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The Power System Transient Stability Analysis under Fault Scenarios using MATLAB

Md. Eftiaz Hossien[1]; Mohammad Tauhidul Islam[2]; Dewan Nishat Tasnim Proma[3]; K. M. Faisal[4]

[1]SIMEC Research Center, Singapore
[2,4]Department of EEE International University of Business Agriculture and Technology Dhaka, Bangladesh
[3]Department of ICT, Bangladesh University of Professionals (BUP) Dhaka, Bangladesh

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Abstract

This research investigates the transient stability of power systems through MATLAB simulations, focusing on both unstable and stable conditions. In the context of a single-machine infinite bus power system, the study investigates how tiny signal disruptions, such as circuit breaker actions, affect system behavior. The MATLAB software calculates crucial metrics such as maximum power, synchronizing power coefficient, un-damped frequency of oscillation, and damping ratio, which provide information on the system's transient stability under unstable conditions. Furthermore, the study provides an example of a stable condition employing state-space modeling and a step function to respond to rotor angle and frequency. The research examines stability settings comparable to those used in the unstable scenario and shows how the system behaves when the power input is changed slightly. The MATLAB simulations generate plots illustrating load angle and frequency for both stable and unstable conditions. In the discussion and conclusion section, consider the significance of transient stability analysis in power systems, highlighting the need for ongoing study in this field. The research finishes by recommending further research into multi-machine power systems to improve our understanding of transient stability dynamics. This study provides useful information for power system engineers and researchers, assisting in the development of solutions to preserve the stability and dependability of electrical power networks.

Keyword: *Infinite Bus, Transient Stability Analysis, Critical Clearing Times, Clearing Critical Angle, Equal Area Criteria, Steady State Stability, Power System Stability, MATLAB Simulations, Small Signal Disturbances, Circuit Breaker Operations, State-Space Modeling, Step Response, Multi-Machine Power Systems.*

I. INTRODUCTION

The voltage level by transport is becoming more and more high as the distance of electricity transmission becomes longer and longer, and its capacity increases. As the electric power system advances, the network's instability becomes more noticeable. Transient stability refers to an electrical device's capacity to maintain synchronization following a significant transient disturbance, such as the development of a fault, sudden connection reduction, or unexpected load insertion or removal [1]. Changes in angular variations are just as likely to throw the equipment out of pace as a large disruption. Transient instability is the term used to describe this kind of instability. When a generator is getting ready to respond to a disturbance, transient stability may be a quick development, typically occurring per second [2]. The electrical output of adjacent generators is decreased during the fault, whereas the output of distant generators is largely unaffected. The resulting fluctuations in acceleration cause variations in speed throughout the fault's time span, thus it's critical to address the problem as soon as feasible. One or more transmission elements are eliminated by the fault clearing, which weakens the system. The power plant rotors' angle changes as a result of the transmission device adjustments. If the changes lead the accelerated machines to take on more load, they slow down and a new equilibrium function was achieved. Within a second of the initial issue, there was a noticeable lack of time[3]. Faults on higher-loaded lines are more likely to generate instability than those on weakly-loaded lines because they produce more acceleration during the fault. More acceleration is produced by three-part faults than by one- or two-phase conductor failures. Angle deviations are frequently caused by faults within neighboring generators that haven't been cleared by the main fault. Furthermore, the backup fault clearing is performed after a time delay, resulting in unusually high oscillations. An important load from a big production station significantly disrupts the network [4].

II. OBJECTIVE

- To review rotor dynamics of synchronous generator
- Consider a thorough instance, like a single-machine infinite bus power system including double-circuit transmission lines
- To determine the critical power angle and critical time clearance when selecting a circuit breaker, maximum power will transfer in the pre-fault and post-fault, and during fault conditions of a three-phase fault with respective MATLAB simulation
- To determine whether a three-phase failure in the transmission wire and a sudden rise in power input could be the cause of the system's instability
- To examine the conditions of rapid increases in input power and three-phase faults on the transmission line and then inquire whether the system can cause system instability.

III. METHEDOLOGY

In this paper, some strategies are employed to successfully conduct the study. Figure 1 describes the step-by-step approach undertaken to complete the research, starting from the initial section to the concluding part.

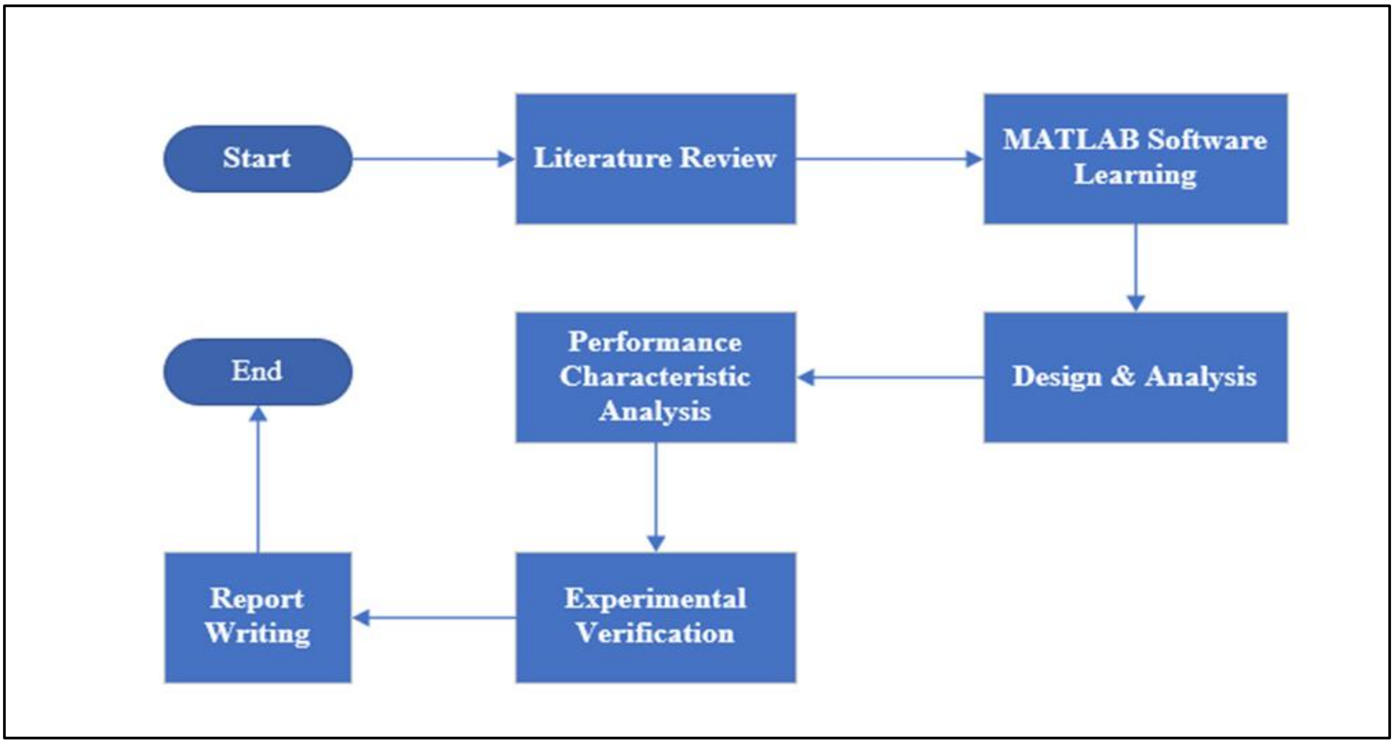

Fig 1 A Block diagram of MATLAB Simulation

Initially, the research target was developed following an extensive literature review to identify gaps in power system transient analysis. Experiment has been conducted to improve the stability of power system transient stability testing using MATLAB simulations. Furthermore, the study analyses performance characteristics, yielding results for power system analysis. Following that, the methodology, basic ideas, and findings explained accordingly.

