Optimal Location of Facts Devices to Enhance the Voltage Stability and Power Transfer Capability

[1] Mahmoud H. M ; M. A. Mehanna[2] and S. K. Elsayed[2]

[1.] Managing Director of Information System with the Egyptian Electricity Holding Company
[2.] Electrical Engineering Department, Faculty of Engineering, AL-Azhar University
engsasa2005@yahoo.com

Abstract: This paper focuses on increasing stability and maximum loadability of a system by considering the optimal location of Flexible AC Transmission Systems (FACTS) devices in multimachine power system. Identification of a suitable location for installation of (FACTS) costly device is a vital task; several criteria are to be satisfied before selecting the best location .Two types of (FACTS) devices, static var compensator (SVC) and thyristor controlled series compensator (TCSC) can be installed on buses and transmission lines respectively. Improving the system's reactive Power handling capacity via (FACTS) devices is a remedy for prevention of voltage instability and hence voltage collapse using continuation power flow (CPF) method to find the best location of shunt (FACTS) device then evaluate the effect of this device on the system . Also the continuous change in power demand and supply altered the power flow patterns in transmission networks which raise serious challenge in operating the power system, to prevent this problem series (FACTS) is used, using optimal power flow (OPF) method to find best location then evaluate the effect of this device on the system by using (CPF) method. It will perform the control of power flow with (FACTS) devices on the test system and also the time domain simulation for three phase fault applied, the simulation is made without and with (FACTS) devices. The effectiveness of the method is tested and illustrated on IEEE 14-bus system. Power System Analysis Toolset (PSAT), a computational tool under Matlab program for effective simulation and monitoring is used.

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Key Wards: FACTS, SVC, TCSC, CPF, OPF, Hopf Bifurcations, Lodability Margin.

1. Introduction

The phenomena of voltage collapse have been observed in power systems and analyzed extensively during the two past decades. Many analysis methods have been proposed and currently used for the study of this problem [1-3]. Most of these techniques are based on the identification of system equilibrium where the corresponding Jacobins become singular. These equilibrium points are typically refers to as points of voltage collapse and can be mathematically associated to saddle-node bifurcation [4 - 5]. There are two types of voltage stability based on simulation time; static voltage stability and dynamic voltage stability. With continuous increase in power demand, and due to limited expansion of transmission system, modern power system networks are being operated under highly stressed conditions. Traditionally shunt and series compensation is used to maximize the transfer capability of a transmission line [6]. Recently the new concept of (FACTS) was developed by Electric Power Research Institute (EPRI), which involves a family of fast acting, high power electronic devices, with advanced and reliable controls. By using (FACTS) controllers one can control the variables such as voltage magnitude and phase angle at chosen bus and line impedance [7].

This paper presents an approach of obtaining optimal location of two types of (FACTS) devices based on (CPF) and (OPF) methods. The optimal location of shunt (FACTS) such as static var compensators (SVC) at (critical voltage bus) which Based on (CPF) analysis (the weakest voltage bus) is targeted as the first location for an (SVC). The optimal location of series (FACTS) devices such as thyristor controlled series capacitors (TCSC) in deregulated electricity market to reduce the congestion and/or system losses based on the use of local marginal price (LMP) differences [8].

When a system becomes congested, the effects are reflected in the prices and (LMP) increases. The difference in (LMP) across an interface gives a measure of degree of congestion across the link. Higher is the difference in LMP, the more the link is congested. Either the congested link or the neighborhood lines are the potential locations for installing series (FACTS) devices to reduce the level of congestion. Optimal power flow (OPF) tool has also been used in deregulated electricity markets to calculate generation dispatch and load schedules, to price energy (nodal pricing or LMP). A priority list is formed based on the magnitude of the difference in LMPs. For each line in the priority list, run (CPF) with (TCSC) in that line, the best location of (TCSC) is the one where by placing (TCSC) gives highest maximum loading point .

For small perturbation, one can determine the available Static Margin (SM), which is the maximum loading level beyond which steady state solutions cannot be obtained for the system. This is accomplished by obtaining full P-V curves for normal and emergency (e.g. line outages) conditions. On these P-V curves, Dynamic Margins (DM), which are typically the loading levels at which the system presents oscillatory instabilities associated with Hopf bifurcations, are also depicted. The ability of the system to maintain a stable operation condition under large perturbations (e.g. line outages) at different loading conditions is typically studied using time domain simulation tools.

