

Influence of Virtual Synchronous Generators on Low Frequency Oscillations

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Abstract—By simulating the operating dynamics of synchronous generators (SGs), the use of virtual synchronous generators (VSGs) can help overcome inverter-based generators' shortcomings of low inertia and minimal damping for grid-forming applications. VSGs' stability are very important for their solar and wind electricity applications. Currently, the related research primarily focuses on VSGs and their applications for microgrids. There has been little research to explore how VSGs effect low frequency oscillations in power transmission systems. This paper describes a small-signal model of a VSG-SG interconnected system, which is suitable for studying low frequency oscillation damping in a power transmission grid. Based on this model, the effects of VSGs on low frequency oscillations are compared with the effects of SGs to reveal the mechanism of how VSGs influence damping characteristics. The influence of each VSG control loop on oscillations is also analyzed in this paper. Then, the low frequency oscillation risks with different types of VSGs are described. Finally, experiments on a real-time laboratory (RT-LAB) platform are conducted to verify the small-signal analysis results.

Index Terms—Grid-forming inverters, low frequency oscillation, participation factor, renewable electricity, small-signal model, virtual synchronous generator (VSG).

I. INTRODUCTION

IN recent years, the penetration of distributed sources connected to electric grids using inverters has continued to increase in electric power systems [1]. These inverter-based generators (IGs) are connected to grids through power electronic inverters [2], which do not contribute inertia and damping as do traditional wound-field synchronous generators. They consequently tend to have negative impacts on the dynamics and stability of power systems [3], [4]. For this reason, scholars have proposed virtual synchronous generators (VSGs) [5], which emulate the operating dynamics of

synchronous generators (SGs) [6], [7]. However, in emulating SGs, VSGs inherit their problems with small-signal stability and low frequency oscillations [8].

The existing research on the stability of a VSG can be divided into two main categories. The first category is analysis of the damping characteristics of VSGs when they are connected to infinite buses. These studies primarily focus on the stability and control of a VSG itself. For example, [9] described the influence of VSG control parameters on damping characteristics when a VSG is applied in one-machine infinite bus power systems. The results show that the inertia of the VSG has little influence on its stability, and the frequency modulation coefficient is the key factor determining its damping. In [10], a new decoupling control algorithm was designed based on a linearized model of a one-VSG infinite bus system to achieve independent control of the VSG's active and reactive power components. In [11], the control of a VSG and its virtual inertia was studied in terms of its effects on system stability based on a small-signal linearized model.

The second category of existing research concentrates on VSGs' stability in microgrid systems. For example, [12] discussed the power oscillation problems that can occur when VSG technology is applied in a microgrid. This research analyzed the influence of inertial time constants and damping coefficients on system damping. In [13], an improved VSG control method based on an adaptive inertia scheme was proposed for stabilizing multiple power sources in a microgrid [14] summarized the influences of the primary frequency regulation (PFR) coefficient, inertial time constant, and virtual resistance and virtual reactance on the damping of a microgrid where VSG technology was used.

In summary, the stability of VSGs and their application to microgrids have been extensively researched, and verified by various methods such as small-signal analysis, impedance analysis, and time domain simulation [15]. However, the study of VSGs' influence on low frequency oscillations in transmission systems, such as inter-area oscillations, still faces the following challenges:

1) Because existing research on VSGs' stability has been primarily conducted for one-machine infinite bus systems and for microgrids, the current investigation primarily focuses on the oscillation mode of the VSG itself and its impact on the system-level damping characteristics of microgrids. The mechanism of how VSGs influence inter-area low frequency oscillations needs to be clarified based on a new sample system.

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2) The existing small-signal and impedance models of VSG units ignore their governor characteristics. This simplification has little effect on the traditional subsynchronous and supersynchronous and high frequency damping characteristics. However, it causes significant errors when such models are applied to investigate ultra-low frequency or low frequency oscillations.

This paper develops a small-signal model of VSG units which considers the governor characteristics. The mathematic model of a two-area system, consisting of a VSG and a SG (VSG-SG system), was developed for this study. The mechanism of how VSGs effect inter-area low frequency oscillations was studied. The main contributions are as follows:

1) A small-signal model of a VSG governor was developed, and the differences in the governor between different VSG implementation schemes were refined. Applications included a wind turbine VSG based on pitch control, wind turbine VSG based on overspeed control, photovoltaic VSG based on MPPT control, and a battery storage VSG. The low frequency oscillation characteristics of the system with different VSG implementation schemes were studied. The low frequency oscillation risks of different VSG implementation schemes were analyzed.

2) A small-signal model of a VSG-SG system was constructed. It is suitable for analysis of inter-area low frequency oscillations' damping characteristics. Based on this, the effects of the VSG and SG on the low frequency oscillation modes are compared to reveal the mechanism of how VSGs effect

low frequency oscillation on large-scale power grids.

II. SMALL-SIGNAL MODEL OF A VSG-SG SYSTEM

An overview of the VSG-SG system studied is shown in Fig. 1. Below the dash-dot line, Fig. 1 shows the electrical system, where the VSG is connected to the grid at the point of common coupling (PCC1) through an LC filter. This filter is composed of the filter inductor L_g and capacitor C_g . The VSG and filter constitute the grid sending-end. The SG is connected to the PCC of the receiving-end grid (PCC2) through the transformer (represented by R_{Tran} and L_{Tran}). The sending-end and receiving-end grid connections are via two 220 kV overhead lines (220 km). Under normal operating conditions, the VSG and SG each generate 800 MW to supply the 1600 MW load (R_{load}) in the receiving-end grid.

The control system of the VSG, which is above the dash-dot line in Fig. 1, includes four parts: the governor, outer loop control, virtual impedance control, and the inner loop control.

The state equations of the receiving-end grid, overhead line, sending-end grid, and the VSG control system are introduced in order. The state equations of each part will be combined to form the small-signal VSG-SG system model.

A. State-space Model of the Receiving-end System

Based on Fig. 1, the receiving-end grid is composed of the 900 MVA SG and the 1600 MW load. The state-space equations are:

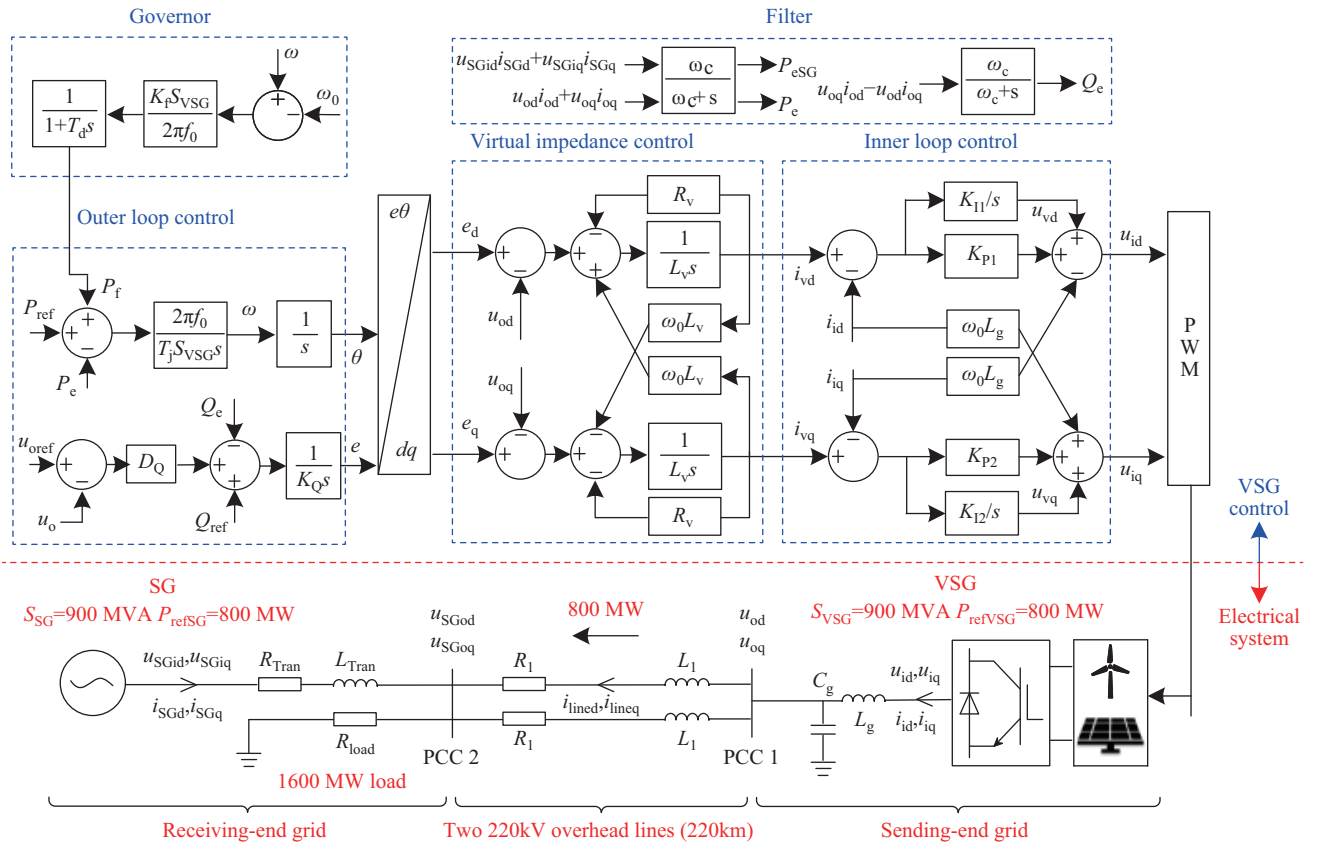


Fig. 1. The studied VSG-SG system.

$$\begin{cases} \frac{d\omega_{SG}}{dt} = \frac{2\pi f_0}{S_{SG}} (P_{refSG} - P_{eSG}) + P_{fSG} \\ d\theta_{SG}/dt = \omega_{SG} \end{cases} \quad (1)$$

$$\begin{cases} \frac{di_{SGd}}{dt} = \frac{1}{L_{Tran}} (\omega_0 L_{Tran} i_{SGq} + u_{SGid} - u_{SGod} - R_{Tran} i_{SGd}) \\ \frac{di_{SGq}}{dt} = \frac{1}{L_{Tran}} (-\omega_0 L_{Tran} i_{od} + u_{SGiq} - u_{SGoq} - R_{Tran} i_{SGq}) \end{cases} \quad (2)$$

$$\begin{cases} 2i_{lined} = -i_{SGd} + u_{SGod}/R_{load} \\ 2i_{lineq} = -i_{SGq} + u_{SGoq}/R_{load} \end{cases} \quad (3)$$

where ω_{SG} and θ_{SG} are the angular frequency and phase angle of the SG voltage, T_{jSG} is the inertial time constant, P_{eSG} is the output electromagnetic power of the SG, S_{SG} is the rated capacity of the SG, f_0 is the nominal frequency (50 Hz), ω_0 is the nominal angular frequency, P_{refSG} is the set value for the active power, P_{fSG} is the primary frequency regulation (PFR) power, u_{SGid} and u_{SGiq} are the SG voltages in the dq frame, i_{SGd} and i_{SGq} are the SG output current in the dq frame, u_{SGod} and u_{SGoq} are the voltages at PCC2 in the dq frame, i_{lined} and i_{lineq} are the current in the 220 kV overhead line in the dq frame, and R_{load} is the resistance of 1600 MW load.

B. State-space Model of the Overhead Line

The parameters of both 220 kV overhead lines are the same. The state-space model is:

$$\begin{cases} \frac{di_{lined}}{dt} = \frac{1}{L_l} (\omega_0 L_l i_{lineq} + u_{od} - u_{SGod} - R_l i_{lined}) \\ \frac{di_{lineq}}{dt} = \frac{1}{L_l} (-\omega_0 L_l i_{lined} + u_{oq} - u_{SGoq} - R_l i_{lineq}) \end{cases} \quad (4)$$

where R_l and L_l are resistance and inductance of each 220 kV overhead line, and u_{od} and u_{oq} are the voltages of PCC1 in the dq frame.

C. State-space Model of the Sending-end System

As shown in Fig. 1, the sending-end grid is composed of the 900MVA VSG and filter. The state-space model is:

$$\begin{cases} \frac{di_{id}}{dt} = \frac{1}{L_g} (\omega_0 L_g i_{iq} + u_{id} - u_{od}) \\ \frac{di_{iq}}{dt} = \frac{1}{L_g} (-\omega_0 L_g i_{id} + u_{iq} - u_{oq}) \end{cases} \quad (5)$$

$$\begin{cases} \frac{du_{od}}{dt} = \frac{1}{C_g} (\omega_0 C_g u_{oq} + i_{id} - 2i_{lined}) \\ \frac{du_{oq}}{dt} = \frac{1}{C_g} (-\omega_0 C_g u_{od} + i_{iq} - 2i_{lineq}) \end{cases} \quad (6)$$

where u_{id} , u_{iq} , i_{id} , and i_{iq} are the output voltages and currents of the VSG in the dq reference frame.

D. State-space Model of the Outer Loop Control

The outer loop control in Fig. 1 includes two parts: the active and reactive outer loop, whose state-space equations

are (7) and (8) respectively:

$$\begin{cases} \frac{d\omega}{dt} = \frac{2\pi f_0}{T_j S_{VSG}} (P_{ref} - P_e + P_f) \\ \frac{d\theta}{dt} = \omega \end{cases} \quad (7)$$

$$\frac{de}{dt} = \frac{D_Q (u_{oref} - \sqrt{u_{od}^2 + u_{oq}^2}) - Q_e + Q_{ref}}{K_Q} \quad (8)$$

where ω and θ are the angular frequency and phase angle of the VSG voltage, T_j is inertial time constant of the VSG, P_e is the output electromagnetic power of the VSG, P_f is the PFR power, S_{VSG} is the rated capacity of the VSG, P_{ref} is active power setting, e is the VSG voltage, K_Q is the voltage regulation coefficient, D_Q is the reactive power droop constant, Q_e is the output reactive power of the VSG, Q_{ref} is the set value of reactive power and u_{oref} is the set value of voltage.

