STABILITY ANALYSIS IN ELECTRIC POWER SYSTEMS

Project Topic:

A 3-phase short circuit fault occurs in the first 15 km section on the generator side of a 154 kV double circuit transmission line. Investigation of the transient stability by clearing this fault with times of tc=0.12s (fast protection clearing) and tc=0.21s (backup protection clearing time.

Prepared by:

ALİ ÖZKAN

1. Introduction

Power system stability; according to the IEEE/CIGRE (2004) definition: "It is the ability to reach a new equilibrium state with system variables remaining bounded when subjected to a physical disturbance under a specific initial operating condition."

Since it is still not possible to economically store large-scale electrical energy despite modern technology, there is a delicate balance that must be instantly maintained between generation and consumption in electric power systems; the amount of active power generated in the system must be equal to the amount of power consumed, including losses, at every moment. In this context, power system stability is defined as the ability of the system to regain its synchronism and normal operating conditions after a disturbance (fault, load change, etc.). Stability problems are of critical importance due to their potential to lead to major outages (blackouts) and the necessity for the system to maintain its integrity in the face of disturbances to which it is constantly exposed. This necessity brings forth the concept of power system stability.

The classic stability classification groups the response of power systems to disturbances under the headings of rotor angle, frequency stability, and voltage stability.

Among these stability types, rotor angle stability lies at the center of the behavior of synchronous machines. For a generator to operate compatibly with the grid, its rotor must rotate at a compatible angle (***δ***) relative to the grid's electrical reference. In the event of a fault or sudden load change, the balance between the generator's mechanical input power (***Pm***) and electrical output power (***Pe***) is disrupted. The physical equivalent of this imbalance on the rotor and its variation with time is expressed by the Swing Equation, which is the basis of power system dynamics:

$$2\frac{H}{w_s}\frac{d^2\delta}{dt^2} = P_m - P_e$$

In this equation, while ***H*** represents the inertia constant and $\boldsymbol{\omega_s}$ represents the synchronous angular velocity; the equality shows that the acceleration of the rotor angle is determined by the net power difference ($\mathbf{P_a=P_m-P_e}$). If the mechanical power is greater than the electrical power, the rotor accelerates and the angle increases; in the opposite case, the rotor slows down. In multi-machine systems as well, machines with different inertia and power values can be converted to a common system base and analyzed like an equivalent machine, and they are examined through this fundamental swing behavior.

To evaluate the transient stability of the system without solving differential equations using the time domain, the Equal Area Criterion is used. Derived from the swing equation, this criterion is based on comparing whether the system can return the kinetic energy gained during a fault (acceleration area, ***A*1**) after the fault is cleared (deceleration area, ***A*2**). The essence of the criterion is the necessity that, for stability to be maintained, the integrals of the difference between accelerating power and decelerating power with respect to the angle must be equal, that is, the gained energy must be completely damped.

The equal area criterion enables the determination of the Critical Clearing Angle **(δ_{cr})** and Critical Clearing Time **(t_{cr})** parameters, which are vital especially in the setting of protection systems. The longer the fault clearing time, the larger the acceleration area (**A1**) becomes, and the smaller the deceleration area (**A2**) available to the system becomes. If the available deceleration area remains smaller than the gained acceleration area (***A2<A1***), the rotor exceeds the critical angle, and the system becomes unstable by falling out of synchronism. Therefore, the equal area method is an indispensable tool for the safe operation of power systems and the analytical determination of stability limits.

2. Theoretical Basis

The basis of power system stability analyses is formed by the electromechanical dynamic laws modeling the physical behaviors of synchronous machines. In this section, the fundamental equations of motion determining the system's stability state, energy conversion principles, and analytical criteria determining stability limits will be summarized.

2.1. Synchronous Machine Dynamics and Law of Motion

The stability of synchronous machines relies on the balance between the rotor's mechanical input power (***P_m***) and the electrical output power (***P_e***) transferred to the grid. In accordance with Newton's second law of motion, the rotational motion of a body is determined by the balance of applied torques. For a synchronous machine, this relationship is expressed as follows:

$$J\frac{dw_m}{dt} = T_m - T_e = T_a$$

Here ***J*** represents the moment of inertia of the rotor, ***w_m*** the mechanical angular velocity, ***T_m*** the mechanical torque, ***T_e*** the electromagnetic torque, and ***T_a*** the net acceleration torque. Under normal operating conditions, mechanical and electrical torques are equal (***$T_m = T_e$***), which ensures the rotor rotates at a constant synchronous speed. However, in the event of a fault or load change, this balance is disrupted; if the mechanical torque is greater than the electrical torque, the rotor accelerates; in the opposite case, it slows down.

2.2. Swing Equation

In power systems, using power instead of torque and electrical angles instead of mechanical radians facilitates analyses. The fundamental differential equation expressing the system dynamics with the electrical rotor angle (***δ***) and power values in per-unit (***pu***) is termed the Swing Equation:

$$2\frac{H}{w_s}\frac{d^2\delta}{dt^2} = P_m - P_e$$

In this equation:

- **H:** Is the Inertia Constant and expresses the kinetic energy stored at synchronous speed relative to the machine's nominal power (MJ/MVA).
- $\boldsymbol{w_s}$**:** Is the synchronous angular velocity.
- ***δ*****:** Is the power angle between the rotor's magnetic field and the grid reference.

The swing equation shows that the second derivative of the rotor angle with respect to time (angular acceleration) is proportional to the net power difference:

$$P_a = P_m - P_e$$

This equation is non-linear because the electrical power generally exhibits a sinusoidal character in the form of:

$$P_e = P_{max} \sin \delta$$

In multi-machine systems as well, machines with different inertia and power values can be reduced to a common system base ($\boldsymbol{S_{sys}}$), allowing the system to be modeled like a single equivalent machine and analyzed with the same equation structure.

