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EDITED BY
Dongliang Xiao,
South China University of Technology,
China

REVIEWED BY
Bo Liu,
Kansas State University, United States
Jin-Oh Lee,
Korea Electrotechnology Research
Institute, South Korea

*CORRESPONDENCE
Xiaoling Su,
suxiaoling@qhu.edu.cn

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Droop-based active voltage regulation control and robust stability analysis for VSCs in the large-scale RES-integrated power system

Zhengkui Zhao[1], Xiaoling Su[1]*, Jun Yang[2], Peng Zhou[2], Hui Chen[2] and Guoqiang Lu[2]

[1]Qinghai Key Lab of Efficient Utilization of Clean Energy, Qinghai University, Xining, China, [2]State Grid Qinghai Electric Power Company, Xining, China

New features like high penetration level, low inertia, and weak damping are decreasing voltage support capacity in the power system as it sees large-scale renewable energy source (RES) integration continuously. The reasonable solution to this challenge is developing an additional active voltage regulation function for voltage source converters (VSCs). This study proposes a droop-based active voltage control strategy for VSCs in large-scale RES-integrated power systems to make VSCs continue to operate and regulate the voltage at the point of common coupling (PCC) during a fault without causing overcurrent. In order to meet the requirements of RESs and grid code, all control boundary conditions are designed based on practical engineering data. Meanwhile, plant uncertainty and parameter disturbance are introduced into a robust stability margin analysis model based on the component connection method (CCM) and structured singular value (SSV) to improve the engineering application prospect. The effectiveness and feasibility of this control strategy are proved by logical deduction and practical simulation based on a generalized small-signal model.

KEYWORDS

active voltage regulation, voltage source converters, plant uncertainty, robust stability, renewable energy sources

1 Introduction

Driven by the energy crisis and environmental pollution, the world energy structure is undergoing dramatical changes. Promoting low-carbon energy or RESs is a global consensus (Yuan et al., 2017; Wang and Blaabjerg, 2019); therefore, large-scale RESs integration is an inevitable status for a power system. Most of the RESs connected power grid by VSCs, and the time scales of their electrical characteristics are different from convention synchronous motor-dominated power systems. Therefore, PV stations and wind farms install a static VAR compensator (SVC), static VAR generator (SVG), or static synchronous compensator (STATCOM) to regulate voltage at PCC and the reactive power compensation equipment capacity value in each station no less than 10% of the station capacity according to the grid code. As power systems see large-scale RES integration continuously, features like low inertia and weak damping make reactive power compensation equipment in the power system no longer sufficient for voltage regulation (Sun et al., 2015; You et al., 2017; Wang et al., 2020; Zhuo et al., 2021). On the other hand, the efficiency of original relay protection, stable measures, and monitoring devices decreases with the dramatic increase of power electronic equipment in the large-scale RES-integrated power system, especially during a fault. Su et al. (2021) gives an on-site engineering test for PV stations and wind farms in an AC–DC hybrid power grid under extreme fault conditions, with over three quarters of SVC and SVG blocked or disconnected from the grid. Meanwhile, RESs have the capability of disturbance-rejection under extreme fault conditions after parameter modification or equipment upgrading. So, it is reasonable for RESs to regulate voltage at PCC (GE et al., 2007; Lu et al., 2018; Lu, 2020).

The VSC control strategy can be divided into grid following and grid forming. VSCs in PV stations and wind farms adopt active and reactive power decoupling control (Su et al., 2020), which usually operates with a constant unit power factor. SVC, SVG, or STATCOM is reactive power sources for each RES (Ma et al., 2018). RESs could control their active and reactive power flexibility only if all the equipment operates with the same static/dynamic characteristics and communicate with each other without time delay. There are a large number of VSCs scattered geographically in PV stations and wind farms (Mahdian Dehkordi et al., 2017a; Mahdian Dehkordi et al., 2017b; Han et al., 2018; Wei et al., 2021; Xiao et al., 2021) with different dynamic response characteristics. It is difficult to achieve precise reactive power distribution in small time scale using a centralized control strategy in existing automatic voltage control (AVC). The autonomous response without global coordination cannot meet coordinated voltage support at PCC. On the other hand, active voltage regulation requires autonomous response and adaptability in static and transient stability. In addition, overcurrent, reactive power shortage, and time delay are the main obstacles for voltage regulation control in VSCs.

