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# Determinations of Reactive Reserve Based On Stability Limit Using Tcsc

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## Abstract

**Determination of the voltage stability is essential in power system operation and planning. It is well known that voltage stability is associated with reactive power flow in the network. To determined the stability limit through power flow analysis, in this paper NR-method with appropriate representation of FACTS device TCSC; is used. NR-method, with accurate model of TCSC controller; is implemented on IEEE 9-bus system. Result is found that TCSC controller significantly increases the loading limit of a power system.**

**Keywords:** voltage stability, TCSC, NR algorithm

## I. Introduction

Voltage control in an electrical power system is important for proper operation of electrical power equipment to prevent damage such as overheating of generators and motors, to reduce transmission losses and to maintain the ability of the system to withstand and prevent voltage instability or voltage collapse. Voltage instability problem associated with reactive power not being met because of limitation on the production or transmission of reactive power and is usually initiated by 1) a continuous load increase and/or,2) a major change in network topology resulting from a critical contingency. A lot of works have been developed for the analysis to enhance voltage stability. In [1] authors have developed a method of reducing a system's vulnerability to voltage collapse by using the first order sensitivities of an energy function to controller changes. For control of static voltage stability, the shunt capacitor and tap-changer were used and a parameter optimization technique developed to determine optimal control parameters for dynamic voltage stability enhancement [2].

On an AC power system, voltage is controlled by managing production and absorption of reactive power. Several papers have been published on reactive power reserve management with the perspective of ensuring voltage stability by ensuring adequate amount of reactive power reserves. With this perspective, the merits of an analytical method for determining the amount of series compensation to increase the steady state power transfer capability discussed in [4] and an optimized reactive reserve management scheme based on the optimal power flow proposed in [9,12].Though, the optimization techniques used are different; Bender's decomposition technique and particle swarm optimization respectively. New developments in high-current, high-power electronics are making systems flexibly possible to control electronically the power flows on the high voltage side of the network during both steady state and transient operation [6].

Now a day, Flexible AC Transmission System (FACTS) devices are being increasingly utilized in many electric power systems to enhance voltage limit by compensating reactive power. Studies and realizations have shown their capabilities in steady-state or dynamic stability. With their ability to change the apparent impedance of a transmission line, FACTS devices may be used for active power control, as well as reactive power or voltage control [4,7]. With conventional methods like P-V and Q-V curves, model analysis, ANN, PSO, LSI etc. of enhancing voltage stability, a proper location is an alternative solution to improve voltage profile and voltage stability [10, 12,-14, 17].

## II. FACTS

Today's changing electric power systems create a growing need for flexibility, reliability, fast response and accuracy in the fields of electric power generation, transmission, distribution and consumption. The rapid development of fast acting and self commutated power electronics converters, well known as FACTS controllers, introduced in 1988 by Hingorani are useful in taking fast control actions to ensure security of power systems [5]. Flexible Alternating Current Transmission Systems (FACTS) are new devices emanating from recent innovative technologies that are capable of altering voltage, phase angle and/or impedance at particular points in power systems. Their fast response offers a high potential for power system stability enhancement apart from steady state flow control. .FACTS could be connected: -in series with the power system (series compensation) -in shunt with the power system (shunt compensation) - both in series and in shunt with the power system

Among the FACTS controllers, Thyristor controlled series capacitor (TCSC) is a series connected FACTS device inserted in transmission lines to vary its reactance and thereby reduces the reactive losses and increases the transmission capacity. But the conventional power flow methods are to be modified to take into account the effects of FACTS devices. Fig.1 shows TCSC configuration.

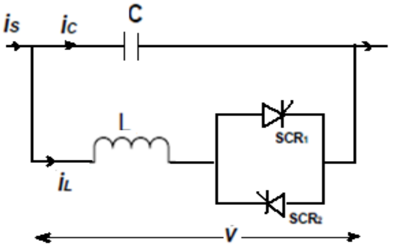

Fig. 1 Configuration of a TCSC

With the concept of reactive power flow, an attempt is made in this paper to describe a method to an equivalent 9-bus system developed from the Newton-Raphson power flow considering FACTS controller TCSC. Voltage stability determination using this FACTs controller is compared in the test system considered and the continuation power flow method is used to determining the critical (CLP) and nose curve (PV curve).

