
Research article

Power sharing and circulating current suppression control of M-SMES based on AVSG

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Abstract: By integrating multiple superconducting magnetic energy storage units (SMESU), the multi-superconducting magnetic energy storage system (M-SMES) facilitates the capacity expansion and standardization of energy storage systems. However, during parallel operation, parameter and dynamic mismatches among units often cause uneven power sharing and circulating currents. To address this, an adaptive virtual synchronous generator (AVSG) control method was proposed to achieve stable operation. First, the power transfer characteristics of M-SMES and the circulating current characteristics arising from the cascaded converter structure were analyzed. Second, a coordinated control strategy for the cascaded converters was designed accordingly. The front-stage DC/DC chopper employs voltage-current dual-loop control to guarantee DC-link voltage stability, while the rear-stage DC/AC inverter adopts adaptive inertia and damping control to ensure efficient and stable power delivery, thereby achieving effective active power sharing and reducing active circulating currents. Subsequently, the virtual complex impedance was dynamically adjusted based on the reactive power deviation to accomplish reactive power sharing and suppress reactive circulating currents. Finally, simulation results of a three-unit parallel system on the Matlab/Simulink platform verify the superior performance of the proposed strategy in power sharing and circulating current suppression.

Keywords: M-SMES; power sharing; circulation suppression; virtual synchronous generator; adaptive control

1. Introduction

Superconducting magnetic energy storage (SMES), as a new type of energy storage technology that is both highly efficient and capable of rapid response, has demonstrated significant potential in recent years in areas such as power systems, renewable energy integration, and industrial applications [1]. Leveraging the zero-resistance property of superconductors, SMES can store and release electrical energy with virtually no losses, thereby enabling efficient energy dispatch within milliseconds. This provides innovative solutions to issues such as power grid stability, the smooth integration of intermittent renewable energy sources, and the instantaneous supply of power to critical loads [2]. With the development of high-temperature superconducting materials and advances in power electronics technology, the economic viability and practicality of SMES systems have gradually improved, making them one of the current research hotspots in the field of energy storage [3].

In large-scale application scenarios, employing multiple SMESUs connected in parallel to form an M-SMES represents the core technical approach for achieving capacity expansion of energy storage systems, enabling standardized manufacturing, and enhancing redundant reliability. However, due to parameter variations among SMESUs, line impedance mismatches, and incomplete synchronization of control strategies, the system is highly prone to uneven power distribution and circulating current issues [4,5]. Uneven power distribution can cause some modules to operate under overload, reducing overall efficiency, while circulating currents not only increase additional losses but may also threaten the safety and stability of superconducting coils [6]. Therefore, achieving precise power sharing and circulating current suppression in M-SMES systems has become a key challenge in improving the system's overall performance.

Currently, there is relatively little research on power sharing and circulating current suppression in M-SMES systems, both domestically and internationally; however, there is a significant body of research on multi-energy-storage inverter systems. The focus has been on adapting existing control strategies designed for multi-energy-storage inverter systems to M-SMES systems in order to achieve the specified control objectives. In the field of control optimization for individual SMES units, existing research has enhanced system control performance from various perspectives, including model predictive control, parameter optimization design, and harmonic suppression. In reference [7], model predictive control (MPC) was employed to control an SMES system, and a recursive least-squares identification method was used to estimate system model parameters online, thereby mitigating the impact of model uncertainty on control performance. Model predictive control does not require adjustment of controller parameters but demands high model accuracy and involves significant computational complexity. Reference [8] investigated the influence of SMES operating parameters on voltage distribution characteristics and proposed a comprehensive parameter optimization design method to reduce voltage distribution non-uniformity; however, the computational load remains relatively high. Reference [9] proposed a method combining model predictive control and proportional-integral control for application to the converters in SMES systems, which ensures stable operation while reducing the harmonic components in the DC current of the superconducting coils and minimizing eddy current losses. However, in SMES systems with voltage-source converters, the DC/DC chopper applies high-frequency PWM voltage to the superconducting magnets, causing the PWM voltage to be unevenly distributed within the magnets and compromising their insulation. Reference [10] designed a power regulation control strategy to ensure that, during charging and discharging, the SMES magnets are subjected to a constant DC voltage rather than a high-frequency PWM

voltage, thereby avoiding voltage oscillations within the magnets. The studies in references [7–10] all focus on the operational control of a single SMESU; however, they did not address the collaborative operation mechanism for multiple SMESUs operating in parallel. Furthermore, reference [11] employed a grid-connected VSG approach and proposed a self-stabilizing, induced-stabilizing four-loop analysis framework; reference [12] further introduced an oscillation propagation coefficient and a standardized discriminant procedure, elucidating the physical nature of the oscillation transmission between the frequency and voltage of a single-machine grid-connected VSG. Building upon this coupled-mechanism framework, reference [13] proposed a composite control strategy combining active power deviation feedforward and frequency positive feedback, which effectively suppresses active power oscillations in single-machine grid-connected systems and eliminates steady-state active power deviations under grid frequency disturbances. This strategy is specifically designed for single-stage, single-machine grid-connected topologies; its inverter control methodology can be adapted for use in a standalone SMESU system. However, none of the aforementioned references have investigated the application of these approaches to multi-machine parallel systems.

In the field of coordinated control for multi-energy storage systems, existing research has made certain progress in areas such as frequency regulation and robustness enhancement. References [14,15] proposed a distributed load frequency control strategy based on consensus theory, which achieved rapid frequency regulation through a multi-agent cooperative control framework, effectively addressing the dynamic coordination control issues of multi-energy storage systems during grid-connected operation. References [16,17] enhanced the robustness and dynamic response characteristics of the dual-loop control strategy by incorporating disturbance current compensation and power feed forward control. Although references [14–17] addressed the issues of capacity optimization and coordinated control for multi-energy storage systems, they did not fully consider the impact of power allocation and circulating currents on the system's stable operation. Reference [18] proposed a centralized energy management architecture that achieved proportional power sharing among SMESUs and dynamic SOC balancing in a hybrid AC/DC microgrid, supporting uniform power allocation across the entire system and reducing circulating currents. Reference [19] improved power distribution accuracy and suppressed circulating current by optimizing the DC bus energy management strategy. Reference [20] proposed a novel distributed hierarchical control method for fast frequency recovery based on the underlying real-time VSG control, where the power reference values generated by this strategy can accelerate the frequency recovery process through precise power allocation. However, the aforementioned study did not systematically consider the coupled effect of differences in inverter control parameters and line impedance mismatch on power distribution accuracy, nor has it employed a collaborative control design that takes into account the cascaded nature of the converters; as a result, it is difficult to fully align with the operating characteristics of M-SMES.

In conclusion, this study proposes a composite control strategy based on AVSG to address the issues of uneven power distribution and circulating current suppression from the perspective of cascaded converter collaborative control. This strategy employs a hierarchical control architecture: the front-stage DC/DC chopper utilizes dual-loop voltage- and current-controlled regulation to maintain DC bus voltage stability, while the rear-stage DC/AC inverter incorporates an adaptive regulation mechanism incorporating inertia and damping to meet dynamic response requirements under various operating conditions. Additionally, a dynamic virtual impedance component is integrated to provide real-time compensation for line impedance variations and optimize the reactive power distribution characteristics, thereby achieving multiple objectives—including stable system operation, precise

power equalization, and effective suppression of circulating currents.

The subsequent chapters follow a logical sequence encompassing theoretical analysis, strategy design, and simulation verification. Chapter 2 introduces the overall topology of the M-SMES and the operating principle of its two-stage converter; Chapter 3 derives the system's power transmission characteristics and analyzes the mechanisms underlying circulating current generation as well as the key influencing factors under various operating conditions; Chapter 4 provides a detailed exposition of the complete design process for the proposed control strategy, covering the constant-voltage charging and discharging control for the front-end DC/DC chopper, the AVSG adaptive inertia damping control for the rear-end DC/AC inverter, and the dynamic virtual impedance design, along with a method for tuning key parameters and a proof of system stability; and Chapter 5 constructs a parallel-operating three-machine simulation model using Matlab/Simulink and validates the performance of the proposed strategy in terms of power sharing and circulating current suppression through comparisons under typical operating conditions. This control method addresses the collaborative control challenge associated with the parallel operation of M-SMES systems from a system-level perspective, offering a novel technical approach to enhance system power quality and operational reliability.

