LETTER

Power tracking performance enhancing method with multiple parameters optimization for virtual synchronous generator-based grid-forming power sources

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Received: October 22, 2024; Accepted: November 21, 2024; Published Online: November 23, 2024; https://doi.org/10.59717/j.xinn-energy.2024.100060

Citation: Huang G., Wei J., Huang S., et al., (2024). Power tracking performance enhancing method with multiple parameters optimization for virtual synchronous generator-based grid-forming power sources. The Innovation Energy **1(4)**: 100060.

Dear Editor,

The virtual synchronous generator (VSG) follows the synchronous swing equation with the virtual inertia loop, and the VSG power output always lags behind the power reference. This characteristic reduces the power utilization efficiency of renewable power generation units, such as wind and photovoltaic. To improve the power tracking performance of the VSG, this letter proposes a power tracking performance enhancing method. The VSG power prediction model with the variations of the VSG inertia, damping, and voltage droop coefficients is built, and the VSG power tracking performance optimization problem is constructed, through which the multiple VSG control parameters can be collaboratively tuned to reduce the difference between the VSG power and the power reference. Compared to the existing methods for enhancing the VSG power performance, the proposed method takes into account the combined effects of the VSG synchronous swing equation and the voltage excitation loop. This results in a more effective solution to the power lagging issue of VSG power when following the synchronous swing equation.

With the increasing capacity of renewable energy generation,[1-3] the grid-forming inverter control technologies have also been developed. The virtual synchronous generator (VSG) control is one of the typical grid-forming control strategies for grid-connected converters[4] in distributed power sources. The VSG control makes them act like the synchronous generators (SGs) and add more reliability to grid.

It has been studied[5,6] that both the inertia, damping, and voltage droop coefficient are related to the performance and stability of the VSG. Normally larger inertia adds more status delay and instability to the VSG, larger damping slows the VSG response, larger droop coefficient amplifies the VSG oscillation.

The adaptive inertia,[7] the active damping,[8] the adaptive droop,[9] the cooperative adaptive inertia and damping[10] are developed to enhance the VSG frequency response. Yet the power lagging characteristics of the VSG, which are affected by both the synchronous swing equation and the voltage excitation equation, have not drawn enough attentions.

To deal with the power lagging problem, this letter proposes a VSG power tracking performance improvement method. The inertia, damping, and voltage droop coefficient are collaboratively optimized to reduce the error between the VSG output power and the power reference, and a better power tracking performance in VSG can be obtained with less overshoot and power oscillation.

THE POSSIBILITY TO IMPROVE POWER TRACKING PERFORMANCE OF THE VSGS

The voltage references obtained from the VSG control are normally utilized with the current loop for the grid-connected inverter. Since the current loop settings are designed to match the line filter and the grid parameters, their changes should be avoided. Therefore, the only possible way to regulate the VSG power performance is to tune the VSG parameters. In order to improve the power tracking performance for the VSGs, the modelling of the VSGs is obtained using the multiple VSG control parameters as inputs at first, then the VSGs power under multiple control parameter change is predicted. Then, the power tracking performance optimization problem of the VSGs is constructed and solved, and the VSG parameters are optimized to reduce the error between the VSGs power and the power references. The main idea of the proposed method is shown in Figure 1.

VSGS MODELLING USING GRID-FORMING PARAMETERS

The VSG dynamics in Figure 1A can be written using (1)-(3) as:

$$J_v\frac{d\omega_v}{dt}=\frac{1}{\omega_{g0}}(P_g^{ref}-P_g)-D_v(\omega_v-\omega_{g0}) \tag{1}$$

$$\delta=\int\omega_v dt \tag{2}$$

$$E=K_q(Q_g^{ref}-Q_g)+U_{g0} \tag{3}$$

where δ is the VSG phase angle, ω_v and ω_{g0} represent the VSG frequency and the grid frequency, E is the VSG voltage amplitude, U_{g0} is the grid voltage, P_g^{ref}, P_g, Q_g^{ref}, Q_g are the active & reactive power and the references, J_v is the inertia, D_v is the damping, K_q is the droop coefficient of the Q-U loop. The VSG power can be calculated using (4) as:

$$P_g=\frac{E^2R_g-EU_gR_g\cos\delta+EU_gX_g\sin\delta}{R_g^2+X_g^2} \tag{4}$$

where R_g and X_g represent the line resistance and impedance. P_g is related to δ and E, so the increment of P_g can be linearly written using the increment of δ and E as:

$$\Delta P_g=G_{P\delta}\Delta\delta+G_{PE}\Delta E \tag{5}$$

where $G_{P\delta}=(E_0U_gR_g\sin\delta_0+E_0U_gX_g\cos\delta_0)/(R_g^2+X_g^2)$, $G_{PE}=(2R_gE_0-U_gR_g\cos\delta_0+U_gX_g\sin\delta_0)/(R_g^2+X_g^2)$, the subscript i represent the ith VSG, and the subscript 0 represent the initial value for each calculation.

Based on (1)-(5), the single VSG space-state equation using J_v, D_v, and K_q as inputs can be written in (6) as:

$$\begin{cases}\Delta\dot{x}_{v,i}=\boldsymbol{A_{v,i}}\Delta x_{v,i}+\boldsymbol{B_{v,i}}\Delta u_{v,i}\\ \Delta y_{v,i}=\boldsymbol{C_{v,i}}\Delta x_{v,i}\end{cases} \tag{6}$$

where $\Delta x_{v,i}=[\Delta\omega_{v,i}\Delta\delta_i\Delta E_i\Delta J_{v,i}\Delta D_{v_i}\Delta K_{q,i}]^T,\forall i\in N_{VSG}$, $\Delta u_{v,i}=[\Delta J_{v,i}^{ref}\Delta D_{v,i}^{ref}\Delta K_{q,i}^{ref}]^T,\forall i\in N_{VSG}$, N_{VSG} is the number of VSGs, T_k is the control delay for parameters change.

Based on (6), the space-state equation of multiple VSGs can also be obtained as:

$$\begin{cases}\Delta\dot{x}_v=\boldsymbol{A_v}\Delta x_v+\boldsymbol{B_v}\Delta u_v\\ \Delta y_v=\boldsymbol{C_v}\Delta x_v\end{cases} \tag{7}$$

where $\Delta x_v=[\Delta x_{v,1},\dots\Delta x_{v,N_{VSG}}]^T$, $\Delta u_v=[\Delta u_{v,1},\dots\Delta u_{v,N_{VSG}}]^T$, $\boldsymbol{A_v}=diag[\boldsymbol{A_v},\dots\boldsymbol{A_{v,N_{VSG}}}]$, $\boldsymbol{B}_v=diag[\boldsymbol{B_{v,1}},\dots\boldsymbol{B_{v,N_{VSG}}}]$, $\boldsymbol{C_v}=diag[\boldsymbol{C}_{v,1},\dots\boldsymbol{C_{v,N_{VSG}}}]$, $\boldsymbol{C_{v,i}}=diag[1,\dots1],\forall i\in N_{VSG}$,

