IGEE 402 Power System Analysis – Fall 2024

Experiment 4 Lab Report– Transient Stability

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Objective:

The objective of this experiment is having a comprehensive understanding of the principles of transient stability analysis in power systems. It focuses on simulating and analyzing the dynamic behavior of a simple generator-infinite bus system when subjected to disturbances, using numerical methods to solve the swing equation. Through this process, the experiment aims to provide insights into the system's stability limits and the factors influencing synchronous operation, equipping participants with practical knowledge for assessing and mitigating stability challenges in real-world scenarios.

I. Introduction

In this experiment, we explore how transmission lines work in a steady state within power systems. The goal is to create accurate models of these lines, understand how they behave when operating in parallel, and learn how to improve their performance using compensation techniques. We will simulate different scenarios to see how these lines handle power transfer, voltage changes, and energy losses under various conditions.

II. Experiment and Analysis

Part 1 ***Preliminary Calculations***

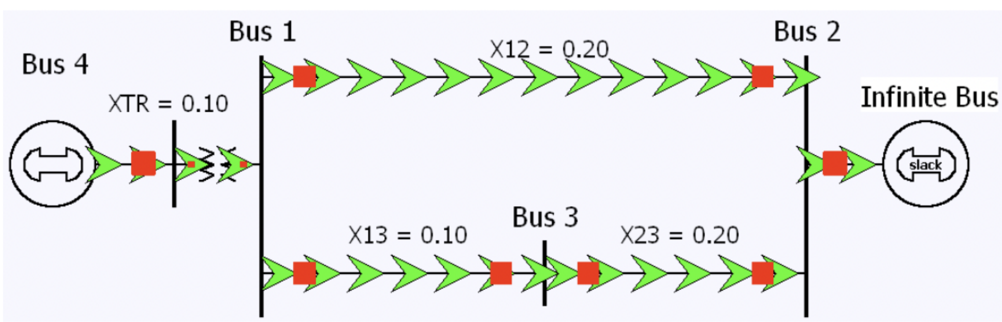

Figure ***Error! Use the Home tab to apply 0 to the text that you want to appear here.****.1 Power system under study*

1. The terminal voltage (magnitude and phase) of generator G1 at t = 0−.

$$P_m = 1.0\ pu$$
$$\frac{P}{pf} = 1.0526\ pu$$
$$S_2 = 1 + j0.32868$$
$$I = (\frac{S}{V})^* = (\frac{1 + j0.32868}{1\angle 0})^* = 1.05\angle - 18.19\ pu$$
$$V_{G1} = 1 + j(\ 0.2 \parallel (0.1 + 0.2) + 0.1) * I = \ 1.09\angle 11.568$$

2. The excitation voltage and the power angle of the generator at t = 0−.

$$E_g = V_2 + j(X'd + X)I = 1 + j\big(0.4 + \ 0.2 \parallel (0.1 + 0.2)\big)(1.05\angle - 18.19\ ) = 1.28\angle 23.90$$
$$\delta_0 = rad(23.90) = 0.4171\ rad$$

3. The mechanical power input into the turbine of the generator at t = 0− and t = 0+.

$$P_m = P_e = 1.0\, p.u.$$

4. The active power transfer expression (from the generator to the infinite bus) for the pre-fault state (both lines connected) as a function of the generator's power angle.

$$P_e = \frac{E_g * V_2}{X_{total}} sin\delta = \frac{1.28 * 1}{0.52} sin\delta = 2.4615 sin\delta$$

5. The active power transfer expression (from the generator to the infinite bus) for the fault state as a function of generator's power angle.
(a) A bolted three-phase fault at Bus 1.

$$P_{e\_bus1} = 2.4615 sin\delta$$

(b) A bolted three-phase fault at Bus 3.