2. The overall architecture of M-SMES

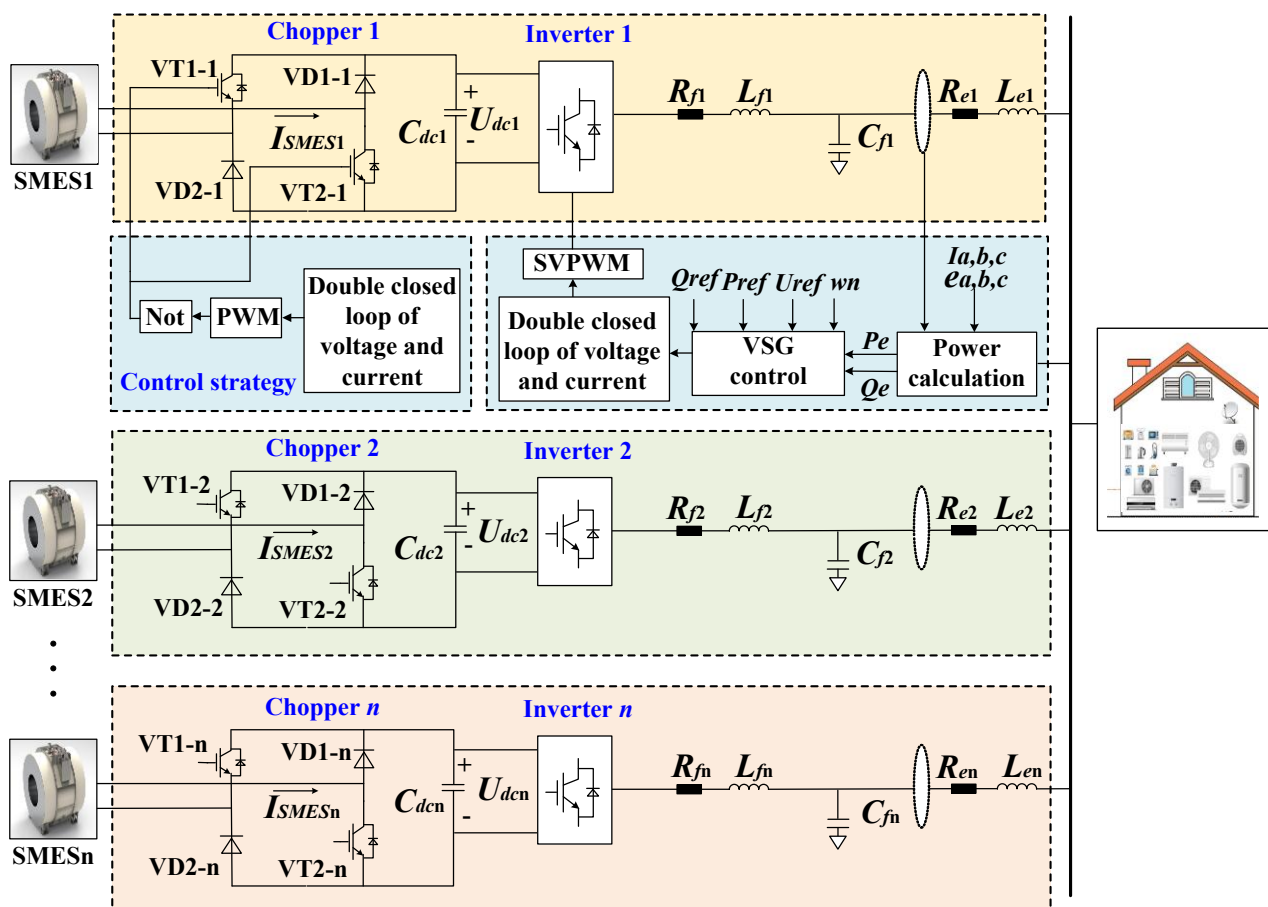


Figure 1. Topological structure of M-SMES.

The topological structure of M-SMES is shown in Figure 1. Each SMESU consists of an SMES, a DC/DC chopper, a DC/AC inverter, and corresponding control circuits, all adopting a two-stage structure to supply power to AC loads. The working principle of the M-SMES is as follows: the voltage-current dual closed-loop control of the DC/DC chopper ensures the effective power supply of the SMES and the stability of the DC-side voltage; the AVSG control and dynamic virtual impedance design of the DC/AC inverter guarantee the stable power supply of AC loads, while realizing power sharing and circulating current suppression of the system, thereby ensuring the safe and stable operation of the M-SMES.

In Figure 1, C_{dc} is the DC-side capacitor; U_{dc} is the DC-side voltage; Z_{si} is the filter impedance, $Z_{si} = R_{fi} + L_{fi}$; C_f is the filter capacitor; Z_e is the line impedance, $Z_e = R_e + L_e$; $I_{a,b,c}$ are the output currents of the inverter; $e_{a,b,c}$ are the midpoint potentials of the inverter bridge arms; P_e and P_{ref} represent the active power output by AVSG and the active power set value, respectively; Q_e and Q_{ref} represent the reactive power output by AVSG and the reactive power set value, respectively; ω_n is the rated angular speed; U_{ref} is the three-phase rated voltage set value output by AVSG; and VD and VT are diodes and switching tubes, respectively.

3. Analysis of the operational characteristics of M-SMES

3.1. Power transmission characteristics

Taking a parallel system of two SMESUs with the same rated capacity as the research object, this paper analyzes its operating characteristics under three-phase balanced load conditions. Under the action of the proposed voltage-current dual closed-loop control strategy for the DC/DC chopper, the SMES and its chopper can be treated as an equivalent constant voltage source, and thus the equivalent circuit of the parallel system of the two SMESUs is obtained as shown in Figure 2.

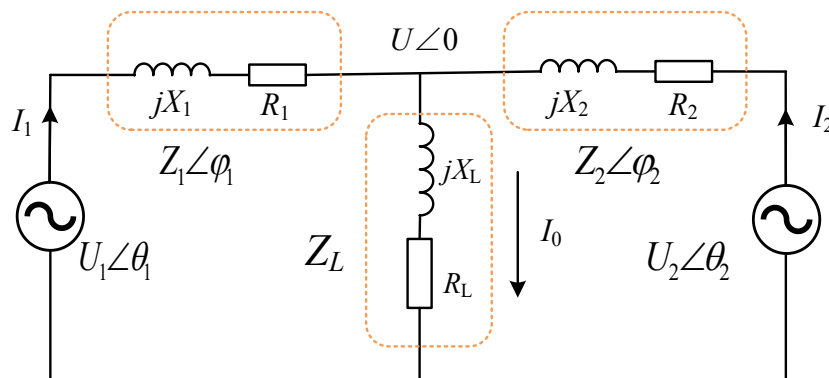


Figure 2. The equivalent circuit of two SMESUs in parallel.

In Figure 2, $U\angle 0$ is the AC bus voltage; Z_L is the AC impedance, $Z_L = R_L + jX_L$; $Z_i (i = 1, 2)$ is the output impedance of each SMESU, $Z_i = R_i + jX_i$; $U_i (i = 1, 2)$ is the electromotive force of each SMESU; $I_i (i = 1, 2)$ is the output current of each SMESU; and I_0 is the AC bus current.

It can be seen from Figure 2 that the active power and reactive power output by each SMESU are respectively as follows:

$$P_i = \frac{\left[(U_i U \cos \theta_i - U_L^2) \cos \varphi_i + U_i U \sin \theta_i \sin \varphi_i \right]}{Z_i} \quad (1)$$

$$Q_i = \frac{\left[(U_i U \cos \theta_i - U_L^2) \sin \varphi_i - U_i U \sin \theta_i \cos \varphi_i \right]}{Z_i} \quad (2)$$

The active and reactive power outputs from each SMESU are given by Eqs 1 and 2, respectively. Under the operating condition of a parallel system, since the phase difference between the AC-side output voltage of each device and the load voltage is very small, the following approximation can be applied: $\sin \theta = \theta$, $\cos \theta = 1$. Thus, the following expression can be derived:

$$\begin{cases} P_i = \frac{U_i U R_i - U^2 R_i + U_i U X_i \theta_i}{R_i^2 + X_i^2} \\ Q_i = \frac{-U_i U R_i \theta_i - U^2 X_i + U_i U X_i}{R_i^2 + X_i^2} \end{cases} \quad (3)$$

According to Eq 3, a detailed analysis of the active power output characteristics of the device can be conducted. This analysis method takes the output voltage amplitude and phase angle of the SMESU as key variables, differentiates the active power, and obtains the following expression:

$$\begin{cases} \frac{dP_i}{d\theta_i} = \frac{E_i X_i U}{R_i^2 + X_i^2} \\ \frac{dP_i}{dU_i} = \frac{U(R_i + X_i \theta_i)}{R_i^2 + X_i^2} \end{cases} \quad (4)$$

According to the result of Eq 4, the phase angle and amplitude of the device's output voltage are both positively correlated with the output of active power. By comparing and analyzing the influence degrees of these two control variables, taking the first SMESU as an example, it can be obtained that:

$$\frac{\frac{dP_1}{d\theta_1}}{\frac{dP_1}{dU_1}} = \frac{U_1 X_1}{R_1 + X_1 \theta_1} = \frac{U_1}{\frac{R_1}{X_1} + \theta_1} \quad (5)$$

When the parallel system is operating stably, the phase angle of the output voltage of SEMSU is relatively small. When the circuit exhibits inductive output characteristics ($R \ll X$), the following approximate relationship can be derived:

$$\frac{\frac{dP_1}{d\theta_1}}{\frac{dP_1}{dU_1}} \gg 1 \quad (6)$$

Similarly, for the reactive power output of the first SMESU, the analysis yields:

$$\begin{cases} \frac{dQ_1}{d\theta_1} = -\frac{U_1 U R_1}{R_1^2 + X_1^2} \\ \frac{dQ_1}{dU_1} = -\frac{U(R_1\theta_1 - X_1)}{R_1^2 + X_1^2} \end{cases} \quad (7)$$

Based on the above analysis, since the circuit is inductive, $R\theta - X < 0$, it follows that $dQ/dU > 0$. Therefore, the reactive power output by the SMESU is positively correlated with the output voltage amplitude and negatively correlated with the voltage phase angle. Thus, we can conclude:

$$\frac{-\frac{dQ_1}{d\theta_1}}{\frac{dQ_1}{dU_1}} = \frac{U_1 R_1}{X_1 - R_1\theta_1} = \frac{U_1}{\frac{X_1}{R_1} - \theta_1} \quad (8)$$

When the circuit exhibits inductive characteristics, the output voltage amplitude of SMESU is much smaller than X/R . Therefore, the calculation result of Eq 8 is much less than 1 and can be reasonably ignored. Based on the above theoretical analysis and approximate assumptions, Eqs 1 and 2 in the original text can be simplified to the following Eqs 9 and 10:

$$P_i = \frac{U_i U}{X_i} \theta_i \quad (9)$$

$$Q_i = \frac{U(U_i - U)}{X_i} \quad (10)$$

It can be known from Eqs 9 and 10 that when the line output impedance is inductive, the output power characteristics of the system are closely related to the line impedance parameters. Specifically, the active power mainly depends on the voltage phase angle difference, while the reactive power is mainly determined by the voltage amplitude difference.