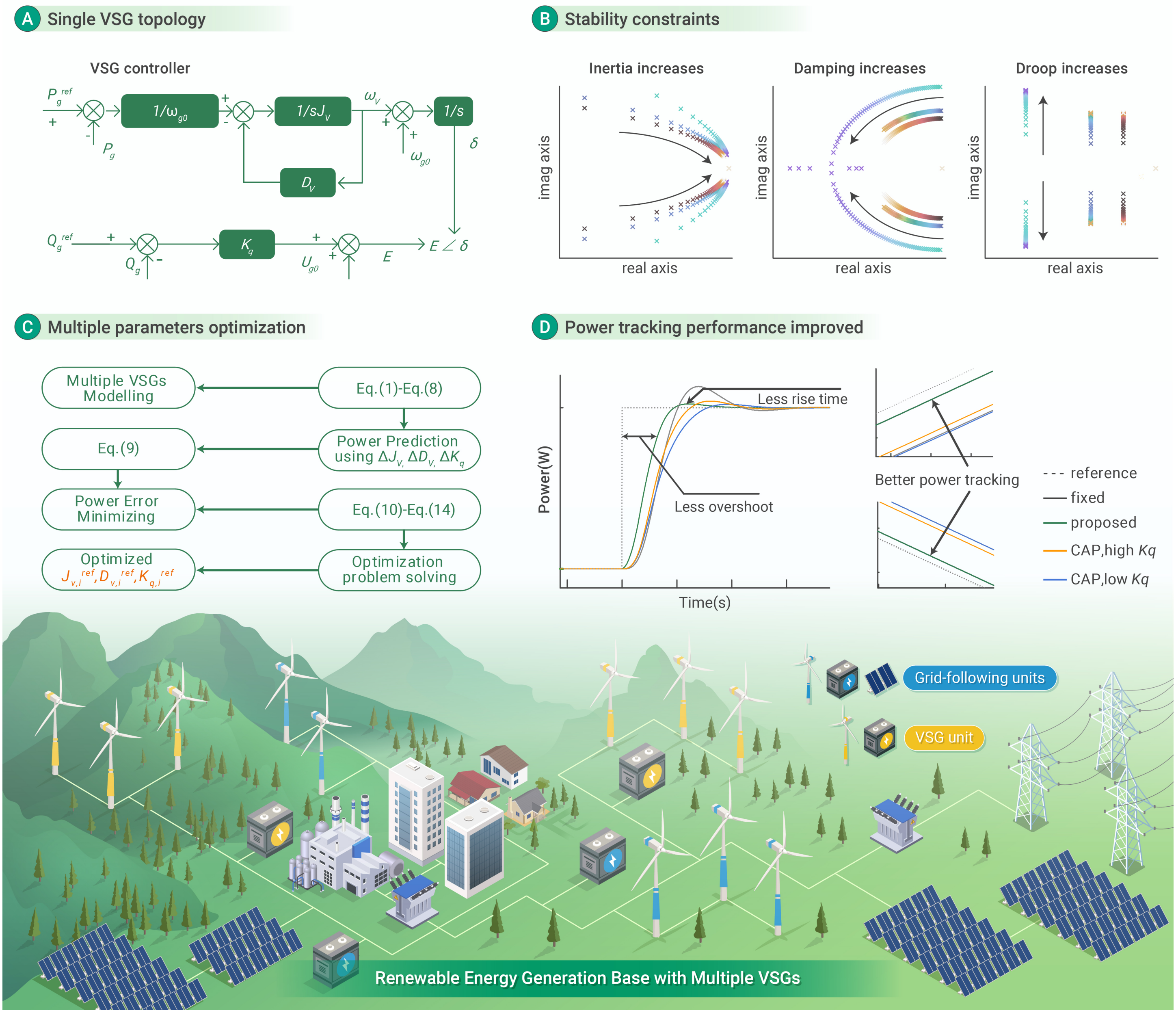

Figure 1. Procedures of the power tracking performance improvement method.

$$
A_{v,i}=\begin{bmatrix}
-\frac{D_{v0,i}}{J_{v0,i}} & -\frac{1}{\omega_0 J_{v0,i}}G_{P\delta,i} & -\frac{1}{\omega_0 J_{v0,i}}G_{PE,i} & \left[\frac{D_{v0,i}}{J_{v0,i}^2}(\omega_{v0,i}-\omega_0)-\frac{P_{g,i}^{ref}-P_{g,i}}{\omega_0}\frac{1}{J_{v0,i}^2}\right] & -\frac{\omega_{v0,i}-\omega_0}{J_{v0,i}} & 0\\
1 & 0 & 0 & 0 & 0 & 0\\
-\frac{K_{q0,i}G_{Q\delta,i}}{1+K_{q0,i}G_{QE,i}} & 0 & 0 & 0 & 0 & -\frac{Q_{g,i}^{ref}-Q_{g,i}}{T_k(1+K_{P0,i}G_{QE,i})}\\
0 & 0 & 0 & -\frac{1}{T_k} & 0 & 0\\
0 & 0 & 0 & 0 & -\frac{1}{T_k} & 0\\
0 & 0 & 0 & 0 & 0 & -\frac{1}{T_k}
\end{bmatrix},
$$

