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Newton Raphson TCSC Model for Power System Stability Improvement

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Abstract – **Load flow problems and stabilityare the most important and essential issues to investigate problems in power system operating and planning. The specified generating and transmission network structure, load flow analysis solves the steady and transient operation states with node voltages and branch power flow.Here load flow in power system, bus classification, improving stability of power system, flexible ac system and advantages of using TCSC as series compensation is described.TCSC gives fair idea of advantages on use of reactive power compensators.The effectiveness and modelling is tested with five bus system with simple Newton Raphson method and usingTCSC.The mathematic model of load flow problem is a nonlinear algebraic equation system without differential equations. Power system dynamic analysis investigates system stability under some given disturbances. Its mathematic model includes differential equations. The analysis is based on load flow analysis and the algorithm of load flow analysis also the base for dynamic analysis methods. Therefore, familiarity with the theory and algorithms of load flow analysis is essential to understanding the methodology of modern power system analysis.**

Keywords – **TCSC (Thyristor Controlled Series Compensator), FACTS.**

INTRODUCTION

In a three phase ac power system active and reactive power flows from the generating station to the load through different networks buses and branches. The flow of active and reactive power is called power flow or load flow. Power flow studies provide a systematic mathematical approach for determination of various bus voltages, there phase angle active and reactive power flows through different branches, generators and loads under steady state condition.Power flow analysis is used to determine the steady state operating condition of a power system. Power flow analysis is widely used by power distribution professional during the planning and operation of power distribution system.The objective of power flow study is to determine the voltage and its angle at each bus, real and reactive power flow in each line and line losses in the power system for specified bus or terminal conditions.
Power flow analysis is very important in planning stages of new networks or addition to existing ones like adding new generator sites, meeting increase load demand and locating new transmission sites.

There are three methods for power flow study
1. Gauss Siedel method
2. Newton Raphson method
3. Fast decoupled method.

Here the Newton Raphson method is used to converge the load flow problem, this is an efficient method for the analysis of the power loss calculation and mismatching calculation with in the defined power system network. This is an effective tool for the modelling and solving of nonlinear equations, because to solve such type of equations, it is so effective by using other existing methods.

Newton-Raphson Method:

In the Newton-Raphson method, the root is not bracketed. In fact, only one initial guess of the root is needed to get the iterative process started to find the root of an equation. The method hence falls in the category of open methods. Convergence in open methods is not guaranteed but if the method does converge, it does so much faster than the bracketing methods.

Let the initial guess of the root of $f(x) = 0$ is at x_i, then if one draws the tangent to the curve $f(x_i)$, the point x_{i+1} where the tangent crosses the x-axis is an improved estimate of the root using the definition of the slope of a function, at $x = x_i$ $f'(x_i) = \tan\theta$ or $= \frac{f(x_i)-0}{x_i - x_{i+1}}$, which gives $x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)}$, (1) So starting with an initial guess, x_i, one can find the next guess, x_{i+1}, by using Equation (1). One can repeat this process until one finds the root within a desirable tolerance.

Algorithm

The steps of the Newton-Raphson method to find the root of an equation $f(x) = 0$ are

1. Evaluate $f'(x)$ symbolically
2. Use an initial guess of the root, x_i, to estimate the new value of the root, x_{i+1}, as

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)}$$

3. Find the absolute relative approximate error $\nabla x = x_i - x_{i+1}$ as
4. Compare the absolute relative approximate error with the pre-specified relative error tolerance, $\in_s$. If $\nabla x > \in_s$, then go to Step 2, else stop the algorithm. Also, check if the number of iterations has exceeded the maximum number of iterations allowed. If so, one needs to terminate the algorithm and notify the user.

The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels. It determines the voltage of the buses. The voltage level at the certain buses must be kept within the closed tolerances and system transmission loss minimizes. There are 3 types of busses defined mainly in power system.

PV Buses: For type PV buses, we know P_i and $|V_i|$ but not Q_i or θ_i. These buses fall under the category of *voltage-controlled buses* because of the ability to specify (and therefore to know) the voltage magnitude of this bus. Most generator buses fall into this category, independent of whether it also has load.

PQ Buses: For type PQ buses, we know P_i and Q_i but not $|V_i|$ or θ_i. All load buses fall into this category, including buses that have not either load or generation.

The third type of bus is referred to as the *swing bus*. Two other common terms for this bus are *slack bus* and *reference bus*. There is only one swing bus, and it can be designated by the engineer to be any generator bus in the system.

