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Enhancement of Transient Stability in a Deregulated Power System using Facts Devices

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ENHANCEMENTOFTRANSIENTSTABILITYINADEREGULATEDPOWERSYSTEMUSINGFACTSDEVICES

Strictly as per the compliance and regulations of :

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J. Srinivasa Rao [α] & J. Amarnath [σ]

Abstract- In a deregulated power system, the electric power demand is increasing day to day which may lead to overloads and loss of generation. Transient stability studies place an important role in power systems, which provide information related to the capability of a power system to remain in synchronism during major disturbances resulting from either the loss of generation or transmission facilities, sudden or sustained load changes. The analysis of transient stability is very important to operate the power system more secure and this paper focuses on increasing the transient stability [1] using FACTS devices like TCSC (Thyristor Controlled Series Capacitor), TCPAR (Thyristor Controlled Phase Angle Regulator), SVC (Static Var Compensator). These FACTS devices are optimally placed on transmission system using Sensitivity approach method. The proposed method is to enhance the transient stability on Modified IEEE-14 bus system and IEEE-24 bus system Using Power World Simulator 17 software.

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I. Introduction

In a deregulated power system structure, customers share a common transmission network for wheeling power from the point of generation to the point of consumption. All parties in this open access environment may try to produce the energy from the cheaper source for greater profit margin. It may lead to overload of the power system. This may result in violation of stability limits and thereby undermine the system security. Transient stability of a system refers to the stability when subjected to large disturbances such as faults and switching of lines. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship.

Transient stability [2] studies place an important role in power systems, which provide information related to the capability of a power system to remain in synchronism during major disturbances resulting from either the loss of generation or transmission facilities, sudden or sustained load changes, in the voltages, currents, powers, speeds and torques of the machines of the power systems as explained.

FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to enlarge the decelerating area and hence improving the first swing stability limit of a system. Due to FACTS device placement in the main power transfer path of the critical machine, the output power of the machine and hence its first swing stability limit can be increased by operating the FACTS device at its full capacitive rating. Control strategy was proposed based upon local input signals can be used for series and shunt compensator devices to damp power swings. Using the proposed control strategies [8], the series and shunt connected compensators can be located in several locations.

Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges being presented today. Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR) and Static VAR Compensator (SVC) are used for enhancement of Transient Stability using Sensitivity based methods.

II. Structure of Regulated and Deregulated Systems

The former vertically integrated utility, which perform all the functions involved in power,(i.e., generation, transmission, distribution and retail sales) known as regulated system, is dis-aggregated in to separate companies devoted to their functions called as Deregulated system.

The main aim of restructuring [6] the power market is as follows:

- To secure that all reasonable demands for the electricity are met.
- Promote competition in the generation and supply of electricity.
- Protect the interests of electricity customers in respect to prices charged, continuity of supply and the quality of services provided.
- Promote efficiency and economy on the part of licensees in supplying and transmitting electricity.

The following figure-1 shows the typical structure of regulated power system which is simply vertically integrated where the cash flow is uni-directional from consumers to electric utility.

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Figure 1 : Typical Structure of Regulated Electricity System

For developing countries, the main issues have been a high demand growth coupled with inefficient system management and irrational tariff policies. This has affected the availability of financial resources to support investments in improving generation and transmission capacities.

The goal of changing the way of operation, i.e., re-regulation or de-regulation, as we say, is to enhance competition and bring consumers new choices and economic benefits.

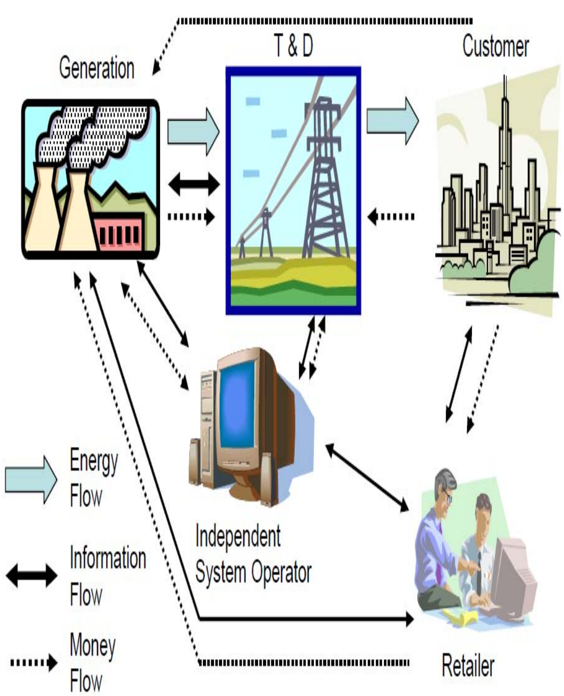

Figure 2 : Typical Structure of Deregulated Electricity System

In a deregulated system a system operator is appointed for the whole system and it is entrusted with the responsibility of keeping the system in balance, i.e. to ensure that the production and imports continuously match consumption and exports. Different power sellers will deliver their product to the customers (via retailers), over a common set of T and D wires, operated by the independent system operator (ISO). The generators, T and D utility and retailers communicate with the ISO.

III. Facts Controllers

a) Thyristor Controlled Series Compensator (TCSC)

Thyristor Controlled Series Capacitor (TCSC) is a capacitive reactance compensator which consists of a series of capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.

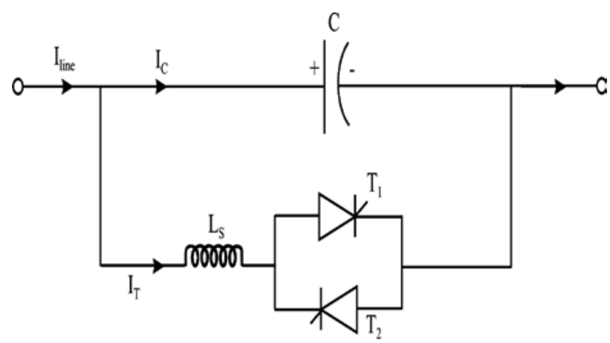

Figure 3 : Thyristor Controlled Series Capacitor

The impedance characteristics of TCSC shows, both capacitive and inductive region are possible though varying firing angle (α).

- $90 < \alpha < \alpha$Llim Inductive region
- αClim $< \alpha <180$ Capacitive region
- αLlim$< \alpha < \alpha$Clim Resonance region

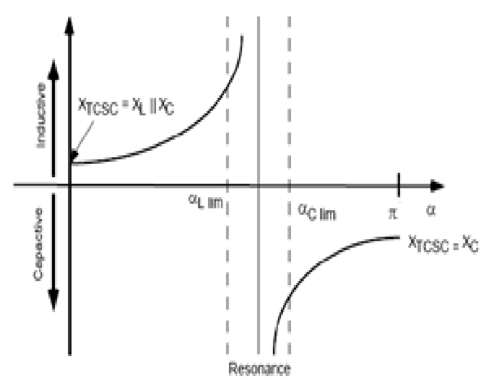

Figure 4 : Variation of impedance in case of TCSC

i. *Static Modelling*

The Figure shows a simple transmission line represented by its lumped pi equivalent parameters connected between bus-i and bus-j. Let complex voltage at bus-i and bus-j are Vi $<$ δi and Vj $<$ δj respectively. The real and reactive power flow from bus-i to bus j can be written as [5] :

$$P_{ij} = V_1^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \quad (3.1)$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] \quad (3.2)$$

Where δij = δi-δj, similarly the real and reactive power flow from bus-j to bus-i is;

$$P_{ji} = V_1^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \quad (3.3)$$

$$Qj_{ji} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] \quad (3.4)$$

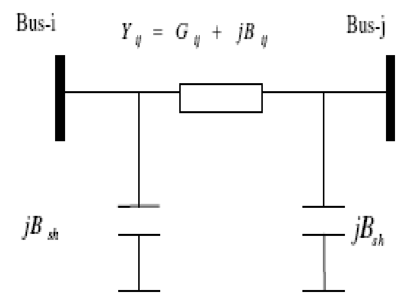

Figure 5 : Model of Transmission line

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Fig. During the steady state the TCSC can be considered as a static reactance -jXc. The real and reactive power flow from bus-i to bus-j, and from bus-j to bus-i of a line having series impedance and a series reactance are,

$$P_{ij}^C = V_i^2 G_{ij}^{'} - V_i V_j (G_{ij}^{'} cos\delta_{ij} + B_{ij}^{'} sin\delta_{ij}) \quad (3.5)$$

$$Q_{ij}^C = -V_i^2 (B_{ij}^{'} + B_{sh)} V_i V_j (G_{ij}^{'} sin\delta_{ij} - B_{ij}^{'} cos\delta_{ij}) \quad (3.6)$$

$$P_{ji}^c = V_j^2 G_{ij}^{'} - V_i V_j (G_{ij}^{'} cos\delta_{ij} - B_{ij}^{'} sin\delta_{ij}) \quad (3.7)$$

$$Q_{ji}^c = -V_j^2 (B_{ij}^{'} + B_{sh}) + V_i V_j (G_{ij}^{'} sin\delta_{ij} + B_{ij}^{'} cos\delta_{ij}) \quad (3.8)$$