2. Power System Modeling

Power systems are modeled by a set of differential and algebraic equations (DAE), i.e.

$$\dot{X} = F(X, Y, \lambda, P) \qquad (1)$$
$$0 = g(x, y, \lambda, p)$$

Where $X \in \Re^N$ is a vector of state variables associated with the dynamic states of generators, loads, and other system controllers; $Y \in \Re^M$ is a vector of algebraic variables associated with steady-state variables resulting from neglecting fast dynamics (e.g. most load voltage phasor magnitudes and angles); $\lambda \in \Re^L$ is a set of uncontrollable parameters, such as variations in active and reactive power of loads, stands for a set of parameters that slowly change in time, so that the system moves from one equilibrium point to another until reaching the collapse point; and $P \in \Re^K$ is a set of controllable parameters such as tap and automatic voltage regulator (AVR) settings, controller Reference voltages and shunt and series compensation levels. The system model can be reduced by the term;

$$\dot{X} = f(x, h(x, \lambda), \lambda, p) = S(x, \lambda, p) \qquad (2)$$

A saddle node bifurcation of the system eq.(2) occurs when the Jacobin $D_X S(X, \lambda, P)$ is singular at equilibrium point (X_0, λ_0, P_0) where two solutions of the system, stable and unstable, merge and then disappear as the parameter λ, i.e. system load changes. At the bifurcation point (X_0, λ_0, P_0), the Jacobin $D_X S(X, \lambda, P)$ has a simple and unique zero Eigen values with normalized right eigenvector V and left eigenvector W [5].

$$D_X S(X_0, \lambda_0, P_0)V = 0 \longrightarrow (3)$$
$$w^t D_X S(X_0, \lambda_0, P_0)V = 0^t \longrightarrow (4)$$
$$w^t \tfrac{dS}{d\lambda} \, at \, (X_0, \lambda_0, P_0) \neq 0 \longrightarrow (5)$$
$$w^t [D_X^2 S(X_0, \lambda_0, P_0)V]V \neq 0 \longrightarrow (6)$$

The above equations guarantee quadratic behavior near bifurcation point and are used to determine the voltage collapse point [5]. The eigenvectors at the bifurcation point provide information on the areas prone to voltage collapse and the control strategies to most effectively prevent this problem. For a given set of controllable parameters P, voltage collapse studies usually concentrate on determining the collapse or bifurcation point $(X_0, Y_0, \lambda_0, P_0)$ where λ typically corresponds to the maximum loading level or loadability margin in P.U., %, MW or MVA depending on how the load variation are defined [9].

3. Continuation Power Flow

The main purpose of Continuation Power Flow is to find the continuity of power flow solution for a given load change .Continuation methods overcome certain difficulties of successive power flow solution methods, as they are not based on a particular system model, and allow the user to trace the complete voltage profile by automatically changing the value of λ; without having to worry about singularities of system equations. The strategy used in these methods is shown in Fig.1. [10]. It starts from a known solution and uses a tangent predictor to estimate a subsequent solution corresponding to a different value of the load parameter. This estimate is then corrected using the same (NR) technique employed by a conventional power flow. A detailed description of these techniques is referred to Kundur [11].

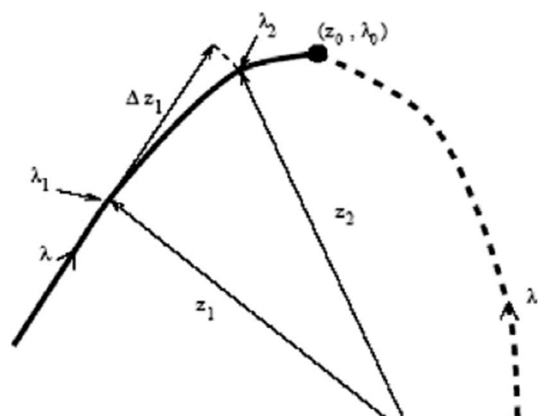

Fig.1. Continuation method

4-Dynamic Analysis

Dynamic voltage stability is analyzed by monitoring the Eigen values of the linearized system as a power system is progressively loaded. When the λ parameter varies, the equilibrium points of the dynamic system also vary accordingly, and so do the Eigen values of the corresponding state matrix Λ_{SYS} as shown in Fig.2. Equilibrium points are asymptotically stable if all the Eigen values have negative real parts. The point where a complex conjugate pair of Eigen values reaches the imaginary axis with respect to changes in λ is known as Hopf Bifurcation point. Which is a local bifurcation in which a fixed point of a dynamical system loses stability as a pair of complex conjugate Eigen values of the linearization around the fixed point cross the imaginary axis of the complex plane? [12-13]. If this particular dynamic problem is studied using gradual changes it can be viewed as Hopf bifurcation problem. Thus by predicting these types of bifurcations well in advance, a possible dynamic instability problem may be avoided.

