An investigation of inertia constant in single generator on transient analysis for an isolated electrical network system

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ABSTRACT

An isolated electrical network which fed by an independent generator for a low voltage system is considerable in remote and islandic areas. Although the network system has less complexity in term of system structure, its stability level is crucial due to frequency dynamical responses. An influence of initial stability margin on frequency stability study during contingency situation is a thing rather than being ignored. Here the initial transient response inherently delivers important info such as system inertia and momentarily power deficit. In this paper, an investigation of transient stability responses under different inertia values is carried out. The investigation is carried out by modelling the isolated system in MATLAB/Simulink environment which consists of state-space mathematical equations. It is confirmed that the generator system inertia shapes the initial slope, speed droop and oscillation. For a verification purpose, the influence of system inertia is also analyzed using bode diagram in which system gain and frequency margin are evaluated.

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1. INTRODUCTION

Due to cost, operation, and management wise [1]-[3], an isolated electrical network with low voltage system based is commonly a choice to serve consumers in the remote and islandic areas. It consists of dispatchable generation and non-dispatchable renewable energy typically, leading to an independent and autonomous operation in regular basis. However, its system behavior is easily disturbed due to the mixed energy sources which inherently disturbs network stability level. The dynamical behavior of the generation system must be balanced and ensured within the permissible level to avoid severe system frequency deviations [4]-[7]. It should be noted that network transient stability is not only depend on energy balanced between supply and demand, but it also due to an influence from generation side i.e. a generator system [8]-[10]. Thus, generator specification factor should be counted when dealing with contingency planning.

A review on frequency stability and control has been summarized [11]. Investigations on the influence of frequency load control on power system network fed by multiple distributed generators are reported in [12]-[18]. In [19]-[22], the transient stability was analyzed by means of virtual inertia control when the network is integrated with a wind turbine system. The method to study the effect of synthetic inertia and virtual inertia for photovoltaic system was discussed in [23] and [24]. An analysis on power system angle during transient was discussed in [25]. Furthermore, influences of variation of frequency balancing and control approaches on the dynamical frequency behavior are investigated [26]-[28]. For a given load variations, the automatic generation control (AGC) would result significant influence on the dynamical network's frequency response.

In this paper, an investigation of dynamical frequency responses on the transient stability when an inertia constant, H varies is presented. The investigation deals with system formulation and derivations for an isolated power system fed by single generator. Observation on the influence of H on the transient phenomena would be theoretically advantageous in the early stage of generator selection.

2. RESEARCH METHOD

Figure 1 shows the illustration of the generator supplying isolated load to be study. The network consists of one generator system and connected loads. The mathematical model that has been derived was divided into four main parts which are rotating mass, prime mover, speed governor and load. Each part was modeled separately and augmented all together to become a single model.

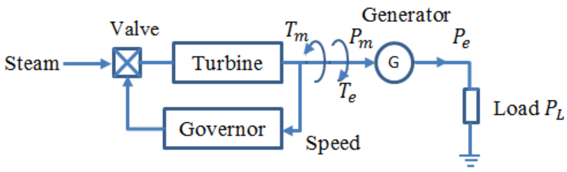

Figure 1. Generator supplying isolated load

2.1. Rotating mass model

This model is related to the behavior of the rotation towards the mechanical torque and electrical torque which satisfied the law of rotation

$$J\frac{d^2\delta_m}{dt^2} = T_m - T_e \quad (1)$$

Noted that J, δ_m, T_m and T_e are the combined inertia constant, mechanical rotor angle, mechanical torque and electrical torque respectively. Multiplying the synchronous speed in mechanical term ω_{sm} to the both sides of the (1) and applying the transformation to the rotor angle with generator pole p, it will turned the equation into power related to the electrical angle as follows:

$$\frac{2}{p}M\frac{d^2\delta_e}{dt^2} = P_m - P_e \quad (2)$$

M is the inertia constant in the kinetic energy $W_k = {}^{M\omega_{sm}}/_{2}$. Substituting W_k into (2) yields,

$$\frac{2}{p}.\frac{2W_k}{\omega_{sm}}.\frac{d\omega_e}{dt} = P_m - P_e \quad (3)$$

In (3) describes the behavior of generator rotor represented in frequency deviations with respect to time and noted that $\frac{d^2\delta_e}{dt^2} = \frac{d\omega_e}{dt}$. Dividing the (3) with the base power and converting the ω_{sm} to the synchronous speed related to electrical with generator pole p, the equation will turned into the generalize equation that commonly called as a swing equation in per unit.

$$2H.\frac{d\omega}{dt} = P_m - P_e \quad (4)$$

Noted that H is the per unit inertia constant and the only parameter that affect the behavior of frequency deviations other than deficit power between mechanical and electrical power.

