

Article

Virtual-Impedance Pre-Synchronization of Flywheel Energy Storage Active-Support Motor Equipment Based on Soft-Start Control Strategy

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Abstract

Active-support motor equipment combining a doubly fed induction machine (DFIM) with a flywheel energy storage unit possesses fast active and reactive power support capability, exhibiting promising prospects for enhancing power system stability. However, the startup process of a DFIM involves multiple dynamic stages, including flux linkage establishment, excitation converter connection, and rotor-speed acceleration, which may result in large starting currents, electromagnetic-torque fluctuations, and converter power transients. And existing soft-start methods still involve trade-offs among startup inrush suppression, additional hardware requirements, control complexity, and startup performance. Moreover, the coordinated control of rotor-side closing synchronization, closed-loop acceleration, and converter power constraints during the startup of active-support motor equipment requires further investigation. To address these issues, this paper proposes a rotor-side pre-synchronization method based on virtual impedance. A virtual impedance model is established between the rotor-induced electromotive force and the output voltage of the excitation converter. According to the voltage difference and the virtual impedance, a virtual current is calculated, and rotor-side pre-synchronization is achieved by regulating this virtual current to zero, thereby effectively suppressing the inrush current at the closing instant. On this foundation, a complete soft-start control strategy is formulated. Finally, simulation and hardware-in-the-loop (HIL) experiments are carried out to verify the method. The results demonstrate that the proposed strategy reduces the absolute peak value of the three-phase rotor current from 157 A to 21 A, the rotor-current RMS value during the first electrical cycle after closing from 91.287 A to 9.614 A, and the DC-link voltage overshoot from 2.81% to 0.078%, corresponding to reductions of 86.62%, 89.47%, and 97.22%, respectively. These results confirm that the proposed strategy can effectively suppress the rotor-side closing inrush current and improve the smoothness and reliability of the startup process of the active-support equipment.



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Keywords: doubly fed induction machine; flywheel energy storage; variable-frequency startup; virtual impedance; pre-synchronization

1. Introduction

With the continuously increasing penetration of renewable energy generation, the inertia level of power systems keeps declining, making frequency stability issues increasingly

prominent [1]. To improve the transient stability of the grid frequency support capability, flywheel energy storage, owing to its advantages including high power density, long cycle life, and rapid response [2,3], is gradually emerging as one of the key technological approaches for constructing new-type power systems [4]. Meanwhile, the doubly fed induction machine (DFIM) can achieve wide-range speed regulation using only a fractionally rated converter, offering merits such as a small excitation converter capacity, high system efficiency, and low operational costs [5–7]. Therefore, it has thus been widely adopted in wind power generation systems and flywheel energy storage systems [8,9]. Consequently, active-support motor equipment based on the DFIM is emerging as an important development direction in the field of flywheel energy storage. This equipment stores mechanical energy within a flywheel and realizes bidirectional electromechanical energy conversion through the DFIM, thereby possessing the functions of power generation, energy storage, and reactive power support [10,11].

For active-support motor equipment, a startup process from standstill to the high-speed energy-storage state is required. Therefore, the startup performance of the DFIM directly determines whether the equipment can be brought into operation safely and reliably. Since the back-to-back excitation converter on the rotor side of the active-support equipment is generally rated according to the slip power, the startup process must not only limit the inrush current but also ensure smooth machine acceleration and provide overload protection for the excitation converter.

A traditional starting method for the DFIM is to connect additional resistors or reactors in series with the rotor circuit. By increasing the equivalent rotor impedance, this method limits the starting current and improves the starting torque, while the additional impedance is gradually reduced or removed as the rotor speed increases. Although this method is conceptually simple, it requires high-power additional impedances and the corresponding switching devices and involves additional losses, heating, and multistage switching, making it unsuitable for the frequent startup of large-capacity equipment [12,13].

To improve the controllability of the startup process, a short-circuit-assisted converter starting method can be adopted. For example, at the initial startup stage, the stator winding is disconnected from the grid and short-circuited, while the rotor-side converter (RSC) establishes the air-gap magnetic field and electromagnetic torque through constant V/f control or vector control. After the machine reaches a certain speed, the stator short circuit is released, and the stator voltage is regulated to achieve synchronization and grid connection. This method enables active regulation of the electromagnetic torque and reduces power losses during startup. However, it requires an additional stator short-circuit switch and involves multiple operating stages, including short-circuiting, short-circuit release, and grid connection, resulting in a relatively complex control process [14,15].

Another common starting method for the DFIM is direct variable-frequency starting [16], in which the existing excitation converter is used to directly accelerate the machine. In this method, the stator winding is first connected to the grid, and subsequently, the rotor-side excitation converter applies an excitation voltage to the rotor winding to accelerate the flywheel. Compared with the aforementioned methods, direct variable-frequency starting requires neither additional starting impedances nor stator short-circuit devices, resulting in a simpler system configuration [17]. Nevertheless, if deviations in frequency, phase, and amplitude exist between the excitation converter output voltage and the rotor-induced electromotive force, a considerable inrush current will be generated at the instant of rotor-side closing, leading to problems such as converter overcurrent, DC-link voltage fluctuation, and electromagnetic-torque oscillation [18].

To address the synchronization and closing-inrush issues during DFIM startup, Reference [19] proposed a stator-side synchronization starting method at standstill. In this method, with the machine at standstill and the stator-side circuit breaker open, the RSC excites the machine so that the stator-induced voltage satisfies the synchronization conditions with the grid voltage in terms of magnitude, frequency, and phase. The stator-side circuit breaker is then closed, after which the rotor voltage and frequency are gradually reduced under constant V/f conditions to achieve smooth machine acceleration. This method reduces the need for additional starting equipment and mitigates the stator-side grid-connection inrush current. However, the magnetizing current during synchronization is mainly supplied by the RSC, thereby increasing its current burden.

To reduce the magnetizing current supplied by the RSC during synchronization, Reference [20] further proposed a rotor-side synchronization method at standstill based on the method in Reference [19]. In this method, the stator winding is first connected to the grid while the rotor winding remains open-circuited. The output voltage and frequency of the RSC are then regulated to satisfy the synchronization conditions with the rotor-induced electromotive force in terms of magnitude, frequency, and phase. After rotor-side closing, the rotor frequency is gradually reduced under constant V/f conditions to achieve smooth machine acceleration. Since the magnetizing current required during synchronization is mainly supplied by the grid through the stator winding, this method reduces the magnetizing burden on the RSC.

The abovementioned studies have demonstrated the effectiveness of standstill pre-synchronization in suppressing the closing inrush current of a DFIM. Nevertheless, several issues still require further investigation. First, References [19,20] both use the voltage magnitude, frequency, and phase conditions across the circuit breaker as synchronization criteria. However, a closed-loop compensation mechanism that maps multiple voltage deviations into a unified intermediate variable has not yet been established, which hinders the integration of pre-synchronization control with the existing excitation vector control system. Second, after synchronization, both methods mainly regulate the rotor voltage and frequency using constant V/f control to control the variation in the machine speed, whereas precise closed-loop regulation based on the speed deviation is lacking during acceleration. In addition, existing studies mainly focus on general DFIM systems or pumped-storage units, while relatively limited attention has been paid to excitation converter overload in DFIM- and flywheel-based active-support motor equipment under large-slip startup conditions.

