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Transient Stability Analysis and Simulation of a Five-Buses Electric Power System During a Three-Phase Fault Event

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ABSTRACT

Electric transient stability is recognized as one of the most prevalent issues affecting electric power systems. To ensure a secure electric power system, it is essential to examine all facets of system stability. Various aspects of power system stability have been utilized to assess oscillations and interruptions within the electric power system under different scenarios, which may arise from various types of faults. This paper presents a simulation of a five-busbar electric power system using the Electrical Transient and Analysis Program (ETAP). The analysis includes the waveforms of currents, voltages, and frequencies for each component of the power system. When a three-phase fault occurs at any location within the electric power system, oscillations are induced by the fault, leading to instability. If the fault is rectified within a specified timeframe, the power system is likely to regain stability; otherwise, it will continue to operate in an unstable manner.

Keywords: ETAP, transient stability, power angle, Power System Stability, load flow, three-phase fault, busbars.

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تحليل الاستقرار العابر ومحاكاة نظام الطاقة الكهربائية المكون من خمس قضبان توزيع أثناء حدوث عطل ثلاثي الطور

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ملخص البحث

يعتبر الاستقرار الكهربائي العابر أحد أكثر القضايا انتشارًا التي تؤثر على أنظمة الطاقة الكهربائية. لضمان نظام طاقة كهربائية آمن، من الضروري فحص جميع جوانب استقرار النظام. تم استخدام جوانب مختلفة من استقرار نظام الطاقة لتقييم التذبذبات والانقطاعات داخل نظام الطاقة الكهربائية في سيناريوهات مختلفة، والتي قد تنشأ عن أنواع مختلفة من الأعطال. تقدم هذه الورقة محاكاة لنظام طاقة كهربائية بخمسة قضبان باستخدام برنامج الايتاب. يتضمن التحليل أشكال الموجة للتيارات والجهد والترددات لكل مكون من مكونات نظام الطاقة. عندما يحدث خطأ ثلاثي الطور في أي مكان داخل نظام الطاقة الكهربائية، يتم تحريض التذبذبات بواسطة الخطأ، مما يؤدي إلى عدم الاستقرار. إذا تم تصحيح الخطأ في غضون

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إطار زمني محدد، فمن المرجح أن يستعيد نظام الطاقة الاستقرار؛ وإلا، فسيستمر في العمل بطريقة غير مستقرة وفق نظام الطاقة الكهربائية، يكون هناك تذبذب ناتج عن الخطأ المطبق، ويصبح نظام الطاقة غير مستقر. بمجرد إزالة الخلل خلال الوقت المحدد، من المرجح أن يصبح نظام الطاقة مستقرًا، وإلا سيستمر النظام في العمل بشكل غير مستقر.

الكلمات المفتاحية: برنامج الإيتاب، الاستقرار العابر، زاوية القدرة، استقرار نظام القدرة، تدفق الحمل، عطل ثلاثي الطور، قضبان توزيع.

1. Introduction.

The stability of a power system network refers to its ability to develop restoring forces that are equal to or greater than the disturbing forces, thereby maintaining a state of equilibrium. A system is considered stable if the forces that keep machines in synchronism are sufficient to counteract any disturbances [1].

Stability has recently emerged as a significant concern for both utilities and consumers. Any deviation from stable operating conditions can adversely impact the stability of the power supply. Additionally, the volume of power transactions plays a crucial role in exacerbating congestion within the power system, necessitating careful management, particularly under faulty conditions. Consequently, it is imperative to operate the power transmission system at its maximum capacity to accommodate the growing demand for electrical power. The power transfer capability of long and heavily loaded interregional transmission lines is constrained by transient stability issues, which can lead to loss of synchronism following major disturbances. Disturbances in the power system, often caused by load changes, can lead to electromechanical oscillations in electrical generators, commonly referred to as power swings. It is essential to effectively dampen these oscillations to ensure system stability. Electromechanical oscillations have posed a longstanding challenge for power system engineers. In certain instances, inadequate damping of these oscillations can lead to mechanical fatigue in machines and cause undesirable power fluctuations across critical transmission lines. This situation has prompted the adoption of custom power device-based controllers to enhance the damping of these oscillations within the utility network [1].

The implementation of flexible AC transmission system (FACTS) devices within the power system network offers effective solutions to various challenges. This technology was first introduced by the Electric Power Research Institute (EPRI) in the late 1980s [2]. The fundamental principle behind FACTS is the utilization of high-speed power electronic devices to enhance control and optimize the capacity of existing power systems [3]. In the same period, L. Gyugyi proposed a FACTS controller that employs the concept of solid-state synchronous voltage sources (SVSs). An SVS operates similarly to an ideal synchronous machine, generating three-phase balanced sinusoidal voltages with controllable amplitude and phase angle at the fundamental frequency. This capability allows for the generation of both inductive and capacitive reactive power, which is essential for managing system parameters. The SVS can function as either a shunt compensator or a series compensator. When it operates as a shunt reactive compensator, it is referred to as a static synchronous compensator (STATCOM). Conversely, when it acts as a reactive series compensator, it is known as a static synchronous series compensator (SSSC) [4]. The unified power flow controller (UPFC) represents a unique configuration of two SVSs, with one connected in series to the AC system and the other in shunt to the common DC terminals, effectively combining the functionalities of both devices. Additionally, the thyristor-controlled series capacitor (TCSC) serves as a significant series FACTS controller, providing an alternative to the SSSC. This device enhances the power transfer capability of transmission lines and improves system stability by enabling continuous and rapid adjustments of transmission line impedance [5]. A TCSC controller comprises a series fixed capacitor (FC) in parallel with a thyristor-controlled reactor (TCR) [6]. Furthermore, Mithu Ananthan et al. [7], conducted a comparative analysis of power system stabilizers (PSS), static VAR compensators (SVC), and STATCOM controllers for the purpose of damping power system oscillations. A comprehensive examination of the implementation of STATCOM aimed at enhancing voltage stability, along with its assessment through dynamic PV curves and time simulations, has been documented in reference [8]. Kumar et al. [9] have discussed the enhancement of transient stability through the application of UPFC and SVC. The mitigation of power oscillations via controlled reactive power compensation, as well as a comparative analysis of series and shunt methodologies, is detailed in the reference [10]. The authors in [11] have illustrated the use of a unified power flow controller (UPFC) for the suppression of power system oscillations. Lei et al. [12] introduced a method for optimizing and coordinating damping control to enhance the dynamic performance of power system networks. Additionally, a study presented in [13] at the 2018 International Conference on Computing, Power and Communication Technologies (GUCON) focuses on the improvement of power system stability through UPFC.

This research investigates the application of ETAB program – founded in 1986, in California- for the decreased oscillations within a power system network under 3-phase fault conditions, proposing an effective ETAB program to achieve the desired damping of power system oscillations. Standard IEEE 5-Bus System connected with two generators has been proposed for simulation and analysis 3-phase fault disturbances shown in Figure 1. Using Newton-Raphson theory for calculation analysis [14, 15].

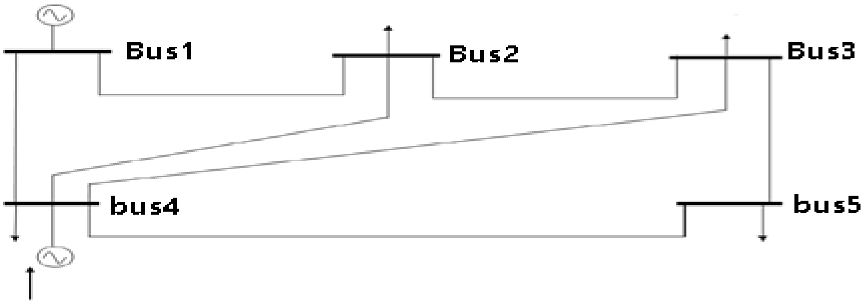
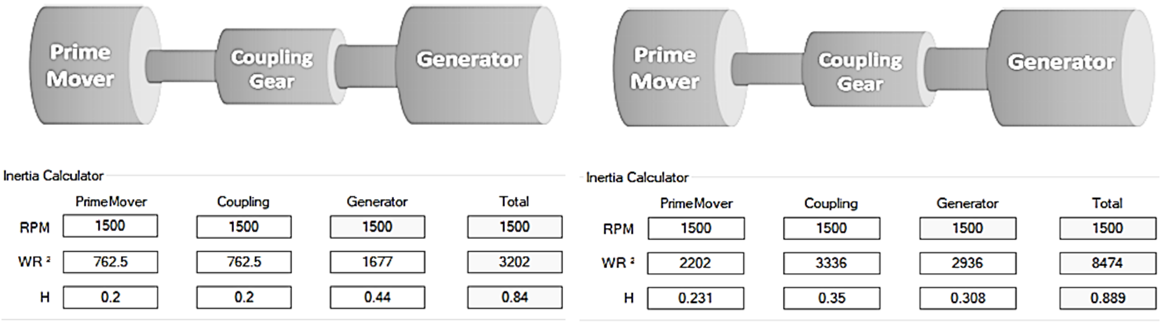


Figure 1. Standard IEEE 5-bus system

The 5-busbars electric power system designed consists of several types of elements, the first type is 3-ph generators (Gen1 & Gen2), both generators are a type of voltage control, in addition to a 3-phase power grid (U1), which also feeds the loads of the electric power systems continuously. Figure 2 below shows the inertia parameters for both GEN.1 & GEN.2.



