International Journal of
Science and Engineering Investigations vol. 10, issue 119, December 2021
Received on December 23, 2021 ISSN: 2251-8843

Impact of Factors and Parameters Change on Transient Stability in Small Scale Multi-Machine Power Systems

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Abstract- To limit the extent of damage to a minimum level and keep the state of power systems stable, the impact of different key factors and parameters change such as fault location, load increment, machine damping factor, fault clearing time, and generator synchronous speed should be evaluated. In this context, this paper presents a detailed comparative evaluation of the impact of those factors and parameters change on transient stability in small-scale multi-machine power systems. To demonstrate the impact of the factors and parameters change on transient stability performance for small-scale systems, an IEEE 5-Busbars network system has been selected as a case study and has been simulated and analyzed using MATLAB®/Simulink® software. All possible operational scenarios of some designated generators in this small-scale test system are highlighted thus, a better relay setting can be recommended.

Keywords- *Transient Stability, Relay, Fault Clearing Time, Synchronous Speed, Damping Factor*

I. INTRODUCTION

The most basic electric power system which was comprising a generator, loads, cable, meter and fuse is constructed in the late 18^{th} century [1]. It was a dc system supplying power at 110 V to a load of about 60 customers. However, the limitations of dc systems such as keeping voltage drops and power losses to acceptable levels made ac systems start to be more numerous than dc systems by the turn of the 20^{th} century [2-4].

The main advantages that made ac systems superior over dc are the low cost of ac-based machines and the capability of transforming ac voltages from one level into another. Such systems must be operated and be capable of withstanding disturbances and thus, any probable contingency can be sustained without losing loads. The earliest problem of stability of ac systems was experienced when insufficient damping caused a hunting oscillation [5]. This problem was solved using damper winding and turbine-type prime movers.

Typically, instability of power system can be seen as the loss of synchronization when generating power machines lost synchronization and they will no longer working at same synchronous speed[6, 7] therefore, voltage and current tend to oscillate drastically and this oscillation can cause damage to loads that receive electric energy from the unstable system [8].

Stability can be influenced by many factors such as machine damping factor, load increment, and machine impedance [9, 10]. Any change or variation in any one of these factors can affect stability and thus, a study of their impact evaluation is needed. The study can be conducted to determine the relaying system needed such as critical fault clearing time of circuit breaker, critical clearing angle, auto reclosing time t_{cr}, voltage level, and transfer capability between working systems.

A generator is said to be synchronized with a Bus-bar when both of them have the same frequency, voltage, and phase sequence. Usually, power system stability is categorized into steady-state and transient stability [11]. Compare to the steady-state, the transient stability has to be given more attention since its influence greatly on the electricity distribution system. A study of transient is needed to ensure that the system can withstand the transient condition following a major disturbance. A short circuit is a severe type of such disturbance.

During a fault, electrical power drawn from the nearby generators is reduced drastically, while powers from remote generators are affected extremely. Such a system may be considered as a stable one even with the existence of sustained fault while in other systems is considered stable only if clearing of the fault was sufficient rapidity. The stability of the system on the occurrence of a fault depends on many factors such as type of the fault, location of the fault, clearing time, and how it be cleared.

The ability of a power system to maintain stability under continuous small disturbances is also known as small-signal stability. In this type, stability can be regained with the inclusion of automatic control devices such as automatic voltage regulators and frequency controllers and usually they take a longer time to clear the disturbances [12]. Also, transient stability can be defined as the capability to retain the synchronism when a severe transient disturbance such as a fault occurrence, unexpected line outage, or unexpected loads adding or removal [6, 7].

The response of the system can involve large values of rotor angles and it can follow the nonlinear power-angle relationship. Following such disturbances in differences of rotor angular, and speed may undergo rapid changes that their magnitudes are the severity of disturbances dependent. According to [13, 14], studying the transient stability was only to determine whether the load angle returns to a steady value following the clearance of the disturbance.