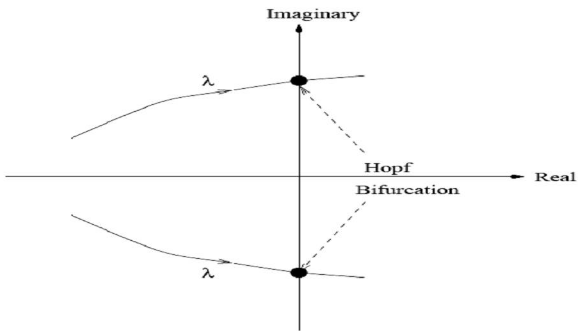

Fig.2. Hopf Bifurcation Point

5. SVC MODEL

The main job of a SVC is to inject a controlled capacitive or inductive current so as to maintain or control a specific variable, mainly bus voltage [14]. The basic structure of an SVC operating under typical bus voltage control is depicted in the block diagram of Fig.3. [15]. Each phase of this FACTS controller is typically made up of a thyristor-controlled reactor (TCR) in parallel with a fixed capacitor bank (FC); the system is then shunt connected to the bus through a step-up transformer bank to bring the voltages up to the required transmission levels. (This transformer will be treated similarly to the other transformers in the system).

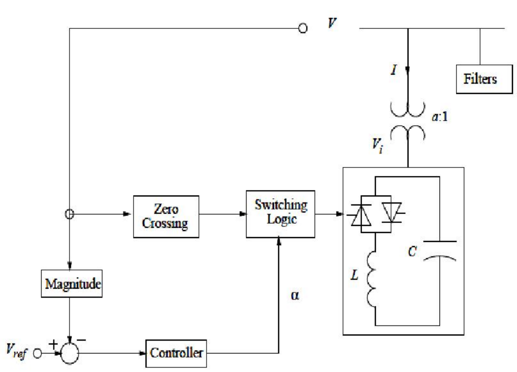

Fig.3. Basic SVC structure with voltage control

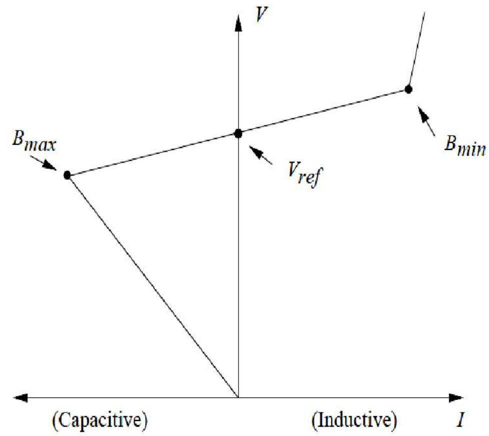

Fig.4. Typical steady state V – I characteristic of a SVC.

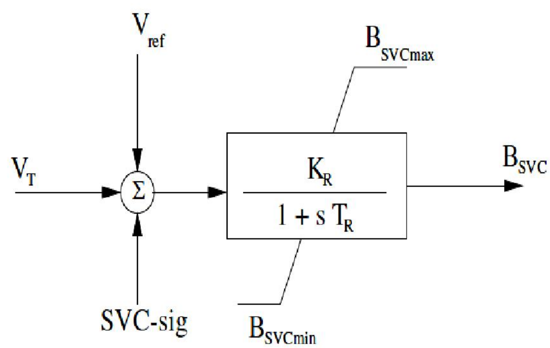

Fig.5. Block diagram of an SVC used in PSAT.

