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Optimization of speed droop governor operation at the gas turbine cogeneration unit

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ABSTRACT

Variations in customer demand for active power can impact frequency levels, potentially leading to instability within the electrical power system. To uphold system stability, it becomes essential to control the provision of active power to ensure the frequency remains consistent. This research aims to develop a simulation model for optimizing of the operation of the speed droop governor at the gas turbine cogeneration unit. This research used the quantitative method and descriptive statistical analysis techniques. The simulation model was employed as a simulator for operating the speed droop governor for frequency regulation in the electrical system. The gas turbine cogeneration unit 2 operational data of the speed droop values was used to analyze the influence of the generating unit's response to changes in frequency. The analysis and simulation results revealed the gas turbine cogeneration unit 2 speed droop value of 4%, which was considered ideal for maintaining the stability of the 60 Hz nominal frequency required by customers.

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1. INTRODUCTION

The successful operation of an electric power system is the achievement of providing reliable, safe, and economical electric power [1]–[5]. This reliability aspect concerns the ability to regulate and control the electric power generation system [6], [7] Continuous changes in frequency, load and voltage due to random disturbances often occur in the operation of electric power systems [8]. This results in transient and dynamic disturbances, which cause the system to be [9], [10]. Subsequently, the operating system becomes uneconomical, damaging the equipment and the generating unit trips. Therefore, a control system is needed to quickly return the generating system to a stable operating condition [11].

In electric power generating units, there is frequency regulation carried out by the governor unit, which acts as the primary fuel supply regulator for the generator unit [12]. To carry out its function, the governor measures the frequency produced by the generator by measuring the rotational speed of the generator shaft because the frequency produced by the generator is proportional to the rotational speed of the generator shaft. There are two governor operating modes, namely isooch (fixed speed governor), which will regulate the valve openings so that the generator output frequency returns to its initial value or setting value [13]–[16]. Secondly, the speed droop governor reduces/increases valve openings according to the maximum capacity of the generator and regulator. This setting is called speed droop or control characteristic. Frequency regulation in speed droop governor-type power generating units is most widely used in multigenerators connected in one interconnection to maintain the nominal frequency against load changes that occur. Therefore, excellent and reliable speed droop of governor control characteristics are needed to respond to changes in frequency in the power plant [16]–[18]. Electric power plants often experience changes in frequency when electrical load increases and load shedding occurs. Meanwhile, the frequency of the network supplying electricity must be maintained at the nominal operational standard limit between ± 0.2 Hz for a frequency of 60 Hz or 50 Hz [19], except during short transient periods, where deviations of ± 0.5 Hz are permitted, as well as during emergencies. So, the generator is expected to respond well to maintain the nominal frequency, especially when a sudden load shedding can cause over-frequency [20]–[22] Also, when a sudden outage occurs, other integrated generators that are operated result in under-frequency on the grid.

There are several basic models in the power system, namely the generator model, load model, governor model and prime mover model, such as the gas turbine generator model [23], [24]. The active load frequency control of the simulation model during normal operating conditions has input in the form of speed deviations [12]. If two generators are parallel with droop control, there is a frequency value where they share the load between them. In terms of load-frequency regulation, control gain is the inverse of permanent loss [25]. Model simulations can be carried out for parallel generator operations, and this is possible because the parallel system is a rigid system, where speed variations are between 95%-107% [26], [27]. In parallel operations, the model can be simplified into a speed droop model [5], [16], [28].

Therefore, the development of the speed droop model still needs to be improved to optimize due to many renewable generators and generators that have intermittency characteristics [29]–[33] This research aims to develop a model of speed droop with the generator response to frequency changes at the gas turbine cogeneration. The speed droop governor of operation optimization was simulated in response to frequency changes caused by changes in load demand using simulation. So, the ideal frequency can be obtained to reference for the system stability.

2. METHOD

This research employed the quantitative method with descriptive analysis technique. Analysis assisted by simulation. The simulation was carried out on the actual data of existing generating units, which was plotted in a relevant model and simulated. In this research, gas turbine cogeneration data was used with a load frequency control simulation, which compared two grid frequency control outputs of signals, namely the speed droop governor (primary control action) that has a steady state frequency error when load additions and reductions occur [11]. Meanwhile, for the second control output signal, a secondary control action was added to return the frequency to its nominal value by adding or reducing each generator's generating power (Pref) with manual operator input and response [6]. This method was slower than the primary control action (speed droop governor). The mathematical modelling of the generating system at the gas turbine in Figure 1 was a block diagram representing load frequency control (LFC) in the gas turbine cogeneration power plant [11], [24]. This modelling was simulated using the MATLAB/Simulink program.