## III. III Static Modeling of TCSC

In the transmission network it is important to locate TCSC devices at suitable place so, that transmission loss become less and stability of system is also improved. Owing to the huge cost of TCSC involved, it is important to find the optimal location of this device in a power system to obtain maximum benefits from it. The transmission model with a TCSC connected between two buses i and j is shown in Figure 3. The equivalent model is used to represent transmission line. TCSC can be considered as a static reactance of magnitude equivalent to -j$X_C$. The controllable reactance Xc is directly used as control variable to implement in power flow equation.

Let $V_i$ $\delta_i$ and $V_j$ $\delta_j$ are the complex voltages at buses i and j. The real and reactive power flow from bus-i and bus-j is :

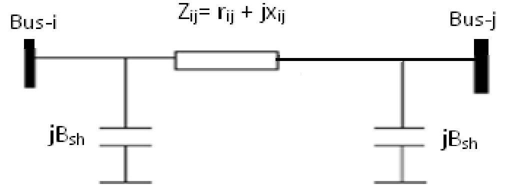

Fig. 2 Model of transmission line

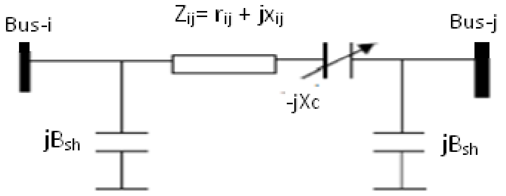

Fig. 3 Model of transmission line with TCSC

$$P_{ij} = V_i^2 \; G_{ij} - V_i \; V_j \left[G_{ij} \; \cos(\delta_{ij}) + B_{ij} \; sin\,(\delta_{ij})\right] \qquad (1)$$

$$Q_{ij} = -V_i^2 \left(B_{ij} + B_{sh}\right) - V_i \, V_j \left[G_{ij}\, sin\,(\delta_{ij}) - B_{ij} \; \cos(\delta_{ij}) \right] \qquad (2)$$

Where $\delta_{ij} = \delta_i - \delta_j$ and then, the real and reactive power flow from bus-j to bus-i is as

$$P_{ij} = V_j^2 \; G_{ij} - V_i \, V_j \left[G_{ij} \; \cos(\delta_{ij}) - Bij \; \sin\delta ij \right. \qquad (3)$$

$$Q_{ij} = -V_j^2 \left(B_{ij} + B_{sh}\right) + V_i \, V_j \left[G_{ij} \sin(\delta_{ij}) + Bij \cos\delta ij \right. \qquad (4)$$

Figure 3 shows the model of transmission line with a TCSC connected between two buses -i and j. In steady state condition TCSC is considered as a static reactance –jXc

$$P_{ij}^c = V_i^2 \, G_{ij}' - V_i V_j \left(G_{ij}' \; \cos \, \delta_{ij} + B_{ij}' \; \sin \delta_{ij} \right) \quad (5)$$

$$Q_{ij}^c = -V_{ij}^2 \left(B_{ij}' + B_{sh}\right) - V_i \, V_j \left(G_{ij}' \; \sin \delta_{ij} - Bij' \cos\delta ij \right. \qquad (6)$$

$$P_{ij}^c = V_i^2 \; G_{ij}' - V_i V_j \left(G_{ij}' \; \cos \, \delta_{ij} - Bij' \; \sin\delta ij \right. \qquad (7)$$

$$Q_{ij}^c = -V_{ij}^2 \left(B_{ij}' + B_{sh}\right) + V_i \, V_j \left(G_{ij}' \; \sin \delta_{ij} - Bij' \cos\delta ij \right. \qquad (8)$$

The line having TCSC then the active and reactive power loss can be written as,

$$P_L = P_{ij} + P_{ji} = G_{ij}' \left(V_i^2 + V_j^2\right) - 2V_i V_j B_{ij}' \cos\delta_{ij} \qquad (9)$$

$$Q_L = Q_{ij} + Q_{ji} = \left(V_i^2 + V_j^2\right)\left(B_{ij}' + B_{sh}\right) - 2V_i V_j B_{ij}' \; \cos\delta_{ij} \qquad (10)$$

