International Journal of Scientific Research & Engineering Trends
Volume 10, Issue 6, Nov-Dec-2024, ISSN (Online): 2395-566X

# Advanced Load Flow Analysis Techniques in MATLAB the Swing Equation and Newton-Raphson Method

**Mr.Barkat Ali Lone, Assistant Professor Mr. Kamaljeet Singh, Assistant Professor Mr. Parwinder Singh**
Electrical Engineering.
IET Bhaddal Technical Campus

**Abstract- This paper presents a brief idea on load flow in power system, bus classification, improving stability of power system, flexible ac system, various controllers of FACTs and advantages of using TCSC in series compensation. It presents the modelling scheme of TCSC and the advantages of using it in power flow network. The plots obtained after simulation of network using MATLAB both with and without TCSC gives fair idea of advantages on use of reactive power compensators. load flow studies are fundamental in power system analysis for ensuring efficient and stable operation of electrical networks. This thesis investigates the application of the swing equation and the Newton-Raphson method in performing load flow analysis, aiming to enhance the accuracy and efficiency of power system evaluations. The swing equation, representing the dynamic response of a generator's rotor to changes in system conditions, is used to model the transient behaviour of generators in power systems. This dynamic model is crucial for understanding how generators respond to load variations and network disturbances. However, for steady-state analysis, which is essential for system planning and operation, the swing equation's role is more implicit, focusing on power balance and network equilibrium. In this study, we integrate the swing equation into a comprehensive load flow analysis framework, combining it with the Newton-Raphson method—a robust iterative technique for solving nonlinear algebraic equations. The Newton-Raphson method is employed to solve the power flow equations, which describe the relationship between generator outputs, load demands, and network configurations. The thesis details the formulation of the power flow equations and the application of the Newton-Raphson method to solve these equations efficiently. The integration of the swing equation helps refine the analysis by incorporating generator dynamics into the power flow study. The effectiveness of this approach is demonstrated through various case studies on different network configurations, showing improvements in both accuracy and convergence speed compared to traditional methods**

**Index Terms- Newton-Raphson, networks, Renewable sources**

## I. INTRODUCTION

Load-flow studies are probably the most common of all power system analysis calculations. They are used in planning studies to determine if and when specific elements will become overloaded. Major investment decisions begin with reinforcement strategies based on load-flow analysis. In operating studies, load-flow analysis is used to ensure that each generator runs at the optimum operating point; demand will be met without overloading facilities; and maintenance plans can proceed without undermining the security of the system.

The objective of any load-flow program is to produce the following information:

- Voltage magnitude and phase angle at each bus.
- Real and reactive power flowing in each element.
- Reactive power loading on each generator.

The above objectives are achieved by supplying the load- flow program with the following information:

- Branch list of the system connections i.e., the impedance of each element, sending-end and receiving-end node #. Lines and transformers are represented by their π-equivalent models.
- Voltage magnitude and phase-angle at one bus, which is the reference point for the rest of the system.
- Real power generated and voltage magnitude at each generator bus.
- Real and reactive power demanded at each load bus.

The foregoing information is generally available since it either involves readily known data (impedances etc.) or quantities which are under the control of power system personnel (active power output and excitation of generators.)

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Simply stated the load-flow problem is as follows:

- At any bus there are four quantities of interest: │V│, θ, P, and Q.
- If any two of these quantities are specified, the other two must not be specifiedotherwise we end up with more unknowns than equations.
- Because records enable the real and reactive power to be accurately estimated at loads, P and Q are specified quantities at loads, which are called PQ buses.

Likewise, the real power output of a generator is controlled by the prime mover and the magnitude of the voltage is controlled by the exciter, so and P and │V│ are specified at generators, which are called PV buses.

- This means that │V│ and θ are unknown at each load bus and θ and Q are unknown at each generator bus.
- Since the system losses are unknown until a solution to the load-flow problem has been found, it is necessary to specify one bus that will supply these losses. This is called the slack (or swing, or reference) bus and since P and Q are unknown, │V│ and θ must be specified. Usually, an angle of θ = 0 is used at the slack bus and all other bus angles are expressed with respect to slack.

The foregoing is summarized in the following one-line diagram in which the specified quantities are italicized, while the quantities that are free to vary during the iteration process are indicated with up-and-down arrows. Note that at each bus we can write TWO node equations.