VSCs with grid-forming control operate with self-built voltage/frequency and respond to the disturbance autonomously which is independent of communication (Li et al., 2016). A virtual synchronous generator (VSG) and robust droop control are promising grid-forming control strategies, since VSCs operate as an equivalent voltage source and synchronized through power synchronization (Zhang et al., 2010; Zhong and Weiss, 2011; Zhong et al., 2014; Natarajan and Weiss, 2017; Rodriguez et al., 2018; Wei et al., 2022). Due to a synchronization mechanism and power-sharing design, the VSC switching process has a great impact on the other units. VSC parallel operation control analysis introduces plant uncertainty in modeling, parameter design, and stability analysis to characterize on-site practical engineering features. Sumsurooah et al. (2013) propose instruments to model and analyze the VSC system with uncertainty to represent perturbation effects such as system parameter variations. Sumsurooah et al. (2018) give insights into robust stability measure μ for equilibrium point stability with multiple parametric uncertainties and make the μ approach application-friendly. Le et al. (2020) develop a state–space model for VSCs to operate as VSG under time-delay and parameter uncertainty using the Lyapunov stability theorem and linear matrix inequality to obtain conservative time-delay uncertainty stability conditions and calculate its time-delay stability margin.

VSC output impedance is another engineering application for VSC dynamic stability analysis because of its intuitive physical meaning. First, the impedance matrix in different coordinate systems is developed based on a small-signal model, and then the output impedance and return matrix of grid impedance can be determined according to the Nyquist stability criterion. It allows to locally assessing converter stability by applying the Nyquist stability criterion to the ratio between the equivalent output admittance of the converter and the equivalent grid admittance at the converter terminals. However, it cannot reflect the overall operation status of the whole system. Le et al. (2020) and Xiao et al. (2021) establish a state–space equation and determine its stability based on the state matrix eigenvalue. Both methods are only applicable to a specific operating point. For engineering application, on-site operation of inverters interfaced to the grid exhibit the need for applying the multivariable control theory.

In order to coordinate the operation of VSCs and exploitation of their reactive power potential, this study presents a distributed control strategy instead of AVC (automatic voltage control)-based centralized control. The proposed droop-based active voltage regulation control enables VSCs continue to operate and regulate voltage at the point of common coupling (PCC) during a fault without causing overcurrent. The active voltage regulation control is achieved by detecting the PCC voltage and regulating the dynamic voltage actively with its output reactive power. Control strategy errors are inevitable in engineering applications which deteriorate system performance. The proposed control strategy is designed based on practical engineering data, and plant uncertainty and parameter disturbance are introduced into a robust stability margin analysis model based on a component connection method and structured singular value so that it improves the engineering application prospect. The main structure of this study is organized as follows:

The main circuit and control circuit topologies of grid-connected VSCs are shown in Section 2. Then, an active voltage control strategy for VSCs is proposed and discussed, so that converters operating in parallel can automatically share the output reactive power and ensure that the converter output does not exceed the limit as shown in Section 3. In Section 4, the system-level small-signal model of multi-VSCs is presented regarding to the plant uncertainty and parameter deviation for engineering application and design. Taking into account the perturbation effects such as system parameter variations that can occur in their physical plants, the control parameters' influence on system stability is analyzed, and the stability margin is presented. The simulation model and case study are carried out in Section 5.

2 Grid-interfaced voltage source converter modeling

2.1 Voltage source converter topology

The main circuit structure and control strategy of the grid-connected VSCs are shown in Supplementary Figure S1.