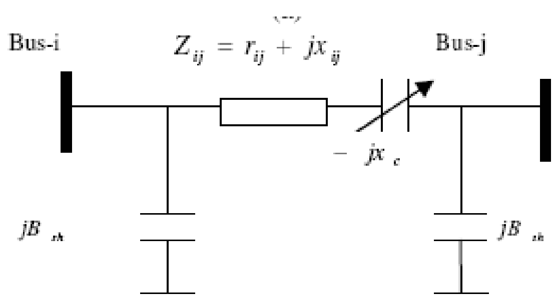

Figure 6 : Model of Transmission line with TCSC

The active and reactive power loss in the line having TCSC can be written as, from equations 3.5, 3.7 & 3.6, 3.8.

$$P_L = P_{ij}^c + P_{ji}^c = G_{ij}^{'} (V_i^2 + V_j^2) - 2 V_i V_j G_{ij}^{'} cos\delta_{ij} \; Q_L = Q_{ij}^c + Q_{ji}^c = -(V_i^2 + V_j^2)(B_{ij}^{'} + B_{sh}) + 2 V_i V_j B_{ij}^{'} cos\delta_{ij}$$

Where, $G_{ij}^{'} = \frac{r_{ij}}{(r_{ij}^2 + (x_{ij} - x_c)^2}$

$$B_{ij}^{'} = -\frac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$$

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Figure.

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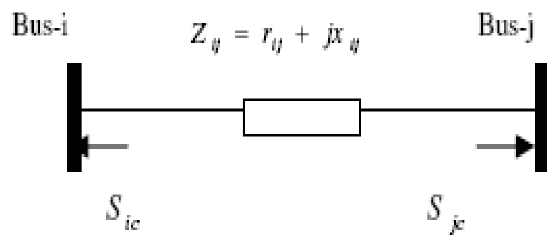

Figure 7 : Injection Model of TCSC

The real and reactive power injections at bus-i and bus-j can be expressed as,

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}] \quad (3.9)$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos\delta_{ij} - \Delta B_{ij} \sin\delta_{ij}] \quad (3.10)$$

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \cos\delta_{ij}] \quad (3.11)$$

$$Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j [\Delta G_{ij} \sin\delta_{ij} - \Delta B_{ij} \cos\delta_{ij}] \quad (3.12)$$

$$\Delta G_{ij} = \frac{x_c r_{ij} (x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)2)}$$

$$\Delta B_{ij} = \frac{-x_c (r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)2)}$$

This Model of TCSC is used to properly modify the parameters of transmission line with TCSC for optimal location.

ii. *Thyristor Controlled Phase Angle Regulator (Tcpar)*

Thyristor Controlled Phase Angle Regulator 'TCPAR' for power flow studies and the role of that modeling in the study of Flexible Alternating Current Transmission Systems 'FACTS' for power flow control are discussed. In order to investigate the impact of TCPAR on power systems effectively, it is essential to formulate a correct and appropriate model for it. The TCPAR, thus, makes it possible to increase or decrease the power forwarded in the line where it is inserted in a considerable way, which makes of it an ideal tool for this kind of use. Knowing that the TCPAR does not inject any active power, it offers a good solution with a less consumption.

a. *Static Modelling of Tcpar*

It is modeled by a voltage source, which represents the branch series, and of a power source representing the branch shunt. In computing the power flow, these devices are modeled using an ideal transformer with complex transformation ratio μ.

In the case of the TCPAR [5], the transformation ratio is expressed as:

$$\overline{\mu} = e^{j\theta} \quad (3.13)$$

Thus, it only affects the voltage angle while its magnitude remains constant.

For a TCPAR introduced into a transmission line as shown in the figure, a voltage *VTr* is introduced and it is expressed as a fraction of the voltage *Vm* at the bus m to which it is connected. It can be written as:

$$\overline{V_t} = \overline{V_m} + \overline{V_{Tr}} \quad (3.14)$$

And as,

$$\overline{V_m} = \overline{V_t}\,\overline{\mu} \quad (3.15)$$

Then,

$$\overline{V_{Tr}} = \overline{V_m} - \frac{\overline{V_m}}{\overline{\mu}}$$

Or

$$\overline{V_{Tr}} = \overline{V_m}(\overline{\mu} - 1/\overline{\mu}) \quad (3.16)$$

For a TCPAR introduced at the bus m of a transmission line as shown in figure 8., the equation which defines the relationship between the currents injected into the line and the voltages at buses *t* and *k* is:

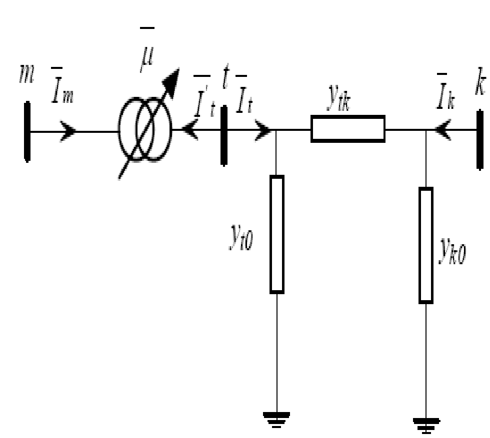

Figure 8 : model of transmission line with TCPAR

$$\overline{I}_t^{'} = Y_{tt}\overline{V_t} + Y_{tk}\overline{V_k} \quad (3.17)$$

$$\overline{I}_K = Y_{Kt}\overline{V}_t + Y_{KK}\overline{V}_K \quad (3.18)$$

Such as,

$$Y_{tt} = Y_{tK} + Y_{t0} \quad (3.19)$$

$$Y_{KK} = Y_{tK} + Y_{K0} \quad (3.20)$$

$$Y_{tK} = Y_{Kt} = -Y_{tK} \quad (3.21)$$

Knowing That,

$$\overline{I}_t^{'} = \overline{I}m\overline{\mu}^* \quad (3.22)$$

Considering above equations, the new expressions of the currents become:

$$\overline{I}m = \frac{Y_{tt}}{\overline{\mu}^*}\overline{V}m + \frac{Y_{tt}}{\overline{\mu}^*}\overline{V}_{Tr} + \frac{Y_{tK}}{\overline{\mu}^*}\overline{V}_K$$

$$\overline{I}_K = \frac{Y_{Kt}}{\overline{\mu}^*}\overline{V}_m + Y_{KK}\overline{V}_K$$

The admittance matrix of the new line has the form:

$$\begin{bmatrix}\overline{I}m \\ \overline{I}_K\end{bmatrix} = [Y]\begin{bmatrix}\overline{V}m \\ \overline{V}_{Tr} \\ \overline{V}_K\end{bmatrix}$$

b) Static Var Compensators (Svc)

A common practice of system voltage adjustment is shunt reactive power compensation. The synchronous condenser was historically an important tool of shunt reactive power compensation. Since it is a rotating machine, its operation and maintenance are quite complicated. New synchronous condensers are now seldom installed. The static shunt reactive power compensation, as opposed to the rotating synchronous condenser, has wide industrial application due to its low cost and simple operation and maintenance.

Conventional static shunt reactive power compensation is to install capacitors, reactors, or their combination, at the compensated buses to inject or extract reactive power from the system. Mechanical switches are used to put the shunt capacitor/reactors into or out of operation.

