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A Simplified Interconnected Microgrids Frequency Response Model Using Frequency Sensitivity Approach

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***Abstract*— With growing the penetration level of distributed generators, increasing of microgrids leads to born a new structure of power grids named interconnected microgrids. Thus, new challenges such as frequency control while power is exchanged between microgrids are introduced. This study is focused on providing a simplified model for load-frequency control in interconnected microgrids. State-space equations are used for this simplification. The final model describes an interconnected microgrids frequency response framework which is suitable for study on frequency control analysis and synthesis. Both original and simplified models are tested in *MATLAB* environment and the results showed that the simplified model can operate as well as the original model. Finally, the obtained frequency response model is realized and fitted to a load-frequency control block diagram structure.**

***Index Terms*-- Interconnected microgrids, load-frequency control, modelling, state-space equations.**

I. Introduction

Increasing amounts of distributed renewable energy (RES), such as wind turbines and solar panels, has introduced a new form of power grids named microgrids [1]. Microgrids can be operated in both islanded and grid-connected modes [2]. The islanding mode creates some new challenges because microgrid in islanded mode cannot exchange power with the other grids. In this condition, if a microgrid has extra power or needs more power for its loads, power loss increases and sensitive load may damage. Interconnected microgrids provide a good solution for these challenges. Because in the interconnected microgrids power exchange between the microgrids is a possible feature.

Power-sharing between microgrids in the autonomous interconnected system has a direct effect on frequency deviations. Few researchers have addressed this issue in [3-6] and considered some control strategies for maintaining frequency at the nominal value. One of the big challenges for study on the frequency control and tie-line power exchange in interconnected microgrids is the absence of a simple and acceptable frequency response model.

Primary models for speed-governing systems and turbines in power system stability studies are performed in [7]. These models present an adequate description for hydro, fossil-fired, and pressurized water reactor nuclear units in most stability analyses. Proper hydraulic designs for a relatively wide range of studies are proposed in [8]. Besides, an experimental identification procedure based on deterministic methods with a rectangular pulse sample signal is introduced to estimate the values of model parameters. These models can be used for tuning the load-frequency control (LFC) systems as well as for organizing and setting up a real-time simulator for dispatchers training [9]. Besides, a comparative analysis of stiff and elastic tie-line models used to simulate the LFC of two-area interconnected power systems is given in [10]. It should be noted that low-inertia sources are analyzed in none of the above references. Some dynamic models are presented in [11-13], but according to [11], a dynamic model of a microgrid provides a mathematical model for the system dynamics to analyze the behavior of the whole system in different conditions. On the other hand, to realize the effect of various phenomena on the system, a dynamic model is needed. Modeling could be done for different purposes, e.g., for analyzing system behavior in a special frequency. In this approach, it is not necessary to obtain a validated model for the whole spectrum of operating frequencies. In other words, it is enough if the obtained model is validated for a special spectrum which is the main object of that study. Thus, according to this logic, a model simplification can be considered as an important component for the LFC analysis and design in the interconnected microgrids.

The present paper aims to introduce a model that is suitable for frequency response analysis in the interconnected microgrids. In this paper, the state-space model is adopted to extract the effective dynamics of the nominal frequency. First,

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state-space models of two interconnected microgrids including the interconnected line are derived, which does not include the high frequency dynamics as it is usual in the literature. Then, a simplified state-space model is obtained to propose a model for study on frequency response analysis and designing controller for the LFC in the secondary loop. Finally, a simple block diagram is presented based on the circuit analysis, and three important time constants are calculated for interconnected microgrids in the frequency response model. These parameters are T_{MG}, T_{LI}, and T_{tie} which represent microgrid, load and tie-line power time constants.

The present paper contains the following sections: First the studied system is introduced. Then the mathematical modeling is derived. In Section 3, a simplified model is proposed. In Section 4, a simple block diagram is presented for the frequency-response model. In Section 5, reachability analysis and simulations are given. Finally, the paper is concluded in Section 6.