Let the $V_i\angle\delta_i \ \ and \ \ V_j\angle\delta_j$ are the voltages of two buses i and jwith phase angle $\delta_i \ and \ \delta_j$ respectively, as the power flows from i to j end. The line impedence between these two buses is $Y_{ij}$and the phase angle is θ_{ij}. Now the real and reactive power flow equations can be written as

$$P_k = \sum_{j=1}^{N} |V_i||V_j|\left(Y_{ij}\cos(\delta_i - \theta_{ij} - \delta_j)\right)$$
$$Q_k = \sum_{j=1}^{N} |V_i||V_j|\left(Y_{ij}\sin(\delta_i - \theta_{ij} - \delta_j)\right) \tag{2}$$

The Jacobian matrix is formed as

$$\overbrace{\underline{J}}^{(2N-1-N_G)\times(2N-1-N_G)} = \begin{bmatrix} \overbrace{\underline{J}^{P\delta}}^{(N-1)\times(N-1)} & \overbrace{\underline{J}^{PV}}^{(N-1)\times(N-N_G)} \\ \overbrace{\underline{J}^{Q\delta}}^{(N-N_G)\times(N-1)} & \overbrace{\underline{J}^{QV}}^{(N-N_G)\times(N-N_G)} \end{bmatrix}$$

At each iteration we have to form a Jacobian matrix and solve for the corrections from an equation given above. For the load flow problem, this equation is of the

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix} \text{ and } \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix}$$

where J is the Jacobian matrix

$$J = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_n} & |V_2|\frac{\partial P_2}{\partial |V_2|} & \cdots & |V_n|\frac{\partial P_2}{\partial |V_n|} \\ \vdots & J_{11} & \vdots & \vdots & J_{12} & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_n} & |V_2|\frac{\partial P_n}{\partial |V_2|} & \cdots & |V_n|\frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} & |V_2|\frac{\partial Q_2}{\partial |V_2|} & \cdots & |V_n|\frac{\partial Q_2}{\partial |V_n|} \\ \vdots & J_{21} & \vdots & \vdots & J_{22} & \vdots \\ \frac{\partial Q_n}{\partial \delta_2} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & |V_2|\frac{\partial Q_n}{\partial |V_2|} & \cdots & |V_n|\frac{\partial Q_n}{\partial |V_n|} \end{bmatrix}$$

II. LOAD FLOW ALGORITHM USING TCSC

The Newton-Raphson procedure with TCSC is as follows:

Step-1: Choose the initial values of the voltage magnitudes $|V|^{(0)}$ of all $n_p$load buses and n − 1 angles $\delta^{(0)}$of the voltages of all the buses except the slack bus.

Step-2: Implementthe TCSC as controlled variable reactance X_{TCSC}.

Step-3: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to calculate a total n − 1 number of injected real power $P_{calc}^{(0)}$and equal number of real power mismatch $\Delta P^{(0)}$.

Step-4: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to calculate a total n_p number of injected reactive power $Q_{calc}^{(0)}$ and equal number of reactive power mismatch $\Delta Q^{(0)}$.

Step-5: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to formulate the Jacobian matrix $J^{(0)}$.

Step-6: Solve for $\Delta\delta^{(0)}$ and $\Delta|V|^{(0}$.

$$\delta^{(1)} = \delta^{(0)} + \Delta\delta^{(0)} \tag{4}$$
$$|V|^{(1)} = |V|^{(0)} + \Delta|V|^{(0)} \tag{5}$$

Step-7: Obtain the updates from

Step-8: Check if all the mismatches are below a small number. Terminate the process if yes. Otherwise go back to step-1 with the updation of X_{TCSC} ($X_{TCSC}^{i+1} = X_{TCSC}^{i} + \Delta X$) to start the next iteration with the updates given by equations5 and 6.

Thyristor Controlled Series Capacitor (TCSC) is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating sub-synchronous resonance (SSR) and improving transient stability [3].The FACTS devices are located in the order to enhance the system security.