To address the aforementioned issues, this paper proposes a rotor-side pre-synchronization control strategy based on virtual impedance. On the basis of the conventional excitation control strategy, a virtual impedance model is constructed between the rotor-induced electromotive force and the output voltage of the excitation converter. A virtual current is generated from the voltage deviation through the virtual impedance. By decomposing this virtual current into d -axis and q -axis components in the synchronous rotating reference frame, phase and amplitude compensation quantities are derived, respectively. This enables the excitation converter output voltage to synchronize with the rotor-induced electromotive force in terms of frequency, phase, and amplitude, thereby effectively reducing the inrush current during rotor-side closing. Furthermore, a full soft-start control strategy for the active-support equipment is established based on the proposed pre-synchronization method. By blocking and unblocking the input error signals of the PI regulators in the speed–current dual-loop vector control system, coordinated transitions among pre-synchronization, rotor-side closing, and subsequent acceleration are achieved. Meanwhile, by limiting the magnitude and rate of change of the speed outer-loop PI-regulator output signal, the electromagnetic torque and stator active power are gradually

established. Consequently, the power flowing through the back-to-back excitation converter is maintained within the allowable range while the motor speed increases smoothly.

To more clearly illustrate the characteristics of different DFIM starting and pre-synchronization methods, Table 1 compares their basic principles, synchronization locations, acceleration strategies, main advantages, and principal limitations.

Table 1. Comparison of DFIM pre-synchronization and starting methods.

Method	Sync. Side	Acceleration	Advantages	Limitations
Rotor-added impedance	—	Gradual impedance removal	Simple; high starting torque	Losses; heating; multiple switching
Short-circuit-assisted	Stator	Converter-controlled acceleration	Torque regulation; reduced losses	Extra switch; multiple operating stages
Direct variable-frequency	—	RSC-controlled acceleration	No additional starting hardware	Rotor-side closing inrush
Stator-side standstill sync [19]	Stator	Constant V/f ramp	Reduced grid-connection inrush	RSC supplies the magnetizing current
Rotor-side standstill sync [20]	Rotor	Constant V/f ramp	Reduced closing inrush and RSC burden	No explicit speed-loop or converter-power constraint
Proposed method	Rotor	Speed–current dual-loop control	Inrush suppression; smooth acceleration; overload protection	Parameter tuning required

To highlight the novelty of this study, the main contributions are summarized as follows:

(1) A virtual-impedance-based rotor-side pre-synchronization method is proposed. Unlike methods that directly use voltage magnitude, frequency, and phase conditions as synchronization criteria, the proposed method uniformly represents the deviation between the rotor-induced electromotive force and the excitation converter output voltage as a virtual current. This enables coordinated compensation of the phase and magnitude deviations, thereby suppressing the rotor-side closing inrush current.

(2) A soft-start control strategy suitable for active-support motor equipment is developed. The speed–current dual-loop control structure remains unchanged throughout the startup process, enabling coordinated transitions among pre-synchronization, rotor-side closing, and subsequent machine acceleration.

(3) A startup power-limiting measure considering the rating constraint of the excitation converter is proposed. By limiting the magnitude and rate of change of the speed outer-loop PI-regulator output signal, the machine speed increases smoothly while overload of the back-to-back excitation converter is prevented.

The remainder of this paper is organized as follows. Section 2 introduces the excitation control principle of the active-support motor equipment, primarily covering the system topology, mathematical model, and the vector control strategy for the RSC. Section 3 provides a detailed analysis of the proposed virtual-impedance-based pre-synchronization method and presents the corresponding complete soft-start control strategy. Section 4 validates the proposed soft-start control method through simulations. Section 5 conducts further verification through hardware-in-the-loop (HIL) experiments. Finally, Section 6 concludes the paper and elaborates on the effectiveness and feasibility of the proposed control strategy.

2. Mathematical Model and Excitation Control Strategy of the Active-Support Motor Equipment

2.1. Mathematical Model of the DFIM

The topological structure of the active-support motor equipment is illustrated in Figure 1. It is primarily composed of a DFIM, an energy storage flywheel, and a back-to-back excitation converter comprising an RSC and a grid-side converter (GSC).

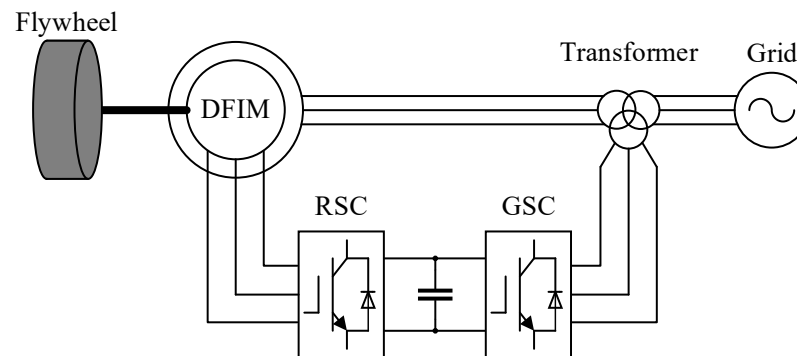


Figure 1. Topology of the active-support motor equipment.

When the generator convention is adopted for the stator side and the motor convention for the rotor side of the DFIM, its mathematical model expressions in the dq reference frame under constant-amplitude transformation are as follows, including voltage equations [21,22]

$$\begin{cases} u_{sd} = -R_s i_{sd} + p\psi_{sd} - \omega_1 \psi_{sq} \\ u_{sq} = -R_s i_{sq} + p\psi_{sq} + \omega_1 \psi_{sd} \\ u_{rd} = R_r i_{rd} + p\psi_{rd} - \omega_2 \psi_{rq} \\ u_{rq} = R_r i_{rq} + p\psi_{rq} + \omega_2 \psi_{rd} \end{cases} \quad (1)$$

flux linkage equations [21,22]

$$\begin{cases} \psi_{sd} = -L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = -L_s i_{sq} + L_m i_{rq} \\ \psi_{rd} = -L_m i_{sd} + L_r i_{rd} \\ \psi_{rq} = -L_m i_{sq} + L_r i_{rq} \end{cases} \quad (2)$$

an electromagnetic torque equation [22]

$$T_e = \frac{3}{2} n_p L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad (3)$$

and a rotor motion equation [22]

$$T_e = -\frac{1}{n_p} (Jp + D)\omega_r \quad (4)$$

where u , i , and ψ denote voltage, current, and flux linkage, respectively; the subscripts s and r denote the stator and rotor sides, respectively; and the subscripts d and q denote the d -axis and q -axis components in the synchronous rotating reference frame, respectively; R_s and R_r are the stator and rotor resistances, respectively; L_s , L_r , and L_m are the stator inductance, rotor inductance, and stator–rotor mutual inductance, respectively; T_e , n_p , J , and D are the electromagnetic torque, number of pole pairs, rotor moment of inertia, and torque damping coefficient, respectively; ω_r , ω_1 , and ω_2 are the rotor electrical angular

speed, synchronous angular speed, and slip angular speed of the DFIM, respectively; and p is the differential operator.

