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Transient Stability Analysis of Power System Using ETAP

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Abstract

The importance of the electric market is increasing as economic pressures and more transactions are pushing electric power networks closer to their security limitations. Some of the main reasons for industrial power system instability include short-circuit faults, loss of utility tie connections, generator rejections, starting of large synchronous loads, switching operations in the lines, and various other factors. If the system is unstable, it can lead to a runaway situation, such as a significant increase in the angular separation of rotors or a significant decrease in bus voltages. The consequences of such instability can be severe, including permanent equipment damage and process shutdowns, to causing a widespread power outage. This study focuses on the fundamentals of transient stability analysis of a single machine connected to an infinite bus. In this research, the three-phase faults on transmission lines in various cases of a single machine system connected to an infinite bus are analyzed using the simulation software ETAP. Additionally, the simulation is used to analyze whether the use of high-speed circuit breakers helps to improve the transient stability of the system.

Keywords : *ETAP, transient stability, infinite bus, synchronism, power angle.*

1. Introduction

The biggest machines in all power systems are synchronous, which includes nearly all of the generators, as well as a significant portion of the motors. It is critical to preserve synchronism on such systems to deliver a high level of service to customers. Load changes, switching operation, and, in particular, faults create temporary

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disturbances. Thus, maintaining synchronism and restoring balance after a disruption are critical for electrical utilities. 'Stability' can be translated as 'synchronism maintenance.' Both of these names are commonly used. The current trend is toward interconnection of the power system, which results in increasing length and reactance of the system, posing an urgent challenge of system stability maintenance. The word 'power limit' is also sometimes read as 'stability,' since in order for the system to be of maximum usefulness, it must be capable of delivering maximum power without producing instability. In general, stability may be described as the capacity of a power system to adapt to a disruption in its regular operation by reverting to a state where the operation is once again normal.

The Electrical Transient Analyzer Program (ETAP) is a simulation-based modeling computer software for electrical engineers use to create a "electrical digital twin" to examine the behavior, transients, and safety of electrical network. ETAP was built for business and nuclear analysis of power systems and operation on the MS-DOS operating system. Power system model includes a power system network model that incorporates system joining, layout, device physiognomies, system response, and concurrent operations data. ETAP employs an electrical digital twin to enable electrical engineers and operators to undertake the electrical studies either offline or online [1].

Some of the key reasons of industrial power system instability are short-circuit fault, loss of utility tie connection, generator rejection, starting of a huge synchronous load, switching operations in the lines and various other factors. If the electrical environment is stable, it will influence a new equilibrium state with nearly the whole system intact; the actions of automatic controllers and maybe human operators will eventually restore the system to its usual state. If it is unstable, it will suffer a run-away situation, such as an advanced increase in the angular parting of the rotors or an advanced decrease in bus voltages. The consequences of such instability are often severe, ranging from permanent equipment damage and process shutdown to triggering a whole-area power outage. The difficulty of maintaining synchronized functioning has always been one of stability. Preserving synchronism, or being "in step," is a crucial criterion for optimal system operation since power systems rely on synchronous equipment to create electrical power. An electrical system's dynamic performance is crucial in its design and working [2].

The main objective of load flow analysis using ETAP is to improve the performance and efficiency of power systems. This is achieved by analyzing the system's variable performance during both construction and operation phases. Specifically, load flow analysis using ETAP computes rotor power angles and speed aberrations, voltage regulation and frequency, machine's reactive and real flows, power flows of transformers and lines, and output voltages of the system's buses. Additionally, the research aims to help in the improvement of power system quality, calculate the critical clearing time of faults, and determine the fault level in the system. These objectives are essential in ensuring that power systems operate within safe and secure limits, and that they are able to meet the increasing demand for electricity.

2. Theoretical Background of Transient Stability

2.1 Rotor Angle Stability

It is the capacity of the power system's linked synchronous to maintain synchronism. The stability issue is concerned with the stability of the electromechanical fluctuations intrinsic in power systems. The way synchronous machines' power output fluctuates as their rotors oscillate is a key aspect in this dilemma. It is mainly ordered into two categories: Small Signal and Transient stability [3].

2.1.1. Small Signal Stability

It refers to the power system's capacity to maintain synchronism in the face of minor distresses. Because of slight differences in loads and generations, such disruptions occur on the system all the time. Instability can take two forms: a constant change in rotor angle due to a lack of adequate torque, or due to a lack of appropriate damping torque. The system's reaction to tiny disturbances is determined by several features, including the beginning operation, sort of generator excitation used and transmission system strength.

2.1.2. Transient Stability

The capacity of a power system to retain synchronism in the face of a huge transient disruption, such as faults, the abrupt outage of a line, or the sudden load application or removal, is referred to as transient stability. The nonlinear power-angle connection impacts the system response, which incorporates considerable expeditions of generator rotor angles. Following such abrupt power system disturbances, rotor angular disparities, rotor speeds, and power transmission experience rapid changes whose magnitudes are depending on the severity of the disturbances. Changes in angular disparities may be so great for a large disturbance that the machine falls out of sync. Transient Instability is the name given to this form of instability. Transient stability is a quick phenomenon that generally occurs within a few seconds for a generator located near to the source of the disturbance. The goal of this research is to determine if the load angle recovers to a stable value once the disturbance has been cleared. The influence of transmission line failures on generator synchronism is studied in transient stability studies.

During the fault, the power from adjacent generators is lowered while the electricity from faraway generators remains relatively constant. The resulting disparities in acceleration cause speed variances across the fault's time interval, therefore it is critical to remove the fault as soon as feasible. The fault clearing process destroys one or more transmission components, weakening the system. The generator rotor angles fluctuate when the transmission system changes. If the alterations cause the accelerated machines to pick up extra load, they slow down and attain a new equilibrium position. Within one second of the first disruption, synchronism will be lost.

Because they create higher acceleration during the event, faults on strongly laden lines are more likely to induce instability than faults on weakly loaded lines. Three-phase faults create larger accelerations than one- or two-phase faults. Faults that are not cleared by the major fault cause greater angle deviations in neighboring generators. Furthermore, the backup fault clearing occurs after a time delay, resulting in significant oscillations. The loss of a big load or producing station causes severe disruption in the system [4].

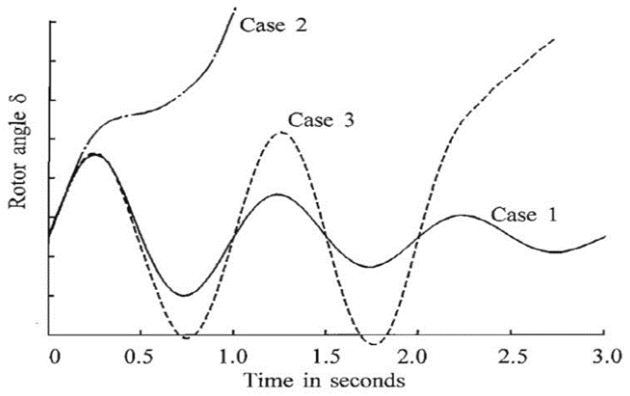


Figure 1. Behavior of a synchronous generator for stable and unstable cases [4].