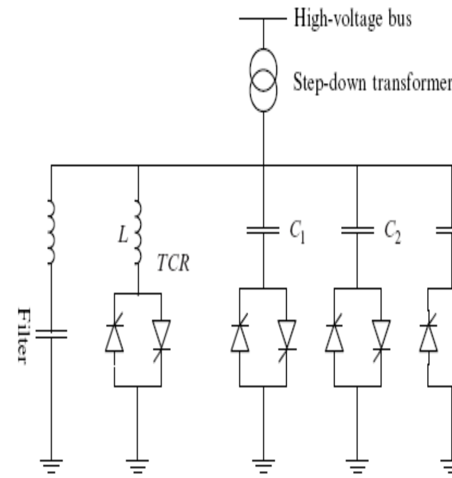

Figure 9 : SVC basic diagram

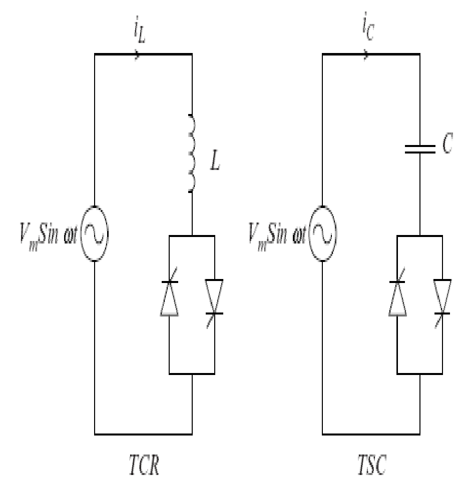

Figure 10 : TCR and TSC branches

Apparently the inductor current is zero when the two valves are off. When the valve conducts, neglecting the resistance in the reactor, the inductor current is

$$L\frac{di_L}{dt} = V_m sin\omega t \quad (3.23)$$

Where L is the inductance of the reactor, Vm is the magnitude of the system voltage.

Its general solution is

$$i_L = K - \frac{V_m}{\omega L}cos\omega t \quad (3.24)$$

Where K is the integral constant. Since the inductor current is zero at firing, the above equation yields

$$i_L = K - \frac{V_m}{\omega L}\cos(\alpha + K\pi) = 0 \quad (3.25)$$

Substituting the solution of K in to equation 3.25 gives rise to the inductor current.

$$i_L = \frac{V_m}{\omega L}[cos(\alpha + K\pi) - cos\omega t] \quad K = 0,1,2, \ldots .\ldots$$

Based on the above equation, inductor current returns to zero at

$$\omega t = (K+2)\pi - \alpha$$

Thus the valve conducting period is

$$\omega t \, \epsilon \, [K\pi + \alpha, (K+2)\pi - \alpha] \;\; K = 1,2,3, \ldots.$$

The adjustment of firing angles changes the current peak values and conducting periods. Applying Fourier analysis to the current yields the magnitude of the fundamental frequency Component.

$$I_{L1} = \frac{2}{\pi}\int_{\alpha}^{2\pi-\alpha} \frac{V_m}{\omega L}(cos\alpha - cos\theta)\cos\theta \, d\theta = \frac{V_m}{\pi\omega L}[2(\alpha-\pi) - sin2\alpha] \qquad (3.26)$$

And the instantaneous value of fundamental frequency component is

$$i_{L1} = I_{L1}cos\omega t = \frac{V_m}{\pi\omega L}(2\beta - sin2\beta)sin\left(\omega t - \frac{\pi}{2}\right) \qquad (3.27)$$

The equivalent fundamental frequency reactance of the TCR branch is

$$X_L(\beta) = \frac{\pi\omega L}{2\beta - sin\,2\beta}\beta \in [0, \tfrac{\pi}{2}]$$

Thus the TCR equivalent reactance of fundamental frequency components is the function of conducting angle β or the firing angle α. The control of firing angle α can smoothly adjust the equivalent shunt reactance. The reactive power consumed by TCR is

$$Q_L = \dot{V} i_{L1}^* = \frac{V^2}{X_L(\beta)} = \frac{2\beta - sin\,2\beta}{\pi\omega L}V^2 \qquad (3.28)$$

The TSC branch consists of a capacitor connected in series with two thyristors connected in parallel and in opposite directions. The TSC source voltage is the same as TCR. Its waveforms are in Figure. The TSC creates two operating states for the capacitors through valve control: shunt capacitors in service or out of service. Stopping the firing can simply put the capacitor out of service. Note that the natural switch-off from conduction happens when the capacitor current is zero and its voltage at the peak of source voltage. Neglecting the capacitor leakage current, capacitor voltage maintains the peak value if firing stops after the Natural switch-off. We need to pay attention to the timing of putting the capacitor into service.
The reactive power injection of the capacitors is

$$Q_C = \omega C V^2 \qquad (3.29)$$

Where C is the capacitance of the capacitor. From above two equations [3.28] & [3.29] we have the reactive power injection from the SVC is

$$Q_{SVC} = Q_C - Q_L = (\omega C - \frac{2\beta - sin\,2\beta}{\pi\omega L})V^2 \qquad (3.30)$$

The SVC reactive power injection can be smoothly adjusted when β€ [0,π/2]. To expand the regulation ranges of SVC, we can have many TSC branches in one SVC, based on the compensation requirements. Figure shows an SVC with three TSCs. When all three TSCs are in service, the C in above equation is C1+C2+C3. To guarantee a continuous adjustment, the TCR capacity should be slightly larger than a group of TSCs, that is, ωC1 < 1/ωL.

Based on above equation the equivalent reactance of SVC is

$$X_{SVC} = -\left(\omega C - \frac{2\beta - sin2\beta^{-1}}{\pi\omega L}\right) = \frac{\pi\omega L}{2\beta - sin2\beta - \pi\omega^2 LC}$$

In Figure, shown below there is a straight line going through the original corresponding to every β. The slope of the straight line is XSVC. Suppose that the system voltage characteristic is V1. The control scheme is to make the TCR conducting angle β1= π/2, corresponding to maximum equivalent inductive reactance. The SVC operating point is the crossover point A between system voltage characteristic V1 and the straight line β1. With system voltage characteristic V2 and TCR conduction angle β2 < β1, XSVC decreases and the SVC operating point shifts accordingly. Until system voltage characteristic is V6 and conduction angle β6= 0, SVC equivalent reactance is maximum capacitive with operating point B.

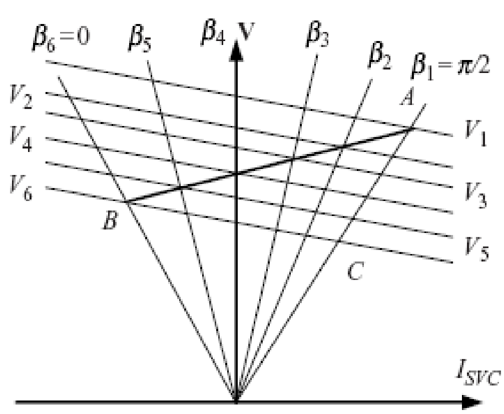

Figure 11 : Equivalent reactance variation with β as voltage changes

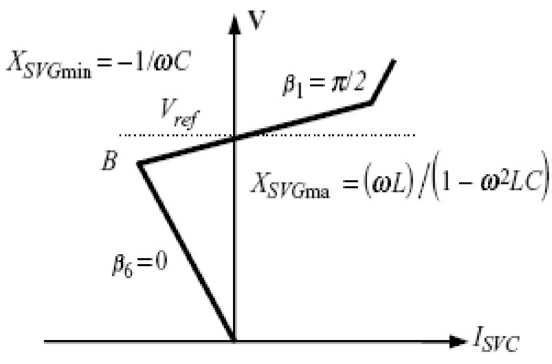

Figure 12 : Voltage–current characteristic

Apparently, voltage at B is higher than at C. When voltage changes between V1 and V6, the adjustment of b puts voltage under control. All the operating points constitute the straight line AB. The slope of AB and the crossover point with voltage axis Vref is determined by the control scheme of β. From voltage control point of view, the slope of AB is zero at best, without steady-state error. To maintain the control stability, SVC should have a small steady-state error and the slope of AB is around 0.05. Taking into consideration the steady-state control scheme, the SVC voltage–current characteristics are shown in Fig. voltage characteristics. When system voltage varies within the SVC control range, SVC can be seen as asynchronous condenser having source voltage of Vref and internal reactance of Xe.

$$V = V_{ref} + X_e I_{SVC}$$

Where Xe is the slope of the straight line AB in Voltage Characteristics, V and ISVC are the SVC terminal voltage and current. When system voltage is out of the SVC control range, SVC becomes a fixed reactor, XSVCmin or XSVCmax. SVC is considered as a variable shunt reactor in system stability and control analysis. SVC controller determines its admittance. We have introduced SVC basic principles. Special attention needs to be paid in industrial applications of SVC to capacity settings of reactors and capacitors, control strategy, flexibility of adjustments, protection, elimination of harmonics, etc .For example, in practical operation of an SVC, the range of the control angle is slightly less than [π/2, π] to make sure that valves can be triggered on and turned off securely.

