

GRID-CONNECTION STABILITY CONTROL OF V2G CHARGING STATIONS BASED ON VIRTUAL SYNCHRONOUS MACHINES

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Abstract - To enhance the grid-connection stability of V2G charging stations for electric vehicles and improve their grid support capabilities, this study proposes an adaptive virtual inertia and damping cooperative control strategy that accounts for battery state of charge (SOC). This approach is achieved by constructing a two-level V2G charging station topology based on virtual synchronous machine technology. The study established a small-signal model of the V2G charging station grid-connected system, revealed the quantitative relationship between virtual parameters and system dynamic characteristics, and designed an online tuning scheme for virtual parameters based on SOC fuzzy inference. Finally, a simulation model of a 15 kW V2G charging station was developed using the MATLAB/Simulink platform for validation. The results demonstrate that the proposed control strategy reduces the total harmonic distortion (THD) of the grid-connected current to 1.52% and shortens the frequency deviation recovery time by approximately 40% under grid frequency fluctuation conditions, effectively balancing the grid-connection stability of V2G charging stations with the flexibility of charging and discharging regulation.

Keywords: Virtual Synchronous Machine, V2G Charging Station, Grid-Connection Stability, State of Charge, Adaptive Control

1. Introduction

By 2025, the global electric vehicle fleet had exceeded 40 million units, and the large-scale participation of electric vehicles in grid interaction via V2G technology has become a key component of the development of new power systems. As the energy exchange interface between electric vehicles and the grid, the grid-connection stability of V2G charging stations directly impacts grid power quality and operational safety. Traditional V2G charging stations typically employ grid-following control strategies, relying on phase-locked loops to achieve grid synchronization; however, this approach is prone to oscillatory instability in weak grid or high penetration scenarios.

In recent years, virtual synchronous generator (VSG) technology has garnered significant attention in the field of renewable energy grid integration due to its inherently grid-friendly inertia and damping characteristics. Li et al. [1] proposed an adaptive virtual inertia control method for distributed photovoltaic grid-connected scenarios, verifying the effectiveness of VSGs in frequency support. Wu et al. [2] investigated a control strategy for energy storage inverters based on virtual synchronous generators,

achieving active support for grid frequency through active power-frequency droop characteristics. Zhang et al. [3] applied virtual DC motor control to the energy storage interface of a DC microgrid, simulating the inertia response characteristics of a DC motor using an equivalent model of the armature circuit. However, the aforementioned studies primarily focused on virtual motor control for single interfaces, with limited attention given to the coordinated control of AC and DC interfaces in V2G charging stations. Zhang et al. [4] proposed a virtual synchronous motor control method for electric vehicle fast-charging interfaces, but did not fully consider the impact of battery state of charge (SOC) on the tuning of virtual parameters. Liu et al. [5] reviewed the topologies and control strategies of power electronic converters in V2G systems, pointing out that adaptive control accounting for SOC is a key direction for improving V2G system performance.

This paper focuses on the grid-connection stability of V2G charging stations and proposes a coordinated AC/DC dual-side control architecture based on virtual synchronous machines. The main innovations are as follows: (1) A small-signal model for the control of virtual synchronous motors and virtual DC motors in a two-level V2G charging station was established,

revealing the mechanism by which virtual parameters affect system stability; (2) By introducing the SOC signal to adjust the virtual inertia and damping coefficients, we achieved the coordinated optimization of charging/discharging power allocation and grid-connection stability; (3) By connecting the AC and DC interfaces via an isolated bidirectional DC/DC converter, we effectively suppressed harmonic currents at the grid-connection point.

2. V2G Charging Station System Topology and Control Architecture

2.1 Two-Stage V2G Charging Station Topology

The V2G charging station adopted in this study employs a two-stage power conversion structure (Figure 1). The front-end unit utilizes a bidirectional AC/DC converter based on virtual synchronous motor control theory to achieve parallel connection with the power grid; the rear-end unit employs a bidirectional DC/DC converter based on a virtual DC motor control scheme, specifically designed to handle the charging and discharging control of the electric vehicle's battery pack; Electrical isolation and voltage regulation between the two-stage power units are achieved via an isolated dual-active-bridge DC/DC converter [6-7].

