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Power Flow Study and Performance of STATCOM and TCSC in Improvement Voltage Stability and Loadability Amplification in Power System

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ABSTRACT

Power systems operation becomes more important as the load demand increases all over the world. This rapid increase in load demand forces power systems to operate near critical limits due to economical and environmental constraints. The objective in power systems operation is to serve energy with acceptable voltage and frequency to consumers at minimum cost. This paper studies the important power system phenomenon and voltage stability by using continuation power flow method and steady-state modeling of Static Synchronous Compensator (STATCOM) and Thyristor Controlled Series Capacitor (TCSC) for continuation power flow studies has been represented and discussed in details.also this paper studies voltage stability by using continuation power flow method and Comparison between performance of TCSC and STATCOM for improve voltage stability has been done. Case studies are carried on 9 bus network. Simulation is done with PSAT in MATLAB. Power Flow and Continuation Power Flow is was implemented using Newton-Raphson method. Simulation results show the proper performance of TCSC and STATCOM to improve voltage control and power flows on the lines and significantly increase the loadability margin of power systems.

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1. INTRODUCTION

In recent years, the increase in peak load demand and power transfers between utilities has elevated concerns about system voltage security [1]. Power systems operation becomes more important as the load demand increases all over the world. This rapid increase in load demand forces power systems to operate near critical limits due to economical and environmental constraints. The objective in power systems operation is to serve energy with acceptable voltage and frequency to consumers at minimum cost. Reliability and security are also important parameters for power systems and should be satisfied. By reliability, it is meant that the system has adequate reserves in the face of changing energy demand. By security, it is meant that upon occurrence of a contingency, the system could recover to its original state and supply the same quality service as before. All these objectives can be achieved by proper planning, operation and control of power generation and transmission systems. Since generation and transmission units have to be operated at critical limits voltage stability problems may occur in power system when there is an increase in load demand. Voltage instability is one of the main problems in power systems. In voltage stability problem some or all buses voltages decrease due to insufficient power delivered to loads. In case of voltage stability problems, serious blackouts may occur in a considerable part of a system [2]. This can cause severe social and economic problems. In fact, more than 50 cases of voltage instability or voltage collapse were reported all over the world between 1965 and 1996. For example, a voltage collapse in the North American Western Systems Coordinating Council system on July 2, 1996, resulted in service interruptions to more than 6 million people [2]. The most common methods used in voltage stability analysis are continuation power flow, point of collapse, minimum singular value and optimization methods. In this study, continuation power flow method, widely used in voltage stability analysis, is utilized in order to analyze voltage stability of power systems. Voltage stability can be analyzed by using bifurcation theory. With the rapid development of power system, especially the increased use of transmission facilities due to higher industrial output and deregulation, it becomes necessary to explore new ways of maximizing power transfer in existing transmission facilities, while at the same time maintaining the acceptable levels of the network reliability and stability. On the other hand, the fast development of power electronic technology has made FACTS (flexible AC Transmission system) promising solution of future power system. FACTS controllers such as Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow controller (UPFC) are able to change the network parameters in a fast and effective way in order to achieve better system performance [3], [4], [5], [6]. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady-state conditions [7],[8], [9], [10], [11].

This paper focuses on the development of STATCOM and TCSC models and their implementation in Newton-Raphson load flow method, to control voltage of the bus and active power across the line and improve of voltage stability. In section (2) of this paper the concept of voltage stability phenomena is described, and in section (3) equations of Newton's method for load flow studies are focused. Voltage stability can be analyzed by using bifurcation theory, so in section (4) we focus on bifurcation theory and in section (5) we focus on Continuation Power Flow method, one of the methods used in voltage stability analyze. The rest of the sections are organized as follows:in section(6) modeling of STATCOM is presented and in section (7) modeling of TCSC is presented. The Case Study and simulation and results are presented in section (8).Finally; conclusion is discussed in section (9).

2. VOLTAGE STABILITY

Power system stability can be divided into two as voltage stability and rotor angle stability. Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism [12]. In this kind of stability, power-angle equations are handled since power output of a synchronous machine varies as its rotor oscillates. Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [12]. Voltage stability can be attained by sufficient generation and transmission of energy. Generation and transmission units have definite capacities that are peculiar to them. These limits should not be exceeded in a healthy power system. Voltage stability problem arises when the system is heavily loaded that causes to go beyond limitations of power system. A power system enters a state of voltage instability when a disturbance, increase in load demand power or change in system condition causes a progressive and uncontrollable decline in voltage. The main factor causing instability is the inability of the power system to meet the demand for reactive power [12].