E. State-space Model of the Governor

When VSG technology is applied, there are many implementation schemes. They include a wind turbine VSG based on pitch control, a wind turbine VSG based on overspeed control, a photovoltaic VSG based on MPPT control, and a battery storage VSG. The main differences between the above four implementation schemes are their PFR response speed (how fast the P_f can track the change of system frequency). For example, in the VSG based on pitch control, the response time of the PFR is about 3~8 s (affected by the pitch control speed), and the response time lag of PFR in the VSG based on overspeed control is about 0.5~2 s. Based on the above results, the governor model was developed. This led to the diagram shown in Fig. 1, which reflects the frequency modulation speed of the VSG. The specific state equation is:

$$\frac{dP_f}{dt} = \frac{1}{T_d} \left(\frac{K_f S_{VSG}}{2\pi f_0} (\omega - \omega_0) - P_f \right) \quad (9)$$

where K_f is the primary frequency regulation droop coefficient, and T_d is the response time of PFR.

According to the state equation for the VSG governor, a similar state equation of the SG governor is given as follows:

$$\frac{dP_{fSG}}{dt} = \frac{1}{T_{dSG}} \left(\frac{K_{fSG} S_{SG}}{2\pi f_0} (\omega_{SG} - \omega_0) - P_{fSG} \right) \quad (10)$$

where K_{fSG} is the PFR droop coefficient, and T_{dSG} is the response time of PFR of SG.

F. State-space Virtual Impedance Control Model

The virtual impedance control in Fig. 1 can simulate the stator resistance and leakage reactance of a SG. The corresponding state equation is:

$$\begin{cases} \frac{di_{vd}}{dt} = \frac{1}{L_v} (e_d - u_{od} + \omega_0 L_v i_{vq} - R_v i_{vd}) \\ \frac{di_{vq}}{dt} = \frac{1}{L_v} (e_q - u_{oq} - \omega_0 L_v i_{vd} - R_v i_{vq}) \end{cases} \quad (11)$$

where i_{vd} and i_{vq} denote the integrator states for virtual impedance control, and e_d and e_q are VSG voltages in dq frame, L_v and R_v are the virtual inductance and resistance.

G. State-space Model of the Inner Loop Control

The state and output equations of the inner loop control, which is shown in Fig. 1, are given by:

$$\begin{cases} \frac{du_{vd}}{dt} = K_{I1} (i_{vd} - i_{id}) \\ \frac{du_{vq}}{dt} = K_{I2} (i_{vq} - i_{iq}) \end{cases} \quad (12)$$

$$\begin{cases} u_{id} = u_{vd} + K_{P1} (i_{vd} - i_{id}) - \omega_0 L_g i_{iq} \\ u_{iq} = u_{vq} + K_{P2} (i_{vq} - i_{iq}) + \omega_0 L_g i_{id} \end{cases} \quad (13)$$

where u_{vd} and u_{vq} denote the integrator states of the PI controller in the inner loop control, and K_{P1} , K_{P2} , K_{I1} , and K_{I2} represent the proportional and integral coefficients in the PI controller.

H. State-space Filter Processing Model

Values for P_{eSG} , P_e , and Q_e of SG and VSG are obtained by filtering the instantaneous power. The instantaneous power is calculated using the voltages and currents of SG and VSG. The state equations of the filter are:

$$\begin{cases} dP_{eSG}/dt = \omega_c (u_{SGid} i_{SGd} + u_{SGiq} i_{SGq} - P_{eSG}) \\ dP_e/dt = \omega_c (u_{od} i_{od} + u_{oq} i_{oq} - P_e) \\ dQ_e/dt = \omega_c (u_{oq} i_{od} - u_{od} i_{oq} - Q_e) \end{cases} \quad (14)$$

where ω_c is the cut-off frequency of the applied filter.

I. Small-signal Model of the VSG-SG System

By combining (1)–(14), a state-space model of the VSG-SG system can be developed [16]. The corresponding linearized small-signal model can be built from the state-space model and defined by the general form given by (15):

$$\Delta \dot{\mathbf{x}} = \mathbf{A} \Delta \mathbf{x} + \mathbf{B} \Delta \mathbf{u} \quad (15)$$

where $\Delta \mathbf{x} = [\Delta i_{SGid}, \Delta i_{SGiq}, \Delta \omega_{SG}, \Delta \theta_{SG}, \Delta i_{lined}, \Delta i_{lineq}, \Delta i_{id}, \Delta i_{iq}, \Delta u_{od}, \Delta u_{oq}, \Delta i_{od}, \Delta i_{oq}, \Delta \omega, \Delta \theta, \Delta e_d, \Delta i_{vd}, \Delta u_{vd}, \Delta i_{vq}, \Delta u_{vq}, \Delta P_{eSG}, \Delta P_e, \Delta Q_e, \Delta P_{fSG}, \Delta P_f]^T$ and $\Delta \mathbf{u} = [\Delta u_{oref}, \Delta P_{ref}, \Delta Q_{ref}]^T$.

The model defined by (15) expresses the characteristics for small-signal deviations around the point of the linearization. Therefore, the states ($\mathbf{x}$) and input ($\mathbf{u}$) are denoted by Δ .

III. ANALYSIS OF LOW FREQUENCY OSCILLATIONS

Based on the small-signal model of the VSG-SG system, the key system parameters are shown in Table I. The rated capacity and voltage use to calculate the values in p.u. 900 MW and 220 kV. For the operating conditions at $P_{ref} = 800$ MW, $Q_{ref} = 0$ MVar for the VSG. All the eigenvalues of the system can be calculated. Participation factors are also analyzed to obtain the main related state variables for every eigenvalue [17]. The resulting eigenvalues are given in Table II.

Based on the participation factors, the eigenvalues λ_{21-22} correspond to the inter-area low frequency oscillation mode. The low frequency oscillation mode is one of the modes with a small damping ratio. The following sections focus on the effects of various parameters on λ_{21-22} .