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

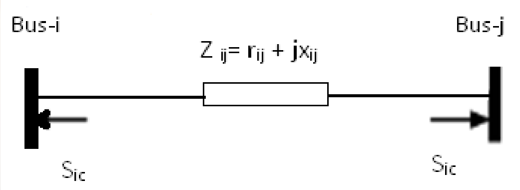

Fig. 4.Injection model of TCSC

Figure 4 shows 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. The real and reactive power injection at both buses i and j can be expressed as

$$P_{ic} = V_i^2 \, \Delta \, G_{ij} + V_i \, V_j \left[\Delta \, G_{ij} \; \cos\delta_{ij} + \Delta \; Bij \sin\delta ij \right. \qquad (11)$$

$$P_{jc} = V_i^2 \, \Delta \, G_{ij} - V_i \, V_j \left[\Delta \, G_{ij} \; \cos\delta_{ij} - \Delta \, B_{ij} \; \sin\delta_{ij}\right] \qquad (12)$$

$$Q_{ic} = -V_i^2 \, \Delta \, B_{ij} - V_i \, V_j \left[\Delta \, G_{ij} \; \sin\delta_{ij} - \Delta \; Bij \cos\delta ij \right. \qquad (13)$$

$$Q_{jc} = -V_i^2 \, \Delta B_{ij} + V_i V_j \left[\Delta G_{ij} \sin\delta_{ij} + \Delta\, Bij \cos\delta ij \quad (14)\right.$$

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

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

## IV. IV Problem Formulation

### Reactive Reserves

The different reactive power sources of a power system are synchronous generators and shunt capacitors. During a disturbance or contingency the real power demand does not change considerably but reactive power demand increases dramatically. This is due to increased voltage decay with increasing line losses and reduced reactive power generation from line charging effects. Sufficient reactive power reserve should be made available to supply the increased reactive power demand and hence improve the voltage stability limit.

The reactive power reserve is the ability of the generator to support bus voltages under increased load or disturbance condition. Amount of reactive power, which can be fed to network, depends on present operating condition, location of the source, field and armature heating of the alternators and how much more reactive power that it can generate, be determined from its capacity curves. The reserves of reactive sources can be considered as a measure of the degree of voltage stability.

Hence the basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactance correspondingly. The position of TCSC at the critical branch will move the critical loading point (CLP) to a higher value. Series capacitive compensation effectively increases the voltage stability limit by canceling a portion of the line reactance and thereby, in effect, providing a "stiff" voltage source for the load. The TCSC is modeled as variable reactance, where the equivalent reactance of line Xij is defined as:

$$X_{ij} = -0.8X_{line} \leq X_c \leq 0.2X_{line} \quad (15)$$

where, *Xline* is the transmission line reactance, and $X_C$ is the TCSC reactance. The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive (15).

## V. Algorithm for Newton-Raphson power flow method

Step-1. We assume a suitable solution for all the buses except the slack bus. We assume a flat voltage profile i.e. $V_i$ = 1.0 + j0.0 for i= 1,2,…,n, i ≠s, Vs = a + j0.0. where s denotes specific value

Step-2. We then set a convergence criterion = ε i.e. if the largest of absolute of the residues exceeds ε, the process is repeated, or else it's terminated.

Step-3. Set the iteration count k=0.

Step-4. Set the bus count i=1.

Step-5. Check if a bus is a slack bus. If that is the case, skip to step 10.

Step-6. Calculate the real and reactive powers Pi and Qi respectively, using the equations

$$P_i = \sum_{j=1}^{n} \left(e_i\left(e_j G_{ij} + f_j B_{ij}\right) + f_i\left(f_j G_{ij} - e_j B_{ij}\right)\right)$$

$$Q_i = \sum_{j=1}^{n} \left(f_i\left(e_j G_{ij} + f_j B_{ij}\right) - e_i\left(f_j G_{ij} - e_j B_{ij}\right)\right)$$

Step-7. Evaluate $\Delta P_i^k = P_{si} - P_i^k$

Step-8. Check if the bus p is a generator bus. If that is the case, compare $Q_i^k$ with the limits. If it exceeds the limits, fix the reactive power generation to the corresponding limit and treat the bus as a load bus for that iteration and go to the next step. If lower limit is violated, set $Q_{si} = Q_{i\,min}$ . If the limit is not violated evaluate the voltage residue. $|\Delta V_i|^2 = |V_i|^2{}_s - \left|V_i^k\right|^2$ and go to step 10.

Step-9 Evaluate $\Delta Q_i^k = Q_{si} - P_i^k$.

Step-10 Advance the bus count by 1, i.e. i=i+1 and check if all the buses have been accounted. If not, go to step 5.

Step-11 Determine the largest of the absolute value of the residue.

step-12 If the largest of the absolute value of the residue is less than ε, go to step 17.

Step-13 Evaluate elements for Jacobian matrix.

Step-14 Calculate voltage increments $\Delta e_i^k$ and $\Delta f_i^k$.