II. SYSTEM DESCRIPTION AND MATHEMATICAL MODEL

In this section, a state-space model with more dynamic details is introduced for an interconnected system. Fig. 1 shows the schematic diagram of the studied two interconnected microgrids, which R_t, L_t, R_s, L_s, R_l, R, C, L_l, V_t, V_d, I_l, I_t and I_{IL} represent resistance and inductance of *DG*, resistance and inductance of interconnected line, resistance, inductance and capacitance of the local load, microgrid voltage, output voltage, load current, microgrid current and interconnected line current, respectively. Each microgrid includes some distributed generations connected to a local load with an *RL* line. An equivalent model could be assumed for this structure as shown in Fig. 2. According to Fig. 2, each microgrid is modeled as an equivalent *DG* with an equivalent inverter-based primary source and load. Here, each *DG* is presented by a three-phase controlled voltage source and a series *RL* branch and each load is represented by a parallel *RLC* network [11]. The interconnected line between two microgrids is represented by series *RL* elements. System parameters are selected according to the test simulated system as listed in Table 1.

Table 1. Study System Parameters.

Parameter	value	Parameter	value
$R_{eq1}(\Omega)$	10	$R_{eq2}(\Omega)$	12
$C_{eq1}(\mu F)$	24	$C_{eq2}(\mu F)$	24
$R_{eql1}(\Omega)$	5	$R_{eql2}(\Omega)$	7
$L_{eqt1}(mH)$	125	$L_{eqt2}(mH)$	128
$L_{eql1}(mH)$	35	$L_{eql2}(mH)$	40
$R_{eqs}(\Omega)$	4	$L_{eqs}(mH)$	4
$R_{eqt1}(\Omega)$	12.5	$R_{eqt2}(\Omega)$	8.3

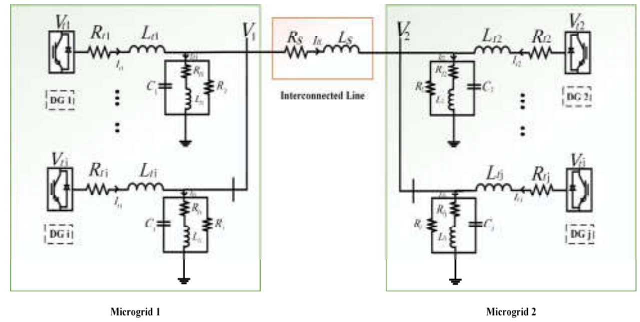


Fig. 1. Circuit schematic diagram of studied interconnected microgrids.

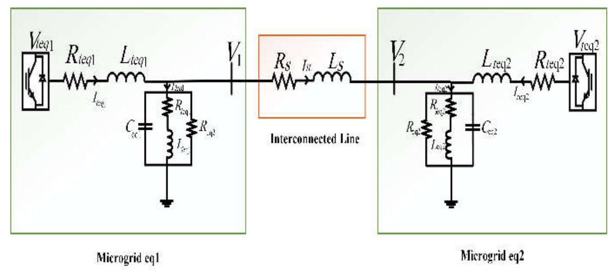


Fig. 2. Equivalent schematic of studied interconnected microgrids.

According to Fig. 2, the mathematical model of microgrid 1 in the *abc* three-phase framework base can be written as:

$$I_{eqt1}=\frac{V_1}{R_{eq1}}+I_{eql1}+C_{eq1}\frac{dV_1}{dt}+I_{eqIL}$$
$$V_{eqt1}=L_{eqt1}\frac{dI_{eqt1}}{dt}+R_{eqt1}I_{eqt1}+V_1 \quad (1)$$

For the second microgrid, since the dynamics are completely similar to the dynamics of the first microgrid, (1) can be rewritten for microgrid 2. The mathematical model of the interconnected line can be written as follows:

$$V_1=L_{eql1}\frac{dI_{eql1}}{dt}+R_{eql1}I_{eql1}$$
$$V_2=V_1-R_sI_{IL}-L_s\frac{dI_{IL}}{dt} \quad (2)$$
$$V_2=L_{eql2}\frac{dI_{eql2}}{dt}+R_{eql2}I_{eql2}$$