2.2. Vector Control Strategy for the RSC

In this paper, a stator-flux-oriented vector control strategy is adopted, where the d -axis of the dq reference frame is aligned with the stator flux linkage vector [23]. Under this condition, the following relationships hold:

$$\begin{cases} \psi_{sd} = \psi_{sm} \\ \psi_{sq} = 0 \end{cases} \quad (5)$$

where ψ_{sm} is the magnitude of the stator flux linkage. When the stator resistance is neglected, the relationship between the stator flux linkage and the stator terminal voltage can be expressed as [23]:

$$\begin{cases} u_{sd} = 0 \\ u_{sq} = \omega_1 \psi_{sm} = U_{sm} \end{cases} \quad (6)$$

where U_{sm} is the magnitude of the stator voltage. The stator power expressions can be further derived as [23]:

$$\begin{cases} P_s = \frac{3}{2} \frac{L_m}{L_s} U_{sm} i_{rq} \\ Q_s = \frac{3}{2} \frac{L_m}{L_s} U_{sm} (i_{rd} - \frac{U_{sm}}{\omega_1 L_m}) \end{cases} \quad (7)$$

It follows from Equation (7) that the stator active power P_s is proportional to i_{rq} , while i_{rd} determines the stator reactive power Q_s . Hence, decoupled control of the active and reactive power of the DFIM can be achieved by regulating the d -axis and q -axis components of the rotor current.

Under stator-flux-oriented control, the rotor voltage equations can be expressed as [21,24]:

$$\begin{cases} u_{rd} = (R_r + \sigma L_r p) i_{rd} - \omega_2 \sigma L_r i_{rq} \\ u_{rq} = (R_r + \sigma L_r p) i_{rq} + \omega_2 \sigma L_r i_{rd} + \omega_2 \frac{L_m}{L_s} \psi_{sm} \end{cases} \quad (8)$$

where σ denotes the defined leakage coefficient, satisfying $\sigma = (L_r L_s - L_m^2)/(L_r L_s)$. The feedforward compensation terms Δu_{rd} and Δu_{rq} are defined as [21,24]:

$$\begin{cases} \Delta u_{rd} = -\omega_2 \sigma L_r i_{rq} \\ \Delta u_{rq} = \omega_2 \sigma L_r i_{rd} + \omega_2 \frac{L_m}{L_s} \psi_{sm} \end{cases} \quad (9)$$

Under normal operating conditions, Equations (7)–(9) constitute an excitation control strategy based on power–current dual-loop control for the active-support motor equipment. This strategy can effectively regulate the active and reactive power output of the DFIM.

During the startup process, to achieve smooth regulation of the rotor speed, the stator active-power outer loop on the q -axis is replaced by a speed loop. By combining the electromagnetic torque equation (Equation (3)) with the rotor motion equation (Equation (4)), the following expression can be derived:

$$\omega_r = -\frac{3}{2} \frac{n_p^2 L_m U_{sm} i_{rq} / \omega_1 L_s}{Jp + D} \quad (10)$$

It can be seen from Equation (10) that the motor speed can be controlled by regulating i_{rq} . Therefore, speed–current dual-loop control is maintained throughout the soft-start process, without switching between the stator active-power outer loop and the speed outer loop. The excitation control block diagram of the active-support motor equipment is shown in Figure 2.

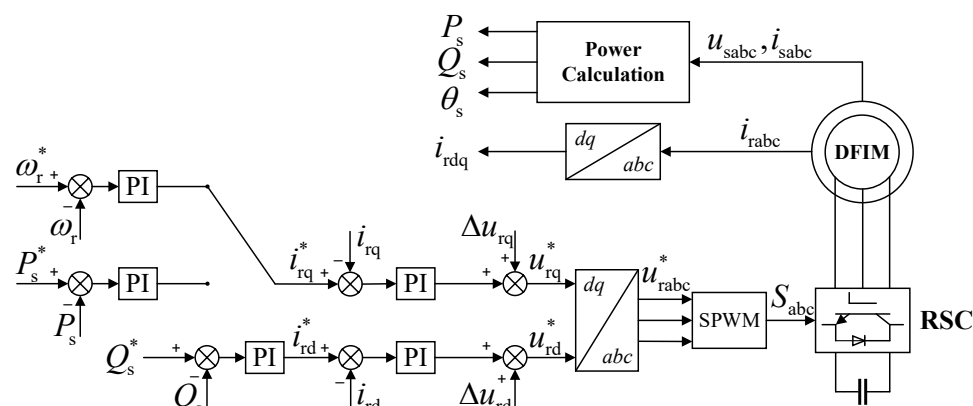


Figure 2. Control block diagram of the RSC.

3. Soft-Start Control Strategy for the Active-Support Equipment

3.1. Analysis of the Inrush Current Generation Mechanism

Prior to startup, the stator winding of the DFIM in the active-support equipment is first connected to the grid. So, the machine remains stationary, and a corresponding induced electromotive force is generated in the rotor winding. Since the excitation converter has not yet been connected to the rotor winding before startup, the rotor current is zero, i.e., $i_{rd} = i_{rq} = 0$. By combining the voltage equation (Equation (1)), the flux linkage equation (Equation (2)), and Equation (5), the expression for the rotor-side-induced electromotive force under open-circuit conditions can be derived as:

$$\begin{cases} u_{rd}^{open} = \frac{L_m}{L_s} \frac{d\psi_{sm}}{dt} \\ u_{rq}^{open} = \frac{L_m}{L_s} \omega_2 \psi_{sm} \end{cases} \quad (11)$$

For the excitation converter, before startup, the input error signals of the four PI regulators are typically set to zero, leaving only the feedforward terms in effect. Furthermore, since the rotor current is zero, the generated feedforward voltage command can be obtained from Equation (9) as:

$$\begin{cases} \Delta u_{rd} = 0 \\ \Delta u_{rq} = \frac{L_m}{L_s} \omega_2 \psi'_{sm} \end{cases} \quad (12)$$

where ψ'_{sm} denotes the flux linkage magnitude estimated in real time by the simplified voltage model with the stator resistance neglected in the RSC vector control, typically taken as $\psi'_{sm} = u_{sq}/\omega_1$, or directly converted from the voltage magnitude obtained by a PLL.

Comparing Equations (11) and (12) yields the difference between the rotor-side-induced electromotive force under open-circuit conditions and the excitation converter output voltage as:

$$\begin{cases} u_{rd}^{err} = u_{rd}^{open} - \Delta u_{rd} = \frac{L_m}{L_s} \frac{d\psi_{sm}}{dt} \\ u_{rq}^{err} = u_{rq}^{open} - \Delta u_{rq} = \frac{L_m}{L_s} \omega_2 (\psi_{sm} - \psi'_{sm}) \end{cases} \quad (13)$$

It can be observed from Equation (13) that the deviation consists of two components:

(1) The d -axis voltage deviation: this component arises from the transient variation in the stator flux linkage magnitude and becomes non-zero when grid voltage fluctuations or motor speed variations occur.