2.2 Power Angles in Synchronous Machine

Synchronous machines have a significant part in stability because their power angles (or rotor angles) oscillate

during and after disturbances, causing power flow oscillations in the system. The electromechanical balance in the system may be broken and instability may arise contingent on the level of these oscillations. As a result, power system stability is also known as "synchronous machine power angle stability." The most commonly used equations in transient stability analysis are:

Torque Equation (Generator Case) is shown in equation 1.

$$T = \frac{\pi P^2}{8} \varphi_{air} F_r sin\delta \tag{1}$$

Swing Equation (Generator Case) is shown in equation 2.

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

Solving the swing equation yields the swing curve: a plot of time vs torque angle. They are used to calculate the system's stability. When the rotor angle hits a maxima and subsequently lowers, it indicates that the arrangement is transiently stable. If the rotor angle continues to climb forever, the system is unstable [5].

2.3 Power Angle Curve

A synchronous generator is connected to an infinite bus through a lossless line. Then current flowing in the transmission line is calculated using equation 3.

$$I = \frac{E\angle\delta - V\angle 0^\circ}{jX_d + JX_l} = \frac{E\angle\delta - V}{jX} \tag{3}$$

where, $X_d + X_l$= X = total transfer reactance

The real power output from the generator is calculated using equation 4.

$$P = \frac{EV}{X} sin\delta = P_{max} sin\delta \tag{4}$$

The plot of this equation in the Power vs angle graph is called power angle curve [6].

2.4 Transfer Reactance

Suppose that, prior to the fault, the grid is in some stable operational condition. Following the fault, the transient stability complexity is characterized as determining if the system will achieve an appropriate steady-state operational point.

The sub transient duration is often quite brief in comparison to the rotor swing period. The influence of such events on electromechanical characteristics can be ignored. When the swing equation is given, the classical model may be employed to examine the transient stability. During a serious fault, the equivalent reactance will vary, causing power output to shift and the power stability to be disrupted. This will cause energy allocations between the generators, resulting in rotor oscillations.

For pre fault condition, the reactance is calculated using equation 5.

$$X_i = X_d + \frac{(X_1)(X_2)}{X_1 + X_2} \tag{5}$$

Corresponding power angle is calculated using equation 6.

$$P_e = \frac{EV}{X_1} sin\delta \tag{6}$$

So the transfer reactance during fault is calculated using equation 7.

$$X_{ii} = \frac{(X_d)(X_1) + (X_1)\left(\frac{X_2}{2}\right) + (X_d)\left(\frac{X_2}{2}\right)}{\frac{X_2}{2}} \tag{7}$$

Corresponding power angle is calculated using equation 8.

$$X_{ii} = \frac{(X_d)(X_1)+(X_1)\left(\frac{X_2}{2}\right)+(X_d)\left(\frac{X_2}{2}\right)}{\frac{X_2}{2}} \quad (8)$$

For post fault the reactance is calculated using equation 9.

$$X_{iii} = X_d + X_1 \quad (9)$$

Corresponding power angle is calculated using equation 10.

$$P_e = \frac{EV}{X_{iii}} sin\delta \quad (10)$$

2.5 Equal Area Criterion

The transient stability experiments entail determining whether or not synchronism is maintained after a major disturbance to the equipment. This might be due to a rapid load application or loss, generation loss, or a system breakdown. The size of the oscillations in most disturbances is such that linearization is not possible. The developed nonlinear nature of the swing equation must be analyzed. For a rapid forecast of stability, the equal-area criteria can be implemented. This approach uses a graph illustration of the energy stored in the spinning machine to assess if it retains its stability. The approach is only relevant to a simple machine system connected to an infinite bus. In the swing equation, the accelerating power will consist of a sine term. As a result, the equation is a differential equation of non-linear nature with a difficult solution. It is feasible to determine if a system has transient stability or not for two machine systems and one machine linked to an infinite bus bar without solving the swing equation. The Equal Area Criterion refers to a criterion that determines stability by utilizing equal area in a power angle diagram. Thus, the Equal Area Criterion refers to the notion of determining stability under transient situations without calculating the swing equation but instead using areas in a power angle diagram [7].

2.6 Fault Clearing Time

The removal of a faulty element necessitates the use of a protective relay system to identify the fault and activate the working of a circuit breaker, which causes the faulty element to be separated from the system. The overall fault clearing time so consists of the relay time and the breaker interrupting time. The relay time is the time elapsed between the start of the fault current and the start of the trip signal to the circuit breaker. The interrupting time is the period between when the trip signal is activated and when the electricity through the breaker is interrupted. Normal relay periods on HV and EHV transmission systems range from 15 to 30 ms (1 to 2 cycles), while circuit breaker interrupting durations range from 30 to 70 ms (2 to 4 cycles). Critical Clearing Time (CCT) is an important parameter used in power system analysis to determine the time required to clear a fault in the system to avoid a cascade of failures that could lead to system collapse. It is defined as the minimum time required to disconnect a faulted element in the power system to restore stable operation of the system. [8]

3. Result and Analysis

3.1. Calculation Results

From the calculation for the required critical clearing time and critical clearing angle, the Critical Clearing Angle (δc) is calculated to be 157.06 degrees and the Critical Clearing Time (tc) is calculated to be 0.3905 sec.This means that for the fault to be adequately cleared in the system, circuit breakers must operate and isolate the system within 0.3905 seconds such that the rotor angle doesn't increase above 157.06 degrees. Detailed calculations are given in the Appendix section.