IV. MATERIALS AND METHODS

- *Power System Transient Stability:*

Transient state Stability is a system's capacity to maintain stability in the face of massive, significant, and explosive disturbances. Faults, fulminant load shifts, producing unit loss, line alterations, and enormous disturbances are a few examples of the system's potential problems. These are significant lightning strikes and losses of transmission cables carrying significant electricity due to overloading. In the transient stability experiments, it determines whether synchronization is maintained after a significant shock to the machine [5]. Disturbing phenomena's are:

- Quick application of load/quick load changing
- Loss of generation
- System Fault

Every generator operates at the same 50 Hz synchronous speed and frequency, and the input mechanical power and output watts are carefully balanced. The system-frequency will decrease if the total power generated is less than the total power consumed. If total generating power exceeds the total load power (including grid losses), the system frequency will rise. A high-voltage transmission line is provided by the generators' connections to one another, the loads, and each other [6]. Any system disturbance will affect the relationship between the generator's mechanical power input and electrical output. This means that certain generators will tend to accelerate more quickly than others. A generator will automatically detach from the system if its inclination to deviate from the rest of the system is too strong, causing it to lose synchronization. The term "generator going out of step" describes this phenomenon [7].

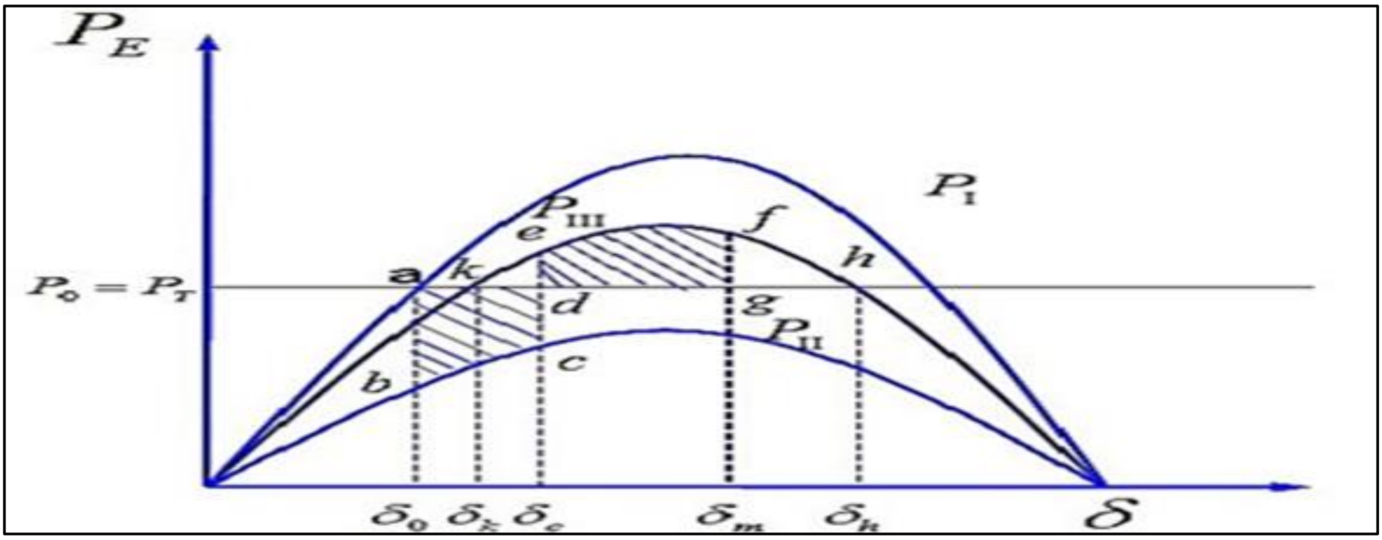

Fig 2 Three Power Characteristic Curves of a Basic Power System under Various Circumstances

The system exhibits transient stability since the rotor's relative speed is zero due to the deceleration area equaling the acceleration area. The system will become unstable if the deceleration area is smaller than the acceleration area. According to the largest acceleration principle, an electrical system is considered transiently stable only if its area is greater than or equal to its accelerated area [8].

Here are some factors influencing transient stability

- Generator Inertia.
- Generator Loading.
- The location and kind of the fault determine the generator output during the fault.
- Fault Clearing Time.
- Post-fault transmission system reactance.
- Generator Reactance.
- The field excitation, or the power factor of the power delivered at the generator terminals, determines the generator internal voltage magnitude.
- The Voltage Magnitude of Infinite bus [8].

➢ *Causes of Transient:*

Transients are disturbances that occur for a short period of time. If no harm is done as a result of the transient, the electrical system instantly returns to normal operation. An electrical transient is an example of cause-and-effect. Transients must occur for a cause, and some explanations are more common than others:

- Turning on or off loads
- Interrupting fault Currents
- Switching in Power Lines
- Switching Capacitor Banks

➢ *Literature Review on Transient Stability:*

The capacity of a power system to return to its initial steady state following any deviations encountered during operation is known as power system stability. Currently, electrical systems are operating nearer their safety limitations due to environmental and commercial factors. Therefore, maintaining the electrical system's steady and secure performance is a crucial and difficult challenge. Recently, power system experts and engineers have focused significantly on transient stability, which is one of the most prevalent sources of power system instability. FACTS devices, transmission line design, AVR (automatic voltage regulators), load shedding, bundled conductors, rapid switching devices, and high-speed excitation systems all contribute to better transient stability, increased transmission capacity, and decreased power loss.

➢ *Transfer Reactance:*

Assume that the power system was in an established steady-state state of operation prior to the problem occurring. Determining whether the system will eventually achieve a safe steady state operating position after the fault is how the problem of electrical instability is then described.

When contrasted with the duration of the rotor swings, the sub-transient period is often relatively brief. It is possible to ignore how sub-transient phenomena affect electromechanical dynamics. When the swings' equation is stated as follows, the generator classical model can be utilized to examine the transient stability problem.

$$M\frac{d^2\theta}{dt^2} = P_a = P_m - P_e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

When a significant defect occurs, like a short circuit, the equivalent reactance X will fluctuate, changing [$P_e = P_{max}\mathrm{Sin}\delta$, affecting power output and upsetting the system's power balance. As a result, power will be divided across the generators, resulting in proportionate rotor oscillations. Typically, a disturbance is accompanied by three states, each with three reactance values that are typically distinct.

- The pre-fault state when reactance
- The condition of failure when the reactance

- The post-fault state when the reactance

The schematic diagram in Figure 3 below provides a clear illustration of the aforementioned circumstance.

In the following diagram, the fault occurs at the middle of the transmission line 2.

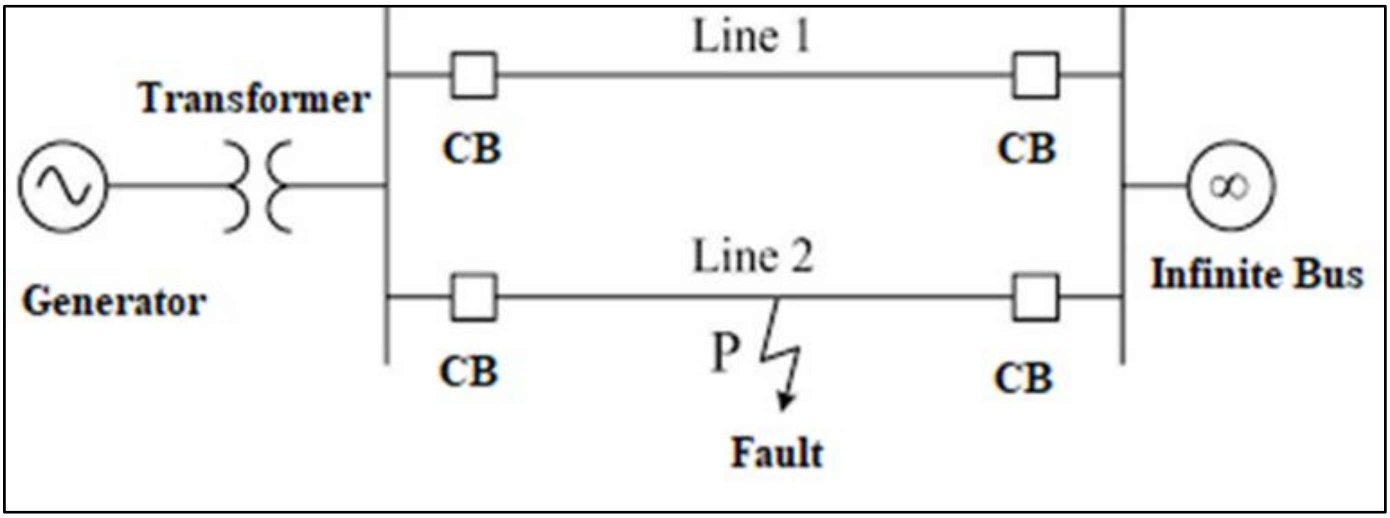

Fig 3 A Fault Transmission Line Diagram

For pre-fault condition, the reactance is

$$\boldsymbol{X_i}=[\boldsymbol{X_d}+\{\frac{(x_1*x_2)}{(x_1+x_2)}\}] \quad \text{(2)}$$