2.1. Factors Affecting Voltage Stability

The main reason for voltage instability is the lack of sufficient reactive power in a system. Generator reactive power limits and reactive power requirements in transmission lines are the main causes of insufficient reactive power.

- **Reactive Power Limits of Generators**

Synchronous generators are the main devices for voltage control and reactive power control in power systems. In voltage stability analysis active and reactive power capabilities of generators play an important role. The active power limits are due to the design of the turbine and the boiler. Therefore, active power limits are constant. Reactive power limits of generators are more complicated than active power limits. There are three different causes of reactive power limits that are; stator current, over-excitation current and under-excitation limits. The generator field current is limited by over-excitation limiter in order to avoid damage in field winding. In fact, reactive power limits are voltage dependent. However, in load flow programs they are taken to be constant in order to simplify analysis [13].

- **Transmission Lines**

Transfer of active and reactive power is provided by transmission lines. Since transmission lines are generally long, transfer of reactive power over these lines is very difficult due to significant amount of reactive power requirement[1].

2.2. Voltage Collapse [12]

Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of system. When a power system is subjected to a sudden increase of reactive power demand, the required demand is met by the reactive power reserves supplied from generators and compensation devices. Most of the time, this can be achieved since there are sufficient reserves. Sometimes, it is not possible to meet this rapid increase in demand due to combination of events and system conditions. Thus, voltage collapse and a major breakdown of part or all of the system may occur. There are some countermeasures that can be taken against voltage instability. Automatic voltage regulators (AVRs), under-load tap changers (ULTCs) and compensation devices are common ways to keep bus voltage magnitude in acceptable ranges[12].

3. NEWTON RAPHSON SOLUTION METHOD FOR POWER FLOW

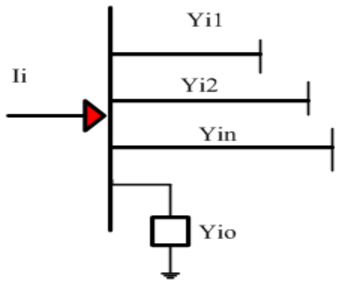

Figure 1. A typical bus of the power system

Power Flow Equation:

Applying KCL to this bus results in:

$$\begin{aligned} I_i &= y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{in}(V_i - V_n) \\ I_i &= (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n \end{aligned} \quad (1)$$

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j \, , j \neq i \quad (2)$$

The real and reactive power at bus *i* is :

$$P_i + jQ_i = V_i I_i^* \quad (3)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} \quad (4)$$

Substituting for Ii in (2) yields:

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j \, , j \neq i \quad (5)$$

Equation (5) is an algebraic non linear equation which must be solved by iterative techniques Power flow equations formulated in polar form. For the system in Fig.1, can be written in terms of bus admittance matrix as:

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j \quad (6)$$

Expressing in polar form;

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \quad (7)$$

Substituting for I_i from Eqn.7 in Eqn. 4

$$P_i - jQ_i = |V_i| \angle -\delta_i \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \tag{8}$$

$$P_i = -\sum_{j=1}^{n} |V_i| |Y_{ij}| |V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

$$Q_i = -\sum_{j=1}^{n} |V_i| |Y_{ij}| |V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{10}$$

Expanding Eqns. 9&10 in Taylor's series about the initial estimate neglecting h.o.t. we get:

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{c|c} \begin{pmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n^{(k)}} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n^{(k)}} \end{pmatrix} & \begin{pmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{pmatrix} \\ \hline \begin{pmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n^{(k)}} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n^{(k)}} \end{pmatrix} & \begin{pmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{pmatrix} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \tag{11}$$

The Jacobian matrix gives the linearized relationship between small changes in $\Delta\delta_i^{(k)}$ and voltage magnitude $\Delta[V_i^k]$ with the small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{12}$$

The diagonal and the off-diagonal elements of J1 are:

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq 1} |V_i| |Y_{ij}| |V_j| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{13}$$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i| |Y_{ij}| |V_j| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{14}$$

Similarly we can find the diagonal and off-diagonal elements of *J2,J3* and *J4* .

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values, known as the power residuals.