$$X_{eq} = 0.4 + 0.1 \ \| \ 0.2 = 0.4666\, pu$$

$$V_{th} = 1.0\angle 0 \ \frac{0.1}{0.3} = 0.33333 \angle 0$$

$$P_{e\_bus3} = \frac{1.28 * 0.33333}{0.4666} sin\delta = 0.9152\ sin\delta$$

Post fault electrical power:

$$P'_{e\_bus3} = \frac{1.28 * 1}{0.6} sin\delta = 2.1353\ sin\delta$$

6. Apply the equal-area criterion to assess the transient stability for the above two contingencies; assume a fault clearing time of 6 cycles:

(a) A bolted three-phase fault at Bus 1. Assume that once the fault is cleared the system is back to its initial topology.

$$\delta(tf) = \frac{\omega}{2H} * P_m * \frac{tf^2}{2} + \delta_0 = \frac{120\pi}{2*3} * \frac{\left(\frac{6}{60}\right)^2}{2} + 0.4171 = 0.731259$$

$$\delta_c = \pi - 0.4171 = 2.72446$$

$$A_{acc} = \int_{\delta_o}^{\delta_{tf}} P_m\, d\delta = 0.731259 - 0.4171 = 0.3142$$

$$A_{dec} = \int_{\delta_{tf}}^{\delta_c} P'_e - P_m = \int_{0.731259}^{2.72446} 2.4615 sin\delta - 1\, d\delta = 2.0894$$

$$A_{acc} < A_{dec}$$

$$\therefore Stability\ can\ be\ restored$$

$$\int_{0.4171}^{\delta_{critical}} 1\ \ d\delta = \int_{\delta_{critical}}^{2.72446} 2.4615 sin\delta - 1\, d\delta$$

$$\delta_{critical} = 1.5477\ rad$$

$$t_{critical} = \sqrt{\frac{12(1.5477 - 0.4171)}{2\pi * 60}} = 0.189s$$

(b) A bolted three-phase fault at Bus 3. Assume that once the fault is cleared, lines between Bus 1 and Bus 3 as well as Bus 2 and Bus 3 remain open.

$$\delta_c = \pi - \sin^{-1}\left(\frac{1}{2.1353}\right) = 2.6542$$

$$\delta(tf) = \frac{\omega}{2H} * P_m * \frac{tf^2}{2} + \delta_0 = \frac{120\pi}{2*3} * \frac{\left(\frac{6}{60}\right)^2}{2} + 0.4171 = 0.731259$$

$$A_{acc} = \int_{\delta_o}^{\delta_{tf}} P_m - P_{e_{bus3}}\, d\delta = \int_{0.4171}^{0.731259} 1 - 0.9152\ sin\delta\ d\delta = 0.158636$$

$$A_{dec} = \int_{\delta_{tf}}^{\delta_c} P'_{e\_bus3} - P_m = \int_{0.731259}^{2.6542} 2.1353\ sin\delta - 1\, d\delta = 1.5529$$

$$A_{acc} < A_{dec}$$

$$\therefore Stability\ can\ be\ restored$$

$$\int_{0.4171}^{\delta_{critical}} 1 - 0.9152\ sin\delta\ d\delta = \int_{\delta_{critical}}^{2.6542} 2.1353\ sin\delta - 1\, d\delta$$

