ANALYSIS OF TRANSIENT INSTABILITY ON A 132KV TRANSMISSION GRID POWER SYSTEM USING 4TH ORDER RUNGE KUTTA TECHNIQUE

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ABSTRACT: *This study examines the transient response of synchronous machines in a 132kV transmission grid power system utilizing 4th order Runge Kutta algorithms. In order to determine the critical clearance angle (CCA) and critical clearing time (CCT) of the transmission grid, a three-phase fault was intentionally introduced. Data were gathered from the Transmission Company Nigeria (TCN) for the specific purpose of analysis and simulation. The Electrical Transient and Analysis Program (ETAP 19.1) is utilized with circuit breaker and relay time settings of (0.00, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.14, 0.16, 0.18, 0.2) to examine the differential variations in generator rotor angles, alterations in generator bus voltage, and changes in system frequency. The obtained results demonstrate that the 4th order Runge Kutta numerical technique is stable and accurate. It exhibits a fast response critical clearing time (CCT) of 0.02s and a critical clearing angle of 76.9 degrees, which is very close to the expected value of 81.5 degrees. The average critical angle was determined from the simulated results. Additionally, a lower percentage error of -51% was observed at the moment of disturbance. The 4th order Runge-Kutta numerical technique is superior due to its sustainability, faster computation, and stability in the presence of transient disturbances, as demonstrated in the study case. It is crucial to promptly and accurately coordinate the circuit breakers and protection relays in order to rapidly clear a symmetrical 3 phase fault at any bus. This will improve the stability margin of the network.*

KEYWORDS: Generators rotor angles, Transmission substation, 4th order Runge Kutta technique, Critical Clearing Angle, Critical Clearing Time.

INTRODUCTION

According to recent studies, the growing population and pursuit of industrial development in emerging nations like Nigeria has resulted in a significantly greater demand for power than generation capability [1]. For a power supply to be considered dependable and stable, the consumers obligation always be fed at a defined voltage and frequency [2]. A power system's stable functioning guarantees a constant match between the electrical energy extracted from the synchronous machine and the energy input going to the prime mover [3]. The utilities may operate the power transmission infrastructure extremely near to the voltage stability limit as a result of the quickly rising demand for electricity [4].

If not correctly checked, this could have a severe impact on the security of the power system, leading to violations of the system stability limit, which in turn creates scenarios of voltage collapse with associated hassles and high costs for both utilities and consumers [5]. Power system security measures the system's level of security in both expected and regular circumstances [6]. Transient stability is one of the key metrics used to evaluate a power system's security [7]. The Nigerian grid network faces a number of difficulties, including transmissionInstability in the system is caused by excessive power losses, sudden generator failure, line outages, and many types of malfunctions [8]. The significance of transient stability evaluation cannot be overstated, given the ongoing demand for power and the dearth of sensitive equipment to identify and stabilize these issues [9]. When a power system returns to equilibrium following significant fluctuations in generator rotor angles, bus voltages, power flow, critical clearing angles, critical clearing times, and other crucial system parameters that are used to evaluate power system stability, it is referred to as transiently stable [10]. Swing Equation, a nonlinear expression, describes the transient period of the power system that describes the swinging response of the synchronous machine.

RELATED WORKS

[11] Reports that they employed modified Euler numerical methods to perform transient stability study on a 132KV power transmission line. Compared to the swing equation technique, the Modified Euler technique is considered to be more precise in forecasting the dynamics of synchronous machines. This includes accurately anticipating the gradual increase in rotor angle at specific time intervals when the system has a malfunction.

In the context of pre-fault control, a study by [12] examined the effectiveness of using a particle swarm optimization support vector machine (PSO-SVM) technique for transient stability analysis. This strategy involves predicting and adjusting the operating points of the power system in order to safeguard it against further instability.

According to [13] and [14], the researchers employed several numerical fault simulations to analyze the transient stability performance of the Ikeja-West sub-transmission network in Nigeria's 330KV system. The primary objective of these simulations was to determine the security thresholds of the sub-transmission network. This was achieved by employing the Electrical Transient Analysis Program (ETAP) software. By redirecting the focus of research towards a pre-fault response system that can react milliseconds before instability occurs,

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Similarly, [15] and [16], transient stability simulation studies were conducted, whereby balanced and unbalanced fault scenarios were examined and various damping approaches were compared with the suggested technique. They looked at improving the transient stability of a test power system by using an optimal unified power flow controller (OUPFC) based on the Lyapunov energy function (LEF). When their proposed OUPFC was compared to the conventional Unified Power Flow Controller (UPFC), they were able to demonstrate notable enhancements, including faster OUPFC damping.

