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Research paper

Analysis of Transient Stability in Synchronous Generator Using Nyquist Method

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Abstract

There are two factors that must be considered for the power quality analysis of an electrical power system, i.e. frequency and voltage stability. The system that can return to the initial condition or the steady state after a disturbance occurred indicates that the system is stable. This paper aims to detect the transient stability of three generators, which have identical specification of 2.25 MW 6.6 kV and are operated in parallel, based on the frequency performance. In this paper, the stability analysis is determined by using the nyquist method, where the system stability is indicated by the value of the response curve of the system. The analysis results show that the system of three paralleled generators have the value that far from 1 + j0 and the phase margin value and gain margin tend to be minimum. These values indicate that the system is unstable. The system slowly changes into more unstable because the oscillations are getting bigger until the final state. So, it is necessary to change the parameters of each generator that can affect the system stability during synchronization state.

Keywords: *Transient stability, synchronous generator, nyquist method, power system stability*

1. Introduction

Electric power system problems include power losses, power stability, losses synchronism, voltage drop, contingency etc. Power stability is the ability of a system to be able to restore conditions after an interruption occurs in the system [1]. For example, there is a sudden release of large loads, the release of the generator from the interconnection system which causes a large voltage drop in the system, and a short circuit on the bus or transformer. Power stability is divided into three classifications: voltage stability, angle stability, and long-term stability [1]. Whereas angle stability is further divided into small signal stability and transient stability. Transient stability is the ability of a system to maintain synchronization when the system experiences transient interference [1]. When a synchronous machine fails or falls (falls out step), the rotor will spin faster or decrease the speed needed to generate the system voltage. Loss of synchronization can also occur between one generator and another.

The stability of the synchronous generator can be determined by using Nyquist method, Routh analysis, or Lyapunov analysis [2]. In this paper, the authors choose the Nyquist method. By using Nyquist stability criterion, a plant that cannot be properly characterized, can be handled. Stability conditions can be determined from the results of the frequency response (performance in the frequency domain) and the response in the time domain [3].

The previous research [4] shows that the system stability is determined by using the pole transfer on the power system stabilizer through dampening the plot and the GEP method. The result, i.e. the Power System Stability (PSS) gain cannot support the GEP method because the method does not produce direct effects when setting excitation. Another research [5] shows that the system stability is determined by adding impedance between source and load. In this case, it is necessary to pay attention to noise sensitivity and error when measuring. The previous works [4][5] investigate one or more generators that operate separately, not in parallel connection.

This paper describes a case study on Pertamina EP where there are three generators with the same specification connected in parallel to one bus. The transient stability is investigated by varying governor settings and load changes using ETAP software and the modeling of three synchronous generators to investigate the system stability through the Nyquist method is generated using MATLAB software. Frequency response methods is easier than the root placement method, especially for large-scale systems, and it can be made accurate with the availability of sinus generators and expanding low frequencies which are important in a system according to the concept of this research.

2. Power system stability

A system that allows it to remain in its initial condition and can return to its initial condition if there is a disturbance in the power system is indicated as a stable system. The analysis can use the ideal model in detecting properties in power system instability. The followings are two types of system stability, i.e. rotor angle stability and transient stability.

2.1. Rotor angle stability

The system stability depends on the component of torque for each synchronous machine, include lack of torque during synchronization that may cause instability due to aperiodic drift at rotor angle. Or, lack of damping torque as the results of oscillation instability The following is the explanation of the system stability considering the rotor angle.

2.1.1. Small signal (or small disturbance) stability

Small disturbances in synchronization are caused by small variations in load and generation. The response of the system in a small disturbance depends on some factors, include the initial operation, the transmission system strength, and the type of generator excitation controls used. For instability in a generator that is connected radially to a large power system, it is determined by a lack of adequate synchronization torque. This instability is gained through a non-oscillatory mode, as shown Fig.1. For continuous operation of voltage regulators, the small-disturbance stability problem can be handled by ensuring sufficient damping of system oscillations. Instability is normally caused by oscillations of increasing amplitude. Fig.2 illustrates the nature of generator response with automatic voltage regulator [1]