3.2. Power circulating current characteristics

When the output power of the DC/AC inverters in SMESUs operating in parallel is not distributed in proportion to their rated capacities, unbalanced circulating currents will be generated within the system. In Figure 2, assume that the two SMESUs have equal transmission impedances, an equivalent output impedance that is inductive, and a line impedance that is much smaller than the equivalent output impedance, $\sin\theta = \theta$ and $\cos\theta = 1$. The corresponding circulating currents are:

$$I_H = \frac{U_1 \angle \theta_1 - U_2 \angle \theta_2}{2jX_1} = \frac{U_1 \theta_1 - U_2 \theta_2}{2X_1} + \frac{U_1 - U_2}{2jX_1} \quad (11)$$

The magnitude of the circulating current is closely related to the difference in output voltage

amplitude, the phase angle difference, and the inductive impedance of the line. The characteristics of the circulating current under different operating conditions and the factors affecting it are summarized in Table 1.

Based on the analysis in Table 1, the mitigation measures for active and reactive circulating currents caused by output voltage phase differences or amplitude differences under various operating conditions can all be summarized as achieving precise synchronization of the output voltage amplitude and phase of each unit through control, as well as effectively increasing the inductive component of the system transmission impedance.

Table 1. Circulation characteristics of M-SMES under different operating conditions.

Operating conditions	Voltage conditions	Dominant circulating current type	Factors affecting circulating currents
1	$U_1 = U_2, \theta_1 \neq \theta_2$	Active current	Positively correlated with the phase difference and inversely proportional to the inductive reactance
2	$U_1 \neq U_2, \theta_1 = \theta_2$	Reactive current	Positively correlated with the amplitude difference and inversely proportional to the inductive reactance
3	$U_1 \neq U_2, \theta_1 \neq \theta_2$	Active and reactive currents	Correlated with both the amplitude difference and the phase difference

The active component circulation will introduce power disturbances into the active control loop of AVSG, causing virtual angular velocity oscillations and reducing the frequency stability margin of the system. The reactive component circulation will disturb the reactive control loop, intensifying the amplitude fluctuations of the output voltage and the voltage drop at the busbar, and weakening the voltage stability of the system.

It should be noted that the above decoupling analysis of active and reactive circulating currents relies on the small power angle assumption ($\sin\theta = \theta, \cos\theta = 1$). Therefore, the applicability of this characteristic is primarily limited to the steady-state operation of M-SMES systems and conventional conditions with minor disturbances. When the system experiences major disturbances, such as a severe short-circuit fault, the system's power angle may deviate drastically. At this point, the linearization approximation based on the small power angle fails, and the system exhibits strong nonlinear characteristics; consequently, the complete decoupling of circulating currents derived from the above analysis will be subject to certain limitations. However, the AVSG control strategy proposed in this paper remains applicable to some extent under such operating conditions. Due to the introduction of an adaptive adjustment mechanism for inertia J and damping D , during the acceleration or deceleration phases at the onset of major disturbances, the system can adjust these coefficients in response to angular velocity fluctuations, effectively suppressing excessive divergence of the power angle and enhancing the unit's transient synchronous stability. Nevertheless, to address major power angle instability caused by severe short-circuit events, the M-SMES system must be supplemented with other control strategies and auxiliary measures, such as emergency current-limiting protection, to ensure system stability and safety.

In conclusion, the power distribution deviation and the circulating current between parallel units will directly affect the operational stability of each SMESU. If the power distribution effect of the

parallel system is poor, some superconducting magnetic energy storage units will be subjected to overload charging and discharging conditions; the current on the superconducting coil side will fluctuate more intensely, which will cause oscillations in the DC bus voltage of the preceding DC-DC converter, thereby introducing disturbances to the power outer loop of the AVSG, reducing the unit's small-signal stability margin. In severe cases, it will bring the risk of superconducting coil overcurrent. On the other hand, the circulating current between parallel units will form secondary power fluctuations on the DC side, introducing additional disturbances to the control loop of the converter, and further affecting the stability of the DC voltage and coil current.

4. Power sharing and circulating current suppression control in M-SMES

4.1. Constant-voltage charge and discharge control of DC/DC choppers

Under the control of the DC/DC chopper, the SMES primarily operates in three modes: charging mode, discharging mode, and storage mode. In charging and discharging modes, the SMES exchanges power with an AC load. In discharging mode, VT1 and VT2 are both turned off, and electrical energy flows from the superconducting coil to the DC-side capacitor. In charging mode, VT1 and VT2 are both turned on, and electrical energy flows from the DC-side capacitor into the superconducting coil. In storage mode, the complementary conduction of VT1 and VT2 forms a hold-up circuit consisting of L_{sc} -VT1-VD1 or L_{sc} -VT2-VD2, which maintains the continuous flow of the superconducting coil current I_{SMES} , thereby keeping the system's stored energy stable [21,22]. The energy stored by the SMES can be expressed as:

$$E_{SMES}(t) = 0.5 \times L_{SC} I_{SMES}^2 \quad (12)$$

The SMES chopper employs dual-loop voltage and current control to achieve constant-voltage charging and discharging; the control block diagram is shown in Figure 3. After comparing the DC-side voltage reference value U_{dc}^* with the measured value, a voltage outer-loop PI controller generates the superconducting coil current reference value I_{SMES}^* . The difference between this reference value and the actual superconducting coil current I_{SMES} is then dynamically tracked by a current inner-loop PI regulator. This signal is modulated via PWM to generate the chopper switching signals, thereby controlling the charging and discharging of the SMES to achieve precise regulation of the DC-side voltage.

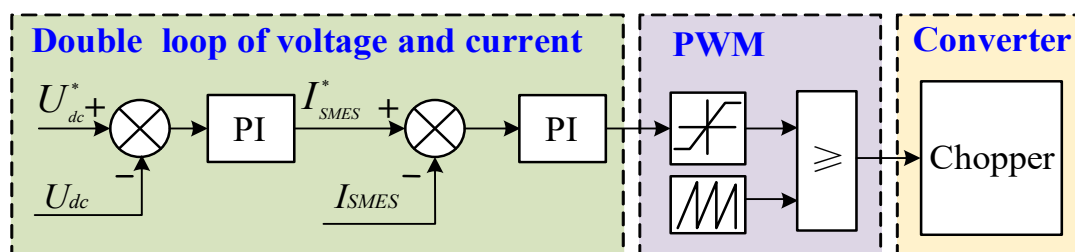


Figure 3. The control block diagram of the DC/DC chopper.

4.2. AVSG control of DC/AC inverter

Based on the stable voltage regulation of the DC side achieved through the previous stage DC/DC chopper, the subsequent DC/AC inverter introduces the virtual synchronous generator (VSG) technology. By simulating the rotor rotational inertia and damping characteristics of a synchronous generator, the M-SMES system acquires electromechanical external characteristics similar to those of a synchronous generator, providing inertia support and damping effects for the system, effectively suppressing frequency fluctuations and voltage drops under disturbances, thereby enhancing the operational stability of the power system. Simultaneously, the unified electromechanical transient simulation mechanism of VSG also provides a consistent synchronization reference for the parallel operation of multiple SMES units, enabling dynamic power coordination allocation among units and effectively improving the flexibility and controllability of the system operation.

Traditional VSGs, which employ fixed inertia and damping parameters and are affected by variations in transmission line impedance, are prone to causing uneven power distribution and circulating current issues when SMESUs operate in parallel [23,24]. To address this issue, this paper proposes an AVSG control strategy that achieves efficient and stable power supply and power sharing through adaptive inertia-damping control of the downstream DC/AC inverter. By dynamically adjusting the virtual complex impedance based on reactive power deviation, the strategy achieves better power sharing and circulating current suppression, significantly enhancing the dynamic coordination capability of the M-SMES. The control block diagram is shown in Figure 4.

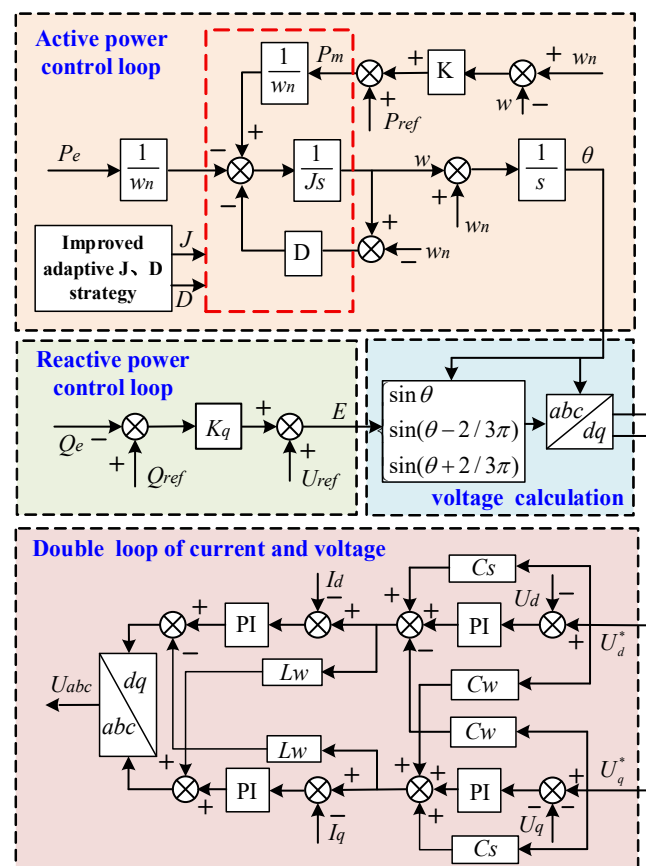


Figure 4. The AVSG control block diagram of the DC/AC inverter.

The core of the AVSG control strategy lies in the simulation of the synchronous generator characteristics using a dual-loop active-reactive control system: its active-power control loop precisely reproduces the synchronous generator inertia response and damping characteristics through equivalent rotor motion equations and active-power-frequency droop equations; the reactive-power control loop, based on reactive-power-voltage droop equations, accurately simulates the synchronous generator voltage regulation characteristics [25]. The specific control equations are expressed as follows:

$$\begin{cases} J \frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_n) \\ T_m - T_e = \frac{P_m - P_e}{\omega_n} \\ P_m = P_{ref} + K(\omega_n - \omega) \\ E = U_{ref} + K_q(Q_{ref} - Q_e) \end{cases} \quad (13)$$

where J and D are the virtual moment of inertia and damping coefficient, respectively; P_m , P_e , and P_{ref} are the mechanical power, electromagnetic power, and active power reference value of the AVSG, respectively; T_m is the mechanical torque; T_e is the electromagnetic torque; ω is the output angular velocity; ω_n is the rated angular velocity; K is the droop coefficient. Q_e and Q_{ref} are the reactive power and reactive power reference value of the AVSG, respectively; U_{ref} is the reference value of the three-phase rated voltage; and K_q is the reactive power-voltage droop coefficient.

