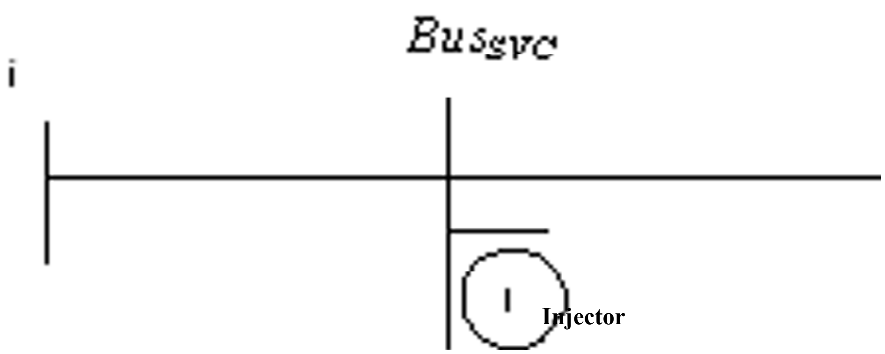

Figure 5: SVC model on Eurostag.

3. RESULTS AND DISCUSSION

3.1. Test system

We adopted the standard IEEE 14-bus network for the numerical simulations. This system contains two generators each one is equipped with voltage and speed regulators and three synchronous compensators to produce reactive power. It also has two transformers with two windings, a three-winding transformer, fifteen transmission lines and eleven loads. All data relating to our test network are extracted from the reference [12].

EUROSTAG considers the model of all generators as the voltage behind transient reactance and constant impedance to model loads and transformers.

3.2. Simulation results

In order toaccurately evaluate the influence of SVC on the stability of electrical network and to determine the limits of its operation, we opted for its implantation in a test network. We will first assess system stability by analyzing its behavior in the presence of various disturbances. We plan a severe disturbance; a short circuit occurs in a bus and a small perturbation; an incremental load increase. We are interested in the simulation results to the behavior of the machine as well as the evolution of bus voltage. Subsequently, a detailed study on the performance of SVC is performed via numerical simulations.

3.2.1. 1st Scenario: Load Increase

Firstly, we study the stability of the test network following a variation of the total load. Thus, we proceed by a gradual increase of all system loads from 5% by a step of 5% until reaching the maximum limit of the network load capacity. The disturbance is started at time t = 200s.

We noted that the load increase caused a voltage drop of all the buses except those equipped with a voltage regulator. The drop is increasingly large as the load augments. Moreover, oscillations of high amplitudes occur in the variation of rotor angles of generators, in their electrical power as well as in the temporal evolution of buses voltages. Faced with these adverse effects, the robustness of the network is more and more damaged until experiencing a total collapse for a load increase of 34%. Thus, we extracted the results of the case 33%.

The oscillatory regime of the evolution of voltage at bus1, shown in Figure 6, lasted about 30s where the highest oscillation reached a magnitude of 1.09pu. However, an increase of 2deg was observed in the variation of the rotor angle of Gen1 after several serious oscillations during 27s as shown in Figure 7.