A basic structure of a SVC with voltage control and its steady state control characteristic, respectively, for an FC-TCR type SVC is shown in the Fig.4. [16]. The SVC is typically modeled using a variable reactance with maximum inductive and capacitive limits as in Fig.5., which directly correspond to the limits in the firing angles of the thyristors. In addition to the main job of the (SVC) controller, which is to control the SVC bus voltage, the reactance of the (SVC) controller may be used to damp system oscillations, as denoted in Fig. 4.by “SVC-sig”.

6. TCSC Model

A TCSC controller is basically a TCR in parallel with a bank of capacitors. The series impedance of a high voltage transmission line is usually inductive, with large X/R ratio. With the introduction of a controllable series capacitor or reactor in series with the transmission line, the line impedance can be varied continuously, below or above its nominal value. Fig.6. shows the block diagram for a TCSC controller operating under current control [15]. The general structure of the stability controller is shown in Fig.7. [17]. It Consists of a washout filter, a dynamic compensator, and a limiter. The washout filter is used to avoid a controller response to the dc offset of the input signal. The dynamic compensator consists of two (or more) lead-lag blocks to provide the necessary phase-lead characteristics. Finally, the limiter is used to improve controller response to large deviations in the input signal.

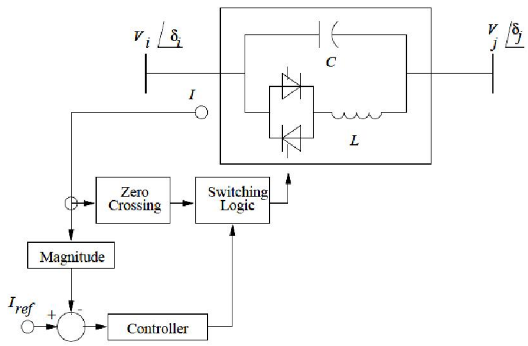

Fig. 6. Basic TCSC structure.

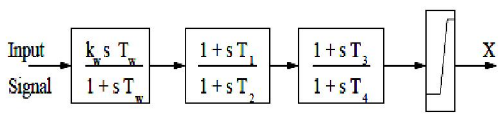

Fig.7 Block diagram of the TCSC stability control loop.

7. Validations Studies

7.1 Test system

The IEEE14- bus test system is used for the objective of these studies.

Fig.8 depicts the single line diagram of the IEEE 14 bus test system used in this paper. It consists of 14 buses, 20 branches, three transformers, and five synchronous machines. The generators are molded as standard PV buses with both P and Q limits; loads are represented as constant PQ loads.

7.2 Tools

PSAT is power system analysis software, which has many features including power flow and continuation power flow [18] .Using continuation power flow feature of PSAT, voltage stability of the test system is investigated.

7.3 Simulation Results

7.3.1 Base case

The behavior of the test system with and without FACTS devices under- different loading conditions is studied. The location of the FACTS controllers is determined through bifurcation analysis. Voltage stability analysis is performed by starting from an initial stable operating point and then increasing the loads by a factor λ until Singular point of power flow linearization is reached. Fig.9 represents three lowest bus voltage magnitudes at bus 14, bus 13 and bus 10. Single emergency were given in the system and it is observed as the severity of the emergency decreases, the static margin (SM) increases. 1-2 contingency was the most severe case followed by 5-6, 7-9, 3-2 and 1-5 (these being top five) based on (CPF) method. Table 1. illustrates the dynamic margin (DM) and static margin (SM) associated with P-V curves shown in Fig. 10, the base case and for line 7-9 and line 5-6 outages.