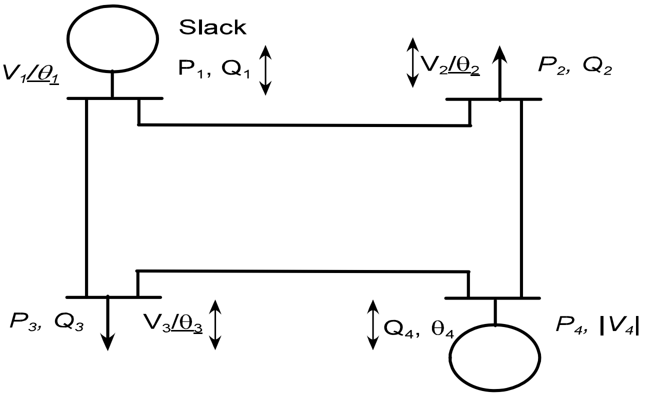


Fig 1: There three methods for load flow studies mainly

**Major Iterative Techniques**
**The Gauss-Seidel Method**
The Gauss-Seidel method is based on substituting nodal equations into each other. It is the slower of the two but is the more stable technique. Its convergence is said to be Monotonic. The iteration process can be visualized for two equations:

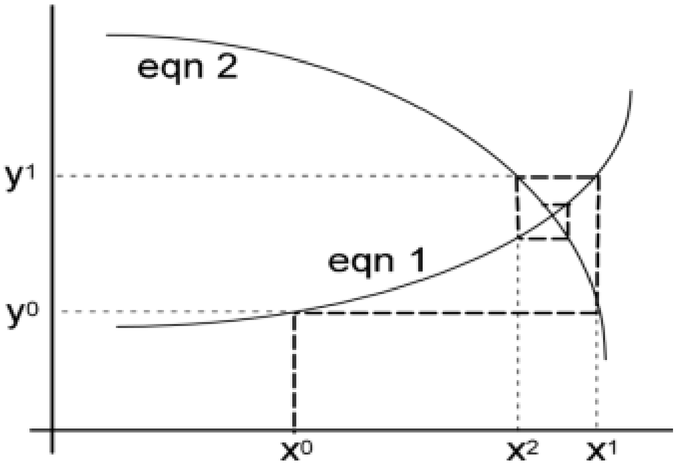


Fig 2 Gauss-Seidel method iterative techniques

Although not the best load-flow method, Gauss-Seidel is the easiest to understand and was the most widely used technique until the early 1970s.
Some software packages use Gauss-Seidel to start the solution process and then switch over to:

**B. The Newton-Raphson Method**
The Newton-Raphson method is the most efficient load-flow algorithm. The basic (no approximations) Newton-Raphson algorithm is based on the formal application of a well-known algorithm for the solution of a set of simultaneous non-linear equations of the form:

**[F(x)] = [0]**
Where: [F(x)] is a vector of functions: $f_1$ --- $f_n$ in the variables $x_1$ --- $x_n$.

The above expression does not equal zero until the Newton-Raphson process has converged (i.e., all the x's have been found) and the iterations have to be performed, starting at some initial set of values $x_1$, $x_2$, --- $x_n$. In the load-flow problem the x's are voltage magnitude and phase angle at all PQ buses and voltage phase angles at all PV buses i.e., angles at all buses except slack and │V│ for all load buses. The iterations are performed by linearizing the non-linear equations [F(x)] = [0] and adjusting the values of x. This process can be visualized in the case of a single variable problem, which could be formed by subtracting the two equations used at the beginning of the Gauss-Siedel section, i.e. f(x) = eqn 1 – eqn 2 {f(x) = 0 at the solution}

**f(x) = 0** is the required solution.

The initial estimate is $\mathbf{x^0 \approx x + \Delta x}$. This can be improved by applying trigonometry once the function has been differentiated.