Inertia Calculator

	PrimeMover	Coupling	Generator	Total
RPM	1500	1500	1500	1500
WR^2	762.5	762.5	1677	3202
H	0.2	0.2	0.44	0.84

Inertia Calculator

	PrimeMover	Coupling	Generator	Total
RPM	1500	1500	1500	1500
WR^2	2202	3336	2936	8474
H	0.231	0.35	0.308	0.889

Figure 2. Inertia characteristics for both GEN.1 and GEN.2

The second type of elements are the electric power transformers connected to the electric power network in different ways. The third type of elements are busbars, circuit breakers, and loads that receive the electric energy. When a 3-ph fault occurs at any point of the electric power system whether transmission line, bus, or transformer, the entire system gets affected causing transients such as frequency changes, voltage rise, etc. In this paper, after designing the electric power system, there will be a case study applied to the electric power system (Transient stability study). The case study was chosen by applying a 3-ph fault at any point of the system and showing how the entire system gets affected whether in terms of current, voltage, frequency, etc. All results will be simulated using Electrical Transient and Analysis Programmer. The capability curves for both generators have the characteristics illustrated in Figure 3 below.

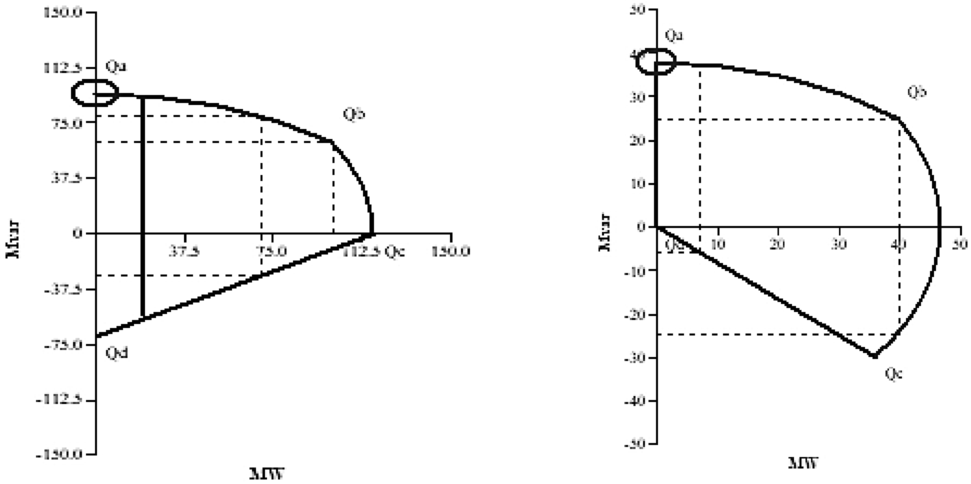


Figure 3. Capability curves for GEN.1 & GEN.2.

2. Classification of Stability

Power system stability, while a singular concept, cannot be effectively studied in isolation. Instability within a power system can present itself in numerous forms and is influenced by a variety of factors. By categorizing stability into pertinent classifications, the analysis of stability challenges is significantly enhanced, allowing for the identification of key variables that contribute to instability and the formulation of strategies aimed at improving stable operation. This approach is based on several considerations:

i. The instability arising from the system's physical characteristics;
ii. The magnitude of the disturbance being analyzed;
iii. The equipment, processes, and timeframes that must be evaluated to determine stability;
iv. The most effective methods for assessing and predicting stability.

The understanding of electric power system stability is rooted in this framework. Power system stability, or PSS, refers to the capacity of an electric power system to return to its equilibrium state after experiencing a physical disturbance, with the primary system variables adjusted to ensure that the system remains fundamentally unchanged, given a specific initial operating condition. Below, Figure 4 illustrates the classifications of power system stability [16, 17].

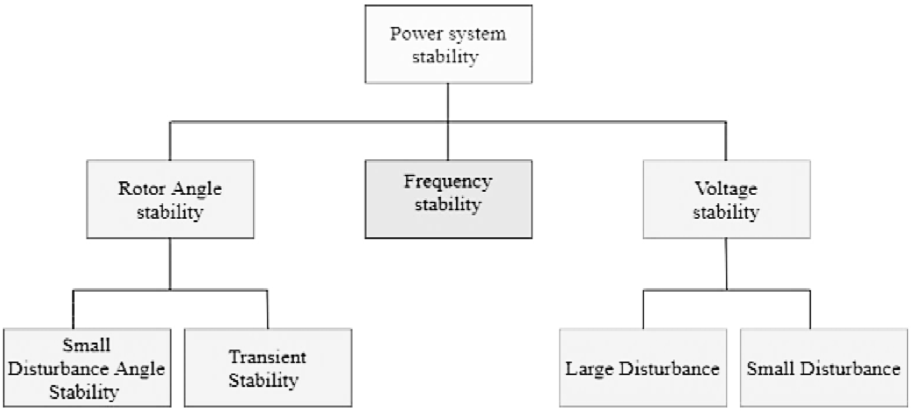


Figure 4. Types of power system stability [16, 17].

3. Newton-Raphson theory.

Any system's load flow analysis is a mathematical technique used to identify the components of any electrical system in normal, stable operation, which is useful for power system design and operation. It is necessary to compute the admittance Y bus to do load flow analysis. Using the primary equations, the nodal equations for a power system network utilizing Ybus may be expressed as follows [18].

$$\mathrm{I} = Y_{bus} * \mathrm{V} \tag{1}$$

$$I_i = \sum_{j=1}^{n} Y_{ij} * V_j \text{ , } where\ i = 1,2,3, \dots\dots\dots n \tag{2}$$

$$P_i + jQ_i = V_i I_i^* \tag{3}$$

$$I_i = (P_i - jQ_i)/V_i^* \tag{4}$$

$$(P_i - jQ_i)/V_i^* = V_i \sum_{j=1}^{n} Y_{ij} - \sum_{j=1}^{n} Y_{ij} V_j \qquad j \neq i \tag{5}$$

Where Pi and Qi are the real and reactive power for bus I, respectively.

Any electrical system's steady state may be analyzed using a variety of load flow techniques. We have chosen the Newton-Raphson strategy and algorithm for this work, utilizing the ETAP. In this research this technique has been applied because it is quicker than other approaches, requires fewer iterations, and has a pretty high level of dependability [18].

To calculate the load flow, the program should first analyze the main equations and substitute them together to get the final result. For instance, by expressing equation (2) and inserting it into equation (3), the real and imaginary components of the equation will be:

$$P_i = \sum_{j=1}^{n} |V_i||V_j|\,|Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{6}$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j|\,|Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{7}$$

where the angles of Vi, Vj, and Yij are δi, δj, and θij. Additionally, equ. (6) & (7) extended on the initial estimate in Taylor's series while excluding any higher-order components and expressing it in matrix form [18].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{8}$$

The Jacobian matrix entries are J1 through J4. J1's diagonal and off-diagonal components are:

$$\partial P_i / \partial \delta_i = \sum_{j\neq 1} |V_i||V_j|\,|Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

$$\partial P_i / \partial \delta_i = |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{10}$$

For the terms ΔPi(k) and ΔQi(k), the discrepancy between the schedule and the computed values known as power residuals is as follows [18]:

$$\Delta P_i^{(k)} = \Delta P_i^{sch} - P_i^{(k)} \tag{11}$$

$$\Delta Q_i^{(k)} = \Delta Q_i^{sch} - Q_i^{(k)} \tag{12}$$

The most recent bus voltage estimations are:

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{13}$$

$$|V^{k+1}| = \left|V_i^{(k)}\right| \Delta \left|V_i^{(k)}\right| \tag{14}$$

4. Electric Transient & Analysis Programmer (ETAP) as a Tool.

For the design, simulation, operation, and automation of industrial power systems, distribution, and generation, ETAP is the most complete analysis platform available. ETAP is a high-impact software that is used globally and is developed under a well-established quality assurance program. With translated output reports in six languages, it is fully localized in four languages. The Simulink software that allows us to draw a system is called ETAP. By giving the rotor a signal, the Power System Stabilizer helps to lessen instability [19].