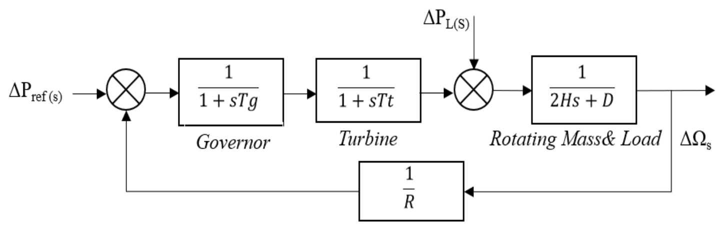


Figure 1. Block diagram as a representation of load frequency control

In can be seen in Figure 1, ΔP_{ref} is the reference set power, constant time governor (Tg), constant time turbine (Tt), ΔP_L as load change, D is load-damping constant, R is speed regulation, $\Delta\Omega s$ is the output result in the block diagram. When setting active power with LFC, another controller was usually added to optimize the performance of the LFC. The controller used by the PI method, which was an additional controller, was expected to speed up the LFC response to any frequency changes that occur in the electric power system.

The three gas turbine cogeneration units have a capacity of 3×104 MW and are limited to a load limit of 85%. Frequency settings used the load limits. If there was a change in frequency between 60.00–60.15 Hz, then these three generators can not respond, either increasing or reducing active power (MW). So, the load of each generator remains the same. A decrease or increase in load due to changes in frequency that exceeded this frequency range would be responded to by the generator with a specified speed droop regulation. Figure 2 is a load frequency control for a simulation model that compares two grid frequency controls for output signals. First, the speed droop governor (primary control action) still has a steady state error frequency when the load increases and decreases. Meanwhile, the second control output signal added a secondary control action to return the frequency to its nominal value by adding or reducing each generator's generating power (Pref) with manual operator input. The response of this method was slower than the primary control action (speed droop governor).

Governor modelling on gas turbine using simulation with gas turbine units having an installed capacity of 3x104 MW with a combination of 3 heat recovery steam generator units limited to a load of 85%. Equipment specifications were gas turbine type of W501D5A, manufacturer by Westinghouse, combustion of 14 pieces, nominal rating of 120 MW, heat rate (Btu/kWh) of 9,900 in SC/6,540 in CC, net efficiency of 35% natural gas/3,600 rpm ISO, inlet filter of 320 pieces (divided into four modules), compressor of 19 stages of the axial flow, turbine 4 stages reaction type turbine. Generator specification was manufactured by brush electric machine, capacity (S) of 141,176 MVA, installed power (P) of 120 MW, nominal voltage (Vn) of 13.8 KV, nominal current (In) of 5,906 A, power factor (PF) of 0.85, frequency (f) of 60 Hz. The gas turbine cogeneration unit 1, unit 2, and unit 3 parameters used in the simulation can be seen in Table 1. The initial condition of the third governor of the gas turbine cogeneration was the frequency setting using a load limit. The system modelling in this research can be seen in Figure 3, using the same droop speed. The load limit operating mode was a unit supply output controller that required a constant (passive) supply that was not influenced by changes in system frequency.

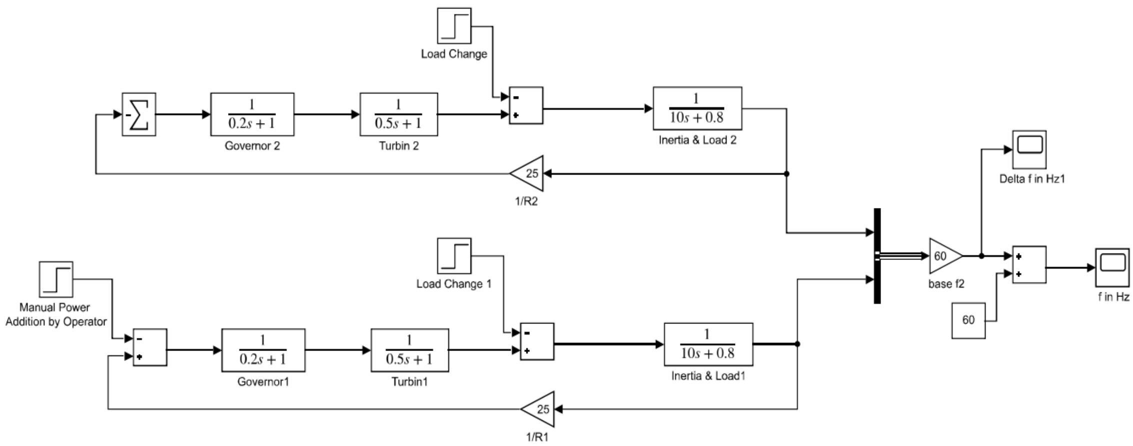


Figure 2. Modeling operation of the speed droop governor and load limit in the gas turbine