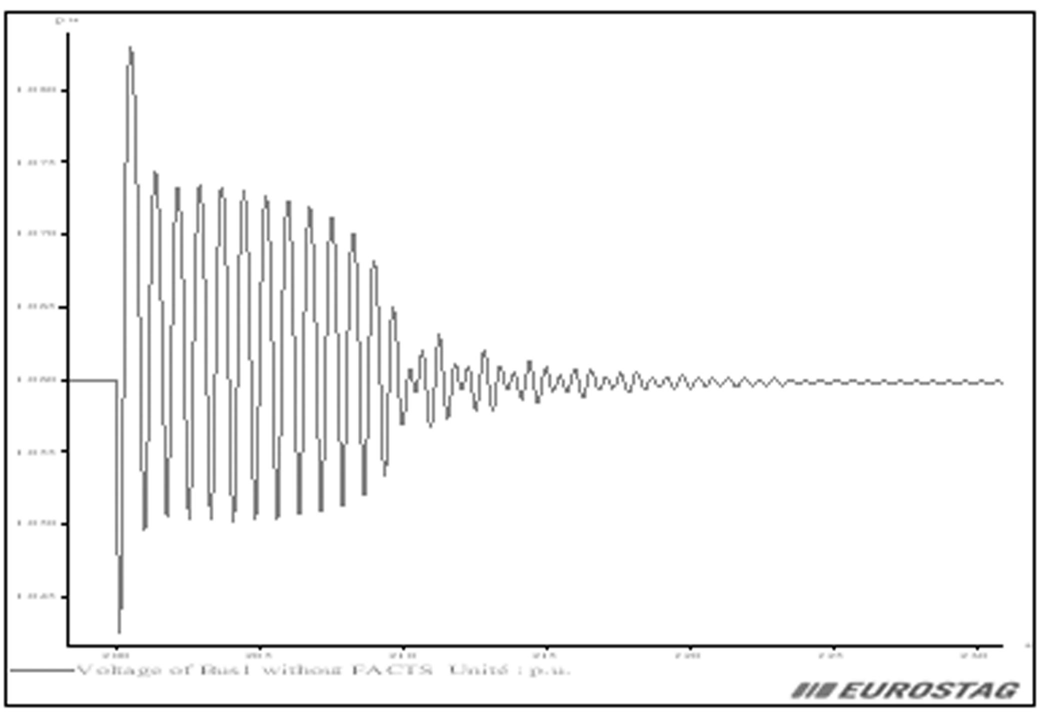

Figure 6: Temporal Evolution of voltage at bus1 for 33% of load increase.

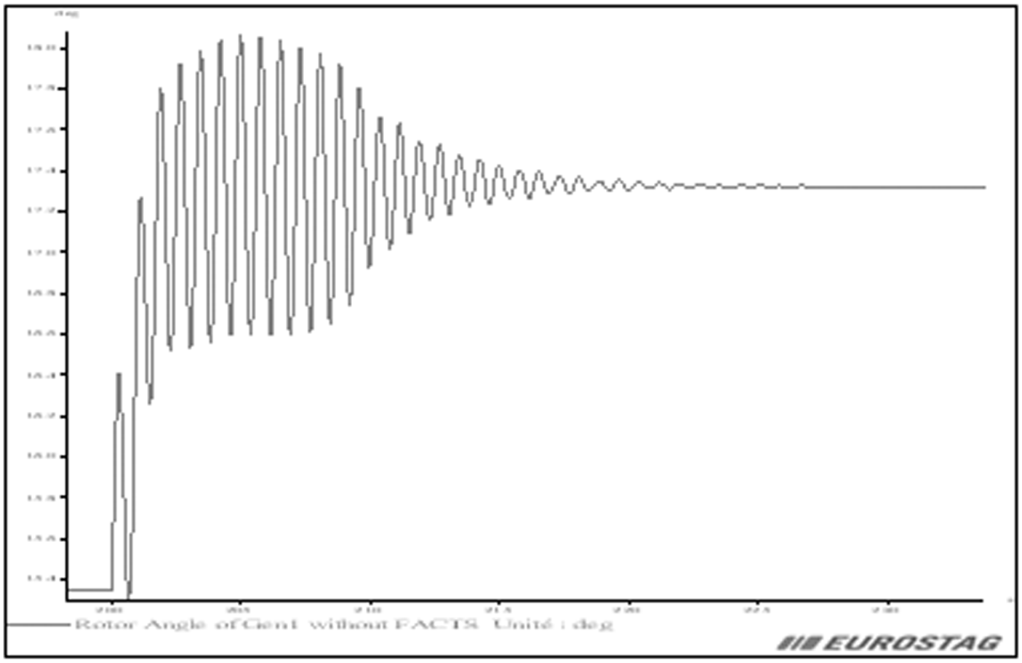

Figure 7: Rotor angle variation of Gen1 for 33% of load increase.

3.2.2. 2nd scenario: Short circuit

For purpose of highlighting the impact of short-circuit on the test network behavior, we consider a three-phase bolted short-circuit at time t = 200s, at bus1, taken as the slack bus. Then, we varied the fault clearing time with a small step to determine the critical time for which the system is instable. Table (1) summarizes the simulation results obtained for the various values of. We note that the network maintains its stability up to 300ms. Beyond this point, severe power oscillations occur and a significant increase in the rotor angle of Gen1 was observed, hence, the stability of the network is not assured. Therefore, the time limit for which the network remains stable is 300ms. The total collapse of the system happened for = 1s.