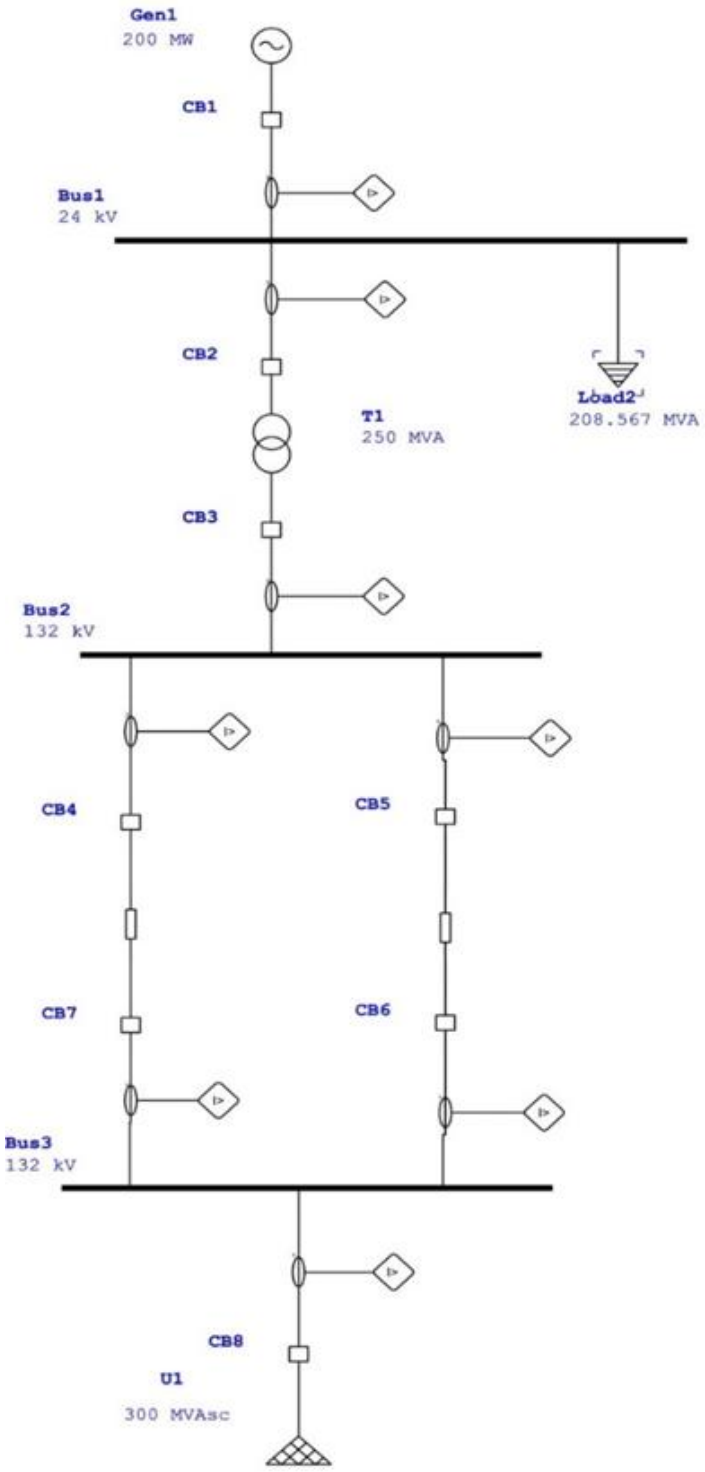


Figure 2. Single line diagram.

3.2 Single Line diagram

The single line diagram shown represents a simplified representation of a power system that consists of a single generator, transmission lines, transformers, and various protective devices such as circuit breakers and relays. The generator (Gen1) is connected to Bus1, which represents the starting point of the power system. The circuit breaker and relay located between the generator and Bus1 help protect the generator from electrical faults that may occur in the system. The power generated by Gen1 is then transmitted to Bus2 through a transformer. The transformer

helps step up the voltage, which is essential for long-distance power transmission. The circuit breaker and relay located between the transformer and Bus2 are used to protect the transformer and the transmission lines. Bus2 is connected to Bus3 through two transmission lines, each consisting of circuit breakers and relays. Finally, Bus3 is connected to the infinite grid.

3.3 Results of Transient Analysis

3.3.1. Case I

When the symmetrical (L-L-L-G) fault is occurred at the mid-point in the Transmission Line-2 of the given power system after 3 seconds of the normal operating condition the fault angle from the graph is seen to be greater than 170 which is greater than the critical clearing angle (i.e., 157.06). Therefore, the system becomes unstable and shuts down; The different output waveforms when the system becomes unstable is shown in the figures below:

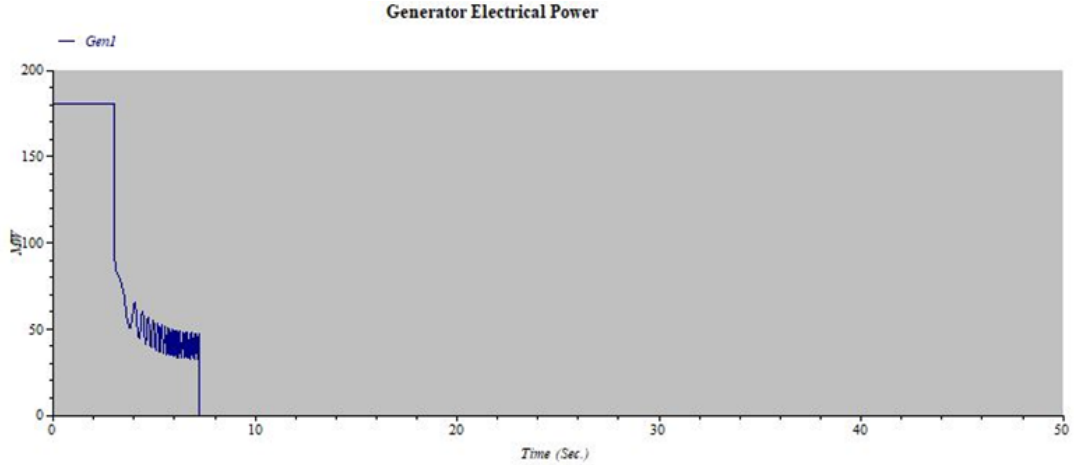


Figure 3. Generator electric power for Case I.

Figure 3 shows a plot of generator electric power vs time. Initially, the generator is operating at its rated power output, which is indicated by a constant horizontal line on the plot. At a certain point in time, a fault occurs in the power system, which causes the electric power output of the generator to sharply decrease to 0. This sharp decrease in power output is indicated by a steep downward slope along with some irregularities in the plot.

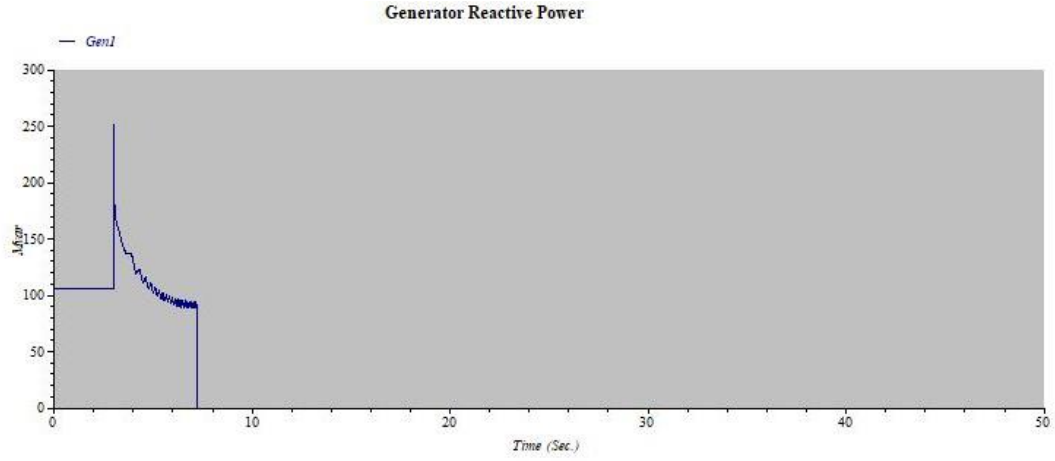


Figure 4. Generator reactive power for case I.