Dual-loop voltage and current control enable the AVSG output voltage to track the voltage reference value calculated by the power loop, using a PI controller to ensure minimal error and fast response.

To achieve precise power sharing and circulating current suppression in an M-SMES system, the limitations of traditional VSG fixed-parameter control must be addressed. Although VSG provides basic control capabilities for simulating a synchronous machine for a single SMESU, fixed J and D values cannot adapt to dynamic operating conditions and unit variations. When a power disturbance occurs in the system, the units with smaller capacity and lower line impedance have a faster rate of power angle change, while the units with larger capacity and higher line impedance respond relatively later. A transient power angle difference forms between the units, which leads to dynamic desynchronization during the disturbance and causes power imbalance and circulating currents. Moreover, the fixed J and D cannot simultaneously meet the requirements of suppressing transient oscillations and providing a rapid response. The relatively small inertia has a fast response speed but a large power angle oscillation amplitude and a long circulating current duration; the relatively large inertia has a low oscillation amplitude but a delayed response, which will cause the peak value of the transient power angle difference to increase, and both are difficult to achieve the optimal power balance and circulating current suppression effect. Therefore, adaptive control of J and D must be introduced to enable all paralleled units to coordinate adjustments to their power and frequency responses during load changes, ensuring stable system operation.

The necessity of AVSG control stems from the dynamic response characteristics of SMESU under grid disturbances. As shown in Figure 5, the process of power output and frequency oscillation of the SMESU after being disturbed can be divided into four dynamic response stages with distinct characteristics. The SMESU operates stably at point a ; after being disturbed, the power angle suddenly changes from δ_0 to δ_1 , and the operating point of the AVSG abruptly shifts from point a to point b .

Due to the presence of the damping coefficient D in the AVSG, the operating point of the AVSG does not change along the line $b-a-c$, but follows the line $b-o-c-o'-d$.

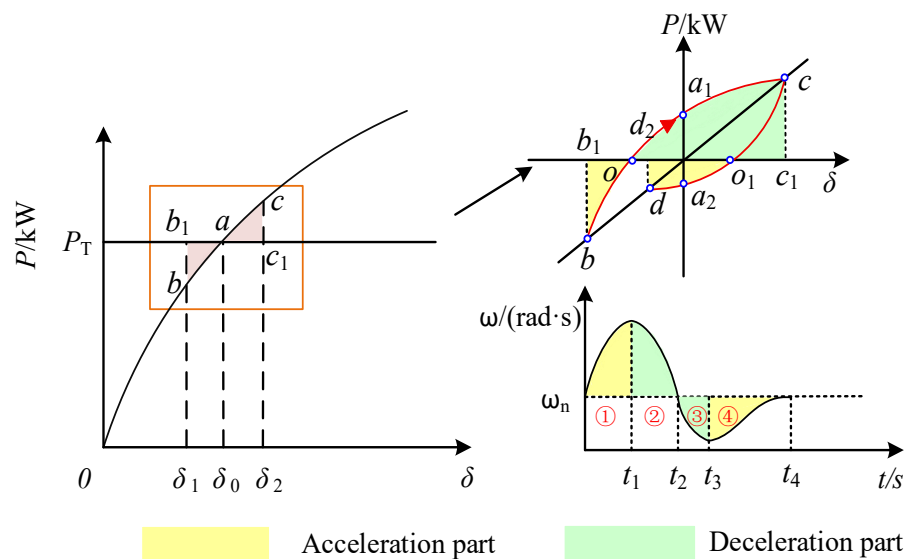


Figure 5. Angular velocity fluctuations and local magnification of power angle characteristics.

In the acceleration phases (Phase 1 and Phase 3) of the SMESU dynamic response to disturbances characterized by $\Delta\omega d\omega/dt > 0$ and a continuous increase in $|\omega - \omega_n|$, the control strategy needs to achieve an optimal balance between inertia and damping. Increasing J can effectively suppress the amplitude of rotor angular velocity deviation, but will sacrifice the system's response speed. Therefore, it is necessary to reduce D in coordination to improve dynamic response performance while ensuring system stability. This coordinated control not only avoids the accumulation of phase deviations caused by the delayed response of high-inertia units but also prevents overshoot in low-inertia units. More importantly, it promotes parallel SMESUs to quickly establish a synchronous state by reducing damping, significantly reducing the initial phase difference and the dispersion of response speeds among units, thereby enhancing the dynamic coordination performance of the M-SMES system. Similarly, in the deceleration phases (Phase 2 and Phase 4), J needs to be reduced to accelerate the recovery of rotor angular velocity to the steady-state value. At the same time, appropriately increasing D can effectively promote faster convergence of all SMESUs to a unified steady-state frequency, thereby shortening the duration of power differences during the recovery process and suppressing system overshoot. The overall rules are shown in Table 2.

Table 2. Changing situation of J and D .

Number	$d\omega/dt$	$\Delta\omega$	$(d\omega/dt) \Delta\omega$	J	D
1	>0	>0	>0	Increase	Reduce
2	<0	>0	<0	Reduce	Increase
3	>0	<0	>0	Increase	Reduce
4	<0	<0	<0	Reduce	Increase

Based on the parameter analysis in Table 1, the adaptive control strategies for J and D are designed as follows:

$$\begin{aligned}
 J &= \begin{cases} J_0 & |\Delta\omega| \leq K_{J_0} \\ J_0 + a \frac{1}{T_{i1}S+1} \left| \frac{d\omega}{dt} \right| + b |\Delta\omega| & |\Delta\omega| \geq K_{J_0}, \left(\frac{d\omega}{dt} \right) \Delta\omega > 0 \cap \left| \frac{d\omega}{dt} \right| > K_{J_1} \\ J_0 + c \frac{1}{T_{i2}S+1} \left| \frac{d\omega}{dt} \right| & |\Delta\omega| \geq K_{J_0}, \left(\frac{d\omega}{dt} \right) \Delta\omega \leq 0 \cap \left| \frac{d\omega}{dt} \right| > K_{J_1} \\ J_0 & |\Delta\omega| \geq K_{J_0}, \left| \frac{d\omega}{dt} \right| \leq K_{J_1} \end{cases} \\
 D &= \begin{cases} D_0 & \Delta\omega \leq K_d \\ D_0 + d |\Delta\omega| & |\Delta\omega| > K_d, \frac{d\omega}{dt} > 0 \cap (-\Delta\omega) \leq K_d, \frac{d\omega}{dt} > 0 \\ D_0 + e |\Delta\omega| + f_i \left| \frac{d\omega}{dt} \right| & \frac{d\omega}{dt} \leq 0 \end{cases}
 \end{aligned} \tag{14}$$

where J_0 and D_0 are the values when the AVSG is operating stably; K_{J0} and K_d are the thresholds for the change of $\Delta\omega$, used to prevent the SMESU from frequent charging and discharging caused by small frequency fluctuations; K_{J1} is the threshold for the change of $d\omega/dt$. T_i ($i = 1, 2$) are the inertia time constants; a, b, c, d, e, f_i are the adjustment coefficients. Through the real-time adjustment of J and D , both the rapidity and stability of the system operation are taken into account.

Introducing an inertia link before $d\omega/dt$ is done for two reasons. First, it is to address the issue that may arise when $d\omega/dt$ undergoes sudden changes, where the dynamic characteristics of the SMES and the inverter may not match. That is, the energy provided by the energy storage device has a certain delay and cannot provide the energy needed at the moment of $d\omega/dt$ sudden change. Second, it is to suppress the fluctuation of J and D around the threshold K_{J1} caused by the interaction of J and D in $d\omega/dt$, which leads to the appearance of spikes in J and D . That is, to make the changes in J and D more gradual.

In the M-SMES system, if there are differences in the dynamic response characteristics of each SMESU to disturbances (such as oscillation amplitude, phase, and attenuation rate), it will lead to an instantaneous power imbalance and trigger power circulation. For this reason, the AVSG needs to perform coordinated control on J and D to ensure that the dynamic processes of the angular velocity ω_i and its rate of change $d\omega/dt$ of each SMESU remain consistent. When the ω_i of all SMESUs converge to be consistent, or the error is negligible, according to the active power control equation (Eq 13), it can be known that $P_{mi} - P_{refi}$ is proportional to K_i . If the droop coefficient K_i of each unit is configured according to the proportion of rated capacity, its active power output will achieve precise proportional distribution. Furthermore, since the dynamic consistency of ω_i ensures the synchronous change of the power angle δ_i , the phenomenon of active power circulation is significantly suppressed.

4.3. Dynamic virtual impedance design of SMESU

In actual power systems, it is difficult to directly and accurately measure the resistance and inductance parameters of lines, especially since online measurement under operating conditions is technically challenging, which makes it hard to obtain accurate line impedances. The uncertainty of these impedance parameters prevents SMESUs operating in parallel from achieving strict proportional distribution of

reactive power according to their capacities, thereby causing system circulating current issues.

Under the traditional VSG control, when the line impedances of parallel-operated SMESU are inconsistent ($Z_{l1} > Z_{l2}$), their reactive power-voltage droop characteristics are shown in Figure 6(a). At this point, the core problem faced by M-SMES is that although each unit adopts the same droop control curve (curves 1 and 2 overlap in the initial state), the equivalent total inductive reactance X_i of each unit is not equal due to differences in actual line impedances. According to the reactive power transmission equation (Eq 13), SMESU1 with a larger line impedance outputs less reactive power ($Q_1 < Q_2$) under the same voltage difference, causing the actual operating point to deviate from the theoretical droop curve and forming a significant reactive power deviation ΔQ_{err} . This deviation directly triggers reactive circulating current I_q between units, which not only reduces system efficiency but also exacerbates voltage sag and power oscillation.