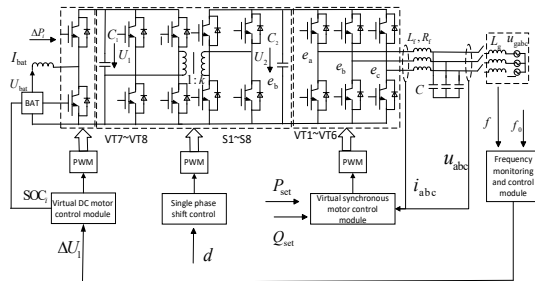


Figure 1: Overall topology diagram of the system

In Figure 1, u_{gabc} represents the three-phase grid voltage, L_g represents the grid-side equivalent inductance, L_f , R_f , and C_f constitute the LCL filter network, u_{abc} represents the filter capacitor terminal voltage, e_a , e_b , and e_c represent the midpoint output voltages of the AC/DC converter bridge arms, and i_{abc} represents the three-phase AC currents; U_{dc} represents the DC bus voltage, U_{bat} represents the power battery terminal voltage; PCC denotes the common coupling point [8-11]. Compared to traditional V2G charging station topologies, the scheme proposed in this paper introduces virtual motor control stages at both the AC and DC interfaces, enabling the converter to actively simulate the inertia response and damping characteristics of a synchronous motor, thereby

providing frequency and voltage support to the power grid. The adoption of an isolated DAB converter ensures electrical safety while also facilitating decoupled control of the virtual motors on both sides.

2.2 Virtual Synchronous Motor Control at the AC Interface

The fundamental concept of virtual synchronous motor control is to enable the power electronic converter to exhibit electromechanical transient characteristics similar to those of a synchronous generator at the grid connection point. The rotor motion equation of a synchronous generator can be expressed as:

$$J \frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_0) \quad (1)$$

where: J is the virtual inertia; ω is the virtual angular velocity; T_m is the mechanical torque; T_e is the electromagnetic torque; D is the damping coefficient; ω_0 is the grid synchronous angular velocity.

Multiplying both sides of Equation (1) by ω yields the equations of motion in power form [12-15]:

$$J\omega \frac{d\omega}{dt} = P_m - P_e - D\omega(\omega - \omega_0) \quad (2)$$

where: P_m is the virtual mechanical power; P_e is the electromagnetic power.

The active power-frequency droop characteristic of a virtual synchronous motor control can be expressed as [16]:

$$P_m = P_{ref} + k_f(\omega_0 - \omega) \quad (3)$$

where: P_{ref} is the active power reference; k_f is the frequency regulation coefficient.

The reactive-voltage droop control equation is:

$$E = E_0 + k_q(Q_{ref} - Q_e) \quad (4)$$

where: E is the virtual internal emf amplitude; E_0 is the no-load voltage; k_q is the reactive power control coefficient; Q_{ref} and Q_e are the reactive power reference and actual values, respectively.

The control block diagram for the virtual synchronous motor is shown in Figure 2. The active power loop generates the virtual phase angle θ based on Equations (2) and (3), while the reactive power loop generates the voltage amplitude command based on Equation (4). These are combined into a three-phase modulated waveform, which is then PWM-modulated to drive the AC/DC converter [17].

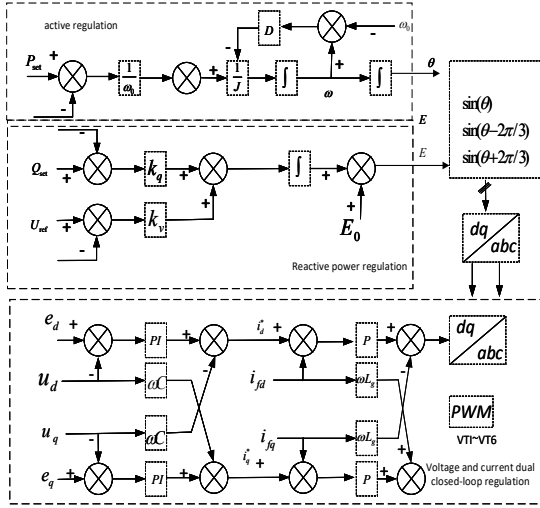


Figure 2: VSG control module

2.3 Virtual DC Motor Control via the DC Interface

Virtual DC motor control simulates the armature circuit characteristics of a separately excited DC motor, causing the DC/DC converter to exhibit inertia and damping characteristics. The armature circuit emf balance equation for a DC motor is [18]:

$$E_a = U_{dc} + I_a R_A \quad (5)$$

$$E_a = C_T \Phi \omega_m \quad (6)$$

Where: E_a is the armature emf; I_a is the armature current; R_A is the equivalent armature resistance; C_T is the torque coefficient; Φ is the magnetic flux; ω_m is the angular velocity of the DC motor.

The equations of motion for a DC motor are [19-20]:

$$J_m \frac{d\omega_m}{dt} = T_m - T_e - D_m(\omega_m - \omega_{m0}) \quad (7)$$

where: J_m is the virtual inertia of the DC motor; D_m is the damping coefficient of the DC motor.

Applying the Laplace transform to Equations (5) through (7) and simplifying yields the small-signal transfer function model for the virtual DC motor control. The transfer function between the grid frequency deviation Δf and the electric vehicle charging/discharging power deviation ΔP_i can be expressed as:

$$\frac{\Delta P_i(s)}{\Delta f(s)} = \frac{k_{vf} C_T \Phi}{(J_m s + D_m)(R_a + s L_a) + (C_T \Phi)^2} \quad (8)$$

Where: k_{vf} is the frequency-to-voltage conversion coefficient; L_a is the equivalent armature inductance.