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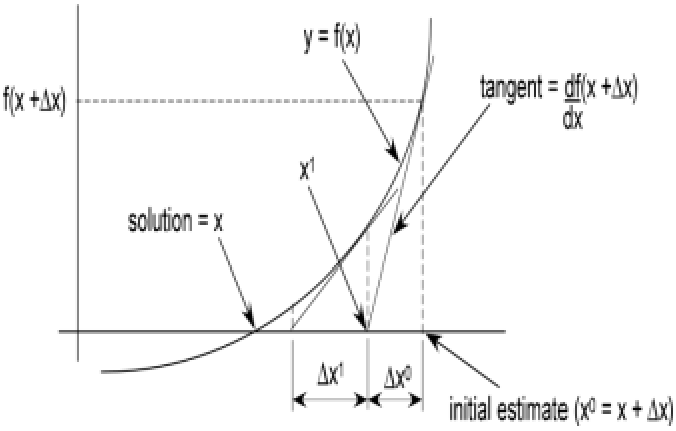


Fig 1 Newton-Raphson method iterative techniques

An estimate for **Δx** is obtained from:

$$\Delta x0 = f(x + \Delta x) \Big/ \frac{df(x + \Delta x)}{dx}$$

Then the estimate of **x** is improved by:

$$\mathbf{x^1 = x^o - \Delta x^o}$$

Information available from load-flow studies

The basic information contained in the load-flow output is:

- All bus voltage magnitudes and phase angles w.r.t the slack bus.
- All bus active and reactive power injections.
- All line sending- and receiving-end complex power flows.
- Individual line losses can be deduced by subtracting receiving-end complex power from sending-end complex power.
- Total system losses can be deduced by summing item
- for all lines, or by summing complex power at all loads and generators and subtracting the totals.

The most important information obtained from the load-flow is the voltage profile of the system. If │V│ varies greatly over the system, large reactive flows will result; this, in turn, will lead to increased real power losses and, in extreme cases, an increased likelihood of voltage collapse. When a particular bus has an unacceptably low voltage, the usual practice is to install capacitor banks in order to provide reactive compensation to the load. Load-flow studies are used to determine how much reactive compensation should be applied at a PQ bus, to bring its voltage up to an appropriate level, i.e.:

Re-execute the load-flow with the bus re-designated as PV type with the required voltage level specified.

- Subtract the value of Q obtained from i) from the value obtained in the old load flow when the bus was PQ.
- The result is the value of $Q_c$ needed to bring the voltage up to the specified level. Note that if the specified voltage is not 1 pu, then the value of $Q_c$ has to be adjusted by $1/|V|^2$ in order to specify $Q_c$ at rated voltage.

## II. PROBLEM STATEMENT

The importance of power system stability is increasingly becoming one of the most limiting factors for system performance. By the stability of a power system, we actually mean the ability of the system to remain in operating equilibrium, or synchronism, while disturbances occur on the system. There are three types of stability, namely, steady-state, dynamic and transient stability.

**Stability Definitions**
In the study of electric power systems, several different types of stability descriptions are encountered. There are three types of stability namely,

**Steady-state Stability** –It refers to the stability of a power system subject to small and gradual changes in load, and the system remains stable with conventional excitation and governor controls.

**Dynamic Stability** –It refers to the stability of a power system subject to a relatively small and sudden disturbance, the system can be described by linear differential equations, and the system can be stabilized by a linear and continuous supplementary stability control.

**Transient Stability** –It refers to the stability of a power system subject to a sudden and severe disturbance beyond the capability of the linear and continuous supplementary stability control, and the system may lose its stability at the first swing unless a more effective countermeasure is taken, usually of the discrete type, such as dynamic resistance braking or fast valving for the electric energy surplus area, or load shedding for the electric energy deficient area. For transient stability analysis and control design, the power system must be described by nonlinear differential equations. Transient stability concerns with the matter of maintaining synchronism among all generators when the power system is suddenly subjected to severe disturbances such as faults or circuits caused by lightning strikes, the sudden removal from the transmission system of a generator and/or a line, and any severe shock to the system due to a switching operation. Because of the severity and suddenness of the disturbance, the analysis of transient stability is focused on the first few seconds, or even the first few cycles, following the fault occurrence or switching operation. First swing analysis is another name that is applied to transient stability studies, since during the brief period following a severe disturbance the generator undergoes its first transient overshoot, or swing.

If the generator can get through it without losing synchronism, it is said to be transient stable. On the other hand, if the generator loses its synchronism and cannot get through the first swing, it is said to be unstable.

There is a critical angle within which the fault must be cleared if the system is to remain stable. The equal-area criterion is needed and can be used to understand the power system stability. some simple figures can be utilized to graphically represent the difference between a stable case and an unstable case. In a stable case, as shown in Figure below, if the fault is cleared at tc1 second, or at angle $\delta_{c1}$ where the area Aa (area associated with acceleration of the generator) equals the area Ad (area associated with deceleration of the generator).