2.3. Energy Balance and Equal Area Criterion

To evaluate the system's transient stability without performing differential equation solutions using the time domain, the Equal Area Criterion is used. This criterion is based on the principle of conservation of energy derived from the swing equation. For the system to remain stable, the kinetic energy gained by the rotor during a disturbance (e.g., short circuit) (Acceleration Area, $\boldsymbol{A_1}$) must be able to be damped by the decelerating energy that the system can provide after the fault is cleared (Deceleration Area, $\boldsymbol{A_2}$).

Mathematically, this condition is expressed by the requirement that the integral of the power difference with respect to the rotor angle be zero:

$$\int_{\delta_1}^{\delta_r} (P_m - P_e) d\delta = 0$$

Here $\boldsymbol{\delta_1}$ represents the initial angle, and $\boldsymbol{\delta_r}$ represents the maximum swing angle reached by the rotor. The stability condition is that the available deceleration area is greater than or equal to the acceleration area ($\boldsymbol{A_2} \geq \boldsymbol{A_1}$).

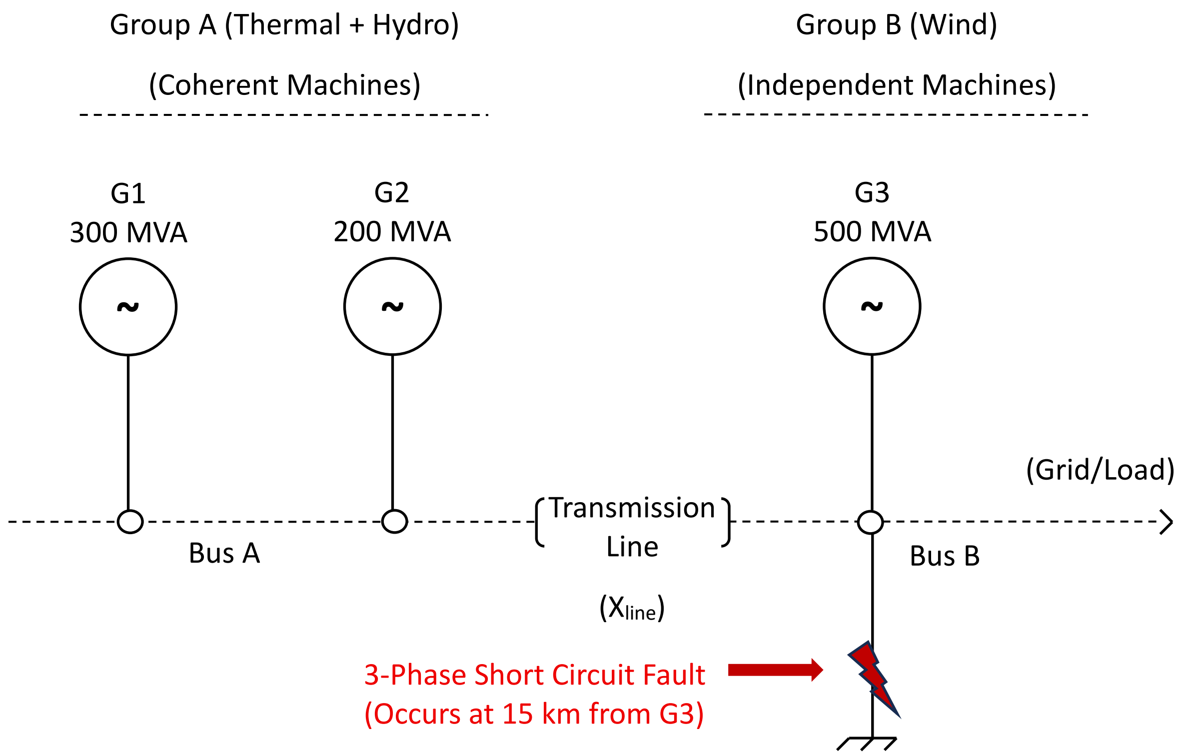
2.4. Critical Clearing Angle and Time

The limit condition where the system can maintain its stability is the moment when the acceleration area and the available maximum deceleration area are equal to each other (***A_2 = A_1***). The angle determining this limit condition is called the Critical Clearing Angle **(δ_{cr})**, and the time elapsed to reach this angle is called the Critical Clearing Time **(t_{cr})**.

The critical clearing angle can be calculated by analytical methods depending on the system's mechanical power (***P_m***) and the amplitudes of the power curves (***P_{max}***) during and after the fault. If the fault is cleared later than the ***t_{cr}*** time, the rotor exceeds the critical angle, the net energy remains positive, and the system becomes unstable by falling out of synchronism.

3. Mathematical Calculations

According to the fault scenario; a 3-phase short circuit occurs in the first 15 km section on the generator side of a 154 kV double circuit transmission line. A visual model of the system, created based on this scenario, is as follows:



The parameters belonging to the three synchronous generators in the transmission region are also as follows:

Table 1: Parameters of Senkron Generators

System Base Power (S_{sys})	100 MVA		
Grid Frequency (f)	50 Hz		
Parameter	***Generator-1 (G1)***	***Generator-2 (G2)***	***Generator-3 (G3)***
Nominal Power (S_N)	300 MVA	200 MVA	**500 MVA**
Reactance (X'_d)	0.25 pu	0.32 pu	**0.25 pu**
Inertia Constant (H)	6.0 s	4.5 s	**5.0 s**
Mechanical Power (P_m)	0.85 pu	0.65 pu	**0.50 pu**

3.1. Conversion of Generator Inertia Constants to 100 MVA System Base

To convert the machine-base inertia constant (***$H_{machine}$***) to the system base (***H_{system}***), we use the following formula:

$$H_{system} = H_{machine} \times \frac{S_{machine}}{S_{system}}$$

Using this formula, let's convert the inertia constants of the three Synchronous Generators in the transmission region to the system base.