$$\delta_{critical} = 1.9812\ rad = 113.5\ deg$$

Part 2 ***Experimental Procedures***

1. The stability of the power system for a three-phase fault at Bus 1

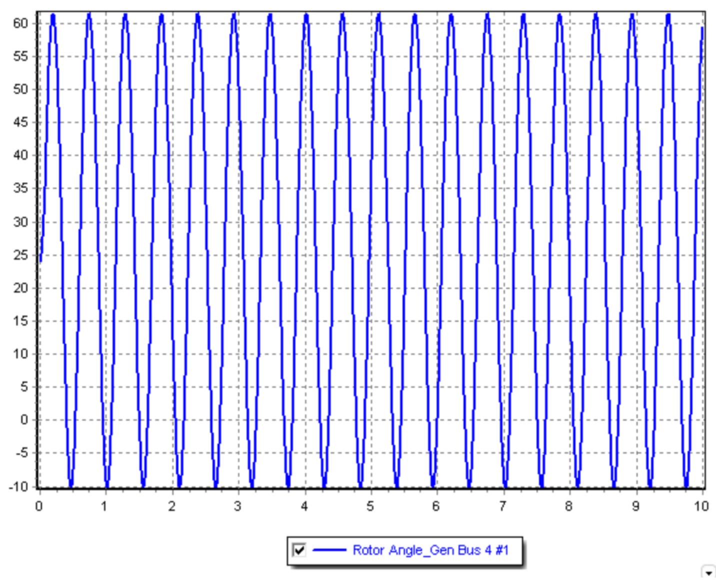

Figure 2.1.1 The Steady-State simulation

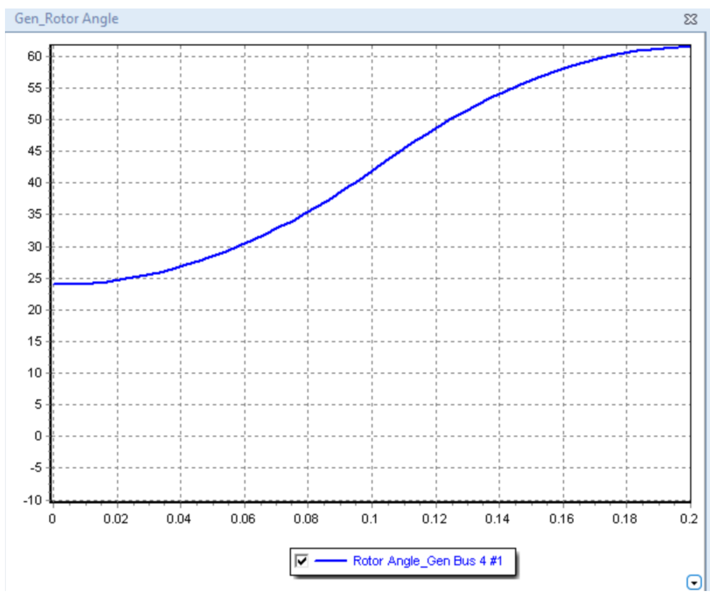

Figure 2.1.2 initial instants of the disturbance of the system

During the simulation for a clearing time of 0.10 seconds (6 cycles), the system experiences a transient instability after the three-phase fault at Bus 1. In the initial instants (0–0.2 s), the rotor angles of the generators show rapid and large oscillations due to the fault, indicating the system's disturbance. Once the fault is cleared, the system begins to recover, with the oscillations gradually dampening as the generators work towards regaining synchronization. Over the simulation duration of 10 seconds, the system transitions into steady-state stability, where the rotor angles exhibit oscillations and maintain predictable behavior. The steady state represents that the system's ability to absorb and recover from the disturbance, demonstrating effective damping mechanisms and overall stability as a cycle.