5. Problem Formulation

Due to the complicity of electric power systems and increasing the demand for feeding different types of loads, there have been many problems appearing in the power systems, which have to be recognized in the way that they should be, to keep the system more reliable and stable as well. Consequently, in this paper, there are 5-busbars electric power systems used as a case study to identify the transient stability when a 3-ph fault occurs at any point of the power system, in addition, how can this appeared fault be cleared within a short period of time for keeping electric power system working efficiently, stable and more secure.

6. Methodology

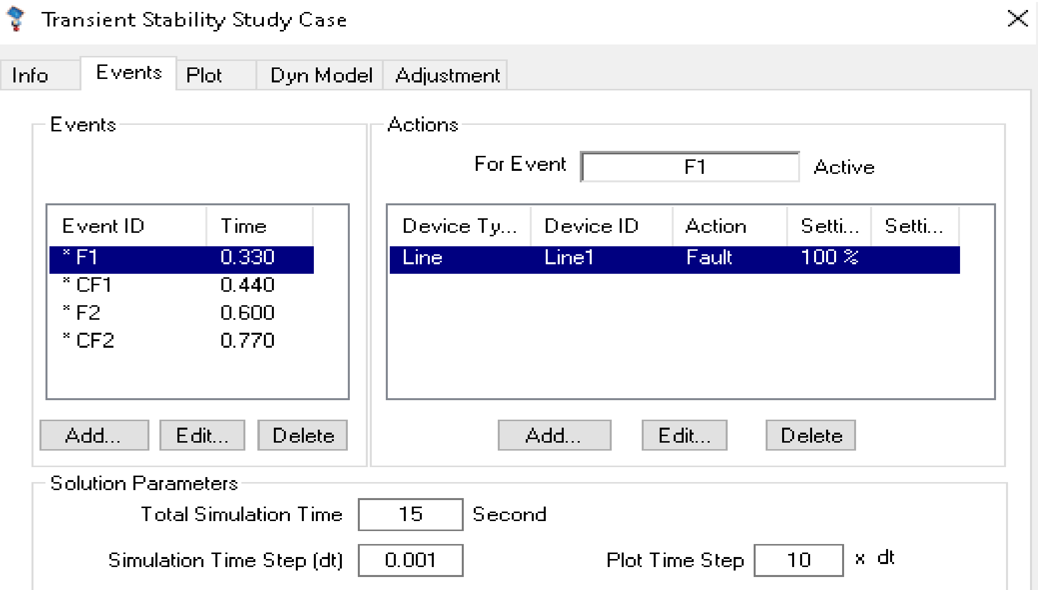
After designing the electric system and entering the required data for every single element using ETAP, it is important to run the load flow study to see the system how is operating. After that, when applying different faults at different zones of the electric power system, there would be different results in load flow illustrating that the system is interrupted due to a 3-ph fault occurring at some points of the system. Basically, to overcome this problem, is necessary to clear the fault that occurred by changing the time event in the transient stability study case to get the system back to its normal conditions as illustrated in Figure 5 below.

7. Electric Power System Module for Five Buses

Electric Transient & Analysis Programmer has been used to design the electric power system used for transient stability study, which is one of the effective and technical tools that can analyse and simulate different types of power systems. Basically, the model shown in Figure 6, shows the components of 5-buses electric power system used for studying the transient stability of the system as illustrated. The components are:

1- Two 3-phase transformer, both are controlled voltage suppliers (GEN1 & GEN2). In addition to a power grid (U1), and the operation of this component is chosen to be Swing.

2- Two 3-phase transformers.
3- 5 Buses
4- 3 Transmission lines with different characteristics
5- Different types of loads (heavy & light loads)


Transient Stability Study Case

Events

Event ID	Time
* F1	0.330
* CF1	0.440
* F2	0.600
* CF2	0.770

Actions

For Event F1 Active

Device Ty...	Device ID	Action	Setti...	Setti...
Line	Line1	Fault	100 %	

Solution Parameters

Total Simulation Time 15 Second

Simulation Time Step (dt) 0.001

Plot Time Step 10 × dt

Figure 5. Events setting for transient stability case study interfaceusing ETAP.

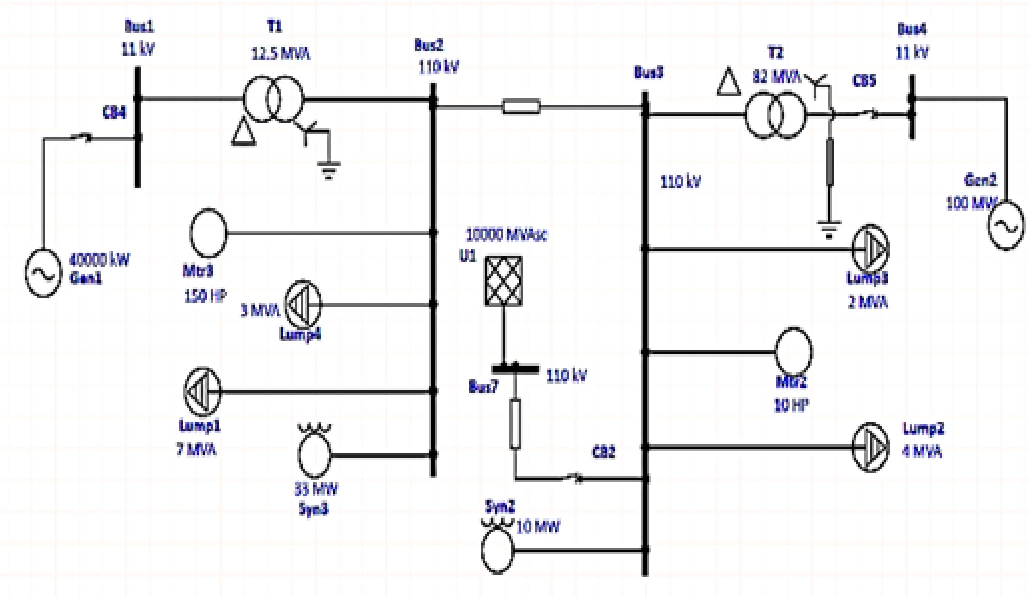


Figure 6. 5-Busbars electric power system used for a transient stability study

8. Scenarios of the research design.

The analysis is divided into two scenarios.

Scenario 1: This examines the behavior of the electric power system when faults occur at busbars 2 and 4. The analysis involves performing a load flow study following the occurrence of a three-phase fault at these busbars. Subsequently, the waveform characteristics are plotted, including the power angle of generators GEN.1 and GEN.2, as well as the frequency and voltage profiles of these generators.

Scenario 2: Similar to the first scenario, this case considers the impact of a three-phase fault, but here it is applied to transmission line 3. The analysis results include the voltage and current characteristics of all buses, along with the phase angle profiles of generators GEN.1 and GEN.2.

9. Results and Discussion

Scenario (1): 3- phase fault occurred on (busbar 2 and busbar 4 individually)

Figure 7 illustrates the results of the load flow analysis, demonstrating that the electric power system operates as designed under normal conditions. Figure 8 provides the interface of the load flow analysis applied to the system before any faults, highlighting that the system maintains operation within acceptable voltage and frequency ranges, ensuring its reliability and stability.

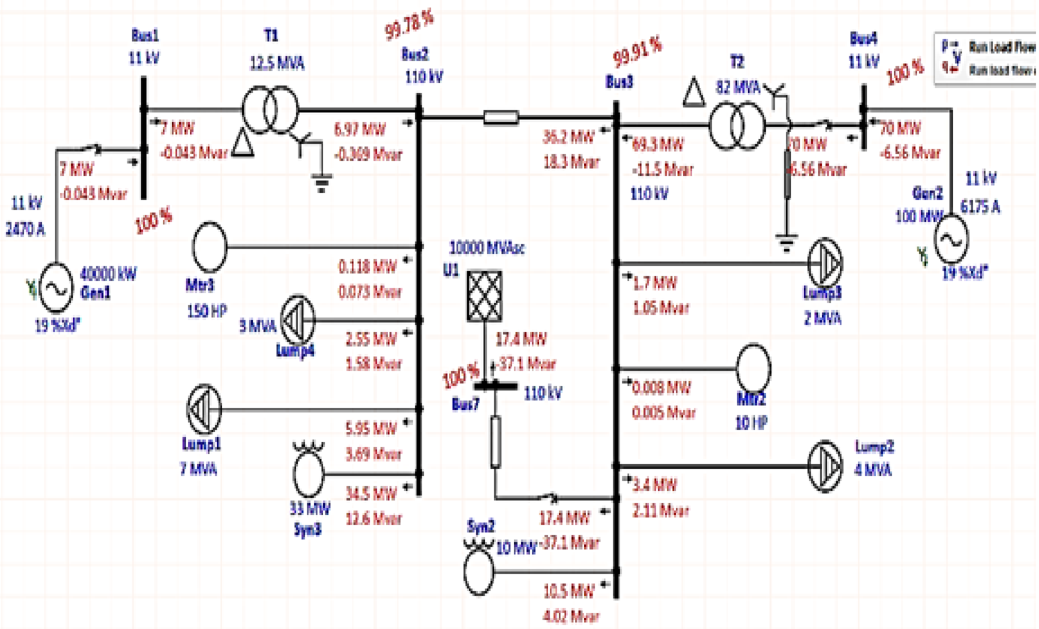


Figure 7. Load flow analysis when the electric power system working at normal conditions (No faults applied).