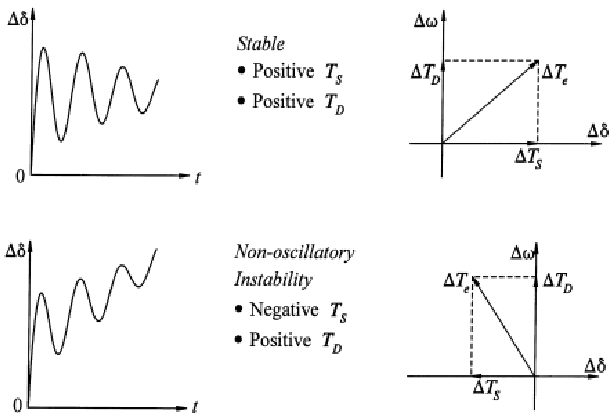


Fig. 1 Nature of small disturbance response with constant field voltage [1]

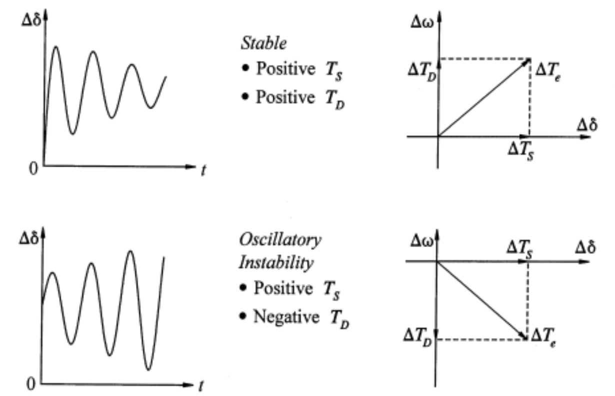


Fig. 2. Nature of small disturbance response with excitation control [1]

2.1.2. Transient stability

The ability of a system to return to its normal state when a fault occurs is called transient stability. The system stability depends on the initial operation and the high disturbance. In general, the system is changed in a steady state condition after disturbance occurs so that the system can return to normal condition. The severity of the disturbance usually considered are short-circuit of different types: phase-to-ground, phase-to-phase-to-ground, or three-phase. They are usually assumed to occur on transmission lines, but occasionally bus or transformer faults are also considered. The fault is assumed to be cleared by the opening of appropriate breakers to isolate the faulted element. In some cases, this process is assumed to be fast and appropriate.

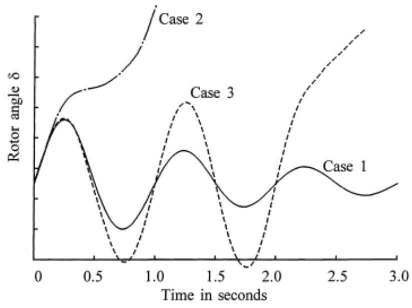


Fig. 3 Rotor angle response to a transient disturbance [1]

The behavior of a synchronous machine for a stable and unstable situation illustrated in figure 3. It shows a stable response and two unstable response of the rotor angle. For the stable case (case 1), the rotor angle increases to a maximum. After reaching the maximum value, the response moves into the steady state value by decreasing the amplitude (forming an oscillation waveform) until it reaches a steady state. In case 2, the rotor angle keeps increase until it lost the synchronism. In case 3 the system is stable in the first swing, but as case 2, the response becomes unstable, because of the oscillation of the response is increasing until it lost the synchronism. This unstable condition is not necessarily as a result of the transient disturbance, but because of the instability "small-signal" that generally occurs in the postfault steady-state condition itself [1].

2.2. Frequency response

The basis of Nyquist's original work on the stability of feedback amplifier is a Frequency response. Frequency response can be calculated quite easily, if tediously, from state space equations and a powerful tool for control system design.

Given a state space system (A, B, C, D) the frequency response may be calculated by replacing d/dt by Iω and eliminating the state variable x to give [1].

$$i\omega\, x = Ax + Bd$$
$$x = (i\omega I - A)^{-1}Bd$$
$$y = Cx + Dd$$
$$= (C(i\omega\, I - A)^{-1}B + D)d \quad (1)$$

To provide the required frequency response, it is necessary to calculate the gain margin and the phase margin. If the frequency setting is not available, the system cannot be controlled and observed. Frequency response can be observed well if using mathematical model validation to be used in the control system and stability analysis

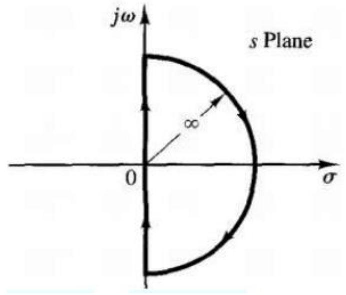


Fig. 4: Close loop transfer function [1]