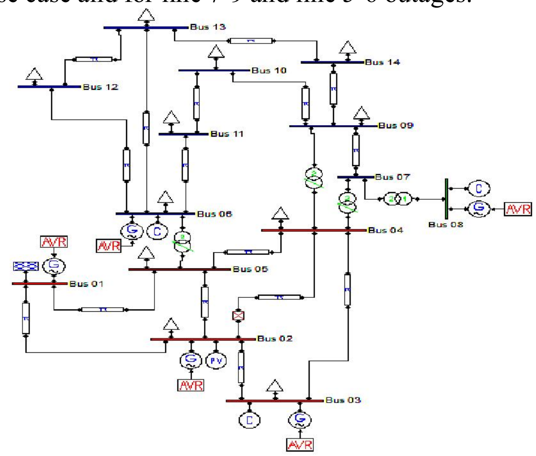

Fig.8 Single line diagram of IEEE 14 bus test

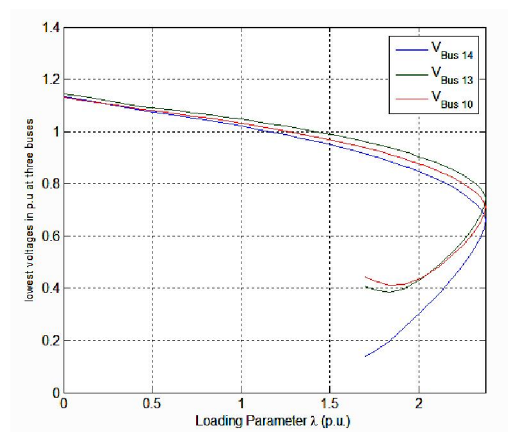

Fig.9 P-V curves for the three lowest bus voltages magnitudes

Table 1: Dynamic and Static Margins for Base case System

	Normal operating	Line outage 7-9	Line outage 5-6
SM	2.37	1.85	1.72
DM	1.53	1.45	1.34

To study the behavior of the system under large perturbations, a time Domain simulation was performed for a line 5-6 outage at the operating point defined by **λ** = 1.6 where A short circuit fault happens at Bus 5 at t =1.s. The fault is cleared at 1, 08 s by opening the faulted line. Thus, Fig.11 and Fig.12 shows the corresponding time domain simulation results. From these figures, one can conclude that line 5-6 outage leads the system to an oscillatory unstable condition.

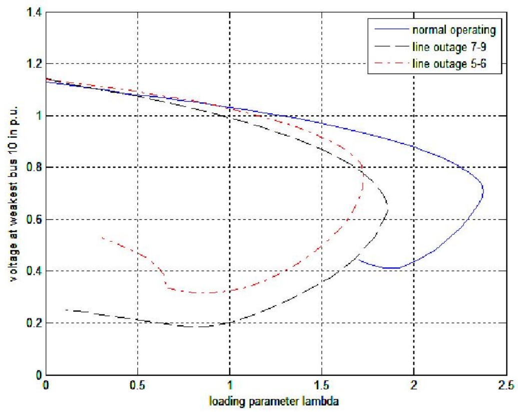

Fig.10 P-V curves at bus 10 for different emergencies.

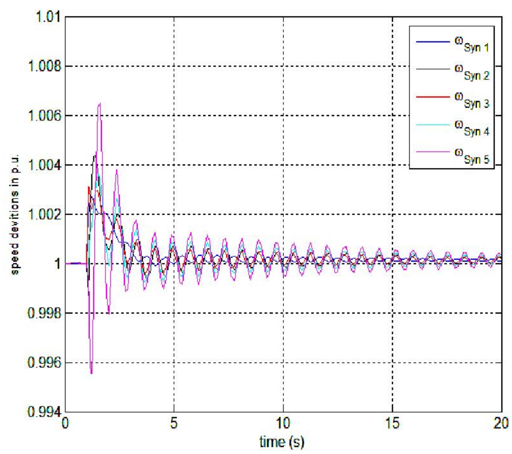

Fig.11 generator speed oscillation due to line 5-6 outage at **λ**=1.6 p.u.

7.3.2 Simulation with svc

Based on collapse analysis bus 10 is targeted as the first location for an SVC, to show the effect of this controller on the system the results of locating the SVC at the desired.

Bus are depicted in the fig.13 for voltage profile at the base case, line 7-9 and Line 5-6 outages. The new maximum loading level in this condition is **λ** = 2.65. Also Table 2 illustrates the dynamic margin DM and static margin SM associated with P-V curves shown in Fig. 13. It is clear that The SM and DM has increased in all cases and that the voltage profiles are also improved by the introduction of the controller**.** A time Domain simulation was performed for a line 5-6 outage at the operating point defined by **λ** = 1.6. Thus, Fig.14 and Fig.15 shows the corresponding time domain simulation results. From these figures, one can conclude that for line 5-6 outage with SVC at the suggested bus this leads to improving for the system to an oscillatory condition.