Figure 4 shows a plot of generator reactive power vs time. Initially, the generator is operating at its rated power output, which is indicated by a constant horizontal line on the plot. At a certain point in time, a fault occurs in the power system, which causes the electric power output of the generator to sharply increase in an instance and finally sharply decrease to 0. This sharp decrease in power output is indicated by a steep downward slope along with some irregularities in the plot.

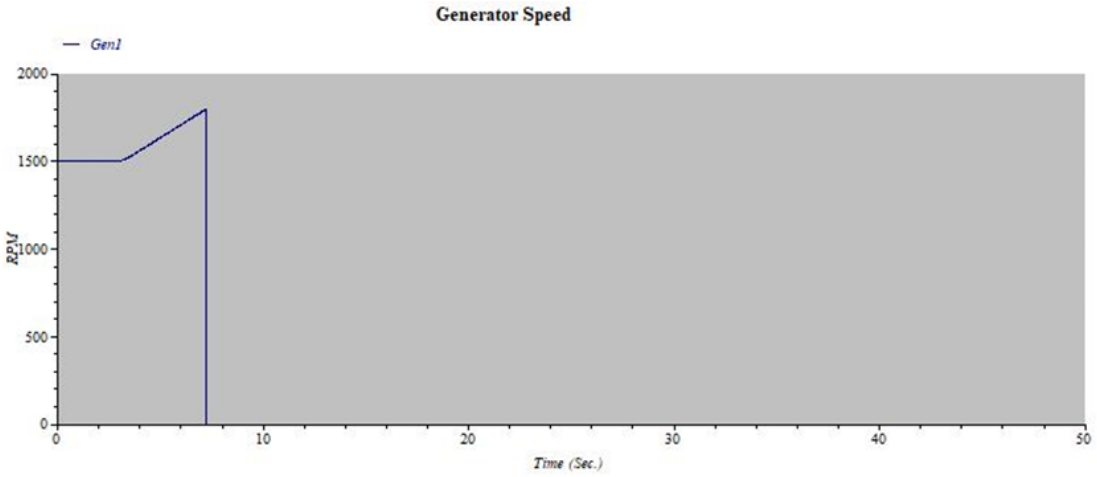


Figure 5. Generator speed for case I.

Figure 5 shows a plot of generator speed vs time. Initially, the generator is operating at its rated speed, which is indicated by a constant horizontal line on the plot. At a certain point in time, a fault occurs in the power system, which causes the speed of the generator to increase in an instance in order to match the high current demand caused by the fault and finally sharply decrease to 0. This indicates that the generator has fully stopped.

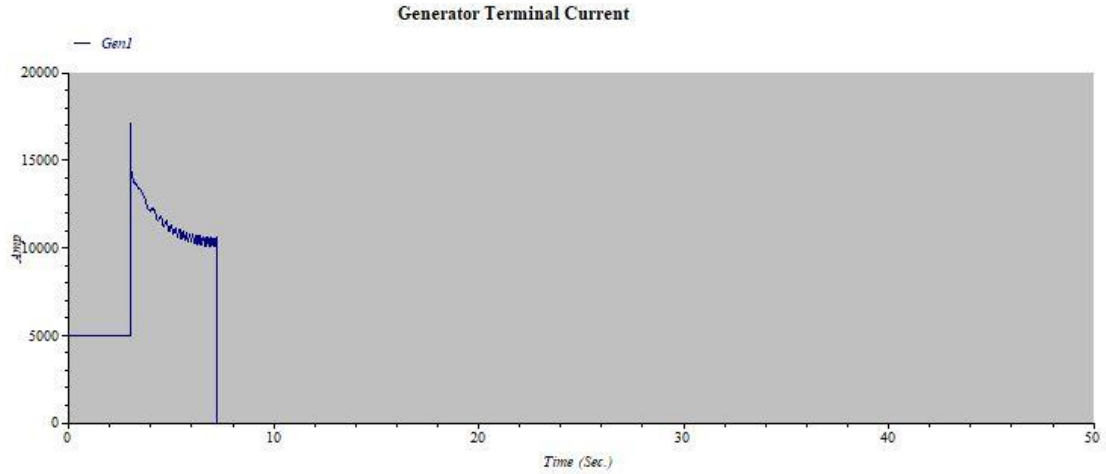


Figure 6. Generator terminal current for Case I.

Figure 6 shows a plot of generator terminal current vs time. Initially, the generator is operating at its rated current output, which is indicated by a constant horizontal line on the plot. At a certain point in time, a fault occurs in the power system, which causes the electric power output of the generator to sharply increase in an instance and finally sharply decrease to 0. This sharp decrease in power output is indicated by a steep downward slope along with some irregularities in the plot.

3.3.2 Case II

When the symmetrical fault is occurred at the mid-point in the transmission line-2 of the given system after 3 seconds of normal operating condition, then the fault is cleared by the circuit breakers after 300 ms of the fault. Since the fault clearing time i.e., 300 ms is less than the critical clearing time of the fault the instability of the system i.e., fault was removed timely and hence the power system returns to its stable condition and hence the stability is maintained. From the output graph the fault clearing angle was found to be <80. The different output waveforms when the system becomes stable are shown below.

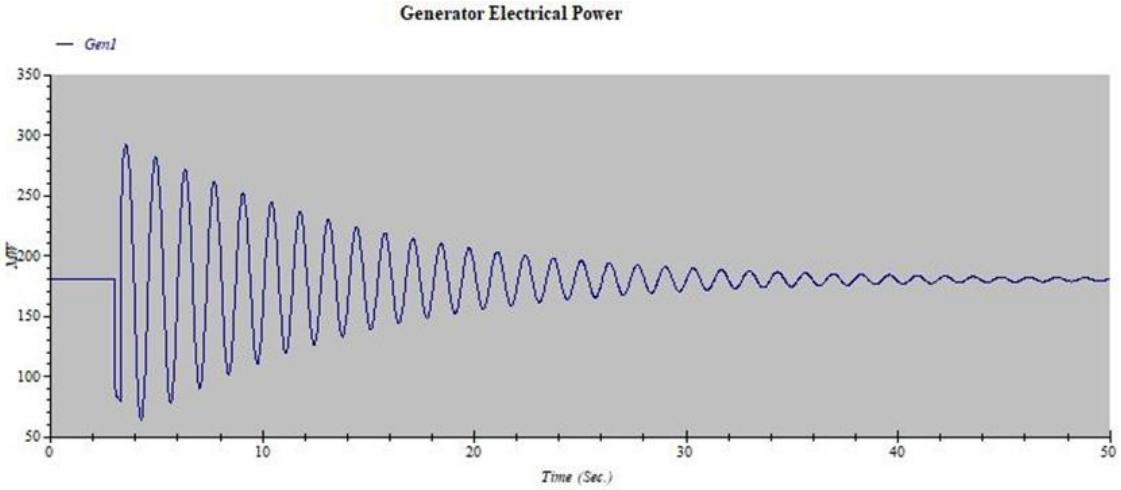


Figure 7. Generator electric power for case II.