They used the Gravitational Search Algorithm (GSA) to build the best static synchronous series compensator (SSSC) for power system transient investigations, according to [17]. In order to time the SSSC parameters and hence reduce oscillations in the power system, GSA makes advantage of the law of gravity and interactions between masses [18]. For validation, the Bacteria Foraging Algorithm (BFA) and Genetic Algorithm (GA) are compared with the GSA approach [19].

MATERIALS AND METHOD

According to Figure 1.1, the materials under consideration came from the Afam power generating plant and were sent to the 3/60MVA injection substation of the Port Harcourt Mains (Zone 2) transmission transformer. The injection substation had an incoming voltage level of 132 kV and an outgoing voltage level of 33 kV.

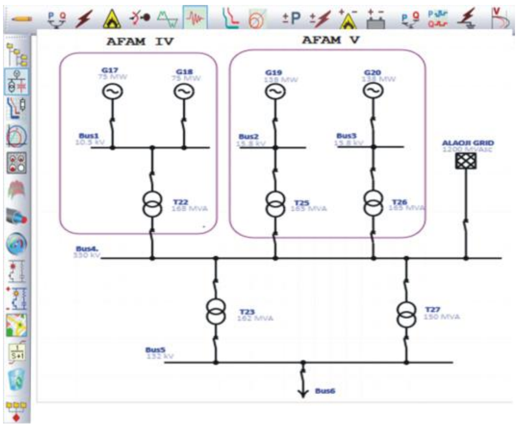

Figure 1.1: Afam Power Generating Station's Single Line Diagram prior to Simulation

The load capacities are shown in Table 1.1.
Table 1.1 shows the 132KV transmission network connected to the Rumuobioakani-based Port Harcourt Mains transmission substation.

33KV Feeder	Load Connected (MW)	Transformer Location Name	Transformer Size (MVA)

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Abuloma	12	T_1A	
REF 1	10.5		60
RSPUB 2 REF 2	17.5		
	18		
Elekiah	14		
Uniport	25	T_2A	60
RSPUB 1 (Woji)	12		
FDR 3	18		
FDR 2	16	T_3A	60
Airport Feeder	24.5		

(Source: Transmission Company of Nigeria, 2024)

The maximum and minimum load ranges from the Afam producing plant data base represent the bus loading conditions for the network that is being studied. Table 1.2 displays the network data and generator system used in this study.

Table 1.2: Bus Loading for the Transmission Network

Bus	MW (Max)	MW (Min)	MVAR (Max)	MVAR (Min)
T_1A	18	10.5	14.4	8.4
T_2A	25	12	20	9.6
T_3A	24.5	16	19.6	12.8

Source: (Transmission Company of Nigeria, 2024)

Transient Stability Analysis Technique

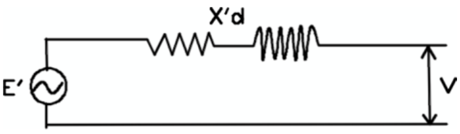

Figure 1.2: Model of an Equivalent Machine

The synchronous machine is operating at its stable pre-fault equilibrium points under typical operating conditions. The machine's behavior is determined by:

$$\frac{Md^2\theta}{dt^2} = Pm - Pe \qquad (1)$$

Equation (1) can be written as

$$\frac{H}{\prod f}\frac{d^2\delta}{dt^2} = Pm - Pe(Pu) \qquad (2)$$

Equation (2) was referred as the Equivalent Machine Model under normal operating conditions, the synchronous machine was assumed to be operating at its stable pre-fault equilibrium points. The behavior of the machine is given by:

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$$\frac{H}{\prod f}\frac{d^2\delta}{dt^2} = \Delta Pm - \Delta Pe \qquad (3)$$

It was assumed that the mechanical power of the generator was constant as shown in (3) and remodel in (4).