IV. Optimal Location based on Sensitivity Approach for Tcsc, Tcpar and Svc

The static devices are considered in order to achieve the following in the power system:

1. Reduction in total system losses
2. Increased transfer capability
3. Reduction in total MVAR losses

a) Selection of optimal location of FACTS devices

Using loss sensitivity index, the FACTS devices are placed in a suitable location as follows:

The Reduction of Total System Reactive Power Losses Method sensitivity factors with respect to the parameters of TCSC , TCPAR and SVC are defined as:

- Loss sensitivity with respect to control parameter X_{ij} of TCSC placed between buses i and j,

$$a_{ij} = \frac{\partial QL}{\partial X_{ij}}$$

- Loss sensitivity with respect to control parameter X_{ij} and θ_{ij} of TCPAR placed at buses i and j

$$b_{ij} = \frac{\partial QL}{\partial \theta_{ij}}$$

- Loss sensitivity with respect to control parameter *Qi* of SVC placed at bus *i*,

$$C_i = \frac{\partial QL}{\partial Q_i}$$

These factors can be computed for a base case power flow solution. Consider a line connected between buses *i* and *j* and having a net series impedance of *Xij*. The loss sensitivities with respect to *Xij*, θ_{ij} and *Qi* can be computed as:

$$a_{ij} = \frac{\partial QL}{\partial X_{ij}}$$

$$= \left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i-\delta_j)\right]\frac{R_{ij}^2 - X_{ij}^2}{\left(R_{ij}^2 + X_{ij}^2\right)^2} \quad (4.1)$$

$$b_{ij} = \frac{\partial QL}{\partial \theta_{ij}} = \left[-2V_iV_jB_{ij}\sin\theta_{ij}\right] \quad (4.2)$$

and $$C_i = \frac{\partial QL}{\partial Q_i} = \frac{2V_j^2[\cos(2\alpha)-1]}{\pi X_l} \quad (4.3)$$

Where Vi is the voltage at bus i

Vj is the voltage at bus j

Rij is resistance of line connected between bus i and j

Xij is the reactance connected between bus i and j

B_{ij} is the susceptance connected between bus i and j

α is the firing angle of SVC

θ_{ij} is the net phase shift in the line.

The FACTS device must be placed on the most sensitive lines. With the sensitive indices computed for each type of FACTS device, TCSC , SVC and TCPAR should be placed in a line (K) having most positive value and absolute value of sensitivity respectively.

V. Simulation and Results Discussion

The study has been conducted on transient stability of an IEEE 14 BUS system and IEEE 24 BUS system using power world simulator 17.0.

For each system the enhancement of Transient stability is determined by placing different FACTS devices like TCSC, TCPAR and SVC in the optimal location using sensitivity approach method.

The two systems are modeled internally using power world simulator. The internal models includes generator model, exciter model, stabilizers…e.t.c. The following section contains the detailed results.

a) Case study-1: IEEE 14 Bus System

This system consists of 14 buses, 17 line sections, 5 generator buses and 8 load buses.

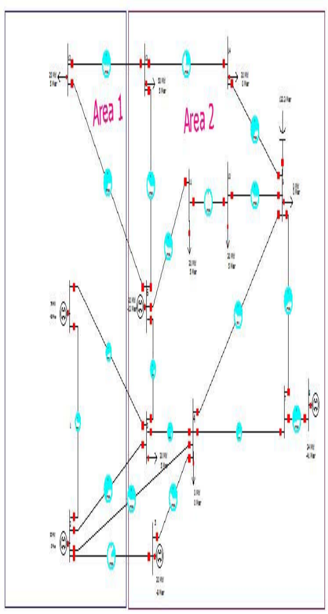

Figure 13 : single line diagram of IEEE 14 bus system

Table 1 : Sensitivity Factors For TCSC, TCPAR In IEEE 14-Bus System

Line	From Bus To Bus	Sensitivity Index			
		TCSC (30%) (a_{ij})	TCSC (40%) (a_{ij})	TCPAR (30%) (b_{ij})	TCPAR (40%) (b_{ij})
1	1-2	-1.2637	-1.3633	-0.0044	-0.0059
2	1-5	-0.4879	-0.5853	-0.0106	-0.0141
3	2-3	-0.0608	-0.0733	-0.1565	-0.0011
4	2-4	-0.1888	-0.2030	-0.0084	-0.0112
5	2-5	-0.1702	-0.1836	-0.0054	-0.0072
6	3-4	-0.0352	-0.0339	-0.0047	-0.0063
7	4-5	-0.1332	-0.1459	-0.0291	-0.0388
8	4-7	-0.5426	-0.7386	0	0
9	4-9	-0.2127	-0.2894	0	0
10	5-6	-0.7320	-0.9964	0	0
11	6-11	-0.0114	-0.0106	0	0
12	6-12	-0.0297	-0.0220	0	0
13	6-13	-0.0713	-0.0460	0	0
14	7-8	-0.1812	-0.2467	0	0
15	7-9	-0.8918	-1.2138	0	0
16	9-10	-0.2503	-0.2487	0	0
17	9-14	-0.0312	-0.0242	0	0
18	10-11	-0.0514	-0.0456	0	0
19	12-13	0.0013	0.0018	0	0
20	13-14	-0.0277	-0.0195	0	0

For this system, from table-1 the following are considered:

- TCSC is placed with a compensation of 40% in the line 13(12-13) and is operated.
- TCPAR is placed with a phase shift of 2 and unity tap ratio.

By using sensitivity approach, the sensitivity index at line 13 is more positive than remaining lines hence the compensation is provided at that line. Similarly the sensitivity index at line 3 is the highest absolute value i.e. -0.1565 and -0.0011 for 30% and 40% compensation of TCPAR.

By placing these devices in a line the transient stability is improved i.e. generator rotor angles, voltages, generator power, accelerated power are improved as shown.

i. *Rotor angle improvement*

The following graphs shows the variation of rotor angle with time and it also shows the enhancement of rotor angle with and without FACTS device during Transient Stability.