The research work in [15] proposed a new method for steady-state stability analysis of synchronous machines. The method is based on a new swing equation, which is a second-order differential equation whose variables are the internal phase angle and the rotational slip. The authors applied the approach of steady-state analysis to two types of synchronous machines, but this approach discussed the two instabilities on a common basis.

Research work in [16] presented an article to review the theory of transient energy and stability. The authors discussed the theory based on the basic concepts which were including the swing equation and equal criterion, equilibrium points of stability, and instability. The purpose of this article was to provide a concise review of the equal-area criterion and to introduce a transient energy method for the one machine infinite Bus-bar case only. The research work in [17] presented an extension of the equal-area criterion for multi-machine systems and applies it for the determination of the transient stability margin for a machine that is critically disturbed. Article [18] has come with a solution to improve the power transient stability assessment by using critical fault clearing time function. The article was only an analytical investigation of a method to overcome the problem of calculation cost that simulation methods require to access accurately transient stability due to faults. Work done in [19] was used energy function to apply direct methods of transient stability analysis to multi-machine power systems. The functions are used to describe the transient energy that can cause a synchronous generator to leave the initial-state of equilibrium and also, used to describe the ability of power networks to absorb of such energy and how a synchronous machine can be change to a new state of post-disturbance of equilibrium. Research work in [20] presented a new simulation method to analyse the transient stability of the power system including three-phase unbalanced impedances. The method is based on the phase coordinate method, and only had analyzed a system that has elements of unbalanced three-phase impedances. Research work presented in [21] presented a new simulation method to analyze the transient stability of a power system including three-phase unbalanced impedances. The work was an extension to the work in [20]. This paper investigates a method for solving the swing equation and evaluates in-depth the transient stability performance that may have influenced by the change or variation in some key factors and parameters in of power systems. It is providing an in-depth comparison when a fault occurs close to/far from generating facilities. The MATLAB®/Simulink® software is used for simulating and analyzing the transient behavior of a selected test system at potential operational scenarios. The remainder of the paper is organized as follows: Section-II explains the methodology of work in analyzing transient stability of power systems. Section-III gives details about the IEEE 5-Busbars network used and its parameters. Section-IV presents the results of the analysis transient stability of the power system using MATLAB®/Simulink®. Section-V gives conclusions and future work suggestions.

II. METHOD

In typical studies of power system stability, the rotor motion of a synchronous machine is represented by the swing equation for a single machine as:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{1}$$

where P_m is the input power to the shaft of the machine, P_e is the electrical power that can cross the air gap, and P_a is the power that accelerating the rotor and it is accounts for any unbalance, and $H = \frac{0.5J\omega_S^2}{S_{rated}}$. This swing equation and its solution will show how the rotor angle changes in respect to a time following disturbance. Equation-1 can be written as a pair of first-order differential equations, according to the form:

$$\dot{\omega} = \frac{\omega_{\mathrm{Re}}}{2H}\left[P_m - P_e(\delta(t))\right] \tag{2}$$

$$\dot{\delta} = \omega \tag{3}$$

The solution to equations 2 and 3 is found by integrating both sides of each equation, resulting in:

$$\omega(t) = \int_0^t \dot{\omega}(\tau)d\tau \tag{4}$$

$$\delta(t) = \int_0^t \dot{\delta}(\tau)d\tau = \int_0^t \omega(\tau)d\tau \tag{5}$$

More compactly, it may define x_1=ω and x_2=δ, so that equation 4 and 5 may be written as:

$$\left.\begin{aligned}\dot{x}_1 &= f_1(x_1,x_2)\\ \dot{x}_2 &= f_2(x_1,x_2)\end{aligned}\right\} \Rightarrow \dot{x} = f(x) \tag{6}$$