$$\frac{H}{\prod f}\frac{d^2\delta}{dt^2} = \Delta Pm(Pu) - Pe(Pu) \qquad (4)$$

equation (4) was considered for the maximum electrical transfer.

$$\frac{H}{\prod f}\frac{d^2\delta}{dt^2} = Pm - P\max Sin\delta \qquad (5)$$

$$\mathrm{PS} = \frac{dp}{d\delta}\Big|\delta o\ 0 = P_{max}\ \mathrm{Cos}\,\delta o \qquad (6)$$

PS = P_{max} Cos δo: The slope of the power angle curve at δo, when $0^o < \delta < 90^o$, Ps was positive Where:

P_S: The power of the shaft

δo: The machine initial operating angle

Determining the Network Parameters using base of 250MVA.

$$\mathrm{Pe} = \frac{381}{250} = 1.524\mathrm{Pu}$$

$$\mathrm{Pm} = \frac{383}{250} = 1.532\mathrm{Pu}$$

Reactance, X_{eq} = the reactance of the generator + the reactance of the line + the reactance of the transformer

X_{eq} = j0.275 + j0.097 + j0.0405

X_{eq} = j0.4125pu

$$\text{Real power (s)} = \frac{Pe}{Pf}\angle Cos^{-1}(\theta)$$

Where Pf = $\theta = 0.8.8$

$$\mathbf{S} = \frac{1.524}{0.8}\left[Cos^{-1}(0.8)\right] = 1.905\ \angle -36.87^o$$

$$\text{Current, I} = \frac{S^*}{V^*} = \frac{1.905\angle -36.87^0}{1.0\angle 0}$$

$I = 1.905\ \angle -36.87^o)$

Excitation voltage,

$E^1{}_g = V + JX_d{}^1$

$E^1{}_g = 1\angle^o + (j0.4125)\ (1.905\ \angle -36.87^0$

$E^1{}_g$ = 1 + j0 + 0.4715 + j0.6286

$E^1{}_g$ = 1.4715 + j0.6286

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$E^1_g = 1.600 < 23.2^o$pu.
Initial operating power angle becomes.
$\delta o = 23.20^o = 0.4049$rad
Synchronous speed,
$W_o = 2\prod f = 2\prod \text{ x } 50 = 314.1593$rad/sec.

The Application of Swing Equation Technique to get the Transient Stability of the Network

$$\frac{H}{\prod f}\frac{d^2\delta}{dt^2} = Pm - Pe$$

$$\frac{8.08d^2\delta}{\prod x50dt^2} = (1.532 - 0) \quad \text{during fault,}$$

Pe = 0

$$\frac{d^2\delta}{dt^2} = \frac{\prod x76.6}{8.08}$$

The both sides was Integrated as:

$$\frac{d\delta}{dt} = \int \frac{\prod x76.6}{8.08} dt + 0$$

Integrating again

$$d\delta(t) = \frac{\prod x76.6}{16.16} t^2 + \delta 0$$

$$\delta(t) = \frac{\prod x76.6}{16.16} t^2 + 0.4049$$

The calculation is repeated for tenth cycles.

Application of 4th Order Runge-Kutta Technique to Transient Stability

Recalling the two first order differential swing equations are:

$$\frac{d\delta_L}{dt} = \omega_L - \omega_s \quad (9)$$

$$\frac{d\omega_L}{dt} = \frac{\pi f}{H}(P_s - P_e) \quad (10)$$

Where
δ_L : Is the latest rotor angle.
ω_L :Is the latest angular velocity.
ω_s : Is the synchronous speed.
f : is Frequency.
P_s : Is shaft power.
P_e: is Electrical power
During fault condition, $P_e = 0$
Initial point of solution is $\left(0, \delta_{(0)}, \omega_{(0)}\right)$

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The synchronous speed, $\omega_s = 2\pi f = 2\pi \times 50 = 314.1593 rad/sec$

If the shaft power is 1.532pu and $H_{eq} = 8.08 MJ/MVA$ as calculated before, $\frac{\pi f}{H} = \frac{50\times\pi}{8.08} = 19.4405$