Table 1
State system test based on T_{Elim}

	Faultduration (ms)						
Network Settings	100	200	300	500	700	900	1000
δ_1 (deg)	15.3	15.35	15.4	69	70	125	
Power Oscillations	Acceptable	Acceptable	Acceptable	Serious	Serious	Serious	Collapse
State System	Stable	Stable	Stable	Instable	Instable	Instable	

Transient stability is judged by evaluating rotor angles and electrical power output before and after the fault, whereas the examination of voltage evolution is used to analyze voltage stability. Thus, we present in Figures 8, 9 and 10 respectively, the rotor angle of Gen1, its electrical power and voltage at bus1 for T_{Elim} = 200 ms; 900ms and 1000ms.

For T_{Elim} = 200ms, the angle rotor of Gen1 oscillates around its initial value with an amplitude increasingly attenuated and stabilizes at time t = 210s. The electrical power is close to zero until the fault is cleared and then it experiences a damped oscillatory regime to join after a period of 13s, its initial value. As for the voltage at bus1, it followed a similar behavior to that of power but with very slight oscillations and a voltage peak just after the isolation of the short circuit equal to 1.3pu. By increasing the duration of the fault up to 900ms, the rotor angle joined another equilibrium state after some oscillations; we noticed the same intensiveness of power oscillations with very high amplitudes while the voltage at bus1 has reached

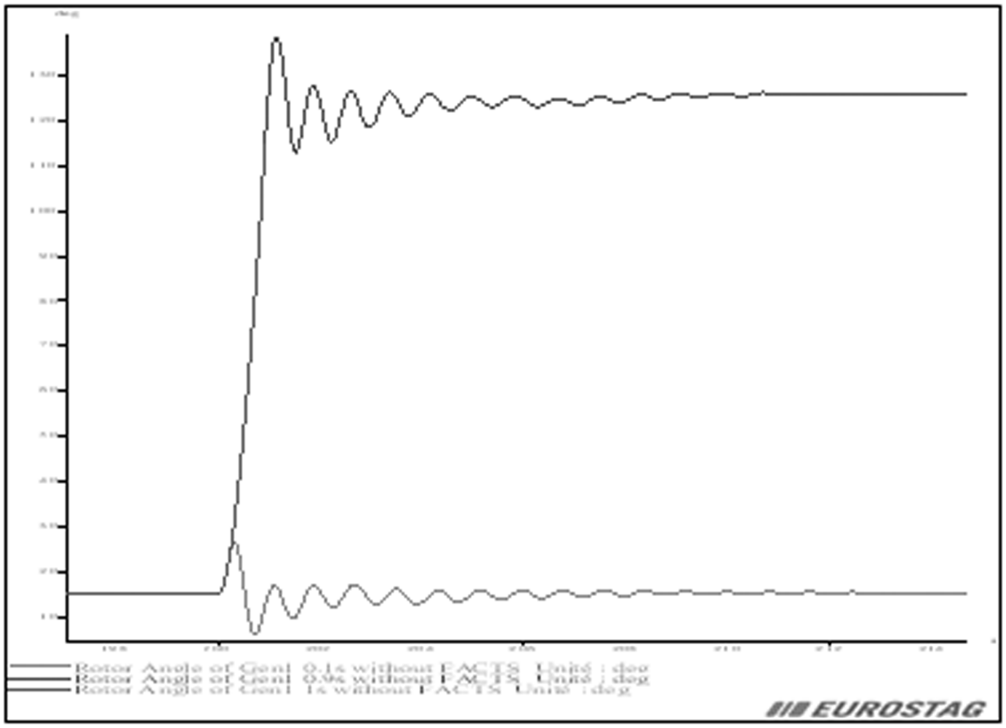

Figure 8: Temporal evolution of rotor angle in relation to.