One can see that the angle reaches its maximum at and never gets greater than this value. In the unstable case, as shown in Figure, the fault is cleared at $t_{c2}$ second with the area Aa greater than the area Ad.

Also, it is very clear that for an unstable case, with the fault cleared at $t_{c2}$ the angle keeps increasing and goes out-of-step, or unstable, as shown in Figure below.

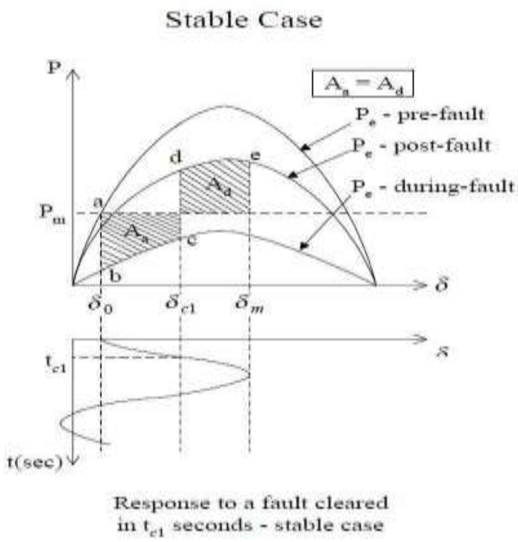


Fig 4 First swing analysis for a stable case

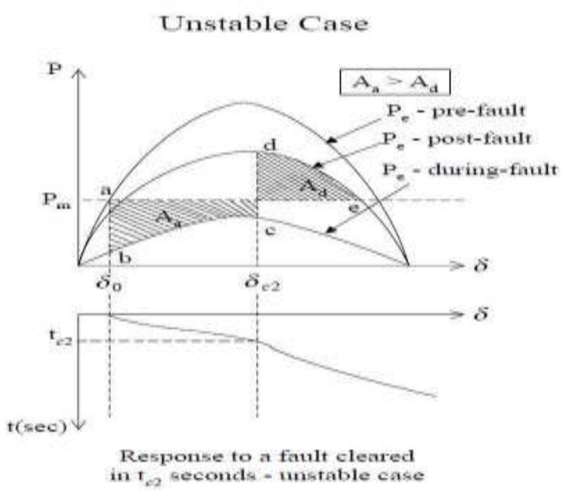


Fig 5 First swing analysis for an unstable case

**Swing Equation**

The moment of inertia and the accelerating torque of a synchronous machine can be related as following

$$\frac{Jd^2\delta m}{dt^2}$$

Where J=moment of inertia
$\delta m$= mechanical angle

And $T_a=T_M$ - $T_e$= accelerating torque= the difference mechanical torque and electromagnetic torque.

The relationship between the mechanical angle and the electrical angle can be expressed

$$\delta == p\delta m/2$$

Where p is the number of poles of the machine.

Then the equation of accelerating torque can be written as

$$J.2.\frac{d^2\delta}{pdt^2} = \omega_s.T_a = P_a$$

A commonly used constant, inertia constant H is defined as the ratio between the stored energy in watt-seconds and VA rating of the machine, namely

$$H=\frac{1}{2}J\omega_s./S$$

It can be re-arranged as

$$2HS = J\omega_s$$

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One can relate this equation to the equation for the accelerating power Pa

$$2\frac{H}{\omega_{s.}}S.2.\frac{d^2\delta}{pdt^2} = P_a$$

If one defines

$$\omega_s = P\omega_{s'}/2$$

Then the above equation can be expressed as

$$2\frac{H}{\omega_s}.\frac{d^2\delta}{dt^2} = P_a/S$$

Where all the quantities are in their actual values

Finally, the swing equation with the accelerating power in per unit value can be obtained as follows

$$2\frac{H}{\omega_o}.\frac{d^2\delta}{dt^2} = P_a$$

Or

$$M\frac{d^2\delta}{dt^2} = P_a$$

,
Where M is the angular momentum

And $M = 2\frac{H}{\omega_0} = H/60\pi$

For the frequency of 60 hertz.