To find an *LTI* model, the most common method is converting the three-phase circuit equations into the *dq0* frame using the Park transformation [11]. The dynamical equations of microgrid 1 and the interconnected line in *dq0* frame can be obtained as follows:

$$
\begin{aligned}
\frac{dI_{eqt1,d}}{dt} &= \frac{1}{L_{eqt1}}\left[V_{eqt1,d} + L_{eqt1}\omega I_{eqt1,q} - \mathrm{R}_{eqt1} I_{eqt1,d} - V_{1,d}\right] \\
\frac{dI_{eqt1,q}}{dt} &= \frac{1}{L_{eqt1}}\left[V_{eqt1,q} - L_{eqt1}\omega I_{eqt1,d} - \mathrm{R}_{eqt1} I_{eqt1,q} - V_{1,q}\right] \\
\frac{dI_{IL,d}}{dt} &= \frac{1}{L_s}\left[V_{1,d} - R_s I_{IL,d} + L_s\omega I_{IL,q} - V_{2,d}\right] \\
\frac{dI_{IL,q}}{dt} &= \frac{1}{L_s}\left[V_{1,q} - R_s I_{IL,q} - L_s\omega I_{IL,d} - V_{2,q}\right] \\
\frac{dV_{1,d}}{dt} &= \frac{1}{C_{eq1}}\left[I_{eqt1,d} - \frac{V_{1,d}}{\mathrm{R}_{eq1}} - I_{eql1,d} + C_{eq1}\omega V_{1,q} - I_{IL,d}\right] \\
\frac{dV_{1,q}}{dt} &= \frac{1}{C_{eq1}}\left[I_{eqt1,q} - \frac{V_{1,q}}{\mathrm{R}_{eq1}} - I_{eql1,q} - C_{eq1}\omega V_{1,d} - I_{IL,q}\right] \\
\frac{dV_{2,d}}{dt} &= \frac{1}{C_{eq2}}\left[I_{eqt2,d} - \frac{V_{2,d}}{\mathrm{R}_{eq2}} - I_{eql2,d} + C_{eq2}\omega V_{2,q} - I_{IL,d}\right] \\
\frac{dV_{2,q}}{dt} &= \frac{1}{C_{eq2}}\left[I_{eqt2,q} - \frac{V_{2,q}}{\mathrm{R}_{eq2}} - I_{eql2,q} - C_{eq2}\omega V_{2,d} - I_{IL,q}\right]
\end{aligned} \tag{3}
$$

Similarly, the *dq0* frame-based models can be performed to construct the *state-space* model of the overall system:

$$
\begin{aligned}
\dot{x} &= Ax + Bu \\
y &= Cx
\end{aligned} \tag{4}
$$

where, u, x and y which represent inputs, states, and outputs, respectively.

$$
x^T = (I_{eqt1.d} \cdot V_{1.d} \cdot I_{eqt2.d} \cdot V_{2.d} \cdot I_{eqIL.d} \cdot I_{eql1.d} \cdot I_{eql2.d} \cdot I_{eqt1.q} \cdot V_{1.q} \cdot I_{eqt2.q} \cdot V_{2.q} \cdot I_{eqIL.q} \cdot I_{eql1.q} \cdot I_{eql2.q})
$$

$$
u^T = (V_{eqt1.d} \cdot V_{eqt2.d} \cdot V_{eqt1.q} \cdot V_{eqt2.q})
$$

$$
y^T = (V_{1.d} \cdot V_{2.d} \cdot V_{1.q} \cdot V_{2.q})
$$

The A, B and C matrices are presented in appendix A.

III. SIMPLIFIED MODEL

It is very difficult to say which model is the best in general, particularly for a non-linear system such as interconnected microgrids. Therefore, a wide choice of model structures with different orders is possible for introducing a suitable structure for the frequency response model. Based on the state-space equations of two interconnected microgrids, a new model is considered. The proposed method is implemented by two interconnected microgrids that are connected with the *RL* line and *RLC* loads. The process of this method is summarized as shown in Fig. 4. According to this flowchart, the simplified model is obtained for the system equivalent schematic diagram shown in Fig. 2. In this process, first differential equations of mentioned system are obtained, then the equations are converted to the *dq0* frame and the *A, B, C*, and *D* matrices are determined. Then, in MATLAB, the eigenvalues of the state-space matrix *A* is used for test stability of the system. In continuation, the state space of the system is calculated using the obtained matrices and the step response is analyzed for the generated state-space system. In this work, V_{1d} is assumed as the output of the system. In the next step, the fast Fourier transformation (FFT) of the state space system is calculated and the changes of the frequency spectrum in the nominal frequency range will be investigated. Using changes in the value of the parameter, the effect of each component on the frequency in the nominal range is measured. The latter two steps must be repeated. Then, we will remove the ineffective component and obtain a simplified model. Based on the results, it is clear that the R_{eq1}, R_{eq2}, C_{eq1}, and C_{eq2} have no significant effective impact on the frequency response in the interested range, thus it is possible to ignore these four components. This simplified model will be more effective in interconnected microgrids with more than two microgrids. Finally, T_{MG}, T_{LI}, and T_{tie} are obtained based on the previous analysis.