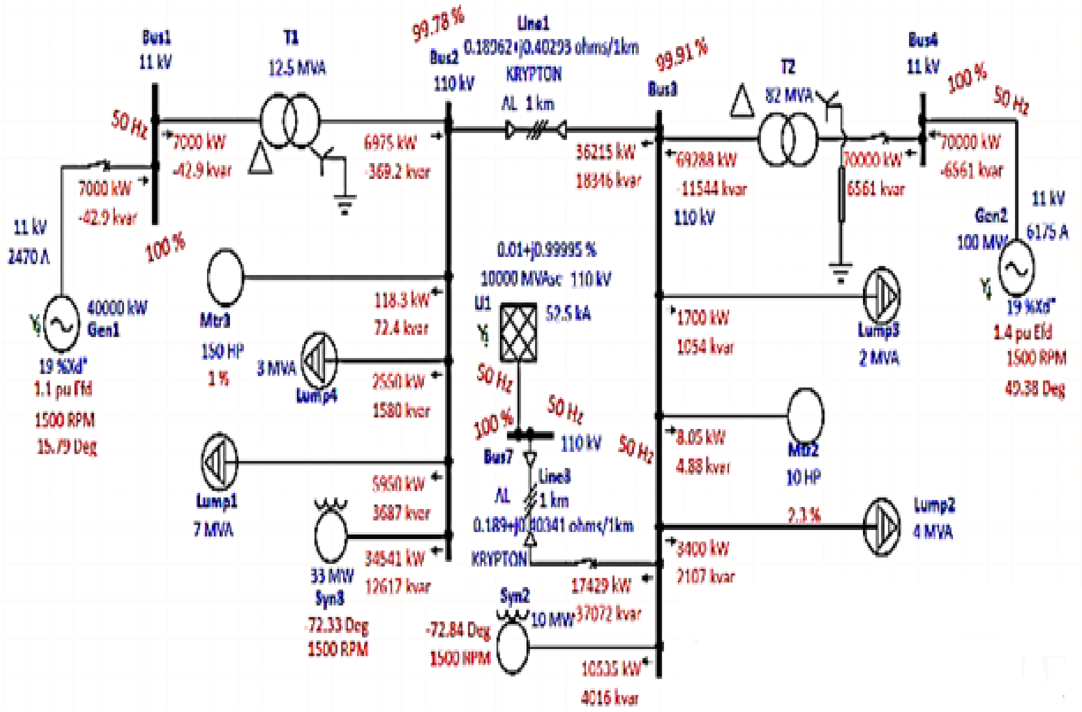


Figure 8. Transient stability analysis interface before a three-phase fault occurred.

The occurrence of a three-phase fault at bus 2, followed by a subsequent fault at bus 4, induced instability in the power system over varying time intervals. This instability resulted in significant fluctuations in critical system parameters, including frequency and voltage levels across the buses, as well as variations in the power angles of the generators. Upon clearing the faults, the system effectively regained stability, as illustrated in Figures 9 and 10.

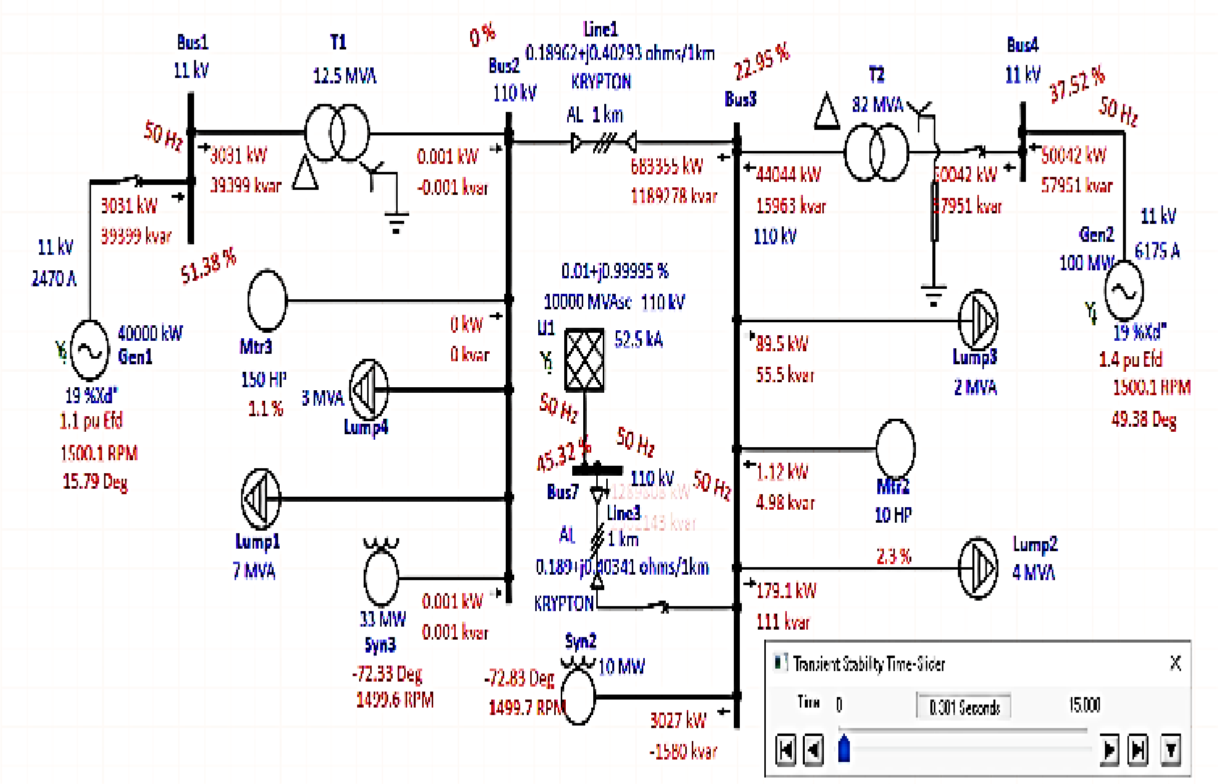


Figure 9. A three-phase fault occurred at busbar 2 characteristics when the transient stability time-slider is set at 0.301 seconds.

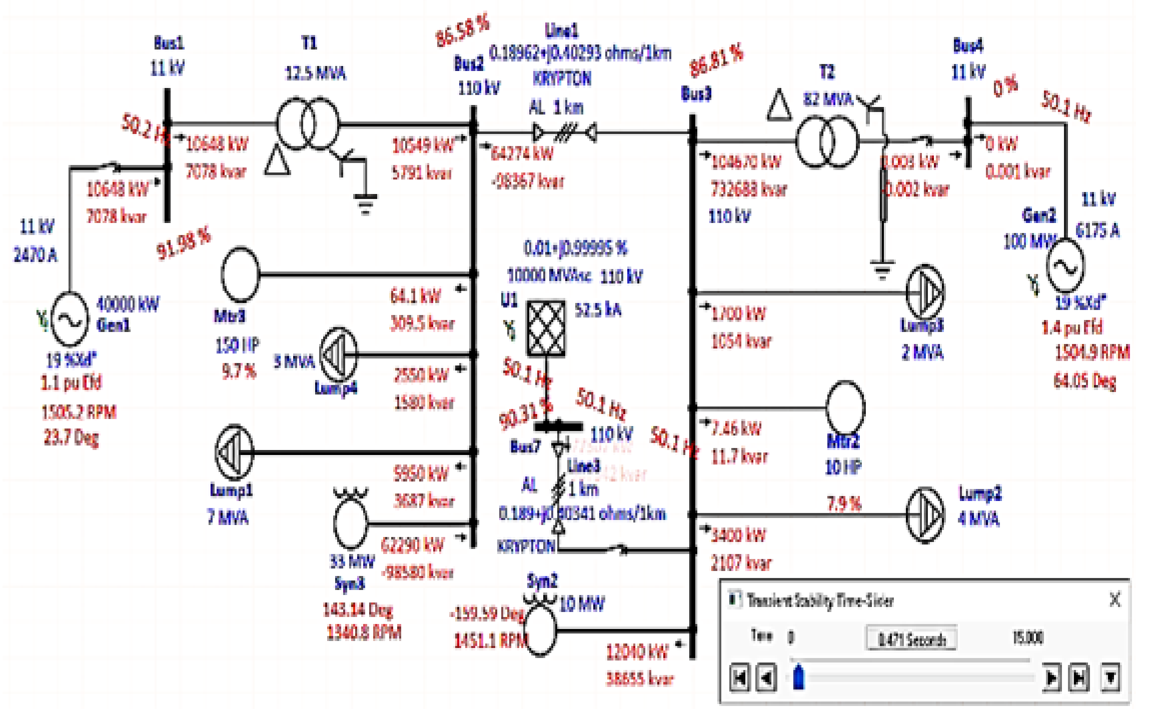


Figure 10. A three-phase fault occurred at busbar 4 when the transient stability time-slider is set at 0.471 seconds

In Figure 11 below, the power angles of GEN1 & GEN2 have changed due to the three-phase fault. The system has become unstable in a short time, which may affect the entire system, whether transformers, loads, transmissions, etc. For generator1, the rotor angle is at about 49 degrees and at about 0.322 seconds the fault occurs, thus the rotor angle starts to swing and then becomes about 49 degrees again as it was because the fault is cleared after about 8 seconds. For generator 2, the maximum value of the power angle is less than the power angle waveform of generator 2, and the rotor angle is about half of that in GEN-2.