For Generator-1 (G1):

$$H_{1sys} = 6.0 \times \frac{300}{100} = \mathbf{18.0\ s}$$

For Generator-2 (G2):

$$H_{2sys} = 4.5 \times \frac{200}{100} = \mathbf{9.0\ s}$$

Generatör-3 (G3) için:

$$H_{3sys} = 5.0 \times \frac{500}{100} = \mathbf{25.0\ s}$$

These obtained values are the mass inertias we will use in the swing equations.

3.2. Calculation of Pre-Fault Rotor Angles (δ_0) of Generators

When the bus voltage (**V**) and internal emf (**E'**) value of a Synchronous Generator are accepted as 1.0 **pu**, the maximum power (P_{max}) it can transmit depends on its reactance:

$$P_{max} = \frac{\bar{E} * V}{X'_d} \approx \frac{1}{X'_d}$$

The steady-state power equation of the synchronous machine:

$$P_e = P_m \sin(\delta_0)$$

In the pre-fault steady state, mechanical power will be equal to electrical power.

$$P_m = P_e$$

In line with this information; the pre-fault rotor angles ($\boldsymbol{\delta_0}$) of each machine are calculated using the following formula.

$$\delta_0 = \arcsin(\frac{P_m}{P_{max}})$$

For Generator-1 (G1):

G1 Parameters	
P_{1m}	: 0.85 pu
X'_{1d}	: 0.25 pu

$$P_{1max} \approx \frac{1}{0.25} \approx \boldsymbol{4.0\ pu}$$

$$\delta_{0,1} \approx \arcsin\left(\frac{P_{1m}}{P_{1max}}\right) \approx \arcsin\left(\frac{0.85}{4.0}\right) \approx \arcsin(0.2125) \approx \mathbf{12.27}°$$

For Generator-2 (G2):

G2 Parameters	
P_{2m}	: 0.65 pu
X'_{2d}	: 0.32 pu

$$P_{2max} \approx \frac{1}{0.32} \approx \mathbf{3.125\ pu}$$

$$\delta_{0,2} \approx \arcsin\left(\frac{P_{2m}}{P_{2max}}\right) \approx \arcsin\left(\frac{0.65}{3.125}\right) \approx \arcsin(0.208) \approx \mathbf{12.01}°$$

For Generator-3 (G3):

G3 Parameters	
P_{3m}	: 0.50 pu
X'_{3d}	: 0.25 pu

$$P_{3max} \approx \frac{1}{0.25} \approx \mathbf{4.0\ pu}$$

$$\delta_{0,3} \approx \arcsin\left(\frac{P_{3m}}{P_{3max}}\right) \approx \arcsin\left(\frac{0.50}{4.0}\right) \approx \arcsin(0.125) \approx \mathbf{7.18}°$$

3.3. Assuming G1 and G2 Swing Together During the Fault, for Group-A: Calculation of Equivalent Inertia Constant H_a and Equivalent Mechanical Power Pm_a Values

As stated in the system model, G1 and G2 are swinging together. In this case, the two machines will behave like a single equivalent machine. In this step, this equivalent model will be derived.

Equivalent Inertia (H_a):

In this step, the **H** values previously converted to the system base will be used.

Inertia Constants of G1 and G2 Converted to System Base	
H_{1sys}	: 18.0 s
H_{2sys}	: 9.0 s

Formula to be used for calculation:

$$H_a = H_{1sys} + H_{2sys}$$

Calculated equivalent inertia (H_a):

$$H_a = 18.0 + 9.0 \ = \mathbf{27.0\ s}$$

Equivalent Mechanical Power (P_m):

Before this step, we need to convert the machine-base mechanical power values of each machine to the system base.

To convert the machine-base mechanical power value ($P_{machine}$) to the system base (P_{system}), we use the following formula:

$$P_{system} = \ P_{machine} \times \frac{S_{machine}}{S_{system}}$$

Using this formula, let's convert the mechanical power values of the three synchronous Generators in the transmission region to the system base.

For Generator-1 (G1):

$$P_{1sys} = 0.85 \times \frac{300}{100} = \mathbf{2.55\ pu}$$

For Generator-2 (G2):

$$P_{2sys} = 0.65 \times \frac{200}{100} = \mathbf{1.30\ pu}$$

For Generator-3 (G3):

$$P_{3sys} = 0.50 \times \frac{500}{100} = \mathbf{2.50\ pu}$$

These obtained values are the mechanical powers we will use in the swing equations.

After these calculations, the equivalent mechanical power of Generator-1 (G1) and Generator-2 (G2) Generators can be calculated.

Formula to be used for calculation:

$$P_{ma} = P_{1sys} + P_{2sys}$$

Calculated equivalent mechanical power (***P_{ma}***):

$$P_{ma} = 2.55 + 1.30 = \mathbf{3.85\ pu}$$

3.4. Calculation of Independent Swing Equation for G3

Generator-3 (G3) moves independently. Therefore, the general formula of the swing equation belonging to this generator:

$$2\frac{H}{w_s}\frac{d^2\delta}{dt^2} = P_m - P_e$$

In this equation, the synchronous angular velocity (***w_s***) is calculated as follows due to the grid frequency being 50 Hz:

$$w_s = 2 \times p \times f \ = 100\pi \approx \mathbf{314.16\, rad/s}$$

G3 Parameters	
H_{3sys}	: 25 s
P_{3sys}	: 2.5 pu

In line with the information calculated and given above, the independent swing equation calculated for G3 is as follows:

$$2\frac{25}{314.16}\frac{d^2\delta_{0,3}}{dt^2} = 2.5 - P_{3e}$$

$$\mathbf{0.1592\,\frac{d^2\delta_{0,3}}{dt^2} = 2.5 - P_{3e}}$$

3.5. Calculation of Acceleration Equations ($\bar{\delta}$) for Group-A and G3 During the Fault

During a three-phase short circuit fault, since it is a fault close to the generator terminals, it is accepted that the electrical power output (***P**e*) falls to zero or decreases significantly. Therefore, if taken as $P_e \approx 0$ during the fault, acceleration will depend only on mechanical power.