Table 1. Parameter for the gas turbine cogeneration unit 1, unit 2, and unit 3

Parameter	Value
Constant time governor T_{G1}, T_{G2}, T_{G3}	0.2
Constant time turbine T_{T1}, T_{T2}, T_{T3}	0.5
Moment inertia M_1, M_2, M_3	10
Damping load D_1, D_2, D_3	0.8
Speed regulation R_1, R_2, R_3	0.04
System load	0.02

The setting of the governor's droop speed was adjusted to the sensitivity of the governor's work in response to changes in frequency. The more minor the speed droop value adjustment, the more sensitive the governor was to changes in frequency in the system. The (1) can determine the drop speed. Where, (SD) speed droop (%), R1 was no-load rotation (rpm), R2 was full load rotation (rpm), Rp nominal rotation (rpm). Speed droop states the proportion value of changes in generator MW output to changes in system frequency, which can be using the (2) [11]:

$$\text{SD} = \frac{R1-R2}{R}\ X\ 100\% \tag{1}$$

$$\text{SD} = \frac{\Delta f/fo}{\Delta P/Po}\ x\ 100\% \tag{2}$$

where, required power response ΔP, installed nominal power P_O, Δf is the frequency change (%), fo is the nominal frequency, and SD is the speed droop (%). The governor's response to load changes based on the speed droop value can be obtained using the (3). By obtaining the ΔP value or how much power was needed to return the frequency value to its nominal value. It can be known value of the active power load need (MW) at that time with the generator output active power (Pout) with the (4) [10], [23].

$$\Delta \mathrm{P} = \frac{\Delta f \ \%}{SD \ \%} \ X \ P_0 \tag{3}$$

$$P_{TOT} = P_{Out} + \Delta P \tag{4}$$

A system with several generator units can resemble a large generator with some speed droop. In this case, the term static system was often used. This number showed that many MW was required to increase the system frequency by 1 Hz without secondary control. These statistics depend on the number of generator units running in the system and the speed settings using (3) [9]:

$$K = \frac{1}{S} \ x \ \frac{Po}{f0} \tag{5}$$

where: K = participation factor (MW/Hz), P_0 = unit nominal power (MW), f_o = frequency (Hz), S = speed droop. The generator frequency is very closely related to the rotation of the generator prime mover which can be obtained using (5).

3. RESULTS AND DISCUSSION

3.1. Simulation results and analysis of governor operation

In the modelling process in Figure 3, there was a change in load demand in one example case used to analyze the operation of speed droop. The simulation provided speed droop parameter values that vary from 2% to 6% for each generator. The results provided the information that the speed droop parameter responds most quickly to changes in frequency. The simulation result of model-based Figure 3, that is depicted in Figure 4.