$x(0)$ is known (the initial angle $\delta(0)$ and speed $\omega(0)$), so it is an initial value problem (i.e. $\delta(0)$ comes from the solution of the power flow equations, while $\omega(0)$ can be assumed equals to zero). Equation-6 can be written in one dimension (i.e., a single state variable)

$$\dot{x} = f(x(t)), \quad x(0) = x_0 \tag{7}$$

$$x(t) = \int_0^t \dot{x}(\tau)d\tau = \int_0^t f(x(\tau))d\tau \tag{8}$$

To find numerical solution for equation-8, it requires transformer it to a discrete-time equation as follows:

$$\begin{aligned} x(kT) &= \int_0^{kT} f(x(k\tau))d\tau \\ &= \underbrace{\int_0^{kT-T} f(x(k\tau))d\tau}_{x(kT-T)} + \int_{kT-T}^{kT} f(x(k\tau))d\tau \end{aligned} \tag{9}$$

Or, it can be written as:

$$x(kT) = x(kT - T) + \int_{kT-T}^{kT} f(x(k\tau))d\tau \qquad (10)$$

Equation-10 says that, if *x* wanted to be known at the "next" step, *kT*, it needs to know *x* at the "last" step, *kT-T*, and also the integral term needs to be known. This integral term is giving us the change in x from the last step to the next, i.e.,

$$\Delta x = \int_{kT-T}^{kT} f(x(k\tau))d\tau \qquad (11)$$

Since $x(0)$ is known, it can say that x is known at the "last" step. Thus, solving the problem requires only the ability to compute the integral term in equation 11.

III. IEEE 5-Busbars Test System

A 60-Hz, 230-kV small-scale transmission system as shown in Fig.1 is used as a test system. It consists of 5-Busbars of which 2 Busbars are generator Busbars, 2 transformers, 2 generators, 4 transmission lines, and 2 loads. In this section, the test data and parameters are introduced and given in details in the appendix. The purpose of introducing these data is to make the test system more limpid to the reader.

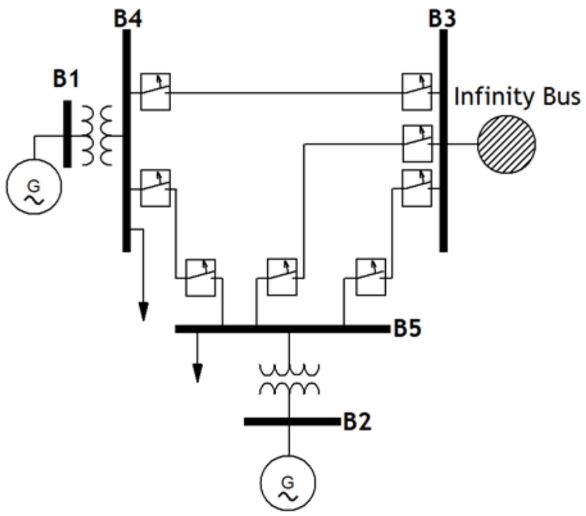

Figure 1. IEEE 5-Busbar system [19].

The test system comprises 4 transmission lines. Each transmission line has a different length with different resistance, reactance, and susceptance per unit length depending on the material. However, since the length of the transmission line does not affect the analysis in this paper, only the per-unit parameters are provided in Table-1 in the appendix. In this table, the data are in a per-unit system at the base voltage of 230 kV and 100 MVA. The resistance, impedance, and susceptance are given for the total length of transmission lines. The transformer's data consists of RT (Resistance) and XT (Reactance) which are the equivalent of the primary and secondary windings of the transformer. Table-2 in the appendix provides the parameters of the transformer. All the data given in this table are in per unit based on 20 kV for the primary windings and 230 kV for the secondary. There are 2 generators in this 5-Busbars test system.

The 2 generators are connected to Busbar-1 and Busbar-2. Busbar-3 is considered as a slack Bus-bar, while Bus-bars 1 and 2 are considered PV Bus-bars. The two remaining Bus-bars are all called PQ Bus-bars. Table-3 in the appendix provides the initial load flow conditions of the 10 generators Bus-bars. All the values are based on 100 MVA and the machines rated terminal voltages. Loads of this system are represented by fixed impedance for simplification in this paper. Table-4 in the appendix provides the data of the 2 loads of the system.