The corresponding Power angle is

$$\boldsymbol{P_e}=\{(\frac{\boldsymbol{EV}}{\boldsymbol{X_i}})*\boldsymbol{Sin\delta}\} \quad \text{(3)}$$

During a fault, the equivalent circuit is as shown below,

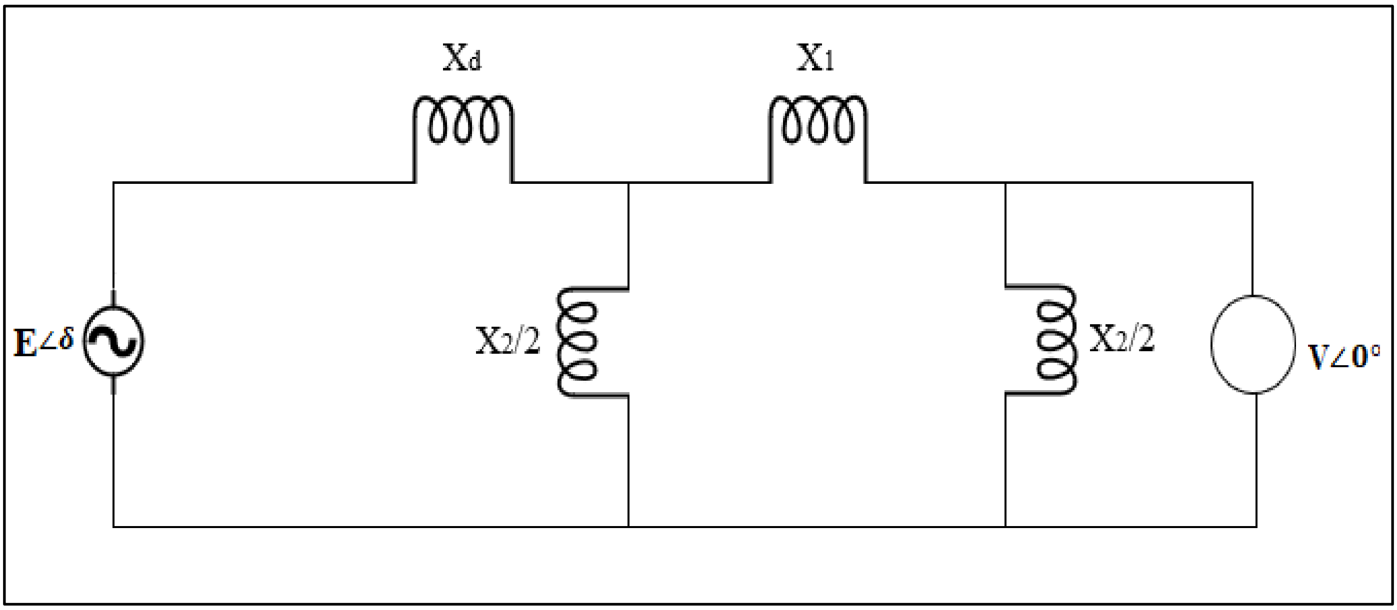

Fig 4 During Fault Equivalent Circuit

So, the transfer reactance is,

$$\boldsymbol{X_{ii}}=[\frac{\{(x_d*x_1)+(x_1*\frac{x_2}{2})+(x_1*\frac{x_2}{2})\}}{(\frac{x_2}{2})}] \quad \text{(4)}$$

The corresponding power angle is,

$\boldsymbol{P_e}$={($\frac{\boldsymbol{EV}}{\boldsymbol{X_{ii}}}$) ∗ $\boldsymbol{Sin\delta}$} ………………………..….. ……………………………………………………………….(5)

The similar circuit under post-fault conditions can be observed in the Figure 5 below.

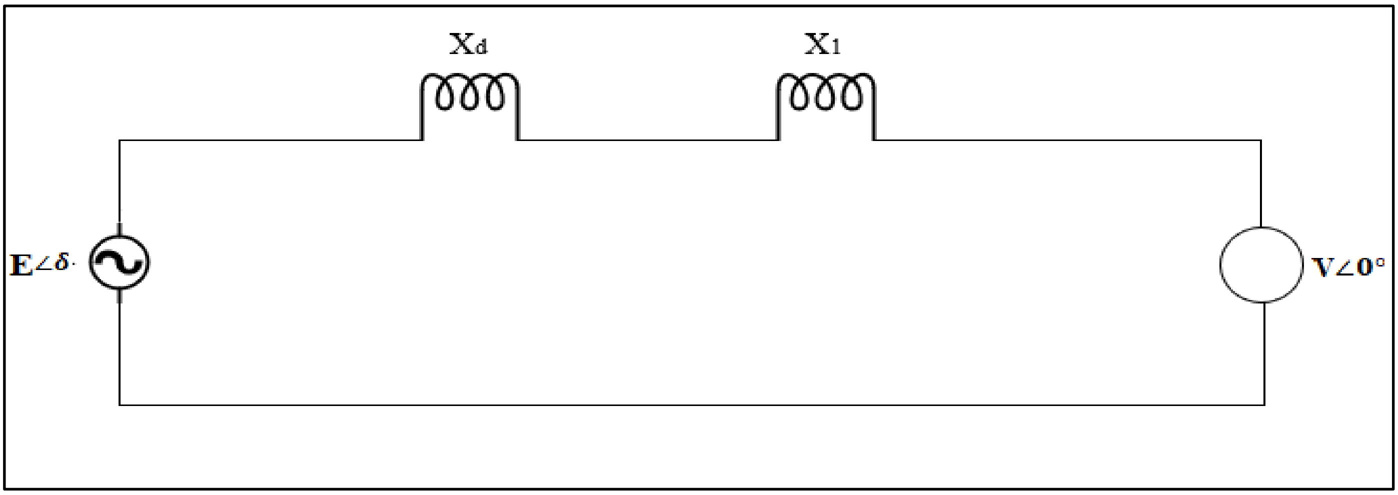

Fig 5 Post Fault Condition

The reactance is,

$X_{iii} = (X_d + X_1)$ …………………..………...….... …….(6)

The appropriate power angle is as follows:

P_e={($\frac{EV}{X_{iii}}$) ∗ $Sin\delta$} ………….…………...…...……… (7)

When the fault occurs at the end of transmission line 2, the power angle will shift and transferring reactance will be infinite (x= ∞)

$$P_e=\{(\frac{EV}{X_{iii}}) * Sin\delta\} = 0$$

However, equation 3 and equation 7 will still apply to transfer the reactance and the power angle before and after the failure occurred.