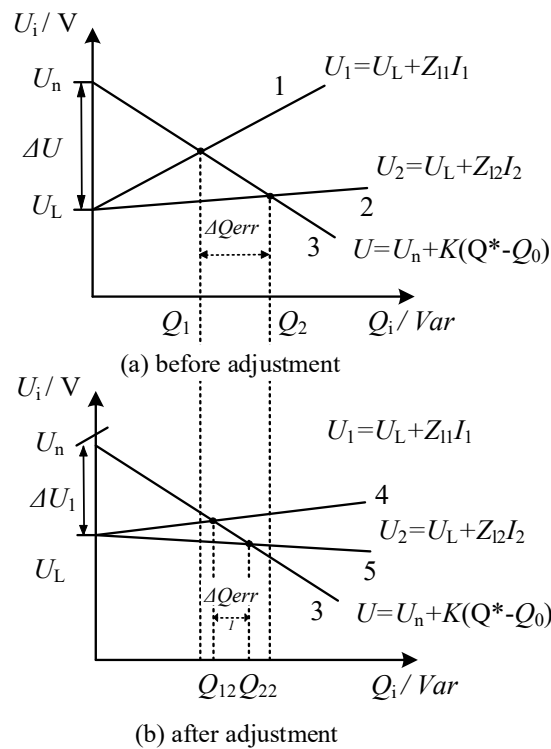


Figure 6. The reactive power-voltage sag curve of AVSG.

To dynamically compensate for the voltage sag caused by line impedance differences, a dynamic virtual impedance control strategy is proposed. This strategy constructs a variable virtual impedance by introducing reactive power and adopts a dynamic adjustment method to reconstruct the output impedance, thereby improving the reactive power sharing accuracy of M-SMES and effectively suppressing the system's reactive circulating current. The expression of the dynamic virtual impedance is:

$$Z_v(s) = -R_v + [L_v + k_L(Q^* - Q_o)]s \quad (15)$$

where L_v is the initially given virtual inductance; k_L is the impedance adjustment coefficient; Q^* is the

reactive power command value; Q_o is the measured reactive power value.

In Figure 6, the high impedance zone refers to the operating area where the equivalent output inductive reactance is larger and the reactive-voltage sag slope is steeper, meaning that the change in reactive power corresponding to a unit voltage deviation is smaller. Conversely, the low impedance zone corresponds to the area with a smaller equivalent reactance and a gentler sag slope. The adjustment mechanism of the dynamic virtual impedance is shown in Figure 6(b). For SMESU1 with high line impedance, its large actual line impedance causes the output reactive power to be lower than the command value ($Q_{o1} < Q^*$) due to impedance voltage drop, generating a positive deviation ($Q^* - Q_{o1} > 0$). After this deviation signal is amplified by the adjustment coefficient K_L , the virtual impedance value is dynamically increased, thereby compensating for the insufficient reactive power output caused by the excessively high line impedance and shifting its droop characteristic curve 1 to the high-impedance region to curve 4. Conversely, for SMESU2 with low line impedance, its actual reactive power output often exceeds the command value ($Q_{o2} > Q^*$), forming a negative deviation ($Q^* - Q_{o2} < 0$). This deviation reduces the virtual impedance value through the regulator, effectively suppressing its excessive reactive power output and causing its droop characteristic curve 2 to move to the low-impedance region to curve 5.

Through the continuous adjustment of the dynamic virtual impedance, the droop characteristic curves of each SMESU are finally rematched, making the system operating points tending to be consistent. This control strategy can achieve high-precision reactive power sharing with $\Delta Q_{err} \approx 0$, effectively eliminating the reactive voltage deviation caused by line impedance differences, and thus significantly suppressing system circulating current.

In conclusion, the AVSG proposed in this paper adopts a three-layer collaborative working mechanism. The base layer simulates the characteristics of synchronous generators to provide a synchronization foundation for multi-unit parallel operation. The middle layer adjusts J and D adaptively to unify the dynamic responses of each unit and suppress active power imbalance and active current circulation. The dynamic virtual impedance studied in this section serves as the top-level compensation mechanism, which real-time corrects the output impedance to compensate for the line impedance difference, achieve precise reactive power distribution, and suppress reactive current circulation, jointly enabling the stable operation and precise power distribution of the M-SMES.

Furthermore, there is a bidirectional coupling stability relationship between the DC side voltage and the AC side frequency. The previous DC/DC stage maintains the DC voltage at a stable level, while the AVSG in the subsequent stage controls the frequency and AC voltage. These two stages are physically coupled through energy balance. When the AC side experiences frequency fluctuations, the AVSG releases active power, which instantly pulls the energy of the DC bus capacitor, causing a drop in the DC voltage. Subsequently, the DC/DC stage responds, extracting energy from the superconducting coil to restore the DC voltage. The fluctuation of the DC side voltage, conversely, affects the active current loop of the AVSG, thereby affecting the stability of the AC frequency. The two-level collaborative architecture of voltage regulation in the previous stage and adaptive control of the AVSG in the subsequent stage adopted in this paper precisely suppresses this coupling disturbance from both ends, achieving the coordinated stability of DC voltage and frequency.

4.4. Main parameter tuning

For J_0 and D_0 during steady-state operation in the AVSG control strategy, tuning can be performed using the optimal second-order system method, where J_0 satisfies the following conditions:

$$J_0 \leq \frac{P_{\max}}{\max\{\omega(d\omega/dt)\}} \quad (16)$$

where $P_{\max}$ is the maximum active power output of the AVSG.

$$0 < D_0 < \frac{T_{m\max} - T_e}{\omega_{\max} - \omega_n} \quad (17)$$

where $T_{m\max}$ and $\omega_{\max}$ represent the maximum allowable mechanical torque and the maximum angular frequency deviation of the system, respectively.

First, regarding the selection of thresholds K_{J0} , K_d , and K_{J1} , this paper selects 0.1% of the system rated frequency as the action dead zone, which serves as the dead zone for adaptive adjustment. This avoids frequent parameter adjustments caused by minor load fluctuations and measurement noise. The corresponding angular velocity deviation threshold is $K_{J0} = K_d = 0.1\% \times 314 = 0.314$ rad/s. K_d and K_{J0} take the same value to ensure consistency in the triggering boundaries of inertia and damping adjustment, avoiding additional power oscillations due to misalignment of the action sequence of the two. The frequency change rate $d\omega/dt$ can reflect the imbalance degree of the system's power. This paper comprehensively considers the simulation conditions and selects $K_{J1} = 2$. This value ensures both a rapid response to large disturbances and the filtering out of false triggers in small disturbances.

The inertia time constants T_1 and T_2 are used to achieve smooth and gradual changes of J and D , avoiding power surges caused by parameter sudden changes. The values need to be greater than the response time of the power outer loop and less than 1/5 of the system oscillation period to ensure the followability of the adjustment. In this study, $T_1 = T_2 = 0.2$ are selected.

The adjustment coefficients a , b , c , d , e , and f_i will, to some extent, affect the response speed and control accuracy of the system's frequency stability. The actual selection needs to be determined comprehensively based on specific circumstances.

Second, the parameters L_v and R_v of the dynamic virtual impedance directly determine the accuracy of reactive power equalization and the suppression effect of reactive current circulation. They need to be comprehensively set considering the line impedance deviation, voltage deviation constraints, and stability requirements. The impedance adjustment coefficient k_L determines the convergence speed and adjustment accuracy of reactive power deviation. The value needs to take into account the allocation accuracy and system stability. The larger k_L is, the faster the reactive power deviation converges, but it will reduce the system phase margin and cause reactive power oscillation. This study selects it as $1e-4$ based on a comprehensive consideration of the simulation conditions.

Finally, the selection of other parameters needs to be determined comprehensively based on specific circumstances.

4.5. Stability analysis

To investigate the impact of the proposed method on system stability, first, the front-end DC/DC chopper uses dual-loop voltage-current control to quickly and accurately maintain the stability of the DC-side voltage U_{dc} . Therefore, when analyzing stability, the front-end chopper and the superconducting coil are treated as an ideal constant-voltage source.

Second, a small-signal stability analysis is performed on the AVSG inverter. By solving Eqs 9, 10,

and 13 simultaneously and combining the results with the system structure analysis shown in Figure 4, the closed-loop transfer function for active power of the AVSG can be derived:

$$G_i(s) = \frac{P_i(s)}{P_{refi}(s)} = \frac{\frac{U_i U}{X_i} \theta_i}{J\omega_n s^2 + (D\omega_n + K)s + \frac{U_i U}{X_i} \theta_i} \quad (18)$$

From Eq 18, the characteristic equation and the characteristic roots of the system are obtained as follows:

$$J\omega_n s^2 + (D\omega_n + K)s + \frac{U_i U}{X_i} \theta_i = 0 \quad (19)$$

$$s_{1,2} = \frac{-(D\omega_n + K) \pm \sqrt{(D\omega_n + K)^2 - 4J\omega_n \cdot \frac{U_i U}{X_i} \theta_i}}{2J\omega_n} \quad (20)$$