TABLE I
PARAMETERS OF THE STUDIED SYSTEM

Parameter	Value	Parameter	Value	Parameter	Value
S_{SG}/MVA	900	P_{refSG}/MW	800	Q_{refSG}/kvar	0
S_{VSG}/MVA	900	P_{ref}/MW	800	Q_{ref}/kvar	0
K_{fSG}	30	K_f	30	$L_g/\text{p.u.}$	0.24
T_{dSG}/s	0.5	T_d/s	0.1	$C_g/\mu\text{F}$	60
T_{iSG}/s	12	$R_{SG}/\text{p.u.}$	3e-5	$L_{SG}/\text{p.u.}$	6e-6
T_i/s	12	$R_v/\text{p.u.}$	9e-3	$L_v/\text{p.u.}$	3e-3
K_{P1}, K_{I2}	0.64	K_{I1}, K_{I2}	100	ω_c/Hz	10

TABLE II
SYSTEM EIGENVALUE

No.	Oscillation frequency/Hz	Damping ratio	State variables of highly sensitive
λ_{1-2}	4721	0.06	u_{od}, u_{oq}
λ_{3-4}	4640	0.06	i_{vd}, i_{vq}
λ_{5-6}	49.5	0.56	i_{od}, i_{oq}
λ_{7-8}	47.9	0.54	i_{iSGd}, i_{iSGq}
λ_{9-10}	1.37	1	i_{dd}, i_{iq}
λ_{11-12}	0.83	0.75	ω_{SG}, δ_{SG}
λ_{13-14}	0.4	1	P_e, Q_e
λ_{15-16}	0	1	i_{lined}, i_{lineq}
λ_{17-18}	0	1	e_d
λ_{19-20}	0	1	P_{eSG}, Q_{eSG}
λ_{21-22}	2	0.12	$\omega_{SG}, \omega_{VSG}$
λ_{23-24}	0	1	u_{vd}, u_{ovq}

A. Impact of the Inertial Time Constant

The inertial time constants of the VSG and SG (T_j and T_{jSG}) are defined in (9) and (1). The inter-area low frequency oscillation eigenvalue (λ_{21-22}) trajectories with T_j or T_{jSG} , swept from 1 s to 30 s, are shown in Fig. 2.

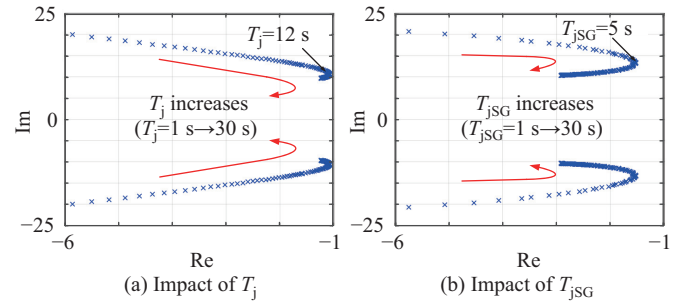


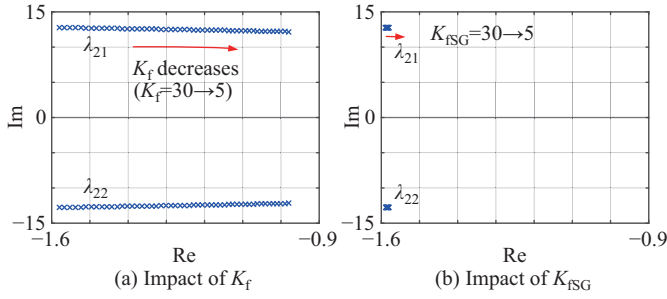
Fig. 2. Impacts from T_j and T_{jSG} on λ_{21-22} .

In Fig. 2(a), we can observe that λ_{21-22} move monotonically toward the right as T_j increases from 1 s to 12 s, indicating that the damping of low frequency oscillation modes decreases rapidly. When T_j is greater than 12 s, λ_{21-22} will move to left for increasing values of T_j . The influence of T_{jSG} on λ_{21-22} is similar to the influence of T_j . The complex values of λ_{21-22} will first move toward the right with increasing T_j and then move towards the left when T_{jSG} is bigger than 5 s.

B. PFR Coefficient Impact

The PFR coefficient of the VSG and SG (K_f and K_{fSG}) are defined by (9) and (1). The inter-area low frequency oscillation eigenvalue (λ_{21-22}) trajectories, with K_f or K_{fSG} swept from 30 to 5, are shown in Fig. 3.

From Fig. 3(a), it is observed that λ_{21-22} monotonously moves toward the right as K_f decreases. This indicates a rapid

Fig. 3. Impacts from K_f and K_{ISG} on λ_{21-22} .

decrease in damping. However, λ_{21-22} is insensitive to changes in K_{ISG} , which implies that the low frequency oscillation is not influenced by K_{ISG} .

C. Reasons for the Differences between the Low Frequency Oscillation Characteristics of VSGs and SGs

According to Figs. 2 and 3, the inertial time constants of the VSG and SG have basically the same effect on low frequency oscillations, but the influences of K_f and K_{ISG} are different. To understand the reasons for this difference, the participation factors of state variables for low frequency oscillation mode were studied. The values of the participation factors represent the impacts from each state variable on eigenvalue λ_{21-22} [17]. The method to calculate participation factors is given in [18]. The specific results (normalized participation factors) are shown in Table III.

TABLE III
PARTICIPATION FACTORS FOR LOW FREQUENCY OSCILLATION MODE

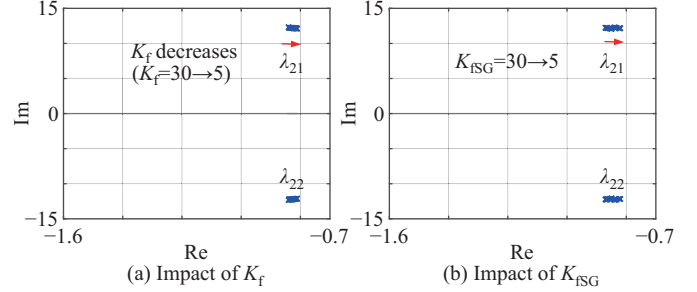
State variable	Participation factor	State variable	Participation factor	State variable	Participation factor
$\Delta\omega_{SG}$	0.1992	$\Delta\delta_{SG}$	0.1872	ΔP_{eSG}	0.0385
$\Delta\omega$	0.2486	$\Delta\delta$	0.2037	ΔP_e	0.0419
ΔP_{ISG}	0.0146	Δi_{SGid}	$< 1e-4$	Δi_{id}	$< 1e-4$
ΔP_f	0.0634	Δi_{SGiq}	$< 1e-4$	Δi_{iq}	$< 1e-4$
Δu_{od}	$< 1e-4$	Δu_{vd}	$< 1e-4$	Δi_{ined}	$< 1e-4$
Δu_{oq}	$< 1e-4$	Δi_{vq}	$< 1e-4$	Δi_{ineq}	$< 1e-4$
Δi_{od}	$< 1e-4$	Δe_d	$< 1e-4$	Δu_{vq}	$< 1e-4$
Δi_{oq}	$< 1e-4$	Δi_{vd}	$< 1e-4$	ΔQ_e	$< 1e-4$

In the results, the low frequency oscillation mode is primarily related to the angular frequency, phase angle, electromagnetic power, and PFR power (ΔP_f , ΔP_{ISG}) of the VSG and SG. The participation factor of ΔP_f (0.0634) is about 4.3 times the participation factor of ΔP_{ISG} (0.0146). This indicates that the low frequency oscillation mode is much more affected by the VSG PFR function than it is by the SG PFR. This is why the influence of the VSG PFR coefficient on λ_{21-22} is larger than the influence of the SG PFR coefficient.

