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Average dynamical frequency behaviour for multi-area islanded micro-grid networks

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ABSTRACT

A micro-grid is a part of power system which able to operates in grid or islanding mode. The most important variable that able to give us information about the stability in islanded micro-grid network is the frequency dynamical responses. The frequency analysis for multi-area micro-grid network model may involve a complicated of mathematical equations. This makes the researcher intending to omit several unnecessary parameters in order to simplify the equations. The purpose of this paper is to show an approach to derive the mathematical equations to represent the average behavior of frequency dynamical responses for two different micro-grid areas. Both of networks are assumed to have non-identical distributed generator behavior with different parameters. The prime mover and speed governor systems are augmented with the general swing equation. The tie line model and the information of rotor angle was considered. Then, in the last section, the comparison between this technique with the conventional approach using centre of inertia (COI) technique was defined.

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1. INTRODUCTION

Micro-grid is a part of a power system which used an electricity sources consist dispatchable generation and non-dispatchable renewable energy that are capable of operating in either parallel or independent towards the main power grid [1-4]. Furthermore, micro-grid can operate in both grid connected and islanded mode. When the micro-grid is operates in island mode, the crucial situation is an energy balance between supply and demand because the load is dominantly supplied by the local sources. If there are any imbalance in the network, the system can lead to significant frequency deviations [5-8]. Many research work related to the micro-grid power system frequency study with variety of motivation has been done and most of them involved the large system network with multiple generators and multi area. A lot of mathematical equations has been derived to model the physical network.

The research work in [9-15] discussed about the investigation about frequency load control for the power system network with multiple connected distributed generator. The utilized of neural predictive [16] and linear quadratic regulator (LQR) method [17] in controling the frequency via multi-area microgrid system basically used the large order of mathematical equations. The power sharing and frequency control strategy via multi-area islanded power system is disccused in [18-20]. These works shows the important of frequency deviations information in order to analyse the level of stability of the network.

The complicated mathematical models are crucial to implement and make the researcher think about the way to simplify it by removing the unwanted parameter and put some assumption and approximation. These situation brings the assumption of coherent generator behaviour when the multiple generators are operating in the same area network [21]. Furthermore, same approach have been done for the multi area network with the tie line bias control which interconnected between areas [22-24]. However, the average frequency dynamical response of the whole system is defined through the center of inertia approach, and not in state-space representation [25]. This paper shows an approach to derive the state-space mathematical model of multi-area micro-grid network. The motivation of this research work is to derive and determine the evarage dynamical behaviour of frequency network by using similarity transformation and decomposition approach. The proposed micro-grid model was validated with the different load demand profile. At the end of the analysis, the comparison with the conventional approach using centre of inertia (COI) has been made.

2. RESEARCH METHOD

2.1. Generator model

The main goal is to ensure that the derived mathematical equations must be able to represent the interconnected, load sharing and frequency control. After that, one generator system was derived by using several approximation processes to represent their average behavior. Figure 1 show the interconnected of two areas of micro-grid.

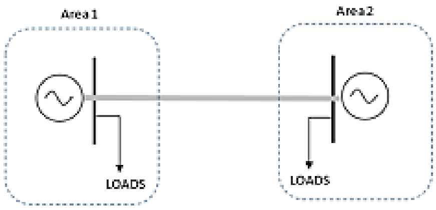

Figure 1: The interconnected of two areas of micro-grids network

The system network is assumed to have 2 busses and 2 generators while each generator is assumed to be equipped with the prime mover and speed governor. The model was divided into four main parts which are rotating mass, prime mover, speed governor and load model. Each part was modeled separately and augmented all together to become one model. The swing equation can be used to model the generator and the micro-grid network as shown in (1). This equation describes the deviations of frequency response in per unit base.

$$\frac{2H}{\omega_s}\frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e \tag{1}$$

Where ΔP_m, ΔP_e and $\Delta\omega$ are the deviations of mechanical power, electrical load demand and frequency respectively. H is the per unit inertia constant which related to the kinetic energy at the synchronous speed with respect to generator rating. The source of mechanical power for rotating mass is commonly known as the prime mover. The model for prime mover is related to the changes in mechanical power output ΔP_m to the changes in steam position ΔP_{gV}. This work, used the simplest prime mover model which can be approximated with a single time constant τ_T resulting in the following:

$$\frac{d\Delta P_m}{dt} = \frac{1}{\tau_T}\left(\Delta P_{gv} - \Delta P_m\right) \tag{2}$$

