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Modeling for Oscillation Propagation With Frequency-Voltage Coupling Effect in Grid-Connected Virtual Synchronous Generator

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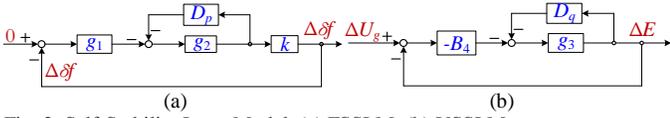


Fig. 2. Self-Stability Loop Model, (a) FSSLM, (b) VSSLM.

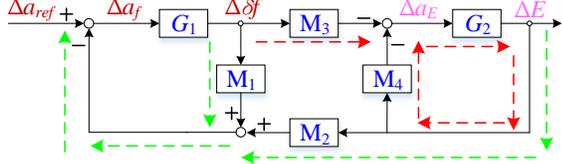


Fig. 3. Induced-Stability Loop Model.

Fig. 1 shows topology and control scheme of a grid-forming virtual synchronous generator (GF-VSG) system. PCU includes power measurement unit and low-pass filter (LPF).

By emulating the dynamic property of synchronous generator, the rotor motion equation of the VSG is depicted as:

$$\begin{cases} 4\pi^2 J_p f_g \frac{df}{dt} + 2\pi D_p \delta f = P_{rf} - P \\ J_q \frac{dE}{dt} + D_q (E - U_g) = Q_{rf} - Q \end{cases} \quad (1)$$

where J_p , D_p , J_q and D_q are control coefficients of the VSG. δf is the frequency offset (FO) between VSG and power grid while E denotes the output voltage of VSG. U_g and f_g denote the grid voltage and grid frequency, P_{rf} and Q_{rf} are the references.

The circuit model of VSG can be derived as in rotational inertial reference frame (RIRF):

$$\begin{cases} E_d - ZI_d + \omega L I_q = U \\ E_q - ZI_q - \omega L I_d = 0 \end{cases} \quad (2)$$

where

$$\begin{cases} E_d = E \cos \delta \theta \\ E_q = E \sin \delta \theta \end{cases}$$

and $Z=R+sL$, $L=L_f+L_g$, $R=R_f+R_g$, $\delta \theta$ signifies the phase difference between VSG output voltage and grid voltage. E_d , E_q , I_d and I_q are the d- and q-axis components of the VSG output voltage and the grid-tied current, indicating the current and voltage transformed into RIRF.

The active and reactive power can be obtained as:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{\omega_B}{s+\omega_B} \begin{bmatrix} I_d & I_q \\ -I_q & I_d \end{bmatrix} \begin{bmatrix} E_d \\ E_q \end{bmatrix} \quad (3)$$

where ω_B is the bandwidth of the LPF.

By combining (1), (2) with (3), the frequency acceleration and voltage acceleration can be derived as in form of FO and voltage magnitude (VM) in the form of small signal model:

$$\begin{bmatrix} \Delta a_f \\ \Delta a_E \end{bmatrix} = \begin{bmatrix} -M_1 & -M_2 \\ -M_3 & -M_4 \end{bmatrix} \begin{bmatrix} \Delta \delta f \\ \Delta E \end{bmatrix} \quad (4)$$

where M_1 , M_2 , M_3 and M_4 are the *coupling* connections FO and VM with frequency acceleration and voltage acceleration. Frequency *acceleration* is defined as rate of change of frequency (RoCoF, i.e., $a_f=df/dt$). Voltage acceleration is defined as rate of change of voltage (RoCoV, i.e., $a_E=dE/dt$).

By rearranging, see Fig. 2, the frequency self-stability loop model (FSSLM) and voltage self-stability loop model (VSSLM) can be derived as:

$$\begin{cases} G_{of} = -\frac{k g_1 g_2}{1+g_2 D_p} \\ G_{oE} = -\frac{g_3 g_4}{1+g_3 D_q} \end{cases} \quad (5)$$

where $g_2=1/(J_p \omega_n s)$, $g_3=1/(J_q s)$, $k=1/(2\pi)$. **FSSLM** is defined as the loop model that depict the coupling between RoCoF and the

frequency, not including the voltage. **VSSLM** is defined as the loop model that includes the dynamics of RoCoV and the voltage, which does not include the frequency dynamics.