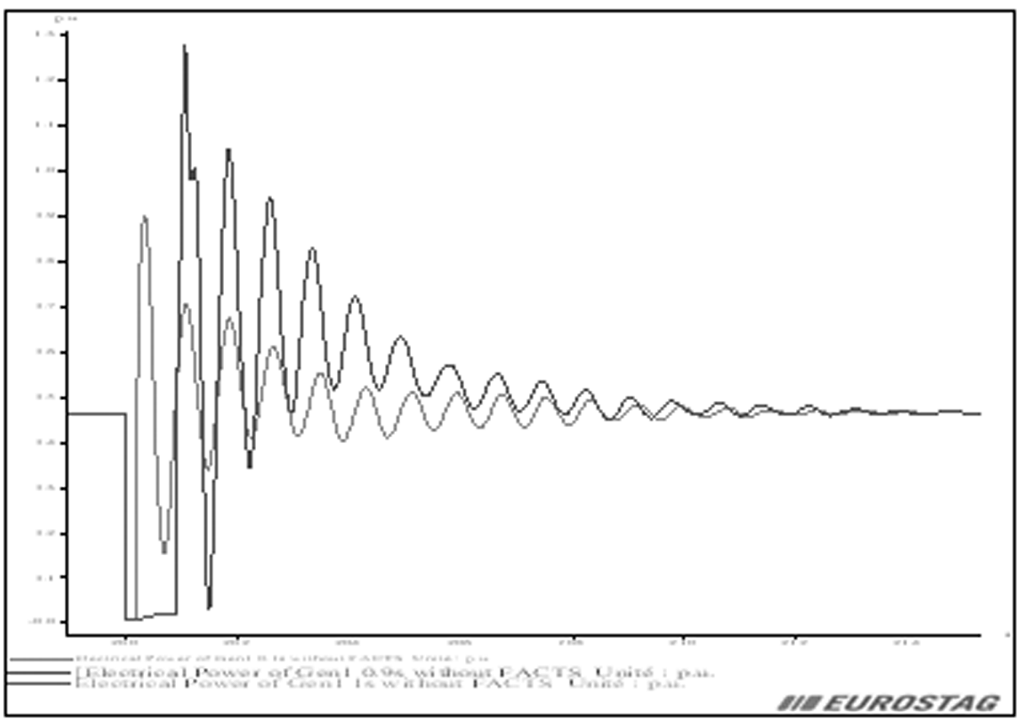

Figure 9: Temporal evolution of electrical power in relation to.

a peak of 1.8pu after an oscillatory regime during 11s. The divergence of the angle took place for the case of T_{Elim} = 1000ms where the electrical power and the voltage collapsed.

3.3. SVC Application

To determine to which extent SVC is efficient in improving the stability, we will test its operation in the presence of two fault scenarios.

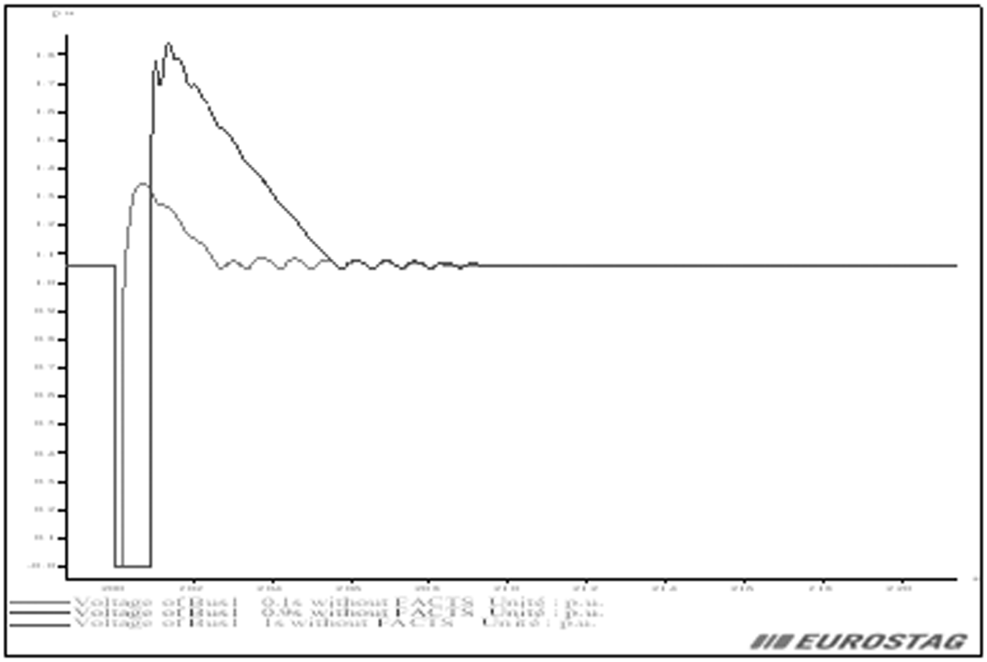

Figure 10: Evolution of bus1voltage in relation to.

Case1: Load Increase

We have considered the case of 33% of load increase identified as the limit for which the network maintains stable conditions. Then, we connected an SVC to bus1, dimensioned to.