2. The critical clearing time for the three-phase bolted fault at Bus 1

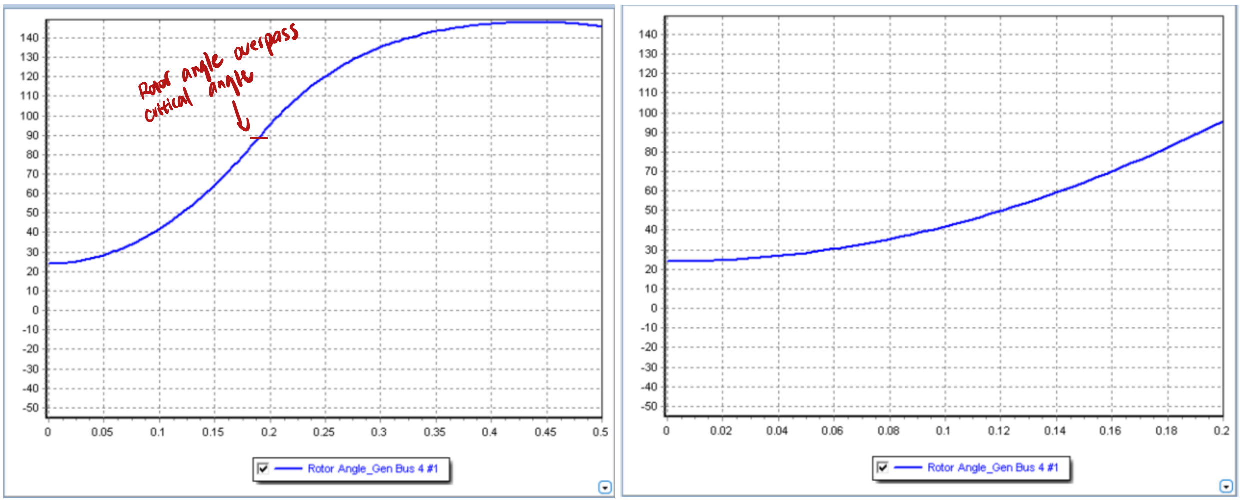

Figure 2.2.1The initial instants of the disturbance of the system to determine the critical clearing time

From the figure, we can observe that the critical clearing time is around 0.189 seconds, after which the system begins to change its rotor angle behavior, with a decrease in angle rotation. The critical clear time agreed with the preliminary calculations.

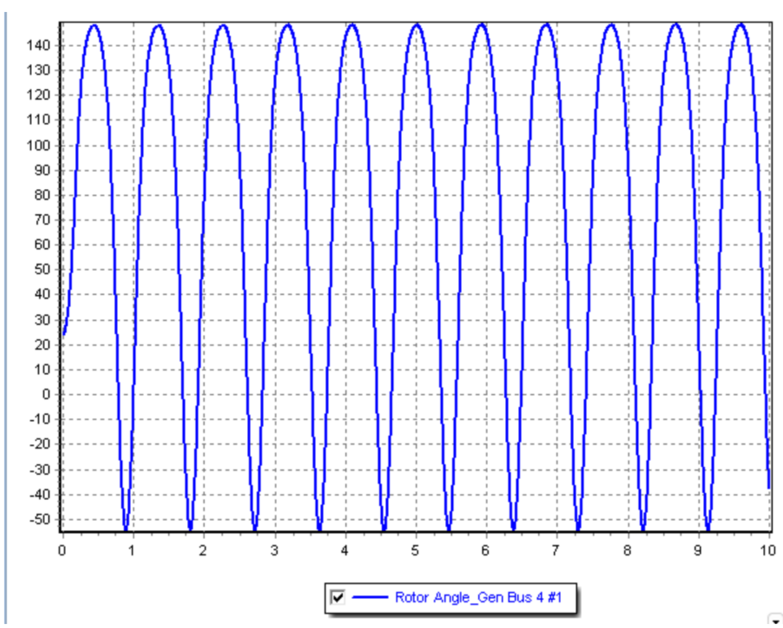

Figure 2.2.2 The long-term stability of the system.

Before reaching the critical clearing time, the system continues to oscillate in the long term, initially experiencing acceleration. Over time, the rotor angle acceleration adjusts to stabilize the system, allowing it to maintain a steady state in a cyclical pattern.