The angular acceleration of the rotor is expressed as follows by arranging the swing equation:

$$\frac{d^2\delta}{dt^2} = \frac{w_s}{2H} P_m$$

Let's obtain this equation for both Group-A and G3 respectively.

$$\bar{\delta} = \frac{d^2\delta}{dt^2}$$

For Group A (G1 and G2):

Since Group A consists of G1 and G2 Generators swinging together, the equivalents calculated in the formulas will be used.

Group A Parameters	
H_a	: 27.0 s
P_{ma}	: 3.85 pu

$$\bar{\delta} \approx \frac{w_s}{2H_a} P_{ma} \approx \frac{314.16}{2 * 27} 3.85 \approx 22.3985 \approx \boldsymbol{22.40\ rad/s^2}$$

This result shows that the rotor of the G1 and G2 generators swinging together accelerates with an acceleration of [value] per second under a 3.85 pu power difference.

For Generator-3 (G3):

The values calculated for Generator-3 (G3) are given in the table below.

G3 Parametreleri	
H_{3sys}	: 25 s
P_{3sys}	: 2.5 pu

$$\bar{\delta} \approx \frac{w_s}{2H_{3sys}}\, P_{3sys} \approx \frac{314.16}{2 * 25}\, 2.50 \approx 15.708 \approx \mathbf{15.71\ rad/s^2}$$

This result shows that the rotor of the G3 generators swinging independently accelerates with an acceleration of $\mathbf{15.71\ rad/s^2}$ per second under 2.50 pu accelerating power.

3.6. Calculation of Critical Clearing Angle Using the Equal Area Criterion

In this section, since the system is analyzed for a fault occurring on the G3 side; calculations for the solution of the Equal Area Criterion will be made by taking the system's most critical independently swinging machine (G3) as a reference. Group A (G1 and G2) will be accepted as the stable part supporting the system (like an infinite bus). The visual model given at the beginning of this section also supports the approach here.

According to the Equal Area Criterion, for the system to remain stable, the Accelerating Area $\mathbf{A_1}$) during the fault must be equal to or smaller than the Decelerating Area $\mathbf{A_2}$) available after the fault. The equality $\mathbf{A_1 = A_2}$ in the limit condition gives us the critical angle.

Before starting the calculations, a parameter table will be created by also calculating the missing parameters.

First, let's start with the pre-fault rotor angle value. In the second step, although calculated theoretically as $\boldsymbol{\delta_{0,3} \approx 7.18}°$, since $\boldsymbol{\delta_{0,3}}$ is defined as $\boldsymbol{\delta_{0,3} \approx 15}°$ in the project parameters, this value will be taken as reference in subsequent analyses and simulations.

During the fault, maximum power ($\mathbf{P_{max2}}$) will be accepted as $P_{max2} \approx 0$ due to the assumption that the fault is at a point close to the G3 output, a full short circuit. According to the values obtained with these assumptions, the parameter table is as follows:

G3 Parameters	
P_m	: 2.5 pu
$\delta_{0,3}$	: 15°
P_{max2}	: 0 pu

Post-fault maximum power ($\mathbf{P_{max3}}$) will be calculated from the steady-state equilibrium of the system in the pre-fault condition. In power systems, it was previously stated that in steady state; the generated mechanical power is equal to the transmitted electrical power. Moving from here, the formula in the balanced state:

$$P_m = P_{\max\_pre} \sin(\delta_{0,3})$$

If we put the values in the table into appropriate places, the solution:

$$P_{\max\_pre} = \frac{P_m}{\sin(\delta_{0,3})} = \frac{2.5}{\sin(15°)} = \frac{2.5}{0.2588} \approx \boldsymbol{9.66\ pu}$$

This value expresses the maximum capacity required for the system for the angle to be 15 degrees while mechanical power is 2.5 pu.

Finally, it is assumed that with one of the lines going out of service after the fault, the capacity falls to 70% of the pre-fault capacity:

$$P_{max3} = P_{\max\_pre} * 0.7 = 9.66 * 0.7 = \mathbf{6.76\,pu}$$

The table belonging to all necessary current parameters together with this calculation is as follows:

G3 Parameters	
P_m	: 2.5 pu
$\delta_{0,3}$	: 15°
P_{max2}	: 0 pu
P_{max3}	: 6.76 pu

Now we must find the maximum swing angle of the system. The maximum angle the system can swing to is the point where the mechanical power intersects the post-fault electrical power curve (unstable):

$$P_m = P_{\max 3} \sin(\delta_{\max})$$

$$\delta_{max} = 180° - \arcsin\frac{P_m}{P_{\max 3}} = 180° - \arcsin\frac{2.5}{6.76} = 180° - 21.7° = \mathbf{158.3}°$$

$$\delta_{max} = \mathbf{2.7629\,rad}$$

In this step, the critical clearing angle will be calculated. For the condition where electrical power flow is zero during the fault ($P_e \approx 0$), the Equal Area Criterion formula:

$$\cos\delta_{cr} = \frac{P_m}{P_{max3}}\left(\delta_{max} - \delta_{0,3}\right) + \cos\delta_{max}$$

Since the angle difference in the formula needs to be written in radians, $\delta_{0,3}$ will be written in radians as $\delta_{0,3} = 15° = \mathbf{0.2618\,rad}$.