Substituting values into equations (3.7) and (3.8)

$$\frac{d\delta_L}{dt} = \omega_L - 314.1593 \quad (12)$$

$$\frac{d\omega_L}{dt} = 19.4405(1.532 - P_e) \quad (13)$$

The differential change in the rotor angle and angular speed with time, using 4th order Runge-Kutta method for analysis of the swing equation is as shown,

$$\frac{d\delta_L}{dt} = (\omega_L - 314.1593)\Delta t \quad (14)$$

$$\frac{d\omega_L}{dt} = 19.4405(1.532 - P_e)\Delta t \quad (15)$$

Recalled the general formula of the RK4 method.

$$\delta_L(\Delta t) = \delta_{(0)} + \frac{1}{6} + [K_1 + 2K_2 + 2K_3 + K_4] \quad (16)$$

$$\omega_L(\Delta t) = \omega_{(0)} + \frac{1}{6} + [L_1 + 2L_2 + 2L_3 + L_4] \quad (17)$$

Case 1: Determination of Rotor angle and angular speed at t = 0.02, 1 cycle

$$K_1 = \frac{d\delta}{dt} = (\omega_L - 314.1593) \times \Delta t$$

$$\omega_{(0)} = 314.1593 rad/sec$$

$$\omega_L = 314.1593 rad/sec$$

$$\Delta t = 0.02$$

$$Pe = 0$$

$$K_1 = (\omega_L - 314.1593) \times \Delta t$$

$$K_1 = (314.1593 - 314.1593) \times 0.02$$

$$K_1 = 0$$

$$L_1 = \frac{d\omega}{dt} = 19.4405(Ps - Pe)\Delta t$$

$$Pe = 0, \Delta t = 0.02, Ps = 1.532$$

$$L_1 = 19.4405(1.532 - 0) \times 0.02$$

$$L_1 = 19.4405(1.532)(0.02)$$

$$L_1 = 0.5957$$

$$K_1 = 0, L_1 = 0.5957$$

$$\delta_1 = \delta_0 + \frac{K_1}{2}$$

$$\delta_1 = 0.4049 + \frac{0}{2}$$

$$\delta_1 = 0.4049$$

$$\omega_1 = \omega_0 + \frac{L_1}{2}$$

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$$\omega_1 = 314.1593 + \frac{0.5957}{2}$$
$$\omega_1 = 314.1593 + 0.2979$$
$$\omega_1 = 314.4572$$
$$K_2 = \frac{d\delta}{dt} = (\omega_1 - 314.1593) \times \Delta t$$
$$K_2 = (314.4572 - 314.1593) \times 0.02$$
$$K_2 = 0.005958$$
$$L_2 = \frac{d\omega}{dt} = 19.4405(1.532 - Pe) \times \Delta t$$
$$Pe = 0, \Delta t = 0.02$$
$$L_2 = 19.4405 \times (1.532)0.02$$
$$L_2 = 0.5957$$
$$K_2 = 0.005958, L_2 = 0.5957$$

Similarly,

$$\delta_2 = \delta_1 + \frac{K_2}{2}$$
$$\delta_2 = 0.4049 + \frac{0.005958}{2}$$
$$\delta_2 = 0.4049 + 0.002979$$
$$\delta_2 = 0.4079$$
$$\omega_2 = \omega_1 + \frac{L_2}{2}$$
$$\omega_2 = 314.7551$$
$$K_3 = \frac{d\delta}{dt} = (\omega_2 - 314.1593) \times \Delta t$$
$$K_3 = (314.7551 - 314.1593) \times 0.02$$
$$K_3 = 0.0119$$
$$L_3 = \frac{d\omega}{dt} = 19.4405(1.532 - Pe) \times \Delta t$$
$$Pe = 0, \Delta t = 0.02$$
$$L_3 = 19.4405 \times 1.532X0.02$$
$$L_3 = 0.5957$$
$$K_3 = 0.0119, L_3 = 0.5957$$
$$\delta_3 = \delta_2 + \frac{K_3}{2}$$
$$\delta_3 = 0.4079 + \frac{0.0119}{2}$$
$$\delta_3 = 0.4139$$
$$\omega_3 = \omega_2 + \frac{L_3}{2}$$

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$\omega_3 = 314.7551 + \frac{0.5957}{2}$
$\omega_3 = 315.0530$