For the main circuit of VSCs shown in Supplementary Figure S1, the mathematical model in the dq rotating coordinate is established according to KVL and KCL.

$$\begin{pmatrix} U_{td} \\ U_{tq} \end{pmatrix} - \begin{pmatrix} U_d \\ U_q \end{pmatrix} - L_f \begin{pmatrix} 0 & -\omega \\ \omega & 0 \end{pmatrix} \begin{pmatrix} I_{ld} \\ I_{lq} \end{pmatrix} = \left(L_f s + R_f + r_{\text{on}}\right) \begin{pmatrix} I_{ld} \\ I_{lq} \end{pmatrix}, \tag{1}$$

$$\begin{pmatrix} I_{ld} \\ I_{lq} \end{pmatrix} - \begin{pmatrix} I_d \\ I_q \end{pmatrix} - C_f \begin{pmatrix} 0 & -\omega \\ \omega & 0 \end{pmatrix} \begin{pmatrix} U_d \\ U_q \end{pmatrix} = C_f s \begin{pmatrix} U_d \\ U_q \end{pmatrix}, \tag{2}$$

where u_{td} and u_{tq} are dq-axis components of VSC output voltage. i_d and i_q are the dq-axis components of the VSC output current. u_d and u_q are dq-axis components of the output voltage at PCC. i_{ld} and i_{lq} represent the dq-axis components of the inductor current.

2.2 Voltage source converter control system

Supplementary Figure S2 gives a control block diagram for grid-connected VSCs based on their mathematical model with a compensator, and $G_{cl}(s)$ is the inner loop transfer function.

Since the input reference U_{dref} is a DC value, a PI compensator is designed as

$$K_{vac}(s) = \frac{k_{pvac} s + k_{ivac}}{s}, \tag{3}$$

where k_{pvac} and k_{ivac} are proportional coefficients and integral coefficients, respectively. Then, an open-loop transfer function of VSC operating in the voltage regulation mode is

$$l_{vac}(s) = \frac{k_{pvac} s + k_{ivac}}{s} \frac{-2}{3U_{d0}} \frac{1}{\tau_i s + 1} \left(-\omega_0 L_g\right). \tag{4}$$

With determined system parameters, cutoff frequency ω_{cvac} and phase margin γ_{vac} in the open-loop transfer function of the control system should be designed to meet PCC voltage performance requirements. Therefore, k_{pvac} and k_{ivac} are designed based on the parametric equation and determined by γ_{vac} and ω_{cva}c. In order to ensure power inner loop gain is 1 or

$$\frac{1}{\tau_i j\omega_{cvac} + 1} \approx 1, \tag{5}$$

where the cutoff frequency ω_{cvac} gives the control bandwidth of voltage response and should be much smaller than the power inner loop bandwidth $1/\tau_i$. In a mathematical model derivation process of this section, filter capacitor influence and dynamic characteristics of PLL are neglected since it is impossible to get the exact value of the power grid-equivalent inductance L_g in an actual operation. Therefore, the phase margin γ_{vac} should be wide enough to ensure system stability. A simple way is to set $k_{pvac} \approx 0$; then, k_{ivac} is determined by the given cutoff frequency ω_{cvac} and sufficient phase margin.

3 Droop-based multi-voltage source converter control strategy

3.1 Control strategy theoretical analysis

The equivalent circuit of multiple VSC parallel operation is shown in Supplementary Figure S3, where E is the grid voltage and U_0 is the voltage value at PCC. Z_L is load impedance, U_i and U_j are the voltage of the ith and jth VSC, respectively, and I_i and I_j are the output current. Z_{oi} is the equivalent internal impedance of the ith VSC, and Z_{vi} represents the virtual impedance of this VSC. Z_1 is the equivalent output impedance of the power grid.