The result obtained when the calculated values are placed in the formula:

$$\delta_{max} - \delta_{0,3} = 2.7629 - 0.2618 = \mathbf{2.5011\,rad}$$

$$\cos(158.3°) = \mathbf{-0.9291\,rad}$$

The result obtained when the calculated values are substituted into the formula:

$$\cos\delta_{cr} = \frac{2.5}{6.76}(2.5011) + (-0.9291) \approx -0.0042$$

$$\delta_{cr} = \arccos(-0.0042) \approx \mathbf{90.24}°$$

4. Results

In this section, the effects of a three-phase short circuit fault occurring in a multi-machine power system on transient stability will be comprehensively examined using theoretical analyses, manual calculations, and computer-aided simulations (MATLAB and Python).

4.1. System Modeling and Equations

In this section, the accuracy of the results will be examined by calculating the mathematical calculations performed for system modeling in MATLAB and Python as well.

In the coding written in the MATLAB program, Swing Equations were solved using the ODE45 solution and Time Domain Simulation was performed. The obtained graph is as follows:

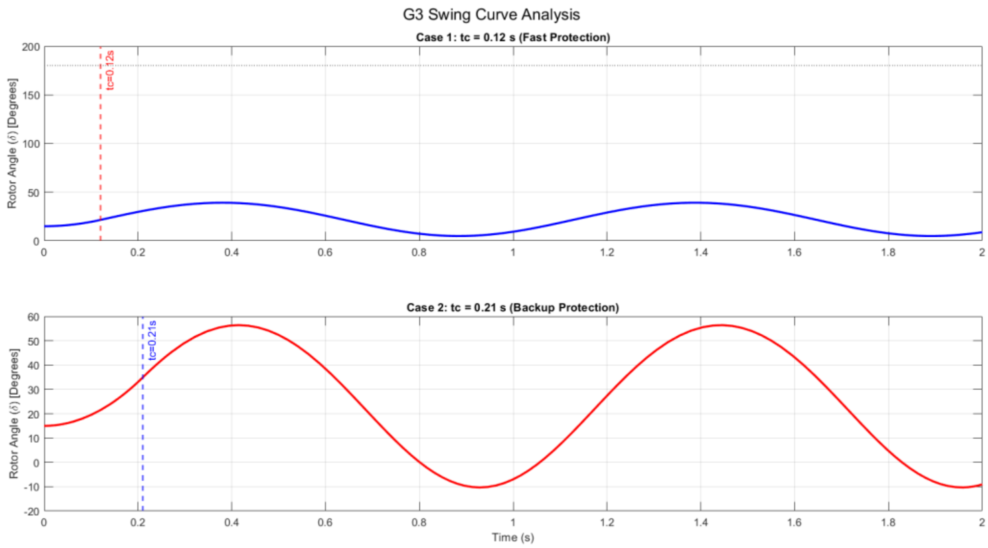


Figure 1: MATLAB- Generator-3 (G3) Time Domain Simulation

In the coding performed with Python, the Swing Equations were defined as a Python function, solved, and Time Domain Simulation was performed. The obtained graph is as follows:

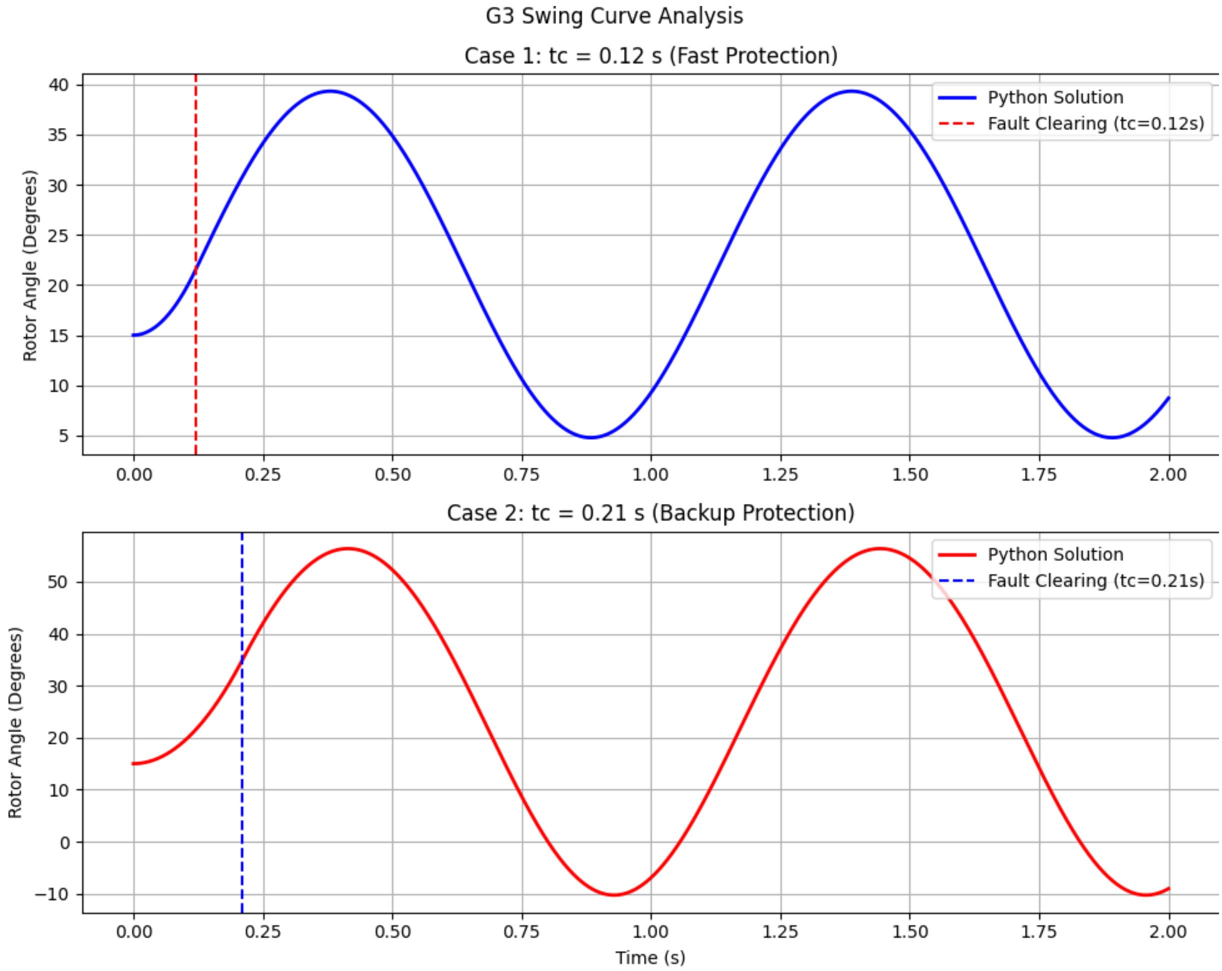


Figure 2: Python- Generator-3 (G3) Time Domain Simulation

System parameters obtained as a result of manual calculations (***H=25s, P_m=2.50 pu***) and derived swing equations were transferred exactly to MATLAB and Python algorithms. The rotor angle calculated as the initial condition (***δ_0= 15°***) was used as the same reference point in all three analysis methods (Manual, MATLAB, Python), and model consistency was ensured.

4.2. Power – Angle Characteristics

The initial angle $\boldsymbol{\delta_0}$ obtained via mathematical calculations and the $\boldsymbol{P_{max}}$ calculation were recalculated using the MATLAB program. In the coding performed with the MATLAB program, the graph belonging to Pre-Fault – During Fault – Post-Fault Power-Angle Characteristics is as follows:

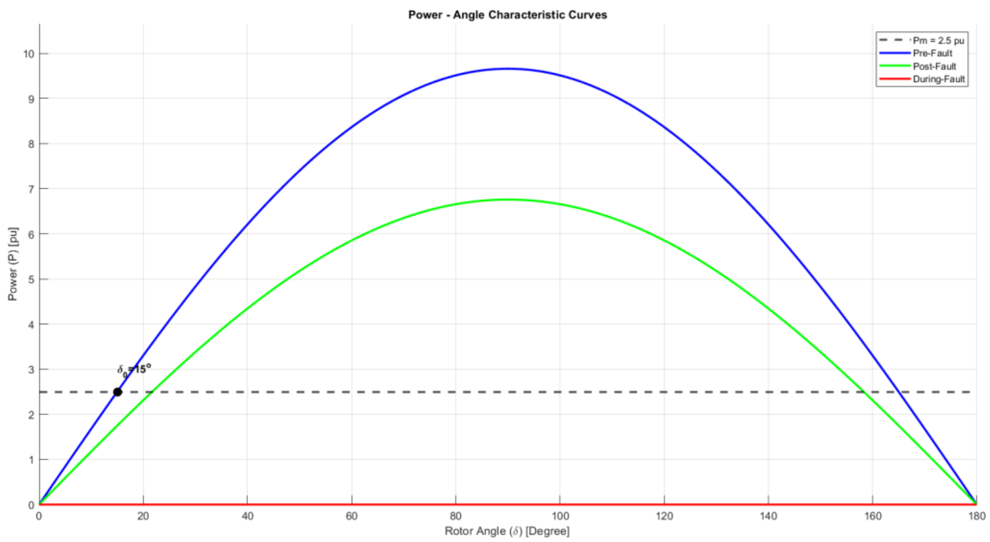


Figure 3: MATLAB- Power-Angle Characteristics Curves

The pre-fault maximum power ($\boldsymbol{P_{max\_pre} \approx 9.66\ pu}$) and post-fault maximum power ($\boldsymbol{P_{max\_post} \approx 6.76\ pu}$) values calculated in the manual analysis show full agreement with the peak points of the Power-Angle characteristic curves plotted in the MATLAB simulation. This situation proves the accuracy of the static modeling of the system.

4.3. Time Simulations

In this section, time simulations were created using MATLAB and Python.

The Rotor Angle Time Graph obtained for t_c**=0.12s** and **0.21s** in the coding performed using the MATLAB program is as follows:

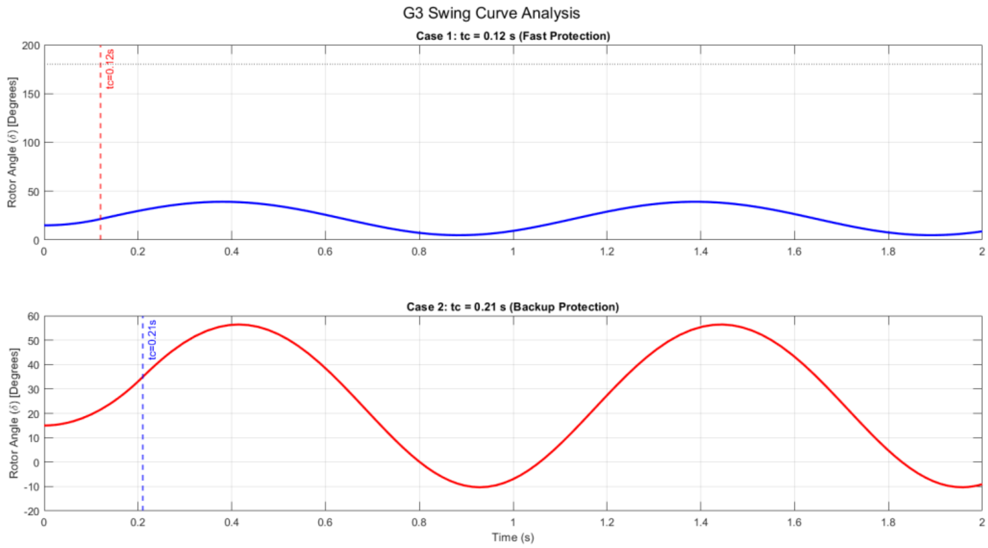


Figure 4: MATLAB- Generator-3 (G3) Time Domain Simulation

The Rotor Angle Time Graph obtained for t_c**=0.12s** and **0.21s** in the coding performed using Python is as follows:

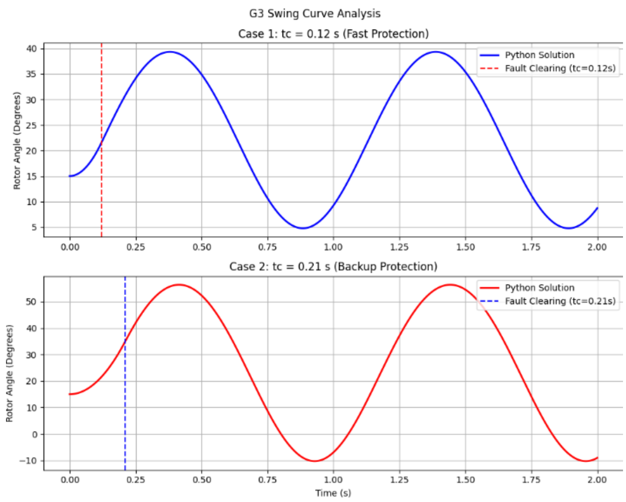


Figure 5: Python- Generator-3 (G3) Time Domain Simulation

Dynamic simulations performed using MATLAB (ode45) and Python (odeint) libraries for ***t_c=0.12s*** and ***t_c=0.21s*** fault clearing times were compared. When the Rotor Angle-Time (**δ - t**) variation graphs obtained from both softwares were plotted on top of each other, it was observed that they overlapped exactly. This result indicates that the numerical solution algorithms verify each other.

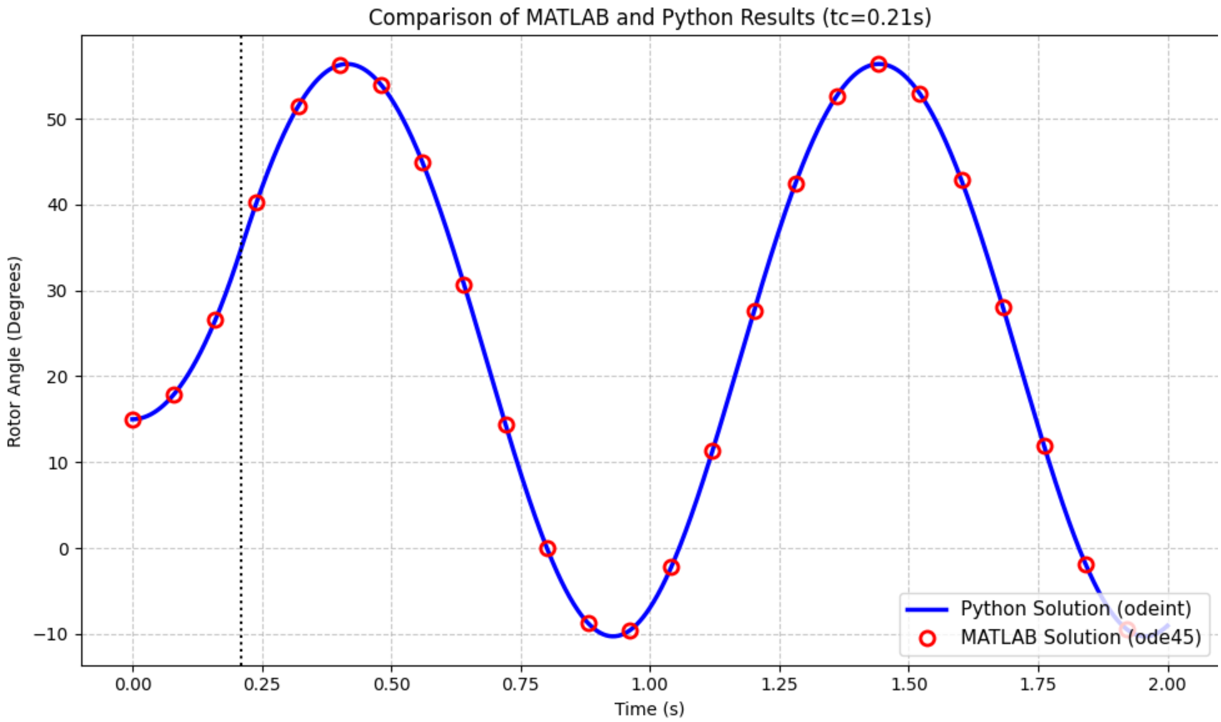


Figure 6: Comparison of MATLAB and Python Results

4.4. Stability Limit

In this section, the recalculation of the $\boldsymbol{\delta_{cr}}$ calculation obtained using the Equal Area Criterion formula was performed using Python. Subsequently, this situation was modeled using the MATLAB program to analyze the instability condition.