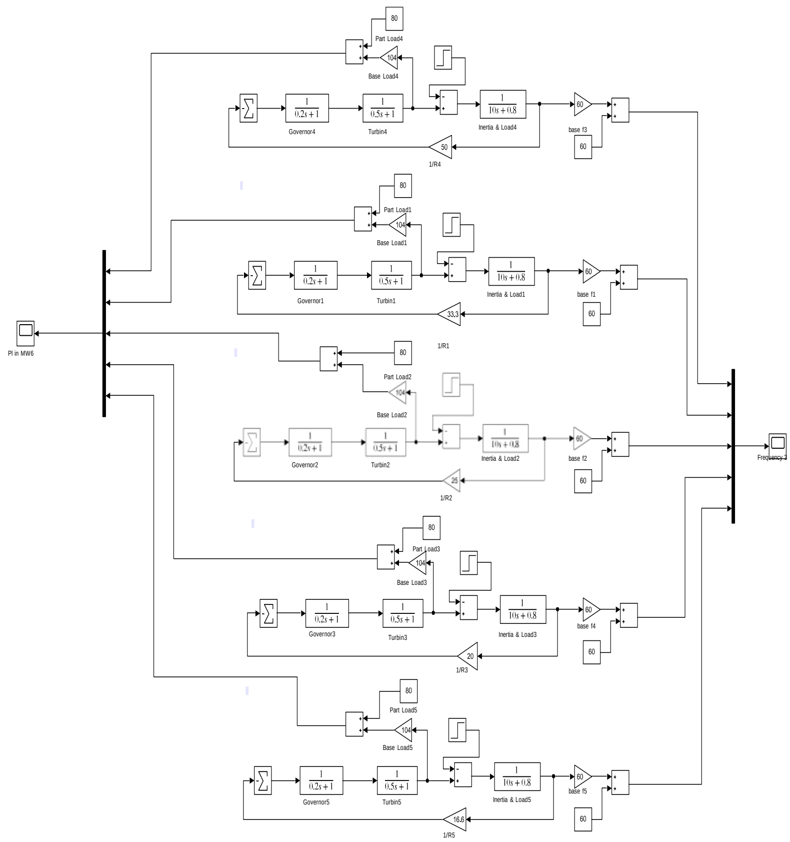


Figure 3. Simulation of 2% ≤ SD ≤ 6% gas turbine cogeneration

Figure 4 shows the frequency change response of each generator with varying speed droop values. Figure 4 depicts a governor with a speed droop = 2% reacting more quickly to changes in load, and the frequency drop was not too significant even though it oscillates quite a bit when compared to a governor with a speed droop value = 6%. Due to an additional load of 0.106 pu, the system frequency decreased. So, the governor of each generator with varying speed droop responded by adding fuel to the turbine, which caused the turbine speed to increase, followed by an increase in frequency.

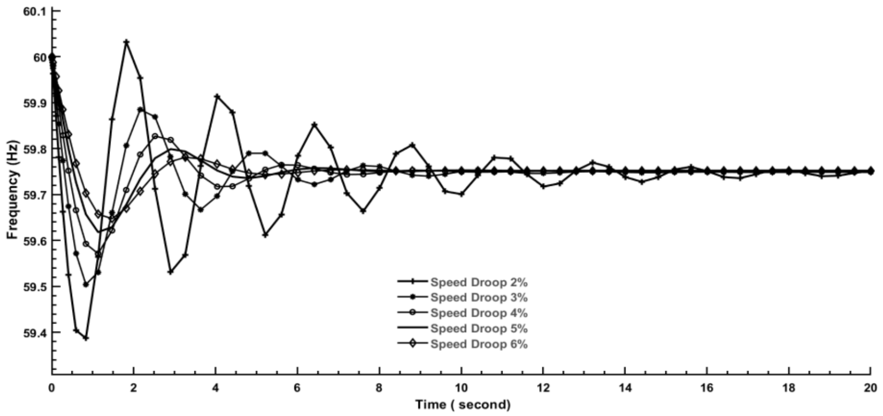


Figure 4. Simulation result of 2% ≤ SD ≤ 6% gas turbine cogeneration

Generators with regulators reacted slowly to changes in frequency. Where as the generators with a slight speed droop, the regulator reacted more quickly to changes in frequency. For the gas turbine cogeneration with a speed droop set at 4%, the participation factor was obtained using the (5). So, there was a load change of 4.3 MW every time, and the frequency would decrease by 0.1 Hz from the nominal 60 Hz to 59.9 Hz. When one of the cogenerations for the gas turbine unit trips, load generation loses 80 MW, so the governor control of each generator would work to detect a decrease in frequency along with a decrease in speed. In this way, other generating units would automatically increase the load by their nominal load. SCADA would regulate the loading of all generators in one grid to return the system frequency to regular operation.

3.2. Simulation response of gas turbine cogeneration unit 2 to increasing the frequency

The simulation results for governor response and frequency response are presented in Figure 5. There was an increase in grid frequency due to load shedding on several feeders. With the droop control configuration in unit 2, the increase in grid frequency can be handled by the governor, which works automatically to detect frequency changes by reducing load generation by ± 11 MW. Figure 5(a) shows the response of the governor when there is an increase in load which results in a decrease in frequency as shown in Figure 5(b). To maintain a steady state frequency of around ± 60.265 Hz within the permitted tolerance limits for a short period until it returns to normal again after adjusting the load by SCADA.

