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# Power Flow Control in Multi-bus System with Auxiliary control of TCSC Controller

**Jayshankar Prasad Pandey*** **and Girraj Prasad Rathor**
Technocrats Institute of Technology & Science (TIT&S), RGPV, Bhopal, Madhya Pradesh, India.
*Corresponding author email id: jayshankarpandey8878@gmail.com

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***Abstract*** **– The most important and essential issues in power systems are load flow problems and stability. The electric power-flow problem, a part of power engineering, needs accurate and real-time calculation of loading at demand (receiving end) and generation (transmission end) levels. The calculation of load flow, which is subjected to stability and transient proficiency of generator, provides voltages and power flows for a specific power system. This paper presents implementation of thyristor control series capacitor (TCSC) and auxiliary control that can be deployed in the network to improve the voltage profile of a system-based reactive control. Also, TCSCs can be used as controllable devices in power flow and voltage control devices. The Jacobian matrix is the core part of power flow analysis, which is the basis for power system planning and operations. This paper estimates the Jacobian matrix in high dimensional space. To control the performance of a power network under these conditions, FACTS devices like TCSC are incorporated. The models used are incorporated in an existing Newton Raphson Load Flow (NRLF) algorithm using standard IEEE 5 bus system.**

***Keywords*** **– TCSC, FACTS, SSR, NRLF, Jacobian, Optimal Power Flow.**

## I. INTRODUCTION

The utilization of electricity becomes mandatory for the whole world. For transmitting power through AC systems were implemented for easier transmission of power, high economizing, and better control compared to DC transmission systems. Power produced through DC machines is costly; does not have neither DC transformer for stepping up voltage nor DC circuit breaker; which are the major restrictions for DC power transmission [1]. The electric power-flow problem, a part of power engineering, requires accurate and real-time calculation of loading at demand (receiving end) and generation (transmission end) levels. 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 [2]. The main aim of the operations of the power system is to meet the demand with proper power supply: providing adequate reactive power compensation; maintaining voltage and frequency through AVR; and ensuring reliable power systems' operations.

One of the important jobs of the voltage regulator is to improve the power system stability of the electricity transmission. Improvement in the power system stability indicates an increase in the maximum power transfer capability for the existing power system network. The major factors affecting voltage stability of a power system are its generators reactive power limit, voltage actions [3] control limits, characteristics of connected loads, reactive power compensation devices characteristics and their actions. The potential benefits of using Flexible AC Transmission system (FACTS) controllers for enhancing power system stability are well known. The use of these controllers gives grid planners and operators a greater flexibility regarding the type of control actions that can be taken at any given time. Thyristor Controlled Series Capacitors (TCSC), in particular, have been widely studied and reported in the technical literature, and have been shown and used in practice to significantly enhance system stability [8].

There some most usable power flow methods are: (i) Gauss-Seidel method (ii) Fast-decoupled-load-flow method (iii) Holomorphic embedding load flow method (iv) Backward-Forward Sweep (BFS) method. In this paper the Newton Raphson method is used to converge the load flow problem. This method begins with initial guesses of all unknown variables (voltage magnitude and angles at Load Buses and voltage angles at Generator Buses). Next, a Taylor Series is written, with the higher order terms ignored, for each of the power balance equations included in the system of equations. 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. The buses exist in the power system are:

### *Slack Bus:*

Slack bus *(or swing bus)*, defined as a Vδ bus, is used to balance the active power |P| and reactive power |Q| in a system while performing load flow studies.

### *Generator Buses:*

PV buses, we know $P_i$ and $|V_i|$ but not $Q_i$ or $\theta_i$

### *Load Buses*:

PQ buses, we know $P_i$ and $Q_i$ but not $|V_i|$ or $\theta_i$, including buses that have not either load or generation.

Let the $V_i\angle\delta_i$ and $V_j\angle\delta_j$ are the voltages of two buses i and j with phase angle $\delta_i$ and $\delta_j$ respectively, as the power flows from i to j end. The line admittance between these two buses is $Y_{ij}$ and existing phase angle is $\theta_{ij}$. Power flow equations are to be written as:

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

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

The Jacobian matrix is formed as

$$\overbrace{\underline{M_J}}^{(2N-1-N_G)\times(2N-1-N_G)} = \begin{bmatrix} \overbrace{\underline{M_J}^{P\delta}}^{(N-1)\times(N-1)} & \overbrace{\underline{M_J}^{PV}}^{(N-1)\times(N-N_G)} \\ \overbrace{\underline{M_J}^{Q\delta}}^{(N-N_G)\times(N-1)} & \overbrace{\underline{M_J}^{QV}}^{(N-N_G)\times(N-N_G)} \end{bmatrix} \tag{3}$$