From Equation (8), it can be seen that the power response characteristics of the virtual DC motor are jointly determined by J_m and D_m . Among these, the damping coefficient D_m primarily affects the steady-

state power distribution ratio, while the virtual inertia J_m primarily affects the dynamic response speed.

3. Adaptive Virtual Parameter Control Strategy Considering SOC

3.1 SOC and Charging/Discharging Power Constraints

The state of charge (SOC) of an electric vehicle's battery directly affects its chargeable and dischargeable capacity, thereby determining the operational limits of a V2G charging station's ability to participate in grid power regulation [21-22]. Define the safe operating range of the SOC for the n th electric vehicle (i) as $[SOC_{min}, SOC_{max}]$, where SOC_{min} is the lower limit of the SOC to prevent over-discharge, and SOC_{max} is the upper limit of the SOC to prevent over-charge. Based on the current SOC value, electric vehicles can be classified into three categories: charging-priority zone, discharging-priority zone, and bidirectional adjustable zone. The classification principle is shown in Equation (9):

$$\begin{cases} SOC_0 \in [SOC_{min}, SOC_{low}], \\ SOC_0 \in (SOC_{low}, SOC_{high}), \\ SOC_0 \in [SOC_{high}, SOC_{max}], \end{cases} \quad (9)$$

where: SOC_{low} and SOC_{high} are the threshold values for the charging-priority zone and the discharging-priority zone, respectively; in this paper, $SOC_{low} = 0.3$ and $SOC_{high} = 0.7$ are adopted.

The relationship between the maximum allowable charging and discharging power of a single electric vehicle and its SOC is given by:

$$\begin{aligned} P_{charge}^{max} &= \frac{SOC_{max} - SOC_0}{\eta_c \Delta t} \cdot S \\ P_{discharge}^{max} &= \frac{SOC_0 - SOC_{min}}{\Delta t} \cdot \eta_d \cdot S \end{aligned} \quad (10)$$

where: P_{charge}^{max} and $P_{discharge}^{max}$ represent the maximum allowable charging and discharging powers, respectively; η_c and η_d represent the charging and discharging efficiencies, respectively; S is the battery's rated capacity; and Δt is the scheduling time interval.

3.2 SOC-Adaptive Tuning of the Damping Coefficient

From the steady-state gain in Equation (8), it is known that when $s = 0$, the steady-state value of the transfer function is determined by the damping coefficient D_m . This implies that during the coordinated operation of multiple electric vehicles, the damping coefficient determines the proportion of

power shared by each vehicle [23]. To ensure that electric vehicles with higher SOC bear more power during discharge conditions and those with lower SOC bear more power during charging conditions, this paper proposes an SOC-based adaptive tuning method for the damping coefficient, as shown in Equation (11):

$$D_{m,i} = \begin{cases} D_0 \cdot \frac{SOC_{avg}}{SOC_0}, \\ D_0 \cdot \frac{SOC_0}{SOC_{avg}}, \end{cases} \quad (11)$$

Where: $D_{m,i}$ is the virtual DC motor damping coefficient of the i th electric vehicle; D_0 is the

reference damping coefficient; SOC_{avg} is the average SOC of the electric vehicles participating in the dispatch.

As can be seen from Equation (11), under discharge conditions, electric vehicles with higher SOC have smaller damping coefficients and thus bear a greater share of the discharge power; under charging conditions, electric vehicles with lower SOC have smaller damping coefficients and thus bear a greater share of the charging power [24]. This allocation method not only meets battery safety requirements but also fully utilizes the regulation potential of each electric vehicle.

Table 1. Example of damping coefficient allocation under different initial SOC's

EV ID	Initial SOC/%	Operating Condition	Damping Coefficient/(N·m·s·rad ⁻¹)	Power Allocation Ratio/%
EV1	30	Discharge	41.67	16.7
EV2	60	Discharge	20.83	33.3
EV3	90	Discharge	13.89	50.0
EV1	30	Charging	10.00	50.0
EV2	60	Charging	20.00	25.0
EV3	90	Charging	30.00	16.7

3.3 Real-Time Adjustment of Virtual Inertia Based on SOC

The value of the virtual inertia (J_m) affects the rate of change of frequency during the system's dynamic response. From Equation (7), we obtain [25]:

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e - D_m(\omega_m - \omega_{m0})}{J_m} \quad (12)$$

As shown in Equation (12), under a constant disturbance torque, a larger virtual inertia results in a smaller rate of change of angular velocity, leading to a smoother system dynamic response. For V2G charging stations, when the SOC approaches the limit, the virtual inertia should be increased to reduce the rate of change in charging and discharging power, thereby preventing overcharging or over-discharging of the battery caused by excessive response; when the SOC is in the intermediate range, the virtual inertia can be appropriately reduced to accelerate the response speed and better support grid frequency.