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{15}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{16}$$

$$\Delta \delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \tag{17}$$

$$\left|\Delta V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta \left|V_i^{(k)}\right| \tag{18}$$

Orientation [14],[15]:

1. For Load buses (P,Q specified), flat voltage start. For voltage controlled buses (P,V specified),δ set equal to 0.
2. For Load buses,$P_i^{(k)}$ and $Q_i^{(k)}$ are calculated from Eqns.9&10 and $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are calculated from Eqns. 15 & 16.
3. For voltage controlled buses, and $P_i^{(k)}$ and $\Delta P_i^{(k)}$ are calculated from Eqns. 9&15 respectively.
4. The elements of the Jacobian matrix are calculated.
5. The linear simultaneous equation 12 is solved directly by optimally ordered triangle factorization and Gaussian elimination.
6. The new voltage magnitudes and phase angles are computed from (17) and (18).
7. The process is continued until the residuals $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are less than the specified accuracy i.e.

$$\left|\Delta P_i^{(k)}\right| \leq \varepsilon \left|\Delta Q_i^{(k)}\right| \leq \varepsilon \tag{19}$$

4. BIFURCATION THEORY

Bifurcation theory is used to describe changes in the qualitative structures of the phase portrait when certain system parameters change. Local bifurcations can be studied by analyzing the vector differential equations near the bifurcation equilibrium points. Voltage collapse in power systems can be predicted by identifying parameter values that lead to saddle-node bifurcations. In order to present the characteristic of bifurcation, Equation 20 is considered.

$$F(x,\lambda) = \dot{x} = \lambda - x^2 \qquad (20)$$

In differential Equation 1, x is the state variable and λ is a parameter. There is a point called equilibrium point where $F(x_0,\lambda_0) = 0$. For this value of λ the linearization of $F(x,\lambda)$is singular.

Figure 2 is obtained for$F(x,\lambda)$, as λ changes. When $\lambda = 0$ there is a saddle node point. For $\lambda < 0$, there is no equilibrium whereas for $\lambda > 0$ there are two equilibrium points as stable and unstable points[16,17].

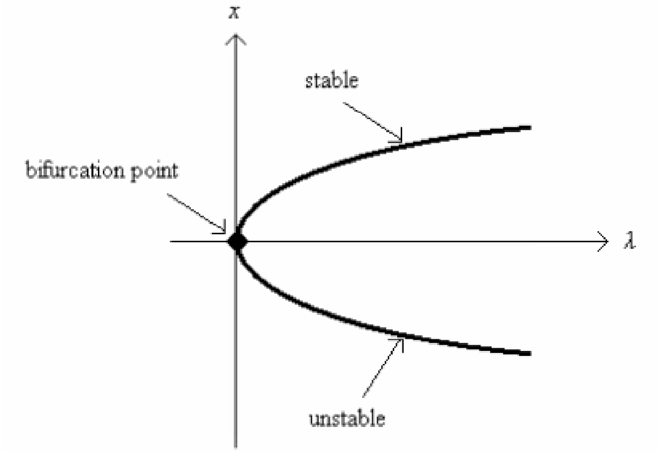

Figure 2. Bifurcation diagram for f(x, λ)[18]

5. CONTINUATION POWER FLOW

The conventional power flow has a problem in the Jacobian matrix which becomes singular at the voltage stability limit. This problem can be overcome by using continuation power flow [19]. Figure 3.shows the predictor – corrector scheme used in the continuation power flow.

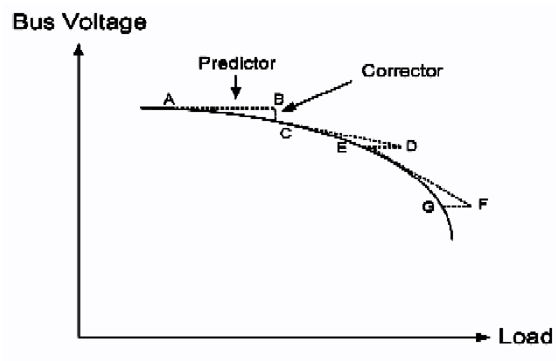

Figure. 3. The predictor – corrector scheme[19]

From the Newton-Raphson, load flow equations can be written as:

$$P_i - \sum_{h=1}^{N} Y_{ij} V_i V_j \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \qquad (21)$$

$$Q_i - \sum_{h=1}^{N} Y_{ij} V_i V_j \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \qquad (22)$$