The speed governor system ΔP_{gv} is depends on the electrical load demand. When the load demand suddenly increased, the electrical load power exceeds the mechanical power and resulting the power deficiency. The amount of power deficiency will influence the amount of kinetic energy stored in the rotating system. The reduction in kinetic energy will cause the turbine speed and consequently the generator frequency to fall. 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. The equation which directly describe the speed governor behavior is as follows:

$$\frac{d\Delta P_{gv}}{dt} = \frac{1}{\tau_{gv}}\left(k\Delta P_{ref} - \frac{\Delta\omega}{R} - \Delta P_{gv}\right) \tag{3}$$

The speed governor mechanism act as the comparator whose take the different between the reference set power P_{ref} and the power $\frac{\omega}{R}$ where R is represent the slope of the curve in speed governor characteristics. k is the integrator gain constant to satisfy the rate of change of P_{ref} during automatic generation control operation. The load on a power system consists of variety of electrical devices. It can be divided into two types which are loads independent of frequency such as lighting and heating loads, and load dependent to frequency such as motor loads. The sensitivity of such loads is depends on their speed-load characteristics and can be approximately defined by:

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{4}$$

ΔP_L is the non-frequency sensitive load change and $D\Delta\omega$ is the frequency sensitive load change. D is expressed as percent change in load divide by percent change in frequency.

2.2. Modeling the two micro-grid area

2.2.1. Tie-line model

In this section, each micro-grid area was assumed to have one generator model. The complete mathematical equation for two micro-grid area take into account the information of generator rotor angle $\frac{d\delta_i}{dt} = \omega_i$. Where i is represented the number of area. This information is important to ensure the cooperative behavior between both areas in term of amount of power sharing over the tie-line. During normal operation, the real power transferred over the tie line is given by:

$$P_{ij} = \frac{|E_i||E_j|}{X_{ij}} sin\delta_{ij} \tag{5}$$

Where $X_{ij} = X_i + X_{tie} + X_j$ and $\delta_{ij} = \delta_i - \delta_j$ while i and j represent the area 1 and area 2 respectively. Linearizing this equation by assuming the small deviation in the tie line power flow ΔP_{12} from the nominal value:

$$\Delta P_{ij} = \left.\frac{dP_{ij}}{d\delta_{ij}}\right|_{\delta_{ij_0}} \Delta\delta_{ij} \tag{6}$$

$$= P_s\Delta\delta_{ij}$$

P_s is the power angle at the initial operating angle $\delta_{ij_0} = \delta_{i_0} - \delta_{j_0}$ and it was defined as the synchronizing power coefficient and then the tie line power deviation is take on the form:

$$\Delta P_{ij} = P_s(\Delta\delta_i - \Delta\delta_j) \tag{7}$$

The direction of power flow is dictated by the rotor angle difference. As shown in (7) show the example of power flows from area one to area two when ΔP_{ij} is positive. As shown in (4) and (7) can be combined into (1) to become one complete equation for rotating generator as follows:

$$\frac{d\Delta\omega_i}{dt} = \frac{1}{2H_i}\left(\Delta P_{mi} - P_s(\Delta\delta_i - \Delta\delta_j) - D_i\Delta\omega_i - \Delta P_{Li}\right) \tag{8}$$

$$\frac{d\Delta\omega_j}{dt} = \frac{1}{2H_j}\left(\Delta P_{mj} - P_s(\Delta\delta_j - \Delta\delta_i) - D_j\Delta\omega_j - \Delta P_{Lj}\right)$$

2.2.2. Tie-line bias control

The rule of thumb of micro-grid system operation connected between two areas is to ensure the whole system operating at the nominal frequency. So, this is able to consider the area control error (ACE) where each area tends to reduce the frequency error to zero. The ACE_i was integrated to have the rate of change with respect to time and its information is used as ΔP_{refi} for combine with speed governor model as shown in (3).

$$\frac{d\Delta P_{refi}}{dt} = \frac{d\Delta ACE_i}{dt} = \Delta P_{ij} + \frac{\Delta\omega_i}{R_i} + D_i\Delta\omega_i \tag{9}$$

$$= \Delta P_{ij} + \Delta B_i$$

2.2.3. State-space representation

As shown in (1-3), (8) and (9) can be written into the state-space representation. From the equation developed, each area will provide five state variables. Since it takes into account all the information required for two areas interconnection, the total state variables will become ten. The system can be represented in state space as follows:

$$\dot{x} = Ax + Bu \tag{10}$$

The matrix A and B is arranged as shown in (11) and (12).