The result of the critical clearing angle in the manual calculation made using the equal area criterion:

$$\cos \delta_{cr} = \frac{2.5}{6.76}(2.5011) + (-0.9291) \approx -0.0042$$

$$\delta_{cr} = \arccos(-0.0042) \approx \mathbf{90.24}°$$

Equal Area Criterion ($\boldsymbol{\delta_{cr}}$ calculation); was recalculated using the Numerical Integration (trapz) Method using Python and compared with the manual result.

```
Clearing Time (tc): 0.21 s
Clearing Angle (delta_cl): 34.85 Degrees
------------------------------
Accelerating Area (A1)          : 0.8659
Available Decelerating Area (A2): 6.4447
------------------------------
RESULT: SYSTEM IS STABLE since A2 > A1.
Stability Margin (Energy)       : 5.5788
```

Figure 7: Output Result of Calculating Equal Area Criterion with Numerical Integration (Trapz) Method

```
----------------------------------------
CALCULATION RESULTS (G3 Parameters)
----------------------------------------
Maximum Swing Angle (delta_max): 158.3003 Degrees
Critical Clearing Angle (delta_cr) : 90.2514 Degrees
----------------------------------------
```

Figure 8: Output Result of Critical Clearing Angle Calculation

The critical clearing angle ($\boldsymbol{\delta_{cr}} \approx \mathbf{90.24}°$) calculated with manual formulas using the Equal Area Criterion and the critical angle value calculated with numerical integration (trapz) and area equalization method in the Python environment confirm each other. The difference between them is negligible, and the reliability of theoretical calculations has been confirmed by the numerical method.

4.4 Instability Analysis

In this section, the Runaway behavior of the Rotor Angle in Cases where Instability Occurs will be modeled via the MATLAB program and shown on a graph.

In the cases of t_c=*0.12s* and t_c=*0.21s* examined within the scope of the project, it was observed that the system remained stable due to its high moment of inertia (***H=25s***) (according to system parameters). In other words; since the critical clearing time (t_{cr}) calculated according to system parameters is greater than the given fault clearing times (***0.12s*** and ***0.21s***), the system is stable in both scenarios and no runaway was observed.

Therefore, in order to observe the runaway behavior requested in the project, an additional simulation was performed using the MATLAB program by increasing the fault clearing time (t_c = ***0.50s***) above the theoretically calculated critical time ($t_{cr} \approx$ ***0.41s***).

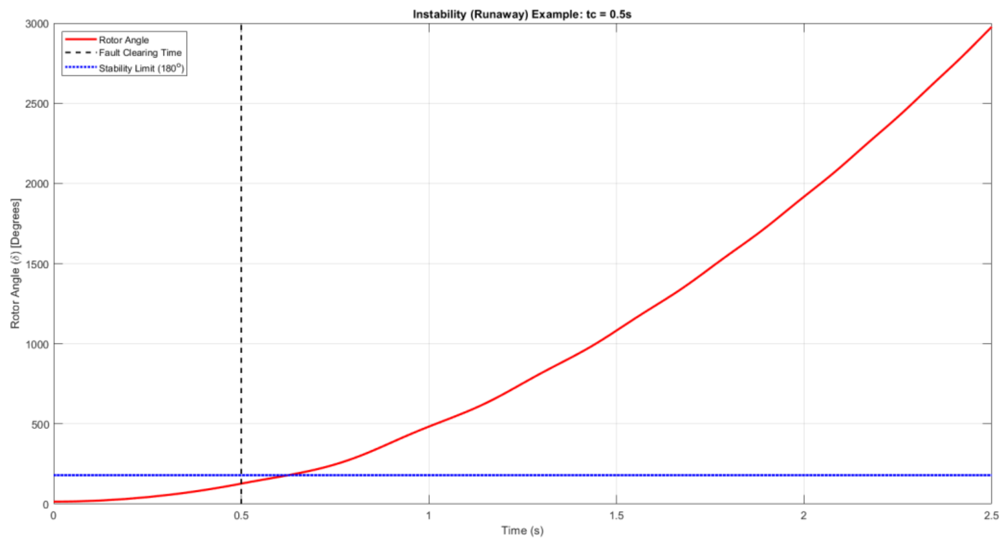


Figure 9: MATLAB- Instability (RUNAWAY) Scenario (Additional Analysis)

5. Conclusion and Evaluation

My fundamental results and engineering evaluations obtained from the analyses performed taking Generator-3 (G3) as reference:

When the manual calculations performed within the scope of the project, MATLAB (ode45) dynamic simulations, and Python numerical analysis results were compared, it was seen that all outputs were in full agreement with each other. Especially the overlap of the critical clearing angle ($\boldsymbol{\delta_{cr}} \approx \mathbf{90.24}°$) calculated manually with the Equal Area Criterion and the results obtained from the Python simulation proved the accuracy and reliability of the established mathematical model and the applied solution methods.

In the examined scenario, the parameters possessed by the system provided a strong stability margin to the system. It was observed that the rotor angle did not exceed the critical value and the system settled back to the stable equilibrium point in both $\boldsymbol{t_c}$***=0.12*** seconds (fast protection) and $\boldsymbol{t_c}$***=0.21*** seconds (backup protection) fault clearing times tested in simulations. This situation indicates that the settings of the existing protection systems are operating in a safe region within the system's stability limits.

The analyzed G3 generator was evaluated as the most critical component in terms of stability due to its independent swinging from the system and having different dynamics compared to other groups. The rotor, accelerating rapidly with the removal of the electrical load during the fault, was able to damp its kinetic energy thanks to the strong decelerating area ($\boldsymbol{A_2}$) that came into play with the clearing of the fault. The fact that the calculated critical angle ($\boldsymbol{\delta_{cr}} \approx \mathbf{90.24}°$) is quite high indicates that the system is resistant to severe fault conditions and possesses a wide stability band.

Finally; this project has revealed that stability analysis in power systems is not just a theoretical concept, but has high importance in power system protection coordination and making relay time settings. The findings obtained also show that simulations performed in advance against possible fault scenarios have a critical importance in terms of system security (prevention of major outages or blackout risk) in the planning and operation of energy transmission systems.