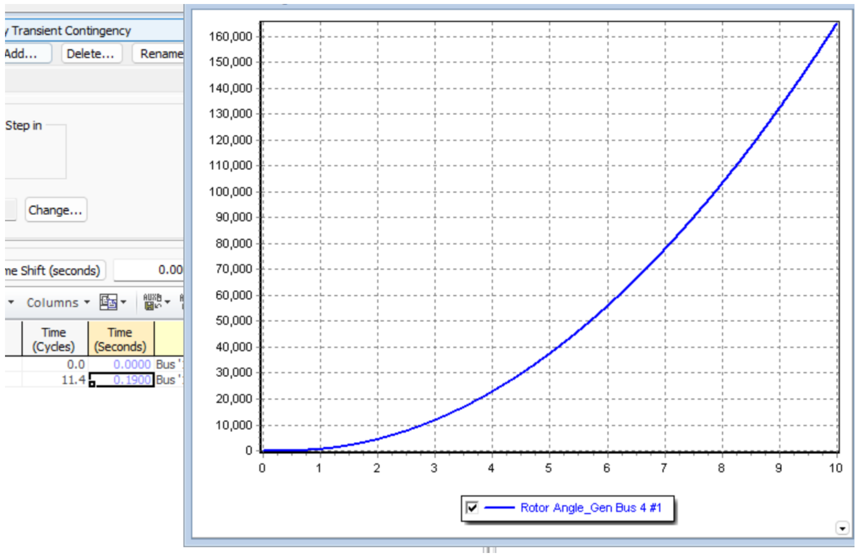

Figure 2.2.3 The long-term instability of the system.

After passing the critical clearing time, the rotor angle continues to increase, leading to long-term instability because the fault was not cleared quickly enough to allow the system to recover. Without clearing the fault within the critical time, the system cannot dampen oscillations or restore synchronization between generators. As a result, the rotor angles diverge, causing the generators to lose synchronization. This misalignment creates energy imbalances, which further exacerbate the instability. The lack of sufficient damping forces means the system enters a state of dynamic instability, where the rotor angle increase indicates that the system is unable to stabilize, leading to sustained oscillations or even complete loss of synchronism.

3. Behavior of adding Damping with value of 1.0 p.u. to the generator model.

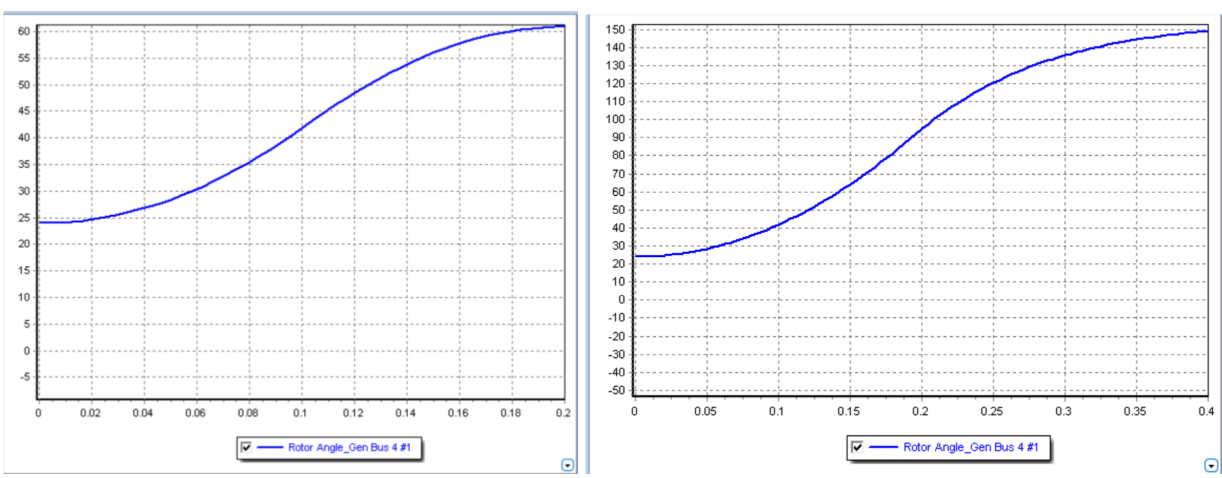

Figure 2.3.1The initial instants of the disturbance of the system to determine the critical clearing time

From the figure, we can observe that the critical clearing time is around 0.192 seconds. After this point, the system's rotor angle behavior changes, with the angle rotation beginning to decrease.