IV. Simulation And Test Results

This section discusses and comments on the various tests that have been conducted on the test system model set up in the previous section for the effects on critical clearing time (CCT). Five main tests are conducted, each with its various trials. These tests include: 1) – test for the effect of fault location test, 2) – test for the effect of friction factor, 3) – test for the effect of variation in inertia constant, 4) – test for the effect of fault type on the synchronous speed and 5) – test for the effect of variation in fault resistance. Each test of those tests will be discussed in detail explaining the procedure and showing the results in graphical form with analysis. The next sub-sections will present the simulation results that are yielded in the simulation environment (MATLAB®/Simulink®).

A. Effect of fault loctaion

This sub-section analyses the effect of fault location in transient stability. A three-phase fault is simulated at two different locations, one close to a generating station and the other one is far from the generating station. Fig. 2 shows the rotor angle of the generators with the generator at Busbar-4 as a reference, when a three-phase fault occurred at Busbar-1 and the fault was cleared at the critical clearing time by removing the line 4-5. The critical clearing time for this case is about 4.2s. Fig. 3 shows the rotor angle of the machines when a three-phase fault occurred at Busbar-3 and the fault was cleared at the critical clearing time by removing the line 3-5.

The CCT for this case is about 4.5 s. When generators swing together, they show their stable equilibrium. It can be observed that the clearing time of the fault close to Busbar-4 is minor compared to that one close to Busbar-3. This result can demonstrate that when a fault occur close to a generating station are rapidly cleared, the system will be stabilized more rapidly than this fault that occurs further away from the generating station.

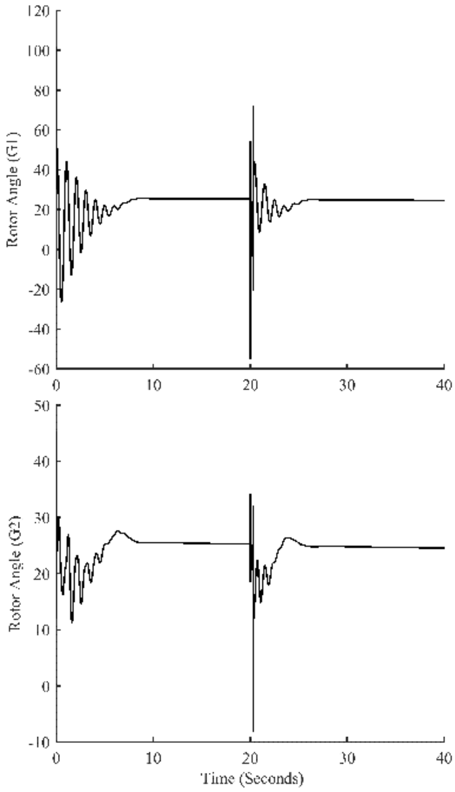

Figure 2. Rotor angle of the generators when a three-phase fault occurred at Bus-bar-4

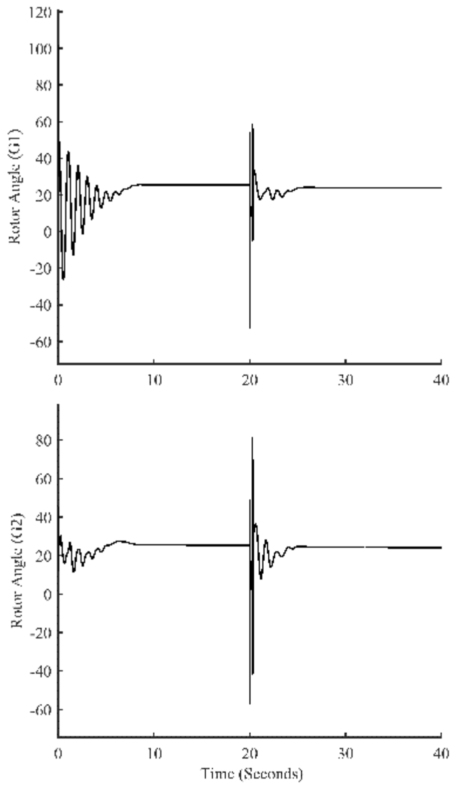

Figure 3. Rotor angle of the generators when a three-phase fault occurred at Bus-bar-3