The new load flow equations consist of load factor are expressed as:

$$P_{Li} = P_{L0} + \lambda(K_{Li} S_{\Delta base} \cos\phi_i) \qquad (23)$$

$$Q_{Li} = Q_{L0} + \lambda(K_{Li} S_{\Delta base} \sin\phi_i) \qquad (24)$$

Where:
$P_{L0,}, Q_{L0}$=original load at bus i, active and reactive power respectively
K_{Li} = multiplier to designate the rate of load change at bus i as λ changes
$S_{\Delta base}$ = a given quantity of apparent power which is chosen to provide appropriate scaling of λ
The power flow equations can be written as:

$$F(\partial, \mathrm{V}, \lambda) = 0 \qquad (25)$$

Then the active power generation term can be modified to:

$$\mathrm{P_{Gi}} = \mathrm{P_{G0}} + (1 + \lambda K_{Gi}) \qquad (26)$$

Where:
P_{G0} = The initial value of active power generation
P_{Gi} = the active power generation at bus i
KG i = the constant of changing rate in generation

To solve the problem, the continuation algorithm starts from a known solution and uses a predictor-corrector scheme to find subsequent solutions at different load levels [20].

6. STATIC SYNCHRONOUS COMPENSATOR

The static synchronous compensator, or STATCOM, is a shunt connected FACTS device. The configuration of STATCOM used in this paper is shown in Fig.4.

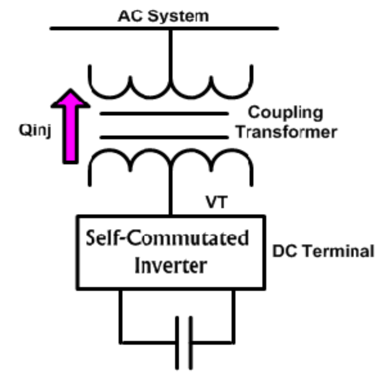

Figure 4. Configuration of a STATCOM

It generates a balanced set of three phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. This type of controller can be implemented using various topologies. However, the voltage-sourced inverter, using GTO thyristors in appropriate multi-phase circuit configurations, is presently considered the most practical for high power utility applications. A typical application of this type of controller is voltage support [21]. In addition to this, this controller has a coupling transformer and a dc capacitor. The control system can be designed to maintain the magnitude of the bus voltage constant by controlling the magnitude and/or phase shift of the VSC output voltage [22]. Few papers address the issue of how to model STATCOM for load flow calculation. It is traditionally modeled for power flow analysis as PV or PQ bus depending on its primary application. The active power is either set to zero (neglecting the STATCOM losses) or calculated iteratively. In a load flow calculation, a STATCOM is typically treated as a shunt reactive power controller assuming that it can adjust its injected reactive power to control the voltage at the Statcom terminal bus. Fig.5 depicts a Statcom and the traditional simple model used in this paper for load flow calculation. In this model reactive power load at bus *i*, *jQi* , is combined with Statcom reactive power output *jQc* and therefore power varies as $|Vi|$. This model is essentially a PV bus with the STATCOM's active power output set to zero.

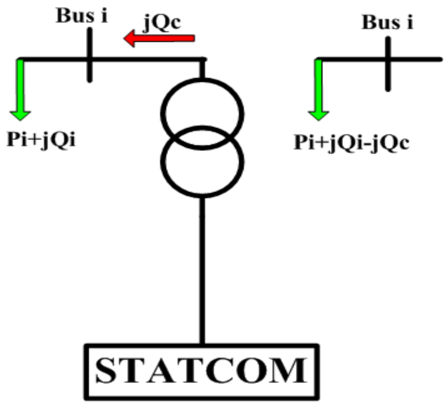

Figure5. Model of STATCOM in load flow calculation

7. THYRISTOR CONTROLLED SERIES CAPACITOR

TCSC is one of the most important and best known FACTS devices, which has been in use for many years to increase the power transfer as well as to enhance system stability. The main circuit of a TCSC is shown in Fig. 6. The TCSC consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristors SCR1 and SCR2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modeled as a fast switch between corresponding reactances offered to the power system[23].