Figures 11-13 below illustrate the impact of the fault on bus voltages. Initially, the voltages remained within normal ranges for a short period. However, when a three-phase fault occurred, the voltages dropped significantly, nearly reaching zero. After the fault was cleared, the bus voltages gradually recovered to their original levels, allowing the system to return to a stable state within the specified time frame.

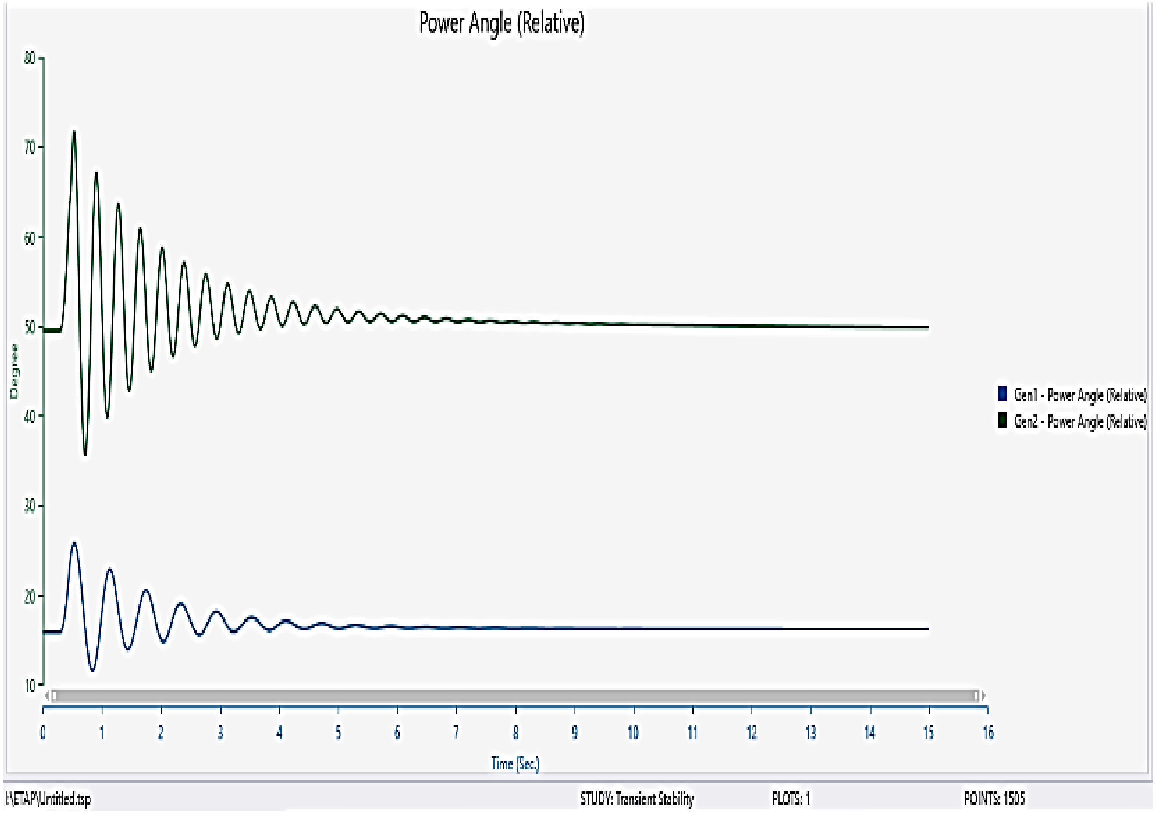


Figure 11. Power angle (relative) for both GEN1 & GEN2 characteristics.

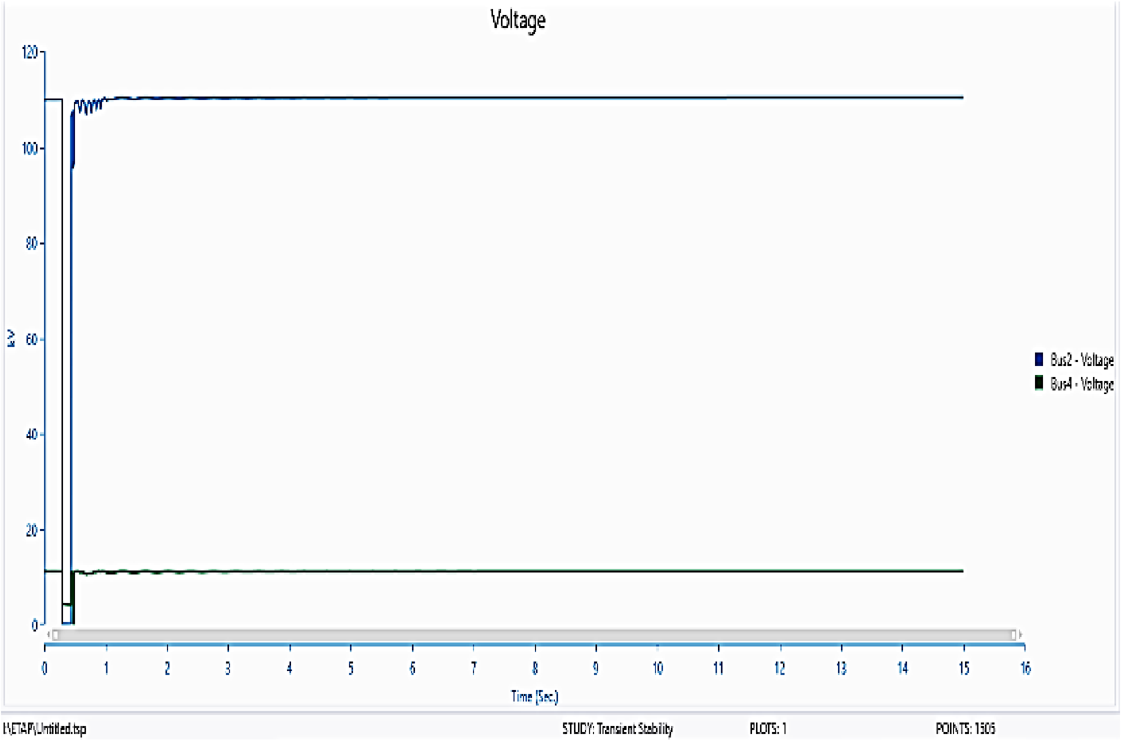


Figure 12. Voltage characteristics when three-phase faults occurred at both busbars 2 & 4.