**Objective of the Load Flow Study**

- 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.
- 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 is helpful in determining the best location as well as optimal capacity of proposed generating station, substation and new lines.
- It determines the voltage of the buses. The voltage level at the certain buses must be kept within the closed tolerances.
- System transmission loss minimizes.
- Economic system operation with respect to fuel cost to generate all the power needed
- The line flows can be known. The line should not be overloaded, it means, we should not operate the close to their stability or thermal limits.

## III. PROPOSED WORKS

**Overview of Proposed Works**

The proposed work is based on the renewable source of energy and has been utilized for the stand-alone purpose during failure of the main power grid. the Simulation idea of 100kW grid-connected solar PV system by utilizing MATLAB/SIMULINK. Solar array characteristics depend on the sunlight radiation and temperature these are in nonlinear nature its power is shifts consistently with climate evolving conditions. In this condition, MPPT is utilized to track the most extreme power from the solar array. A 100-kW PV array is connected to a 25-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the 'Incremental Conductance + Integral Regulator' technique.

**Problem Statement**

**Newton–Raphson Method For Power Flow Analysis**

The following 5 bus network was taken from G.W. Stagg & A.H. El- A biocomputer methods in power system analysis,1968 McGraw Hill.

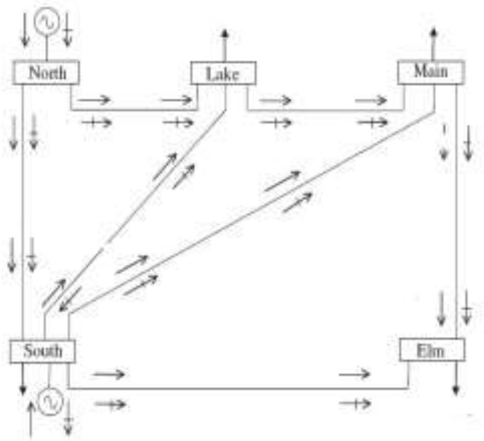


Fig 6.bus network problem statement

- North – bus 1
- South – bus 2 □ Lake – bus 3
- main – bus 4
- elm - bus 5

**Steps to write the MATLAB program and analyse the data using MATLAB**

The sequence of steps for solution of load flow problem using N-R method are explained as follows:

**Step1:** Assume a suitable solution for all buses except slack bus. Assume $V_p$=1+j0.0 for p=1.2 ….n, p≠ s, $V_s$= a+j0.0

**Step 2:** Convergence criterion is set to ∈ that means if the largest of absolute of the residues exceed ∈ the process repeated else terminated.
**Step 3:** iteration count is set to K=0
**Step4:** Bus count is set to p=1
**Step 5:** Say p is slack bus. if yes skip to step 10
**Step 6:** real and reactive powers $P_p$ and $Q_p$ are calculated respectively using equations

$$Pq = \sum_{q=1}^{n} \{ e_p\,(e_q\,G_{pq} + f_p\,B_p) + f_p(f_q G_{pq} - e_q B_{pq})\}$$

$$Qq = \sum_{q=1}^{n} \{ e_p\,(e_q\,G_{pq} + f_p\,B_p) - f_p(f_q G_{pq} - e_q B_{pq})\}$$

**Step7:** Calculate $\Delta\, P_p^k = P_{sp} - P_p^{\,k}$
**Step 8:** Check for bus to be generator bus. If yes compare the reactive power $Q_p^k$ with the upper and lower limits.
if $Q_{gen} > Q_{max}$ set, $Q_{gen} = Q_{max}$

else if $Q_{gen} < Q_{min}$ set $Q_{gen} = Q_{min}$
else if the value is within the limit, the value is retained. If the limits are not violated, voltage residue is evaluated as $|\Delta V_p|^2 = |V_p|^2_{spec} - |V_k^p|^2$
and then go to step 10.
**Step 9:** $\Delta Q_p^k = Q_{sp} - Q_p^k$ is evaluated
**Step 10**: bus count is incremented by 1, i.e p=p+1 and check if all buses have been accounted
else,go to step 5.
**Step 11**: Determine the largest of the absolute value of residue.
**Step 12**: If the largest of the absolute value of the residue is less than ∈ then go to step 17
**Step 13**: jacobian matrix elements are evaluated.
**Step 14**: voltage increments $\Delta e_p^k$ and $\Delta f_p^k$ are calculated
**Step15**: calculate new bus voltages $e_p^{k+1} = e_p^k + \Delta e_p^k$ and $\Delta f_p^k = f_p^k + \Delta f_p^k$ Evaluate cos$\delta$ and sin$\delta$ for all voltages.
**Step 16**: Advance iteration count is K =K+1, then go to step 4
**Step 17**: Finally bus and line powers are evaluated and results printed.