Figure 11 illustrates the evolution in time of voltage at bus1 with and without the integration of the shunt regulator. The action of SVC is clearly distinguishable; indeed, oscillations are well damped while keeping the voltage level of the pre-disturbance. In addition, the steady state was established more quickly compared to the uncompensated system.

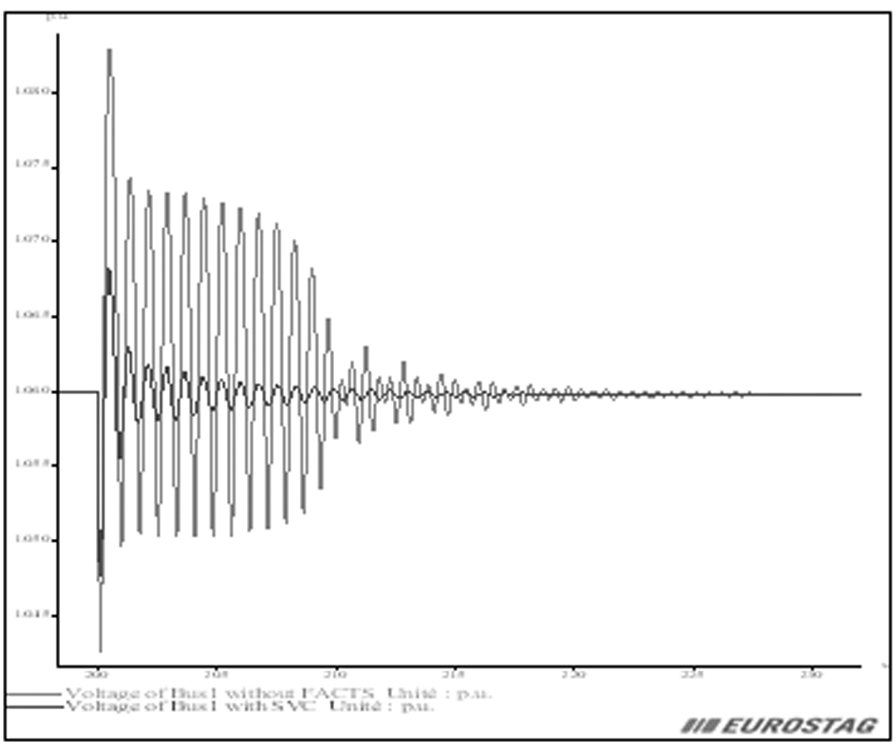

Figure 11: Evolution of bus1 voltage with and without SVC.

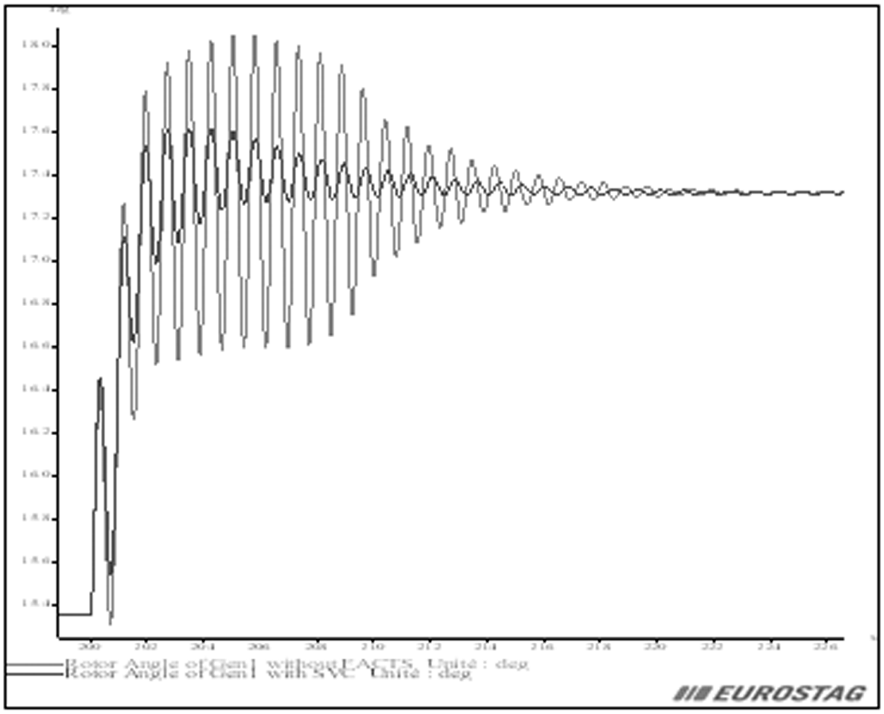

Figure 12: Temporal evolution of rotor angle with and without SVC.