$$A = \begin{bmatrix} -D_1/2H_1 & 0 & -P_s/2H_1 & P_s/2H_1 & 1/2H_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -D_2/2H_2 & P_s/2H_2 & -P_s/2H_2 & 0 & 1/2H_1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/\tau_{T1} & 0 & 1/\tau_{T1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1/\tau_{T2} & 0 & 1/\tau_{T2} & 0 & 0 \\ -1/\tau_{gv1}R_1 & 0 & 0 & 0 & 0 & 0 & -1/\tau_{gv1} & 0 & K_1/\tau_{gv1} & 0 \\ 0 & -1/\tau_{gv2}R_2 & 0 & 0 & 0 & 0 & 0 & -1/\tau_{gv2} & 0 & K_2/\tau_{gv2} \\ -B_1 & 0 & -P_s & P_s & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -B_2 & P_s & -P_s & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} -\frac{1}{2H_1} & -\frac{1}{2H_2} & 0 & 0 & 0 \ldots\ldots 0 \end{bmatrix}^{T(1x10)} \tag{12}$$

2.2.4. An average behavior

In this section, an average behavior was determined by using similarity transformation method. The new state variables are introduced which described the plus-minus average behavior as follows:

$$z_a = \frac{1}{2}\upsilon_1 + \frac{1}{2}\upsilon_2 \tag{13}$$

$$z_b = \frac{1}{2}\upsilon_1 - \frac{1}{2}\upsilon_2 \tag{14}$$

z is the new state variables while υ is the generator state variable. This equation would generate the transformation matrix which would be used to generate the new vector matrix. A system in previous section can be transformed to a similar system,

$$\dot{z} = TAT^{-1}z + TBu \tag{15}$$

T is the transformation matrix where the columns are the coordinates of the basis vectors of the new state vectors z space.

3. SIMULATION SETUP

Area 1 and area 2 are assumed to have different parameters as shown in Table 1 so that their behavior towards any load change is not identical.

Table 1. Parameter of two area micro-grid

Area	1	2
Speed regulation, R	0.05	0.0625
Frequency-sensitivity, D	0.6	0.9
Inertia constant, H	5	4
Governor time constant, τ_{gv}	0.2	0.3
Turbine time constant, τ_T	0.5	0.6
Integrator gain, Ki = 0.3		

By utilizing the matrix as shown in section 2.3 and 2.4, then substitute the parameters in Table 1, the state-space representation is composed and transformed into plus-minus averaging model as follows:

$$\begin{bmatrix} \omega_a \\ \delta_a \\ P_{ma} \\ P_{gva} \\ P_{refa} \\ \omega_b \\ \delta_b \\ P_{mb} \\ P_{gvb} \\ P_{refb} \end{bmatrix} = \begin{bmatrix} -0.0862 & 0 & 0.1125 & 0 & 0 & 0.0263 & 0.05 & -0.0125 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1.8350 & 1.8350 & 0 & 0 & 0 & -0.1650 & 0.1650 & 0 \\ -76.6650 & 0 & 0 & -4.1650 & 1.25 & -23.3350 & 0 & 0 & -0.8350 & 0.25 \\ -18.75 & 0 & 0 & 0 & 0 & -1.85 & 0 & 0 & 0 & 0 \\ 0.0263 & 0 & -0.0125 & 0 & 0 & -0.0862 & -0.45 & 0.1125 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.1650 & 0.1650 & 0 & 0 & 0 & -1.8350 & 1.8350 & 0 \\ -23.3350 & 0 & 0 & -0.8350 & 0.25 & -76.6650 & 0 & 0 & -4.1650 & 1.25 \\ -1.85 & 0 & 0 & 0 & 0 & -18.75 & -4 & 0 & 0 & 0 \end{bmatrix} \tag{16}$$

This is the state-space representation for describing the average behavior of two areas system. It can be seen that the state vectors of the equation are divided into two partitions which related to the plus-minus average. In order to get an average behavior of the whole network, it is possible to reduce the system order by only taking the upper half of the state vectors and state matrix and ignore the minus average model equations at the lower half of state vectors. The proposed model was tested under two conditions which are single sudden load change in area 1 with 0.2 per unit deviation. The equation is reduced as follow:

$$\dot{Z_{av}} = A_{av}Z_{av} + B_{av}u$$

$$A_{av} = \begin{bmatrix} -0.0862 & 0 & 0.1125 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1.8350 & 1.8350 & 0 \\ -76.6650 & 0 & 0 & -4.1650 & 1.25 \\ -18.75 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (17)$$