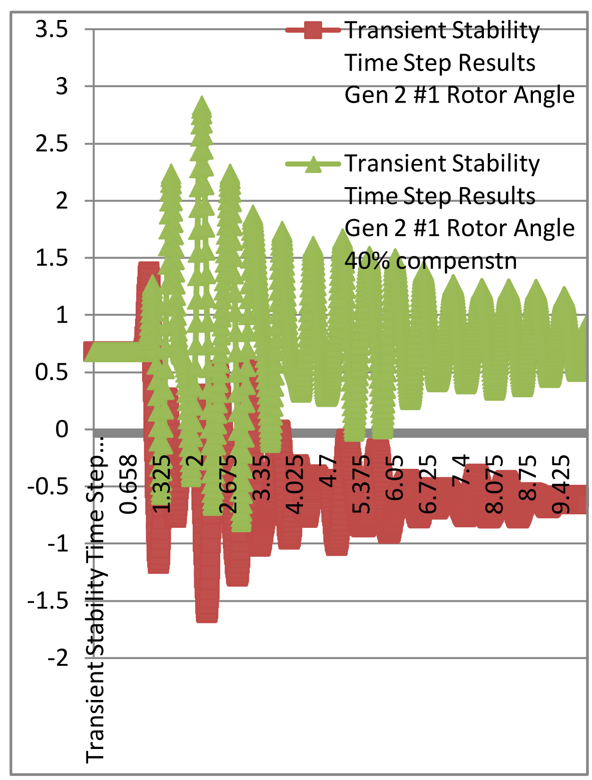

Figure 14 : Generator-2 rotor angle curves with and without compensation

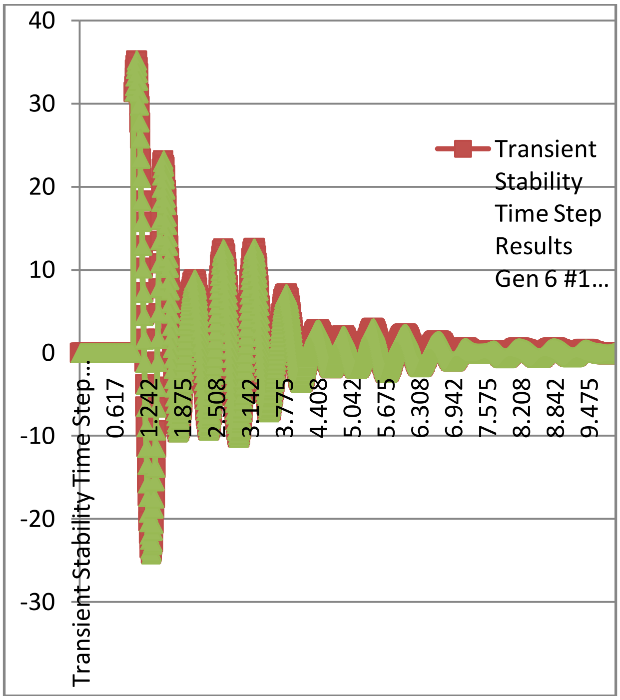

Figure 15 : Generator-6 rotor angle curves with and without TCPAR

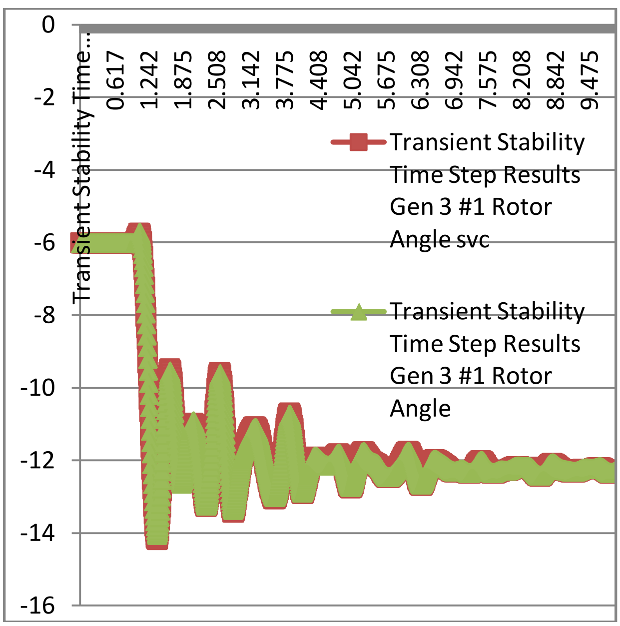

Figure 16 : Generator-3 rotor angle curves with and without SVC

ii. *Voltage Improvement*

The following figures show the plot varying between voltage and time and they also shows the enhancement of voltage by placing FACTS devices in a system during Transient Stability.

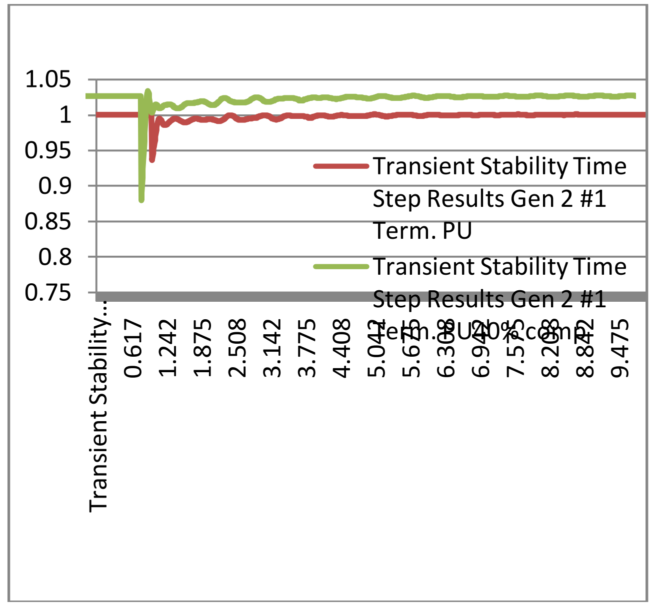

Figure 17 : Generator-2 voltage curves with and without compensation of TCSC

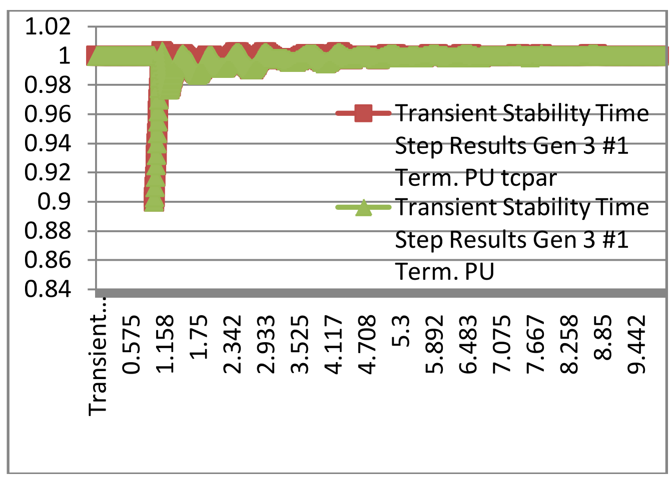

Figure 18 : Generator-3 voltage curves with and without TCPAR

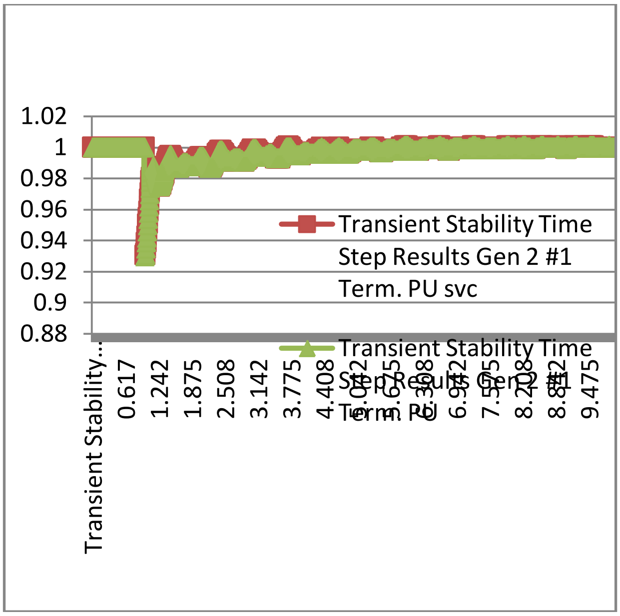

Figure 19 : Generator-2 voltage curves with and without SVC

iii. *Speed Vs Rotor angle*

The following figures show the variation of speed with rotor angle and the enhancement by placing the FACTS devices.