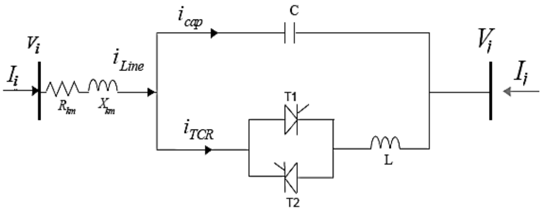

Fig.1. TCSC model adjusted between two buses

III. TCSC MODELLING

TCSC consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors T1 and T2. 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 operating principle of the TCSC, it can control the active power flow for the line *l* (between bus- *i*and bus- *j* where the TCSC is installed).

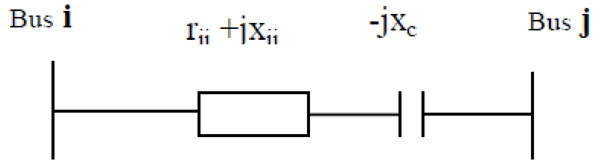

Fig 2. Equivalent Circuit of TCSC

The real power $P_{i\,inj}^{TCSC}$ and reactive power $Q_{i\,inj}^{TCSC}$ injected at bus I can be expressed as

$$P_{i\,inj}^{TCSC} = G_{ii}V_i^2 + (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij})V_iV_j$$

$$Q_{i\,inj}^{TCSC} = -B_{ii}V_i^2 + (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij})V_iV_j$$

where

$$G_{ij} = r_{ij} / (r_{ij}^2 + (X_{ij} - X_c)^2)$$

$$B_{ij} = X_{ij} - X_c / (r_{ij}^2 + (X_{ij} - X_c)^2)$$

Here, the only difference between normal line power flow equation and the TCSC line power flow equation is the controllable reactance x_c where TCSC acts as the capacitive or inductive compensation respectively. In this study, the reactance of the transmission line is adjusted by TCSC directly. The rating of TCSC depends on the reactance of the transmission line where the TCSC is located.

$$X_{ij} = x_{line} + x_{tcsc}$$

$$x_{tcsc} = r_{tcsc} . x_{line}$$

Where, x_{line} is the reactance of the transmission line and r_{tcsc} is the coefficient which represents the degree of compensation by TCSC. To avoid overcompensation, the working range of the TCSC is chosen between (-0.015 X line and 0.015 X line). By optimizing the reactance values between these ranges optimal settings of reactance values can be achieved.

(1) Equality constraints

The equality constraints of the OPF reflect the physics of the Power System as well as the desired voltage set points throughout the system. The physics of the Power System are enforced through the power flow equations which require that the net injection of real and reactive power at each bus sum to zero.

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) = 0$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) = 0$$

where P_{Gi} and Q_{Gi} are the real and reactive power outputs injected at bus- i respectively, the load demand at the same bus is represented by P_{Di} and Q_{Di}, and elements of the bus Admittance matrix are represented by $|Y_{ij}|$ and θ_{ij}.

(2)Inequality constraints

The inequality constraints of the OPF reflect the limits on physical devices in the Power System as well as the limits created to ensure system security. This section will lay out all the necessary inequality constraints needed for the OPF (optimal power flow).

Generators real and reactive power outputs

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1,\ldots,N_G$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i = 1,\ldots,N_G$$

Voltage magnitudes at each bus in the network

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1,\ldots,N_L$$

TCSC constraints: Reactance constraint of TCSC

$$X_{TCSC\,i}^{\min} \le X_{TCSC\,i} \le X_{TCSC\,i}^{\max}\, i = 1,2,\ldots,n_{TCSC}$$

where

X_{TCSCi} = Reactance of TCSC at line

$X_{TCSCi}^{\min}$ = Minimum reactance of TCSC at line

$X_{TCSCi}^{\max}$ = Maximum reactance of TCSC at line *i*

NTCSC= number of TCSC's

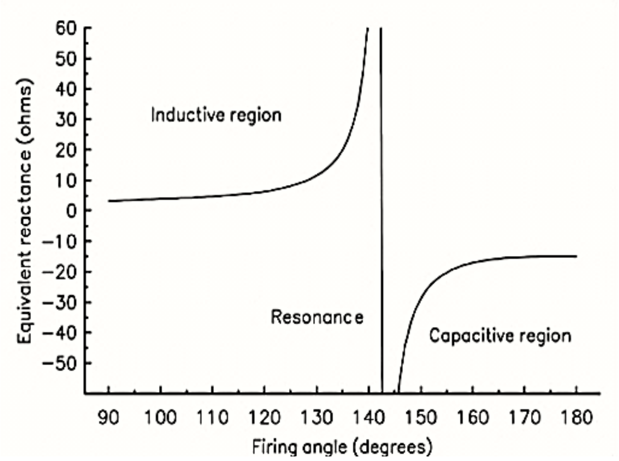

Fig.3. Relationship Between Firing Angle (α) and XTCSC

Working and implementation is completely described by the flow chart shown below.