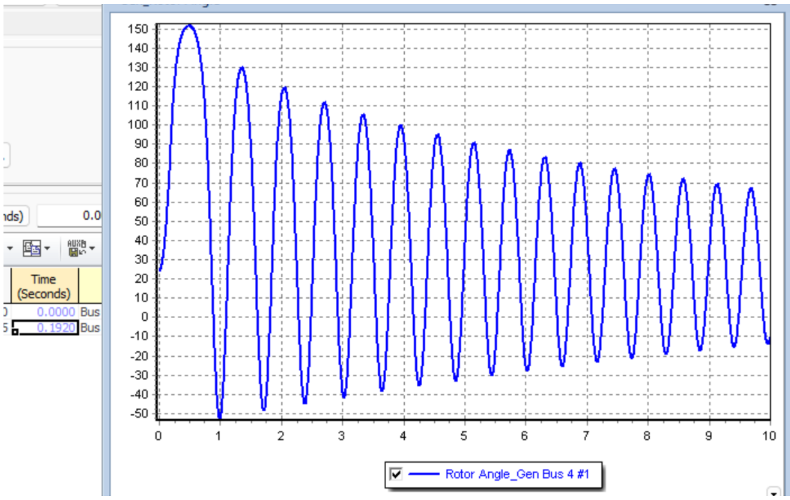

Figure 2.3. 2 The long-term stability of the system

The decreasing amplitude of the rotor angle oscillations over time shows the system is stabilizing due to damping, which dissipates oscillation energy into other forms like heat. This behavior follows the dynamics of a damped system, where oscillations gradually decay based on the damping ratio and natural frequency. Mechanical resistance and electrical controllers, like power system stabilizers, help absorb this energy, guiding the system toward equilibrium. However, the remaining oscillations suggest the damping is not yet sufficient to fully eliminate them.

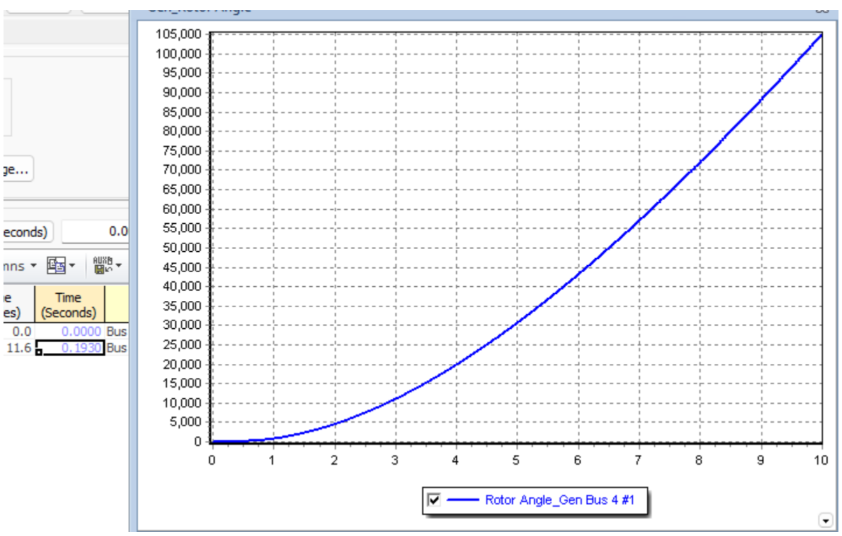

Figure 2.3.3 The long-term instability of the system.

Adding damping to the system does affect the critical clearing time, but the increase is not highly significant. This is because the critical clearing time is primarily determined by the system's inherent ability to maintain synchronization during a fault such as system inertia, and power transfer. Damping reducing the amplitude of oscillations and helping the system stabilize after a disturbance. However, its influence in the post-fault recovery phase rather than during the fault itself. While damping slightly extends the critical clearing time by mitigating angular acceleration and improving the system's response, its impact is limited compared to other factors governing transient stability.