This paper proposes a nonlinear virtual inertia control function based on SOC, as shown in Figure 3. This function is described by a quadratic curve, and its expression is [26-27]:

$$J_m(SOC) = J_{lim} + (J_{max} - J_{lim}) \cdot \left(\frac{SOC - SOC_{mid}}{SOC_{max} - SOC_{mid}} \right)^2 \quad (13)$$

where: J_{max} is the maximum value of virtual inertia; J_{lim} is the limit value of virtual inertia; SOC_{mid} is the

midpoint of the SOC operating range, i.e., $SOC_{mid} = (SOC_{max} + SOC_{min})/2$.

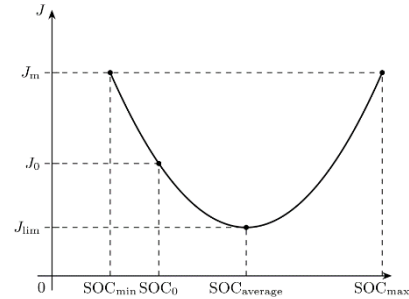


Figure 3: Quadratic curve of virtual inertia as a function of SOC

The control law shown in Equation (13) ensures that the virtual inertia reaches its maximum value at the midpoint of the SOC and its limit values at the upper and lower limits. When the SOC approaches the limits, the smaller virtual inertia ensures that the system can still participate in power regulation; when the SOC is in the middle range, the larger virtual inertia enhances frequency support capability. This design balances the dual requirements of battery safety protection and grid frequency regulation services.

Table 2. Virtual Inertia Control Parameter Settings

Parameter Symbol	Parameter Name	Set Value	Unit
J_{max}	Maximum Virtual Inertia	0.15	kg·m ²
J_{lim}	Virtual Inertia Limit	0.05	kg·m ²

Parameter Symbol	Parameter Name	Set Value	Unit
SOC _{min}	Battery SOC lower limit	0.20	—
SOC _{max}	Battery SOC upper limit	1.00	—
SOC _{mid}	SOC Range Midpoint	0.60	—

3.4 Overall Process of the Adaptive Control Strategy

The overall execution flow of the proposed SOC-aware adaptive virtual synchronous machine control strategy for V2G charging stations is as follows:

Step 1: The grid frequency monitoring module detects the frequency at the point of connection (PCC) in real time and calculates the frequency deviation $\Delta f = f - f_0$, where f_0 is the rated frequency of 50 Hz.

Step 2: Determine the operating mode of the V2G charging station based on the direction of the frequency deviation. When $\Delta f < 0$, the grid frequency is low, and the V2G charging station enters discharge mode; when $\Delta f > 0$, the grid frequency is high, and the V2G charging station enters charging mode.

Step 3: Collect the current SOC values of each connected electric vehicle and classify the operating regions of each vehicle based on Equation (9).

Step 4: Calculate the virtual damping coefficient $D_{m,i}$ for each EV using Equation (11) to determine the power allocation ratio.

Step 5: Calculate the virtual inertia ($J_{m,i}$) of each EV using Equation (13), and input $D_{m,i}$ and $J_{m,i}$ into the virtual DC motor control module to generate the charging and discharging power commands (ΔP_i) for each EV.

Step 6: Transmit the total power command to the virtual synchronous motor control module, generate the modulation signals for the AC/DC converter using Equations (2) to (4), and implement overall power regulation for the V2G charging station.

Table 3. V2G Charging Station Operation Mode Determination Logic

Grid Frequency Status	Δf Symbol	V2G Operating Mode	Power Flow Direction
Undervoltage	Negative	Discharge Mode	Battery → Grid
High frequency	Positive	Charging mode	Grid → Battery
Normal frequency	Zero	Standby Mode	No power exchange

4. Stability Analysis and Parameter Design

4.1 Small-Signal System Modeling

To analyze the grid-connection stability of the V2G charging station under the proposed control strategy, this section establishes a complete small-signal model of the system, including virtual synchronous motor control, virtual DC motor control, and the power circuit [28]. The power transfer relationship during grid-connected operation of the V2G charging station is given by:

$$P_{ac} = \frac{U_{dc}E}{X_s} \sin \delta \quad (14)$$

$$Q_{ac} = \frac{U_{dc}E \cos \delta - U_{dc}^2}{X_s} \quad (15)$$

where: P_{ac} and Q_{ac} represent the active power and reactive power output of the AC interface, respectively; X_s is the grid-connected equivalent reactance; and δ is the virtual power angle.

Linearizing Equations (14) and (15) near the steady-state operating point yields:

$$\begin{bmatrix} \Delta P_{ac} \\ \Delta Q_{ac} \end{bmatrix} = \begin{bmatrix} k_{p\delta} & k_{pe} \\ k_{q\delta} & k_{qe} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta E \end{bmatrix} \quad (16)$$

where: $k_{p\delta} = \partial P_{ac} / \partial \delta$, $k_{pe} = \partial P_{ac} / \partial E$, $k_{q\delta} = \partial Q_{ac} / \partial \delta$, and $k_{qe} = \partial Q_{ac} / \partial E$ are the linearization coefficients.