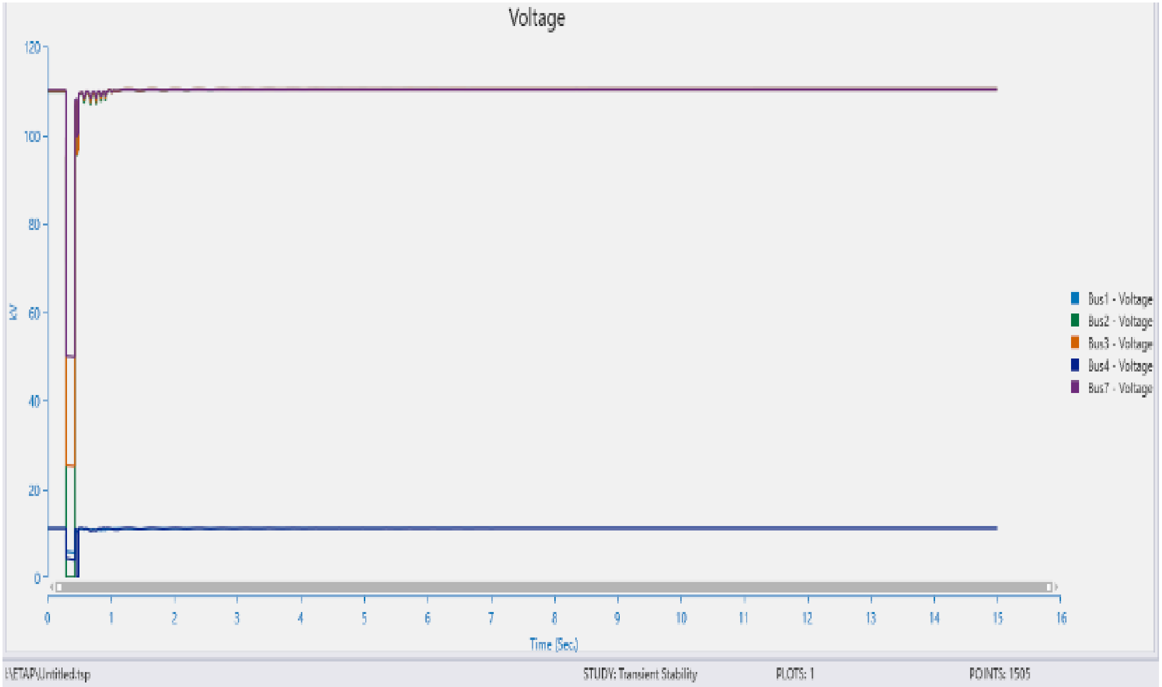


Figure 13. Voltage characteristics when three-phase faults occurred at all connected busbars.

Figures 14 and 15 below illustrate the frequency variations at each bus following the occurrence of a three-phase fault. This fault impacted the entire system temporarily, affecting not only the frequencies but also the voltages and currents. To restore the system to stability, it was necessary to clear the fault.

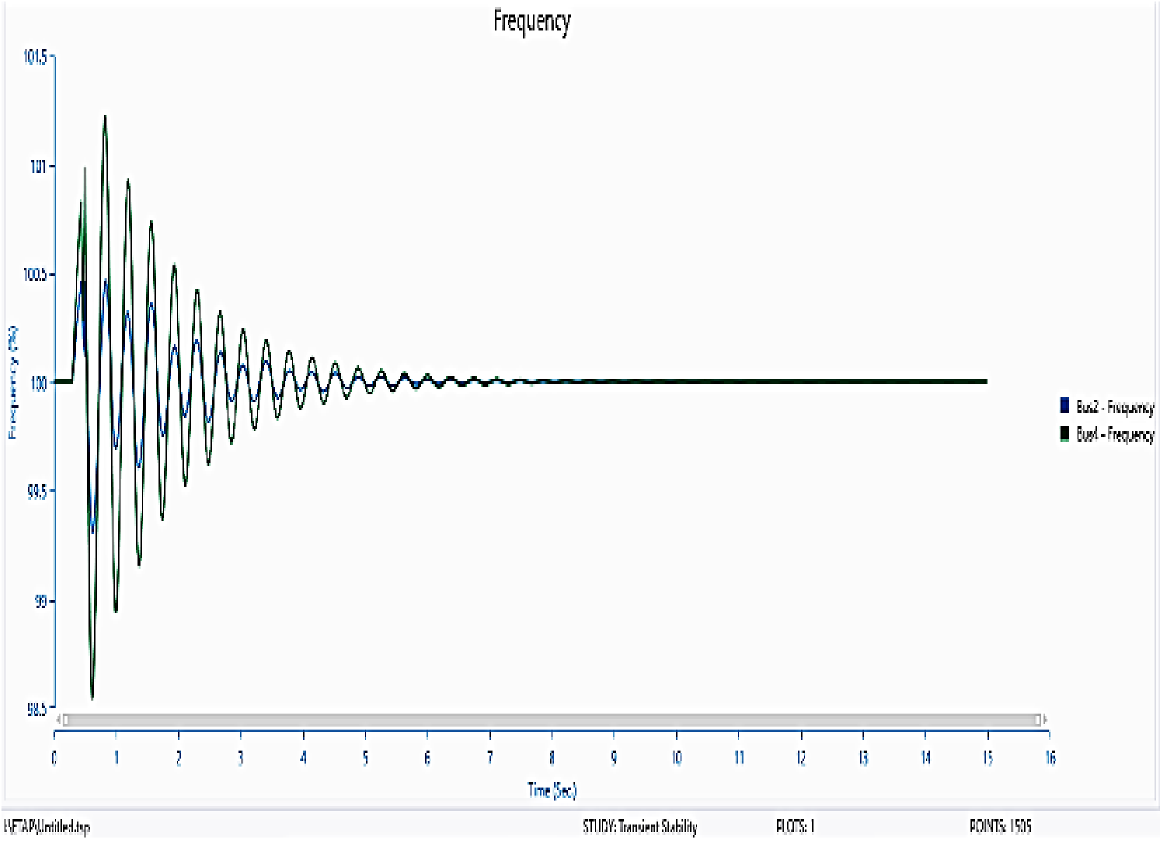


Figure 14. Illustrates the frequency of the fualted busbars (busbars 2 and 4).

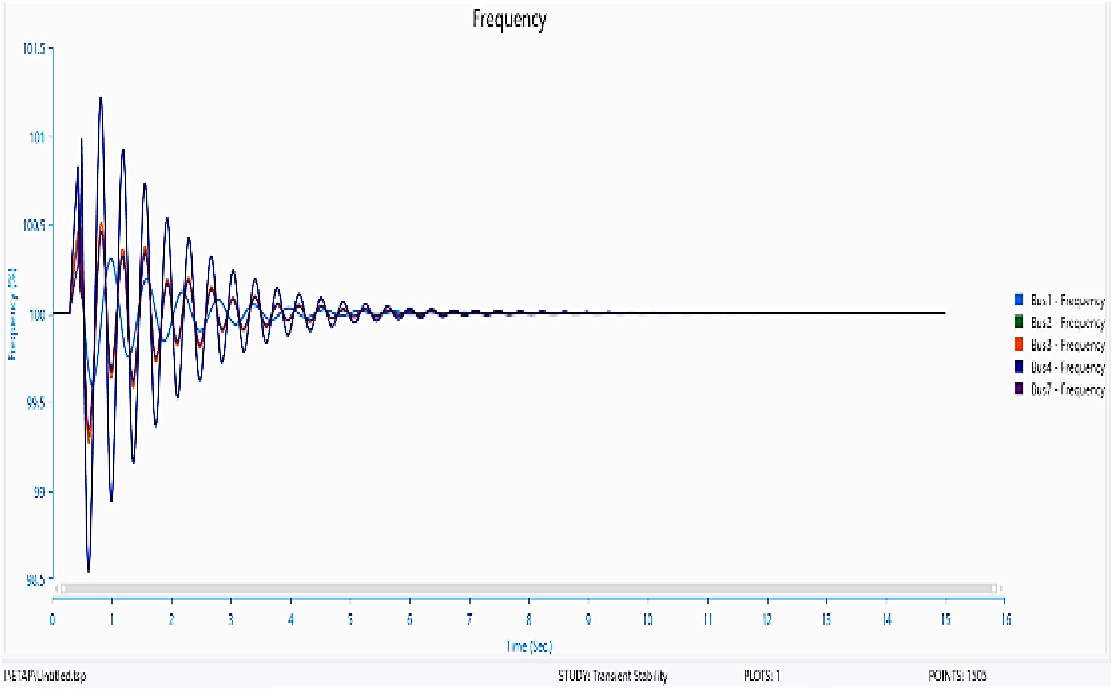


Figure15. Characteristics of the frequency when a three-phase fault occurred at all busbars.

Scenario (2): 3- phase fault is occurred on the middle of transmission line 3

Figure 16 below shows the normal operating power system, so there is no fault occurred, thus the electric power system is working stably. This operation of stability can be noticed by the value of frequency at each element of the power system, which is about 50Hz. When a three-phase fault occurred at the transmission line (3), the system became unstable and the frequency was reduced to 49.8Hz. All currents, voltages, and frequencies have changed due to the applied 3-ph fault as illustrated in Figure 17 below.