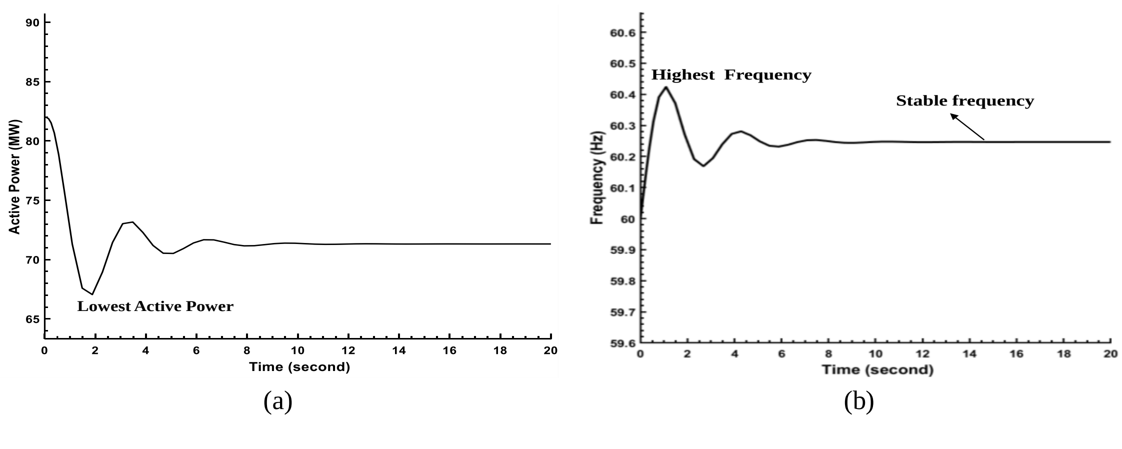
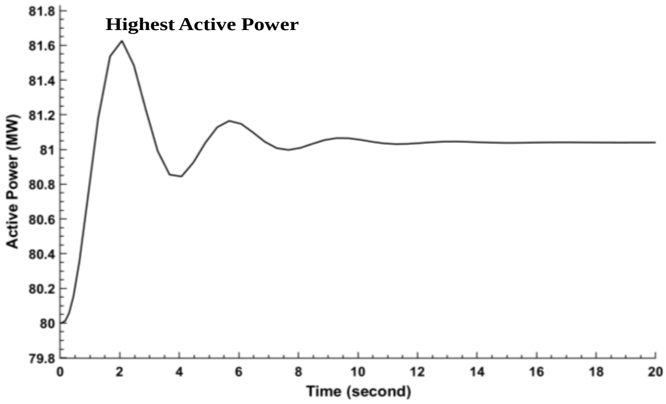


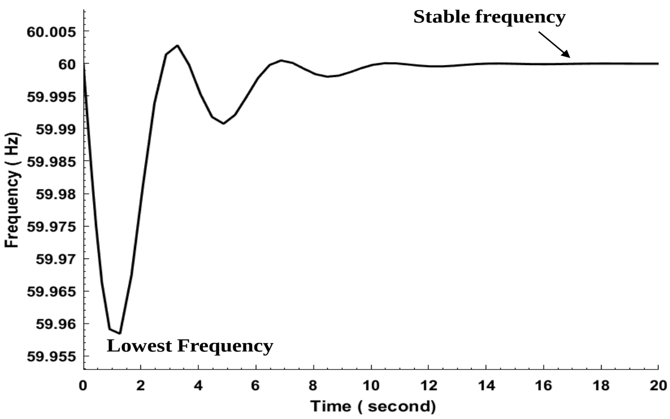
Figure 5. Simulation results when load shedding occurs (a) governor response and (b) frequency response

3.3. Simulation response of gas turbine cogeneration unit 2 to decreasing the frequency

The simulation results for gas turbine cogeneration to decreasing the frequency are presented in Figure 6. The grid frequency experienced a significant decrease due to cogeneration gas turbine unit 1 tripping, so the system frequency dropped to ± 59.81 Hz. This decrease in grid frequency was responded to well by the governor of gas turbine cogeneration unit 2, which automatically worked to detect changes in grid frequency by increasing the load generation of unit 2 by ± 11 MW as shown in Figure 6(a) shows the response of the governor when there is an increase in load and resulting in a decrease in frequency as seen in Figure 6(b). To maintain the system frequency at steady state ± 59.75 Hz, within the permitted tolerance limits for a short period until the frequency returns to normal after system loading is coordinated quickly and well by SCADA.