Figure 7 shows the behavior of a power system during a fault-cleared condition. The figure shows that initially, the generator is running at its rated power output. However, when a fault occurs in the system, there are sharp irregularities introduced in the line, which causes a significant alteration in the electric power output of the generator. The sharp irregularities in the line indicate that the system is experiencing transient instability due to the fault. As the fault is cleared in a timely manner, these irregularities are slowly eliminated, and the system is restored to a stable state. This is indicated by the almost straight line in the final seconds of the plot, which represents the stable power output of the generator after the fault is cleared. The figure is important in understanding the behavior of a power system during a fault condition and highlights the importance of timely fault clearing to restore system stability.

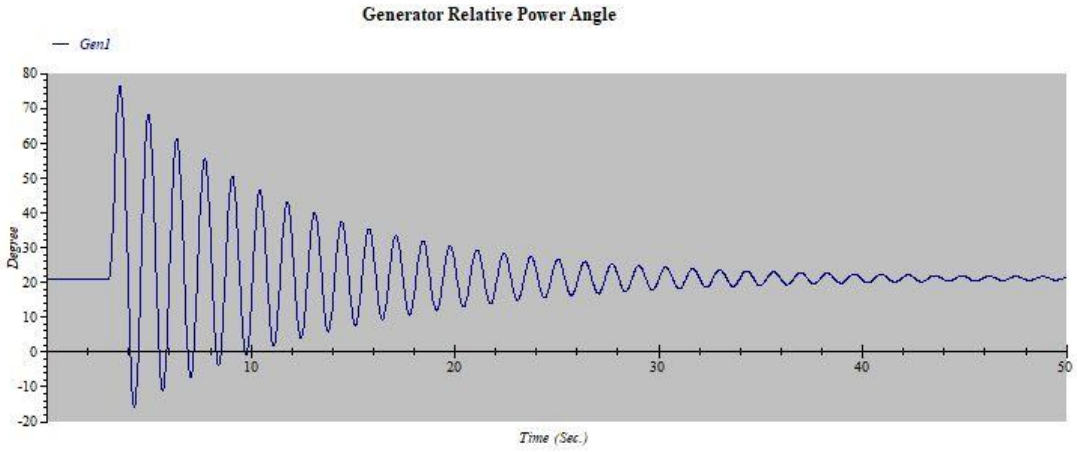


Figure 8. Generator relative power angle for case II.

Figure 8 shows that initially, the generator is running at its rated power angle. However, when a fault occurs in

the system, there are sharp irregularities introduced in the line, which causes a significant change in the rotor angle. As the fault is cleared in a timely manner, these irregularities are slowly eliminated, and the system is restored to a stable state, which represents the return of the stable power angle after the fault is cleared.

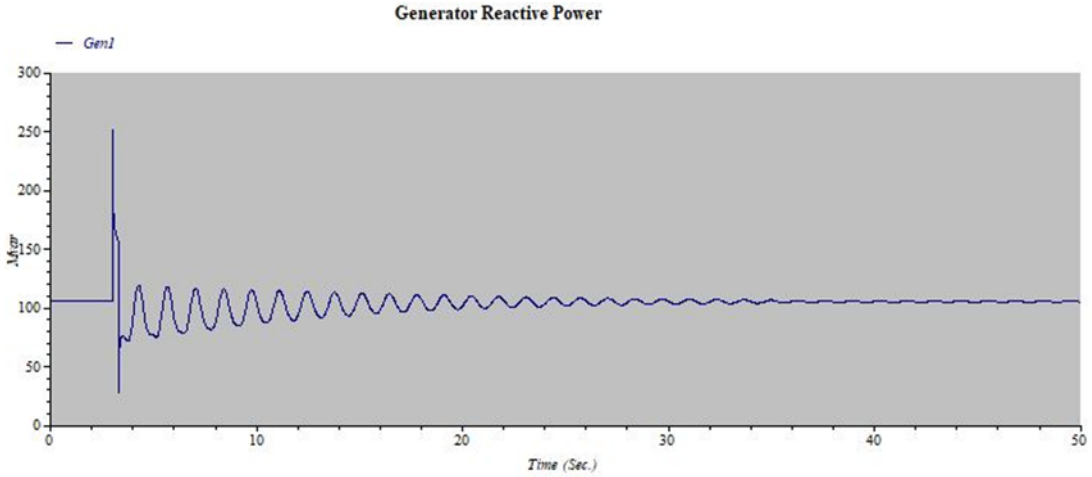


Figure 9. Generator reactive power for case II.

Figure 9 shows that initially, the generator is running at its rated reactive power output. However, when a fault occurs in the system, there are irregularities introduced in the line, which causes a significant alteration in the reactive power output of the generator. As the fault is cleared in a timely manner, these irregularities are slowly eliminated, and the system is restored to a stable state.

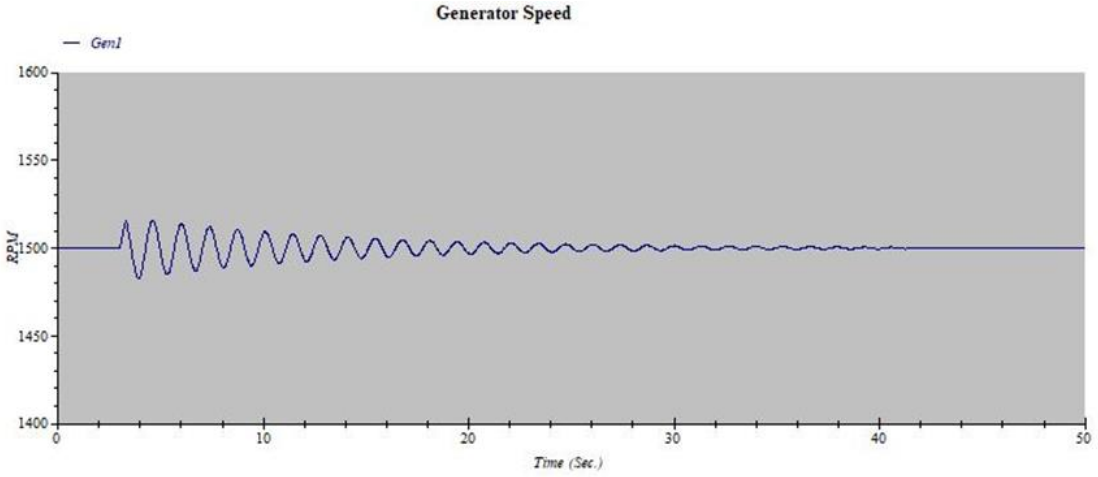


Figure 10. Generator speed for case II.