(2) The q -axis voltage deviation: it arises from the discrepancy between the estimated flux linkage magnitude ψ'_{sm} and its actual value ψ_{sm} in the vector control, which is primarily attributable to the neglected stator resistance voltage drop, the dynamic lag of the flux

linkage estimation stage, and the mismatch between the inductance parameters set in the controller and their actual counterparts.

In summary, even under steady-state conditions ($d\psi_{sm}/dt = 0$), the q -axis voltage deviation persists due to the inaccuracy of ψ'_{sm} . Moreover, since the rotor speed is zero before startup, ω_2 is relatively large, which further amplifies the q -axis voltage deviation, rendering it the dominant factor causing the inrush current at the instant of rotor-side closing.

Therefore, to suppress the inrush current generated in the rotor winding during the startup process, a rotor-side pre-synchronization control strategy based on virtual impedance is adopted. This approach ensures that the excitation converter is not connected until the deviation between its output voltage and the rotor-induced electromotive force becomes sufficiently small.

3.2. Virtual-Impedance-Based Rotor-Side Pre-Synchronization Control

As revealed by the preceding analysis, prior to the connection of the rotor-side excitation converter to the DFIM rotor winding, there are deviations in both magnitude and phase between the converter output voltage $\dot{U}_r$ and the rotor-induced electromotive force $\dot{E}_r$ of the machine. The voltage deviation between the two is defined as:

$$\dot{U}_{err} = \dot{E}_r - \dot{U}_r \quad (14)$$

To achieve synchronization between the excitation converter output voltage and the rotor-induced electromotive force, a virtual impedance $Z_v = sL_v + R_v$ is introduced between them, as depicted in Figure 3. Here, I_v and θ_{iv} denote the magnitude and phase of the virtual current, respectively. E_r and U_r are the magnitudes of the rotor-induced electromotive force and the excitation converter output voltage, respectively; and θ_e and θ_u are their corresponding phases.

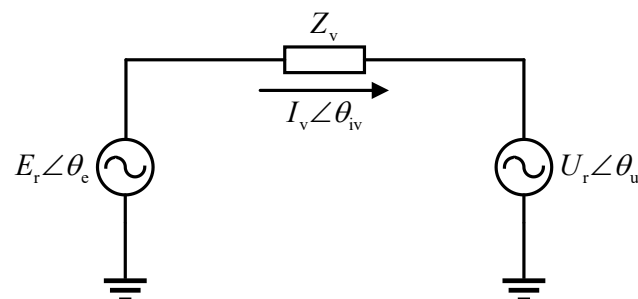


Figure 3. Rotor-side equivalent circuit.

Dividing the voltage deviation by the virtual impedance yields the virtual current, and we obtain

$$\dot{I}_v = \frac{\dot{E}_r - \dot{U}_r}{Z_v} \quad (15)$$

This can be further expressed as:

$$\dot{I}_v = \frac{E_r(\cos \theta_e + j \sin \theta_e) - U_r(\cos \theta_u + j \sin \theta_u)}{Z_v} \quad (16)$$

When the magnitudes and phases of the excitation converter output voltage and the rotor-induced electromotive force are equal, i.e., $E_r = U_r$ and $\theta_e = \theta_u$, the two voltages are synchronized. Irrespective of whether the virtual impedance is inductive or resistive, the virtual current will become zero. Hence, synchronization between the excitation converter output voltage and the rotor-induced electromotive force can be achieved by designing a corresponding control strategy that regulates the virtual current to zero.

To simplify the control structure and enhance the direct reflection of the phase deviation, a purely resistive virtual impedance is adopted. In this case, the phase of the virtual current is identical to that of the voltage deviation, and its expression is given as:

$$\dot{I}_v = \frac{U_{err}}{R_v} \angle \theta_{err} \quad (17)$$

where U_{err} is the magnitude of the voltage deviation and θ_{err} is its phase.

The virtual three-phase currents are then obtained as:

$$\begin{cases} i_{va} = I_v \cos \theta_{err} \\ i_{vb} = I_v \cos(\theta_{err} - \frac{2\pi}{3}) \\ i_{vc} = I_v \cos(\theta_{err} + \frac{2\pi}{3}) \end{cases} \quad (18)$$

The transformation matrix from the three-phase stationary abc reference frame to the two-phase rotating dq reference frame is expressed as:

$$T_{abc_dq} = \frac{2}{3} \begin{pmatrix} \sin \theta_{ref} & \sin(\theta_{ref} - \frac{2\pi}{3}) & \sin(\theta_{ref} + \frac{2\pi}{3}) \\ \cos \theta_{ref} & \cos(\theta_{ref} - \frac{2\pi}{3}) & \cos(\theta_{ref} + \frac{2\pi}{3}) \end{pmatrix} \quad (19)$$

where θ_{ref} denotes the phase of the excitation converter output voltage. From Equations (18) and (19), the following can be derived:

$$\begin{pmatrix} i_{vd} \\ i_{vq} \end{pmatrix} = T_{abc_dq} \begin{pmatrix} i_{va} \\ i_{vb} \\ i_{vc} \end{pmatrix} = I_v \begin{pmatrix} -\sin(\theta_{err} - \theta_{ref}) \\ \cos(\theta_{err} - \theta_{ref}) \end{pmatrix} \quad (20)$$

Furthermore, it can be inferred from Equation (6) that, under vector control, the direction of the excitation converter output voltage aligns with the q -axis of the dq reference frame. Based on this, the phasor diagram of the voltage and current during the pre-synchronization control process can be plotted, as shown in Figure 4.

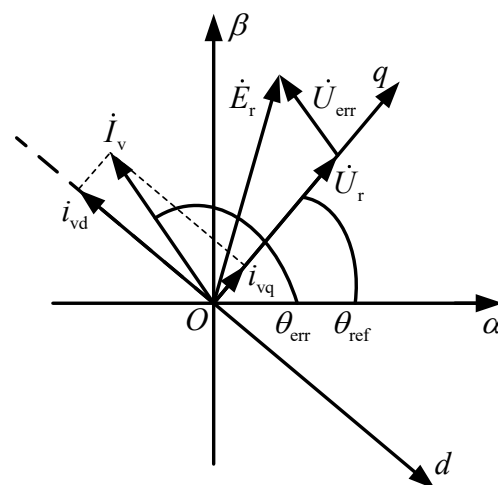


Figure 4. Phasor diagram of the pre-synchronization control process.

The relationship among the phasors is analyzed through Figure 4. When the rotor-induced electromotive force remains constant, the d -axis component of the virtual current, i_{vd} , reflects the phase relationship between the excitation converter output voltage and the rotor-induced electromotive force, while the q -axis component, i_{vq} , reflects their magnitude relationship.

When the phase of the rotor-induced electromotive force leads that of the excitation converter output voltage, $i_{vd} < 0$; when it lags, $i_{vd} > 0$. And when the two are in phase, i.e., $\theta_{err} = \theta_{ref}$, $i_{vd} = 0$. After phase synchronization is achieved, if a magnitude deviation exists between the two, $i_{vq} \neq 0$; if their magnitudes are equal, i.e., $U_{err} = 0$, $i_{vq} = 0$.

Thus, it can be concluded that phase synchronization between the excitation converter output voltage and the rotor-induced electromotive force can be realized by regulating i_{vd} to zero, while magnitude equality can be achieved by regulating i_{vq} to zero.