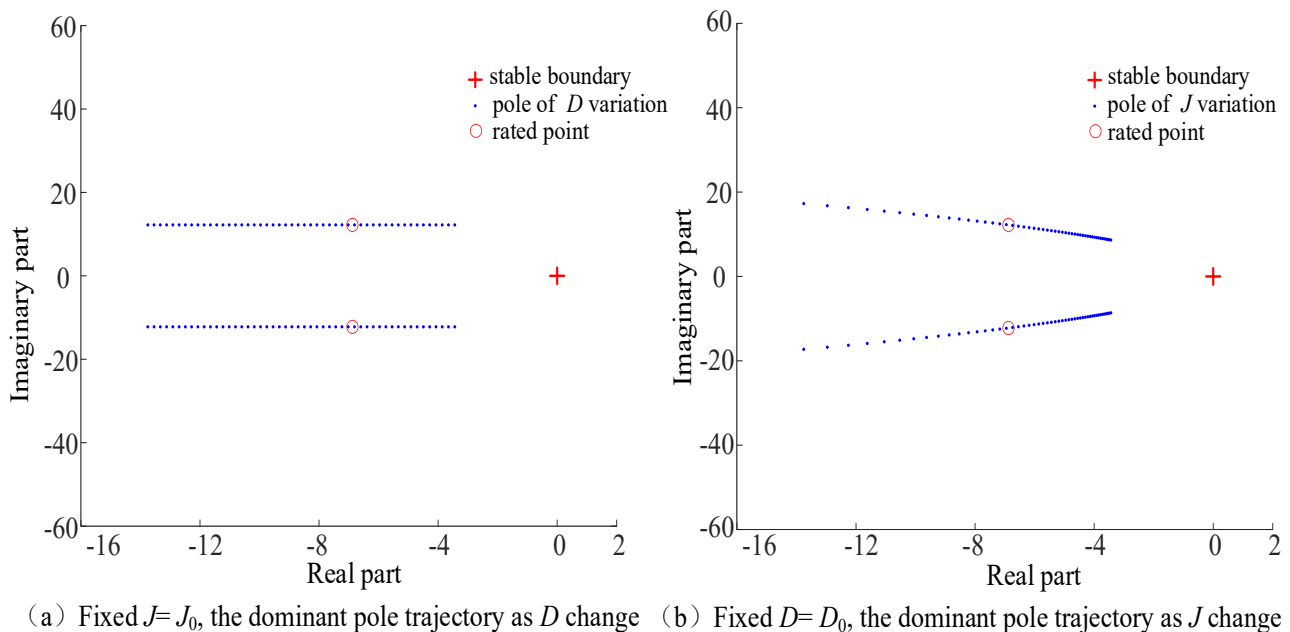


Figure 7. Full-range closed-loop pole distribution diagram of adaptive parameters.

The real part of the characteristic root is $Re(s_{1,2}) = -(D\omega_n + K)/2J\omega_n$. In the adaptive control strategy proposed in this paper, the virtual inertia J and damping coefficient D are always greater than zero, and the damping coefficients K and ω_n are also always greater than zero. Therefore, $Re(s_{1,2}) < 0$ holds true at all times. Consequently, over the entire range of adaptive parameter changes, the system poles always lie in the left half-plane of the complex plane. The distribution of closed-loop poles across the entire range of adaptive parameters is shown in Figure 7. Here, the rated operating condition refers to the system operating state without adaptive parameter adjustment, i.e., when the system uses J_0 and D_0 . It can also be seen that the magnitude of the adaptive parameter adjustments ensures that the characteristic roots always lie in the left half-plane, thereby ensuring that the system remains gradually stable.

5. Simulation experiment verification

To verify the effectiveness of power sharing and circulating current suppression of the M-SMES under the proposed control strategy, an M-SMES composed of three SMESUs was built in the Matlab/Simulink environment, with the main parameters listed in Tables 3 and 4.

Table 3. Circuit model parameter.

Parameter	Value	Parameter	Value
Magnetic inductance L_{sc}/H	8	Line resistance Z_1/Ω	$0.5 + j1.3e-3$
SMES capacitor C_{dc}/F	$5e-3$	Line resistance Z_2/Ω	$0.48 + j1.2e-3$
DC side voltage U_{dc}/V	1500	Line resistance Z_3/Ω	$0.46 + j1.1e-3$
Superconducting coil current I_{sc}/A	200	Rated frequency f/Hz	50
Filter capacitor C_f/F	$10e-6$	Filter inductor L_f/H	$2e-3$

Table 4. Control strategy parameters.

Parameter	Value	Parameter	Value
Moment of inertia J_0	4	Virtual inductor L_v/mH	0.8
Damping coefficient D_0	30	Virtual resistor R_v/Ω	0.5
Inertial time constant T_1, T_2	0.2	Impedance coefficient $K_L/(Var)$	$1e-4$
Threshold K_{J0}, K_d	0.314	Threshold K_{J1}	2
Adjustment coefficient a	0.4	Adjustment coefficient d	0.5
Adjustment coefficient b	0.5	Adjustment coefficient e	0.5
Adjustment coefficient c	-0.01	Adjustment coefficient f_i	0.1

5.1. Working condition 1: Connection and disconnection of SMESU

The simulation experiment settings are as follows: The total simulation duration is 3 s. The initial state of the system is that SMESU1 and SMESU2 are running in parallel, and the initial load power is set to 150 kW active power and 15 kVar reactive power. At $t = 1$ s, SMESU3 is connected to achieve parallel operation of the three machines, and then SMESU3 is removed from the system at $t = 2$ s. Figures 8–11 present the simulation comparison results of the traditional VSG control and the improved AVSG control proposed in this paper under the condition of three SMESUs operating in parallel. The simulation analysis shows that the traditional VSG control, due to not considering the influence of line impedance differences, has obvious problems of unbalanced reactive power distribution, accompanied by large circulating currents. At the same time, its inherent active power-reactive power coupling characteristic leads to a longer dynamic adjustment time and significant power fluctuation phenomenon in the system power distribution process. In contrast, the improved AVSG control with dynamic virtual impedance exhibits superior dynamic performance. As can be seen from Figures 8 and 9, when disturbance is switched on and off within 1 second, the peak-to-peak fluctuation amplitude of active power decreases from 320 to 100 kW, with a fluctuation suppression rate of 68.8%. Similarly, the fluctuation suppression rate of reactive power reaches 83.3%, and the transient response speed is significantly improved, while the distribution accuracy of active

and reactive power is significantly improved.

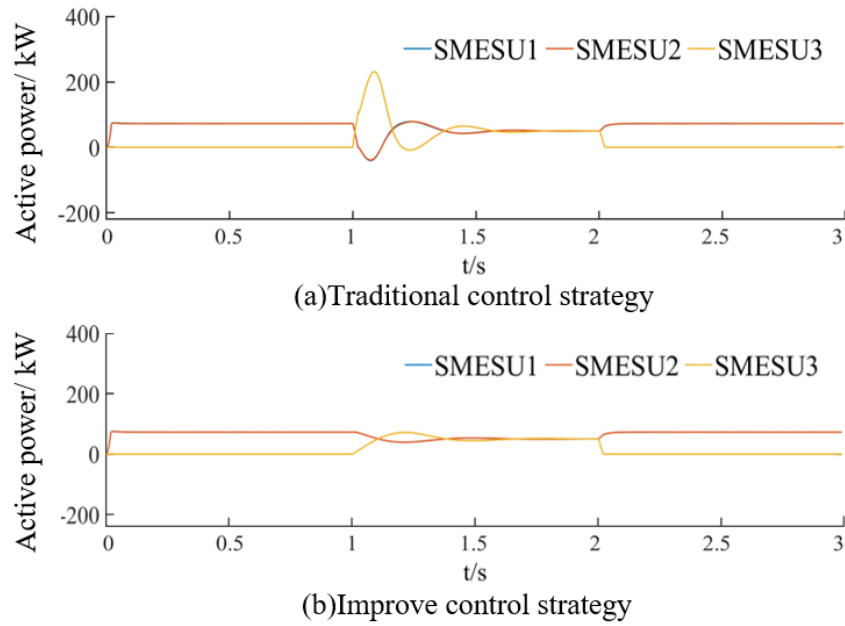


Figure 8. Comparison of the active power of three SMESUs under different strategies.

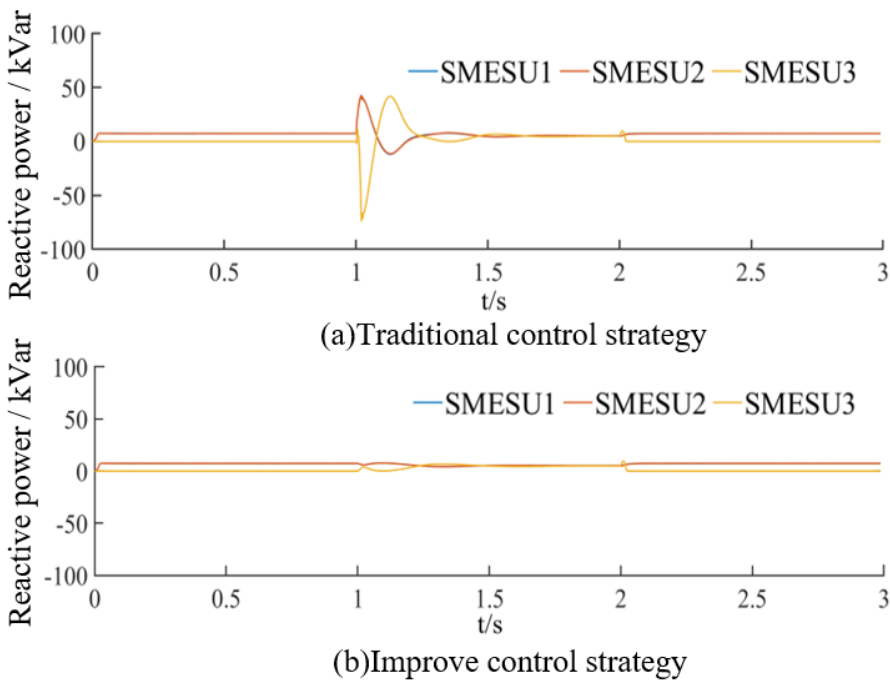


Figure 9. Comparison of the reactive power of three SMESUs under different strategies.