Similarly,
$K_4 = \frac{d\delta}{dt} = (\omega_3 - 314.1593) \times \Delta t$
$K_4 = (315.0530 - 314.1593) \times 0.02$
$K_4 = 0.0179$
$L_4 = 19.4405\ (1.532 - Pe) \times \Delta t$
$Pe = 0, \Delta t = 0.02$
$L_4 = 19.4405 \times 1.532X\ 0.02$
$L_4 = 0.5957$
$\delta_4 = \delta_3 + \frac{K_4}{2}$
$\delta_4 = 0.4139 + \frac{0.0179}{2}$
$\delta_4 = 0.4229$
$\omega_4 = \omega_3 + \frac{L_4}{2}$
$\omega_4 = 315.0530 + \frac{0.5979}{2}$
$\omega_4 = 315.3509$

Recalled the general formula of the RK4 method,
$\delta_{L(\Delta t)} = \delta_{(0)} + \frac{1}{6}[K_1 + 2K_2 + 2K_3 + K_4]$
$\omega_{L(\Delta t)} = \omega_{(0)} + \frac{1}{6}[L_1 + 2L_2 + 2L_3 + L_4]$
Where $\delta_{(0)} = 0.4049rad, \omega_{(0)} = 314.1593rad/sec$
$\delta_{(0.02)} = 0.4049 + \frac{1}{6}[0 + 2(0.005958) + 2(0.0119) + 0.0179]$
$\delta_{(0.02)} = 0.4049 + \frac{1}{6}[0.053616]$
$\delta_{(0.02)} = 0.4138rad$

Similarly,
$\omega_{(0.02)} = \omega_0 + \frac{1}{6}[L_1 + 2L_2 + 2L_3 + L_4]$
$\omega_{(0.02)} = 314.1593 + \frac{1}{6}[0.5957 + 2(0.5957) + 2(0.5957) + 0.5957]$
$\omega_{(0.02)} = 314.1593 + \frac{1}{6}[3.5742]$

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$\omega_{(0.02)} = 314.755 rad/sec$

Error Analysis of the 4th Order Ruggu Kutta Technique Solution

The mathematical discrepancy between a mathematical quantity's actual value and its error. A mathematical error is the discrepancy between a mathematical quantity's actual value and

Mean absolute error (MAE)= $\frac{\sum (X_o - X)^3}{n}$ (17)

Where:

n = number of errors

X_o =actual value

X = measure or calculated value

The real number, Xo, was the answer obtained using the traditional swing equation technique. Furthermore, it's thought to provide an accurate depiction of the rotor angles.

Table 1.3: Average Absolute Error in Rotor Angle Solution with Increasing Time

Incremental time(s)	**Conventional swing method δ (rad) X_o**	**RK4 δ (rad) = X_1**	**Error in X_1**
0.02	0.4109	0.4138	0.0029
0.04	0.4287	0.4645	0.0358
0.06	0.4585	0.5568	0.0983
0.08	0.5202	0.6909	0.1705
0.1	0.5538	0.839	0.3128
0.12	0.6193	1.0839	0.4646
0.14	0.6968	1.3429	0.6461
0.16	0.7361	1.6439	0.9078
0.18	0.8874	1.9864	1.099
0.20	1.0006	2.37-6	-1.37

the percentage mean absolute errorfrom the 4th order of Rung Kutta technique.

% MAE= $\frac{-5.1081}{10} x100 =$ -51

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The Critical Clearing Angle and Critical Clearing Time Calculation

The computation of critical clearing time is displayed below [8]:

Critical clearing time,

$$t_{cr} = \sqrt{(\delta_{cr} - \delta o)\frac{4H}{W_s P_m}} \tag{8}$$

Where:

T_{cr}: represent the time for Critical Clearance

δ_{cr}: represent the angle for Critical Clearance

W_o: Synchronous Speed

P_m: Mechanical Power

H: Inertia constant

When Runge Kutta numerical technique for 4th order was applied, the fault clearance of the relay was programmed to clear fault at 7 cycles, the critical clearing angle is 1.3429 radians (76.90) to prevent the rotor angle from reaching the zone of instability, which is 1.6439 radians (94.20).