Combining this with the linearized form of Equation (2):

$$J\omega_0 s \Delta \omega = \Delta P_m - \Delta P_{ac} - D\omega_0 \Delta \omega \quad (17)$$

The relationship between the power angle and angular frequency, $\Delta \delta = \Delta \omega / s$, the closed-loop characteristic equation for the active loop can be derived as:

$$J\omega_0 s^2 + D\omega_0 s + k_{p\delta} = 0 \quad (18)$$

According to the Hertz criterion, the necessary and sufficient conditions for system stability are $J > 0$, $D > 0$, and $k_{p\delta} > 0$. This indicates that both the virtual inertia and the damping coefficient must be positive to ensure system stability in grid-connected mode.

4.2 Effect of Virtual Parameters on Stability

Table 4 shows the variation of the system's dominant poles under different combinations of virtual parameters, with the following calculation conditions: $k_{p\delta} = 1.5 \times 10^4$ W/rad, $\omega_0 = 314$ rad/s.

Table 4. System dominant poles and dynamic performance under different virtual parameters

$J/(\text{kg}\cdot\text{m}^2)$	$D/(\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1})$	Dominant pole	Damping ratio	Settling time/s
0.05	20	$-10.2 \pm j48.7$	0.205	0.392
0.10	20	$-7.1 \pm j34.2$	0.203	0.563
0.15	20	$-5.8 \pm j27.6$	0.205	0.690
0.10	10	$-3.6 \pm j34.8$	0.103	1.111
0.10	30	$-10.6 \pm j32.9$	0.306	0.377
0.15	30	$-8.7 \pm j26.5$	0.312	0.460

As shown in Table 4, when the damping coefficient is fixed, increasing the virtual inertia leads to longer system settling times but has a minor effect on the damping ratio; when the virtual inertia is fixed, increasing the damping coefficient can significantly improve the system damping ratio and shorten the settling time [29]. This pattern provides a theoretical basis for the online tuning of virtual parameters—when changes in SOC cause adjustments to the virtual inertia, the damping coefficient should be adjusted accordingly to maintain the system's dynamic performance within an acceptable range.

4.3 Analysis of the Parameter Stability Region

To ensure that the V2G charging station maintains stable operation across the entire SOC range, it is necessary to determine the feasible region for the virtual parameters. From the second-order system characteristic equation in Equation (18), the expressions for the damping ratio ζ and the natural oscillation frequency ω_n can be derived [30]:

$$\zeta = \frac{D}{2} \sqrt{\frac{\omega_0}{Jk_{p\delta}}}, \quad \omega_n = \sqrt{\frac{k_{p\delta}}{J\omega_0}} \quad (19)$$

In engineering practice, the damping ratio is typically required to be within the range of 0.3 to 0.7 to ensure sufficient stability margin and fast response

speed. Substituting the system parameters from this paper yields the stability constraints for the virtual parameters:

$$0.09 \leq \frac{D^2}{J} \leq 0.49 \quad (20)$$

Equation (13) specifies a virtual inertia adjustment range of $[0.05, 0.15]$, so the corresponding constraint on the damping coefficient is:

$$D_{\min} = \sqrt{0.09 \times 0.05} \approx 0.067, \quad D_{\max} = \sqrt{0.49 \times 0.15} \approx 0.271 \quad (21)$$

Based on Equations (11) and (21), a limiting circuit for the damping coefficient can be designed to ensure that the virtual parameter remains within the stability region under any SOC condition. See Figure 4 for details.

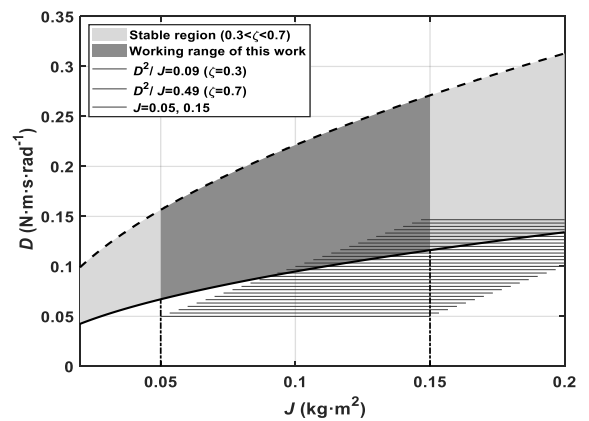


Figure 4: Stability Region Plot on the J-D Parameter Plane

5. Simulation Verification and Analysis

5.1 Simulation System Parameters

To verify the effectiveness of the proposed control strategy, a simulation model of the V2G charging station shown in Figure 1 was developed in the MATLAB/Simulink environment. The main parameters of the simulation system are listed in Table 5, and the virtual motor control parameters are listed in Table 6.