1) Impact of PFR Speed

By comparing (9) and (10), it can be seen that when the capacity and PFR coefficient of a VSG are the same as the corresponding values of an SG, the difference in the PFR response times between the VSG and SG (T_d , T_{dSG}) may be the key factor leading to differences in participation factors between ΔP_f and ΔP_{ISG} . The results in Fig. 3 and Table III were calculated based on the assumption that $T_d = 0.1$ s and $T_{dSG} = 0.5$ s (as shown in Table I). Assuming that the VSG

and SG's governor have the same response time ($T_d = 0.5$ s, $T_{dSG} = 0.5$ s) and recalculating the effects of K_f and K_{ISG} on λ_{21-22} (as shown in Fig. 4), we can calculate the participation factors of λ_{21-22} (as shown in Table IV). In Table IV, PF_{PeSG} represents the participation factor of the state variable ΔP_{eSG} with respect to the low frequency oscillation mode.

Fig. 4. Impacts from K_f and K_{ISG} on λ_{21-22} .

As Fig. 4 shows, when the governor response times of the VSG and SG are the same, the influences of K_f and K_{ISG} on low frequency oscillations are similar. The comparison between Fig. 4 and Fig. 3 indicate that the inconsistency of the governor response times between VSGs and SGs are an important reason for the differences in low frequency oscillation characteristics between VSG and SG. Meanwhile, results in Table IV clarify that when the response time of the governor of VSG is one fifth that of an SG ($T_d = 0.1$ s, $T_{dSG} = 0.5$ s), the participation factor of ΔP_f (PF_{Pf}) is 4.3 times that of ΔP_{ISG} (PF_{PISG}). When $T_d = T_{dSG} = 0.5$ s, PF_{Pf} and PF_{PISG} are basically the same, showing that the inconsistency of governor response speeds of VSGs and SGs is a key factor leading to the differences in their low frequency oscillation characteristics.

TABLE IV
PARTICIPATION FACTORS FOR STUDIED OSCILLATION MODE WHEN T_d CHANGES

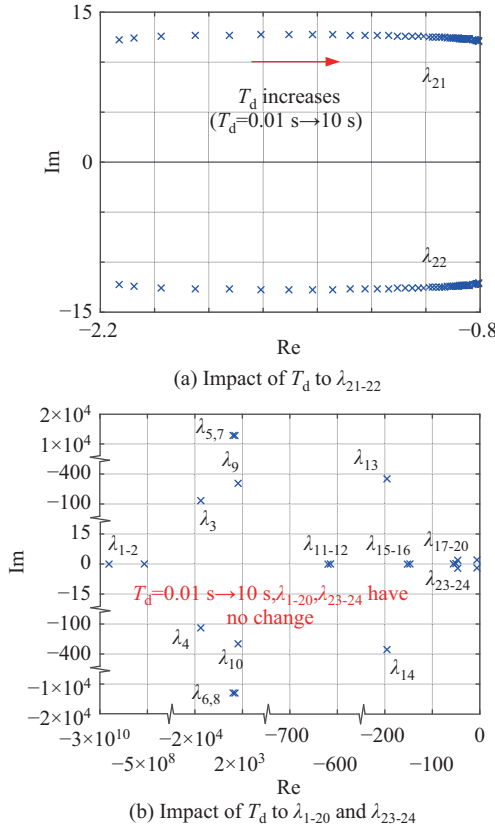
$T_d = 0.1$ s, $T_{dSG} = 0.5$ s				$T_d = 0.5$ s, $T_{dSG} = 0.5$ s			
Participation factor	Participation factor	Participation factor	Participation factor	Participation factor	Participation factor	Participation factor	Participation factor
PF_{PeSG}	0.0385	PF_{PISG}	0.0146	PF_{PeSG}	0.0429	PF_{PISG}	0.0181
PF_{Pe}	0.0419	PF_{Pf}	0.0634	PF_{Pe}	0.0407	PF_{Pf}	0.0172
$PF_{\omega SG}$	0.1992	$PF_{\delta SG}$	0.1872	$PF_{\omega SG}$	0.2305	$PF_{\delta SG}$	0.2200
PF_{ω}	0.2486	PF_{δ}	0.2037	PF_{ω}	0.2186	PF_{δ}	0.2090

The results in Table IV and Fig. 4 indicate that when T_d is changed from 0.1 s to 0.5 s, the participation factor of ΔP_f is reduced by 73%, and the influence from K_f to λ_{21-22} is also significantly reduced. This proves that increasing the VSG governor's response time will weaken the influence of VSG PFR functions on low frequency oscillations.

2) Risk Analysis of Low Frequency Oscillations in Different VSG Implementation Schemes

Based on Section 3.3.2, T_d affects the low frequency oscillation characteristics of the VSG-SG system. The inter-area low frequency oscillation eigenvalue (λ_{21-22}) trajectories with T_d swept from 0.01 s to 10 s are given in Fig. 5.

In Fig. 5, it can be seen that λ_{21-22} monotonically moves toward the right when T_d increases. The other eigenvalues are

Fig. 5. Impact from T_d to λ_{21-24} .TABLE V
PARTICIPATION FACTORS FOR LOW FREQUENCY OSCILLATIONS

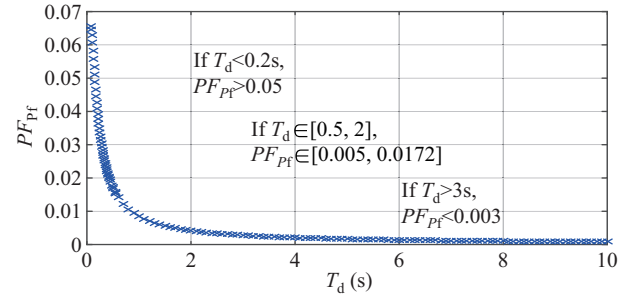
VSG implementation schemes	T_d
Wind turbine VSG based on pitch control	3~8 s
Wind turbine VSG based on overspeed control	0.5~2 s
Photovoltaic VSG based on MPPT control	0.5~1.5 s
Battery storage VSG	0.1~0.5 s

insensitive to changes in T_d . This indicates that the faster the VSG governor speed, the greater its modal damping of low frequency oscillations.

From the perspective of governor speed, the low frequency oscillation risks of the four VSG implementation schemes in Table V are analyzed. The governor of the VSG based on pitch control is the slowest, leading to the highest risk of low frequency oscillation. Similarly, the risk of oscillations due to battery storage VSGs is minimal due to their fast response. The governor speeds of VSG based on overspeed controls and photovoltaic VSG based on MPPT control are similar, indicating that the risks of low frequency oscillation with those sources are similar too.