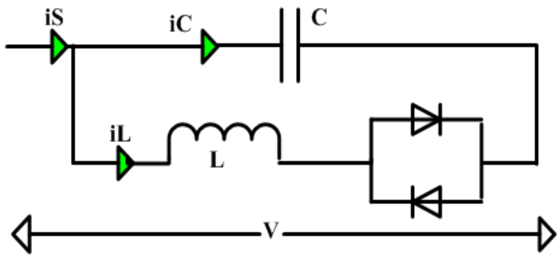

Figure 6. Configuration of A tcsc

8. CASE STUDY AND SIMULATION RESULT

9-bus test system is used to assess the effectiveness of STATCOM and TCSC models developed in this paper. Fig.7 show the single line diagram of system, with 230 kv and 100MVA base has been considered. Two cases are considered, STATCOM is connected at bus 8, TCSC connected between bus 7-8. Our study is divided into two parts. In the first part, we analyze the effect of STATCOM and TCSC on power flow study. In second part impact of them on the voltage stability discussed.

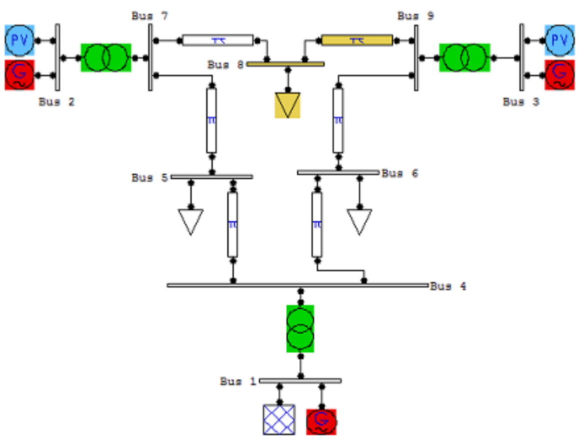

Figure 7.single line diagram of system

8.1.Power Flow Study

In this test system, bus1 is chosen as slack bus, bus 2 and bus 3 are voltage control Bus and other buses are load buses. Sample test system consists of 3 generators, 9 transmission lines,3 Transformers and 4 loads. power flow method is applied to sample test system using PSAT program and result of the power flow give in table2-6. The test network was tested without STATCOM and UPFC and with UPFC and SVC. In all three simulation time of 0.062 seconds is done by software PSAT. The maximum convergence error for each iteration in with and without FACTS device are given in the table1.

Table 1. maximum convergence Error

iteration	Without TCSC&STATCOM	WithTCSC	With STATCOM
1	0.17263	0.17134	0.17248
2	0.012643	0.010359	0.010361
3	0.00017163	0.0001357	0.000127
4	4.1876e-8	1.8947e-8	1.9327e-8

Table 2. Voltage magnitude and phase angle for 9-bus test system with and without STATCOM and TCSC(PF)

Bus	Without FACTS		STATCOM at bus 8		TCSC 7-8	
1	17.16	0	17.16	0	17.16	0
2	18.45	9.28	18.45	9.1954	18.45	9.215
3	14.14	4.6648	14.14	4.6197	14.14	4.805
4	235.9	-2.216	236.2	-2.212	235.9	-2.201
5	228.9	-3.988	229.5	-3.984	228.9	-4.006
6	2336	-3.687	235.2	3.6841	235.7	-3.614
7	235.9	3.7197	236.8	3.6565	235.6	3.649
8	202.9	0.7275	233.3	0.6681	203.1	0.921
9	237.4	1.9667	238.1	1.9299	238.1	2.115

Table 3. Power Flow for 9-bus test system

Line	From-To bus	Power Flow	
		P(MW)	Q(Mvar)
1	9-8	24.1834	3.1195
2	7-8	76.3799	0.79733
3	9-6	60.8166	18.0748
4	7-5	86.6201	8.3808
5	5-4	-40.6798	-38.6873
6	6-4	-30.5373	-16.5434
7	2-7	163	6.6537
8	3-9	85	10.8597
9	1-4	71.641	27.0459

Table 4. Power Flow for 9-bus test system with TCSC

Line	From-To bus	Power Flow	
		P(MW)	Q(Mvar)
1	9-8	22.9067	-3.0384
2	7-8	117.3166	2.1367
3	9-6	62.0933	-17.2584
4	7-5	85.841	-8.8807
5	5-4	-41.4203	-39.029
6	6-4	-29.3107	-15.7907
7	2-7	163	8.3718
8	3-9	85	-16.122
9	1-4	71.1486	26.5486