Figure 10 shows that initially, the generator is running at its rated speed. When a fault occurs in the system, there are irregularities introduced in the line, which causes a small but significant change in the speed of the generator. As the fault is cleared in a timely manner, these irregularities are slowly eliminated, and the system is restored to a stable state.

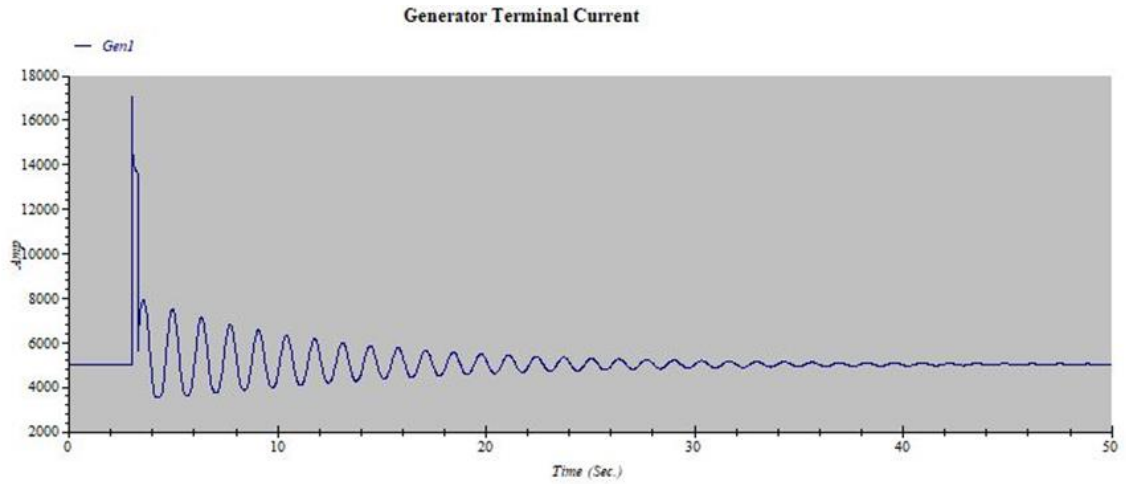


Figure 11. Generator terminal current for case II.

Figure 11 shows that initially, the generator is running at its rated current output. When a fault occurs in the system, there are sharp irregularities introduced in the line, which causes a significant change in the terminal current. As the fault is cleared in a timely manner, these irregularities are slowly eliminated, and the system is restored to a stable state.

3.3.3 Case III

When the symmetrical fault is occurred at the middle of the transmission line-2 of the given system after 3 seconds the fault was cleared by the action of the circuit breakers after 500 ms of the fault. Because the clearing time i.e. 500 ms is more than the critical clearing time we see the system becomes unstable even after the fault is cleared. Also, the power angle of the system becomes higher than the critical clearing angle. Therefore, the system becomes unstable. The different output waveforms when the system becomes unstable are shown below:

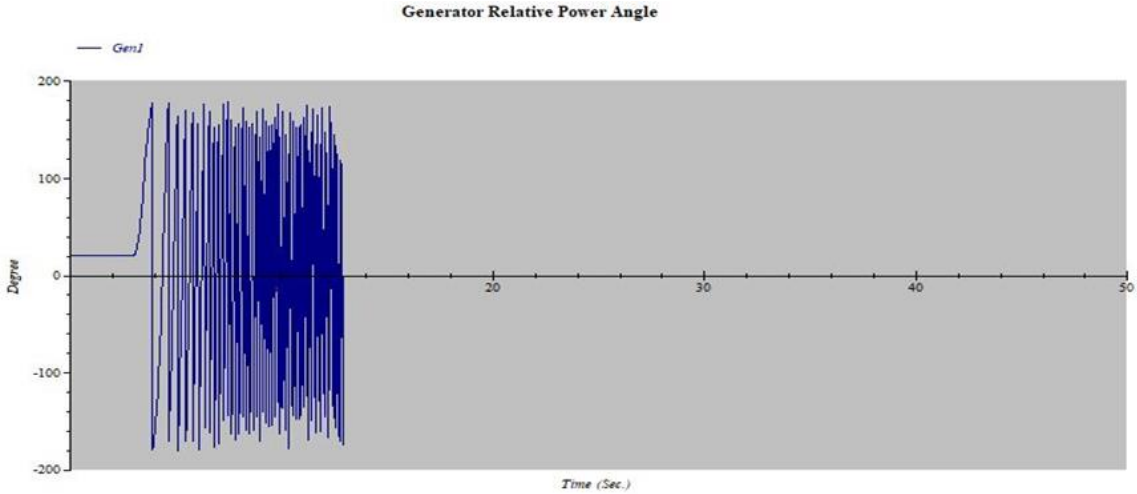


Figure 12. Generator relative power angle for case III.

Figure 12 shows the plot of generator relative power angle vs time indicating the behavior of the power system during a fault event. At the beginning of the plot, the generator is running at the rated power with a stable relative power angle. However, when a fault occurs, the system experiences sharp irregularities in the relative power angle due to the fault impedance. In this case, the fault is not cleared in time due to the fault clearing time being greater

than the critical clearing time. As a result, the irregularities in the relative power angle persist even after the fault is eliminated, and a stable state is not achieved in the power system. Overall, the plot highlights the importance of fast fault detection and clearance to ensure power system stability and prevent potential damage to equipment and disruption of service.