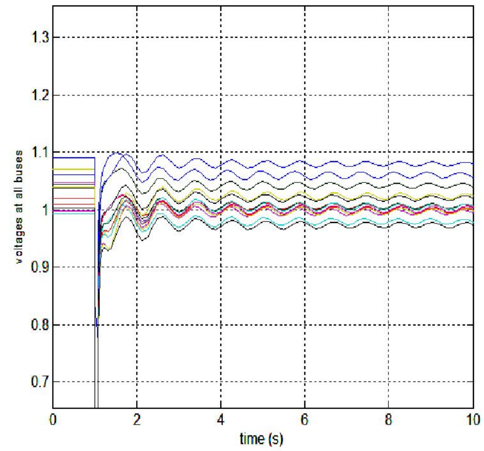

Fig.12 Voltages at all buses due to line 5-6 outage at **λ**=1.6 p.u

Table 2: Dynamic and Static Margins for System with svc

	Normal operating	Line outage 7-9	Line outage 5-6
SM	2.65	2.55	2.34
DM	1.63	1.61	1.43

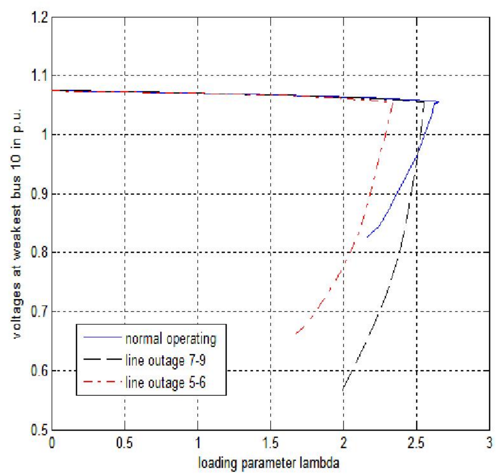

Fig.13. P-V curves at bus 10 for different emergencies with svc at bus 10.

7.3.3 Simulation with tcsc

The TCSC is used to compensate the line that presents the largest increase in power at the point of collapse. So, the selection of TCSC location is based on maximum power increase at the collapse point with respect to normal operation in the system. For the test system the best location in series with line 1-5, is used for the studies presented here based on the theory [the best line is the more congested line. The results of locating the TCSC in the desire line are depicted in the Fig.16 for voltage profile at the base case, line 7-9 and line 5-6 outages. The new maximum loading level in this condition is **λ** = 2.91. Table3 illustrates the dynamic margin DM and static margin SM associated with P-

V curves shown in Fig. 16. It is clear that The SM and DM have increased in all cases and that the voltage profiles are also improved by the introduction of the controller**.** A time Domain simulation was performed for a line 5-6 outage at the operating point defined by **λ** = 1.6. Thus, Fig.17 and Fig.18 shows the corresponding time domain simulation results. From these figures, one can conclude that for line 5-6 outage with TCSC at the suggested line this leads to improving for the system to an oscillatory condition.

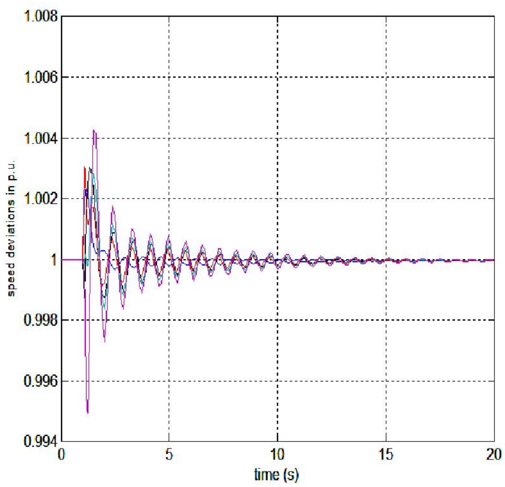

Fig.14 generator speed oscillation due to line 5-6 outage at **λ**=1.6 p.u. With svc at bus 10

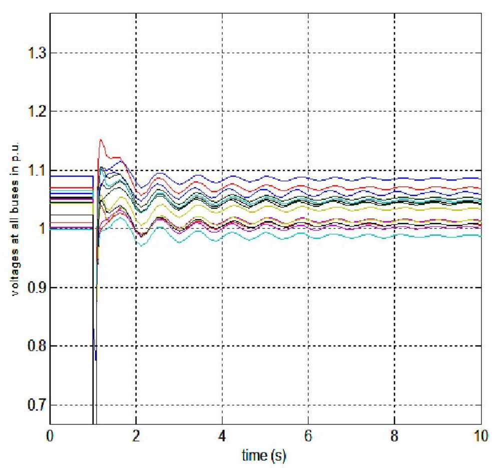

Fig.15 Voltages at all buses due to line 5-6 outage at **λ**=1.6 p.u. With svc at bus 10