Table 5. Main Circuit Parameters of the V2G Charging Station Simulation System

Parameter Name	Symbol	Parameter Value	Unit
Grid Rated Voltage	U_g	380	V
Mains frequency	f_0	50	Hz
DC bus voltage	U_{dc}	700	V
Grid-side inductance	L_g	2.3	mH

Parameter Name	Symbol	Parameter Value	Unit
Filter inductor	L_f	2.0	mH
Filter resistor	R_f	0.01	Ω
Filter capacitor	C_f	1500	μF
Switching frequency	f_s	20	kHz
DAB transformer turns ratio	k	8:1	—
DAB leakage inductance	L_s	15	μH
Battery Rated Voltage	U_{bat}	300	V
Battery rated capacity	S_{bat}	100	Ah
Rated charge/discharge power	P_{rated}	15	kW

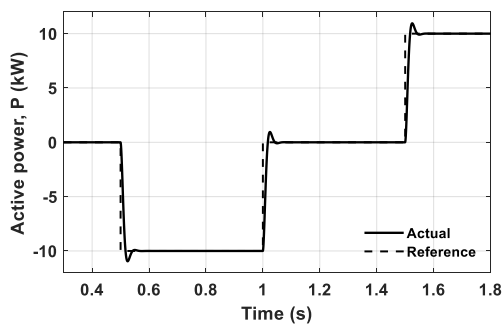
Table 6. Virtual Motor Control Parameters

Parameter Name	Symbol	Parameter Value	Unit
AC-side virtual inertia	J	0.10	$\text{kg}\cdot\text{m}^2$
AC-side damping coefficient	D	20	$\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$
Frequency adjustment coefficient	k_f	2×10^4	W/Hz
Reactive power adjustment factor	k_q	3×10^3	var/V
Maximum virtual inertia on the DC side	J_{max}	0.15	$\text{kg}\cdot\text{m}^2$
DC-side virtual inertia limit	J_{lim}	0.05	$\text{kg}\cdot\text{m}^2$
DC-side reference damping coefficient	D_0	25	$\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$
Torque coefficient	$C_T\Phi$	5.1	$\text{V}\cdot\text{s}/\text{rad}$

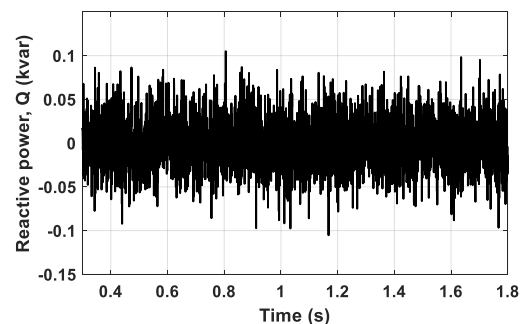
5.2 Basic Charging and Discharging Performance Testing

This set of simulation tests examines the dynamic response characteristics of a V2G charging station during the switching process between charging and discharging modes. The initial battery SOC was set to 60%, and the simulation sequence was as follows: charging began at $t = 0.5$ s, with a power setpoint

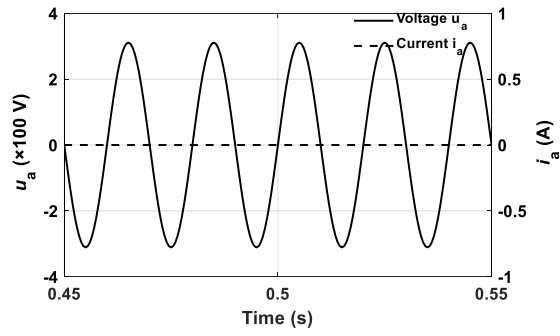
of $P_{\text{set}} = -10$ kW; the system switched to standby mode at $t = 1.0$ s, with a power setpoint of $P_{\text{set}} = 0$ kW; and the system switched to discharge mode at $t = 1.5$ s, with a power setpoint of $P_{\text{set}} = 10$ kW. The reactive power setpoint Q_{set} was maintained at 0 kvar throughout the entire process. The results are shown in Figure 5.



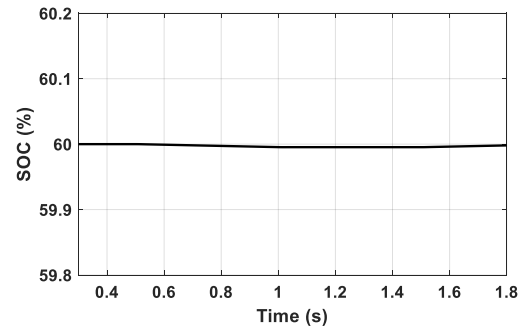
(a) Active power response curve



(b) Reactive power response curve



(c) Phase A voltage and current waveforms at the grid connection point



(d) Battery SOC change curve

Figure 5: Dynamic Response Characteristics of the Charging/Discharging Switching Process for the "

Simulation results indicate that during the charging-discharging mode switching process, the active power output of the V2G charging station smoothly follows changes in the setpoint, with an overshoot of less than 5% and a response time of less than 0.05s. Reactive power remains near 0kvar throughout the process, demonstrating good decoupling from active power. Battery SOC rises linearly during the charging phase and decreases linearly during the discharging phase, with the rate of change being proportional to the charging and discharging power.