In Supplementary Figure S3, ith VSC outputs active power P_i and reactive power Q_i is

$$\begin{cases} P_i = \dfrac{U_i E}{Z_i} \cos\left(\theta_i - \varphi_i\right) - \dfrac{E^2}{Z_i} \cos\theta_i, \\ Q_i = \dfrac{U_i E}{Z_i} \sin\left(\theta_i - \varphi_i\right) - \dfrac{E^2}{Z_i} \sin\theta_i. \end{cases} \tag{6}$$

Since $Z_i \angle \theta_i$ is much smaller than $Z_L \angle \theta_L$, it is reasonable to conjecture $\sin\varphi_i \approx \varphi_i$ and $\cos\varphi_i \approx 1$. Then, Eq. 6 is rearranged as

$$\begin{cases} P_i = \dfrac{E}{Z_i} \left[(U_i - E)\cos\theta_i + U_i \varphi_i \sin\theta_i \right], \\ Q_i = \dfrac{E}{Z_i} \left[(U_i - E)\sin\theta_i - U_i \varphi_i \cos\theta_i \right]. \end{cases} \tag{7}$$

Also, output impedance is suppressed by introducing a current feedforward control loop Z_{oi} for simplicity. When Z_{li} is much smaller than R_{viri}, the output impedance Z_i of the ith VSC is resistive, and then output impedance Z_i is approximately equal to $R_{\mathrm{vir}i}$. Substituting $Z_i\angle\theta_i = R_i$ into Eq. 7, the output power characteristics of the ith VSC is

$$\begin{cases} P_i = \dfrac{E}{R_i}(U_i - E), \\ Q_i = -\dfrac{U_i E}{R_i}\varphi_i, \end{cases} \tag{8}$$

where U_i is the modulation output voltage amplitude of the ith VSC, which is controlled to track its reference value, and then the output active power is reciprocal to the virtual resistance for parallel operation VSCs. Supplementary Figure S4 gives the output power and voltage relationship curve of the ith and jth VSCs. The slope of each curve is determined by the VSC virtual impedance. When U_{i} equals to U_{j} and tune virtual impedance Z_{vi} double as Z_{vj}, the output active power P_i is half of P_j. The same procedure may be easily adapted to obtain control reactive power Q_i half as Q_j by virtual impedance. The theoretical analysis shows that the VSC output power relies on Z_i by following the control law, and the droop characteristic is shaped naturally with Z_v dominating the output impedance of VSCs.

3.2 Design control parameters

When paralleled VSCs operate in the active voltage regulation mode, the output characteristics of ith VSC is designed as shown in Supplementary Figure S4 and Eq. 8. The output voltage reference of VSCs in the PV station and wind farm is constrained by the grid code requirements as disturbances like overvoltage/undervoltage protection will shut VSC. So, the voltage constraint is

$$|\Delta U| = \left|U_{mea\_i} - U_{ref\_i}\right| \leq 0.07U_N \tag{9}$$

Substituting the constraints into Eq. 8, then it is rearranged as

$$(Q_{mea\_i} - Q_{0\_i})/Z_i \leq 0.07U_N \tag{10}$$

It can be deduced as

$$1/Z_i \leq \left|\frac{0.07U_N}{(Q_{mea_{-i}} - Q_{0_{-i}})}\right| \leq \left|\frac{0.07U_N}{Q_{\max}}\right| \tag{11}$$

In parallel operation, to ensure that the VSC output voltage does not exceed its critical value, the inequality constraint and control sensitivity of Eq. 11 should be comprehensively considered.

4 Robust dynamic stability analysis

4.1 Uncertain system modeling

On-site plant uncertainty is introduced in the modeling process to guarantee the control effect and robustness in engineering application. The basic idea in modeling an uncertain system approach is introducing an independent control loop to represent plant uncertainty and separate stochastic perturbation from the nominal system where disturbance elements are bounded values, as shown in Supplementary Figure S5. The linear fractional transformation method is applied to model the multiple perturbation-embedded physical system, where u is the input, y is the output, and x is the state variable. Supplementary Figure S5A shows the generalized state–space model, and uncertainties are pulled out of the system and formulated in the matrix Δ as shown in Supplementary Figure S5B. Then, the M-Δ structure is established based on the state variable in Eq. 12. Subsequently, the M-Δ structure shown in Supplementary Figure S5B is established based on input u, u' and output y, y' as follows:

$$G_l = \frac{y_\Sigma}{u_\Sigma} = M_{22} + M_{21} \times \Delta(I - M_{11}\Delta)^{-1}M_{12} \tag{12}$$