Table 5. Power Flow for 9-bus test system with STATCOM

Line	From-To bus	Power Flow P(MW)	Power Flow Q(Mvar)
1	**9-8**	24.1515	-3.0264
2	**7-8**	76.3884	-8.1833
3	**9-6**	60.8485	-17.5027
4	**7-5**	86.6116	-7.4669
5	**5-4**	-40.6755	-37.5132
6	**6-4**	-30.4993	-15.7557
7	**2-7**	163	0.15529
8	**3-9**	85	-16.3501
9	**1-4**	71.5871	24.8141

Table 6. Total Losses for 9-bus test system with and without STATCOM and TCSC

	P(MW)	Q(MVAR)
Without FACTS	4.641	-92.1601
WithSTATCOM	4.5871	-93.5077
With TCSC	4.1486	-77.5183

When Table 2 is examined it can be seen that the most reduction in bus voltages occurs in 8 buse. It can be concluded from this result that bus 8 is the weakest bus in this sample system, so with installation STATCOM at bus 8 **,** voltage is increased from 202.9 MW to 233.3 MW. TCSC is connected between bus 7 and bus 8, the objective control is increase the active power of that line, real power flow in line 7-8 increased from 76.3799 MW to 117.3166 MW.

8.2. Continuation Power Flow Study and Voltage Stability

In this part we study voltage stability by using continuation power flow method**.** When Table 7 is examined it can be seen that the most reduction in bus voltages occurs in 8 buse. It can be concluded from this result that bus 8 is the weakest bus in this sample system, The bus with the highest voltage sensitivity factor can be thought as the weakest bus in a system. Weakest bus is more sensitive to load changes. In other words, the load connected to this bus is affected more than other loads in case of an unexpected load increase. Sample system loses its voltage stability at the critical point where the load parameter value is 2.4933 as seen in Figure 8 and Table 8. The critical point can be taken as voltage collapse point. System becomes voltage unstable beyond this point and voltage decreases rapidly due to requirement of reactive power in the system. In the next part, effect of STATCOM and TCSC installed, on voltage stability are Study. result of the Continuation power flow give in table7.

Table 7. Voltage magnitude and phase angle for 9-bus test system with and without STATCOM and TCSC(CPF)

Bus	Without FACTS		STATCOM at bus 8		TCSC 7-8	
1	17.16	0	17.16	0	17.16	0
2	18.45	27.975	18.45	1.040	18.4	26.85
3	14.14	12.419	14.14	12.343	14.14	11.67
4	205.1	-7.633	220	-8.016	204.2	-8.839
5	197.	-15.91	201.5	-16.55	199.2	-18.83
6	197.3	-12.93	199.5	-13.62	235.2	-15.06
7	206.4	1.949	206.8	13.151	220.4	9.879
8	187.4	1.6118	235.7	1.341	187.5	-0.041
9	217.7	5.0671	226.8	4.4693	229.3	3.7831

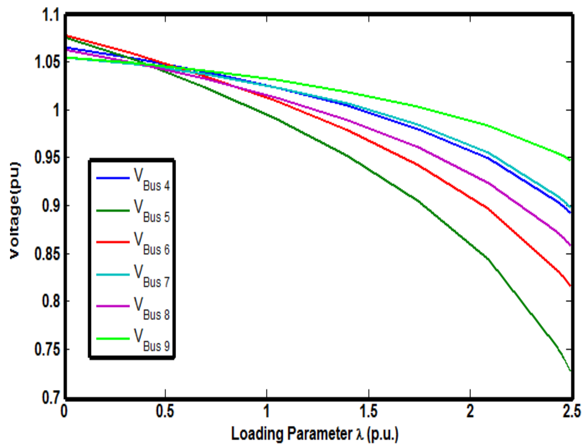

Figure 8. PV curves for test system without FACTS

8.2.1. Effect of STATCOM at bus 8 on Voltage Stability

In order to illustrate the effect of STATCOM in voltage stability, STATCOM installed at bus 8(weakest bus) and continuation power flow is performed. We expect to increase maximum loading parameter. Figure 9 shows the voltage profiles for buse 4-9 in continuation power flows. It is obviously seen that maximum loading point increases. The new maximum loading level in this condition is λmax =2.78 *p.u.*