It is noted likewise that the voltage drop just at the moment of the disturbance decreased from 1.042pu to 1.047pu. As for the oscillations of the rotor angle of Gen1, shown in Figure 12, they are also amortized after 20s with the action of SVC; and they regain another equilibrium state.

Similarly, in the curve of the electrical power generated by Gen1, we note a rapid and significant damping of the oscillations as shown in Figure 13.

We tested also SVC in improving the margin of network stability. To do this, we have integrated it in the case of the total collapse which corresponds to 34% of increase in load. Nonetheless, the network

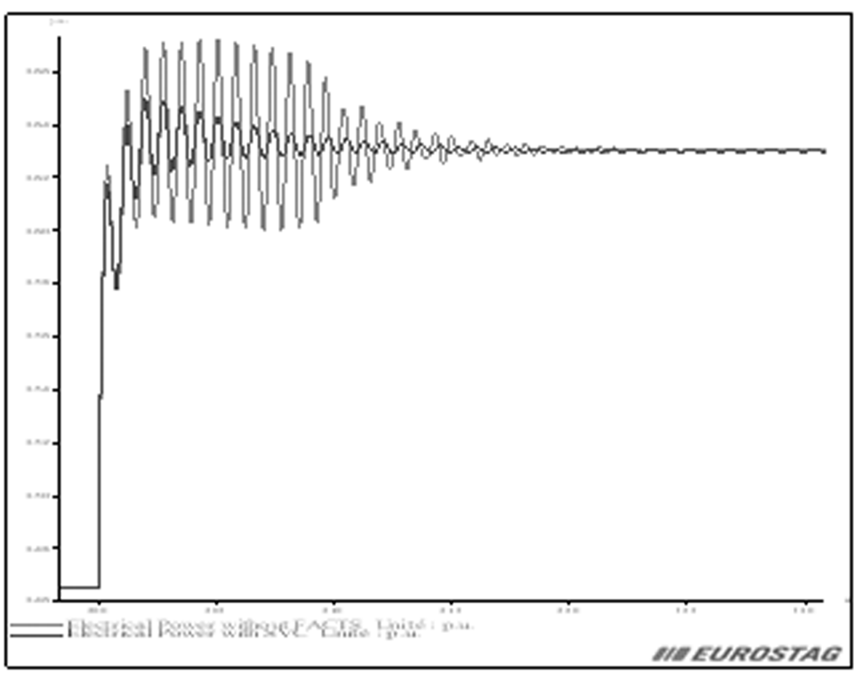

Figure 13: Temporal evolution of electrical power with and without SVC.

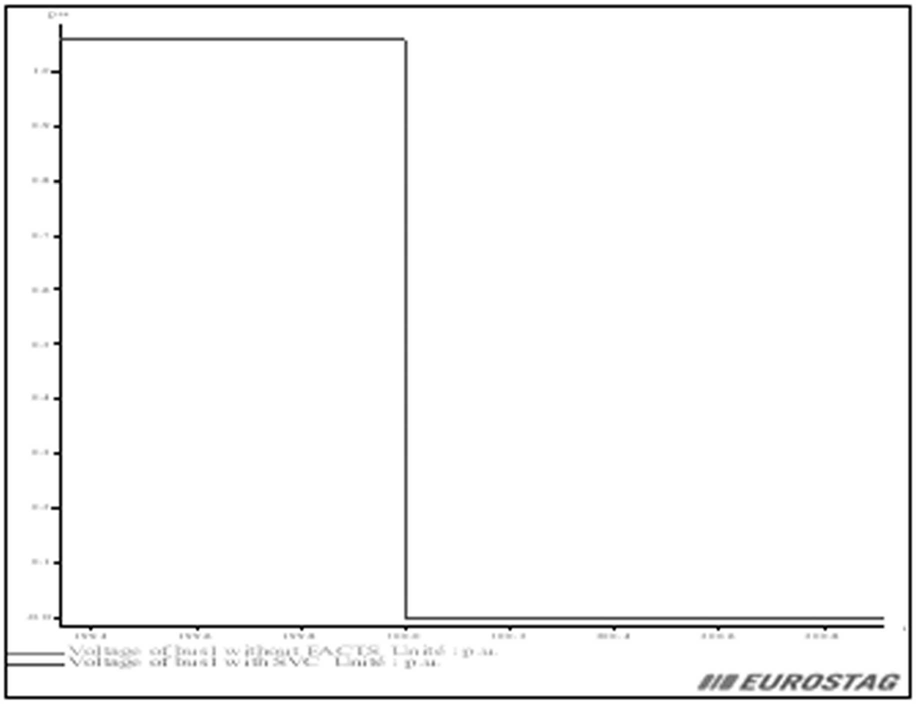

Figure 14: System collapse with and without SVC.