B. *Effect of friction factor*

The machine friction factor represents the natural damping of the system. This sub-section evaluates the effect of friction factor on transient stability. Fig. 4 shows the rotor angle behaviour of generators with a friction coefficient for generator-1 and a three-phase fault on Busbar-4. Occurrence of fault will make generator's rotor angle to start oscillating and this oscillation will either decay or grow based on the configuration of the system. The friction factor should prevent the growth of such oscillations when the machine is properly damped. However, machine that has a poor damping factor is observed to be unstable one and its rotor angle will grow continuously even if the fault is cleared.

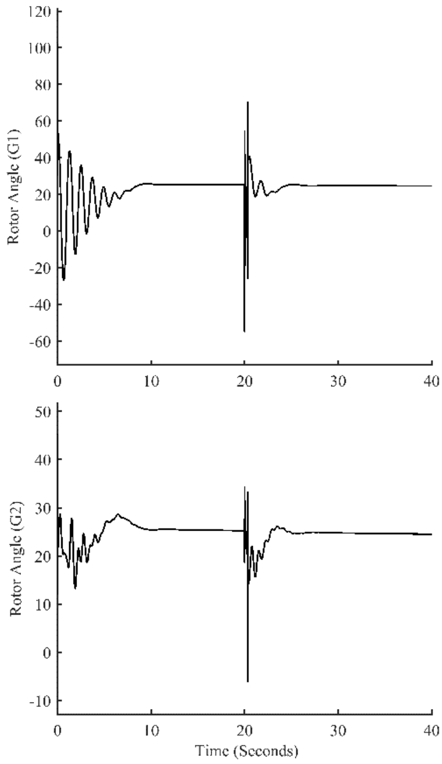

Figure 4. Rotor angle behavior of generators when generator-1 with friction coefficient =0.5 pu

C. *Effect of variation in inertia constant*

In this subsection, the variation in electric machine inertia constant (*H*) and its effect on the system stability has been investigated for the test system selected in section III. The friction factor is kept constant during the simulation. The machine *H* value was varied with an increase of 0.5 and 1 pu, respectively. Fig. 5 and 6 show the stability behaviour of the rotor angle of generators for the increase assigned of *H* value. At a very high value of *H* (Fig. 6), the CCTs are increased and the oscillations appear. As a general assumption, a higher value of *H* will assure a system with greater stability. The plots in this figure show a trend towards decreasing CCT for a very large value of *H*. The variation is significant only in the range under 1.0 pu.