Nyquist used a method, called the principle of the Argument to determine the number of zeros of a transfer function which lie in the right-hand half plane, provided that the number of poles if the transfer function which lie in the right-hand half plane are known. The method is based on Cauchy's residue theorem [1].

$$\oint_c w(z)dz = 2\pi\, i \sum residues\ of\ w(z) within\ c \quad (2)$$

C is any closed contour in an Argand diagram and the contour is traversed in the anti-clockwise direction. Consider a transfer function having the form

$$T(s) = \frac{\prod_1^{Z_n}(s-z_i)^{a_i}}{\prod_1^{P_n}(s-p_k)^{b_k}} U(s) \quad (3)$$

Where:
the z_i are zeros in the right hand half of the s plane,
the p_k are poles in the right hand half of the s plane, and U(s) is analytic in the whole of the right hand half of the s plane

Now, if we take the natural log of T(s) and differentiate with respect to s we get

$$W(s) = \frac{d\ln(T(s))}{ds} = \sum_{i=1}^{Z_n} \frac{a_i}{s-z_i} - \sum_{k=1}^{P_n} \frac{b_k}{s-p_k} + \frac{U'(s)}{U(s)} \quad (4)$$

The residues of W(s) are the multiplicities of the zeros and poles of T(s) in the right hand half of the s plane.
We next integrate W(s) around a specific contour (shown in Figure 8) that encloses the whole of the right hand half of the s plane, i.e

$$\oint_c W(s)ds = -2\pi\, i(\sum_{i=1}^{Z_n} - \sum_{k=1}^{P_n} b_i) \quad (5)$$

In this case, because of the right-hand side of 3.18 is negative, the contour is traversed in the clockwise direction. Because of its analytic in the right-hand half s plane, so the contribution term of U'(s)/U(s) doesn't count. There are no poles in the result of the right-hand plane. Now let $T(s) = re^w$, then

$$\frac{d\ln(T(s))}{ds} = \frac{dr}{ds} + i\,\frac{d\theta}{ds} \quad (6)$$

and

$$\oint_c W(s)ds = \oint_c dr + i \oint_c d\theta \quad (7)$$

The first term is zero, since r has the same value at the start and end of the contour. If $\theta = \theta_1$ at the start of the contour and $\theta = \theta_2$ at the end of the contour, then

$$\theta_2 - \theta_1 = -2\pi\, i(N_z - N_p) \quad (8)$$

N_z is the number of zeros, and N_p is the number of poles, taking into account their multiplicity. This is the *Principle of the Argument*, and we can determine the difference between the number of zeros and poles of a transfer function by determining the number of rotations that the transfer function angle makes, in the clockwise (negative angle) direction, about the origin as the frequency varies from $-\infty\ to + \infty$ [1].

3. Conventional Nyquist Design

In this research, the use of the Nyquist stability criteria method where a plant that cannot be properly characterized can be handled. Stability conditions can be seen from the results of the Frequency response (performance in the Frequency domain) and the response in the time domain [1]. Compared to the root placement method, frequency response methods are easier and can be made accurate with the availability of a sine generator and expand low frequencies which are important in a system in accordance with the concept of this research.
The Nyquist plot for a transfer function G(s) is the plotting of G(jω) in the complex plane (G(s)-plane) while is varied from −∞ to +∞ . For linear dynamic systems with real coefficients, half of NP-related to ω varying from 0 to +∞ is a mirror image in the real axis of the other half related to ω varying from 0 to −∞. Therefore, the analysis may be carried out computing only the half-part related to the positive frequencies. The Nyquist stability criterion establishes that Pc = P0 + N [7–8], where N is the number of clockwise encirclements of the point (−1,0) in the complex plane made by the NP and Po is the number of unstable poles of the OLTF, while Pc is the number of unstable poles of the CLTF. For the NP with positive frequencies, only the poles with positive imaginary part are considered. Assume that a transfer function G(s) has an unstable complex conjugated pair of poles o± jωo, with o > 0. In this case, Po = 1 and Pc must be made equal to zero by designing a feedback controller H(s) so the compensated OLTF encloses the point (−1,0) of the complex plane in the counter clockwise direction (N= − 1). Therefore, the design of H(s) for feedback stabilization, is focused on ensuring the mapping of the compensated OLTF encircles the point (−1,0) in the counter clockwise direction [7-8].
Otherwise, for closed-loop stability situation, the poles must have a negative real part, which corresponds to the roots (i.e., zeros) of the characteristic polynomial 1+ kL(s). The poles of 1 + kL(s) which also the poles of L(s), construct the region D as a D-shaped region that containing an arbitrarily large part of the complex right-half plane. Note that even the amount of it part was large, but it still a finite unit.
Note that *s* moves along the boundary of this region, 1 + *kL*(*s*) encircles the origin $N = Z - P$ times, where