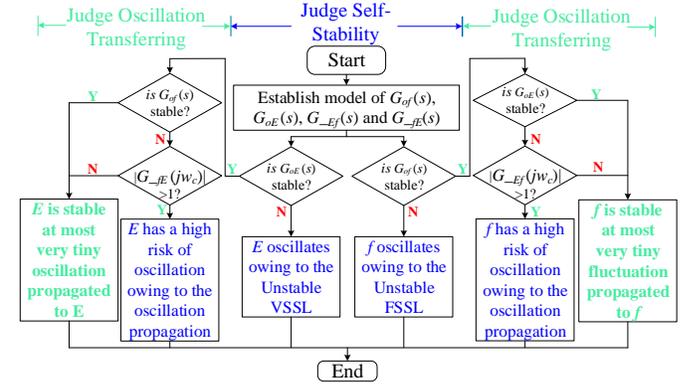


Fig. 4. Flowchart of judgment procedure of Self-Stability and oscillation propagation for frequency and voltage dynamics in VSG system.

Motivation of the proposed model: Although FSSLM and VSSLM can analyze the frequency self-stability and voltage self-stability as well as its *margin*, it is difficult to evaluate the dynamic coupling and oscillation propagation mechanism between frequency and voltage. Motivated by this, an **induced-stability-loop-model (ISIM)** is proposed to clarify the mechanism of coupling effect as well as oscillation propagation between frequency and voltage. Thus, **ISIM** can be derived as:

$$\begin{cases} G_{_Ef}(s) = -\frac{M_2 G_1}{1+M_1 G_1} \\ G_{_fE}(s) = -\frac{M_3 G_2}{1+M_4 G_2} \end{cases} \quad (6)$$

where $G_{_Ef}(s)$ is defined as the frequency ISIM (F-ISIM) and $G_{_fE}(s)$ is defined as the voltage ISIM (V-ISIM). By using the F-ISIM and V-ISIM, mechanism of oscillation propagation and coupling effect between frequency and voltage can be illustrated. A flowchart of judgment with Self-Stability and *oscillation propagation* is presented in Fig. 4.

The procedure of judgment and criterion is summarized as:

- Step 1:** To establish model of $G_{of}(s)$, $G_{oE}(s)$, $G_{_Ef}(s)$ and $G_{_fE}(s)$.
- Step 2:** To judge whether $G_{of}(s)$ and $G_{oE}(s)$ is stable or not. If $G_{of}(s)$ is stable, then jump to **Step 3.1**. Otherwise, frequency oscillation occurs owing to an unstable frequency self-stability loop (FSSL). If $G_{oE}(s)$ is stable, then jump to **Step 3.2**. Otherwise, VM oscillates due to unstable VSSL.
- Step 3.1:** The judgment results of $G_{oE}(s)$ in **Step 2** can be directly used, which do not need to re-identify again. According to the judgment results of stability of $G_{oE}(s)$ in **Step 2**, frequency stability can be identified. If it is stable, frequency is stable. Otherwise, it jumps to **Step 4.1**.
- Step 3.2:** The judgment results of $G_{of}(s)$ in **Step 2** can be used, which do not need to re-identify. Following judgment results of stability of $G_{of}(s)$ in **Step 2**, voltage stability can be identified. If it is stable, voltage is stable. Otherwise, it jumps to **Step 4.2**.
- Step 4.1:** To judge whether $|G_{_Ef}(j\omega_c)|$ is above 1 (0 dB) or not. If it is below 1, the voltage oscillation propagation has the risk of being weakened as the oscillation propagation k_{Ef} gets smaller. Otherwise, *oscillation propagation* has the risk of occurrence, causing frequency oscillation. It should be noted that this risk will be higher if the $|G_{_Ef}(j\omega_c)|$ is much lower or higher than 1 (0 dB). The critical threshold is existing if $|G_{_Ef}$

$(j\omega_c)$ is a little bit lower or higher than 1 (0 dB).

Step 4.2: To judge whether $|G_{fE}(j\omega_c)|$ is above 1 (0 dB) or not. If it is below 1, the frequency oscillation propagation has the risk of being weakened as k_{fE} gets smaller, then voltage is stable. Otherwise, *oscillation propagation* has the risk of occurrence, causing voltage oscillation. It should be noted that this risk will be higher if the $|G_{fE}(j\omega_c)|$ is much lower or higher than 1 (0 dB). The critical threshold is existing if $|G_{fE}(j\omega_c)|$ is a little bit lower or higher than 1 (0 dB).