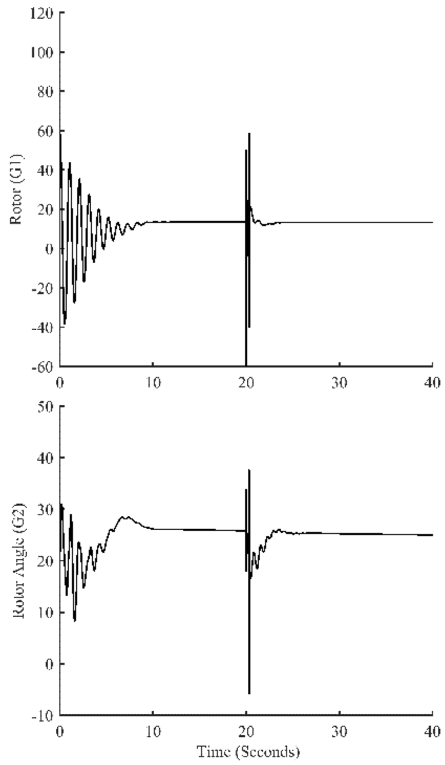

Figure 5. Effect of electric machine inertia constant with 0.5 pu increase

D. Effect of type on the synchronous

In this sub-section, the rotor synchronous speed (ω_s) response is evaluated against a fault type. Consider a three-phase fault occurs close to Bus-bar-4, which can be cleared by removing the line 4-5. Suppose the generators are initially operate at equilibrium (i.e. P_m being equal to P_e) and there is a fault occurs in the system, then P_m will become greater than P_e and thus, the rotor will accelerate and the system initial configuration will be lost. The excess in P_m will store more kinetic energy, and leads to increase the power angle.

When the power angle is increased, the P_e will start to increase until it balances P_m. At this the moment when the fault is cleared, the rotor is still running at above its synchronous speed even the power of the acceleration is zero. If $P_m < P_e$, the rotor starts to decelerate toward ω_s until the critical value of the power angle reached then, the rotor angle will remain oscillating at the natural frequency and the friction will eventually subside the oscillations. Graphs in Fig. 7 and 8 show the deviation from the synchronous speed at different fault types (Single-line to ground fault and three-phase fault) and how it eventual returns to the synchronous speed after clearing the fault. It can be shown that the worst-case occurs when there is a three-phase fault with a maximum overshoot of 0.002 pu for generator-2.

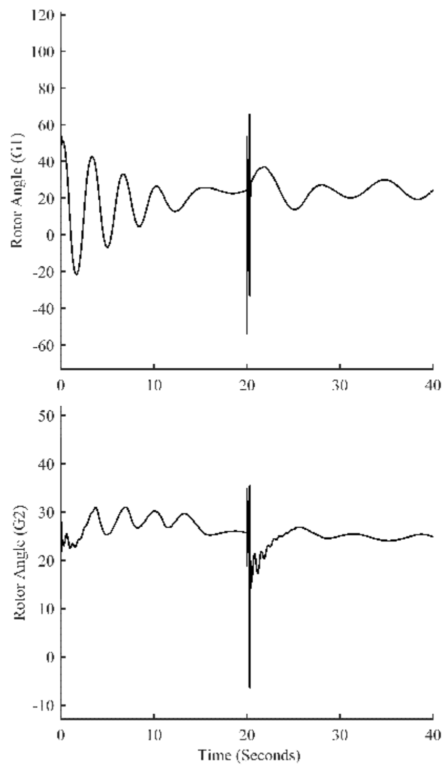

Figure 6. Effect of electric machine inertia constant with 10 pu increase

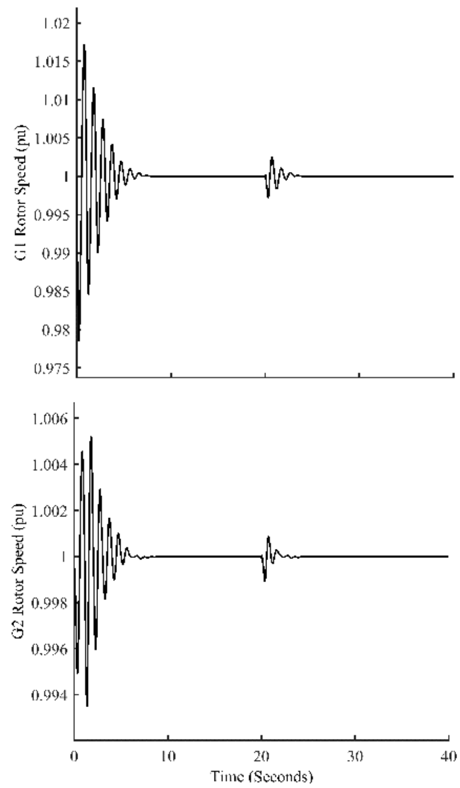

Figure 7. Response of generators' synchronous speed to the occurrence of a single-line to ground fault