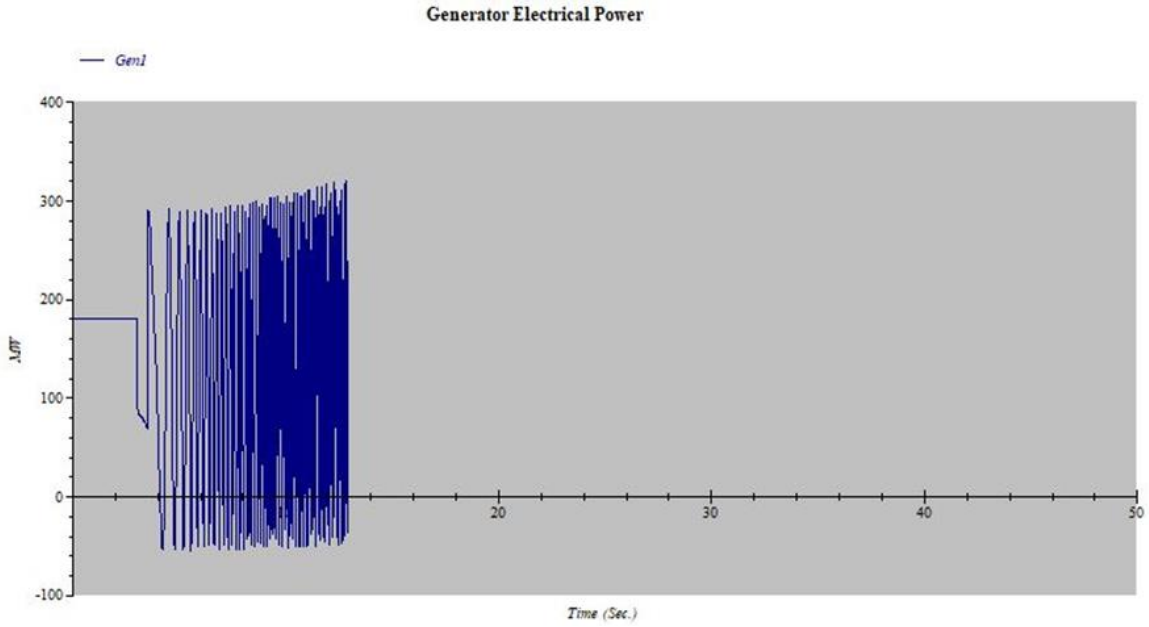


Figure 13. Generator electrical power for case III.

Figure 13 shows the plot of generator electrical power vs time. At the beginning of the plot, the generator is running at the rated power. When the fault occurs, the system experiences sharp irregularities in the power output. The irregularities in the relative power angle persist even after the fault is eliminated, and a stable state is not achieved in the power system due to the fault clearing time being greater than the critical clearing time.

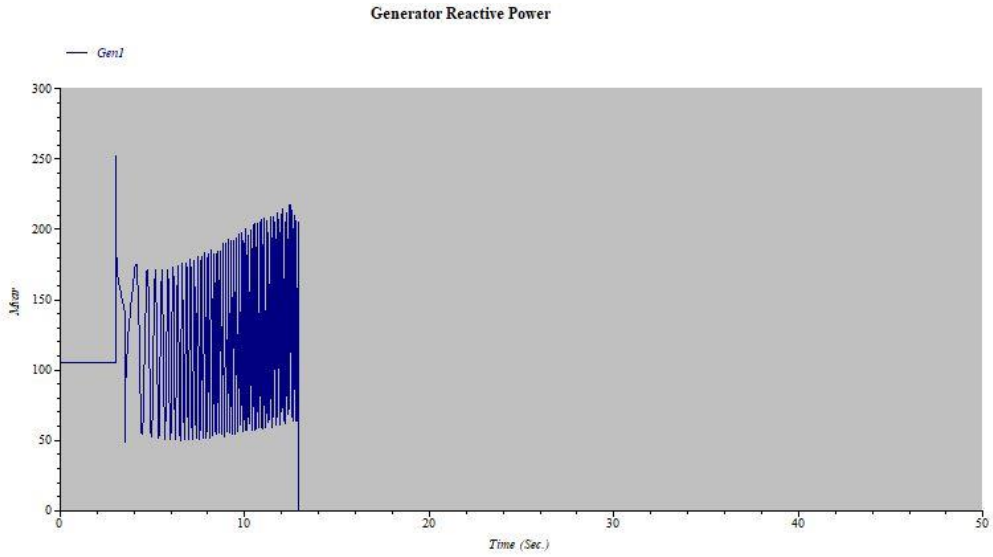


Figure 14. Generator reactive power for case III.

Figure 14 shows the plot of generator reactive power vs time. At the beginning of the plot, the generator is running at the rated power. When the fault occurs, the system experiences sharp irregularities in the reactive power

output. The irregularities in the relative power angle persist even after the fault is eliminated, and a stable state is not achieved in the power system due to the fault clearing time being greater than the critical clearing time.

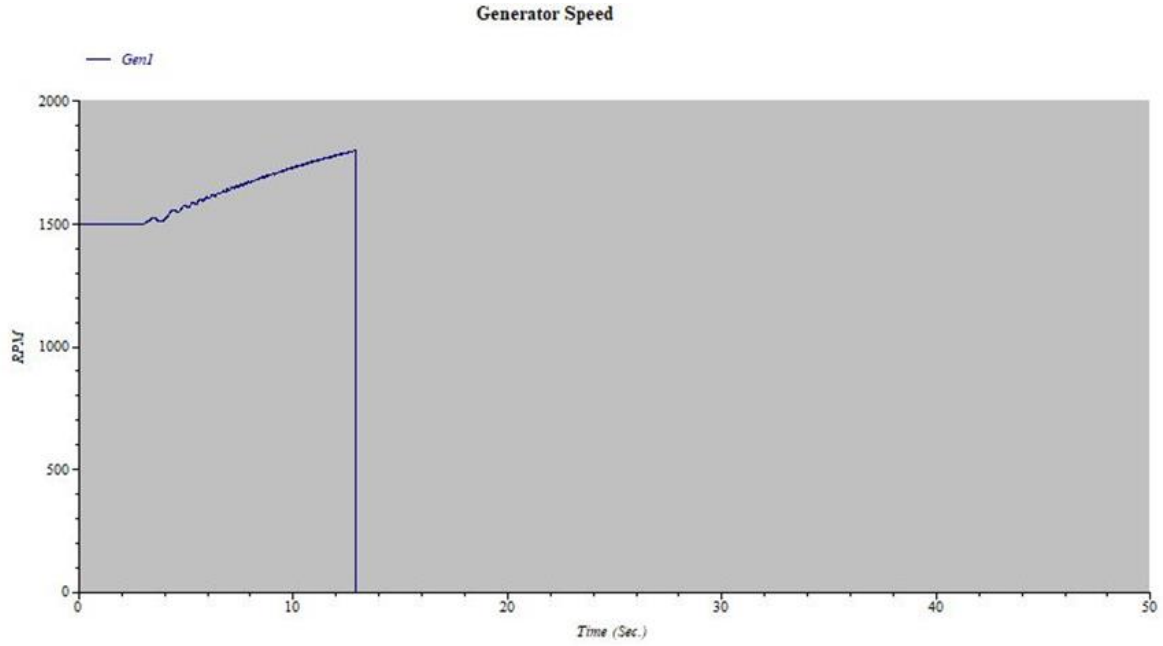


Figure 15. Generator speed for case III.

Figure 15 shows the plot of generator speed vs time. At the beginning of the plot, the generator is running at the rated speed. When the fault occurs, the system experiences some irregularities in the speed. The irregularities in the speed persist even after the fault is eliminated, and a stable state is not achieved in the power system due to the fault clearing time being greater than the critical clearing time. The speed of the generator finally drops to zero indicating the generator has stopped the system will never be stable.