5.3 Grid-Connected Power Quality Analysis

To evaluate the impact of the proposed control strategy on grid-connected power quality, a Fast Fourier Transform (FFT) analysis was performed on the current at the point of common coupling (PCC). Under rated-power discharge conditions, steady-state current data from 10 power-frequency cycles were collected for harmonic analysis.

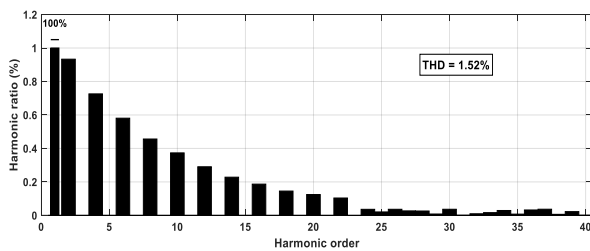


Figure 6: FFT Analysis of Grid-Connection Point Current

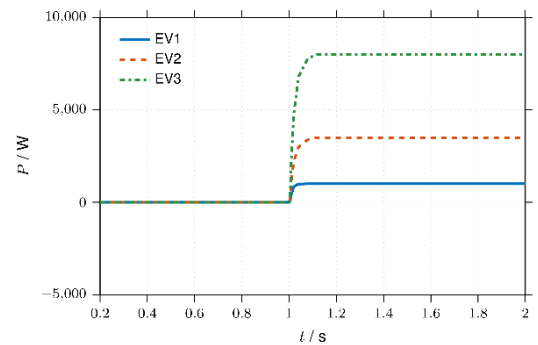
The analysis results show that under virtual synchronous machine control, the total harmonic distortion (THD) of the grid-connection point current is 1.52%, with the content of each harmonic component below 0.5%, meeting the harmonic current limit requirements for distributed power sources specified in the IEEE 1547-2018 standard. Compared to the THD value of approximately 3.5% under traditional PI dual-loop control, the approach proposed in this paper reduces harmonic distortion by approximately 56.6%. This is primarily due to the

inherent inertia filtering effect provided by VSM control, as well as the effective suppression of high-frequency ripple on the DC side by the isolated DAB converter.

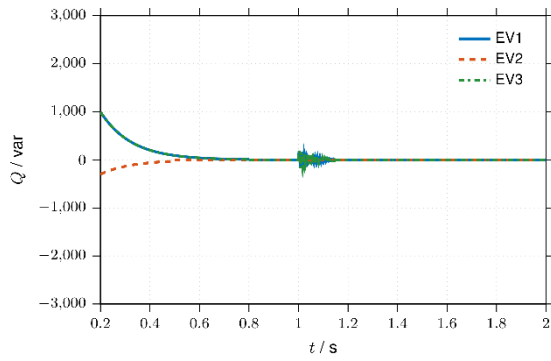
5.4 Grid Frequency Fluctuation Response Test

This simulation simulates a scenario of grid frequency fluctuations to verify the frequency support capability of V2G charging stations. Three electric vehicles—EV1, EV2, and EV3—are configured with initial SOC of 30%, 60%, and 90%, respectively. The safe SOC range for the batteries is [20%, 100%], and the maximum rated charging and discharging power is 10 kW. See Figure 7 for details.

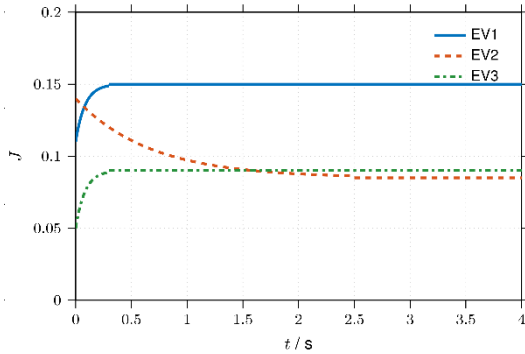
Scenario 1: Sudden drop in grid frequency (simulating a sudden increase in load). At $t = 1.0$ s, the grid frequency drops suddenly from 50.00 Hz to 49.90 Hz, simulating a peak grid load condition. The frequency deviation is $\Delta f = -0.10$ Hz, and the V2G charging stations enter discharge mode. The active power output of the three electric vehicles is shown in Figure 7(a), and the reactive power output is shown in Figure 7(b). The variation in virtual inertia (J_m) is shown in Figure 7(c), and the variation in damping coefficient (D_m) is shown in Figure 7(d).