It should also be noted that $i_{vd} = 0$ and $i_{vq} = 0$ represent the ideal pre-synchronization state. Considering the sampling errors, switching ripple, and parameter deviations present in practical control systems, error thresholds are introduced as the criterion for determining the completion of pre-synchronization. Let $\Delta\theta_{th}$ denote the allowable phase error between the excitation converter output voltage and the rotor-induced electromotive force, and let ε_{th} denote the allowable relative voltage magnitude error. According to the relationships between the virtual-current components and the phase and magnitude deviations, the corresponding thresholds can be expressed as follows:

$$\begin{cases} I_{vdth} = \frac{E_{rf}}{R_v} \sin \Delta\theta_{th} \\ I_{vqth} = \varepsilon_{th} \frac{E_{rf}}{R_v} \end{cases} \quad (21)$$

where E_{rf} is the fundamental-component magnitude of the rotor-induced electromotive force. With reference to the relevant synchronization standards and existing synchronization-control studies [25], and considering the control requirements of rotor-side pre-synchronization, the allowable errors are set to $\Delta\theta_{th} = 5^\circ$ and $\varepsilon_{th} = 3\%$, respectively. When $|i_{vd}| \leq I_{vdth}$ and $|i_{vq}| \leq I_{vqth}$ are simultaneously satisfied, the pre-synchronization process is considered complete.

In summary, the control block diagram of the proposed virtual-impedance-based rotor-side pre-synchronization control is presented in Figure 5. Pre-synchronization is accomplished by eliminating the voltage deviation between the excitation converter output voltage and the rotor-induced electromotive force before the rotor-side closing.

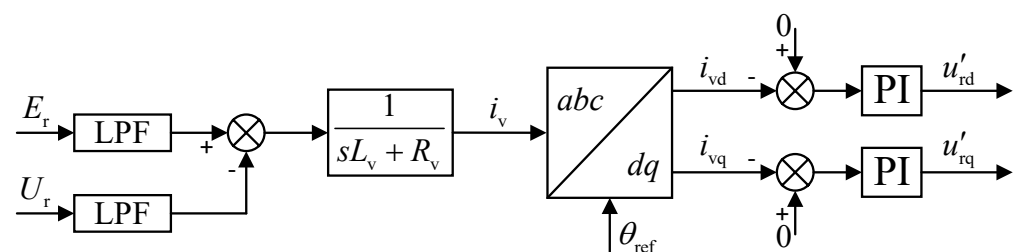


Figure 5. Block diagram of the virtual-impedance-based rotor-side pre-synchronization control.

This control strategy primarily consists of two stages: the phase compensation stage u'_{rd} is employed to achieve phase synchronization of the excitation converter output voltage, and the magnitude compensation stage u'_{rq} is employed to achieve magnitude equality. Using the reference phase signal θ_{ref} of the RSC vector control as the basis for coordinate transformation, the virtual current i_v is transformed to obtain its d -axis and q -axis components i_{vd} and i_{vq} . Since both components are DC quantities, zero-steady-state-error control can be realized through PI regulation. The phase compensation term u'_{rd} is superimposed onto the feedforward compensation term Δu_{rd} , and the magnitude compensation term u'_{rq} is superimposed onto the feedforward compensation term Δu_{rq} .

Accordingly, the excitation voltage command for the RSC during the pre-synchronization process is obtained as:

$$\begin{cases} u_{rd}^* = \Delta u_{rd} + u'_{rd} \\ u_{rq}^* = \Delta u_{rq} + u'_{rq} \end{cases} \quad (22)$$

Since the virtual impedance in the proposed control scheme is implemented through software control, no additional physical impedance circuit is required. However, implementation of the proposed scheme requires a rotor-side circuit breaker and the sampling of voltage signals on both sides of the breaker. During the pre-synchronization stage, the rotor-side circuit breaker remains open, and the motor rotor winding is open-circuited. Therefore, the rotor terminal voltage measured on the machine side of the circuit breaker can be used as the rotor-induced electromotive force E_r , whereas the voltage measured on the RSC side of the circuit breaker is the excitation converter output voltage U_r . After sampling and low-pass filtering, the two voltage signals are fed into the existing excitation controller to calculate the voltage deviation, virtual current, and corresponding compensation quantities. Once the pre-synchronization completion criterion is satisfied, the excitation controller issues a closing command to the rotor-side circuit breaker and subsequently executes the soft-start control.

Since the virtual current does not physically exist, the virtual impedance can be chosen within a fairly wide range. Meanwhile, it jointly determines the pre-synchronization control performance together with the subsequent PI regulators. Therefore, the value of the virtual impedance should be tuned coordinately with the subsequent PI parameters. The low-pass filter parameters, virtual-impedance parameters, and PI control parameters adopted in this paper are listed in Table 2. In addition, the reasonableness of the designed parameters is verified through a frequency-domain analysis based on the system Bode plots.

Table 2. Pre-synchronization control system parameters.

Parameter	Value
Low-pass filter cutoff frequency f_f	500 Hz
Virtual resistance R_v	1 Ω
Virtual inductance L_v	0 H
Proportional gain K_p	1
Integral gain K_i	100

The block diagram of the pre-synchronization closed-loop control system can be derived from Figure 5, as shown in Figure 6.

It can be seen from Figure 6 that the d -axis and q -axis channels of the pre-synchronization closed-loop control system have identical control structures and parameters. Here, $G_f(s)$ denotes the equivalent model of the low-pass filter, which is expressed as follows:

$$G_f(s) = \frac{2\pi f_f}{s + 2\pi f_f} \quad (23)$$

The equivalent model of the RSC, $G_c(s)$, represents the transfer function from the voltage command signal to the actual converter output voltage. Considering the PWM modulation and the sampling-signal delay, it can be expressed as follows:

$$G_c(s) = \frac{K_{PWM}}{T_d s + 1} \quad (24)$$

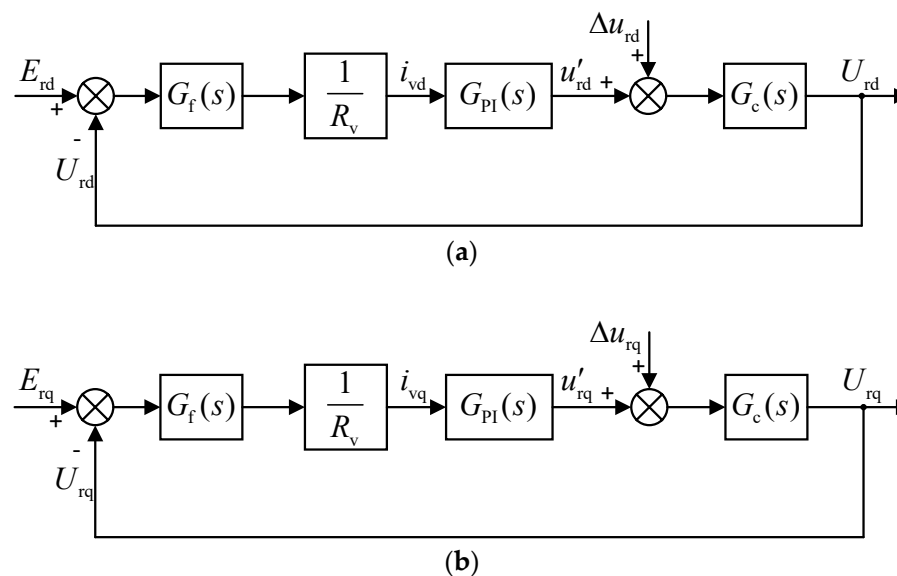


Figure 6. Block diagram of the pre-synchronization closed-loop control system: (a) d -axis channel; (b) q -axis channel.