3.4 Analysis of the cases

The critical clearing time and critical clearing angle of single machine system is calculated in the initial state by the use of formulas which was found to be 383 ms and 151.77o respectively. In order to maintain the stability of the power system, it is essential to clear the fault as quickly as possible. It can be seen that the system becomes unstable when the fault clearing time is greater than the critical clearing time. The plots of various generator parameters vs time show the variation of the parameters during a fault. If the fault clearing time is greater than the critical clearing time, the power angle continues to oscillate even after the fault is cleared, indicating that the system is still unstable. This can lead to further disturbances in the system, causing damage to the equipment and possibly even leading to a blackout. It is important to ensure that the fault clearing time is less than the critical clearing time to maintain the stability of the power system. If the fault clearing time is greater than the critical clearing time, the system can become unstable and lead to further problems.

4. Conclusion

Transient instability in large systems may not necessarily arise as the first swing instabilities linked to a single case; it may emerge as a result of greater deviation produced by superposition of numerous modes of oscillation

creating substantial rotor angle excursions. In this study, the time period of interest is generally confined to 3 to 5 seconds after the fault. For highly large systems with strong inter-area swings, it may be extended to 10 seconds. In this research, the three-phase fault on transmission lines and buses at various cases of single machine system connected to infinite bus, isolated multi-machine system, and grid connected multi-machine system are analyzed by using the simulation software i.e., ETAP. Also, from the simulation it is analyzed whether the use of high-speed circuit breakers helps to improve the transient stability of the system. The quicker the circuit breaker operates, the faster the fault is removed from the system and chances of system to regain its stability is improved. But tripping of not-faulted elements would weaken the system further and could lead to system instability. In the case when the generation does not meet the required demand, Under Frequency Relay (U.F.R.) can be used to shed the extra load for the stability of the power system. It is also found that the transient stability of the system heavily depends upon the inertia constant (H) and transient reactance (Xd´) of the machine. The higher is the value of H could lead to the system towards stability but within the limit and vice-versa. Also, by reducing the value of transient reactance of the machine, the system becomes more stable.

The critical clearing angle and critical clearing time can be calculated for a single machine system. But, it is tedious to calculate for multi-machine system, because the transmission line which is lightly loaded may remain stable after also long-term disturbances and if the transmission line is heavily loaded then the system may go unstable when there is also short interval of disturbances to the system.

References

[1] P. S. Patil and K. B. Porate., "Starting analysis of induction motor: A computer simulation by ETAP power station.," in 2009 Second International Conference on Emerging Trends in Engineering & Technology, 2009.

[2] M. M. Adibi, L. R. J. Kafka and D. P. Milanicz., "Expert system requirements for power system restoration.," IEEE Transactions on Power Systems , vol. 9, no. 3, pp. 1592-1600, 1994.

[3] N. A. M. Amin and N. Aqilah, "Power system transient stability analysis using matlab software.," Diss. Universiti Tun Hussein Onn Malaysia, 2013.

[4] M. N. Hidayat, S. Izza and R. I. Putri., "Analysis of Transient Stability in Synchronous Generator Using Nyquist Method," Int. Journal of Engineering and Technology 7, pp. 22-27, 2018.

[5] R. E. Doherty and C. A. Nickle, "Synchronous machines-iii torque-angle characteristics under transient conditions," Transactions of the American Institute of Electrical Engineers, vol. 46, pp. 1-18, 1927.

[6] K. M. Amirthalingam and R. P. Ramachandran, "Improvement of transient stability of power system using solid state circuit breaker.," American Journal of Applied Sciences., vol. 10, no. 6, pp. 563-569, 2013.

[7] S. Wang, J. Yu and W. Zhang, "Transient stability assessment using individual machine equal area criterion PART I: Unity principle," IEEE Access, vol. 6, pp. 77065-77076, 2018.

[8] A. B. Rehiara, "Transient Stability of SMIB: a Case Study," in Proceedings of CITEE, 2009.

Appendix

Calculation details:

A 4*555 MVA, 24 KV, 50 Hz synchronous generator has following values:

Inertia constant H= 5 MJ/MVA

Transient reactance Xd'=0.35 p.u.

It is delivering real power of 0.6 p.u. at 0.85 power factor (lagging). It is linked to an infinite bus through

two transmission circuits. Also, the transformer, line-1 and line-2 reactances are

Xtr=0.125 p.u.

X1=0.1585 p.u.

X2=0.2243 p.u. respectively.

Calculation of Critical Clearing Time

Base MVA = 2220 MVA

Rating of generator (G) = 1 p.u.

The inertia constant (H) = 5 MJ/MVA

Angular momentum (M) = (G*H)/ (180*f) = (1*5)/(180*50)= 0.0005555 p.u.

During normal operation:

Generator reactance, Xd′ = 0.35 p.u.

Transformer reactance, Xtr′= 0.125p.u.

Transient reactance of the system,

X = 0.35+0.125+(0.1585*0.2243)/(0.1585+0.2243)

= 0.5679 p.u.

Maximum power transferred,

Pmax = (1.0063*1)/0.5679

= 1.772 p.u.

PE = Pmax sin δ

Initial power angle is given by the expression,

1.772 sin δo = 0.6

Or, sin δo = 0.6/1.772

Or, δo = sin-1(0.6/1.772)

∴ δo = 19.791o

Under fault condition:

X′ = (0.5215*0.03286+0.03286*0.0465+0.0465*0.5215)/0.03286

X′ = 1.3048 p.u.

Power transferred,

P′E = P′max sin δ =1.0063*1/1.3048

= 0.77123 sin δ.

post fault condition:

Transient reactance of system,

X′′ = 0.475+0.1585

= 0.6335 p.u.

Power transferred,

PE′′ = 1.0063*1/0.6335

= 1.5885 sin δ

Y1 = (reactance before fault)/reactance during fault

Y1 =0.5679/1.3048

= 0.435

Y2 = max power that can be transferred after isolation of fault/max power that can be transferred initially

Y2 = 1.5885/1.772

= 0.896

Since,

δ m = π- sin-1sin δ0 $Y2$

= π-sin-10.338 0.896

= 157.830

And,

cos δc = ((sin δ0*(δm – δ0) –Y1cos δ0 +Y2cos δm))/(Y2-Y1)

= (0.338*(2.7547-0.345)-0.425*1.218+0.896*(-0.926))/(0.896-0.425)

= -0.9209

Critical Clearing Angle (δc) = cos-1(-0.9209)

=157.06

∴ δc = 151.770

Critical Clearing Time (tc) = √{(2H(δc- δ0))/πfPs}

= √{({2*5(2.7412-0.345))/(π*50*1)}

∴ tc = 0.3905 sec.