$$
B_{v,i}=\begin{bmatrix}
0 & 0 & 0\\
0 & 0 & 0\\
0 & 0 & \frac{Q_{g,i}^{ref}-Q_{g,i}}{T_k(1+K_{q0,i}G_{QE,i})}\\
\frac{1}{T_k} & 0 & 0\\
0 & \frac{1}{T_k} & 0\\
0 & 0 & \frac{1}{T_k}
\end{bmatrix},\forall i\in N_{VSG}
$$

Then, (7) can be discretized as:

$$\begin{cases} \Delta x_v(k+1) = \boldsymbol{A_{vd}}\Delta x_v(k) + \boldsymbol{B_{vd}}\Delta u_v(k) \\ \Delta y_v(k) = \boldsymbol{C_{vd}}\Delta x_v(k) \end{cases} \tag{8}$$

where $\boldsymbol{A_{vd}} = e^{\boldsymbol{A_v}T_s}$, $\boldsymbol{B_{vd}} = \int_0^{T_s} e^{\boldsymbol{A_v}t}\boldsymbol{B_v}dt$, $\boldsymbol{C_{vd}} = \boldsymbol{C_v}$, T_s is the sampling time.

MULTIPLE PARAMETERS OPTIMIZATION FOR VSGS POWER TRACKING PERFORMANCE IMPROVEMENT

Based on (5), the power of VSGs can be predicted as:

$$P_{g,i}(k+1) = P_{g0,i} + \sum_{k=1}^{N_p} G_{PE,i}\Delta E_i(k) + \sum_{k=1}^{N_p} G_{P\delta,i}\Delta\delta_i(k) \tag{9}$$

where N_p is the predict steps.

Combining with (8) and (9), the main cost function of the power tracking performance optimization problem can be written into the quadratic programming form as:

$$Obj_1 = min\sum_{k=1}^{N_p}\sum_{i=1}^{N_{VSG}} ||P_{gi,}(k) - P_{g,i}^{ref}||^2 \tag{10}$$

Meanwhile, the parameter fluctuations should be limited as:

$$Obj_2 = min\sum_{k=1}^{N_p}\sum_{i=1}^{N_{VSG}} (\alpha_J||\Delta J_{v,i}^{ref}(k)||^2 + \alpha_D||\Delta D_{v,i}^{ref}(k)||^2 + \alpha_K||\Delta K_{q,i}^{ref}(k)||^2) \tag{11}$$

Through (8), (10), (11), the output power of multiple VSGs will be closer to the power reference by coordinately tuning J_v, D_v, and K_q. The stability constraints as shown in Figure 1B are obtained from the related studies[4,5] as:

$$J_v^{min} < J_{v,i}^{ref} < J_v^{max}, \forall i \in N_{VSG} \tag{12}$$

$$D_v^{min} < D_{v,i}^{ref} < D_v^{max}, \forall i \in N_{VSG} \tag{13}$$

$$K_q^{min} < K_{q,i}^{ref} < K_q^{max}, \forall i \in N_{VSG} \tag{14}$$

By solving the quadratic optimization problem in (10)-(14), the inertia, damping and voltage droop coefficient for multiple VSGs can be simultaneously optimized so that the power references can be better tracked. The procedures of the proposed method are shown in Figure 1C.

EFFECTS

In order to verify the validity of the proposed method, 5 VSGs in parallel connection are connected to the grid through the transformers, the transmission line exists between the grid and the first VSG node, and it also exists between each VSG node. The cooperative adaptive parameters (CAP) control[9] and the fixed parameters are selected as the compared cases.

The step and ramp power response of VSG are compared in Figure 1D. As shown in the results, the VSG can better track the power reference through the proposed method under both step and ramp commands. It can also be noticed from the two CAP cases that high K_q offers a better power tracking performance.