(a)



(b)

Figure 6. Simulation results when load increases (a) governor response and (b) frequency response

3.4. Calculation of required power when frequency increases and decreases

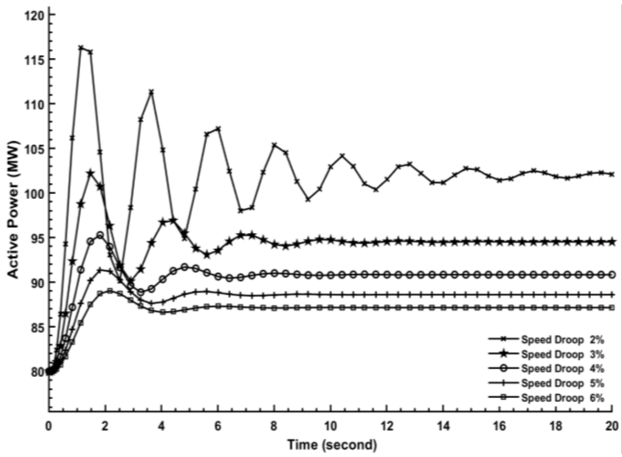
The calculation results show that the speed droop value is 2%, so the frequency change is only 0.19% or 0.12 Hz. Furthermore, it can be seen in Table 2 for more details, with variations in speed droop values from 2% to 6% for the same power generation response, namely 10 MW. It can see the differences in frequency change values.

Table 2. Comparison of speed droop to frequency changes

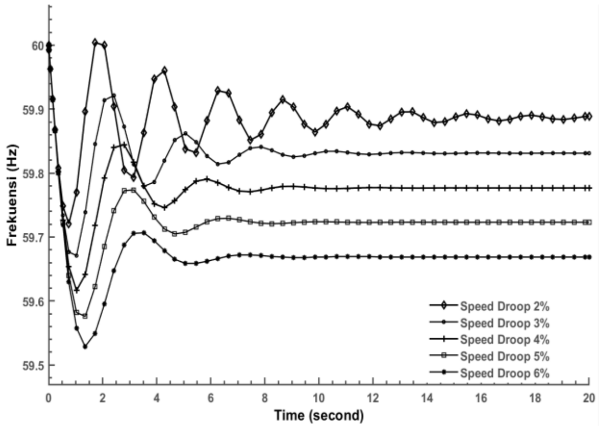
SD (%)	Generator response (MW)	Δ Frequency (%)	Δ Frequency (Hz)	$f_{Steady\ State}$ (Hz)
2	10	0.19	0.12	59.88
3	10	0.29	0.18	59.82
4	10	0.38	0.23	59.77
5	10	0.48	0.29	59.71
6	10	0.57	0.35	59.65

Based on Table 2, for the exact change in active power of 10 MW, the smaller the speed droop value, the smaller the change in frequency. It can be seen that when the speed droop value is 2%, there is only a frequency change of 0.19% or 0.12 Hz. In this case, the frequency range is 59.88 Hz and 60.12 Hz. When the speed droop value is 3%, there is a change in frequency of 0.29% or 0.34 Hz, which means that the frequency range is 59.82 Hz and 60.29 Hz. Even with a speed droop value of 6%, there is a significant frequency decrease, 0.57% or 0.35 Hz in the 59.65 Hz and 60.35 Hz range.

Figure 7 based on the simulation results in Figure 7(a), the exact active power change of ± 9.6 MW for each characteristic speed droop value from 2% to 6% produces different frequency change responses, which have a tolerance error of ± 1% from the calculation results. Frequency changes can be seen in the simulation results in Figure 7(b). Therefore, it can be concluded that the more minor the speed droop value, the smaller the frequency change with the same active power change response. The characteristics of speed droop values can be compared with changes in the same frequency (ΔFreq). For example, if the frequency change value is the same, namely 0.43% (0.26 Hz) with a characteristic variation in the speed droop value from 2% to 6%, then using (3), it can see the change in active power (MW) value in Table 3.