i. the number of the unstable closed-loop poles denoted as Z (zeros of 1 + *kL*(*s*) in the rhp);
ii. the number of unstable open-loop poles denoted as P (poles of 1 + *kL*(*s*) in the rhp);

Note that *s* moves along the boundary of this region, *L*(*s*) encircles the −1/*k* point $N = Z - P$ times, where

a. the number of unstable closed-loop poles denoted as Z (zeros of 1 + *kL*(*s*) in the Nyquist contour);
b. the number of unstable open-loop poles denoted as P (poles of 1 + *kL*(*s*) in the Nyquist contour);

$$\angle L\,(-j\omega) = -\angle L\,(-j\omega) \quad (9)$$

Hence the plot of L(s) when s moves on the boundary of the Nyquist contour is just the polar plot + its symmetric plot about the real axis. The requirement for the open-loop condition of the Nyquist on Bode plot have to be stable first, then in order for the stable condition of the closed-loop, the Nyquist plot of L(s) should not encircle the -1 point. In other words, the value of the |L(j ω)| have to be less than 1 whenever ∠L(j ω) = 180 (|L(j ω)| < 1). So the indicators in the Bode plot, that the magnitude plot should be less than 0 dB line if/when the phase plot crosses the −180 ◦ line. Note that the condition that already discussed above is valid only if the stable condition for the open loop is approached. In another case (including non-minimum phase zeros) it is strongly recommended to double check any conclusion on closed-loop stability by using other methods, for example by using Nyquist and root locus method.

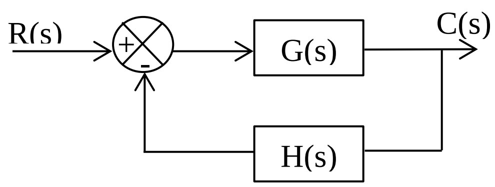


Fig. 5: Close loop transfer function [7–8]

A system showing unstable or poorly damped oscillations may be damped through the feedback of a stabilizer H(s) at a control loop described by the transfer function G(s), as shown in Fig. 5. The open loop transfer function (OLTF) F(s) and the closed loop transfer function (CLTF) T(s) are defined in (10) [7–8].

$$F_{(s)} = G_{(S)}H_{(s)},\ T_{(s)} = \frac{G_{(s)}}{1+G_{(s)}H_{(s)}} \quad (10)$$

The Nyquist criterion states that the system will be stable if the plane after the right of the G (s) H (s) curve does not cover the point (-1.0). The level of system stability can be measured by Gain Margin (GM) and Phase Margin (PM).

$$Gain\ Margin\ (GM) = \frac{1}{a} = 20\log_{10} a\ (dB) \quad (11)$$

$$Phase\ Margin\ (GM) = -180 + \theta \quad (12)$$

On a stable system, GM and PM values are always positive. The greater the GM and PM values, the more stable the system is. The Nyquist diagram is used to predict the stability and performance of a closed-loop system by observing the behavior of the open loop. In describing a Nyquist diagram, you must pay attention to the positive and negative frequencies (from zero to infinity)..

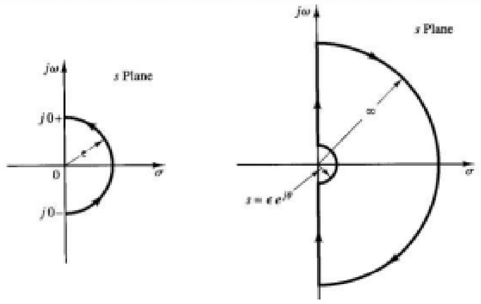


Fig. 6.. The Nyquist track system is stable [10].

To see the transient stability in a system that is by looking at the "optimum" transient response if: [11]

- The Phase margin of 30° to 60°
- Margin gain> 6 dB

For the minimum phase system, the 300-600 phase margin means that the slope of the Bode G (JW) curve at ω_gco must be more sloping than -40dB / dec (ie -20dB / dec) to be stable. If the slope reaches -60 dB / dec, the system is almost certainly unstable. While the phase system is minimum stable when the gain margin and the phase margin are positive.