Iteration wise there will be four equations. For the load flow problem, this equation is of the

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = M_J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix} \text{and} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n \end{bmatrix}$$

Where $M_J$ is the Jacobian matrix $M_J = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_n} & |V_2|\frac{\partial P_2}{\partial |V_2|} & \cdots & |V_n|\frac{\partial P_2}{\partial |V_n|} \\ \vdots & M_{J11} & \vdots & \vdots & M_{J12} & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_n} & |V_2|\frac{\partial P_n}{\partial |V_2|} & \cdots & |V_n|\frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} & |V_2|\frac{\partial Q_2}{\partial |V_2|} & \cdots & |V_n|\frac{\partial Q_2}{\partial |V_n|} \\ \vdots & M_{J21} & \vdots & \vdots & M_{J22} & \vdots \\ \frac{\partial Q_n}{\partial \delta_2} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & |V_2|\frac{\partial Q_n}{\partial |V_2|} & \cdots & |V_n|\frac{\partial Q_n}{\partial |V_n|} \end{bmatrix}$

## II. LOAD FLOW ALGORITHM USING TCSC

*Newton-Raphson Method:*

Let the initial set the root of $Ø(x) = 0$ is at $x_i$, then if it is drawn the slop to the curve $Ø(x_i)$, the point $x_{i+1}$ where the tangent crosses the $x$-axis will become optimal estimate of the root using the definition of the slope of a function, at $x = x_i$ $Ø'(x_i) = \frac{Ø(x_i),-0}{x_i - x_{i+1}}$, which gives

$$x_{i+1} = x_i - \frac{Ø(x_i)}{Ø'(x_i)} \tag{5}$$

The NR method for the calculation of power mismatch:

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: Implement the 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 $\Delta|V|^{(0)}$.

$$\delta^{(1)} = \delta^{(0)} + \Delta\delta^{(0)} \tag{6}$$

$$|V|^{(1)} = |V|^{(0)} + \Delta|V|^{(0)} \tag{7}$$

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.

*Transmission Line Model:*

Overhead transmission lines are modelled by their equivalent pi ($\pi$) model as shown in Fig. 1. The series impedance Z or its inverse which is the admittance Y depends on the short circuit current, Ish, whereas the admittance ($g_l + jb_l$) is a function of the no-load current. Io.

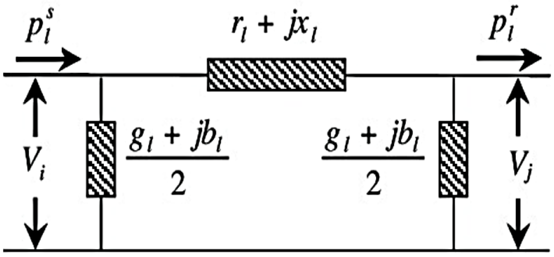

Fig. 1. Transmission line pi $(\pi)$ model [1].

## III. TCSC MODELLING

To divert power flow through the TCSC compensated line when a parallel path is overloaded, one would need to first sense that such a condition exists. Therefore, the current in the parallel tie line is measured. In case, the current magnitude in the parallel tie line is greater than the permissible value due to thermal limit, increase the power (or current) flow in the TCSC compensated line by increasing the TCSC capacitive reactance. Since the effective impedance of the TCSC compensated line is reduced, it will take on a larger share of the total power flow between the two areas [1].

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.

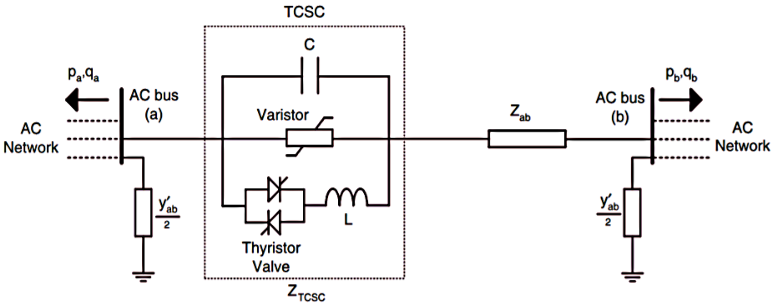

Fig. 2. TCSC model for power flow in AC systems [6].