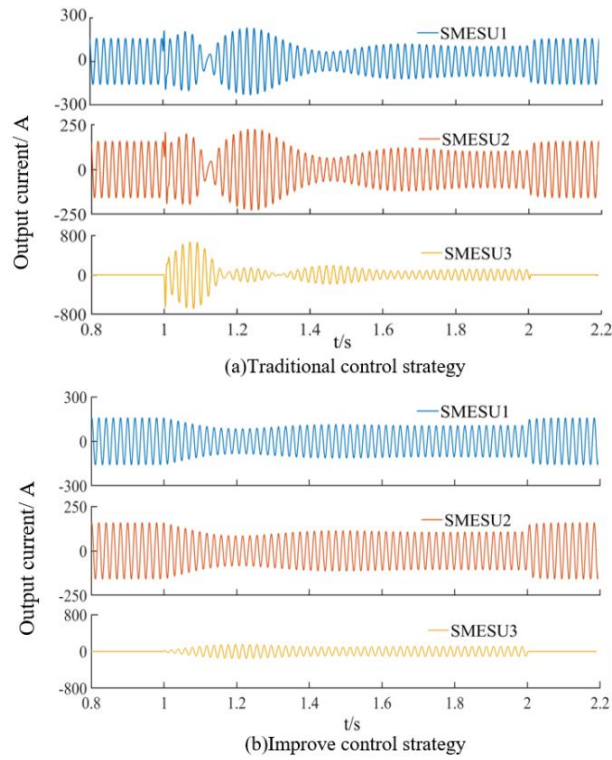


Figure 10. Comparison of the output currents of three SMESUs under different strategies.

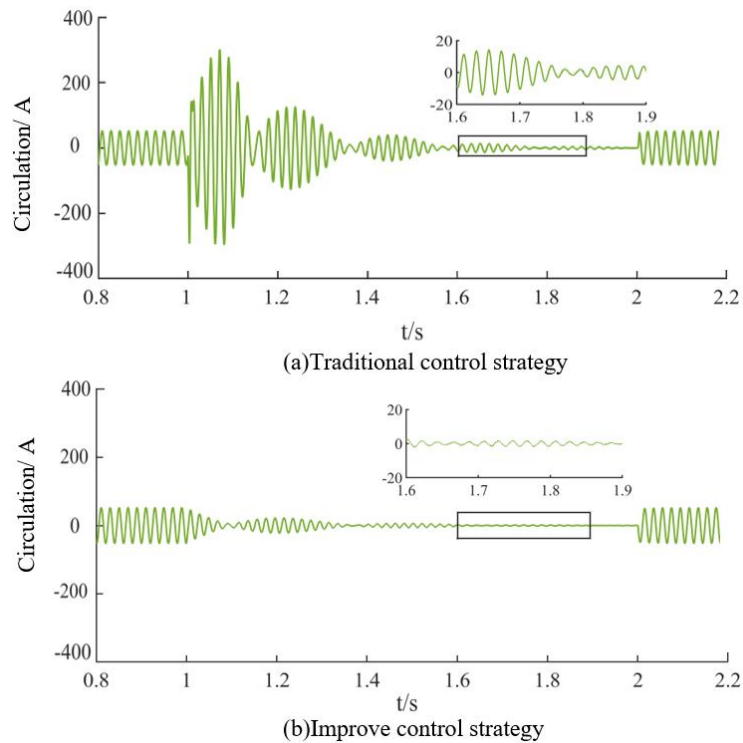


Figure 11. System circulation under different strategies.

By analyzing Figures 10 and 11, it can be observed that the peak circulation of the system has decreased from 300 to 40 A, and the circulation during steady-state operation has been effectively suppressed. This comparative result fully validates the effectiveness of the proposed control strategy in improving the operational performance of the M-SMES.

5.2. Working condition 2: Sudden increase and decrease in AC load

To verify the dynamic response characteristics of the proposed improved control strategy under the condition of sudden load changes, the following simulation conditions are designed: the total simulation duration is 3 s, and the system initially operates under the load conditions of 300 kW active power and 15 kVar reactive power. At $t = 1$ s, a 60 kW common load is put into operation to simulate the step increase of the load, and the load is removed at $t = 2$ s to examine the system recovery characteristics. Figures 12–15 illustrate the dynamic response characteristics of the traditional VSG control and the improved AVSG control under load sudden change conditions. The simulation analysis shows that, although the output current gap between the two control strategies is very small, the traditional control strategy with fixed virtual impedance has a significant increase in reactive power distribution deviation when the load suddenly increases, and the system circulating current level significantly rises, with the average circulating current reaching $3.599\text{e-}4$ A. In contrast, the improved control strategy based on dynamic virtual impedance demonstrates superior control performance: it not only achieves the distribution of active and reactive power but also effectively suppresses the average circulating current to $2.422\text{e-}4$ A, reducing the circulating current amplitude by approximately 32.7%, significantly enhancing the operational stability and robustness of M-SMES under load sudden change conditions.

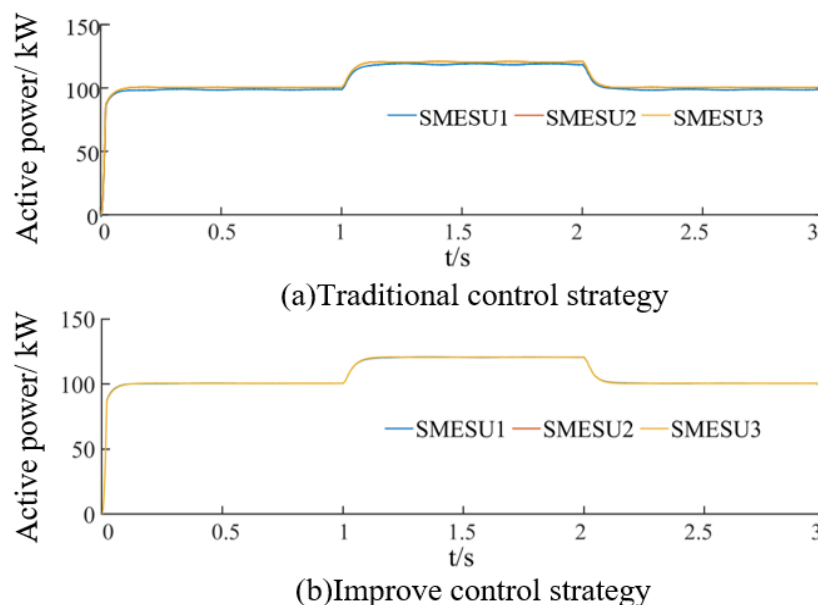


Figure 12. Comparison of the active power of three SMESUs under different strategies.

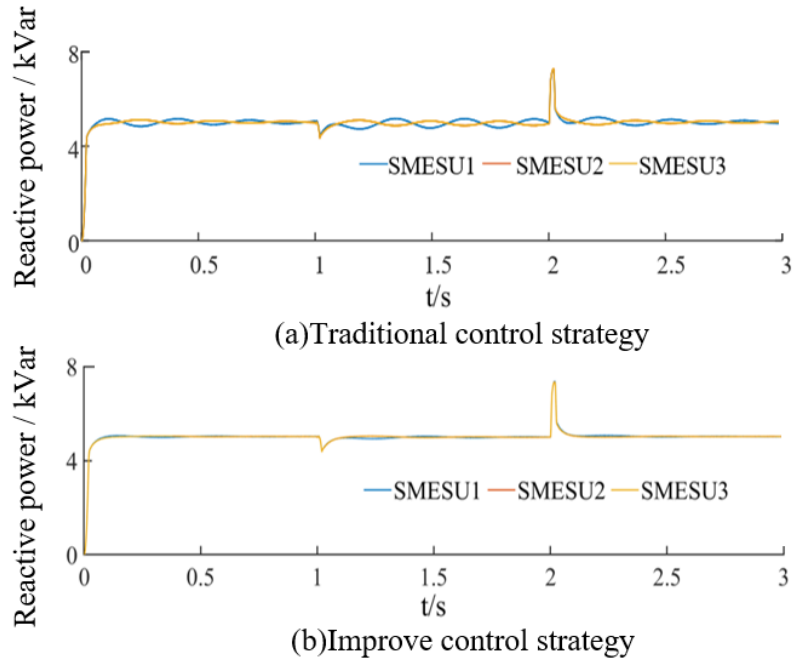


Figure 13. Comparison of the reactive power of three SMESUs under different strategies.

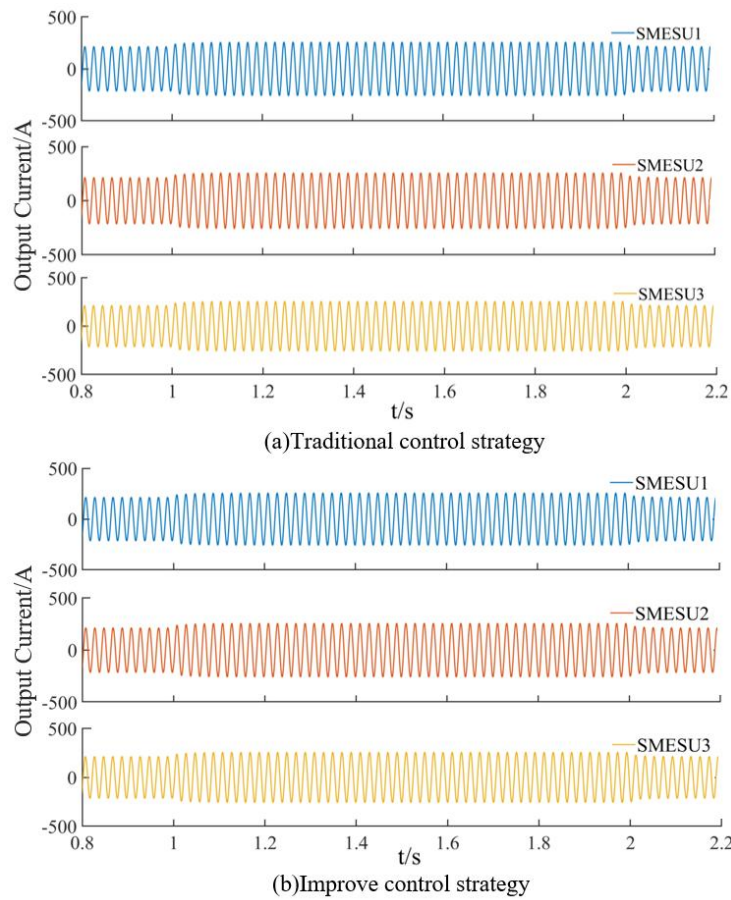


Figure 14. Comparison of the output currents of three SMESUs under different strategies.