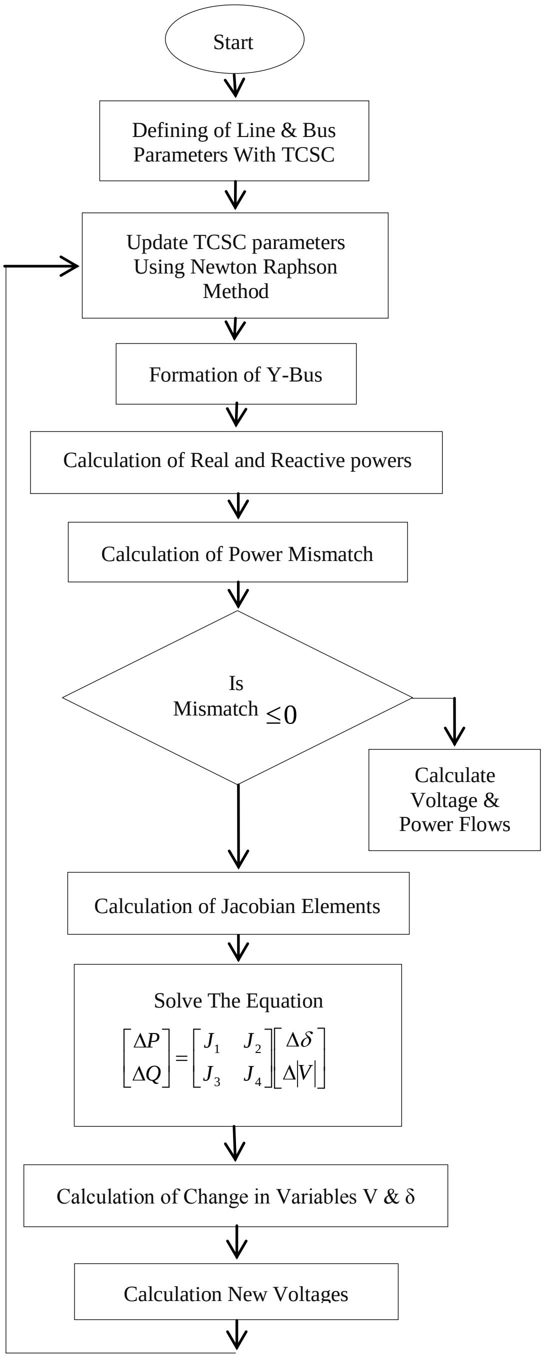

Fig. 4.Load Flow Algorithm using TCSC

III. LINE AND BUS DATA STANDARDISATION

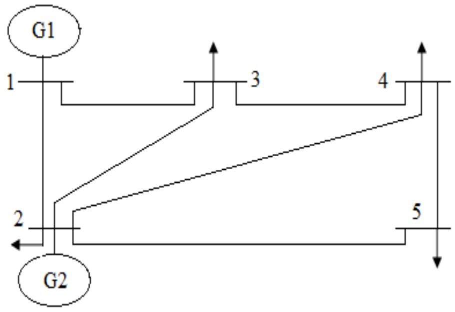

Fig.5. IEEE 5-bus system

Figure 2.1 shows a single line diagram of a 5 bus system with two generating units, seven lines. Per-unit transmission line series impedances and shunt susceptances are given in p.u. in Table1. Real power generation, real and reactive power loads in p.u. are given in Table 2.

With Bus 1is a slack bus, obtain a load flow solution by using Newton-Raphson method with tolerance of 0.002p.u for the real and reactive bus powers.