3.1. Modelling of Synchronous Generator

This research begins by modeling 3 synchronous generators. Each generator has the same rating:

Spesification of generator

Type	:TC30A
Rated output	:2250 kW
Output voltage	:6,6 kV
Frequency	:50 Hz
Current	:237 A
Phase	:3 ø
Gas turbine	:M1T-13A
Generator	:NTAKL-DCK

Synchronous Generator modeling includes amplifiers modeling, exciter modeling, generator modeling, and sensors modeling. The form of a diagram block at Synchronous Generator modeling as shown in Fig 7. Synchronous Generator modeling is performed using of linear differential equations and Laplace transform.

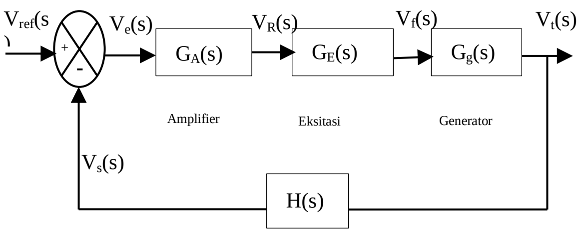


Fig. 7: Block diagram synchronous generator modelling [11]

A. Modelling of amplifier

The transfer function G(s) of an amplifier is given in.

$$G_a(s) = \frac{K_A}{1+T_A s} \quad (13)$$

The transfer function of amplifiers with 2 parameters is amplifiers gain constant (K_A) and amplifiers time constant (T_A). Amplifiers gain constant have a range value of 10.0000 until 40.000 while amplifiers time constant have a range value of 0.0200 sec until 0.1000 sec.

B. Modelling of exciter

The transfer function G(s) of the exciter is given in.

$$G_E(s) = \frac{K_E}{1+T_E s} \quad (14)$$

The transfer function of exciter with 2 parameters is exciter gain constant (K_E) and exciter time constant (T_E)). Exciter gain constant have a range value of 1.0000 until 10.000 while exciter time constant have a range value of 0.4000 sec until 1.0000 sec.

C. Modelling of generator

The transfer function G(s) of the generator is given in.

$$G_G(s) = \frac{K_G}{1+T_G s} \quad (15)$$

The transfer function of generator with 2 parameters is generator gain constant (K_G) and generator time constant (T_G). Generator gain constant have a range value of 0.7000 until 1.000 while generator time constant have a range value of 1.0000 sec until 2.0000 sec.

D. Modelling of sensor

The transfer function G(s) of sensor is given in.

$$H_S(s) = \frac{K_R}{T_R s+1} \quad (16)$$

The transfer function of sensor with 2 parameters is sensor gain constant (K_R) and generator time constant (T_R). Sensor gain constant have a range value of 0.9000 until 1.1000 while generator time constant have a range value of 0.0010 sec until 0.0600 sec.

While electrical system modeling is a full single line diagram of a system that includes generators, transformers and some of the loads installed on the system in fig.8. There are a number of variations in the load including essential loads and non-essential loads. In addition, the condition when the system is in a normal load has a power of 6467.82 kVA. While in peak load conditions it has a power of 7000.66 kVA. The following is a single line diagram image of a system with 3 generators which are paralleled with varying loads using ETAP 12.6 software.

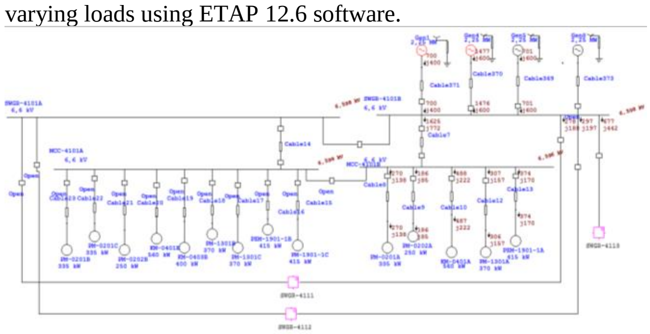


Fig. 8: Single line diagram of the system

4. Synchronous Generator Simulations

Transient stability analysis on 3 synchronous generators using the Nyquist plot, and using the help of ETAP 12.6 software and also MATLAB software.