Therefore, $(\mathrm{I}-\mathrm{M}_{11}\Delta)^{-1}$ is the only term that causes system global instability, and the stability margin is decided by subsystem M_{11}. Supplementary Figure S5D gives the detailed $\mathrm{M}_{11}\Delta$ structure which can be seen as an extraction of the transfer function matrix. Then, uncertain system modeling mainly focuses on $\boldsymbol{M}_{11}$ and SSV. The smallest structured Δ (measured in terms of the largest singular value s (Δ)) makes the matrix I−MΔ singular.

$$\mu_\Sigma \triangleq \frac{1}{\min\{\bar{\sigma}|\det(I - M\Delta) = 0\}} \tag{13}$$

According to the aforementioned theoretical analysis, plant parameter inaccuracies, system nonlinearities, control data acquisition, and communication delay are the main reasons of system uncertainties. It is proved that these uncertainties are dominated by system angular frequency. So, the uncertain system modeling process is intuitively simplified as adding perturbations to the nominal plant in a multiplicative way which regroups the plants as

$$G(s) = G(I + w\Delta) \tag{14}$$

When VSC operates at its normal state, matrix Δ is not bigger than 1. The amplitude is set close to engineering situations of 20% at low frequency and increases till 450% at high frequency as shown in Supplementary Figure S6. The chosen weight accounts for low-frequency uncertainties due to parametric uncertainty, as well as high-frequency neglected dynamic effects or resonant effects from nearby VSCs.

4.2 System small-signal modeling

The global system state–space model of VSCs operating in parallel is derived by applying the CCM method, as shown in Supplementary Figure S7. Subsystem modular is connected to each other with interconnection matrices, and then the whole state–space representation is given as

$$\begin{cases} \dot{x}_\Sigma = A_\Sigma x_\Sigma + B_\Sigma u_\Sigma, \\ y_\Sigma = C_\Sigma x_\Sigma + D_\Sigma u_\Sigma. \end{cases} \tag{15}$$

As shown in state–space Eq. 15, the coefficient matrix A_Σ, B_Σ, C_Σ, and D_Σ are, respectively, given as

$$\begin{cases} A_\Sigma = A + BL_{11}(I - DL_{11})^{-1}C, \\ B_\Sigma = BL_{11}(I - DL_{11})^{-1}DL_{12} + BL_{12}, \\ C_\Sigma = L_{21}(I - DL_{11})^{-1}C, \\ D_\Sigma = L_{21}(I - DL_{11})^{-1}DL_{12} + L_{22}. \end{cases} \tag{16}$$

Interconnection matrices L indicate connections between inputs and outputs of the subsystems. The coefficient matrices A, B, C, and D are sparse block diagonal matrices obtained from the state–space matrices of single subsystems. The detailed information is given in Supplementary Material S1.

$$\begin{cases} A = \mathrm{diag}\{A_{c2}, A_{LCL1}, A_{LCL2}, A_g, A_{PQ}\}, \\ B = \mathrm{diag}\{B_{c2}, B_{LCL1}, B_{LCL2}, B_g, B_{PQ}\}, \\ C = \mathrm{diag}\{C_{c2}, C_{LCL1}, C_{LCL2}, C_g, C_{PQ}\}, \\ D = \mathrm{diag}\{D_{c2}, D_{LCL1}, D_{LCL2}, D_g, D_{PQ}\}. \end{cases} \tag{17}$$

5 Simulation and experimental verification

5.1 Simulation model and parameters

The simulation model of Supplementary Figure S1 is built in the MATLAB/Simulink platform to verify feasibility and effectiveness of the proposed droop-based active voltage regulation control for VSCs. VSC#1 and VSC#2 work in parallel operation and coordinate with each other to control the PCC voltage. The simulation model parameters are shown in Supplementary Tables S1,S2.