Table 1

Bus code From – to	Impedance R +jX	Line Charging B/2
1 - 2	0.02+j0.06	0.0+j0.030
1 -3	0.08 + j 0.24	0.0 + j0.025
2-3	0.06 + j0.18	0.0 + j0.02
2-4	0.06 + j0.18	0.0 + j0.02
2-5	0.04 + j0.12	0.0 + j 0.015
3-4	0.01 + j0.03	0.0 + j0.010
4-5	0.08 + j0.24	0.0 + j0.025

Table 2

Bus No	Bus Voltages	Generation MW	Generation MVAR	Load MW	Load MVAR
1	1.06+j0.0	0	0	0	0
2	1.00+j0.0	40	30	20	10
3	1.00+j0.0	0	0	45	15
4	1.00+j0.0	0	0	40	5
5	1.00+j0.0	0	0	60	10

IV. RESULT AND DISCUSSION

The proposed algorithm isimplementation using MATLAB and analysed for its perfectness. The TCSC is implemented between bus 1 and bus 2, the 5 bus system stability improves because of the reactive power compensated by TCSC within the system. The TCSC reactance variation according to step by step updation with respect to iteration is shown below. The maximum and minimum limit of reactance is allowed to vary is 0.050 p.u. and -0.050 p.u.

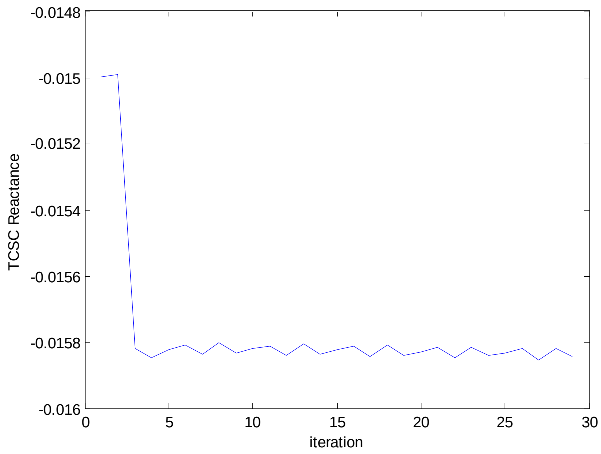

Fig.6. TCSC reactance variation according to Reactive Power compensation requirement

Here the reactance is varying with the requirement of -0.015 p.u at first iteration while it increases significantly iteration by iteration and adjusted significantly.

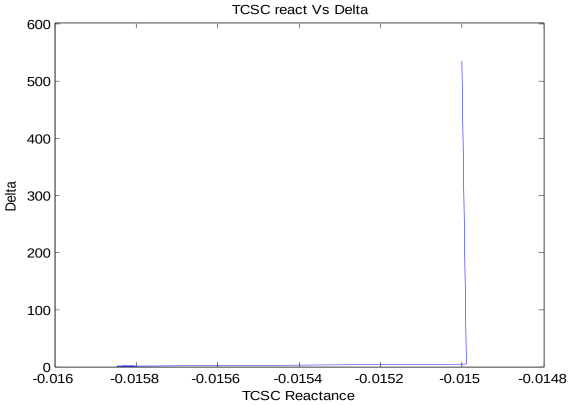

Fig.7. TCSC reactance variation with respect to the load angle (delta)

Here the TCSC is introducing capacitive reactance with the change in delta as per the reactive power compensation demand. From the figure (7) it is very clear that TCSC is introducing capacitive reactance.

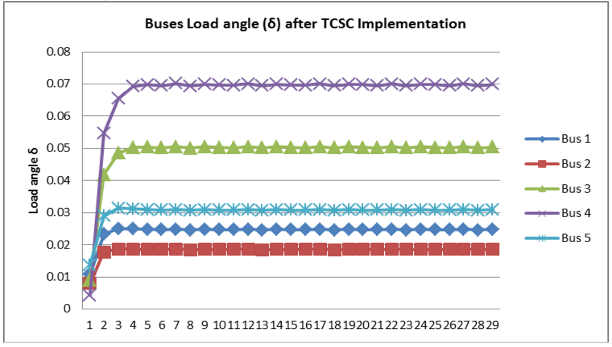

Fig.8. Updation of load angle (VA) with iteration with TCSC

The power angle for different buses updated precisely iteration by iteration, TCSC is implemented between bus 1 (slack bus) and load bus 2.

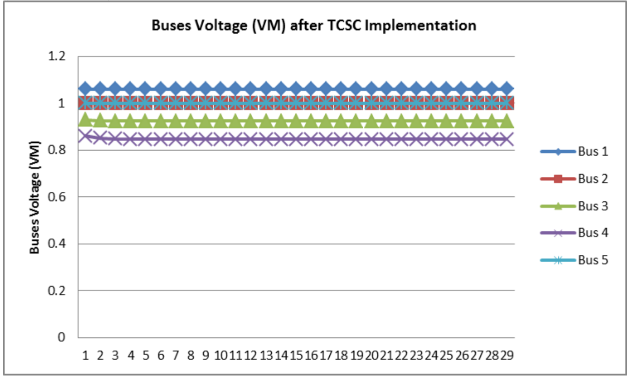

Fig.9. Updation of busesVoltage (MV) with iteration with TCSC

In the buses the voltage magnitude updated and compensated with the updation of bus parameters and TCSC parameters. The magnitude of voltage is maintained at 1.000065 p.uin bus 2.