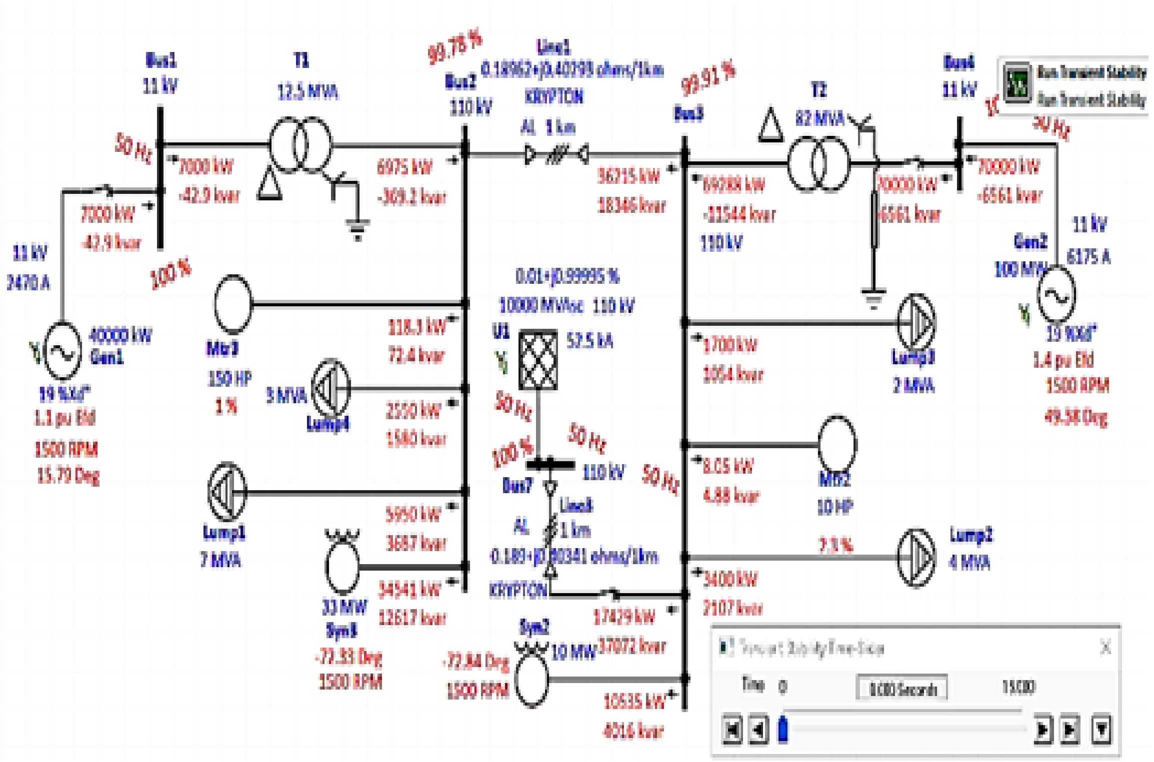


Figure16. Load flow analysis when the electric power system working at normal conditions (No Faults applied).

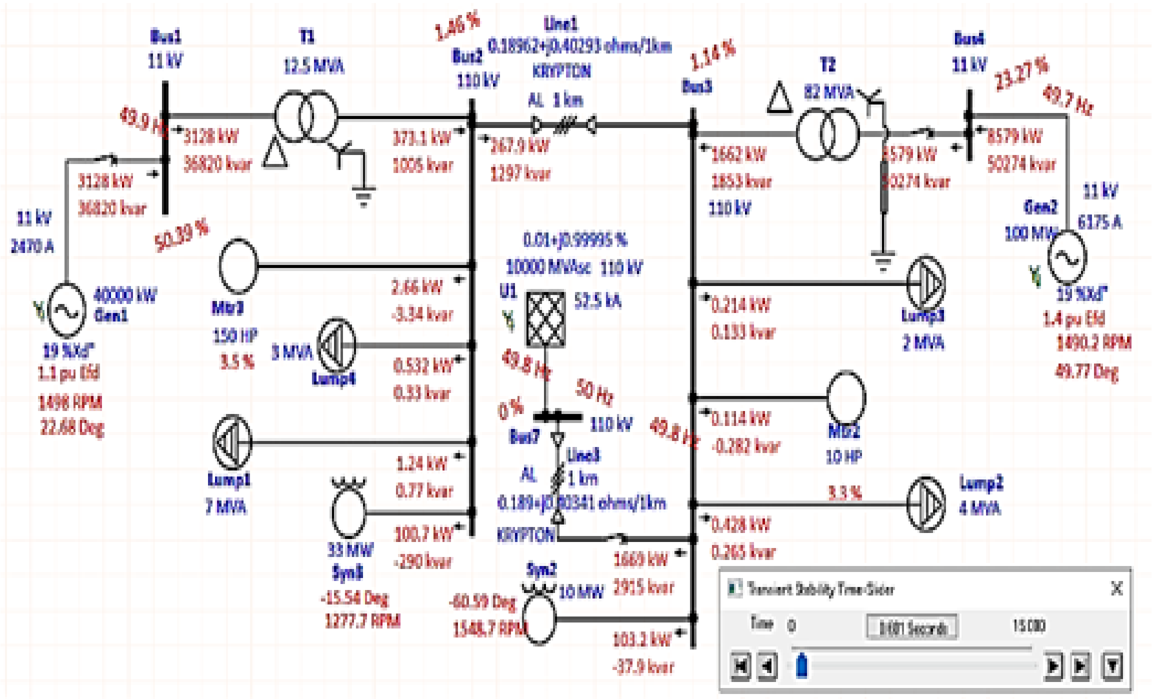


Figure17. A three-phase fault occurred at transmission line (3) when the transient stability time-slider was 0.601 seconds.

Figures 18 to 21 show the characteristics of power angle, voltages, frequency and current behavior. It can be illustrated that the electric power system was operating properly in the beginning, and when a three-phase fault occurred at the transmission line (3), the system became unstable, thus the entire system became unstable as well. When the fault is cleared within the specified time, the electric power system has come back again to stability. When there is a fault, the power system gets interrupted causing significant damage to the whole system, in addition to causing disasters whether to the power system equipment and/or to those who work at that power plant.

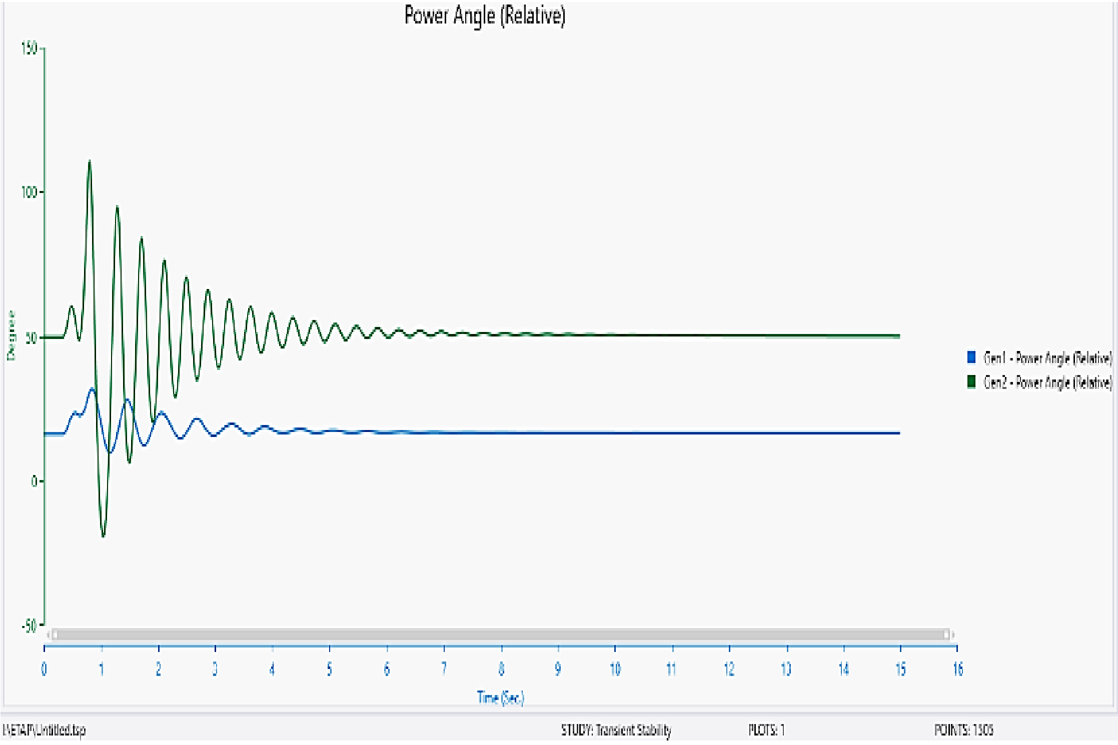


Figure 18. Power angle (relative) for both GEN1 & GEN2 characteristics.