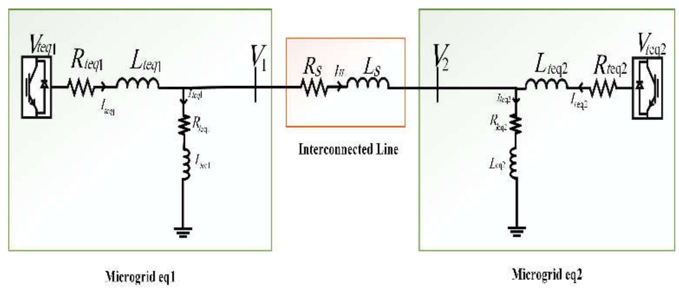


Fig. 3. Simplified schematic of studied interconnected microgrids.

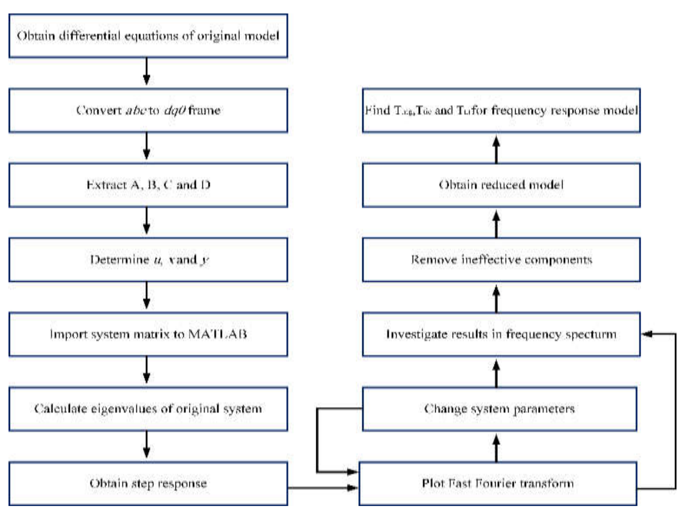


Fig. 4. Flowchart of the proposed method.

As mentioned above, introducing a simplified model for interconnected micrograms is an important step for design suitable controllers for LFC issue. The dynamic frequency response model presented in this paper is obtained based on the frequency sensitivity of the system to the parameters change and analyzing the FFT of the state-space model for the interconnected microgrids. As shown in Fig. 3, the frequency response of the interconnected microgrids is almost independent of the capacitive and resistive part of the loads.

IV. Frequency Response Model

As shown in Fig. 5, the interconnected microgrids can be divided into three distinct categories, generation part, load and inertia of the whole system and tie-line power sections. According to this division, three transfer functions with special time constants can be presented for each category.

Thus, these three regions show generation, loads and system inertia, and tie-line power sections, respectively as shown in Fig. 6. $K_{i\text{-}j}$ shows the effect of area-i frequency on area-j, Δf_i and Δf_j represent frequency deviation in area-i and area-j, respectively.

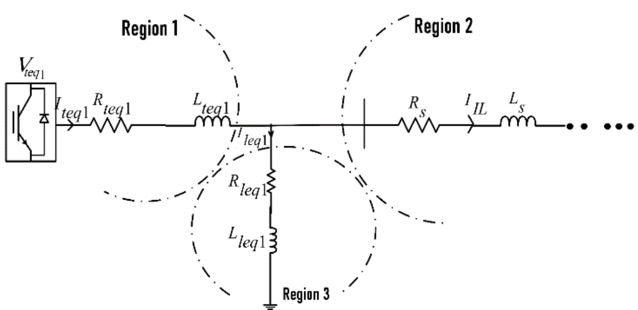


Fig. 5. Three regions of interconnected microgrids.

Therefore, three time constants are defined for these three areas.