**END**

## IV. SIMULATION WORK IN MATLAB

Proceeding as per the algorithm and developing the MATLAB code the results obtained as are follows:

**Solution**
it = 6
VM =
1.0600 1.0000 0.9872 0.9841 0.9717
VA =
0 -2.0612 -4.6367 -4.9570 -5.7649
PQ send =
Columns 1 through 4
0.8933 + 0.7400i 0.4179 + 0.1682i 0.2447 - 0.0252i 0.2771 0.0172i
Columns 5 through 7
0.5466 + 0.0556i 0.1939 + 0.0286i 0.0660 + 0.0052i
PQ rec =
Columns 1 through 4
-0.8685 - 0.7291i -0.4027 - 0.1751i -0.2411 - 0.0035i -0.2725 - 0.0083i
Columns 5 through 7
-0.5344 - 0.0483i -0.1935 - 0.0469i -0.0656 - 0.0517i
Answers found out match the given results.

## V. RESULTS

**1. Phase angle difference (fault cleared at 0.4s)**

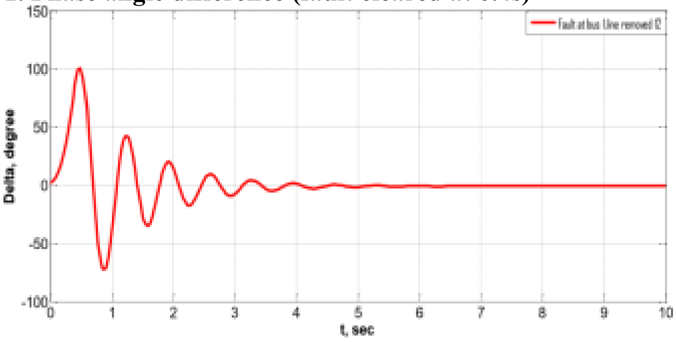


Fig 7 Fault at bus 1, line removed 12

**2. Phase angle difference (fault cleared at 0.4s)**

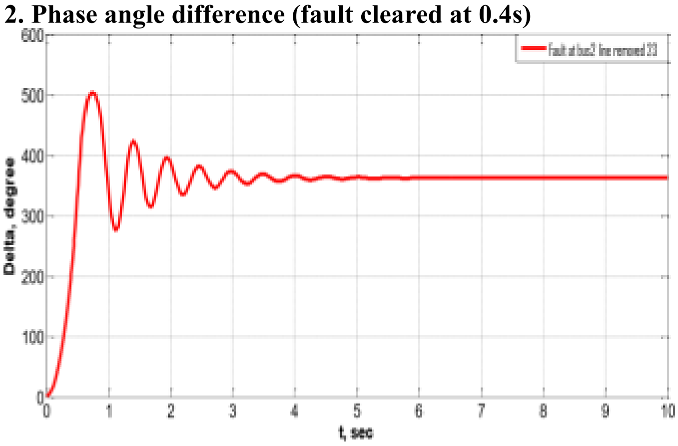


Fig 8 Fault at bus 2 line removed 23

**3. Phase angle difference (fault cleared at 0.4s)**

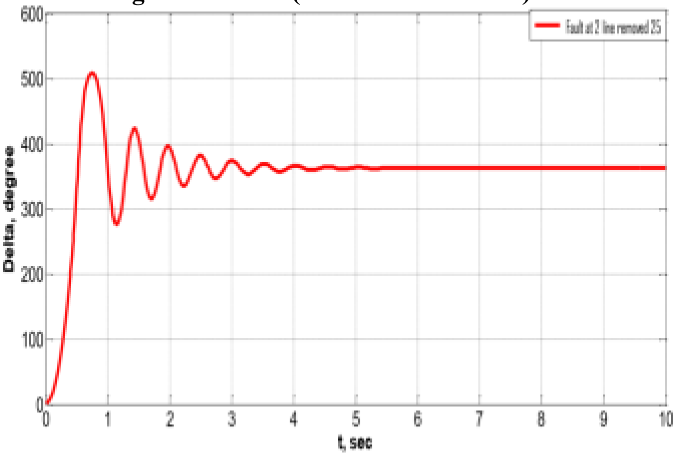


Fig 9 Fault at bus 2 line removed 25:

**4. Phase angle difference (fault cleared at 0.4s)**

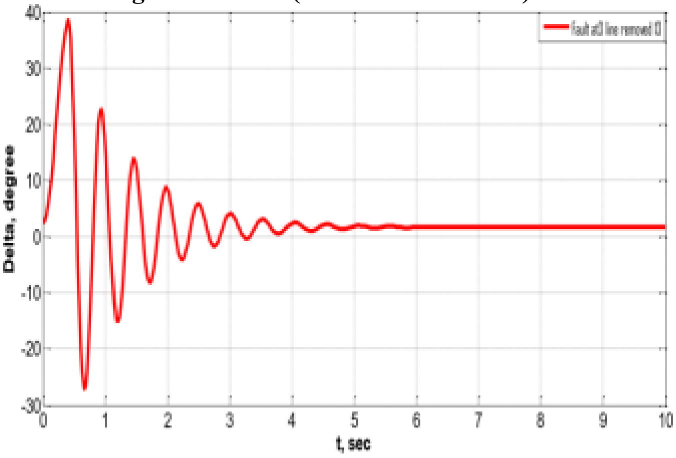


Fig 10 Fault at bus 3 line removed 13:

**5. Phase angle difference (fault cleared at 0.4s)**

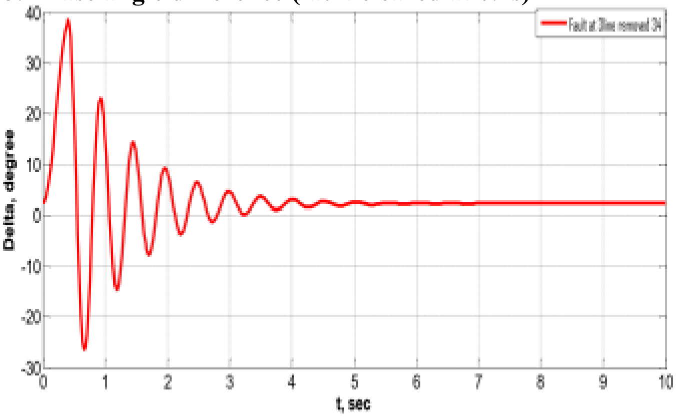


Fig 11 Fault at bus 3 line removed 34:

**6. Phase angle difference (fault cleared at 0.4s)**

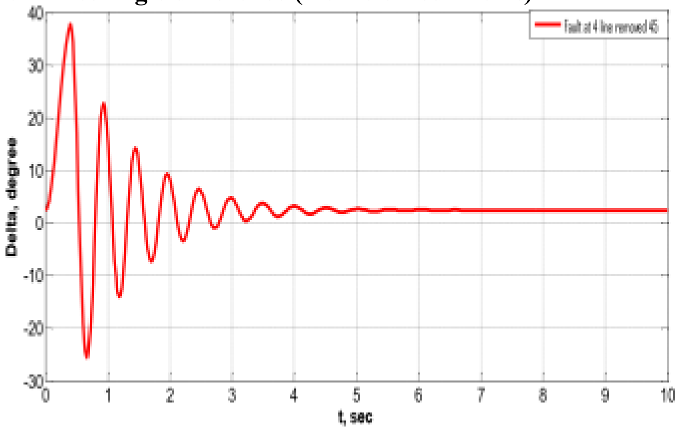


Fig 12 Fault at bus 4 line removed 45:

**7. Phase angle difference (fault cleared at 0.4s)**

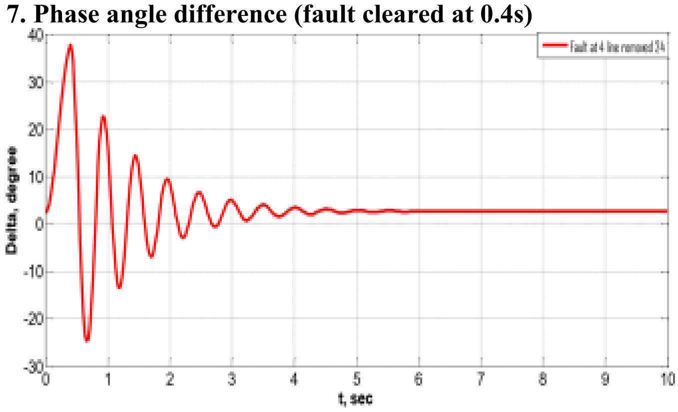


Fig 13 Fault at bus 4 line removed 24:

**8. Comparison between transient stability with & without TCSC**

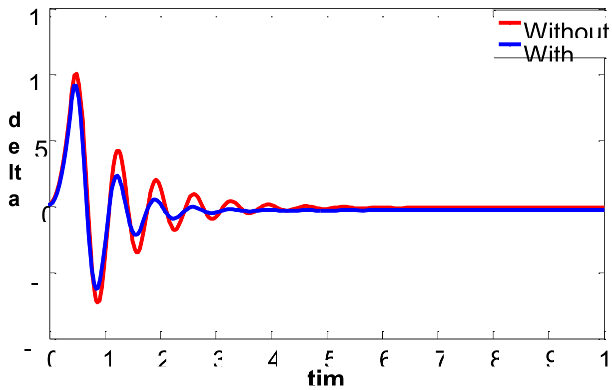


Fig 14 When fault at bus 1, line removed 12:

**9. Comparison at bus 2 line removed 23**

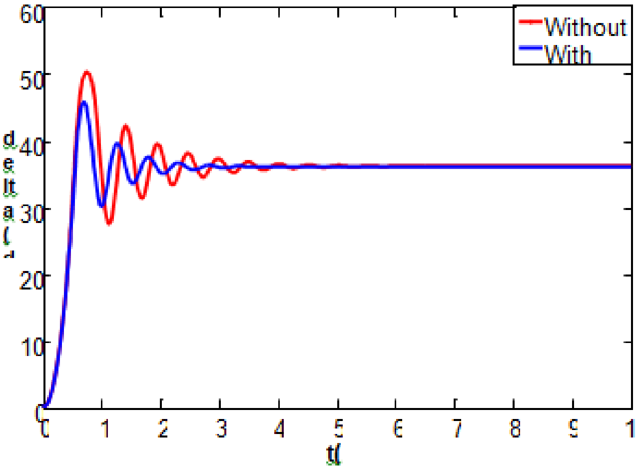


Fig 15 When fault at bus 2, line removed 23:

**10. Comparison at bus 2, line removed 25**

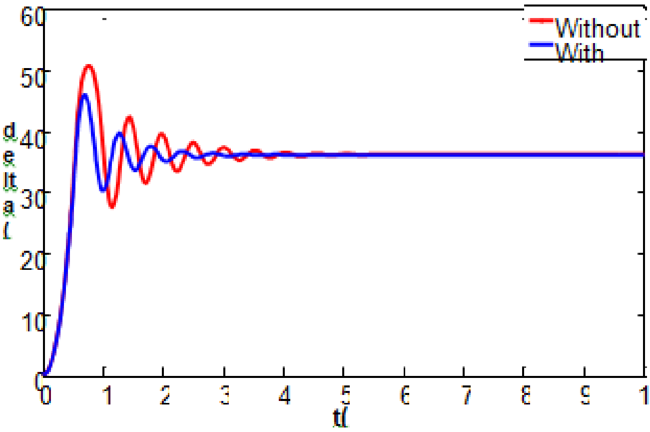


Fig 16 When fault at bus 2 ,line removed 25:

## VI. CONCLUSION

The comparison of simulations of both the both the networks shows the TCSC controller enhances stability of power system. From the transient analysis it is quite clear that electromechanical damping increases on using these controllers. For large interconnected systems it is essential. Then, a simple transfer function model of TCSC controller for stability improvement is developed and the parameters of the proposed controller are optimally tuned. The minimization of the rotor angle deviation following a severe disturbance is formulated as an optimization problem and the optimal TCSC controller parameters are obtained by means of genetic algorithm the performance of the TCSC controller is tested over a 3-machins 9-bus power system, for the most severe situation in terms of critical fault clearing time. Nonlinear simulation results show the effectiveness of TCSC controller in enhancing the critical fault clearing time of the system and damping power system oscillations.

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