(a)



(b)

Figure 7. Simulation results (a) variations in speed droop values with changes in frequency and (b) variations in speed droop values with changes in active power

Tabel 3. Comparison of speed droop to generator response

Speed droop (%)	Δ Frequency (%)	$F_{Steady\ State}$ (Hz)	Active power change (MW)
2	0.43	59.75	22.36
3	0.43	59.75	14.90
4	0.43	59.75	11.18
5	0.43	59.75	8.94
6	0.43	59.75	7.45

From Table 3 regarding the comparison of the characteristics of speed droop values with the generator response, it can be concluded that with the exact change in frequency value, it is 0.43% or 0.26 Hz. The smaller the characteristic speed droop value, the more significant the change in active power generated. It can be seen that with a speed droop value of 6%, there is a change in active power of only 7.45 MW. When the speed droop value is 3%, the change in active power produced is significant, amounting to 14.90 MW. Even with a speed droop value of 2%, there is a significant change in active power, namely 22.36 MW, which proved that speed droop with a smaller percentage value will respond more diligently to changes in load or be sensitive to maintaining the frequency value with more significant changes in load. However, the smaller the percentage of speed droop value, the shorter the life of the equipment because when there is even a slight decrease in frequency, the work of the turbine and generator responds by increasing the power.

3.5. Speed droop calculation for frequency increase

The calculation of speed drop concerning increasing frequency can be proven by calculating the speed drop value installed on the gas turbine cogeneration unit two using (2). Therefore, it was known that the nominal power was 104 MW with a nominal frequency of 60.00 Hz. The data result was based on the load change data followed by frequency changes, as shown in Figure 8.

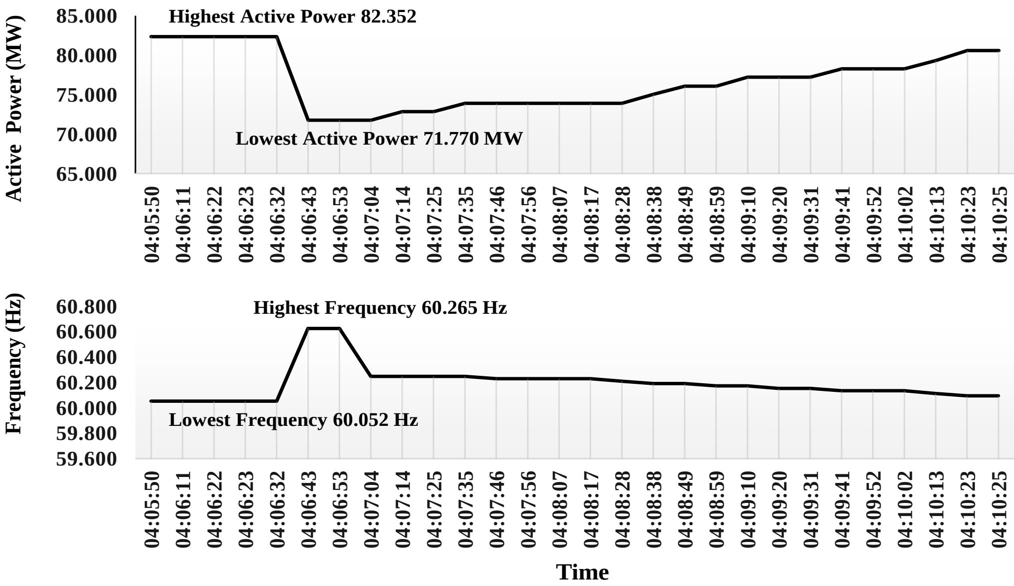


Figure 8. The data of active power and frequency for gas turbine cogeneration unit 2

From the data of active power and frequency for gas turbine cogeneration unit two in Figure 8, the power difference of ΔP=82.352 MW-71.770 MW=10.582 MW. The frequency difference was $\Delta f = f2 - f1$, namely 60.265 Hz-60.052 Hz=0.213 Hz. Then, the speed droop value was obtained using (2). The calculation results were proven to be a speed drop of 3.9%. Therefore, the speed droop value of gas turbine cogeneration unit two was 4%. It meant that by increasing the frequency by 4%, the controller reduced the maximum electrical output by 104 MW.

3.6. Speed droop calculation for frequency decrease

Likewise, the speed of droop can decrease in frequency. Hence, the speed droop value of the gas turbine cogeneration unit two can also be calculated using (2). Based on the data used when a decrease follows an increase in load in frequency, it can be seen in Figure 9.

The active power and frequency data for gas turbine cogeneration unit 2 in Figure 9 revealed the power difference of ΔP=102.732 MW-91.658 MW=11.065 MW and the frequency difference of $\Delta f = f2 - f1$, namely 60.72 Hz-59.81 Hz=0.26 Hz. Then, the speed droop value can be obtained using (2). The calculation results prove that the speed droop value of the gas turbine cogeneration unit two was 4.1%. It means a 4% frequency drop occurred, so the controller increased the maximum electrical output by 104 MW.