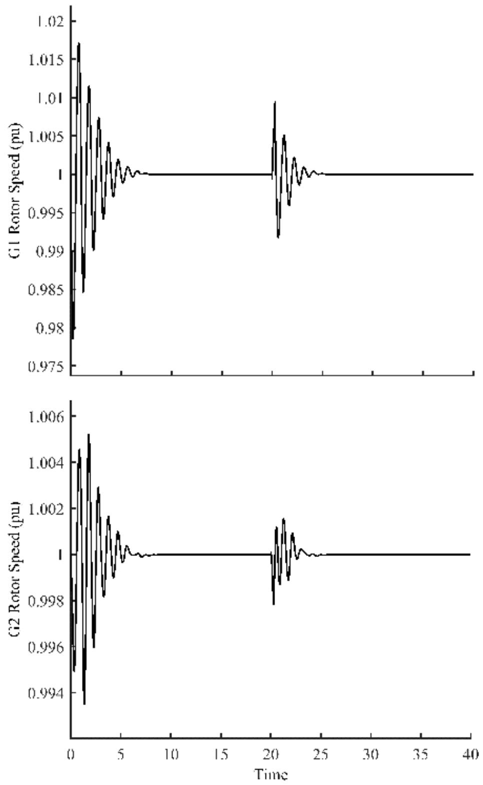

Figure 8. Response of generators' synchronous speed to the occurrence of a three-phase fault

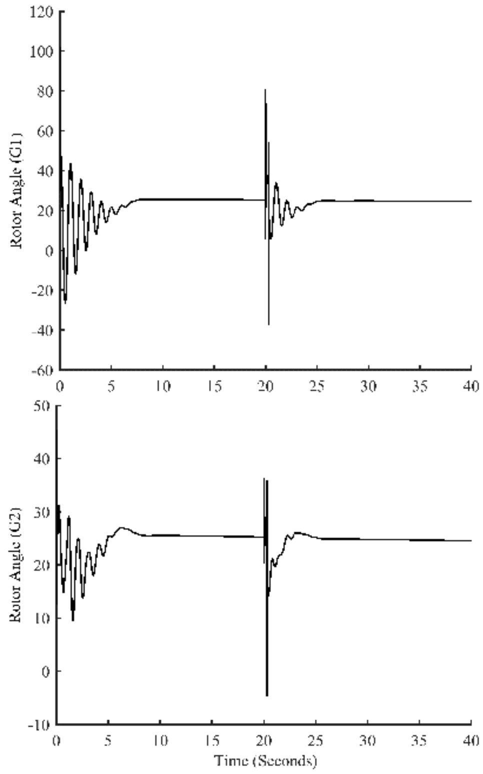

Figure 9. Response of rotor angles at fault resistance= 1 Ω

E. Effect of variation in fault resistance

In this sub-section, the effect of the variation in fault resistance (R_f) versus CCT in the test system is investigated. Here, R_f is assumed to be composed of the tower's effective grounding resistance (R_G) and the arc resistance (R_A). In reality, the grounding impedance is mainly considered a resistive and the inductive part can be considered only when there are ground wires. It is recommended that the fault resistance not to be ignored and, it can be assigned a common value in the range of $1<X/R_f<4$. Thus, a better performance of the transient stability can be achieved when R_f has a smaller value. To search the limit value of R_f that can cause any probable contingency not to be sustained in the test system being selected in section-III, the value of R_f is made varied from 1 **Ω** to 4 **Ω**. Fig. 9 and 10 depict the impact of increasing R_f on the stability performance.