In this paper, the DC-link voltage is $U_{dc} = 900\text{V}$, and the amplitude of the triangular carrier is $U_{tri} = 1000$. Therefore, the value of K_{PWM} under SPWM modulation can be calculated as follows:

$$K_{PWM} = \frac{U_{dc}}{2U_{tri}} = \frac{900}{2 \times 1000} = 0.45 \quad (25)$$

The delay time T_d is generally set to approximately $5/4$ of the switching period [24]. In this paper, since the switching frequency is set to 10 kHz , $T_d = 125\text{ }\mu\text{s}$.

In summary, the open-loop transfer function $G_{open}(s)$ of the pre-synchronization closed-loop control system can be derived as follows:

$$G_{open}(s) = \frac{G_f(s)G_{PI}(s)G_c(s)}{R_v} \quad (26)$$

Substituting the transfer functions of the individual stages yields:

$$G_{open}(s) = \frac{2\pi f_f \cdot K_{PWM} \cdot (K_p s + K_i)}{R_v s(s + 2\pi f_f)(T_d s + 1)} \quad (27)$$

By combining the parameters listed in Table 2 with those calculated above, the corresponding open-loop transfer-function Bode plot can be obtained, as shown in Figure 7.

It can be seen from Figure 7 that the crossover frequency of the system is $f_c = 8.02\text{ Hz}$, and the phase margin is $PM = 115.46^\circ$. For converter outer loops with similar dynamic characteristics, the bandwidth is generally designed to be approximately $1/50$ – $1/10$ of that of the fast inner loop, and the corresponding crossover frequency typically lies in the low-frequency range well below the carrier frequency. Therefore, the crossover frequency of the system is within a reasonable range, while the sufficient phase margin is also provided, verifying the reasonableness of the designed pre-synchronization control system parameters.

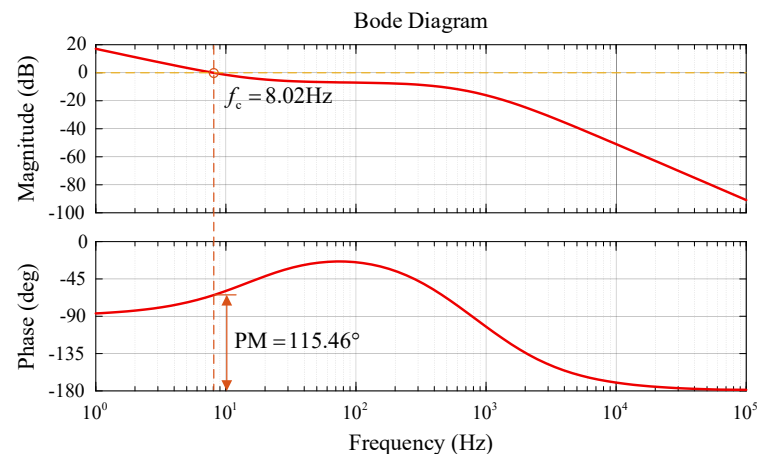


Figure 7. Bode plot of the open-loop transfer function of the pre-synchronization closed-loop control system.

3.3. Soft-Start Control Strategy

When employing the excitation converter for direct variable-frequency motor starting, in addition to suppressing the inrush current generated at the instant of rotor-side closing, two critical issues must be addressed. First, the rotor power should be limited within the rated capacity of the excitation converter throughout the entire startup process. Second, the electromagnetic torque during startup should be maximized to shorten the startup duration.

To achieve the above objectives, the vector control of the RSC based on the speed loop and the current loop is optimized as follows:

(1) At the initial instant of motor startup, the input error signals of both the speed loop and the current loop are relatively large. Meanwhile, the excitation converter is not yet connected to the rotor winding, so the closed-loop control cannot be established, which may lead to continuous accumulation of the error signals. Due to the integral action, this incorrect regulation effect will remain until the rotor-side closing operation. Consequently, the output voltage of the excitation converter will change abruptly, deviate significantly from the rotor-induced electromotive force, and thereby generate a large inrush current. This will not only lead to closing failure but also bring the risk of damaging the motor and the excitation converter.

To avoid this condition, the input error signals of the four PI regulators in the excitation control system should be blocked, i.e., forced to zero, before rotor-side closing, and unblocked after closing; i.e., the actual error signals are fed to the PI controllers.

(2) Prior to the connection of the RSC, the control scheme proposed in the preceding section is employed to realize rotor-side pre-synchronization; i.e., the output voltage of the excitation converter is regulated to be substantially equal to the rotor-induced electromotive force in frequency, phase, and magnitude, thereby effectively mitigating the inrush current at the closing instant. Upon completion of the pre-synchronization process, the rotor-side closing is executed, and the input error signals of the PI regulators are simultaneously unblocked. The complete pre-synchronization control block diagram is illustrated in Figure 8.

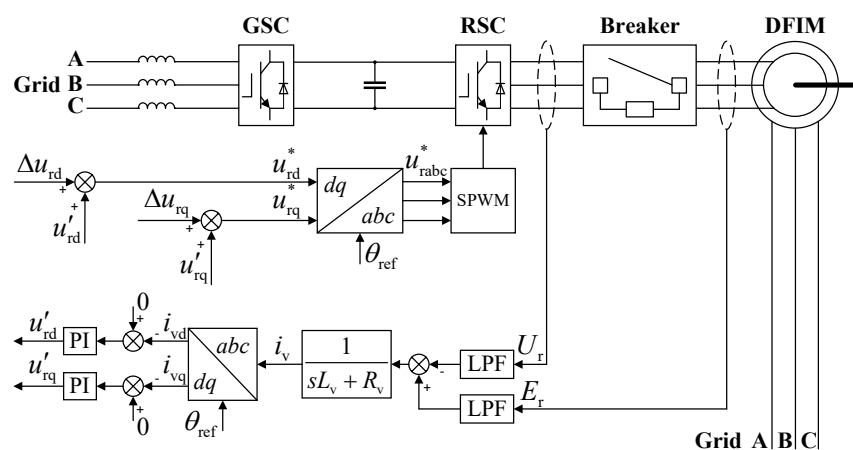


Figure 8. Block diagram of the pre-synchronization control.

(3) The output of the speed outer-loop PI regulator is limited, and the rate at which its output reaches the limit value is constrained, thereby keeping the startup power of both the stator and the rotor within the permissible range.

At the initial instant of motor startup, the error signal of the speed loop is relatively large, causing its PI output to rise rapidly. As analyzed in Section 2, limiting the PI output of the speed outer loop can effectively restrict the stator active power.