collapsed also despite the presence of the FACTS which explains its inability to expand the margins of power system stability. This is clearly shown in Figure 14.

Case 2: Short circuit

We applied a three-phase bolted short- circuit at bus1 for a duration of 200ms at time t = 200s. Then, to the fault bus, we connected an SVC with a capacity of [-50MVAR, + 50MVAR]. The results describing the state of the disturbed system before and after incorporating the FACTS are presented below.

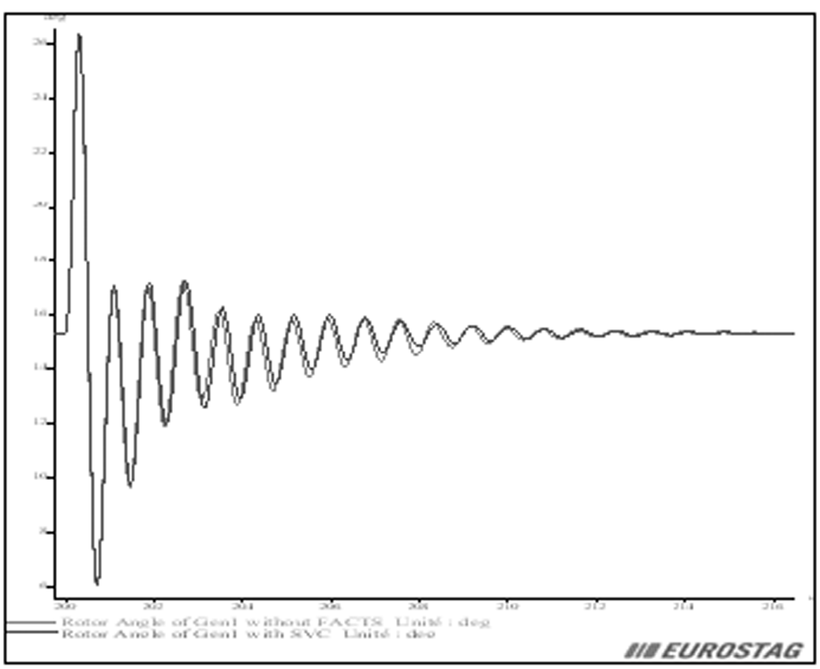

Figure 15: Electrical power of Gen1 after a short circuit with and without SVC.