4. Stability of the power system for a three-phase fault at Bus 3.

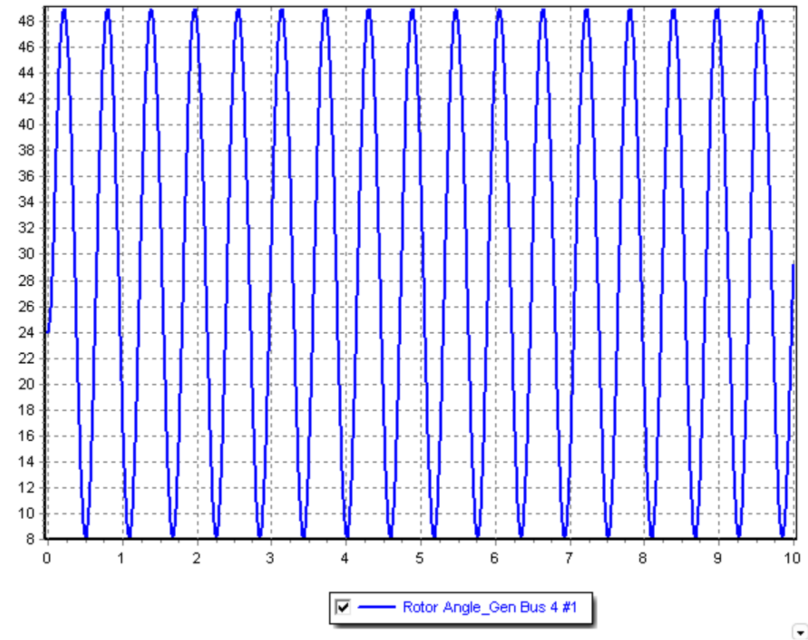

Figure 2.4.1 The long-term stability of the system with No Damping

When the damping is removed, the system dissipate energy is also removed which caused sustained oscillations in the rotor angle instead of decaying to a steady-state value. In the provided rotor angle plot, we can observe periodic and continuous oscillations around the system's equilibrium point. The amplitude of these oscillations remains consistent over time, indicating that the system maintains undamped oscillatory behavior. This response reflects the system's attempt to restore balance, but without damping, it cannot settle to its original steady-state.

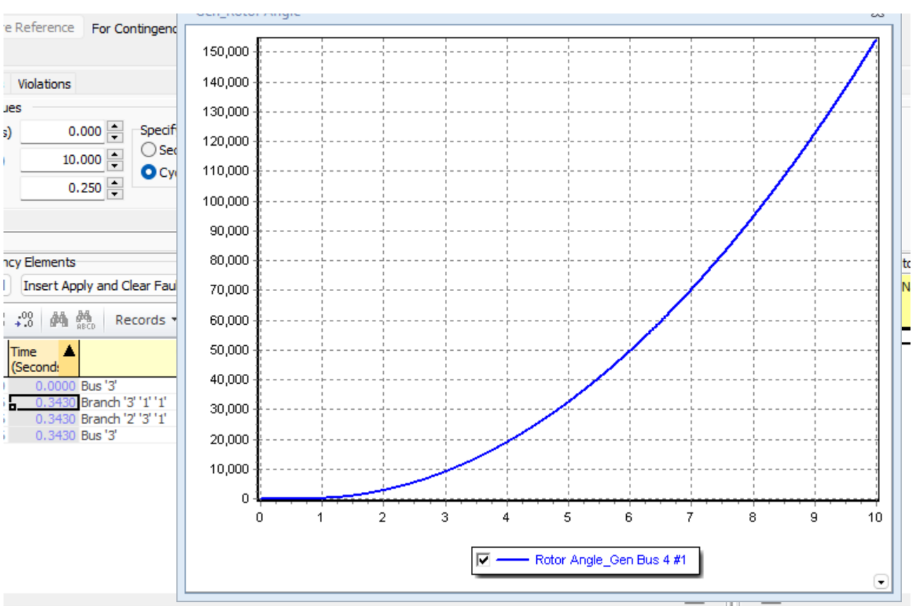

Figure 2.4.1 The long-term instability of the system overpass critical clearing time