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).

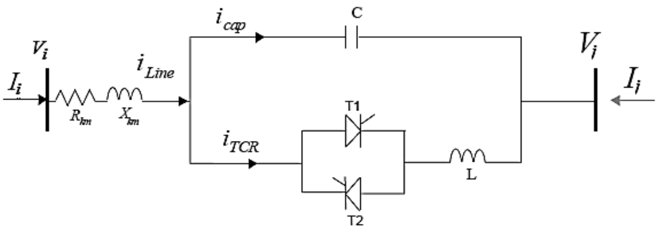

Fig. 3. TCSC model adjusted between two buses [9].

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

$$P_{i\,inj}^{TCSC} = G_{ii}V_i^2 + (G_{ij}cos\theta_{ij} + B_{ij}sin\theta_{ij})V_iV_j \tag{8}$$

$$Q_{i\,inj}^{TCSC} = -B_{ii}V_i^2 + (G_{ij}sin\theta_{ij} - B_{ij}cos\theta_{ij})V_iV_j \tag{9}$$

where

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

TCSC works in-

1. *Blocking mode:* In this mode the TCSC performs like a fixed series capacitor.
2. *Bypass mode:* In this case the TCSC behaves like a parallel connection of the series capacitor and the inductor.

The rating of TCSC depends on the reactance of the transmission line where the TCSC is located.

$$X_{ij} = {}^{x}line\ {}^{+x}tcsc \tag{10}$$

$$x_{tcsc} = r_{tcsc} \cdot x_{line} \tag{11}$$

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.

### *Optimal Power Flow Inequality Constraints*

For the optimal power flow, the inequality constraint are the important assumptions to ensure the system stability in power systems.

Generators real and reactive power outputs

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

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

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

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*.

$N_{TCSC}$ = Number of TCSC's.

$$X_{t\,csc} = \frac{X_c\left[\pi(k^2-1)^2 - k^2(k^2-1)(2\beta + \sin 2\beta) + 4k^2\cos^2\beta(k \tan k\beta - \tan\beta)\right]}{\pi(k^2-1)^2} \tag{12}$$

Where, $k = \sqrt{\frac{X_c}{X_L}}$, $\beta = \pi - \alpha$, $X_C$ and $X_L$ are reactance's

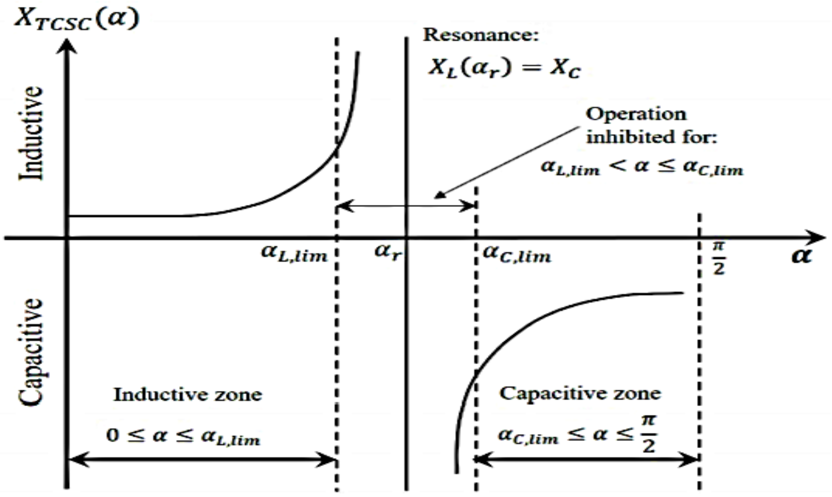

Fig. 4. Relationship between Firing Angle (α) and XTCSC [10].

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

Steps of the proposed approach to solve the power flow problem:

1. Feed the Line & Bus Parameters including TCSC.
2. Formation of Y-Bus.
3. Adjust TCSC reactance by Newton Raphson optimization.
4. Calculate Real and Reactive Power Mismatch.
5. Take decision to decide the minimal mismatch.
6. Calculate Jacobian Elements.
7. Calculate change in Variables V & δ.
8. Calculate New Voltages and firing angle.