Furthermore, the capacity of the RSC must be considered. The back-to-back excitation converter is designed based on the slip power, and a capacity of only 20–30% of the DFIM rated power is sufficient to control the full power output of the machine. However, during startup, the slip remains relatively large for an extended period, causing the active power passing through the stator and rotor to be close in magnitude, which can easily overload the RSC.

To address this issue, the time for the speed-loop PI output to reach its limit value is restricted. This prevents the stator active power P_s from rapidly increasing to the rated value. Meanwhile, as the motor speed gradually increases, the slip continuously decreases, effectively reducing the active power flowing through the excitation converter and avoiding overload.

When the flywheel speed approaches the reference speed, the input error signal of the speed loop becomes small, and its output is no longer held at the limit value. At this stage, the speed loop begins to take effect, and the speed ultimately stabilizes around the reference value.

In summary, the startup process of the active-support equipment proceeds as follows. First, the stator winding is directly connected to the grid while the rotor winding remains open-circuited. The vector control strategy based on the speed and current loops is selected, and the input signals of the four PI regulators are blocked. Then, the virtual-impedance-based rotor-side pre-synchronization control is employed to regulate the deviation between the excitation converter output voltage and the rotor-induced electromotive force within the prescribed allowable range. When the defined error-threshold conditions are satisfied, the pre-synchronization process is considered complete. Subsequently, the rotor-side breaker is closed, and the inputs of the PI regulators are unblocked. The excitation converter then regulates the motor speed to increase toward the reference value as required, while ensuring that the stator and rotor active powers do not exceed their rated values throughout the startup process. It should be noted that speed–current dual-loop control is maintained throughout the entire soft-start process, without switching between power–current dual-loop control and speed–current dual-loop control. The blocking and unblocking of the PI-regulator input signals, as well as the implementation of the pre-synchronization control,

do not alter the adopted dual-loop control structure. The flowchart of the startup process for the active-support equipment is shown in Figure 9.

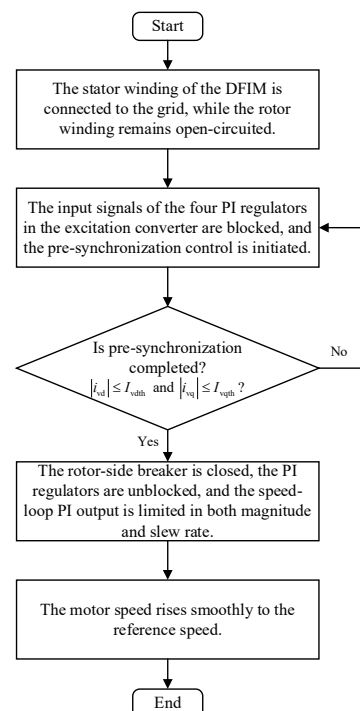


Figure 9. Flowchart of the soft-start process.

4. Simulation Verification and Analysis

A simulation model of the active-support motor equipment under study is built using the MATLAB/Simulink R2022a platform. Selected parameters of the simulation model are listed in Table 3.

Table 3. Simulation parameters.

Parameter	Value
Grid line-to-line RMS voltage U_g	400 V
DC-link voltage U_{dc}	900 V
Motor rated power P_n	100 kW
Filter capacitor C_{dc}	5600 μ F
Stator resistance R_s	0.2147 Ω
Stator inductance L_s	0.06518 H
Rotor resistance R'_r	0.2205 Ω
Rotor inductance L'_r	0.06518 H
Magnetizing inductance L_m	0.06419 H
Moment of inertia J	22.46 kg·m ²
Number of pole pairs p	2
Switching frequency f_s	10 kHz

4.1. Simulation Verification of the Pre-Synchronization Control Strategy

In the simulation, rotor-side pre-synchronization control is performed after the stator winding is connected to the grid. At $t = 0.5$ s, the virtual-current components satisfy the specified error thresholds. Subsequently, the RSC is connected to the rotor excitation winding of the DFIM, and simultaneously, the input signals of the PI controllers are unblocked. Figure 10 shows the waveforms of the rotor-induced electromotive force and

the excitation converter output voltage before and after rotor-side closing, both without and with the proposed pre-synchronization control.

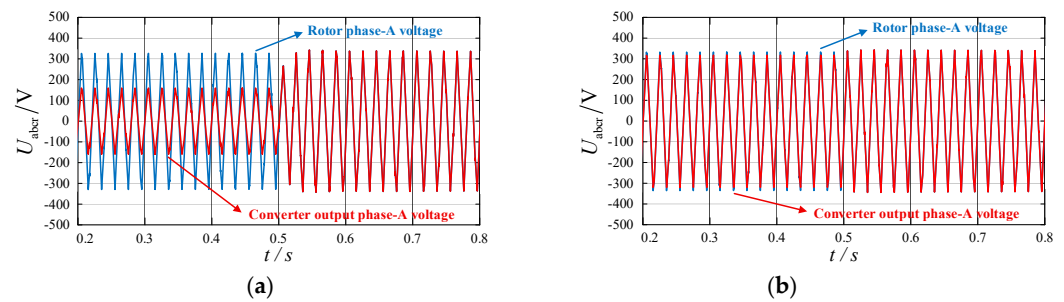


Figure 10. Rotor-side and excitation converter output fundamental voltage waveforms at the rotor closing instant: (a) without pre-synchronization control; (b) with pre-synchronization control.

It can be observed from Figure 10 that without the pre-synchronization control, a certain deviation in both magnitude and phase exists between the rotor-side-induced electromotive force and the excitation converter output voltage prior to closing, which results in a large inrush current at the closing instant. In contrast, with the pre-synchronization control, the rotor-side-induced electromotive force and the excitation converter output voltage become substantially equal before closing, thereby effectively mitigating the inrush current.

Figures 11–14 show the waveforms of the rotor-side three-phase currents, the q -axis component of the rotor current, the d -axis component of the rotor current, and the DC-link voltage at the closing instant during DFIM startup, both without and with the proposed pre-synchronization control.

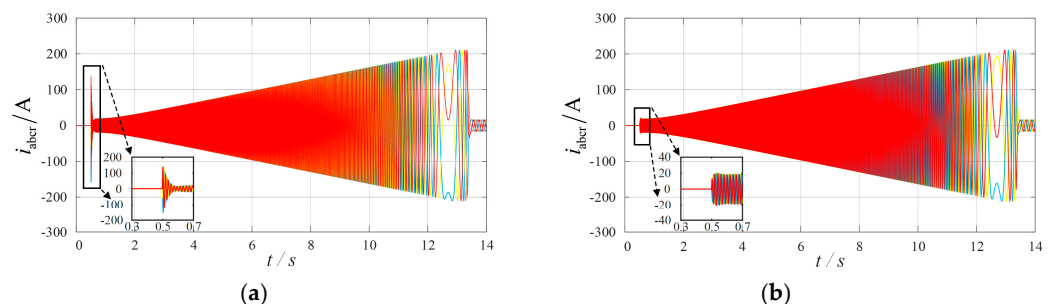


Figure 11. Rotor three-phase current waveforms during motor startup: (a) without pre-synchronization control; (b) with pre-synchronization control.