When we adjusted the critical clearing time that over 0.342s, the fault clearing time exceeds the critical clearing time, the rotor angle diverges uncontrollably. Because of the fault persists for too long, it is causing excessive power imbalance between the generator and the rest of the system. As a result, the generator's rotor accelerates continuously due to the unbalanced electromagnetic torque, leading to a loss of synchronism with the grid. The simultaneous opening of lines Bus 1–Bus 3 and Bus 2–Bus 3 after clearing the fault further isolates the generator, significantly reducing the available pathways for power transfer. This behavior. exacerbates the instability, as the generator is unable to restore equilibrium with the system anymore.

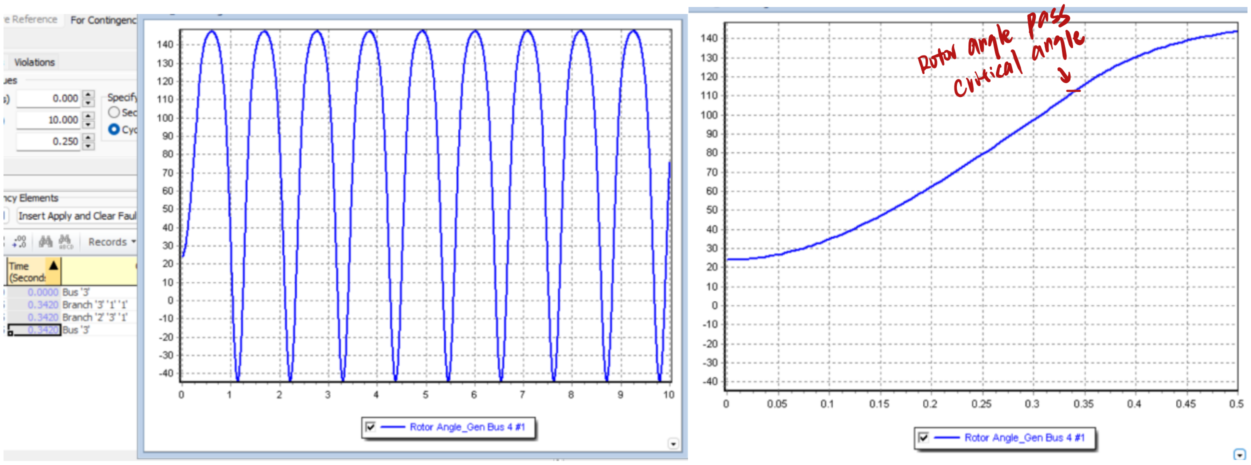

Figure 2.4.1 The stability of the system not yet pass the critical time

The critical clearing time is approximately 0.3422 seconds. When the fault is cleared before this time, the rotor angle remains stable, with bounded oscillations indicating synchronism is maintained. However, clearing the fault after 0.3422 seconds causes the rotor angle to diverge uncontrollably. The delay allows excessive acceleration of the rotor, leading to instability as the system fails to rebalance power flows. This time marks the limit beyond which the system cannot recover stability. The experimental stability limit prediction agrees with the theoretical prediction. The roto angle surpasses the critical angle at 113.5 degrees. The corresponding time is the critical clearing time. Pass this time the system would not self-clear.

III. Conclusion

The transient stability studies the behavior of a power system under fault conditions, emphasizing the importance of maintaining system stability through proper fault clearance and damping mechanisms. The analysis shows how critical clearing time determines system stability, with faults closer to the generator posing a greater risk. Additionally, the inclusion of damping effectively improved stability, demonstrating its significance in mitigating oscillations and enhancing the system's resilience. These findings show the need for robust system design and timely interventions to ensure reliable power system operation during disturbances.