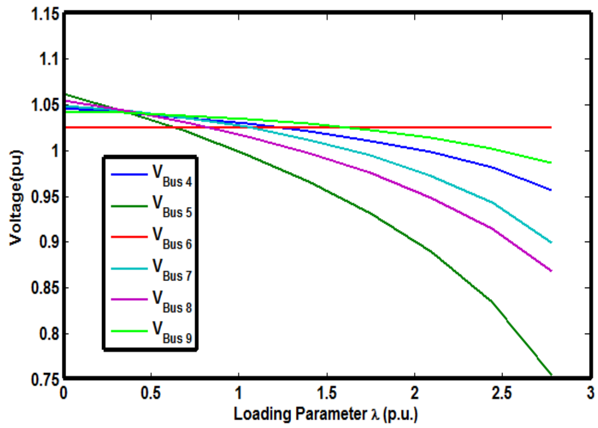

Figure 9. PV curves for test system with STATCOM at bus 8

8.2.2.Effect of TCSC between bus 7 and 8 on Voltage Stability

After presenting the effect of Placing STATCOM, placing UPFC effect on voltage stability is presented by performing continuation Power flow. In order to analyze the effect of placing TCSC again Choose the weakest bus. TCSC installed between bus 7 and 8(weakest bus) and continuation power flow is performed. We expect to increase maximum loading parameter. Figure 10 shows the voltage profiles for buse 4-9 in continuation power flows. It is obviously seen that maximum loading point increases. The new maximum loading level in this condition is λmax =2.8161 *p.u.*

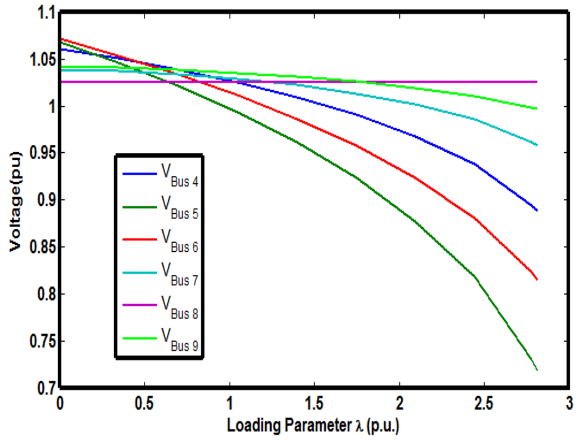

Figure 10. PV curves for test system with TCSC between bus 7-8

Table 8. loading parameter for 9-bus test system without and with FACTS

	Loading Parameter (p.u.)
Base Case	2.4933
With STATCOM	2.78
With TCSC	2.8161

9. CONCLUSION

This paper presented the modeling and simulation of two types of FACTS devices, TCSC and STATCOM to the standard 9 bus power system for load flow studies, also voltage stability phenomena and continuation power flow method, used in voltage stability analysis of power systems, are presented. Voltage magnitude and bus voltage versus load parameter curves are obtained for several scenarios by using a PSAT software which is a one of the toolbox of matlab software. The Numerical result for the standard 9 bus network has been presented how STATCOM and TCSC can be used to increase system stability in practical power systems with the use of simulink model. The effects on static voltage collapse or maximum loading level are presented Simulation results show that by installing STATCOM at bus 8, the bus voltage is increased from 0.8821 to 1.0143 and and maximum loading parameter increased from 2.4933 to 2.78. This means the effect of STATCOM in power system. TCSC is connected between bus 7 and bus 8, the objective control is increase the active power of that line, real power flow in line 7-8 increased from 76.3799 MW to 117.3166 MW, and maximum loading parameter increased from 2.4933 to 2.8161. This means the effect of TCSC in power system. The method used Newton-Raphson algorithm for load flow studies. It was found that the STATCOM and TCSC regulates the voltage of the bus as well as TCSC regulates the active and reactive power of the buses and the lines within specified limits. The results of simulations also show that with the insertion of TCSC, improving these parameters and steady-state stability of the system is more than the case when the STATCOM is inserted in the system.