The reactive power with the TCSC implementation is very low which is negligible.

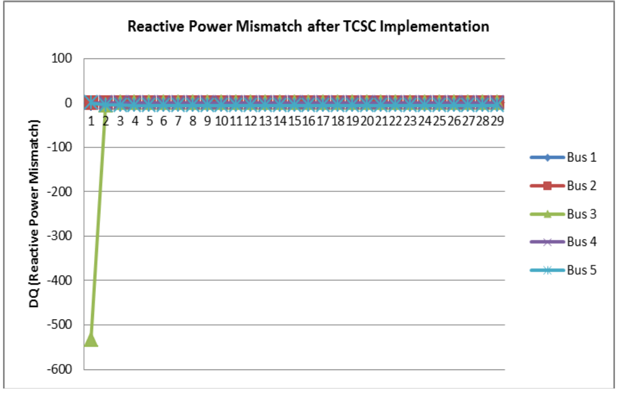

Fig.10. Reactive Power mismatch

Now the load angle stability response is shown in the figure 11, here it is very clear the load angle stabilized more in the 5-bus system than the Newton Raphson based optimisation only.

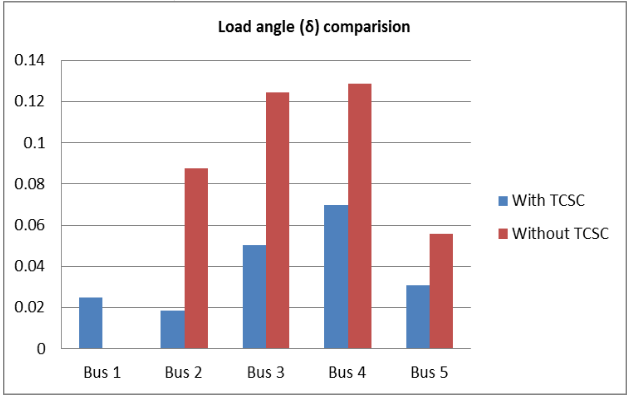

Fig.11. Power angle (δ) stabilization with TCSC and without TCSC

Comparison of buses voltage stabilization is shown below in figure 12, here variation in bus 2 is more with the TCSC implementation as compared to Newton Raphson based optimisation.

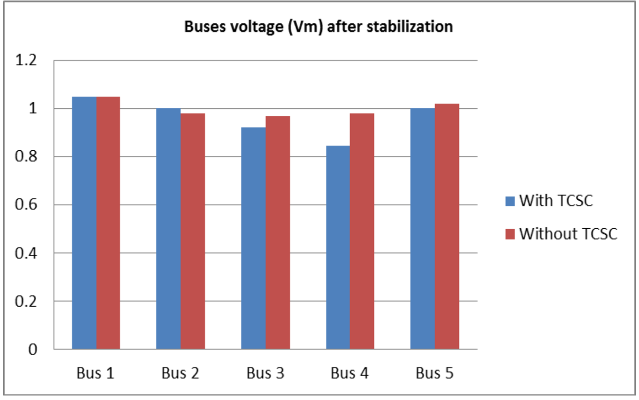

Fig.12. Bus Voltage (δ) stabilization with TCSC and without TCSC

Here the bus voltage stabilization with TCSC and the bus voltage stabilization without TCSC i.e. Newton Raphson only.

V. CONCLUSION

This paper addresses the TCSC power flow model. This model is implemented in Matlab using the Newton-Raphson load flow algorithm, which is capable of solving large power networks very reliably. The algorithm with TCSC retains Newton's quadratic convergence and its efficiency is illustrated by some power flow solutions of the power transmission systems. The calculations of the conventional power flow indicate some suggestions relating to the locations of TCSC. Two case studies for applying the variable series impedance power flow model of TCSC are clear evidences with respect to modelling and using TCSC to control power flows on the power system. The computation results show that suitable allocation of TCSC can improve the transfer capability.

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