- *Equal Area Criterion:*

The transient stability experiments entail determining whether synchronization is maintained after a major disturbance to the equipment. This could be caused by an abrupt application of load, an interruption in generation, an impairment in an important load, or a system breakdown. Most disturbances have oscillations of such a size that solving the nonlinear swing equation is necessary since linearization is not allowed. An easy way to forecast stability is to apply the equal-area criterion approach. This approach uses a representation in graphics of the energy held by the spinning material as a tool for determining whether the device remains stable in the face of a disruption. This method performs only with systems that have two machines or one machine connected to an infinite bus [7]. The swing equation is,

$$\boldsymbol{M}\frac{d^2\delta_m}{dt^2} = \boldsymbol{P_a} = \boldsymbol{P_m} - \boldsymbol{P_e}$$

Where $\boldsymbol{P_a}$ is the accelerating power,
From the above equation,

$$\frac{\mathbf{d^2}}{\mathbf{dt^2}} = \frac{\mathbf{1}}{\mathbf{M}}(\mathbf{P_m} - \mathbf{P_e})$$

Multiplying both sides by **(2∗ $\frac{d\delta}{dt}$),**

$$[2*\frac{d\delta}{dt}*\frac{d^2\delta}{dt^2}] = [\frac{2}{M}(P_m - P_e)\frac{d\delta}{dt}]$$

$$\frac{d}{dt}[(\frac{d\delta}{dt})^2] = [\frac{2}{M}(P_m - P_e)\frac{d\delta}{dt}]$$

Integrating both sides,

$$(\frac{d\delta}{dt})^2 = \frac{2}{M}\int_{\delta_0}^{\delta}(P_m - P_e)\, d\delta$$

$$\frac{d\delta}{dt} = \sqrt{\frac{2}{M}\int_{\delta_0}^{\delta}(P_m - P_e)\, d\delta}$$

The machine's relative speed in relation to the reference framework that revolves synchronously is given by equation (2.8). This speed must be zero following the disruption in order for stability. Consequently, the stability criteria,

$\int_{\delta_0}^{\delta}(P_m - P_e)\, d\delta = 0$……………………….....…….. (8)

Think about the machine running at the mechanical power input $\boldsymbol{P_{m0}} = \boldsymbol{P_{e0}}$'s equilibrium point, δ0. Imagine an abrupt rise in input power, shown by the horizontal Pm line. Since $\boldsymbol{P_m} > \boldsymbol{P_{e0}}$, the power angle $\boldsymbol{\delta}$ rises and the rotor's acceleration power is positive. During the first acceleration, the rotor's access energy was stored as,

Area A1=$\int_{\delta}^{\delta max}(P_m - P_e)\, d\delta$ ……………….…........ (9)

When δ grows, the electrical power also increases (δ=δ1), matching the new input Pm_1. although the acceleration power is now zero, the rotor is rotating with synchronous speed, therefore δ and the electrical power Pe are still increasing. The rotor is now slowing down to synchronous speed till. When the rotor returns to synchronous speed, the energy released is calculated as

$$\text{Area, A2}=\int_{\delta}^{\delta max}(P_m - P_e)\, d\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

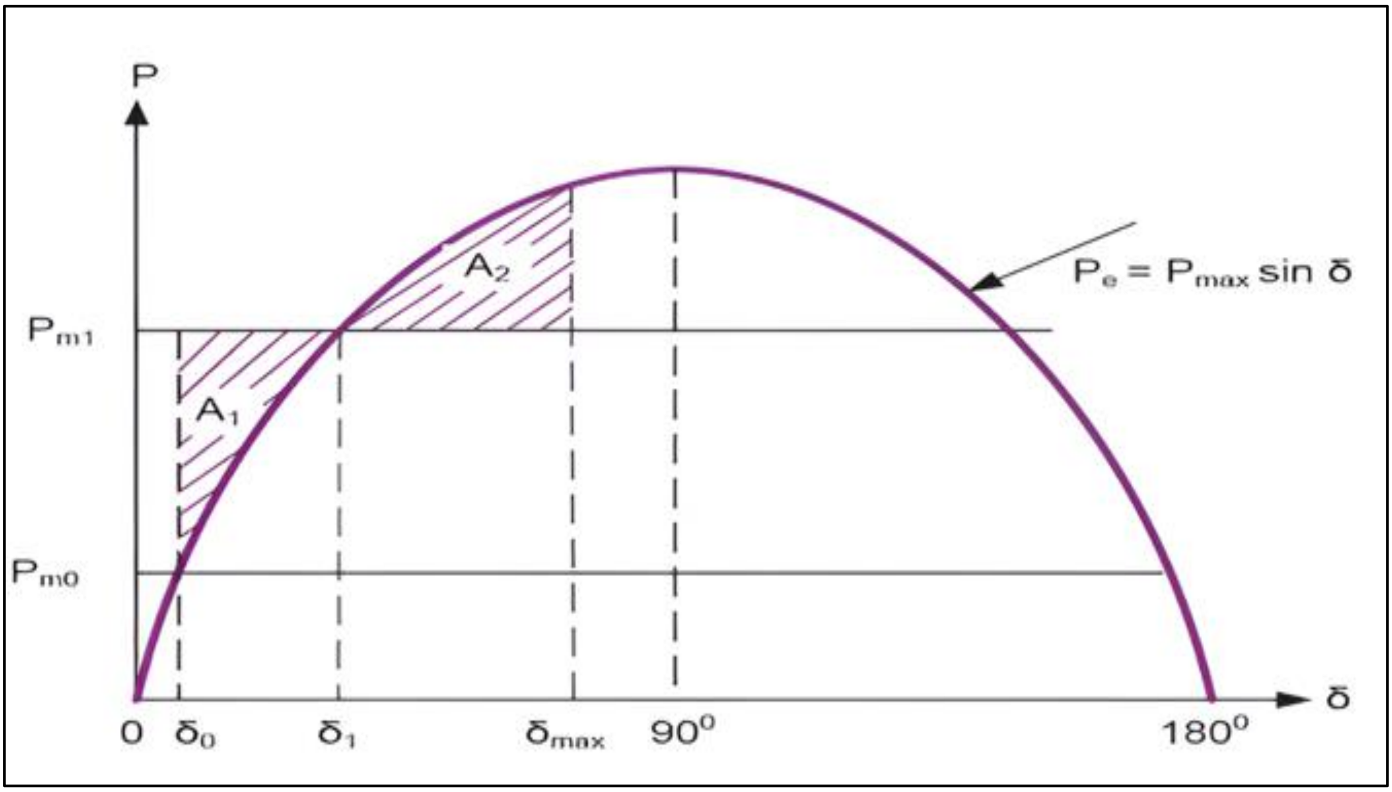

Fig 6 Transient Stability Condition

As a result, the rotor swings to angle δ_{max} and point b, where,

$$|Area\ A1| = |Area\ A2|$$

The equal area criteria refers to this. At its inherent frequency, the rotor angle fluctuated between δ0 and δmax. The machine's dampening will cause these oscillations to halt. These oscillations will stop due to the machine's dampening, and point b will become the new steady-state operation [8].

V. MATEMETICAL ANALYSIS

In Figure 7, a twin circuit transmission line provides 1.0 Pu power from a synchronous machine to an endless bus. The direct axis transient reactance of the generator is 0.3 Pu. Each line has a 0.5 Pu reactance. One of the transmission lines encounters a solid three-phase fault to ground, at which point the system reactance is as seen in Figure 9. All reactance is sent to the machine rating base. Our research will focus on determining the key clearance time and angle at which the faulty line's circuit breakers must activate to preserve stability. [9].