$$B_{av} = [-0.05 \;\; 0 \;\; 0 \;\; 0 \;\; 0]^T \quad (18)$$

4. RESULTS AND ANALYSIS

4.1. Simulation results for frequency dynamical behavior

Figure 2 shows the deviations of per unit frequency dynamical response under load change in area 1 respectively. From the observations, the frequency deviation in area 1 gives more oscillations compare to area 2 since the sudden load change is highly dominant in area 1. The micro-grid system in area 2 gives a back-up role to the micro-grid system in area 1. It clearly be seen that area 2 only contribute several amount of power during the first moment of load change because of small frequency deviations. This phenomenon happened due to the power flow sharing between two areas through the tie-line. Since the model considered the ACE, the system frequency of each area will go back to the nominal after several second. The average frequency response for the whole network can be seen in Figure 3.

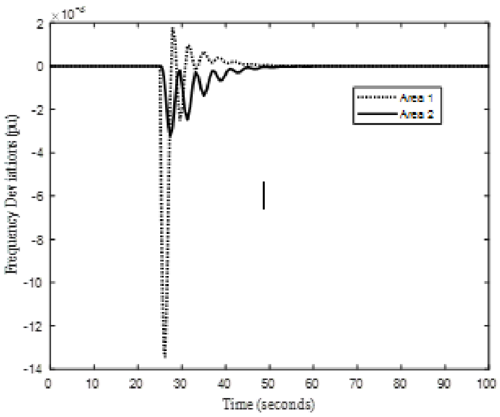

Figure 2. Dynamical frequency responses for each area networks

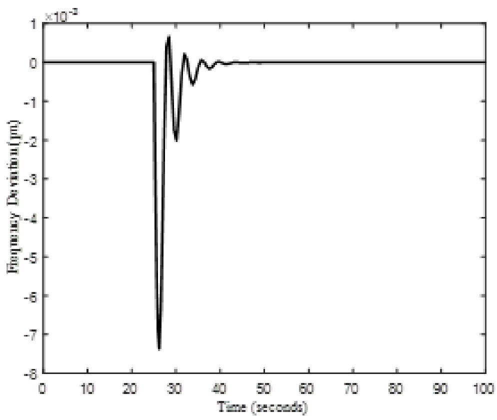

Figure 3. An average frequency deviation of the whole network.

4.2. Comparison with convetional approach

The conventional approach basically only utilizes the information of inertia constant and frequency deviations in each area to form an equation called as the center of inertia (COI) frequency.

$$\Delta\omega_{coi} = \frac{\sum_{i=1,2..} H_i\omega_i}{\sum_{i=1,2..} H_i} \quad (19)$$

Figure 4 shows the results comparison between proposed average state-space model and COI approach as shown in (19). The result shows that the proposed average state-space model yields the similar shape like the conventional. However, the proposed method gives a little bit lower oscillation and goes to steady-state faster compared to COI method.

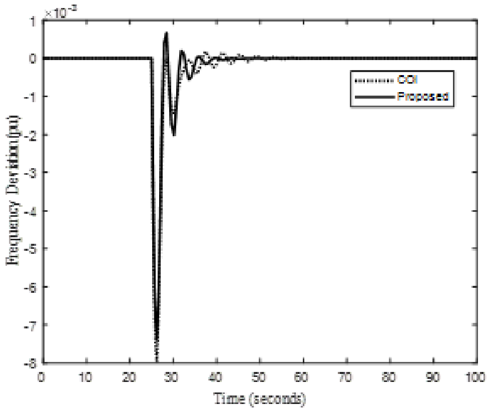

Figure 4. Comparison between proposed model and COI approach

5. CONCLUSION

The state-space mathematical model for two areas micro-grid system have been derived which considered the tie-line model and bias control. The state-space mathematical model for average frequency dynamical behaviour for the whole system have been derived by utilized the similarity transformation and model decomposition technique. Compare with the aveage frequency computed using COI approach, the results shows that the proposed technique is possible to use if the state-space representation model is needed. The proposed average model as shown in (17) is marginally stable due to the zero eigenvalue in the state matrix which would caused the feasiblity problem for the certain cases. However, this zero eigenvalue can be neglected since the other state variables does not depend on it.

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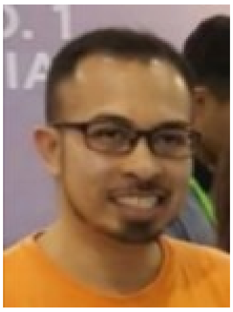

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