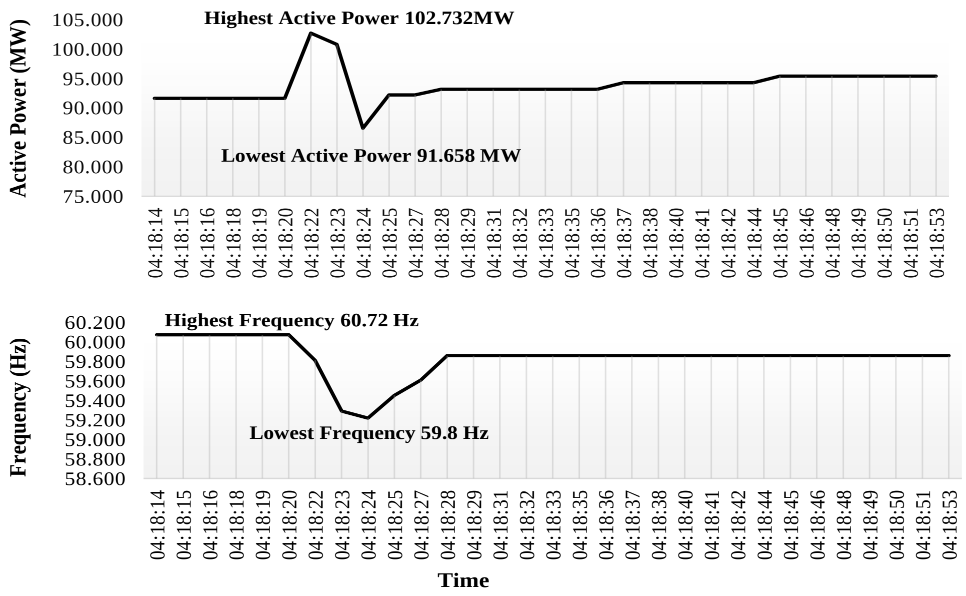


Figure 9. Active power and frequency data for gas turbine cogeneration unit 2

3.7. Deadband frequency

Deadband frequency is the frequency change value at which the governor works the slowest to increase or decrease the active power produced by the generator. Deadband frequency depends on the range of permitted frequency values in which the generating unit can operate according to its characteristics. If the change in frequency value exceeds the limit that the governor can respond to, a deadband effect occurs. A gas turbine cogeneration has a characteristic speed droop value of 4%, so the range of permitted frequency values can be found using the (6).

$$\text{Response of governor} = \text{fo x SD}$$
$$\text{Response of governor} = 60\ \text{Hz x } 4\% \tag{6}$$

The calculations show that the frequency value range for a speed droop of 4% is ± 2.4 Hz, which is interpreted that with this speed droop value, the slowest change in frequency value responded by the governor is at a frequency value of 57.6 Hz to 62.4 Hz. Suppose the change in frequency value exceeds ± 2.4 Hz from the nominal 60 Hz. In that case, the governor cannot respond to return the frequency value to its nominal frequency, and the frequency must be adjusted using secondary regulation. However, the generators in the system do not have secondary regulation, so the grid frequency setting is carried out through commands from the system operations manager. SCADA Division to the generating unit to increase or decrease the load level of the generating unit in order to anticipate changes in load.

4. CONCLUSION

Fluctuations in load changes in active power can affect frequency levels, thus potentially causing instability in the electric power system. Hence, the speed droop model needs to be improved to optimize. This paper aims to optimize the speed droop of gas turbine cogeneration operations by developing a model of gas turbine cogeneration operations with the generator response to frequency changes. The simulations were carried out on actual data from existing generating units, plotted in the relevant model and simulated using simulation. The gas turbine cogeneration data was used with a load frequency control simulation, which compared two grid frequency control outputs of signals, namely the speed droop governor (primary control action) that has a steady state frequency error when load additions and reductions occur. The second control output signal, a secondary control action was added to return the frequency to its nominal value by adding or reducing each generator's generating power (Pref) with manual operator input and response. From the simulation and analysis results, it was found that changes in active power on the load will cause changes in frequency, so that by setting the droop speed at 4%, system stability can be maintained. If the change in frequency value exceeds ± 2.4 Hz from the nominal 60 Hz, then the governor cannot respond to return the frequency value to its nominal frequency, which results in system failure.

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