4.1. Guidelines for Nyquist plot

The proposed method is an extension and improvement of the conventional Nyquist design which is reviewed in this section. The design based on the conventional Nyquist Plot (NP) is well-known and used in different areas of control engineering [7–8].
Its main objective is to assess the stability of a system with feed-back based on the open loop frequency response. The closed-loop transfer function (CLTF) (10) was selected to present the first result. Some modifications were made to make the power plants. The transfer function of equation (13) until (16) substitution into a block diagram at fig.5 Then determine equation by transfer function is given in.

$$G_G(s)H_S(s) = \frac{K_A+K_E+K_G+K_R}{S(1+\tau_A)(1+\tau_E)(1+\tau_G)(1+\tau_R)} \quad (17)$$

Table 1: Parameter of gain constant and time constant

Parameters	Description	Value
K_A	Amplifiers gain constant	1
K_E	Exciter gain constant	1
K_G	Generator gain constant	1
K_R	Sensor gain constant	1.5
T_A	Amplifiers time constant	0.1
T_E	Exciter time constant	1.2
T_G	Generator time constant	0.2
T_R	Sensor time constant	0.02

The Parameter of gain constant and time constant are presented in Table 1 and can be reproduced by the formulas:

$$G_G(s)H_S(s) = \frac{4.5}{(0.00048s^4+0.0316s^3+0.41s^2+1.52s+1)}$$

The form above can be obtained value of phase margin and gain margin:

Gain Margin	1.3045
GM frequency	6.9354
Phase Margin	9.4647
PM frequency	6.0390
Delay Margin	0.0274
DM frequency	6.0390

In accordance with the above results, the Gain Margin is obtained at 1.3045 dB (below 6.0000 dB) while the Phase Margin is obtained at 9,4647 ° (PM limit between 30,000 ° to 60,000 °).

So it can be concluded that the margin gain is below 6 dB and the phase margin has a value below 30,000 ° does not cover the limit which becomes the phase margin range itself so that the system can be said to be unstable. Plot a Nyquist diagram by using the form (17) as follows:

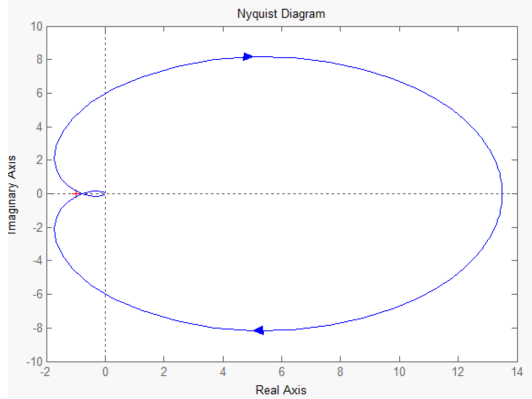


Fig. 9: Nyquist diagram

In accordance with the Nyquist diagram in fig.9, the curve G (jω) is further away from the 1-point + j0 so that the system is said to be unstable. The closeness of the G (jw) curve to the point -1 + j0 is a measure of the stability limit: phase margin and gain margin.

4.2. Transient stability

For transient analysis of synchronous generators, it is simulated using 3 synchronous generators. To do a parallel generator, several factors must be considered including the same frequency, the same voltage, the same phase angle. The frequency of the electric power system can be regulated by regulating the active power generated by the generator. Active power regulation is closely related to the increase in the amount of fuel used to increase active power. This fuel arrangement is done using a governor. So that it can be seen that the governor settings for each generator are as follows:

Ga	Speed droop 4,5 %
Gb	Isochronous
Gc	Isochronous

4.2.1. Change of Source

This simulation is based on case studies that occur in Pertamina EP where synchronization of Gb and Gc will maintain a frequency of 50 Hz but when Ga is synchronized with the droop speed setting of 4.5% with an initial frequency of 52.25 Hz it will decrease by 47.75 Hz. When Ga synchronizes with Gb and Gc in the 0.1-second interval, all generators are still safe and synchronization is achieved. However, in the 0.18 interval, Ga is out of sync with Gb and Gc and detects a decrease in frequency of 47 Hz where the frequency value has exceeded the predetermined setting limit so that Gb and Gc with isochronous settings cannot maintain the nominal frequency resulting in loss synchronization.