NOTE: It is emphasized that $|G_{Ef}(j\omega_c)|=1$ and $|G_{fE}(j\omega_c)|=1$ are the critical state, which is the boundary between propagation and no propagation. Besides, there exists a threshold with the center of $|G_{Ef}(j\omega_c)|=1$ and $|G_{fE}(j\omega_c)|=1$, and within the threshold, propagation is not suppressed and amplified. **Beyond the threshold, propagation effect will be more suppressed and more amplified monotonously.** That is, the propagation effect will be greater as k_{fE} and k_{Ef} gets larger. As for k_{fE} and k_{Ef} is a little bit lower than 0 dB (within threshold), the oscillation propagation effect is of critical state inducing a tiny fluctuation. It is also emphasized that $k_{fE}>1$ or $k_{Ef}>1$ was not a standalone criterion to judge oscillation propagation because it is combined with other judgment, like ‘is G_{oE} stable’ and ‘is G_{of} stable’. And this integrity is the criterion.

B. Analysis

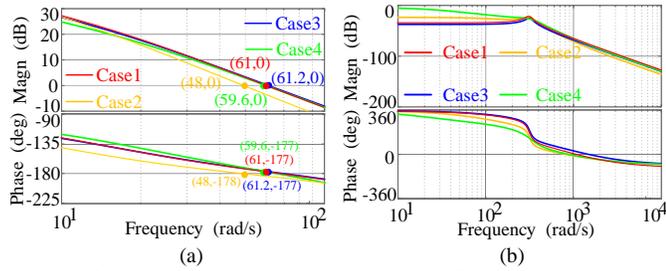


Fig. 5. Self-Stability-Loop-Model, (a) FSSLM, (b) VSSLM. (See Table I)

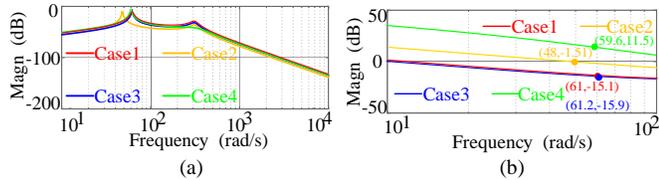


Fig. 6. ISIM, (a) F-ISIM ($G_{Ef}(s)$), (b) V-ISIM ($G_{fE}(s)$). (See Table I)

Firstly, the oscillation propagation coefficient is defined, which is acquired from F-ISIM and V-ISIM, i.e.,

$$\begin{cases} k_{Ef} = |G_{Ef}(s)|_{s=j\omega_c} \\ k_{fE} = |G_{fE}(s)|_{s=j\omega_c} \end{cases} \quad (7)$$

where k_{Ef} is defined as voltage oscillation propagation coefficient (VOPC), which can reflect the frequency induced-stability (FIS). Also here k_{fE} is defined as frequency oscillation propagation coefficient (FOPC), which can clarify the voltage induced-stability (VIS). ω_c is the critical frequency.

The occurrence of oscillation propagation to frequency has two *prerequisites*: 1) $k_{Ef}>1$ (Not a little bit larger), 2) occurrence of voltage oscillation. Occurrence of oscillation propagation to voltage has two *prerequisites*: 1) $k_{fE}>1$, 2) occurrence of frequency oscillation. There is a threshold range near $k_{Ef}/k_{fE}=1$, within which the oscillation propagation critical.

Fig. 5 shows the FSSLM and VSSLM, developed by $G_{of}(s)$

and $G_{oE}(s)$. It is seen that oscillation has the risk of occurrence in frequency due to insufficient phase margins (-3° , -2° , -3° , -3°).

While in Fig. 5(b), it suggests enough gain margins and thus voltage is stable. Following the guidelines of the criterion, it has the high risk of oscillation in the frequency, but voltage stability should be obeying FOPC.

Fig. 6(a) shows that $k_{Ef}<1$ always obeys, indicating oscillation propagation hardly occurring. However, frequency oscillation will be transferred to the voltage because of $k_{fE}>1$ in Case 4. This will induce voltage oscillation occurrence although the VSSL is stable. But oscillation propagation from the frequency is almost weakened in Case 1 to Case 3 given $k_{fE}<1$. Interesting findings from the *analysis* are obtained as:

- 1) Different from the strong coupling between active and reactive power, it has a risk that frequency oscillates but voltage is stable without oscillations at most very tiny fluctuation.
- 2) Although Voltage Self-Stability Loop is stable, the voltage will be oscillating because of the oscillation propagation from the frequency. This propagation will be new point of the study.

To provide more evidence for the justification, a supplemented analytical condition is added here to further strengthen the effectiveness of the theory.