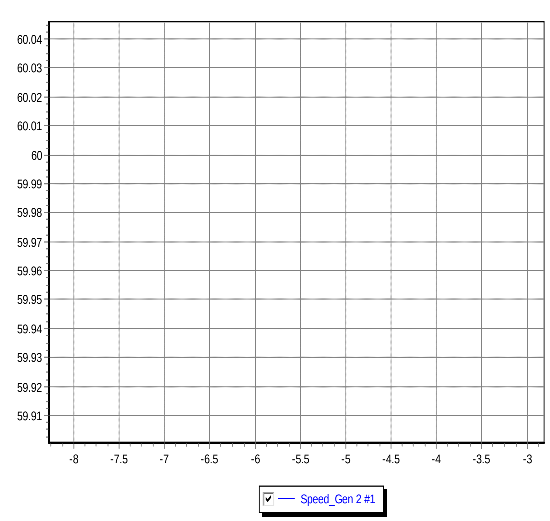

Figure 20: speed vs rotor angle of generator-2 with TCSC

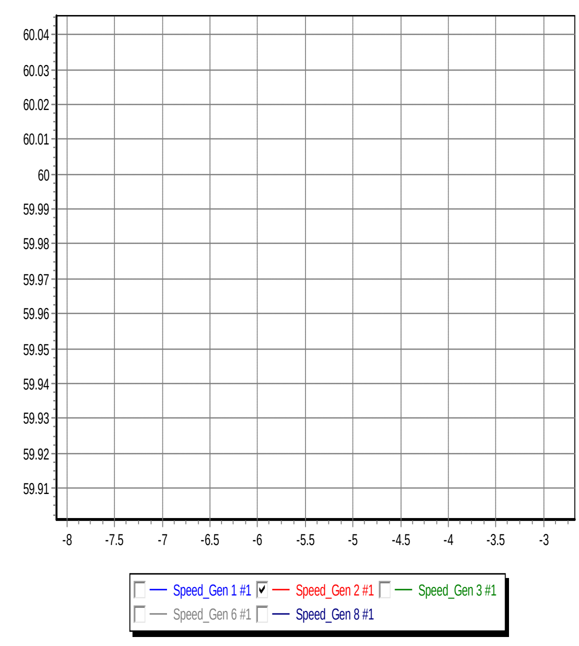

Figure 21 : speed vs rotor angle of generator-2 with TCPAR

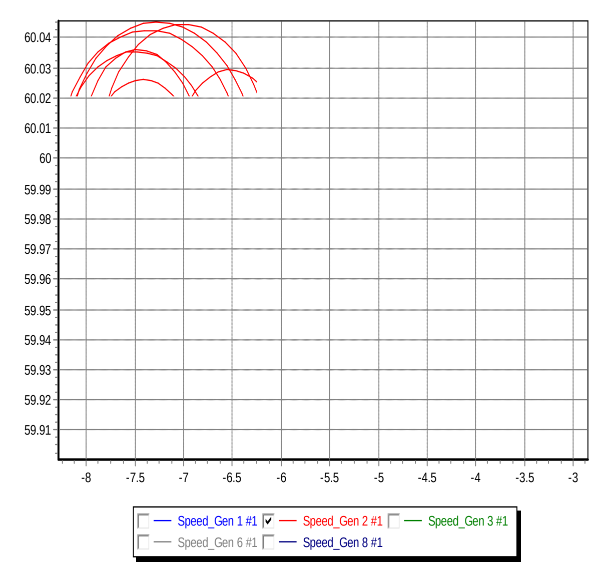

Figure 22 : speed vs rotor angle of generator-2 with SVC

iv. *MVAR terminal*

The following figures show the variation of MVAR with time during Transient stability. The MVAR at the generator terminal decreases by placing the FACTS device as shown.

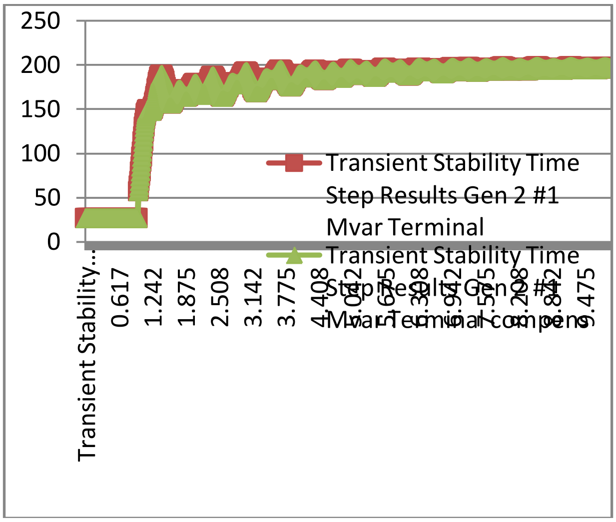

Figure 23 : Generator-2 MVAR with and without TCSC

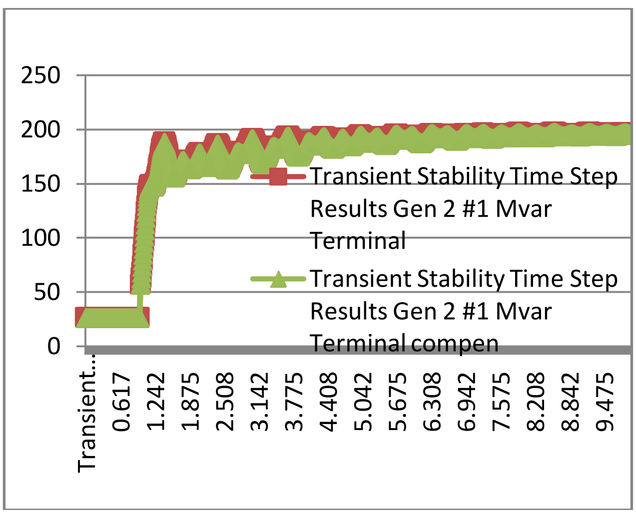

Figure 24 : Generator-2 MVAR with and without TCPAR

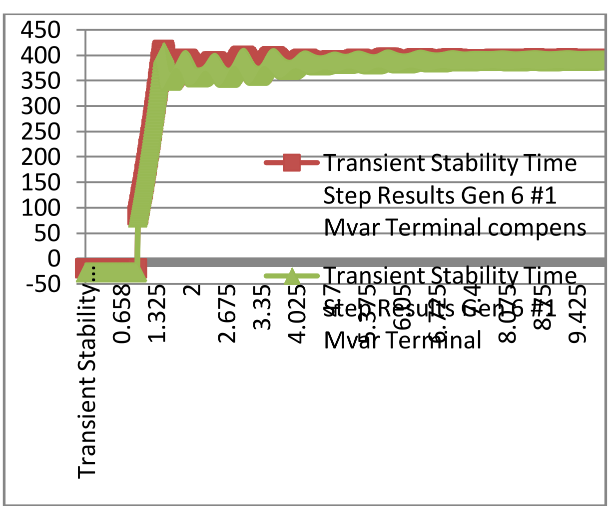

Figure 25 : Generator-6 MVAR with and Without SVC

b) Case Study-2: IEEE 24-BUS system

IEEE-24 bus system consists of 24-buses, 38 line sections, 11 generator buses, 17 load buses as show in the figure.

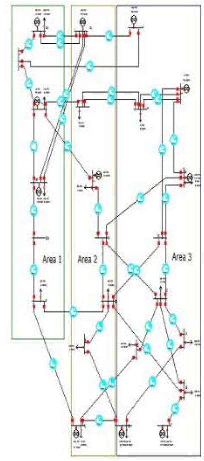

Figure 26 : IEEE 24 BUS system Sensitivity index of IEEE 24-bus system

Table 2 : Sensitivity Factors for TCSC in IEEE 24-Bus System

Line	From Bus To Bus	Sensitivity Index			
		TCSC (30%) (a_{ij})	TCSC (40%) (a_{ij})	TCPAR (30%) (b_{ij})	TCPAR (40%) (b_{ij})
1	1-2	-4.6122	-1.4368	-0.01193	-0.0102
2	1-3	-2.2692	-2.6810	-0.1144	-0.0981
3	1-5	-4.0956	-4.7986	-0.0294	-0.0252
4	2-4	-0.4734	-0.5547	-0.0141	-0.0121
5	2-6	-1.6509	-1.9352	-0.0997	-0.0855
6	3-9	-0.00010312	-0.00012083	0.0030	0.0026
7	3-24	-1.2369	-1.6808	0	0
8	4-9	-5.6109	-6.6787	-0.0368	-0.0312
9	5-10	-2.0481	-2.4232	-0.0168	-0.0144
10	6-10	-0.0526	0.2394	-0.0076	-0.0065
11	7-8	-0.6334	-0.7419	-0.11033	-0.0945
12	8-9	-0.2668	-0.3152	-0.0210	-0.0180
13	8-10	-0.3654	-0.4317	-0.0210	-0.0180
14	9-11	-0.7221	-0.9812	0	0
15	9-12	-0.4065	-0.5524	0	0
16	10-11	-0.9940	-1.3507	0	0
17	10-12	-0.5586	-0.7590	0	0
18	11-13	-0.0872	-0.1148	0.0323	0.0277
19	11-13	-2.2889	-3.0141	-0.0288	-0.0247
20	12-13	-0.4230	-0.5571	0.0210	0.01810
21	12-23	-0.3148	-0.4136	-0.0544	-0.0466
22	13-23	-0.0845	-0.1113	-0.0868	-0.0744
23	14-16	-0.1070	-0.1409	-0.0028	-0.0024
24	15-16	-0.00052124	-0.00070922	-0.0027	-0.0024
25	15-21	-0.0190	-0.0250	0.0065	0.0056
26	15-21	-0.0190	-0.0250	0.0065	0.0056
27	15-24	-1.0830	-1.4255	0.0065	0.0056
28	16-17	-0.1859	-0.2448	0.0039	0.0033
29	16-19	-0.6409	-0.8440	-0.0031	-0.0027
30	17-18	-0.2637	-0.3473	-0.0012	-0.0010
31	17-22	-0.0100	-0.0133	0.1326	0.1136
32	18-21	-0.0876	-0.1151	0.0058	0.0050
33	18-21	-0.0876	-0.1151	0.0058	0.0050
34	19-20	-0.1634	-0.2146	0.0147	0.0126
35	19-20	-0.1634	-0.2146	0.0147	0.0126
36	20-23	-0.1812	-0.2380	0.0048	0.0041
37	20-23	-0.1812	-0.2380	0.0048	0.0041
38	21-22	-0.0211	-0.0278	0.0762	0.0653

The following table- shows the sensitivity index for IEEE 24-bus system.

From the table below the line 10(6-10) has more positive sensitivity index at 30% and 40% compensation of TCSC. Similarly, the line 31(17-22) has high absolute value at 30% and 40% compensation.