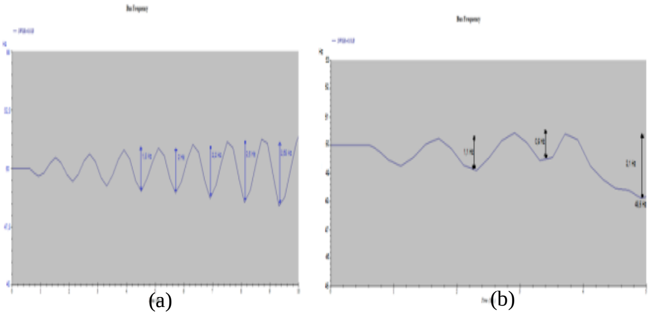
When Ga will synchronize in the interval of 0.1 seconds, the generator is still safe, but in the interval of 0.18, it detaches by detecting a frequency decrease of 47 Hz. Ga and Gb which is set to isochronous cannot maintain its nominal frequency which results in the generator blackout. The following is a comparison of field data with data that has been simulated using ETAP 12.6 software.

Table 2: The result of a simulation load flow

	Gen	Loading	
		MW	Mvar
Data	Gen b	1,477	1,018
Simulation		1,408	0,787
Data	Gen c	1,401	914
Simulation		1,408	0,787

In table 2 shows, when loading before a disturbance occurs, the difference in field data with simulation data is very small so that the simulation can be done according to what happened in the field. Each generator has the same generation power due to the same governor setting, which is the isochronous governor setting.

The source changes in this system are determined by using the governor settings of each generator and removing one of the generator sources as seen from the transient response. Consists of 2 conditions where each generator has a different governor setting.



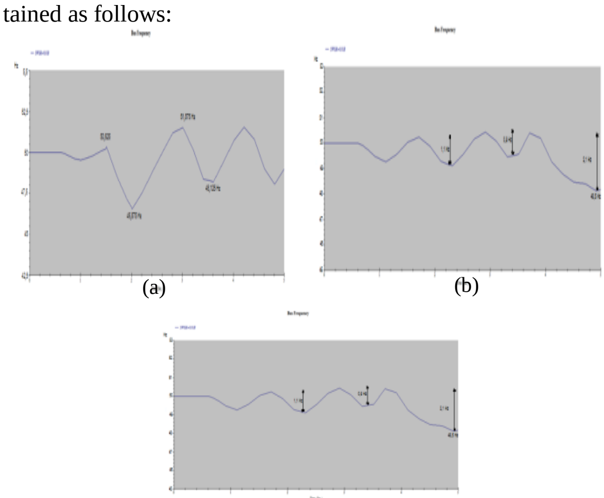
(a) (b)

Fig. 10: (a). Gb and Gc in isochronous settings, (b). When it doesn't come off with GB in the droop and Gc speed settings in the isochronous setting

The condition of the different governor settings can be seen in Fig.10, that when synchronization occurs between 3 generators experiencing poor oscillation and the system cannot return to its steady state condition and the frequency of the lowers is 45-47 Hz.

4.2.2. Change of Load

In this change simulation, the system is set based on varying load changes with the aim of knowing the effect of the generator based on the load power supplied. Then the simulation results are obtained as follows:



(a) (b) (c)

Fig. 11: (a) losses A and B Generators (2.8 MW Load) (b). Loose A and B generators (2.6 MW load) (c). Loose A and B generators (1.9 MW load)

With varying load conditions in fig.11, the transients shown are not optimum and are still experiencing continuous oscillation so that further handling needs to be done so that the oscillations do not experience too long which results in the system becoming worse. The system will experience continuous oscillation until it cannot return to its steady state position. If left unchecked it will experience a synchronization failure. Then it needs to be analyzed from the governor's settings. The solution of this research is by modeling more than one generator using the equation of the transfer function, it can be seen transient stability with different controls. In addition, pay attention to the effect of the angle on the rotor which is related to the regulation of active power (W) and reactive power (VAR) or fuel regulation on each generator.

5. Conclusion

This paper aims to analyze the transient stability of three 2.25 MW 6.6 kV generators which are operated in parallel. The analysis is carried out using the Nyquist method implemented in MATLAB and ETAP 12.6 software. The system stability is investigated through the governor settings and the transient response in ETAP 12.6 software. The transient response shows that the oscillations are increasingly irregular and over a long period of time so that the system is unstable. Besides that, it can be seen from the Gain Margin value of 1.3045 dB while the Phase Margin is obtained at 9,4647 °. So, it can be said that the system is unstable, and the transient response tends to be minimum.

Acknowledgement

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