Table I. Information on stability properties of FSSL, VSSL, FISL and VISL.

	G_{of} (FSSL)	G_{oE} (VSSL)	G_{Ef} (FISL)	G_{fE} (VISL)
Case 5	ω_c : 51.6rad/s PM: 2° GM: 1.24 dB	ω_c : no cross GM: 20.4°	ω_c : 51.7 rad/s Mag: -8.39 dB	ω_c : 51.6rad/s Mag: 12.6 dB
Case 6	ω_c : 51.5 rad/s PM: 2° GM: 1.26 dB	ω_c : no cross GM: 22.2°	ω_c : 51.7 rad/s Mag: -8.54dB	ω_c : 51.5 rad/s Mag: 1.21 dB
Case 7	ω_c : 51.5 rad/s PM: 1.8° GM: 1.26 dB	ω_c : no cross GM: 39.1°	ω_c : 51.7 rad/s Mag: -8.56 dB	ω_c : 51.5 rad/s Mag: -18 dB
Case 8	ω_c : 50.1 rad/s PM: 0° GM: 0.279 dB	ω_c : no cross GM: 19.4°	ω_c : 50.1 rad/s Mag: 5.89 dB	ω_c : 50.1 rad/s Mag: 13.9 dB

It is known that phase margins are insufficient in all the cases in Table I, which induces unstable FSSL. Especially for Case 8, phase margin is zero, indicating the occurrence of unstable oscillation in frequency. However, the FISL model shows that k_{Ef} is below 0 dB ($k_{Ef}<1$) in from Case 5 to Case 7, indicating oscillation propagation has the risk of disappearance.

Following flowchart of judgment procedure, frequency are unstable because the FSSLM approaches unstable (phase margin and gain margin are very nearly to zero) no matter how oscillation propagation behave as. It is inferred that frequency are oscillating. G_{oE} shows sufficient gain margin of VSSLM. However, due to unstable G_{of} , thus the procedure turns to the step ‘is $G_{fE}>1$ ’. $k_{fE}>1$ in Case 5, 6 and 8. Especially in Case 6, k_{fE} is approaching 1, indicating the critical state within thresholds. However, the $k_{fE}<1$ (much lower than 1) in Case 7, indicating oscillation propagation suppressed. Following judgment procedure, voltage E is stable.

Table II. Information on stability properties of FSSL, VSSL, FISL and VISL.

	G_{of} (FSSL)	G_{oE} (VSSL)	G_{Ef} (FISL)	G_{fE} (VISL)
Case 9 (red)	ω_c : 36 rad/s PM: 44° GM: 12.7 dB	ω_c : 214 rad/s PM: 7° GM: 0.861 dB	ω_c : 214 rad/s Mag: -45.5 dB	ω_c : 36 rad/s Mag: 33.7 dB
Case 10 (blue)	ω_c : 36.9 rad/s PM: 43° GM: 12.4 dB	ω_c : 221 rad/s PM: 3.8° GM: 0.466 dB	ω_c : 221 rad/s Mag: -45.5 dB	ω_c : 36.9 rad/s Mag: 33.3 dB
Case 11 (green)	ω_c : 37.3 rad/s PM: 42.3° GM: 12.1 dB	ω_c : 232 rad/s PM: 0.8° GM: 0.095 dB	ω_c : 232 rad/s Mag: -45.8 dB	ω_c : 37.3 rad/s Mag: 32.5 dB

Table II presents the corresponding stability properties and information. Table II shows the system has the sufficient phase margins and good gain margins with G_{of} . It suggests that the frequency self-stability is stable, then it turns to the **Step 3.1** to judge whether G_{oE} is stable or not. It is observed that G_{oE} has very minor phase margins and gain margins especially for the case 11, indicating seriously insufficient voltage self-stability margins. Then, it turns to the **Step 4.1** following the criteria. Then, G_{Ef} shows a low magnitude at ω_c of VSSLM, indicating the oscillation propagation can hardly happen with at most very tiny fluctuation transferred to frequency.

When observing the property of G_{fE} , it shows a propagation effect with magnitude which is above 0 dB at ω_c of FSSL model. Given the stable FSSL, thus oscillation propagation will not occur at this frequency ($\omega_c=36$ rad/s). It is inferred the voltage will oscillates with around 214 rad/s, 221 rad/s and 232 rad/s given oscillation propagation at $\omega_c=36$ rad/s will not happen.