When different random power references are given to the 5 VSGs, the accumulative power error between the sum of 5 VSGs power and the power references are also compared, the accumulative power error of the fixed parameters case is used as the denominator to calculate the error ratio. Compared with the fixed parameters and the CAP cases, the proposed method reduces the accumulative power error by about 7.36% (CAP with low K_q) and 6.41% (CAP with high K_q) within 300s of random power.

CONCLUSION

The virtual synchronous generator-based grid-forming technology is one of the key technologies for ensuring the safe and reliable integration of large-capacity power electronics into the grid. However, grid-forming power sources follow the synchronous swing equation, resulting in slow power responses. In order to deal with the slow power response, this letter proposes a power tracking performance enhancing method with multiple parameters optimization for the virtual synchronous generator-based grid-forming power sources, the error between the VSGs power output and the power references is reduced by coordinately tuning the inertia, damping and voltage droop coefficients, and the better power tracking performance is obtained compared with the similar methods.

Through this method, the conflict between the slow dynamic response of the grid-forming units and the performance requirements of the grid can be resolved, the energy utilization efficiency of renewable energy generators can be increased, and the responsiveness of distributed energy power plants to dispatch power commands can be enhanced.

REFERENCES

1. Gonzalez, N., Serna-Torre, P., Sánchez-Pérez, P. A. et al. (2024). Offshore wind and wave energy can reduce total installed capacity required in zero-emissions grids. Nat. Commun. **15**: 6826. DOI: 10.1038/s41467-024-50040-6.
2. Cheng Y., Li C., Xu Y., et al., (2024). Extreme impacts on electric power systems from non-catastrophic meteorological conditions. The Innovation Energy **1**(1): 100008. DOI:10.59717/j.xinn-energy.2024.100008.
3. Cherp, A., Vinichenko, V., Tosun, J.et al. (2021). National growth dynamics of wind and solar power compared to the growth required for global climate targets. Nat. Energy. **6**: 742–754. DOI: 10.1038/s41560-021-00863-0.
4. Ge, P., Tu, C., Xiao, F., et al. (2023). Design-Oriented Analysis and Transient Stability Enhancement Control for a Virtual Synchronous Generator. IEEE T. Ind. Electr. **70**(3): 2675–2684. DOI: 10.1109/TIE.2022.3172761.
5. Chen, S., Sun, Y., Hou, X., et al. (2023). Quantitative Parameters Design of VSG Oriented to Transient Synchronization Stability. IEEE T. Power Sys. **38**(5): 4978–4981. DOI: 10.1109/TPWRS.2023.3293016.
6. Liu, J., Miura Y., and Ise. T. (2016). Comparison of Dynamic Characteristics Between Virtual Synchronous Generator and Droop Control in Inverter-Based Distributed Generators. IEEE T. Power Electron. **31**(5): 3600–3611. DOI: 10.1109/TPEL.2015.2465852.
7. Chang, G. W. and Nguyen., K. T. (2024). A New Adaptive Inertia-Based Virtual Synchronous Generator with Even Inverter Output Power Sharing in Islanded Microgrid. IEEE T. Ind. Electron. **71**(9): 10693–10703. DOI: 10.1109/TIE.2023.3327515.
8. Wang, Z., Chen, Y., Li, P., et al. (2023). Active Power Oscillation Suppression Based on Decentralized Transient Damping Control for Parallel Virtual Synchronous Generators. IEEE T. Smart Grid **14**(4): 2582–2592. DOI: 10.1109/TSG.2022.3233121.
9. Wang, R., Chen, L., Zheng, T., et al. (2017) VSG-based adaptive droop control for frequency and active power regulation in the MTDC system. CSEE J. Power Energy Sys. **3**(3): 260-268. DOI: 10.17775/CSEEJPES.2017.00040.
10. Wang, Z., Meng, F., Zhang, Y., et al. (2023). Cooperative Adaptive Control of Multi-Parameter Based on Dual-Parallel Virtual Synchronous Generators System. IEEE T. Energy Convers. **38**(4): 2396–2408. DOI: 10.1109/TEC.2023.3283048.

DECLARATION OF INTERESTS

The authors declare no competing interests.