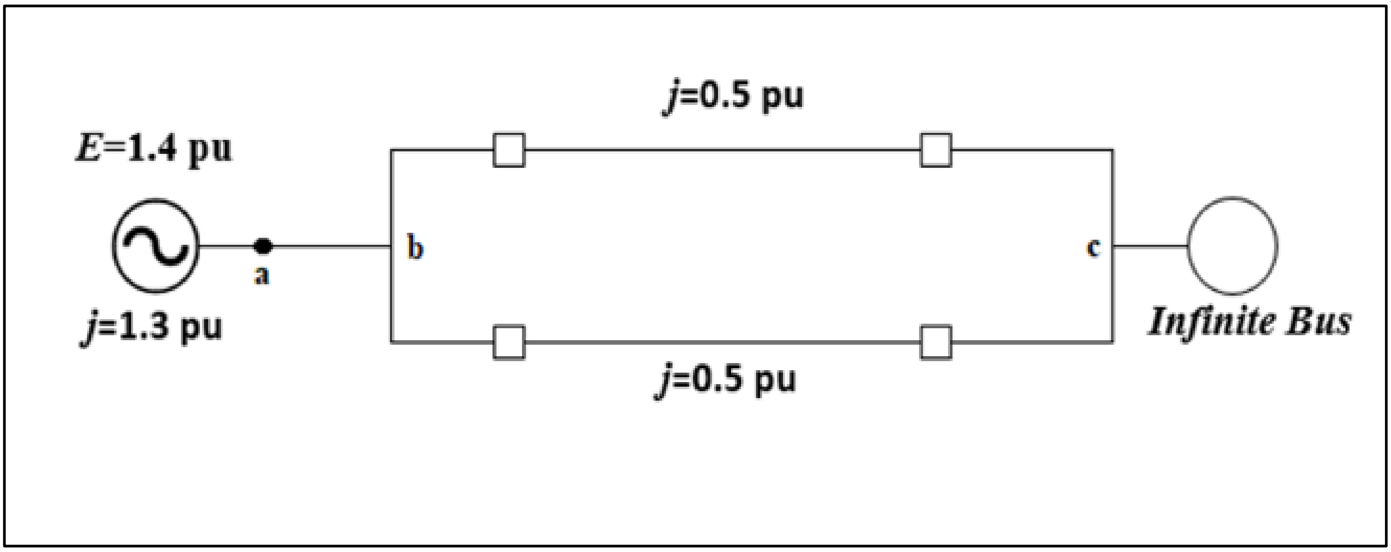

Fig 7 A Reference Circuit Diagram for Calculation

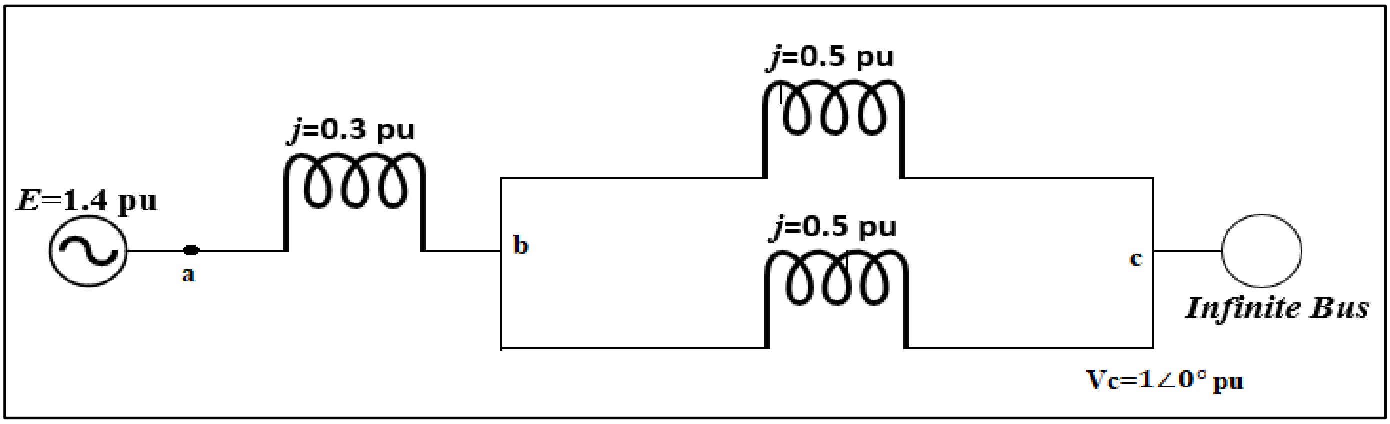

Fig 8 Reference Circuit Simplifying

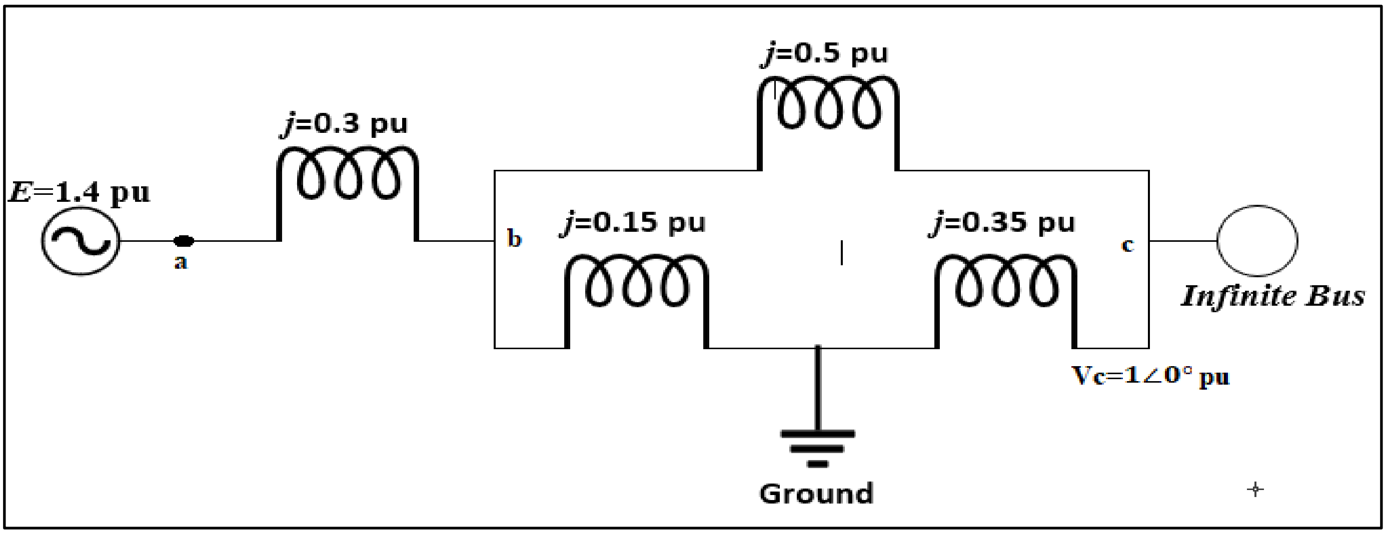

Fig 9 Simplify Circuit of Reference Circuit

➢ *Pre- Fault Condition:*

From Fig. 8, the transformer reactance between 7 and 9 given by

$$\therefore\ X = \{0.3 + (0.5 \parallel 0.5)\}$$

$$= \{0.3 + \frac{(0.5\times0.5)}{(0.5+0.5)}\}$$

$$\therefore\ X = 0.55\ \text{Pu}$$

The pre-fault power-angle curve is defined as,

$$\therefore\ P_{e1} = [\frac{(E \times Ve)}{\sin\delta}]$$

$$= [\frac{(1.4\times1)}{(0.5)} \times \sin\delta]$$

$\therefore\ P_{e1} = (2.545*\sin\delta c)$; in equation……………….(11)

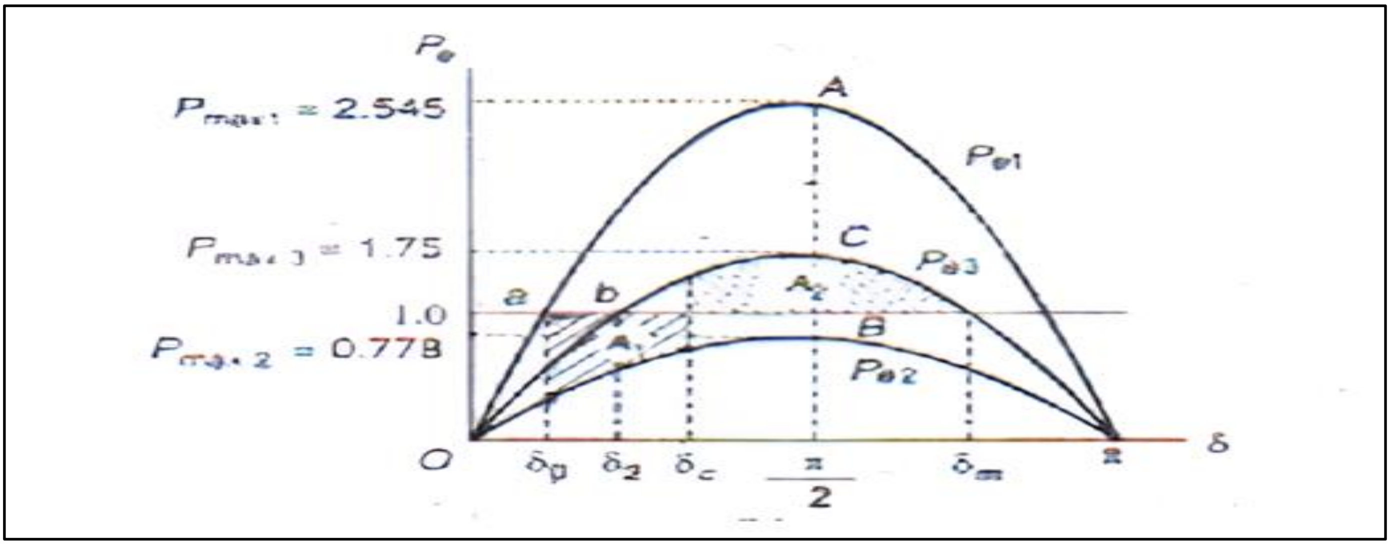

Fig 10 Transient Stability Curve

Figure 10, shows the pre- fault curve A, at point a on the pre- fault curve.