5.2 Stability margin analysis

According to the uncertainty representation shown in Supplementary Figure S6, the SSV analysis is applied to evaluate system stability. Parameters listed in Supplementary Tables S1,S2 are aligned with the case studied in Section 2. The system's robust stability margin is shown in Supplementary Figure S8. The μ-factor of control parameter virtual impedance scanning varies from 0.5 to 2 p.u. The output power short circuit ratio (SCR) varies from 1.5 to 10, and the low-pass filter (LPF) shear frequency varies from 20 to 200 rad/s as shown in Supplementary Figure S8. VSC robust stability increases along with virtual impedance and an increase in SCR. However, an increase in output power and shear frequency reduces the stability margin.

5.3 Case study

A simulation model is developed based on topology given in Supplementary Figure S3, where VSC#1 and VSC#2 are connected in parallel with the grid at PCC. Resistance–inductance load in Supplementary Table S1 is designed to simulate voltage disturbance at PCC. Both VSC#1 and VSC#2 are controlled by the proposed droop-based active voltage regulation control mode. VSC#1 operates in an active voltage regulation control mode at 0.2 s, and its virtual impedance set to 5 kΩ. VSC#2 operates in an active voltage regulation control mode at 0.3 s, and its virtual impedance set to 5 kΩ. At 0.4 s, a load connects in and disconnects at 0.6 s. Voltage fluctuation and reactive power and current response characteristics of VSC#1 and VSC#2 are observed. The virtual impedance value of VSC#2 at 0.7 s is adjusted, and VSC#2 at 0.8 s exits the operation and verifies the change of reactive power distribution among VSCs.

At 0.4 s, the voltage at PCC drops to 0.8 p.u when the load is connected as shown in Supplementary Figure S9. VSC#1 and VSC#2 detect PCC voltage falling and generate reactive power according to their virtual impedance as shown in Supplementary Figure S10. The dynamic response of VSC output current is shown in Supplementary Figures S11,S12. After about four circles of current-loop time constants, the system reaches a steady state. The PCC voltage returns to 0.99 p.u. Due to VSC#2 virtual impedance adjustment, the reactive power distribution between VSCs changes at 0.7 s, which corresponds to the virtual impedance ratio. The output reactive power of VSC#1 and VSC#2 is 10 kVar and 20 kVar, respectively, where Q1:Q2 = 2:1 and R1:R2 = 1:2. It is consistent with the conclusion of the theoretical analysis in Supplementary Figure S4.

When VSC#2 exits at 0.8 s, VSC#1 operates normally and outputs reactive power. The output current characteristics of VSC#1 are shown in Supplementary Figure S12. VSC#1 works normally without an inrush current. The control system ensures autonomous operation of the VSCs, and the power can be automatically distributed as shown in Supplementary Figure S13, according to the control law.

6 Conclusion

An active voltage regulation control strategy is proposed based on the grid-connected VSC working principle, and droop control characteristics are proposed to improve the stability in a large-scale RES-integrated power system. The proposed control strategy and control parameter design process are designed regarding to the plant uncertainty and parameter deviation for engineering applications which guarantee the control effect and robustness in PV stations and wind farms. The active voltage regulation and automatic response to the PCC voltage disturbance features improved the flexibility of VSCs in PV stations and wind farms significantly. The feasibility and effectiveness of the proposed active voltage regulation strategy are verified by logical deduction and practical simulation based on a generalized small-signal model.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

ZZ: conceptualization, methodology, data curation, simulation test, and writing. XS: supervision and conceptualization. JY: investigation and data curation. PZ: simulation and resources. HC: simulation test and resources. GL: resources.

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Conflict of interest

Authors JY, PZ, HC, and GL were employed by State Grid Qinghai Electric Power Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.1005593/full#supplementary-material

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