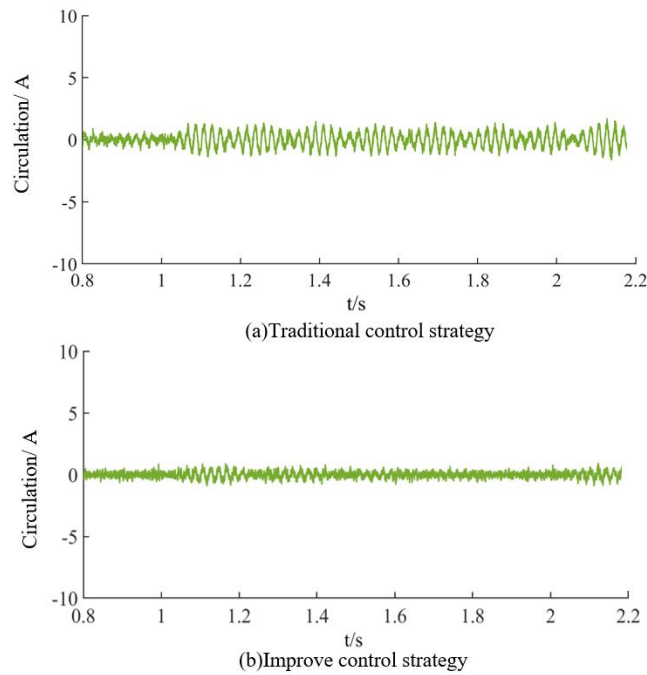


Figure 15. System circulation under different strategies.

5.3. Working condition 3: Controlled experiment

To further verify the proposed control strategy, a comparative experiment is conducted using the grid-forming virtual synchronous generator feedforward-feedback composite control strategy proposed in [13]. The total simulation duration is 1 s, and the system initially operates under a load condition of 300 kW active power and 15 kVar reactive power. At $t = 0.5$ s, a 60 kW public load is introduced to simulate the load step increase, and a comparative analysis is conducted from four dimensions: active power distribution, reactive power distribution, circulating current level, and system frequency characteristics. The simulation results are shown in Figures 16–19.

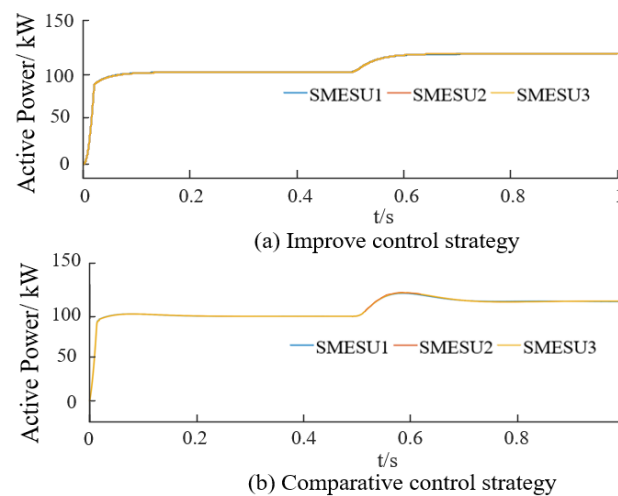


Figure 16. Comparison of the active power of three SMESUs under different strategies.

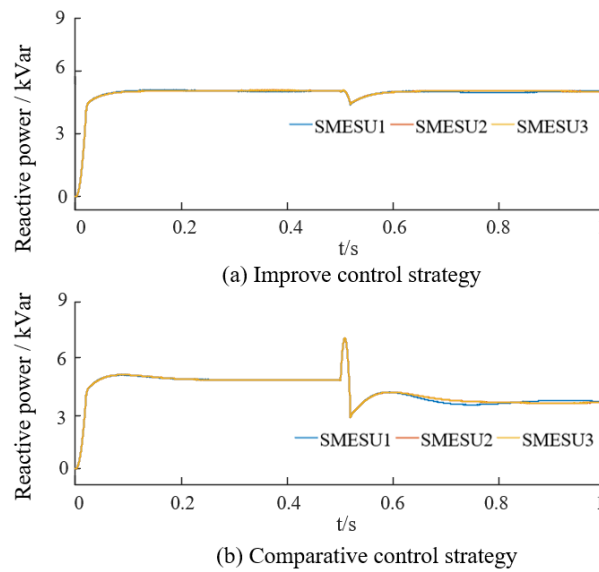


Figure 17. Comparison of the reactive power of three SMESUs under different strategies.

From the results shown in Figures 16 and 17, it can be seen that, compared with the composite control strategy in reference [13], the active power of the control strategy proposed in this paper converges faster after load disturbance, has smaller transient fluctuations, and higher steady-state allocation accuracy. The reactive power does not have obvious spikes during sudden load changes, and the steady-state allocation error is extremely small. However, the active and reactive powers of the comparison strategy exhibit significant reactive spikes at the disturbance instant, and there is also a certain allocation deviation in the steady state.

As shown in Figure 18, the system's circulation amplitude of the strategy proposed in this paper remains at a relatively low level with a small fluctuation range, while the circulation amplitude corresponding to the composite control strategy in reference [13] is significantly larger and the fluctuation is more intense.

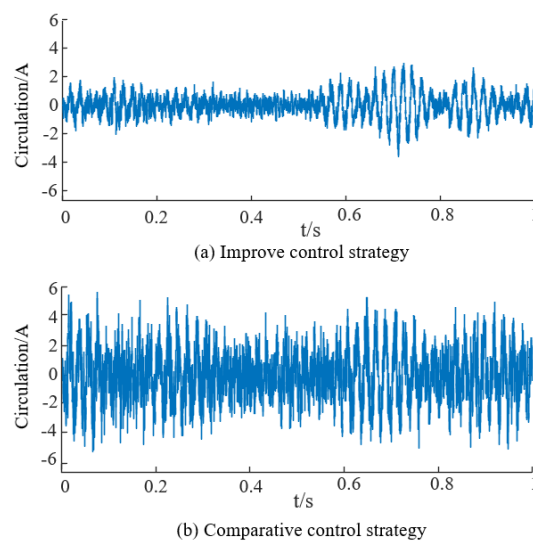


Figure 18. System circulation under different strategies.

In terms of the system frequency characteristics, the comparison results shown in Figure 19 indicate that, under the composite control strategy of reference [13], the amplitude of the system frequency fluctuation is smaller, the recovery speed after disturbance is faster, and the frequency stability is better, while the frequency drop depth of the strategy proposed in this paper is greater, and the dynamic recovery process is relatively slower. The reason for this difference lies in the core control objective of reference [13], which focuses on suppressing power oscillations and eliminating frequency steady-state deviations. Its active power deviation feedforward and frequency positive feedback mechanism directly act on the frequency control loop, providing a more direct and rapid regulation effect on the frequency. In contrast, the strategy proposed in this paper takes power distribution and loop current suppression as the core objectives. The inertia damping adaptive mechanism, while optimizing the distribution performance, sacrifices a certain degree of frequency response speed and stability margin. Based on the above comparative analysis, the control strategy proposed in this paper has obvious advantages in power distribution accuracy and loop current suppression effect.

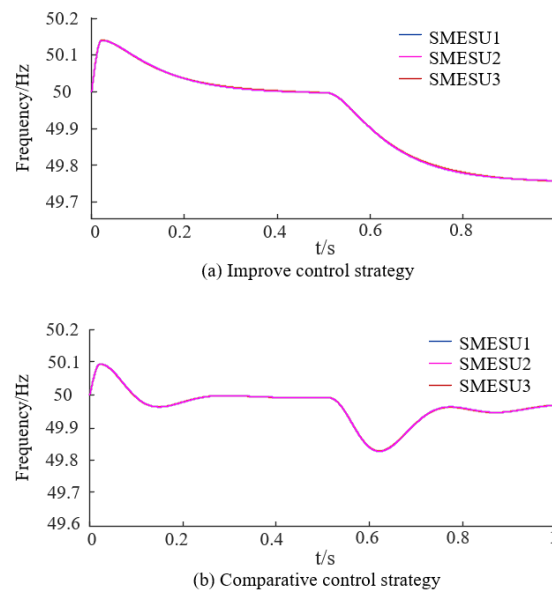


Figure 19. System frequency under different strategies.

6. Conclusions

This paper addresses the power distribution imbalance and circulating current issues during the operation of the M-SMES system and proposes a control strategy based on AVSG. By establishing a collaborative control architecture for the two-level converter, the front-stage DC/DC dual-loop voltage regulation is implemented, while the rear-stage adopts a DC/AC converter combined with adaptive inertia damping regulation and dynamic virtual impedance collaborative control, achieving precise distribution of active and reactive power and suppression of circulating current. Experimental verification was conducted based on the simulation of three SMESUs. The main conclusions are as follows: (1) The proposed AVSG control framework, through an adaptive regulation mechanism, enables stable operation of SMESUs in parallel conditions; (2) the collaborative control strategy ensures high-precision power distribution while reducing the overall circulating current amplitude by

more than 70%, and shortens the power dynamic convergence time by approximately 60% in unit switching and sudden load change conditions; (3) the dynamic virtual impedance regulation reduces the reactive power distribution deviation and the reactive circulating current amplitude by approximately 32.7%, significantly improving the suppression effect. This research provides an effective control solution for the engineering application of M-SMES systems.

Use of AI tools declaration

We confirm that no artificial intelligence assistance was utilised at any stage of this work.

Acknowledgments

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Conflict of interest

The authors declare no conflicts of interest.

Authors contributions

Youbing Zhang: Resources, Supervision, Writing—review & editing, Funding acquisition. Jiayi Fan: Conceptualization, Methodology, Investigation, Writing—original draft, Editing. Hongwu Pan: Data curation, Validation, Writing—review & editing. Jipeng Gu: Conceptualization, Investigation, Writing—review & editing. Luyao Xie: Data curation, Validation, Writing—review & editing. Changlin Yang: Data curation, Validation, Writing—review & editing.

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