$\therefore P_{e1} = 1, \delta = \delta o$

$\therefore 1 = 2.545 \sin\delta o$

$\Rightarrow \sin\delta o = (\frac{1}{2.545})$

$\Rightarrow \sin\delta o = 0.39285$

$\Rightarrow \delta o = sin^{-1}(0.39285)$

$\Rightarrow \delta o = 23.13^{\circ}$

$\therefore \delta o = 0.4037 rad$

$\therefore \sin\delta o^2 + \cos\delta o^2 = 1$

$\Rightarrow \cos\delta o^2 = 1 - \sin\delta o^2 = 1 - (0.39285)^2$

$\therefore \cos\delta o = 0.9196$

- *Condition of During Fault:*

The condition of the network during fault is shown in Figure: 9, in order to determine the transfer reactance between a & c. we have to use delta–star transformation and then star-delta transformer.

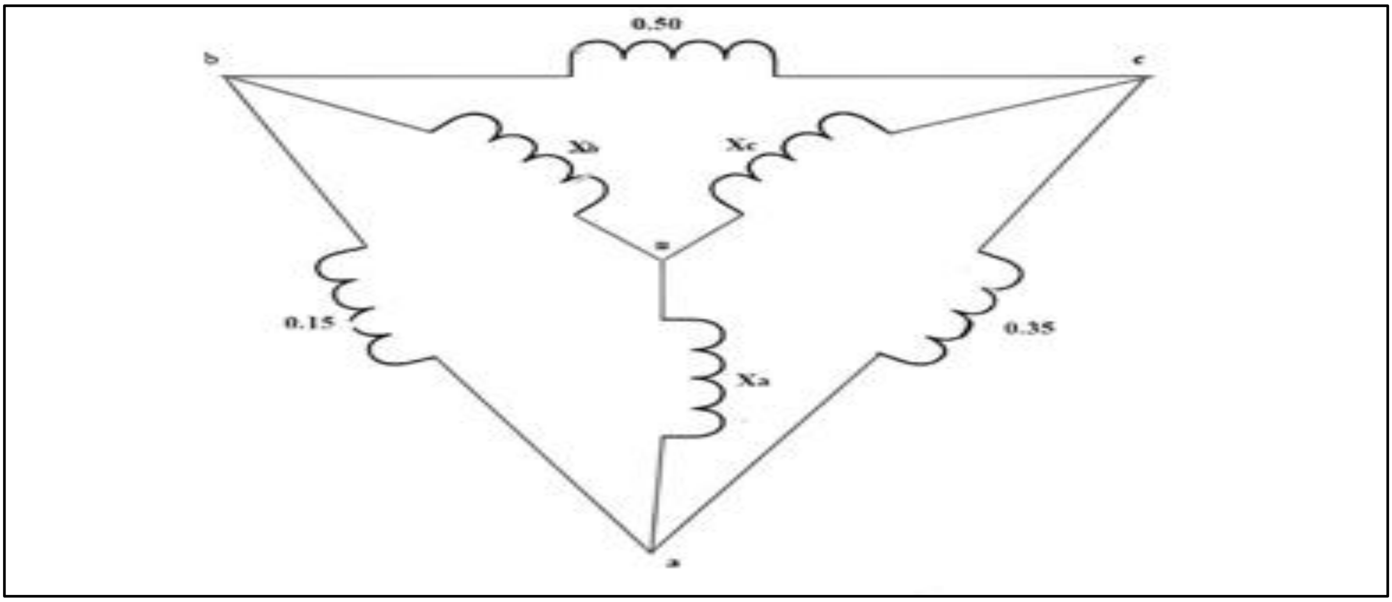

Fig 11 Delta to Star Conversion

In order to star transformation in Figure: 11.

$\therefore X_b = [\frac{(0.5\times0.15)}{(0.5+0.15+0.35)}]$

$\therefore X_b = 0.075$ Pu

$\therefore X_e = [\frac{(0.35\times0.5)}{(0.5+0.15+0.35)}]$

$\therefore X_e = 0.175$ Pu

$\therefore X_e = [\frac{(0.35\times0.15)}{(0.5+0.15+0.35)}]$

$\therefore X_e = 0.0525$ Pu

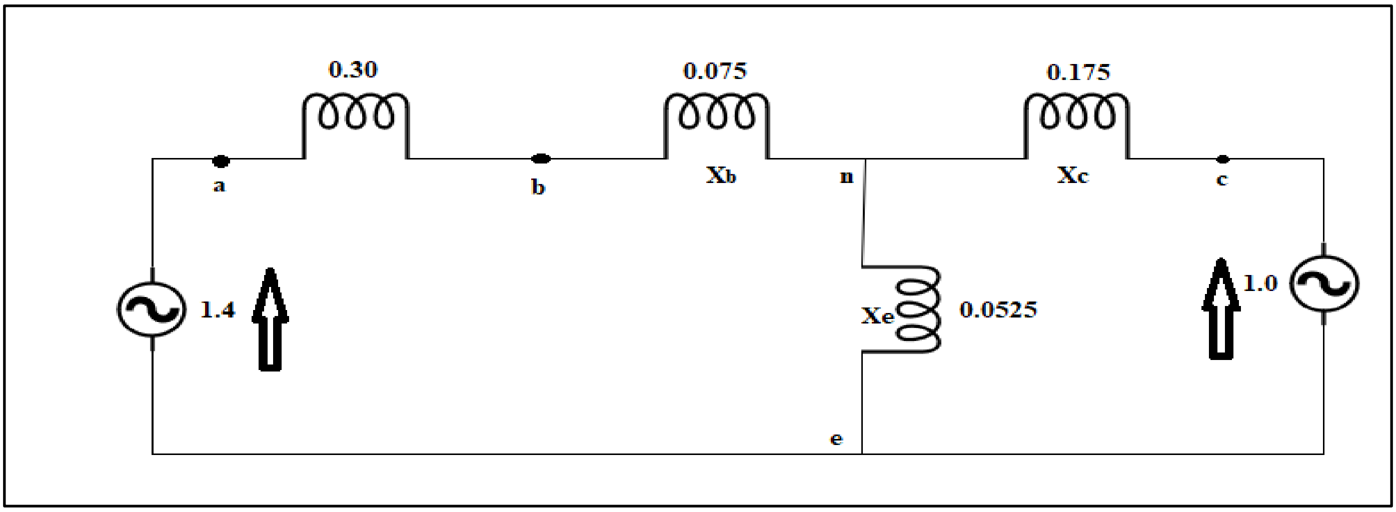

Fig 12 A Simplify Load Circuit Diagram

The equipment circuit of figure 7 is shown in figure 12 Star-delta transmission is done with the help of figure 13.