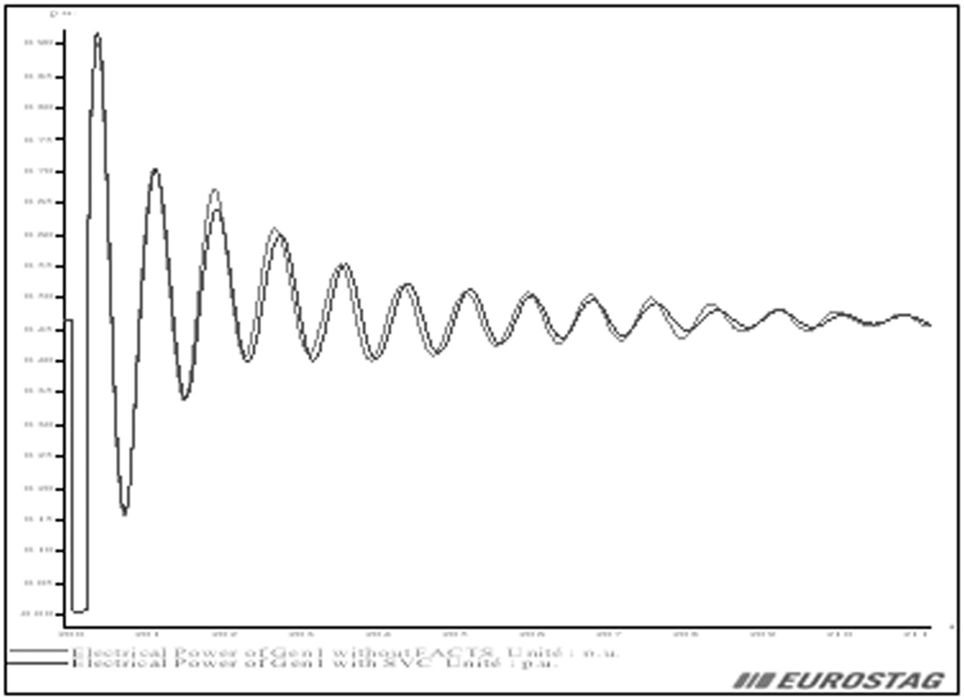

Figure 16: Rotor angle of Gen1 after a short circuit with and without SVC.

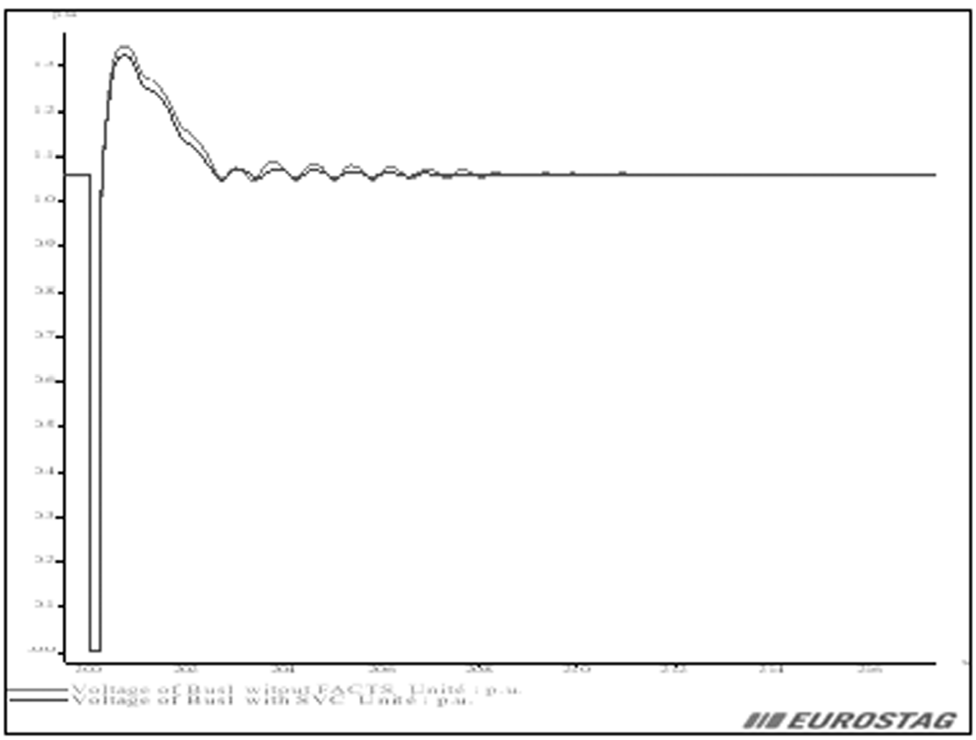

Figure 17: Voltage of bus1 after a short circuit with and without SVC.

Figure 15 shows the electrical power generated by Gen1, we note that the oscillations persist with the same amplitudes even with the presence of SVC while for the evolution of the rotor angle illustrated in Figure 16; the oscillations are slightly damped after the action of the shunt controller.

The damping of the oscillations using SVC is better appreciated in the temporal variation of bus1 voltage, shown in Figure 17. However, the improvement achieved remains very limited and no minimizing of voltage drop at the fault moment was noticed.

4. CONCLUSION

This work focused on the assessment of SVC operation. We have demonstrated through simulations that the effectiveness of this device is not absolute; it is highly dependent on the nature of the fault suffered by the system. Indeed, if it is a small disturbance such as a load variation, SVC provides a proper reactive power support to efficiently stabilize the system. It ensures a good damping of the oscillations of rotor angle, of electrical power as well as of voltage while maintaining the voltage level within the permissible limits. However, it turned out that it is no longer able to improve the margin of the system load capacity. Moreover, in the case of a severe fault as short-circuit; the action of SVC is very limited; the damping of the oscillations is hardly distinguishable either in the behavior of the machine or in the evolution of bus voltage. We propose in our further work to introduce other types of FACTS more efficient in improving power system stability.

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