REFERENCES

[1] V. Ajjarapu and C. Christy. "The continuation power flow: A tool for steady state voltage stability analysis", *IEEE Trans. on Power Systems*, Vol/Issue: 7(1) Pp. 426-423, 1992.
[2] M. Larsson. "Coordinated Voltage Control in Electric Power Systems", *Ph.D. Dissertation*, Lund University, 2000.
[3] N.G. Hingorani, L. Gyugyi. *Understanding FACTS: Concepts and Technology of Flexible ac Transmission Systems*, IEEE Press, New York, 1999.
[4] Enrique Acha et al. *FACTS: Modeling and Simulation in Power Networks*, Wiley, 2004.
[5] A.Edris. "FACTS technology development: an update", *IEEE Eng.Rev*, Vol/Issue: 20(3). Pp. 4-9, 2000.
[6] R.Mohan Marthur and Rajiv K.Varma. *Thyristor Based-FACTS controllers for electrical transmission systems*, Wiley, 2002.
[7] Kirschner L.; Retzmann D.; Thumm G. *Benefits of FACTS for PowerSystem Enhancement*, *Transmission and Distribution Conference and Exhibition: Asia and Pacific*, IEEE/PES. Pp.1-7, 2005.
[8] Yan Ou; Chanan Singh. "Improvement of total transfer capability usingTCSC and SVC, Power Engineering Society Summer Meeting", *IEEE*, Vol 2. Pp. 944-948., 2001.

[9] Perez M.A., Messina A.R., Fuerte-Esquivel C.R. "Application of FACTS devices to improve steady state voltage stability, Power Engineering Society Summer Meeting", *IEEE*, Vol. 2. Pp.1115 – 1120, 2000.

[10] Xingbin Yu; Chanan Singh; Jakovljevic S.; Ristanovic D.; GarngHuang. "Total transfer capability considering FACTS and security constraints**,** Transmission and Distribution Conference and Exposition", *IEEE PES,* Vol. 1. Pp. 73- 78, 2003.

[11] Pilotto L.A.S., Ping W.W., Carvalho A.R., Wey A., Long W.F,. Alvarado F.L., Edris A., "Determination of needed FACTS controllers that increase asset utilization of power systems", *Power Delivery, IEEE*, Vol/Issue: 12(1). Pp 364 – 371, 1997.

[12] P. Kundur. *Power System Stability and Control*, McGraw-Hill, 1994.

[13] S. Repo. *On-line Voltage Stability Assesment of Power System, An Approach of Black-box Modelling*, Tampere University of Technology Publications. Pp.344, 2001.

[14] *Development of constrained-Genetic Algorithm load flow method*, K.P.Wong,A.Li,M.Y.Law,IEE,1997

[15] De Kock, Jan; Strauss, Cobus. *Practical Power Distribution for Industry*. Elsevier. Pp. 74–75, 2004. ISBN 978-0-7506-6396-0.

[16] W. D. Rosehart,C. A. Cañizares. "Bifurcation Analysis of Various Power System Models", *International Journal of Electrical Power & Energy Systems*, Vol. 21. Pp.171-182, 1999.

[17] C. A. Cañizares. "Voltage Collapse and Transient Energy Function Analyses of AC/DC Systems," *Doctoral Dissertation*, University of Wisconsin- Madison, 1991.

[18] Mehmet B. Kesk_n. "Continuation Power Flow and Voltage Stability in Power Systems", A *Thesis* Submitted to the Graduate School of Natural and Applied Sciences of Middle East Technical University, 2007.

[19] Venkataramana Ajjarapu, Colin Christy. "The continuation power flow a tool for steady state voltage stability analysis", *IEEE Transactions on Power Systems*, Vol/Issue: 7(1), 1992.

[20] R. Kalaivani, V. Kamaraj. *Modeling of Shunt FACTS Devices for Voltage Stability Enhancement*, ISSN 1450-216X Vol.61 No.1. Pp. 144-154, 2011.

[21] Pranesh Rao, M. L. Crow, and Zhiping Yang. "STATCOM Control for Power System Voltage Control Applications", *IEEE Trans. On Power Delivery*, Vol/Issue: 15(4). Pp. 1311-1317, 2000.

[22] Nadarajah Mithulananthan, Claudio A.Canizares, John Reeveand Graham J. Rogers. "Comparison of PSS, SVC, and STATCOM Controller for Damping Power System Oscillations", *IEEE Trans. On Power system*, Vol/Issue: 18(2). Pp. 786-792, 2003.

[23] R.M. Mathur, R.K. Varma. *Thyristor-based FACTS Controllers for Electrical Transmission Systems*, IEEE Press, Piscataway, 2002.