The PF_{Pf} (the participation factor of ΔP_f with respect to the low frequency oscillation mode) trajectories with T_d swept from 0.01 s to 10 s is given by Fig. 6.

As Fig. 6 shows, PF_{Pf} decreases monotonically with increasing of T_d , which indicates that the decreasing VSG governor speed weakens the VSG PFR's influence on the low frequency oscillations. If the response time of the VSG governor is greater than 3 s, the ΔP_f participation factor will be less than 0.3%: the effect from a 100% change of

Fig. 6. Impact from T_d to participation factor.

P_f on a low frequency oscillation eigenvalue is less than 0.3%, indicating that the VSG PFR function has little effect on the low frequency oscillation at this time. Therefore, it can be inferred that in the VSG based on pitch control, the effect of the VSG PFR function on the low frequency oscillations can be ignored. However, for battery storage VSG ($T_d < 0.5$ s), the PFR can change a system's low frequency oscillation damping. According to Fig. 3, an increasing VSG PFR coefficient will improve the damping of the inter-area low frequency oscillation. Combining the results shown in Fig. 3 and Fig. 6, a battery storage VSG can provide positive damping for low frequency oscillations.

3) Other Reasons for the Different Low Frequency Oscillation Characteristics of VSGs and SGs

The analysis in Sections 3.3.1 and 3.3.2 points out that governor speed is one of the reasons for different low frequency oscillation characteristics of VSGs and SGs. This section analyzes these other reasons. Comparing the state equations of VSGs and SGs, they are very consistent in their rotor motion characteristics. However, there are some VSG parts that do not exist in SGs, such as virtual impedance control, and inner loop control and filter. This may lead to differences in low frequency oscillation characteristics between VSGs and SGs.

Based on the parameters given in Table I, the virtual resistance and inductance (R_v , L_v), filter inductance and capacitance (L_g , C_g), and inner loop control PI parameters (K_p , K_I) are all enlarged by a factor of 1,000 to investigate how these parameters affect the participation factors for the listed parameters in low frequency oscillation modes. The results are shown in Table VI. Here, PF_{PeSG} represents the participation factor of the state variable ΔP_{eSG} .

Based on Table VI, the filter capacitor and inner loop PI

TABLE VI
IMPACTS OF VSG PARAMETERS ON PARTICIPATION FACTORS

Parameter	$R_v = 9e-3 \rightarrow 9$ (p.u.)	$L_v = 3e-3 \rightarrow 3$ (p.u.)	$L_g = 0.24 \rightarrow 240$ (p.u.)	$C_g = 60 \rightarrow 60000$ (μF)
$PF_{\omega SG}$	0.199 $\rightarrow$ 0.162	0.199 $\rightarrow$ 0.336	0.199 $\rightarrow$ 0.497	no change
PF_{ω}	0.249 $\rightarrow$ 0.143	0.248 $\rightarrow$ 0.116	0.248 $\rightarrow$ 0.002	no change
$PF_{\delta SG}$	0.187 $\rightarrow$ 0.174	0.187 $\rightarrow$ 0.209	0.187 $\rightarrow$ 0.007	no change
PF_{δ}	0.204 $\rightarrow$ 0.162	0.204 $\rightarrow$ 0.109	0.204 $\rightarrow$ 0.003	no change
PF_{PeSG}	0.039 $\rightarrow$ 0.027	0.039 $\rightarrow$ 0.023	0.039 $\rightarrow$ 0.001	no change
PF_{Pe}	0.042 $\rightarrow$ 0.025	0.042 $\rightarrow$ 0.012	0.042 $\rightarrow$ 0.001	no change
PF_{ISG}	0.015 $\rightarrow$ 0.017	0.015 $\rightarrow$ 0.108	0.015 $\rightarrow$ 0.489	no change
PF_{Pf}	0.063 $\rightarrow$ 0.035	0.063 $\rightarrow$ 0.080	0.063 $\rightarrow$ 0.002	no change

parameters have little effect on low frequency oscillations. Increasing virtual or filter inductances decrease PF_ω and increase $PF_{\omega SG}$. Fig. 7 shows the PF_ω and $PF_{\omega SG}$ trajectories with L_v or L_g swept from 3×10^{-3} p.u. to 6 p.u..

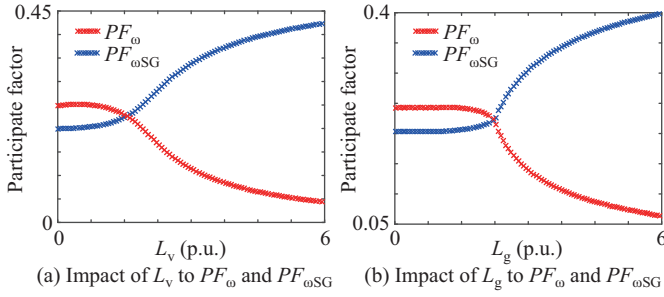


Fig. 7. Impacts from L_v and L_g on participation factors.

As Fig. 7 shows, increasing values of L_v or L_g weakens the VSG PFR's influence ($PF_\omega \downarrow$) and improves the SG PFR's influence ($PF_{\omega SG} \uparrow$) on the low frequency oscillations. When L_v or L_g is greater than 6 p.u., the value of PF_ω will be less than 6% and $PF_{\omega SG}$ will be greater than 40%. This indicates that if a sufficiently large inductance is connected in series at the VSG end (whether it is a virtual inductance or an actual inductance), the inter-area low frequency oscillation characteristics will be determined by the SG.

The λ_{21-22} trajectories with L_v or L_g swept from 3×10^{-3} p.u. to 6 p.u. are shown in Fig. 8.

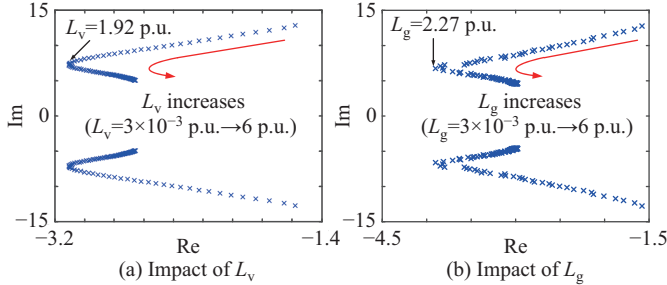


Fig. 8. Impacts of L_v and L_g on λ_{21-22} .

In Fig. 8(a), it can be observed that λ_{21-22} monotonically move toward the left when L_v increases from 3×10^{-3} p.u. to 1.92 p.u. This indicates that the damping of low frequency oscillation modes increases rapidly. When L_v is greater than 1.92 p.u., λ_{21-22} will move to the right when L_v increases, but with the increase of L_v , its influence on λ_{21-22} weakens. The influence of L_g on λ_{21-22} is similar to that of L_v : λ_{21-22} first moves toward the left when L_g increases, and then it changes its direction and moves towards the right when L_g is greater than 2.27 p.u.