Value substitution in equation (3.18)

$$t_{cr} = \sqrt{(1.3429 - 0.4049)\left(\frac{4x8.08}{314.1593x383}\right)}$$

$$t_{cr} = 0.015s \cong 0.02s$$

RESULTS AND DISCUSSIONS

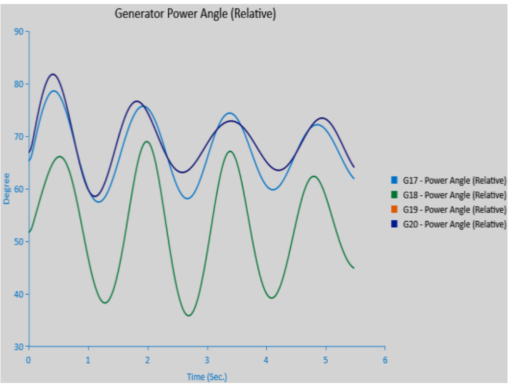

Figure 1.3: Generator Rotor Angle

The simulated result in Figure 1.3. Shows the swinging behavior of generators rotor angles in respects to incremented time. During time t=0, when a 3-phase failure started at bus 6. Now, generators 17 and 18 accelerated to a power angle of 97 and 65 degrees, respectively, while generators 19 and 20 both reached up to 82 degrees of acceleration. They will eventually reach stability if the fault is fixed at 4 cycles, as the oscillation gradually fades. The generators kept the network in sync, and stability was restored.

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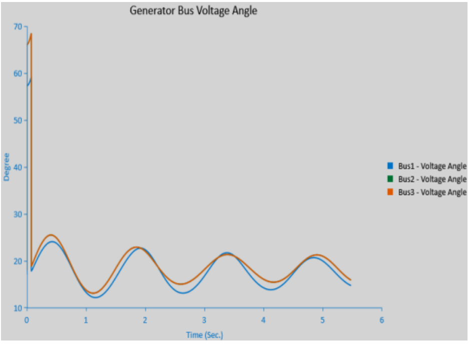

Figure 1.4: Generator Bus Voltage Angle

The simulated result of the generator's bus voltage angle with respect to time is shown in Figure 1.4. It was shown that during a fault, at time t = 0 s, the generator terminal voltage angle for buses 1, 2, and 3 abruptly increases to 68 degrees, correspondingly. The generator-maintained synchronism once the fault was fixed after four cycles, at which point the fluctuation steadily decreased and a steady operating state was attained.

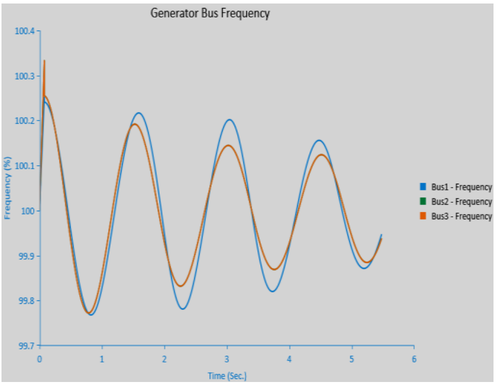

Figure 1.5: Generator Bus Frequency

The simulated result in Figure 1.5. Shows that Time-dependent observations of the generator bus frequency revealed that, beginning at time t = 0 s during the fault, the generator frequency increases to 100.4% for buses 1, 2, and 3, respectively. The oscillation decreased and a stable working condition was attained after the problem was fixed after four cycles. At this point, the generators remained synchronized.

Table 1.4: Percentage Absolute Errors Presentation

Percentage Absolute Error (%)
4th order Rungs Kutta Technique
-51

The result in Table 4.1. Shows the percentage mean error of the solution of 4th order Runge Kutta was -51, it was shown that 4th order Runge Kutta technique was the best absolute accuracy as a study case.

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CONCLUSION

Transient instability has consistently posed a significant challenge to the efficient functioning of power systems for an extended period of time. The simulation was conducted using the Electrical Transient Analysis Program (ETAP) program. The Convectional Swing Equation method and the 4th order Runge Kutta technique were employed to accurately predict variations in the rotor angles of synchronous machines across time increments during a fault occurrence. The simulated results of the analysis were achieved in the test case network, taking into account the analysis error. It can be concluded that the numerical solution obtained using the 4th Order Runge Kutta Technique achieves a good balance between accuracy and efficiency.

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