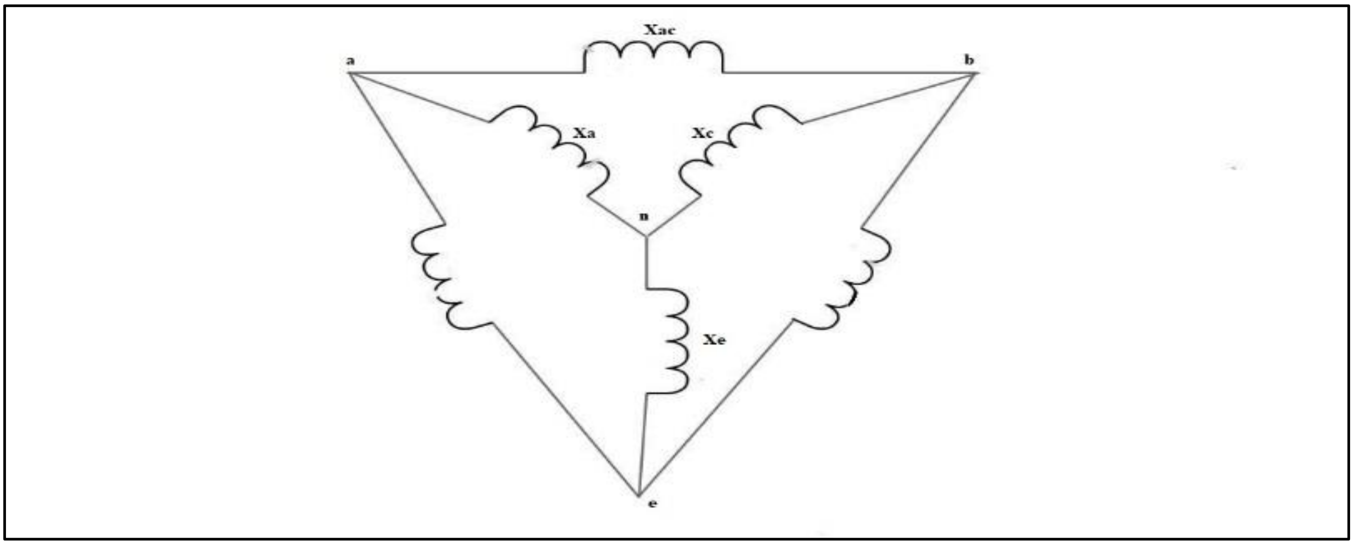

Fig 13 Star to Delta Conversion

$\therefore$ X_{ac}=[$\frac{(0.375*0.75)+(0.175*0.0525)+(0.0525*0.375)}{0.0525}$]

=[$\frac{(0.065625+0.00919+0.0197)}{0.0525}$]

$\therefore$ X_{ac} = 1.8 Pu

In the final star-delta transmission, only the reactance between the nodes a and c need to be calculated as the order two shunt reactance's do not contribute to active power transfer from a and c. Figure 14 shows the analogous circuit in Figure 12.

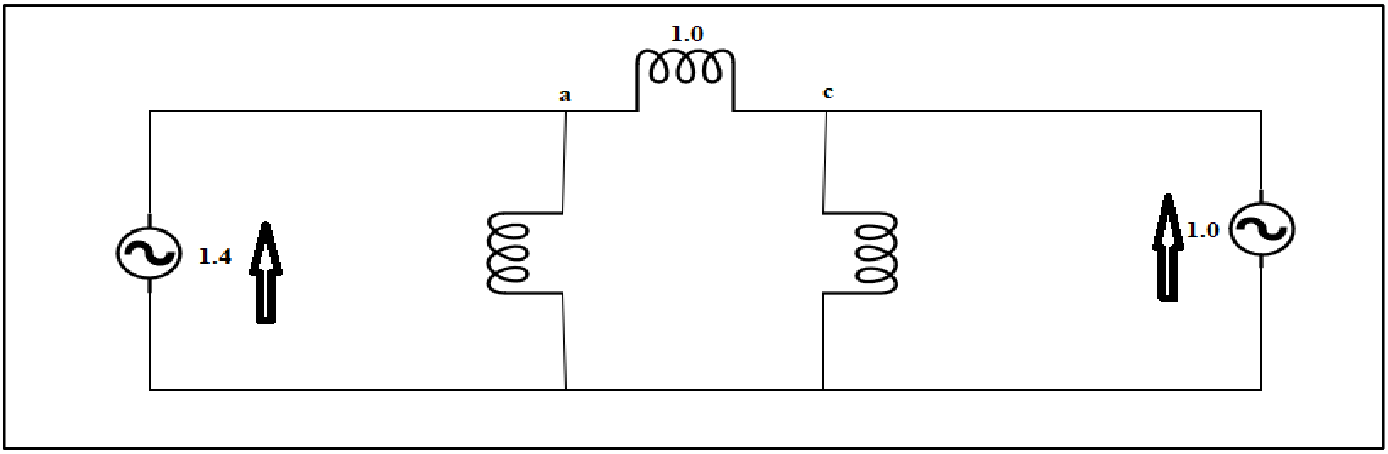

Fig 14 Equivalent Circuit of Figure 12

The power-angle curve during is therefore, given by-

$\therefore$ P_{e2}= [$\frac{E\times Vc}{Xac}$ $\times$sinδ]

= [$\frac{1.4\times 1.0}{1.8}$ $\times$sinδ]

$\therefore$ P_{e2} = 0.778sinδ in Equation …………………… (12)

➢ *Post Fault Condition:*

The post fault power angle curve can be derived from figure 8 with one line out of circuit. The transfer reactance in this case is

$\therefore$ X= (0.3+0.5)

$\therefore$ Pe3 = [$\frac{(E\times Vc)}{X}$ $\times$ sinδ]

= [$\frac{(1.8\times 1)}{0.8}$ $\times$ sinδ]

$\therefore$ Pe3= (1.75* Sinδ) in Equation ……..…………….… (13)

The power angle diagrams for the tree conditions are shown in figure 10. At point b of curve c, Pe3=0, δ=δ2. Substituting these values in equation (3), we get-

$\therefore$ 1= (1.75* sinδ2)

⇒ Sin δ2= $\frac{1}{1.75}$

$\therefore$ δ2 = 0.57

$\therefore$ δ2 = 34.85°

$\therefore$ δ_m= (180-34.85) °

= 145.5°

=2.53 rad

$\therefore \cos\delta_m$ =-0.82

- *Stability:*

  For stability, A1=A2

$$\therefore A_1 = Ps\,(\delta c-\delta o) - \int_{\delta 0}^{\delta c} Pmax2 \times \sin\delta\, d\delta$$

$$= Ps\,(\delta c-\delta o) + Pmax2\,(\cos\delta c - \cos\delta o)$$

$$\therefore A2 = \int_{\delta o}^{\delta m} Pmax3 \sin\delta . d\delta - Ps\,(\delta m-\delta c)$$

$$= Pmax3\,(\cos\delta c - \cos\delta m) - Ps\,(\delta m-\delta c)$$

$\therefore$ A1=A2

$\Rightarrow$ {Ps (δc-δo) + Pmax2 (cosδc-Cosδo) = Pmax3 (Cosδc-Cosδm) - Ps (δm-δc)}

$\Rightarrow${PmaxCosδc-Pmax2Cosδc= Ps (δc-δo) +Ps (δm-δc) +Pmax3Cosδm- Pmax3Cosδo}

$$\Rightarrow \cos\delta c = \left[\frac{\{Ps(\delta c-\delta o)+Ps(\delta m-\delta c)-Pmax2\ \cos\delta o+Pmax3\cos\delta m\}}{(Pmax3-Pmax2)}\right]$$

$$= \frac{[1(2{,}53-0.4037)-(0.778\times 0.9196)+1.75\times(-0.82065)]}{(1.75-0.778)}$$

$$= \left[\frac{(2.1293-0.7154-1.435)}{0.972}\right]$$

$\Rightarrow$ Cosδc = - (0.0258)

$\therefore$ δc = 91.3°

- *Critical time,*

  Let, H= 2.7 MJ/MVA

$$\therefore T_c = \sqrt{\frac{2H(\delta c-\delta o)}{\pi f Ps}}$$

$$= \sqrt{\frac{2\times 2.7\times(51.3-23-1.3)\times\frac{\pi}{180}}{\pi\times 50\times 1}}$$

$\therefore T_c$ = 7.07 Seconds

For the system to be stable the clearing angle should be less than the Critical Clearing Angle.