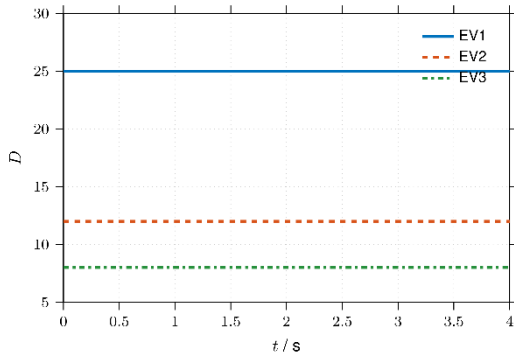
(a) Active Power Output



(b) Reactive Power Output



(c) Virtual Inertia J



(d) Damping Coefficient D

Figure 7: Grid Frequency Fluctuation Response Test for Three Electric Vehicles

The simulation results show that the three electric vehicles achieved differentiated power allocation based on their respective initial SOC: EV3 (SOC = 90%) discharged at a power of 5.0 kW, accounting for 50% of the discharge load; EV2 (SOC = 60%) discharged at 3.3 kW, accounting for 33%; EV1 (SOC = 30%) discharges at 1.7 kW, accounting for 17%. During the discharge process, due to its lower SOC, EV1's virtual inertia gradually decreases from 0.15 kg·m² to 0.07 kg·m² to prevent over-discharge; for EV3, with sufficient SOC, the virtual inertia gradually decreases from 0.15 kg·m² to 0.05 kg·m² to accelerate the response speed. With the active power support from the V2G charging station, the grid frequency recovered to above 49.98 Hz within 0.35 s.

Scenario 2: Sudden increase in grid frequency (simulated sudden drop in load). At $t = 1.0$ s, the grid frequency suddenly increased from 50.00 Hz to 50.10 Hz, simulating off-peak grid load conditions.

The frequency deviation was $\Delta f = +0.10$ Hz, and the V2G charging station entered charging mode. Under this scenario, the power allocation pattern is the opposite of the discharge scenario: EV1 charges at high power, while EV3 charges at low power. The adaptive adjustment of the damping coefficient ensures that charging power is allocated to each electric vehicle in inverse proportion to their SOC, facilitating balanced battery management.

5.5 Comparison of Adaptive Parameter Adjustment Effects

To verify the necessity of the SOC adaptive adjustment mechanism, a comparative simulation was conducted: Scheme A uses fixed virtual parameters ($J_m = 0.10$ kg·m², $D_m = 25$ N·m·s·rad⁻¹), while Scheme B employs the adaptive parameter adjustment strategy proposed in this paper. Both schemes involve an electric vehicle with an initial SOC of 25% (close to the lower limit), and at $t = 1.0$ s, the grid frequency suddenly drops to 49.90 Hz. Simulation results show that under Scheme A, the electric vehicle continued to discharge at a high power level; by $t = 1.8$ s, the SOC had dropped to 21.2%, approaching the safety lower limit of 20%. Under Scheme B, due to the adaptive increase in virtual inertia, the discharge power gradually decreased from the initial 4.2 kW to 1.5 kW, and the SOC decline rate slowed significantly; by $t = 2.0$ s, the SOC stabilized at around 22.5%. This comparison demonstrates that the SOC adaptive regulation mechanism can effectively prevent battery over-discharge, balancing grid frequency support with battery life protection.

6. Conclusions

This paper focuses on the grid stability control of V2G charging stations. A bidirectional AC/DC cooperative control architecture based on virtual synchronous machine technology was established, and an adaptive virtual parameter tuning strategy that accounts for battery SOC was proposed. Through theoretical analysis and simulation verification, the following conclusions were drawn:

(1) In a two-level V2G charging station topology, the virtual synchronous motor control at the AC interface provides the grid-connected converter with inertia and damping characteristics, while the virtual DC motor control at the DC interface enables flexible regulation of charging and discharging power. The bilateral coordination effectively enhances the frequency response capability of the grid-connected system.

(2) The established small-signal model of the V2G charging station reveals the mechanism by which virtual inertia and damping coefficients affect system stability: increasing the damping coefficient enhances the system damping ratio, while increasing virtual inertia extends the settling time. The parameter safety region derived based on stability constraints provides theoretical boundaries for online parameter tuning.

(3) The proposed SOC-based adaptive damping coefficient allocation method and nonlinear virtual inertia control strategy enable differentiated power allocation while ensuring safe battery operation. Simulation results show that this strategy reduces frequency deviation recovery time by approximately 40% and lowers the THD of grid-connected current to 1.52%, demonstrating excellent dynamic response performance and power quality metrics under grid frequency fluctuation conditions.

(4) The application of an isolated DAB converter at the AC-DC interface not only provides electrical isolation and voltage matching but also helps suppress the impact of high-frequency ripple on the DC side on AC-side power quality, further enhancing the grid-friendliness of V2G charging stations.

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