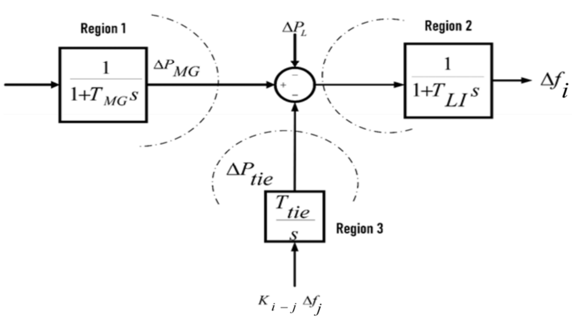


Fig. 6. Block diagram of three regions of interconnected microgrids.

These parameters are obtained as follows:

$$\begin{cases} T_{MG} = \dfrac{L_{eqt}}{R_{eqt}} \\ T_{LI} = \dfrac{L_{eql}}{R_{eql}} \\ T_{tie} = \dfrac{L_s}{R_s} \end{cases} \quad (5)$$

Based on the proposed analyzing method, a simple block diagram can be drawn as shown in Fig. 7(a). Fig. 7(b) shows this block diagram with primary and secondary control loops. Here, $T_{i\text{-}j}$ is synchronizing coefficient, R is speed droop characteristic and ß is a bias factor and its suitable value can be computed as follow [16]:

$$\beta = \frac{1}{R} + D \quad (6)$$

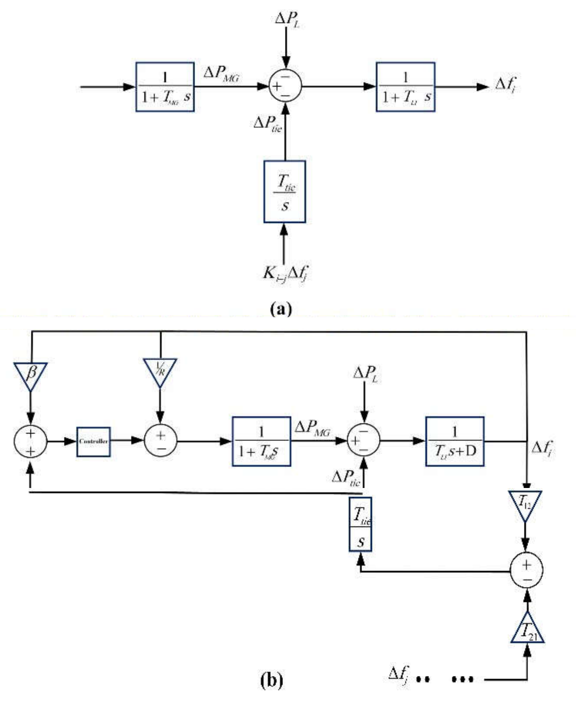


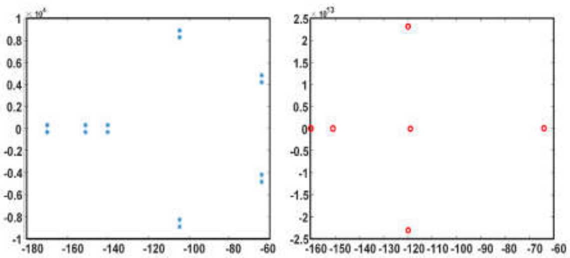
Fig. 7. Frequency response model of interconnected microgrids (a) without control layers; (b) with primary and secondary control.

V. Simulation and Results

The performed simulations are given into two different sections. In the first section, a simplified circuit model is validated in *MATLAB* environment and the frequency response model which is presented in section 4, is examined in *MATLAB/Simulink* environment.

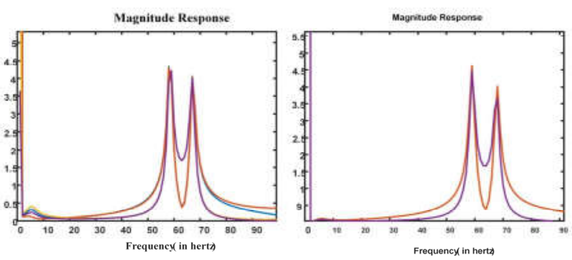
A. Simplified Circuit Model

Both original and simplified systems are modeled in MATLAB. As illustrated in Fig. 8(a) and Fig. 8(b), the eigenvalues of the original model and the simplified model are obtained. The FFT results of both models for the system outputs are shown in Fig. 9(a) and Fig. 9(b). It is clear from the FFT analysis that the proposed model has the same behavior with the original model on the interested frequency range.



a b

Fig. 8. System eigenvalues (a) original model; (b) simplified model.