Step-15 Calculate new bus voltages $e_i^{k+1} = e_i^k + \Delta e_i^k$ and $f_i^{k+1} = f_i^k + \Delta f_i^k$ . Evaluate $\cos\delta$ and $\sin\delta$ of all voltages.

Step-16 Advance iteration count k=k+1 and go to step 4

Step-17 Evaluate bus and line powers and get result.

## VI. VI Result and discussion

In load flow studies the TCSC can be represented in several forms. Here it is on the concept of a variable Series Compensator whose changing reactance adjusts itself in order to constrain the power flow across the branch to a specified value. The reactance value is determined efficiently by means of Newton's method.

This model has been included in a Newton-Raphson load flow algorithm, which is capable of solving large power networks very reliably and its efficiency has been illustrated by numeric examples.

The linearized TCSC power flow equations, with respect to TCSC reactance ($X_c$), are incorporated into Newton-Raphson load flow algorithm. In common with all other controllable plant component models available in our load flow program the TCSC reactance is combined with the nodal voltage magnitudes and angles inside the Jacobian and mismatch equations, leading to very robust iterative solutions.

**Case Study**: To illustrate the NR approach in determining the CLP and voltage stability limit using FACTS device (TCSC), 9 bus system (Fig. 5) is considered. Two scenarios are adapted for the system. In scenario A, the real and reactive load at all load buses are increased simultaneously. Whereas in scenario B, the reactive power at any one of the load bus alone is increased. The nose curve of the system is investigated with and without FACTS devices under loading scenario A and scenario B.

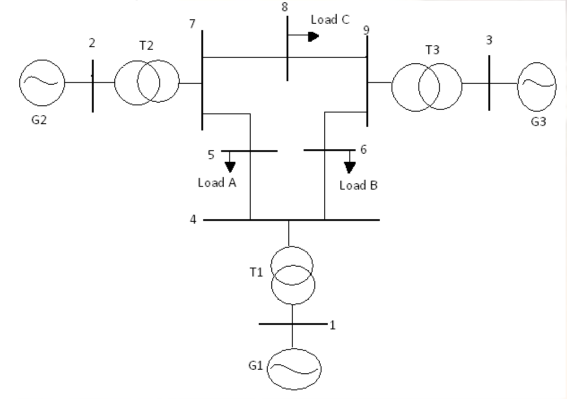

Fig. 5 9-bus system

Table 1 shows the bus data of the 9 bus system. The load and generation details with reactive power limits at the base case are given in the Table 2.

**Scenario A**: In this scenario, the real and reactive powers at all load buses are increased uniformly. In a deregulated environment power transfer can occur in practice from any point of generation to any point of load. Table 2 shows a case study in which the increase in demand is supplied by the generator connected at the slack bus alone.

Table 2 shows scenario A results of the 9 bus system without FACTS devices for some of the iteration. The details of load increase at bus 5, 6 and 8 and the corresponding increase in the generation and the value of continuation parameter '$\lambda$' obtained from the Continuation Power Flow Methodology are given in the Table 2. The convergence (the difference between the two successive values of '$\lambda$' is less than the specified error value) takes place at the 10th iteration, at which the value of $\lambda$ = 5.8194 and the corresponding CLP is 413.432 MW, 272.84 MVar.

The procedure for determination of CLP is repeated and the new value of CLP is calculated as 550.773 MW, 322.98 MVar and the improvement in the loadings is 137.341 MW, 50.14 MVar. Fig. 6 shows the nose curve of the 9 bus system with and without FACTS devices. In this case TCSC (70% of the line reactance of the critical line) is connected between the bus 4 -1.

Table 3 shows the CLP (first entry is P in MW and the second entry is Q in MVar) and its corresponding loading parameter obtained at the voltage collapse point of test system with and without FACTS devices.

**Scenario B:** The CLP is determined without FACTS devices and it is found as $\lambda$=17.6775. The CLP is determined using continuation power flow method and the Fig. 7 shows the improvement in voltage profile and in CLP. With TCSC the CLP is determined as $\lambda$ =36.9171.