For this system, from table above the following are considered:

- TCSC is placed with a compensation of 40% in the line 10(6-10) and is operated.
- TCPAR is placed in the line 31(17-22) with a phase shift of 2 and unity tap ratio.

By using sensitivity approach, the sensitivity index at line 10 is more positive than remaining lines hence the compensation is provided at that line. Similarly the sensitivity index at line 31 is the highest absolute value i.e. 0.1326 and 0.1136 for 30% and 40% compensation of TCPAR.

By placing these devices in a line the transient stability is improved i.e. generator rotor angles, voltages, generator power, accelerated power and MVAR are improved as shown.

c) Rotor angle improvement

The following graphs shows the variation of rotor angle with time and it also shows the enhancement of rotor angle with and without FACTS device during Transient Stability.

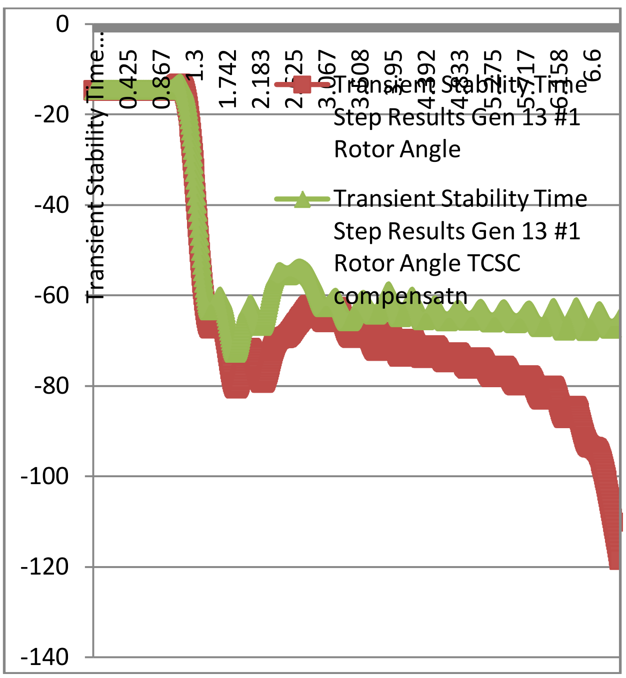

Figure 27 : Generator-13 rotor angle curves with and without compensation of TCSC

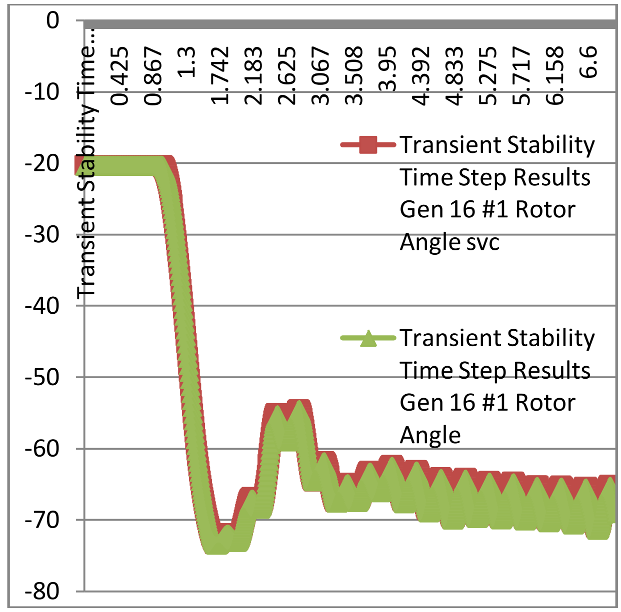

Figure 28 : Generator-16 rotor angle curves with and without compensation of SVC

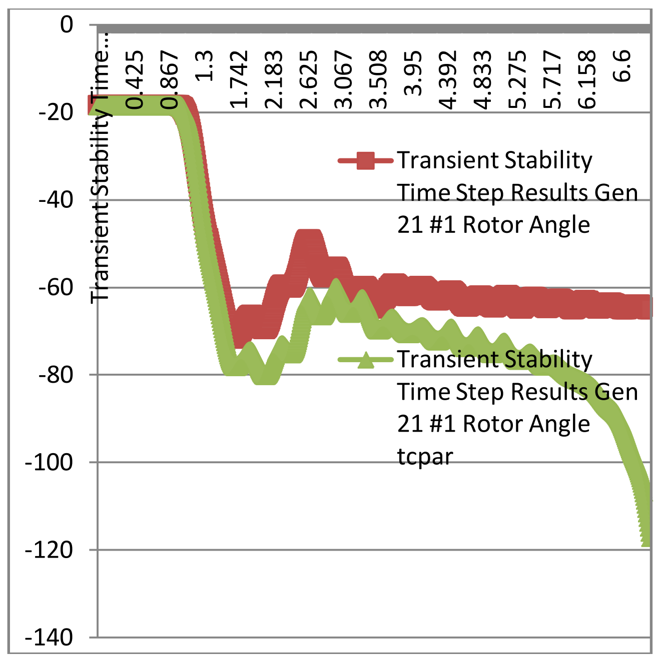

Figure 29 : Generator-21 rotor angle curves with and without compensation of TCPAR

d) Voltage Improvement

The voltage of the system is improved after the transient occurred by using the FACTS devices such as TCSC, TCPAR and SVC as shown below.

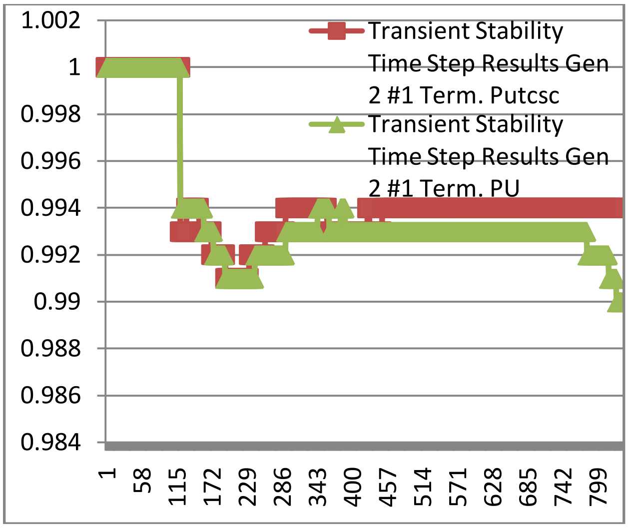

Figure 30 : Generator-2 voltage curves with and without compensation of TCSC

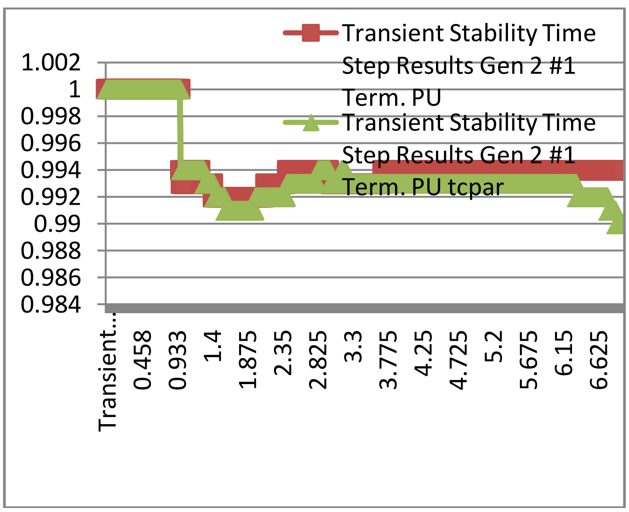

Figure 31 : Generator-2 voltage curves with and without compensation of TCPAR

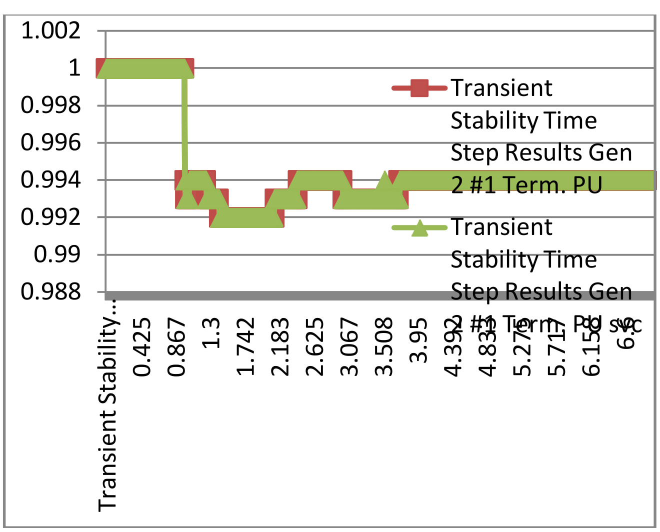

Figure 32 : Generator-2 voltage curves with and without compensation of SVC Speed vs rotor angle curves