C. Case studies

Fig. 7 shows case studies results, where the red, the blue, the green and the yellow curve represent that of Case 5, 6, 7 and 8. It is inferred simulations well validate effectiveness of the analysis because FSSL are unstable in four cases no matter how G_{Ef} behaves as. In Fig. 7(b), voltage oscillation occurs in Case 5 and 8, especially voltage oscillation in Case 8 is a little bit larger than that in Case 5. It is because gain margin in case 8 is a little bit smaller than that in Case 5 and also because that oscillation propagation effect are a little bit stronger in Case 8.

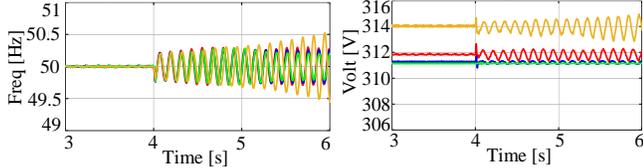


Fig. 7. Case studies, (a) frequency with four cases, (b) voltage with four cases.

In addition, voltage oscillation magnitude is approximately 0.1 V, which is a very small proportional of the steady state value of the voltage, and it can be recognized as nearly stable. It is because the oscillation propagation is only a little bit higher than 1 (0 dB), which means the oscillation propagation effect from frequency is very limited. Moreover, voltage is stable in Case 7 without any fluctuation (green). It is because the gain margin is sufficient. It is also given k_{fE} of much lower than 1.

Measured frequency of the case studies in from Case 5 to Case 8 are **8.269 Hz**, **8.352 Hz**, **8.274 Hz** and **8 Hz**, respectively, which are almost consistent with analytical values of G_{of} in Table I, e.g., **8.212 Hz**, **8.196 Hz**, **8.196 Hz** and **7.974 Hz**. It further consolidate oscillation propagation mechanism and effectiveness of the proposed modeling method.

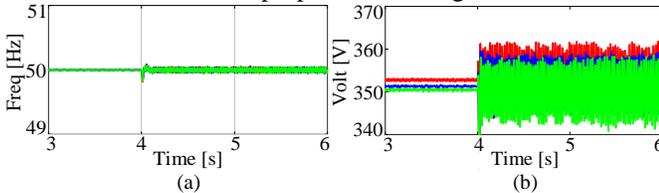


Fig. 8. Supplemented case studies, (a) frequency, (b) voltage.

Fig. 8 shows the results of the supplemented operation conditions, where Fig. 8(a) displays the frequency, and Fig. 8(b) presents the voltage. Frequency is hardly oscillating with very tiny of fluctuation below 0.04 Hz. This fluctuation takes up

approximately **0.08% of the rated frequency value**. It illustrates that voltage fluctuation is hardly propagated to the frequency. It is also seen in Fig. 8(b) that voltage fluctuates obviously, further validating the theoretical analysis.

It is noted that the parameters used in Fig. 7 and Fig. 8 are consistent with that in Table I and Table II. From case 5 to case 7, the D_q is changed. From case 9 to 11, the SCR is varying.

III. EXPERIMENTAL VALIDATION

Fig. 9 displays experiments, where the experimental setup is established based on the topology and control scheme in Fig. 1. It shows that oscillation occurs in frequency from Case 1 to 4. However, voltage maintains stable in Case 1 to 3, which is because VSSLM is stable without oscillation propagation. But it changes in Case 4, where oscillation occurs in voltage given the oscillation propagation although the VSSLM is stable.

In fact, the frequency oscillation magnitudes in case 3 and case 4 are approximately 0.5 Hz, which does not exceed 1 Hz. Indeed it is a little bit large but not very large. This is because the damping of the systems in these cases are very tiny and thus induces VSG cannot provide inertia and damping support.