Table 3: Dynamic and Static Margins for System with tcsc

	Normal operating	Line outage 7-9	Line outage 5-6
SM	2.91	2.08	1.85
DM	1.67	1.57	1.47

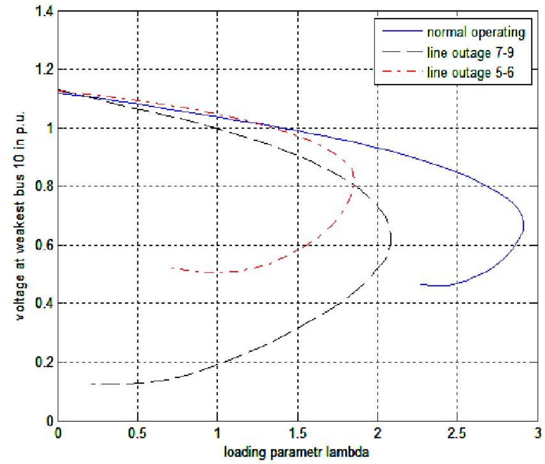

Fig.16 P-V curves at bus 10 for different emergencies with tcsc in line 1-5.

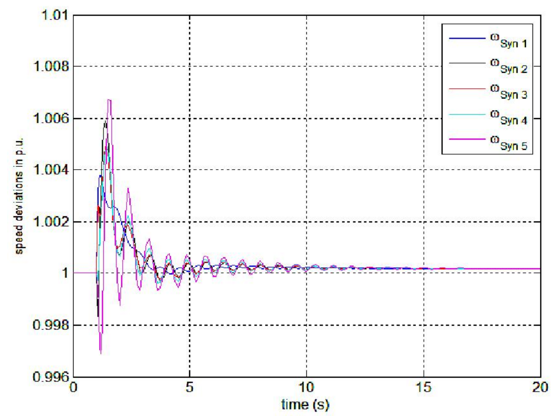

Fig.17 generator speed oscillation due to line 5-6 outage at **λ**=1.6 p.u With tcsc in line 1-5

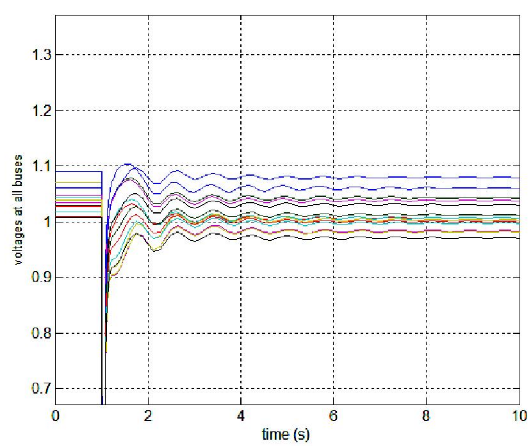

Fig.18 Voltages at all buses due to line 5-6 outage at **λ**=1.6 p.u. With tcsc in line 1-5

8. Conclusion

FACTS devices prove to be an effective remedy in enhancing system voltage stability. And increase maximum loadability margin, but due to high cost of

(FACTS) controllers their placement should be such as to improve both static and dynamic voltage stability. This paper show the optimal placement of (FACTS) devices and the effect of insertion series and shunt (FACTS) devices such as (SVC) and (TCSC) on static and dynamic voltage stability enhancement. The results also presented in this paper clearly show how (SVC) and (TCSC) can be used to increase system loadability in practical power systems. The reactive power requirement of the system may increase under severe contingencies. Therefore, contingency ranking based on Static voltage stability criterion, can be obtained based on the extra reactive support requirement from existing sources. Based on simulation results obtained in the paper can conclude that, (SVC)can increase system loadability or margin to voltage collapse also the dynamic voltage stability will be improved as seen from time domain simulation . The simulation results indicate that TCSC's reactance compensation control strategy can increase maximum loading level in the system. Clearly, results shows that the effect of the (TCSC) controller on the dynamic performance of the test system. Although the system is stable, there is a lightly damped oscillation that could be improved by retuning the controller.

Corresponding author
S. K. Elsayed
Electrical Engineering Department, Faculty of Engineering, AL-Azhar University
engsasa2005@yahoo.com

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