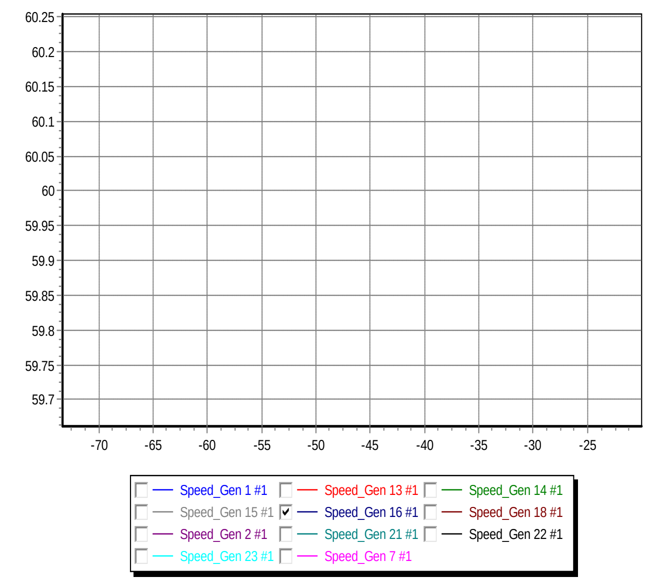

Figure 33 : Generator-16 speed vs rotor angle curves with compensation of TCSC

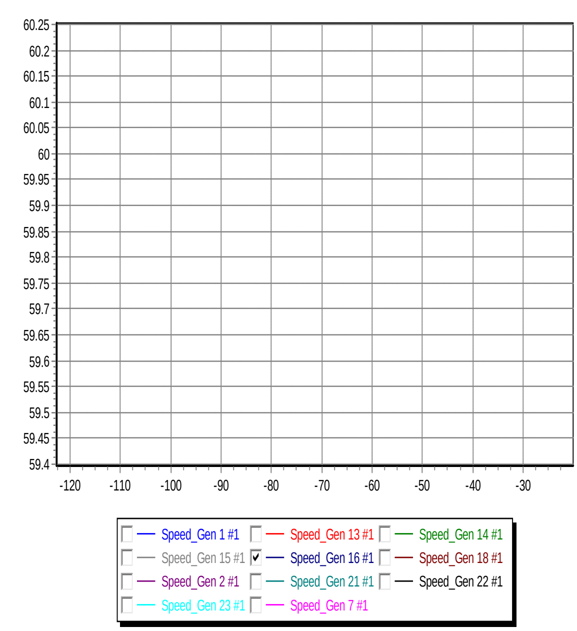

Figure 34 : Generator-16 speed vs rotor angle curves with compensation of TCPAR

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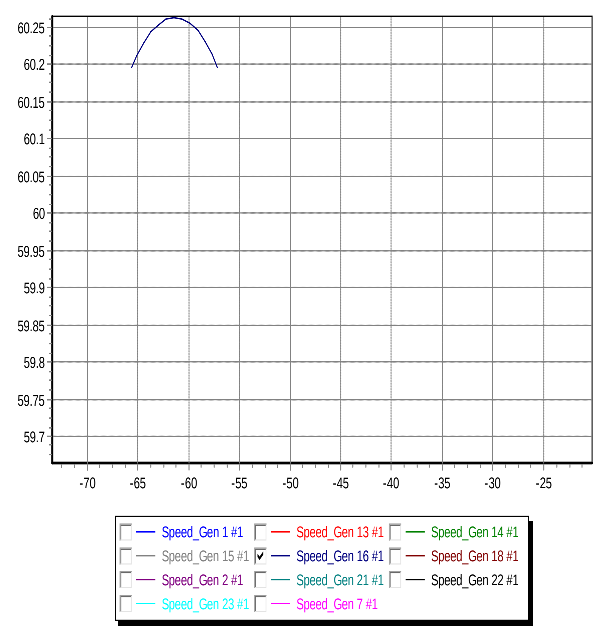

Figure 35 : Generator-16 speed vs rotor angle curves with compensation of SVC

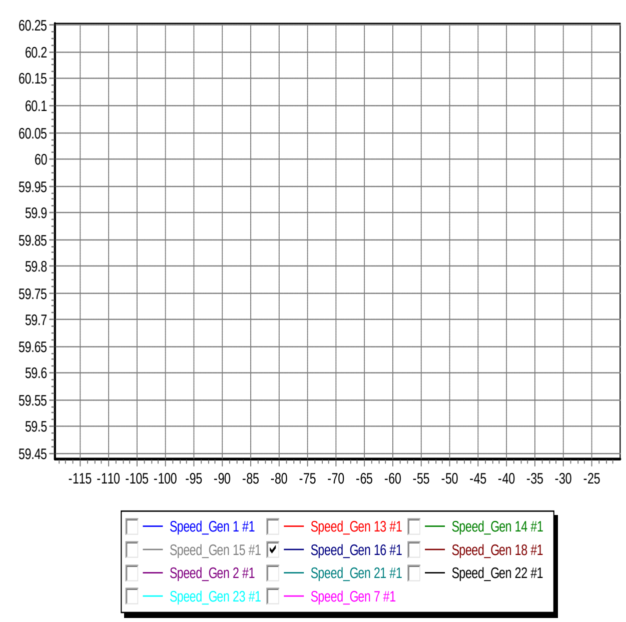

Figure 36 : Generator-16 speed vs rotor angle curves before compensation

VI. Mvar Terminal

The following figures show the variation of MVAR with time during Transient stability. The MVAR at the generator terminal decreases by placing the FACTS device as shown.

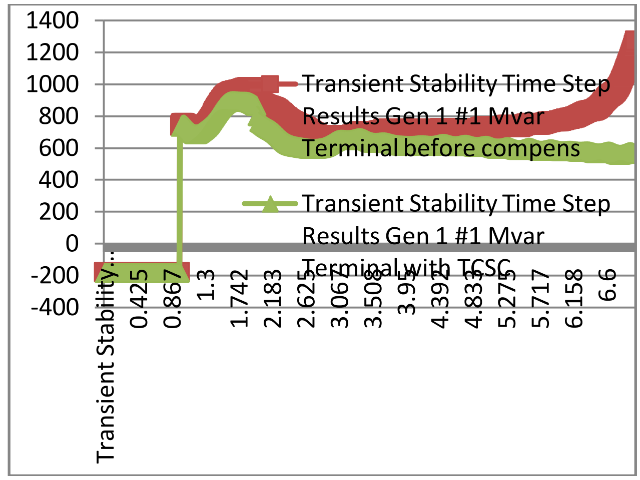

Figure 37 : Generator-1 MVAR terminal with and without compensation of TCSC

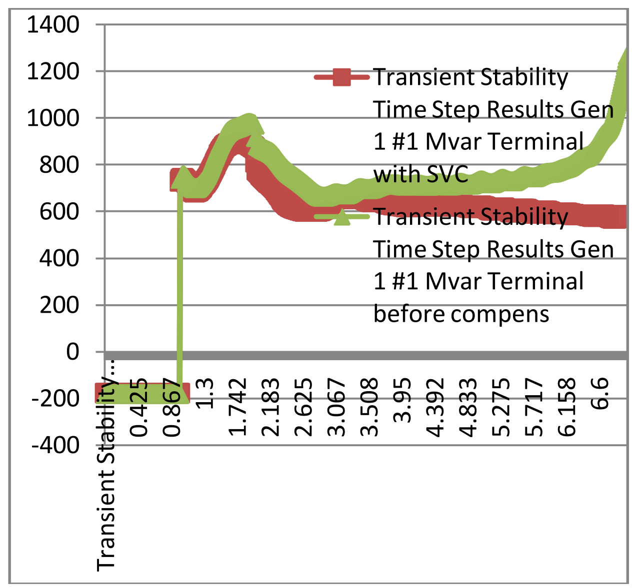

Figure 38 : Generator-1 MVAR terminal with and without compensation of SVC

VII. Conclusion

In this paper a simple sensitivity method is used for determining optimum location of FACTS devices for improving the transient stability. Based on sensitivity index the device is located. The rotor angle, voltage, speed and MVAR terminal of generator are improved using FACTS devices TCSC, TCPAR, SVC as described in this paper.

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