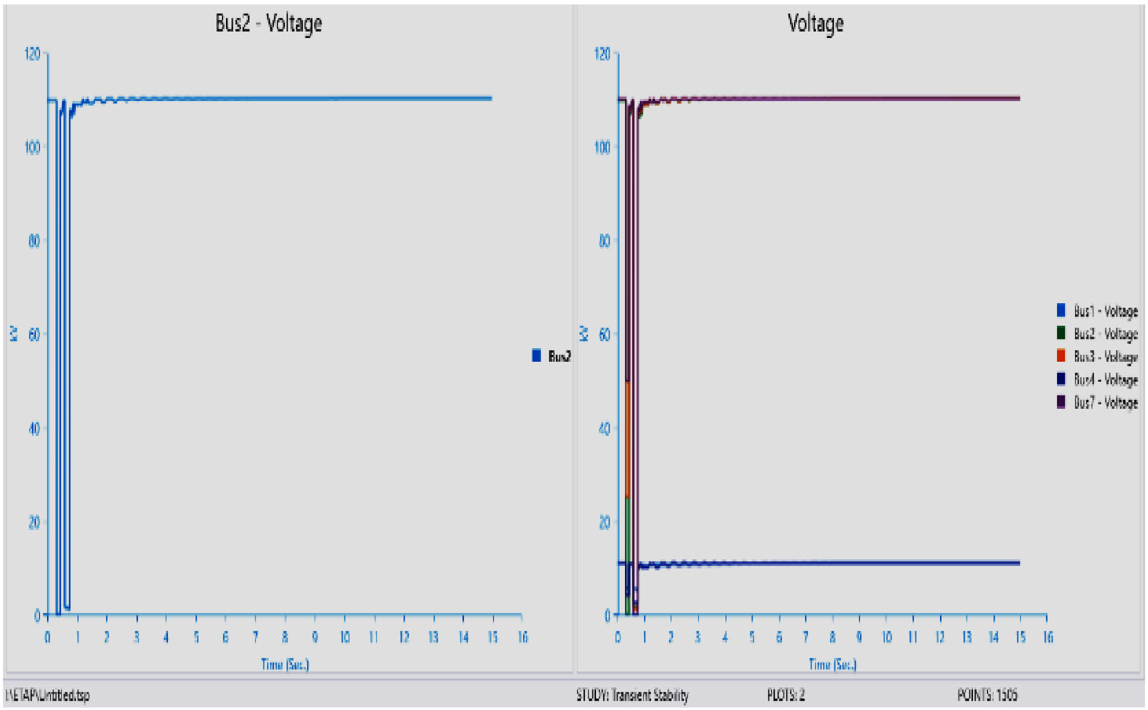


Figure 19. Voltages of a) Busbar (2), b) all connected busbars when a three-phase fault occurred at transmission line (3).

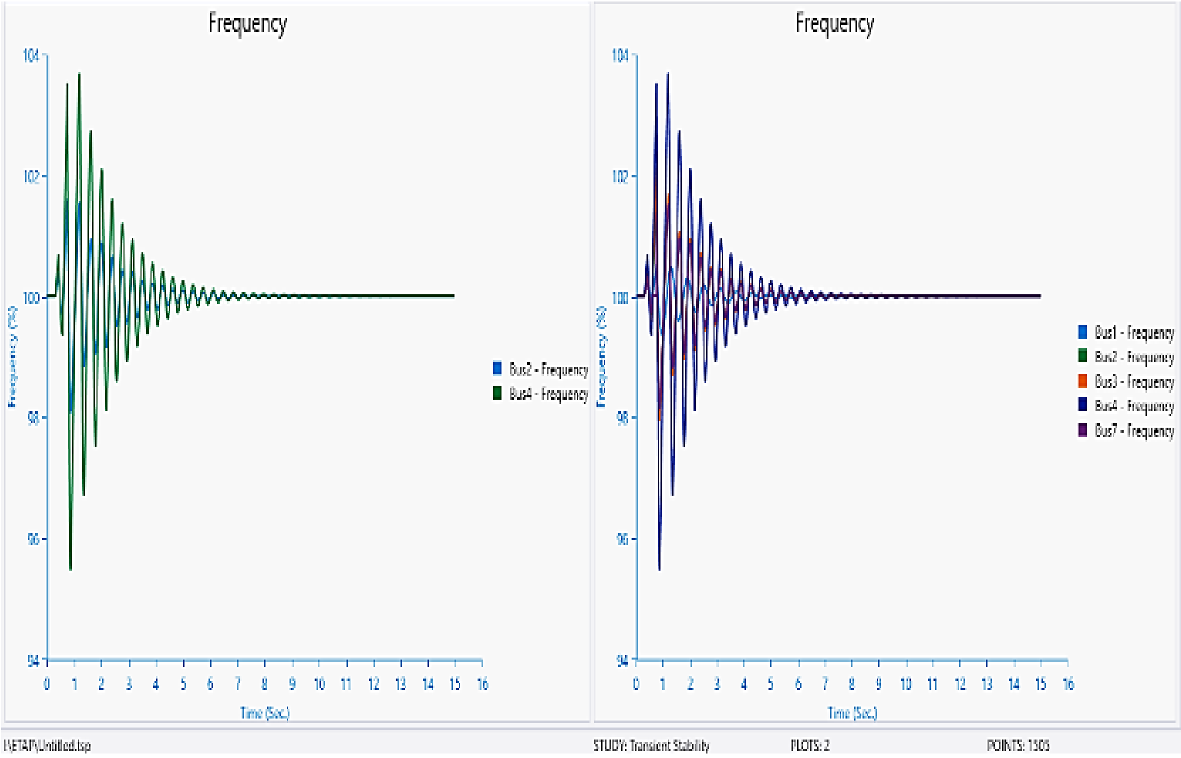


Figure 20. Frequency waveforms of a) Bus2 & bus4, b) all connected buses, when a three-phase fault occurred at transmission line (3).

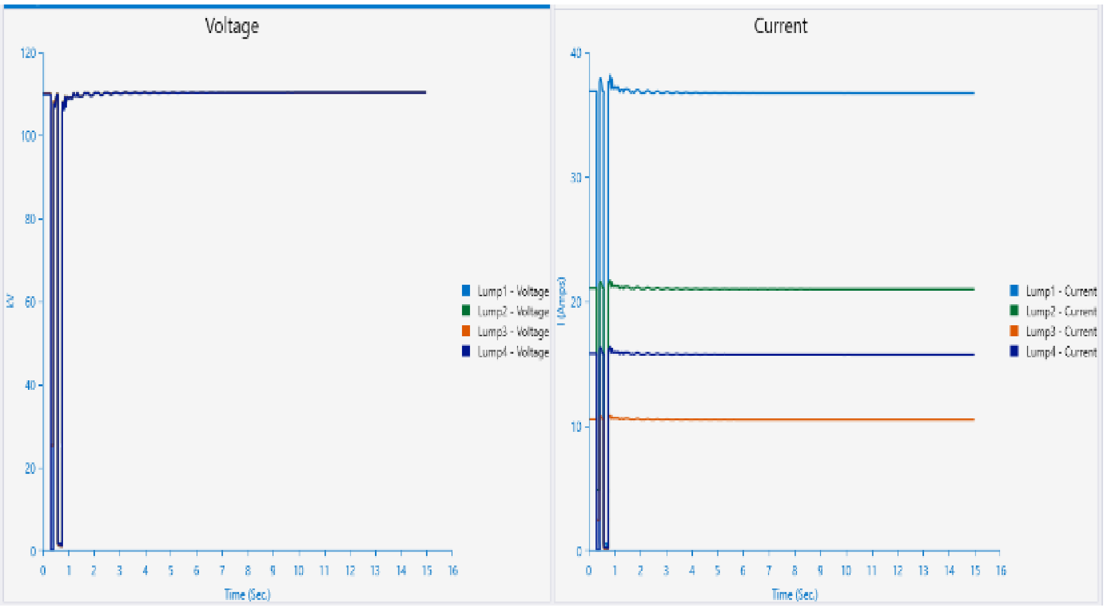


Figure 21. Voltage and current characteristics of all lumped loads, when a three-phase fault occurs at transmission line (3).

In summary, in the base cases illustrated above, there are small and large oscillations that eventually approach a stable value following the occurred fault. The oscillations case had a higher amplitude and continues to maintain irregular values. There are sharp dips in voltage. The simulation results indicate that in the beginning the system was stable and those generators (GEN1 & GEN2) were in synchrony with the electric power network, but after some time and when the fault is occurred, the entire system became unstable. On the other hand, when the fault is cleared within the required time, the electric power system starts maintaining stable values of voltages, frequency, currents and generators power angles as well.

10. Conclusions

This research paper presents the transient stability analysis of a 5-bus electric power system, simulated using the Electric Transient Analysis Program (ETAP). The analysis was conducted under various scenarios, including the examination of bus voltages, transmission line currents, and system frequency across all components of the electric power system. The results indicate that when a three-phase fault occurs at any bus, oscillations arise in the system. However, after clearing the fault using the transient stability module, the system regains stability. Power system stability is a critical aspect not only for minimizing under- and over-shooting but also for ensuring the continuous and reliable operation of the electric power system.

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