As Table VI shows, the virtual resistor also effects low frequency oscillations. Table VI shows that when R_v increases, all of the participation factors related to the state variables in the SG and VSG swing equations decrease. This means that the participation factors of other state variables have increased. According to the calculation results for the participation factors, it is found that when $R_v = 9 \times 10^{-3} \rightarrow 9$ p.u., PF_e

(the participation factor of the VSG voltage e) is increased from 2×10^{-5} to 0.19, it indicates that the increase in R_v increases the influence from the VSG voltage control on the low frequency oscillations.

The λ_{21-22} trajectories with K_q , as defined by (8), were swept from 20 to 5,000 when $R_v = 9 \times 10^{-3}$ p.u. or $R_v = 9$ p.u. are given by Fig. 9(a). The λ_{21-22} trajectory with R_v swept from 9×10^{-3} p.u. to 9 p.u. is given by Fig. 9(b).

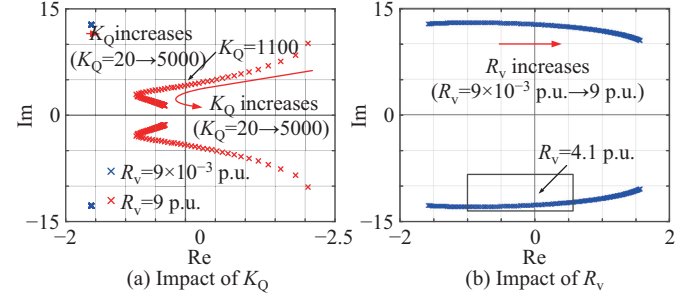


Fig. 9. Impacts from R_v and K_Q to λ_{21-22} .

As Fig. 9(a) shows, when $R_v = 9 \times 10^{-3}$ p.u., the 250-fold increase of K_q in the VSG voltage control has no effect on the values of λ_{21-22} . When $R_v = 9$ p.u. with increasing values of K_q , λ_{21} moves to the lower left and then towards the lower right, indicating that the damping ratio has increased. Comparing the λ_{21-22} trajectories for $R_v = 9 \times 10^{-3}$ p.u. and $R_v = 9$ p.u., it is obvious that increasing R_v improves the influence of the VSG voltage control on low frequency oscillations.

As Fig. 9(b) illustrates, increasing R_v weakens damping of the low frequency oscillations. In the example system, if R_v is greater than 4.1 p.u. the low frequency oscillation damping of the system will be negative.

D. Summary

Summary of the impacts of VSG on inter-area low frequency oscillations:

1) PFR speed: The faster the PFR speed of a VSG, the greater the low frequency oscillation damping that the VSG PFR can provide. For the four common VSGs, wind turbine VSGs based on pitch control, wind turbine VSGs based on overspeed control, photovoltaic VSGs based on MPPT control, and battery storage VSGs, the PFR of a VSG based on pitch control is relatively slow. This slow control means that its risk of oscillation is relatively high. In battery storage VSGs, the PFR speeds are relatively fast. Therefore, battery storage VSG's PFR functions can provide the system with positive low frequency oscillation damping and reduce the risk of low frequency oscillations.

2) The effect of virtual and filter inductances: L_v and L_g have similar effects on low frequency oscillation. When L_v and L_g increases, the degree of influence of VSGs on low frequency oscillations weakens. If enough inductance is connected in series at a VSG's terminals, the inter-area low frequency oscillation characteristics will be determined by other synchronous generators in the system, not the VSG.

3) The effect of virtual resistance R_v : Increased R_v decreases damping of the low frequency oscillations and weakens the influence of VSGs' active power control loop on low frequency oscillations. Also, increased values of R_v enhance the impacts of VSG voltage control loops on low frequency oscillations.

4) Influence of inner loop control and filter capacitor: The inner loop control parameters and filter capacitor parameters of a VSG have no effect on the low frequency oscillations' damping or on the corresponding participation factors.

IV. RT-LAB RESULTS

The VSG controllers are developed using the RT-LAB hardware in the loop (HIL) prototyping platform [21], [22], shown in Fig. 10. Based on the VSG controller, a test system was developed which is consistent with the small-signal system under study. It was used to validate the analytical results discussed in the previous part of this paper. The test system parameters are same as the small-signal model (Table I).

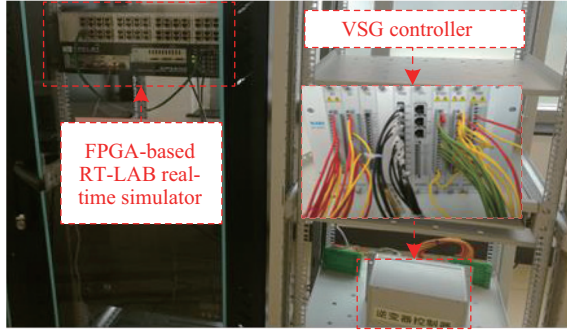


Fig. 10. RT-LAB hardware-in-the-loop test platform.

According to the small-signal analysis results shown in Figs. 5 and 6, increasing VSG governor response times T_d decreases the low frequency oscillations; damping and weakening the influence of VSG PFR functions on low frequency oscillations. To validate this result, a corresponding test was carried out in the RT-LAB test system. The test operational sequence is as follows: at $t = 0$ s (the beginning of the test), the 20 MW active load is connected to the receiving end. The parameters are set to $T_d = 0.1$ s, $K_f = 5$ when $t = 0 \sim 36$ s; At $t = 36$ s, the 20 MW active load is cut off, and set $T_d = 0.1$ s, $K_f = 30$ when $t = 36 \sim 72$ s. Then add the 20 MW active load into the receiving end again at $t = 72$ s and set $T_d = 5$ s and $K_f = 30$ for $t = 72 \sim 108$ s. Then turn off the 20 MW load again at $t = 108$ s, and set $T_d = 5$ s, and $K_f = 5$ when $t = 108 \sim 144$ s. The resulting power oscillations on the inter-area overhead line are:

Prony analysis was performed on the above curve. The method of Prony analysis can be found in [19]. The results are shown in Table VII, where ζ represents the low frequency oscillation damping ratio based on Prony identification [20]:

TABLE VII
RESULTS OF PRONY ANALYSIS ON RT-LAB RESULTS OF T_d

Parameters	$T_d = 0.1$ s	$T_d = 5$ s
$K_f = 30$	$\zeta = 12.4\%$	$\zeta = 6.2\%$
$K_f = 5$	$\zeta = 7.6\%$	$\zeta = 6.2\%$

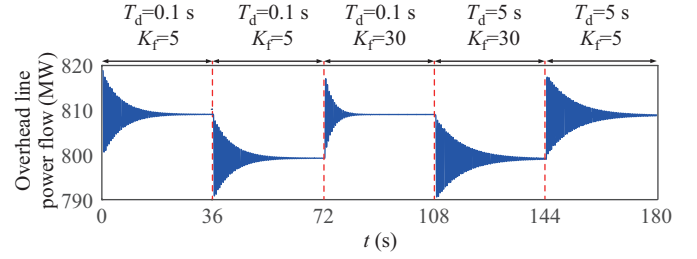


Fig. 11. RT-LAB results for T_d influence.