2.2. Prime mover model

Prime mover is the source of the mechanical power for the rotating mass system. The most effective way to model the prime mover is by relating its behavior with the steam turbine system. The model is related to the mechanical power output P_m to the steam position P_{gV}. This work used the simple prime mover model that can be approximated with a single time constant τ_T resulting in the following transfer function;

$$\frac{P_m}{P_{gv}} = \frac{1}{\tau_T S+1} \quad (5)$$

Converting the transfer function (5) into the differential equation will make the prime mover model become compatible to augment with the rotating mass model in (4). By applying the inverse Laplace transformation, the final equation for the prime mover model can be written as follows

$$\frac{dP_m}{dt} = \frac{1}{\tau_T}(P_{gv} - P_m) \quad (6)$$

2.3. Governor model

When the load demand suddenly increased, the electrical load power exceeds the mechanical power and resulting the power deficiency. The amount of power deficit will influence the amount of kinetic energy stored in the rotating system. The reduction in kinetic energy will affect the turbine speed and consequently the generator frequency going to fall. As a conclusion, the speed governor system P_{gv} is depends on the electrical load demand. This change in speed is sensed by the turbine governor and act to adjust the turbine input valve to change the mechanical power output to bring the speed to a new steady-state level. The equation which directly describes the speed governor behavior is depicted in (7).

$$\frac{dP_{gv}}{dt} = \frac{1}{\tau_{gv}}\left(P_{ref} - \frac{\omega}{R} - P_{gv}\right) \quad (7)$$

where R represents the slope of the curve in the speed governor characteristics as shown in Figure 2 which related to the deviation of frequency with respect to power changed. Noted that this mathematical model does not consider the automatic generation control (AGC).

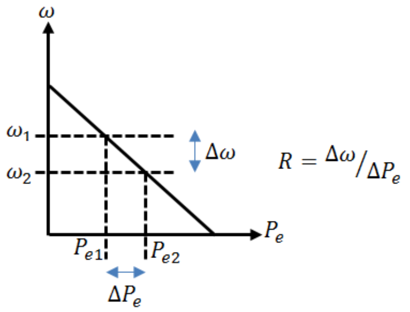

Figure 2. Speed governor characteristic

2.4. Load model

The load on a power system consists of variety of electrical devices. It can be divided into 2 types which are frequency independent loads such as lighting and heating loads, and frequency dependent loads such as motor loads. The sensitivity of such loads is depending on their speed-load characteristics and can be approximately defined by,

$$P_e = P_L + D\omega \quad (8)$$

where P_L is the non-frequency sensitive load change and $D\omega$ is the frequency sensitive load change. D is expressed as the percent change in load divided by the percent change in frequency.

2.5. State space representation

In (4), (6), (7) and (8) can be written into the state-space representation as shown in (9). From the equation, the state variables are $\Delta\omega$, ΔP_m and ΔP_{gv} while the input state is the load demand ΔP_e. Noted that the symbol Δ used in these equations is to represent the deviations of the state.

$$\dot{x} = Ax + Bu \quad (9)$$

The matrix A and B is arranged as shown in (10) and (11).

$$A = \begin{bmatrix} 0 & {}^{1}/_{2H} & 0 \\ 0 & {}^{-1}/_{\tau_T} & {}^{1}/_{\tau_T} \\ {}^{-P_{ref}}/_{T_{gv}R} & 0 & {}^{-1}/_{T_{gv}} \end{bmatrix} \tag{10}$$

$$B = \begin{bmatrix} {}^{-1}/_{2H} & 0 & 0 \end{bmatrix}^T \tag{11}$$

3. RESULTS AND DISCUSSION

The main objective of this work is to investigate the influences of dynamical frequency response towards the multifarious inertia constant value. The isolated power system network was modeled with the relation to the swing equation and augmented with the turbine and governor system. The turbine system was modeled as a non-reheat turbine type while the reference power in the governor system is always equal to zero so that the network model does not consider P_{ref} as required in AGC. Thus, the system will only experience the primary control in its load frequency control mechanism. The parameters of the isolated power system model are shown in Table 1. Noted that the value of inertia constant was arbitrarily varied during the simulation in accordance with the typical generator with non-reheat turbine system and the results were in per unit. The model was tested and verified under 3 inertia constant conditions with sudden 0.3 per unit of load deviation. Then the dynamical frequency responses were analyzed and investigated.

Table 1. Parameters of isolated power system model

Parameters	Value
Speed regulation, R	0.05
Frequency-sensitivity, D	0.6
Inertia constant, H	Varied (2.5 – 6.0)
Governor time constant, τ_{gv}	0.2
Turbine time constant, τ_T	0.3

3.1. Simulation results for frequency dynamical behavior

Figure 3 shows the dynamical frequency responses under the different inertia constant value and 0.3 per unit load deviation. From the observations, it is obviously seen that the inertia constant plays the role in weighting the generator shaft. It can be proved by looking to the size of oscillations during the transient where the higher inertia constant value will result in less oscillation. The initial slope also affected since the inertia constant is the only parameter that influence to the frequency deviation with respect to time and complied the (4). Low inertia constant may put the generator in danger because the initial drop of frequency decay may be out of permissible range when more load demand deviation happened. It can be seen in the graph for inertia constant equal to 2.5, the undershoot nearly reach to 0.03 per unit. Table 2 shows the summary of the results.