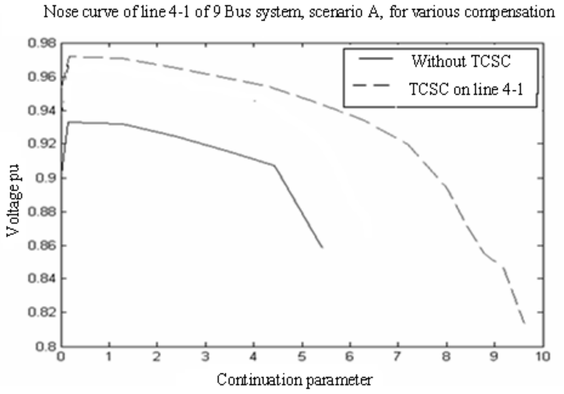

Fig 6 Nose curves for various level of compensation for 9 bus system, scenario A

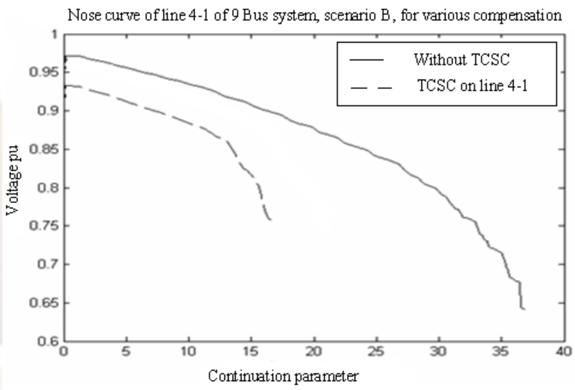

Fig 7 Nose curves for various level of compensation for 9 bus system, scenario B

## VII. Conclusion

This paper presents a Newton-Raphson power flow method considering FACTS controller TCSC. Algorithm is an attempt to increase the loadability limit of the 9- bus test system TCSC. Power flow analysis combined with continuation power flow and FACTS, provided promising results for the test system taken. TCSC also can help to reduce the flow in heavily loaded lines.

Other studies show that the coordinated application of multiple FACTS devices and their optimal location can increase the steady state voltage stability and voltage profile..

Table 1 9-bus Data

| Bus No. | Volt pu | Angle deg. | Load Mw | Load Mvar | Genration MW | Genration Mvar | $Q_{limits}$ Qmin | $Q_{limits}$ Qmax |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1.025 | 0 | 0 | 0 | 163 | 0 | -15 | 10 |
| 3 | 1.025 | 0 | 0 | 0 | 85 | 0 | -15 | 10 |
| 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1 | 0 | 60 | 90 | 0 | 0 | 0 | 0 |
| 6 | 1 | 0 | 90 | 60 | 0 | 0 | 0 | 0 |
| 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1 | 0 | 105 | 65 | 0 | 0 | 0 | 0 |
| 9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 2 Results of 9 bus system for various iterations in scenario A without FACTS devices**

| It No. | Generation | | | | Load | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P_1$ MW | $Q_1$ MVAR | $Q_2$ MVAR | $Q_3$ MVAR | $P_5$ MW | $Q_5$ MVAR | $P_6$ MW | $Q_6$ MVAR | $P_8$ MW | $Q_8$ MVAR | $\lambda$ |
| 0 | 12.2 | 73.9 | 41.19 | 21.22 | 60 | 90 | 90 | 60 | 105 | 65 | 0 |
| 2 | 69.19 | 86.89 | 46.47 | 33.43 | 82.59 | 99.04 | 106.3 | 65.42 | 123.1 | 71.32 | 1.807 |
| 4 | 126.6 | 115.93 | 47.97 | 49.45 | 104.99 | 107.99 | 122.4 | 70.8 | 141 | 77.6 | 3.599 |
| 6 | 149.9 | 150.56 | 49.75 | 48.87 | 113.8 | 111.52 | 128.7 | 72.91 | 148 | 80.06 | 4.304 |
| 8 | 164.2 | 193.82 | 46.72 | 49.91 | 118.87 | 113.55 | 132.4 | 74.13 | 152.1 | 81.48 | 4.709 |
| 10 | 175.5 | 220.39 | 49.04 | 49.91 | 122.87 | 115.15 | 135.3 | 75.09 | 155.3 | 82.6 | 5.819 |

**Table 3 Comparison of CLP in the 9-bus system with and without TCSC**

| Scenario | Without TCSC | | | With TCSC | | |
|---|---|---|---|---|---|---|
| | P(MW) | Q(Mvar) | $\lambda$ | P(MW) | Q(Mvar) | $\lambda$ |
| A | 413.432 | 272.84 | 5.8194 | 550.773 | 322.98 | 9.739 |
| B | 255 | 595.07 | 17.6775 | 255 | 1008.7 | *36.91* |

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