VI. RESULT AND ANALYSIS

- *Unstable Condition:*

  When a small signal disturbance, when Circuit Breakers opens and quickly close using the initial function command.

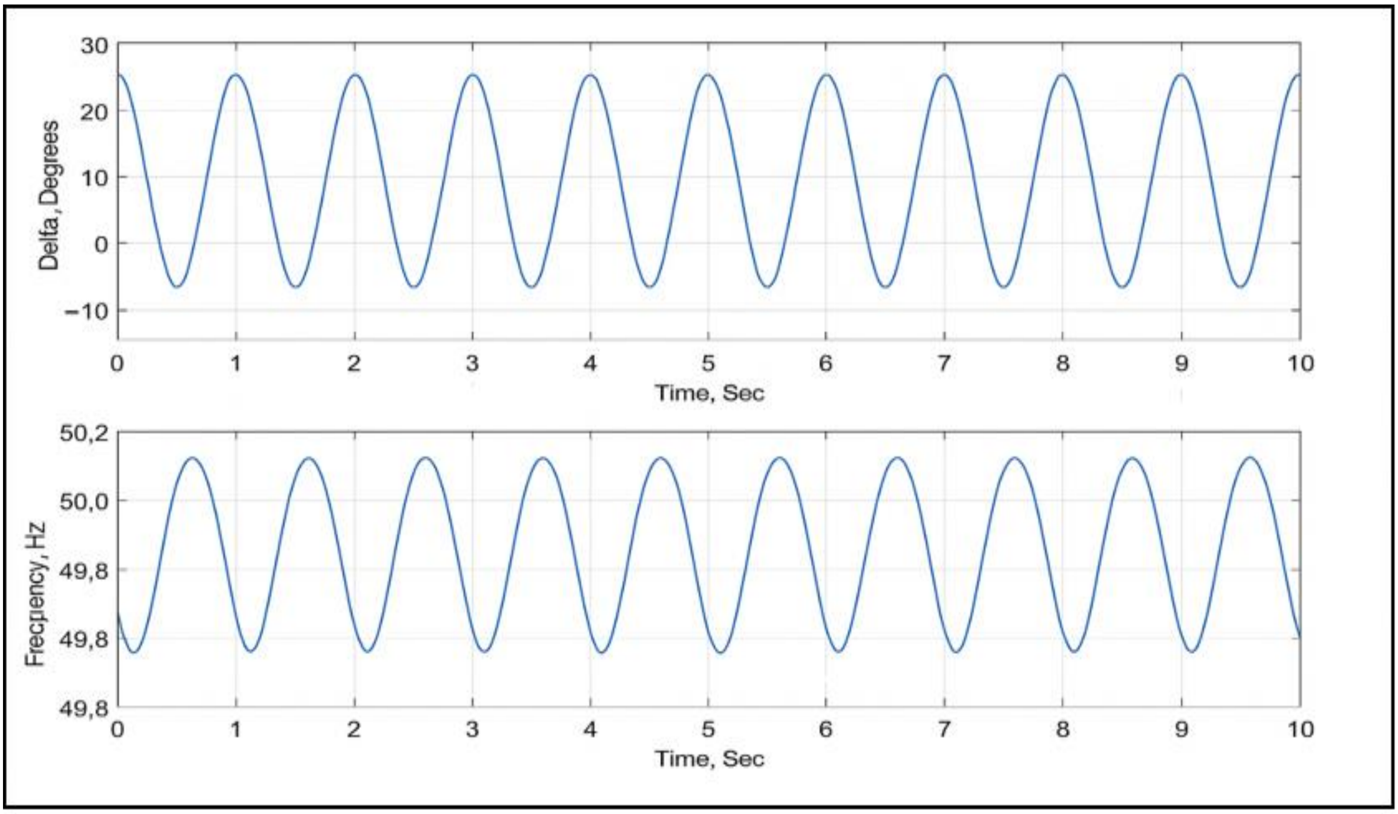

Fig 15 Unstable Condition

- *Stable Condition:*

  Consider the rotor angle and frequency when modeling state space using a step function.

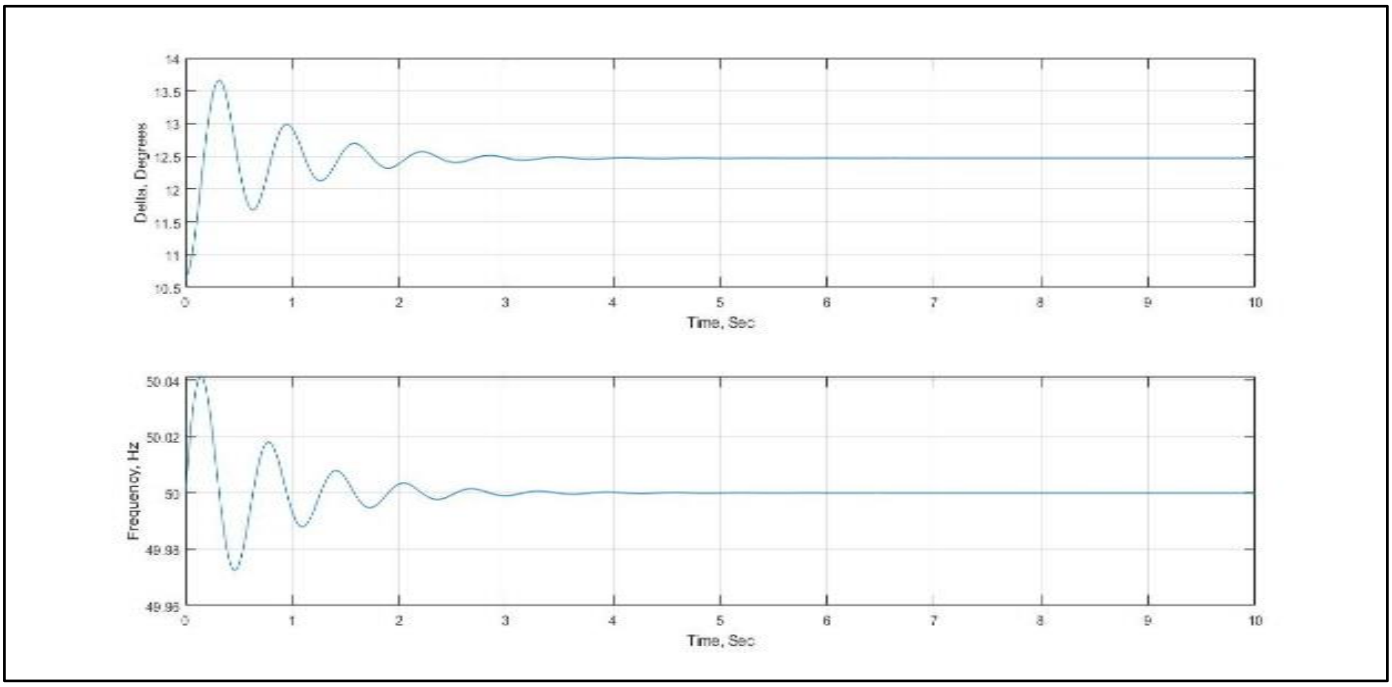

Fig 16 The Resulting Waveform which is a Stable Condition

VII. CONCLUSION

This study investigated both unstable and stable states in transient stability in power systems using MATLAB simulations. A single-machine infinite bus power system has been examined under low signal disturbances, such as circuit breaker operations, which yielded important information about damping ratio, maximum power, synchronization power coefficient, and un-damped frequency of oscillation. The behavior of the system under unstable conditions was illustrated by the load angle and frequency visualization made possible by the MATLAB application. By using a step function and state-space modeling to examine the rotor angle and frequency step response, the study investigated stable situations. The analytical solution for this steady scenario provided better understanding of the system's responsiveness to small changes in power input. The generated plots provided a visual representation of load angle and frequency under both stable and unstable conditions. This research aids power system professionals in developing strategies for enhanced stability and reliability.

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