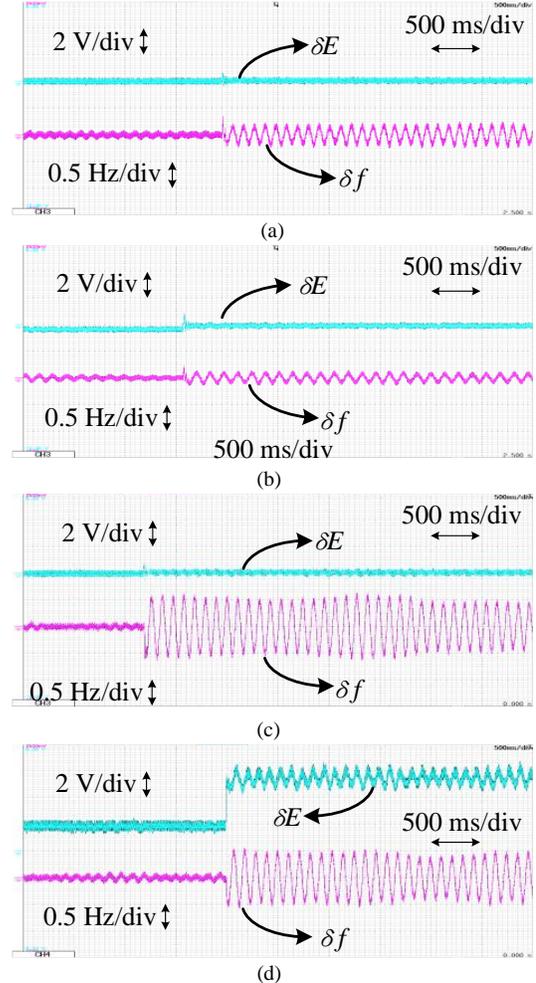


Fig. 9. Experiment results, (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4

From another perspective, as evidenced in Fig. 6(a), the frequency induced loop model shows that the peaks in Case 3 and 4 are higher than that of Case 2, it can also aggravate the frequency oscillation. Indeed, the fluctuation of 0.5 Hz has been surpassing the secure threshold value of power systems

and will impose considerable threatens to the secure operation of power systems, which is the significance of this research.

IV. CONCLUSIONS

This letter has proposed a new modeling method for the oscillation propagation in grid-forming virtual synchronous generator (GF-VSG) connected to the power network. With the modeling, mechanism of oscillation propagation between frequency and voltage was clarified from a new perspective. The main conclusions are:

- 1) Different from the conventional analytical conclusion that active- and the reactive-power are simultaneously stable or unstable due to the strong coupling effect, it was found that stability of frequency and voltage are not always the same.
- 2) It has a probability that frequency oscillates but voltage is stable without oscillation. Besides, the voltage will be oscillating although the voltage self-stability loop is stable, which is because the oscillation propagation from the frequency will impact the dynamics of voltage.
- 3) A new flowchart of the stability criterion is proposed, which finds that the oscillation propagation coefficient plays an important role in stability of the frequency and voltage.

APPENDIX

$$\begin{cases} k_{11} = ((sL + R)U_0E_0\sin\delta\theta_0 + \omega_nLU_0E_0\cos\delta\theta_0)/((sL + R)^2 + (\omega_nL)^2) \\ k_{12} = ((sL + R)(2E_0 - U_0\cos\delta\theta_0) + \omega_nLU_0\sin\delta\theta_0)/((sL + R)^2 + (\omega_nL)^2) \\ k_{21} = (-(sL + R)U_0E_0\cos\delta\theta_0 + \omega_nLU_0E_0\sin\delta\theta_0)/((sL + R)^2 + (\omega_nL)^2) \\ k_{22} = (-(sL + R)U_0\sin\delta\theta_0 + \omega_nL(2E_0 - U_0\cos\delta\theta_0))/((sL + R)^2 + (\omega_nL)^2) \end{cases}$$

$$\begin{cases} B_1 = 1.5\omega_nk_{11}/(s + \omega_n) \\ B_2 = 1.5\omega_nk_{12}/(s + \omega_n) \\ B_3 = 1.5\omega_nk_{21}/(s + \omega_n) \\ B_4 = 1.5\omega_nk_{22}/(s + \omega_n) \end{cases} \begin{cases} M_1 = (D_p s + B_1)/(J_p \omega_n s) \\ M_2 = B_2/(2\pi J_p \omega_n) \\ M_3 = 2\pi B_3/(J_q s) \\ M_4 = (B_4 + D_q)/J_q \end{cases}$$

$$\begin{cases} g_1 = -\frac{2\pi B_1}{s} \\ g_4 = -B_4 \end{cases} \quad G = \frac{B_1 - \frac{B_2 B_3}{J_q s + D_q + B_4}}{J_p \omega_n s^2 + D_p \omega_n s}$$

TABLE III. SYSTEM SPECIFICATIONS FOR ANALYSIS AND EXPERIMENTS

R_g	L_g	J_p	J_q	D_p	D_q
0.2 Ω	6.6 mH	0.035	10	154.8	10000
0.2 Ω	6.6 mH	0.057	20	157	2000
0.2 Ω	6.6 mH	0.035	10	158.6	10000
1 Ω	6.6 mH	0.035	10	206.6	200

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