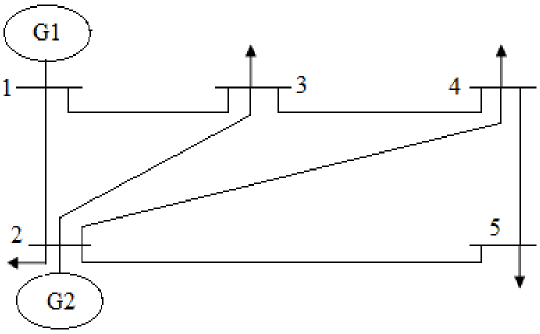

Fig. 5. IEEE 5-bus system.

Figure 5 shows a single line diagram of a 5-bus system with two generating units, seven lines. Per-unit transmission line series impedances and shunt susceptance are given in p.u. in Table 1.

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 (Bus-Bus) | Impedance R +jX | Line Charging Susceptance B/2 |
|---|---|---|
| 1 - 2 | 0.02 + j0.05 | 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 (pu) | Generation (MW) | Generation (MVAR) | Load (MW) | Load (MVAR) |
|---|---|---|---|---|---|
| 1 | 1.05+j0.0 | 0 | 0 | 0 | 0 |
| 2 | 1.00 +j0.0 | 40 | 29 | 20 | 10 |
| 3 | 1.00 +j0.0 | 0 | 0 | 44 | 15 |
| 4 | 1.00 +j0.0 | 0 | 0 | 41 | 4 |
| 5 | 1.00 +j0.0 | 0 | 0 | 61 | 12 |

## IV. RESULT AND DISCUSSION

The proposed work is implemented in MATLAB and found results. TCSC is imparted between bus 1 and bus 2. Variation in mismatch in real and reactive powers is calculate along with the buses voltage and load angle with respect to iterations. The constraint limit of reactance is set to vary between 0.050 p.u. and -0.050 p.u.

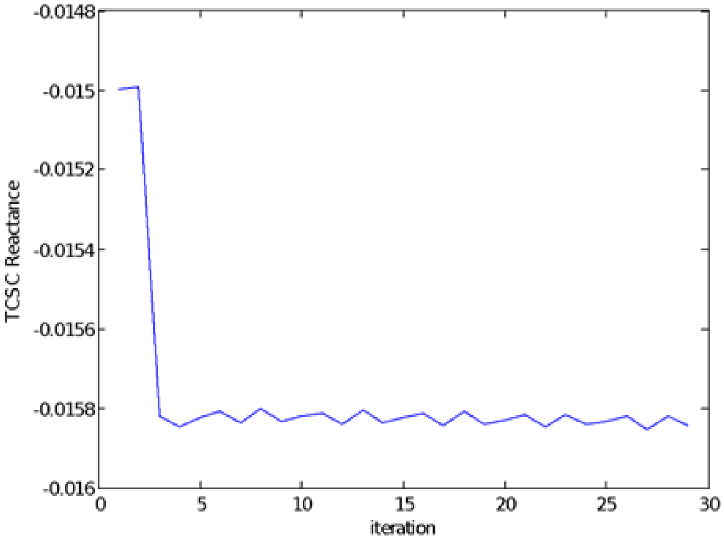

Fig. 6. TCSC reactance ($X_{TCSC}$) variation with the iteration.

From the above fig. 6. It is clear that TCSC is generating reactance with the change in delta in accordance reactive power compensation. TCSC is generating significant capacitive reactance [25].

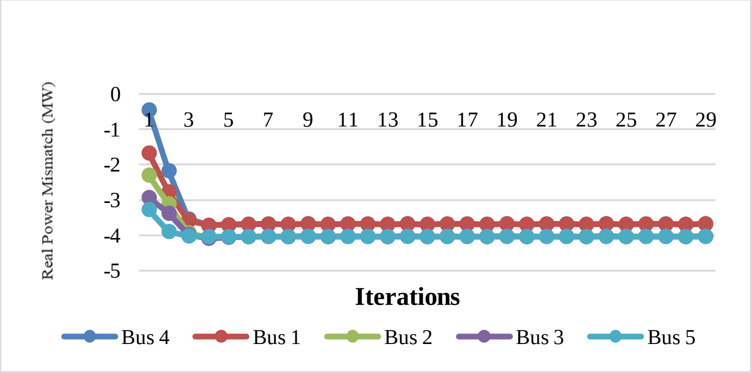

Fig. 7. Real Power Mismatch with the iteration.

The buses active power stabilised with the TCSC implementation. Mismatch in the real power with the pupation of reactance in the line where the TCSC is implemented shown properly in figure (7).