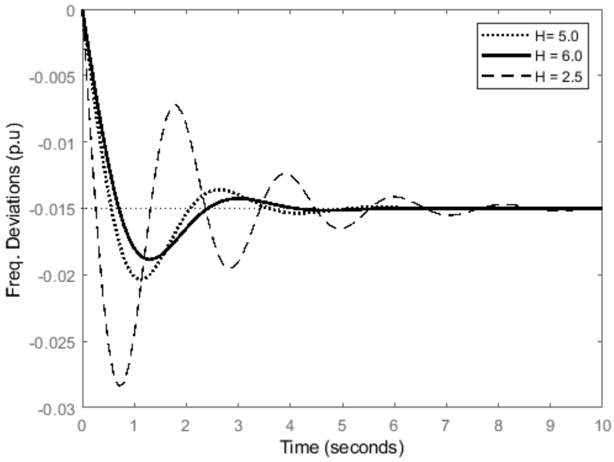

Figure 3. Frequency deviations under multifarious inertia constant

Table 2. The summarization of the transient analysis

Inertia Constant	Undershoot	Initial Slope	Settling time	Oscillation	Steady-state
2.5	89.73%	0.06	7.39s	High	
5.0	35.82 %	0.03	4.45s	Medium	Not influenced
6.0	25.66%	0.25	3.69s	Low	

3.2. Simulation results from bode plot frequency response

In the previous section, the frequency deviations responses with respect to time were recorded. The results show the information about transient stability. In this section, the results were plotted in frequency response through the bode graph as shown in Figure 4. From the observation, the multifarious inertia constant will only influence the gain magnitude in the higher frequency bandwidth while the gain in lower frequency bandwidth is remain unchanged. As such, low inertia constant will lead to the higher deviation of the magnitude gain. This phenomenon has become the evidence that the inertia constant parameter does not perturb the steady-state.

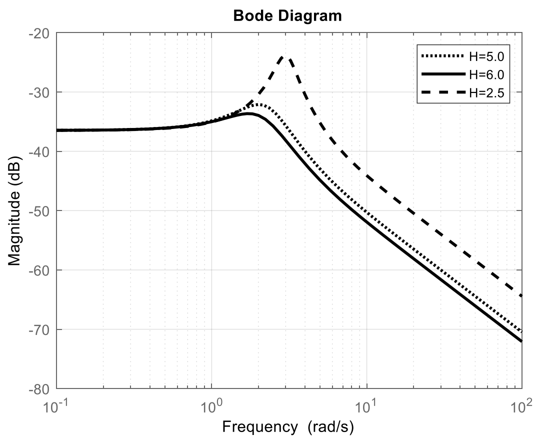

Figure 4. The results plotted in frequency response (Bode diagram)

3.3. Analysis on the frequency transient response

The transient of the dynamical frequency responses can be divided into three regions which are droop region, adaptation region and stabilize region respectively. Figure 5 shows the three regions to illustrate the level of generator responses when the system has purtubed with increased of load demand. The droop region shows the initial negative slope responses with the maximum nadir point towards the sudden changed in power deficit while the adaptation region is when the turbine system starts to change and climb its power from the initial operating point. When the turbine system successfully meets the power demand, the total power deficit will start to decrease and nearly to zero and this phenomenon can be clearly seen in the stabilize region where the transient is already reached the steady-state condition. This transient phenomenon was only covered within 10s of time interval before the frequency stated on the new operating point.

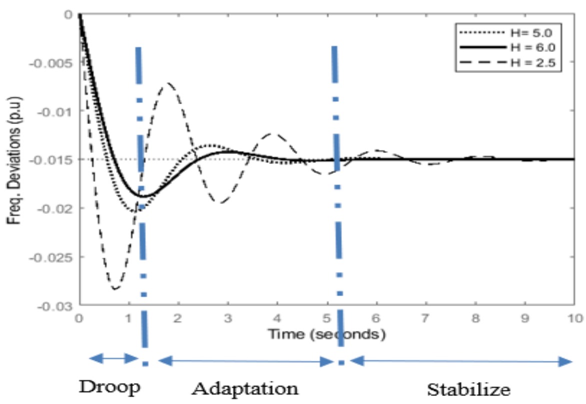

Figure 5. The three regions of dynamical frequency responses towards sudden increased of load demand

4. CONCLUSION

The state-space mathematical model for isolated electrical network with single generator has been derived without considering the automatic generation control. The augmentation of all the models consisting rotating mass, prime mover, speed governor and load has made the overall system become the third-order system. To facilitate the analysis, frequency deviation has been selected as the only state variable to be analyzed upon multifarious inertia constant parameter. According to the derived equation previously, it is observed that inertia constant is the only parameter that contributes to the transient effect. The role of the inertia towards transient stability can be clearly observed in time and frequency responses analysis. From the observations, the investigation can be concluded that the different value of inertia constant parameter may influence only to the initial transient stability of the generator's dynamical frequency response but not the steady-state.

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