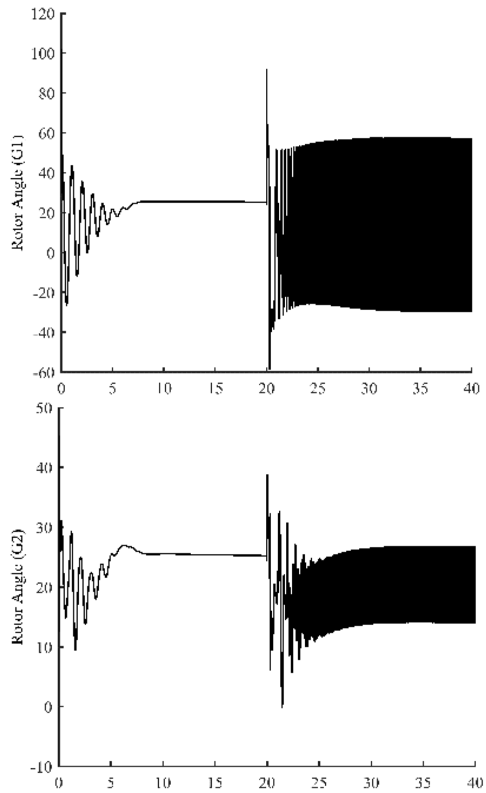

Figure 10. Response of rotor angles at fault resistance= 4 Ω

Increasing the R_f value four times causes the CCT to rise and more oscillations are appearing. This has occurred because the nonlinearity of the relationship becomes higher due to the increase in fault resistance and thus, it has a great effect on CCT. The system can withstand the fault for a longer duration if the fault impedance is smaller. In other words, solid symmetrical faults are the worst type and consequence appears in lowering CCT value and may lose of system stability. So, this simulation is illustrated that the inclusion of fault resistance R_f lowered the CCT value and hence caused the test system to be less stable and unstable for the fault resistance of four times (to a critical value of 4 Ω in this case).

V. CONCLUSTION

Various key factors that can affect transient stability in small-scale power systems were investigated. The factors investigated were the fault location, load increment, machine damping factor, fault clearing time, and generator synchronous speed. From the analysis of the graphs, it can be concluded that the increase in fault resistance will be the worst scenario that can occur and damage the power systems due to the high number of oscillations. On the other hand, it is found that increasing the value of fault reactance can essentially help in decreasing the number of oscillations. It is also found that increasing the value of *H* can cause an increase in CCTs of the circuit breakers.

Furthermore, the simulation results for a three-phase fault showed that the critical clearing time decreases as the fault location becomes closer to the generating units. These results can aid protection engineers to make an informed decision in the early stage of designing a protection scheme. Future work can be doing similar studies for the large-scale power systems and outlining the worst-case scenarios that can occur on the power systems of today.

APPENDIX

TABLE I. TRANSMISSION LINES DATA

LINE	Resistance (pu)	Reactance (pu)	Susceptance (pu)
3 to 4	0.007	0.040	0.082
3 to 5 (1)	0.008	0.047	0.098
3 to 5 (2)	0.008	0.047	0.098
4 to 5	0.018	0.110	0.226

TABLE II. TRANSFORMERS DATA

LINE DATA			
From Bus	To Bus	R_T	X_T
1	4	—*	0.022
2	5	—*	0.040

*negligible

TABLE III. GENERATORS' INITIAL LOAD FLOW

Bus	Generator	Rated Voltage (kV)	Voltage (pu)	P (pu)	Q (pu)
1	1	20	1.03	3.50	0.71
2	2	18	1.02	1.85	0.29
3	-	230	1.00	*SG**	-
4	-	230	1.02	6.32	-
5	-	230	1.01	`5.08	-

Slack Generator

TABLE IV. LOADS DATA

Bus	Rated Voltage (kV)	Load (MW) or (PU)	Load (MVAR) or (PU)
4	230	100 (1 pu)	44 (0.44 pu)
5	230	50 (0.5 pu)	16 (0.16 pu)

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How to Cite this Article:

Abdolkhalig, A., Mohamed, A. & Abusief, F. (2021). Impact of Factors and Parameters Change on Transient Stability in Small Scale Multi-Machine Power Systems. International Journal of Science and Engineering Investigations (IJSEI), 10(119), 37-44. http://www.ijsei.com/papers/ijsei-1011921-06.pdf