The reactive power mismatch is minimum with the TCSC implementation. TCSC works to modify the required effective reactance in the system to overcome the power mismatch problem. This is clearly shown in figure (8).

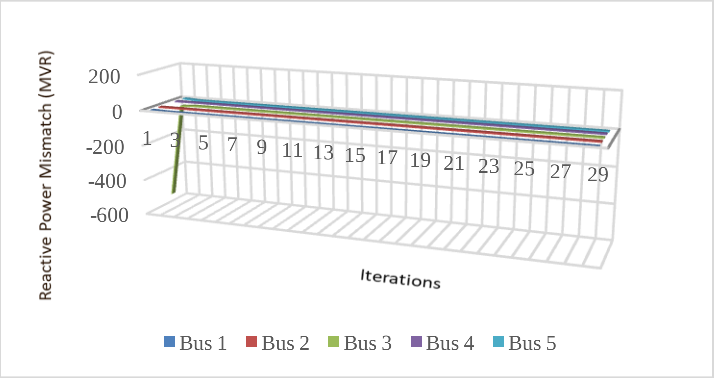

Fig. 8. Reactive Power mismatch (MVR) with iteration

The load angle mismatch response is shown in the figure 9, the load angle stability is more in the 5-bus system than the without TCSC implementation.

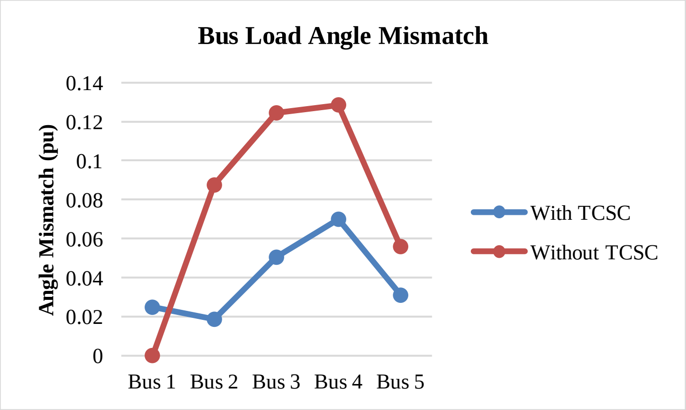

Fig. 9. Bus Load Angle Mismatch.

If we look in the figure (10), it is clear that the bus voltage changes as per the system stability requirement. The comparison results depicting the effectiveness of the proposed method.

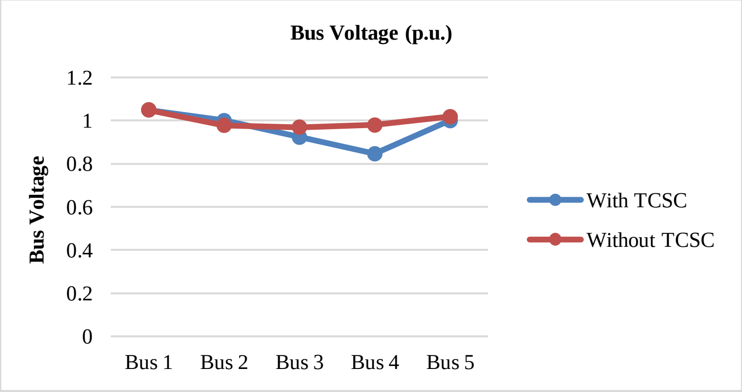

Fig. 10. Buses Voltage with TCSC and without TCSC.

As the effective reactance changes the buses voltage also change accordingly to ensure the system stability requirement.

## V. CONCLUSION

The auxiliary control of TCSC ensures the effective working of it. This is a very good approach to control TCSC with effective optimization approaches. Optimal power flow is very essential to protect the devices and power system itself for the reliable operation for the utility demand and quality. Here a NR approach is opted to control the TCSC reactance to enhance the power system performance and stability. From the results it is clear that the proposed approach works well with the stabilization of power, minimizing power mismatch, minimizing buses voltage and busses load angle. Effective working of the TCSC can be further improved with more effective approaches.

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## AUTHOR’S PROFILE

**First Author**
**Jayshankar Prasad Pandey,** Technocrats Institute of Technology & Science (TIT&S), RGPV, Bhopal, Madhya Pradesh, India.

**Second Author**
**Girraj Prasad Rathor,** Technocrats Institute of Technology & Science (TIT&S), RGPV, Bhopal, Madhya Pradesh, India.