Comparing the results of $T_d = 0.1$ s and $T_d = 5$ s when $K_f = 30$, it is obvious that the larger the value of T_d , the smaller the damping ratio is. This verifies the small-signal analysis conclusion that “increasing T_d decreases the low frequency oscillation damping.”

When $T_d = 0.1$ s, the change of $K_f = 30 \rightarrow 5$ leads ζ to a decrease by 37% ($\zeta = 12.4\% \rightarrow 7.6\%$). When $T_d = 5$ s, the change $K_f = 30 \rightarrow 5$ results in a steady value of $\zeta = 6.2\%$. This validates the small-signal analysis results that “increasing the value of T_d weakens the influence of VSG PFR.”

The small-signal analysis conclusions, summarized in section 3.2.4, were verified as follows. Due to space limitations, the Prony analysis results are given directly without showing the results of the RT-LAB test curve. Table VIII shows the Prony results for the effects from different VSG parameters (virtual inductor L_v , filter inductor L_g , virtual resistor R_v , inner loop control parameters K_P , K_I , and filter capacitor C_g) on the low frequency oscillation damping ratio.

TABLE VIII
IMPACT OF VSG PARAMETERS ON PARTICIPATION FACTORS

Parameters	$L_v = 3 \times 10^{-3}$ p.u.	$L_v = 6$ p.u.
$T_j = 1$	Case a1: $\zeta = 28.7\%$	Case a2: $\zeta = 47.5\%$
$T_j = 5$	Case b1: $\zeta = 14.8\%$	Case b2: $\zeta = 47.5\%$
$T_{jSG} = 1$	Case c1: $\zeta = 25.7\%$	Case c2: $\zeta = 47.5\%$
$T_{jSG} = 5$	Case d1: $\zeta = 12.8\%$	Case d2: $\zeta = 19.5\%$
	$L_g = 3 \times 10^{-3}$ p.u.	$L_g = 6$ p.u.
$T_j = 1$	Case e1: $\zeta = 21.2\%$	Case e2: $\zeta = 36.2\%$
$T_j = 5$	Case f1: $\zeta = 11.1\%$	Case f2: $\zeta = 36.2\%$
$T_{jSG} = 1$	Case g1: $\zeta = 20.6\%$	Case g2: $\zeta = 36.2\%$
$T_{jSG} = 5$	Case h1: $\zeta = 10.9\%$	Case h2: $\zeta = 12.2\%$
	$R_v = 9 \times 10^{-3}$ p.u.	$R_v = 9$ p.u.
$K_Q = 20$	Case i1: $\zeta = 12.4\%$	Case i2: $\zeta = -14.8\%$
$K_Q = 5000$	Case j1: $\zeta = 12.4\%$	Case j2: $\zeta = 11.1\%$
	$C_g = 60\mu\text{F}$	$C_g = 20000\mu\text{F}$
$K_P = 0.64$	Case k1: $\zeta = 12.4\%$	Case k2: $\zeta = 12.4\%$
$K_P = 640$	Case k3: $\zeta = 12.4\%$	Case k4: $\zeta = 12.4\%$
$K_I = 10$	Case k5: $\zeta = 12.4\%$	Case k6: $\zeta = 12.4\%$
$K_I = 10000$	Case k7: $\zeta = 12.4\%$	Case k8: $\zeta = 12.4\%$

Comparing the cases a1/a2 or e1/e2, increasing L_v or L_g improves the low frequency oscillation damping ratio. This result verifies the small-signal analysis results shown in Fig. 8. Comparing cases a1/b1/c1/d1, we know that when L_v is small, the inertia of a VSG or SG has a similar effect on the low frequency oscillations. Comparing cases a2/b2/c2/d2, it is obvious that when L_v is large, the inertia of the VSG has no effect on low frequency oscillations' damping, but the inertia of the SG has a significant effect on the damping. This verifies the results of the small-signal analysis in Table VI that “increasing L_v weakens the influence of VSG on low

frequency oscillations.” Similarly, the comparison between cases e1/f1/g1/h1/e2/f2/g2/h2 verifies the small-signal analysis results shown in Table VI that “the increased L_g weakens the influence of the VSG on low frequency oscillations.” Comparing cases i1/i2 validates the small-signal analysis results that “increasing R_v weakens the damping of low frequency oscillations.” Also, comparing cases i1/j1 or i2/j2 proves that “increasing R_v enhances the influence of the VSG voltage control loop on low frequency oscillations.” Cases k1-k8 verifies the results that “inner loop control parameters and filter capacitors have no effect on low frequency oscillations.” So far, the conclusions obtained by using the small-signal model in Section 3.2.4 have all been verified by the test results obtained from the RT-LAB test system.

V. CONCLUSION

This paper describes a small-signal model of a VSG-SG interconnected system that was developed to study the mechanism of influence of VSG on inter-area low frequency oscillations. The hardware in the loop RT-LAB test system was used to verify the theoretical analysis results. The following main conclusions were found:

1) *Control principle*: In VSG control, the swing equation of SGs was introduced into the inverters to replace the original vector control structure. This makes traditional IGs (without low frequency oscillation modes) inherit the low frequency oscillation characteristic of SGs.

2) *PFR speed*: In different VSG implementation schemes, the PFR response speeds are different. The faster the response speed, the stronger the damping provided by the VSG PFR function. Battery storage VSGs have fast PFR characteristics and can provide positive damping to the low frequency oscillation modes of the power grid. However, the PFR of wind turbine VSG is based on pitch control, which responds slowly. Its PFR has no effect on low frequency oscillations.

3) *Virtual inductance*: Changing the VSG virtual inductance affects the degree of VSGs' influence on inter-area low frequency system oscillations. The influence of VSGs can be enhanced by reducing their virtual reactance. Therefore, if advanced control strategies are used on VSGs to provide positive damping for low frequency oscillations, the decreased virtual inductance can amplify this positive damping effect.

4) *Virtual resistance*: Increasing VSGs' virtual resistance can enhance the influence of VSG voltage control loops and weaken the influence of VSG active power control loops on inter-area low frequency oscillations. If the low frequency oscillations' damping can be improved by advanced VSG voltage control loop strategies, such as emulating the power system stabilizer (PSS) of SGs, the virtual resistance can be appropriately increased to enhance the damping effects. If the low frequency oscillation damping can be improved by advanced strategies for VSG active power control loops (such as simulating the mechanical damping of SG), the virtual resistance can be appropriately decreased to enhance the damping effect.

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