(a) (b)

Fig. 9. FFT results (a) original model; (b) simplified model.

B. Frequency Response Model

The proposed model is simulated in *MATLAB/Simulink* and its performance is compared with a detailed two interconnected *AC* microgrids. Fig. 10(a) shows frequency deviation in normal condition in the detailed test system and Fig. 10(b) shows frequency deviation in normal condition for the proposed frequency response model. The dynamic behavior of both models is similar.

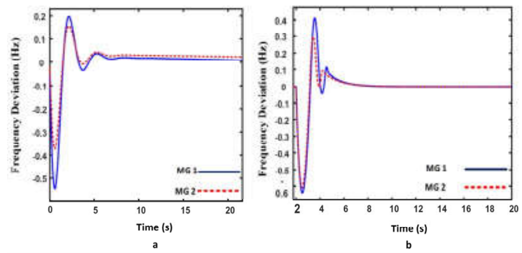


Fig. 10. Frequency deviation for ΔP_L=0.2 in t=2 s (a) test system; (b) proposed frequency response model.

VI. CONCLUSION

This study presents a simplified frequency response model for the interconnected microgrids. In particular, a simplification model by using frequency sensitivity analysis and aggregating of the model component based on the state-space equations, for reducing the model order is proposed. It is shown that the detailed models are not necessary to represent frequency response model. The methodology is tested and the result shows an acceptable performance. It is shown that the simplified model can be used to obtain a responsive frequency response model to support the LFC analysis and synthesis issues.

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Appendix

Matrices A, B and C for the system shown in Fig .2.

$$A = \begin{bmatrix}
\frac{-R_{eqt1}}{L_{eqt1}} & \frac{-1}{L_{eqt1}} & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{C_{eq1}} & \frac{-1}{R_{eq1}C_{eq1}} & 0 & 0 & \frac{-1}{C_{eq1}} & \frac{-1}{C_{eq1}} & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{-R_{eqt2}}{L_{eqt2}} & \frac{-1}{L_{eqt2}} & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{C_{eq1}} & \frac{-1}{R_{eq2}C_{eq2}} & \frac{1}{C_{eq2}} & 0 & \frac{-1}{C_{eq2}} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 \\
0 & \frac{1}{L_{eqs}} & 0 & \frac{-1}{L_{eqs}} & \frac{-R_{eqs}}{L_{eqs}} & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 \\
0 & \frac{1}{L_{eql1}} & 0 & 0 & 0 & \frac{-R_{eql1}}{L_{eql1}} & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 \\
0 & 0 & 0 & \frac{1}{L_{eql2}} & 0 & 0 & \frac{-R_{eql2}}{L_{eql2}} & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 \\
-\omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-R_{eqt1}}{L_{eqt1}} & \frac{-1}{L_{eqt1}} & 0 & 0 & 0 & 0 & 0 \\
0 & -\omega_0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_{eq1}} & \frac{-1}{R_{eq1}C_{eq1}} & 0 & 0 & \frac{-1}{C_{eq1}} & \frac{-1}{C_{eq1}} & 0 \\
0 & 0 & -\omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-R_{eql2}}{L_{eql2}} & \frac{-1}{L_{eqt2}} & 0 & 0 & 0 \\
0 & 0 & 0 & -\omega_0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_{eq2}} & \frac{-1}{R_{eq2}C_{eq2}} & \frac{1}{C_{eq2}} & 0 & \frac{-1}{C_{eq2}} \\
0 & 0 & 0 & 0 & -\omega_0 & 0 & 0 & 0 & \frac{1}{L_{eqs}} & 0 & \frac{-1}{L_{eqs}} & \frac{-R_{eqs}}{L_{eqs}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\omega_0 & 0 & 0 & \frac{1}{L_{eql1}} & 0 & 0 & 0 & \frac{-R_{eql1}}{L_{eql1}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\omega_0 & 0 & 0 & 0 & \frac{1}{L_{eql2}} & 0 & 0 & \frac{-R_{eql2}}{L_{eql2}}
\end{bmatrix}$$

$$B = \begin{bmatrix}
\frac{1}{L_{eqt1}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & \frac{1}{L_{eqt2}} & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{L_{eqt1}} & 0 \\
0 & 0 & 0 & \frac{1}{L_{eqt2}} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}$$

$$C = [0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$$