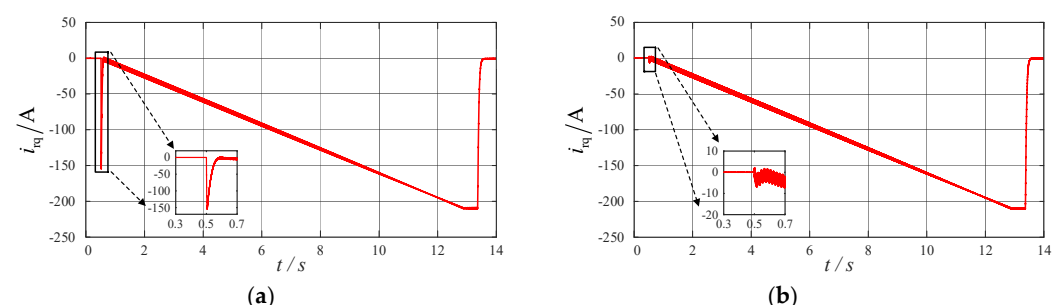


Figure 12. Waveform of the q -axis rotor current during motor startup: (a) without pre-synchronization control; (b) with pre-synchronization control.

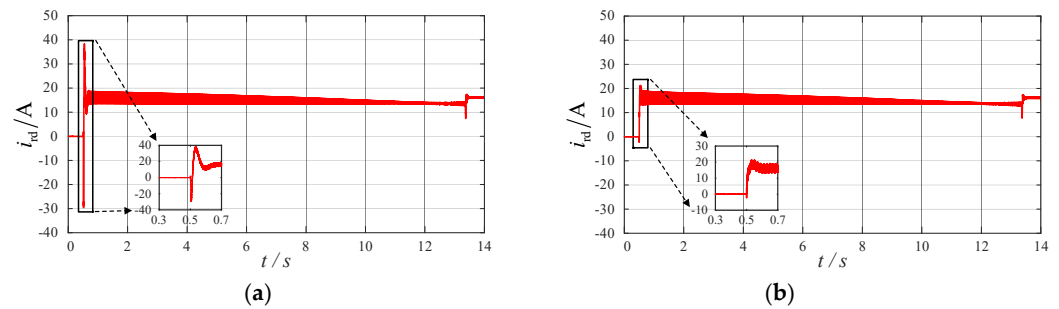


Figure 13. Waveform of the d -axis rotor current during motor startup: (a) without pre-synchronization control; (b) with pre-synchronization control.

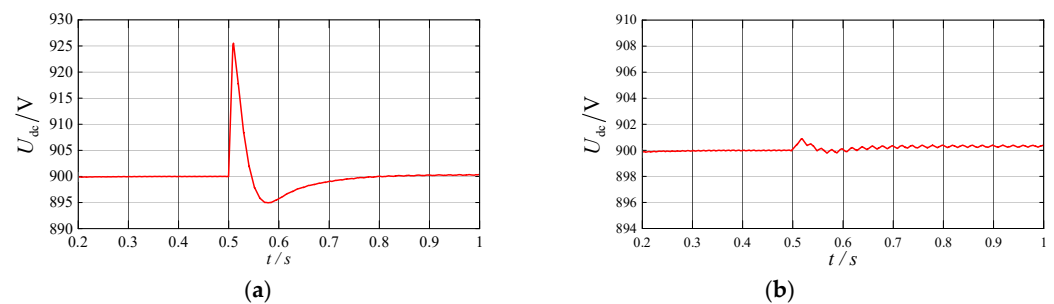


Figure 14. Waveforms of the DC-link voltage at the closing instant: (a) without pre-synchronization control; (b) with pre-synchronization control.

To further quantitatively evaluate the effectiveness of the proposed pre-synchronization control method in improving the rotor-side closing transient, the absolute peak value of the three-phase rotor current, the rotor-current RMS value during the first electrical cycle after rotor-side closing, the peak values of the dq -axis rotor-current components, and the DC-link voltage overshoot are compared under conditions with and without pre-synchronization control. The results are presented in Table 4.

Table 4. Comparison of closing-transient performance with and without pre-synchronization control.

Performance Index	Without Pre-Synchronization Control	With Pre-Synchronization Control	Reduction
Absolute peak of the rotor three-phase currents	157 A	21 A	86.62%
First-cycle rotor-current RMS value	91.287 A	9.614 A	89.47%
Absolute peak of the q -axis rotor-current component	155 A	6.5 A	95.81%
Absolute peak of the d -axis rotor-current component	38.2 A	21 A	45.03%
DC-link voltage overshoot	2.81%	0.078%	97.22%

It can be seen from Table 4 that, without pre-synchronization control, the absolute peak value of the three-phase rotor current reaches 157 A, the three-phase rotor-current RMS value during the first electrical cycle after closing is 91.287 A, and the DC-link voltage overshoot is 2.81%. This indicates that a substantial inrush current is generated during the closing process, while the DC-link voltage also exhibits a considerable overshoot, which may impair the normal operation of the motor itself or the excitation converter and could even cause damage. In contrast, with pre-synchronization control, the absolute peak value of the three-phase rotor current is reduced to 21 A, corresponding to a reduction of

approximately 86.62%; the three-phase rotor-current RMS value during the first electrical cycle is reduced to 9.614 A, corresponding to a reduction of approximately 89.47%; and the DC-link voltage overshoot is reduced to 0.078%, corresponding to a reduction of approximately 97.22%. Meanwhile, the peak values of the dq -axis rotor-current components are also significantly reduced, demonstrating that the proposed pre-synchronization control strategy ensures the smoothness and safety of the active-support equipment during the startup process.

4.2. Simulation Verification of the Startup Performance of the Active-Support Equipment

A simulation analysis of the startup performance of the active-support equipment is conducted using MATLAB/Simulink. Similarly, the excitation converter is connected 0.5 s after the motor stator is connected to the grid. The speed reference is set to 1650 r/min, and the reactive power reference is set to 0 kVar. Figures 15–18 present the simulation waveforms during the motor startup process.

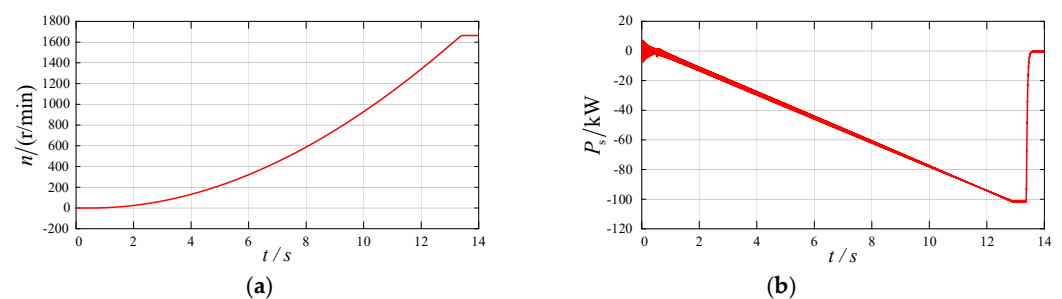


Figure 15. Simulation waveforms of rotor speed and stator active power: (a) rotor speed; (b) stator active power.

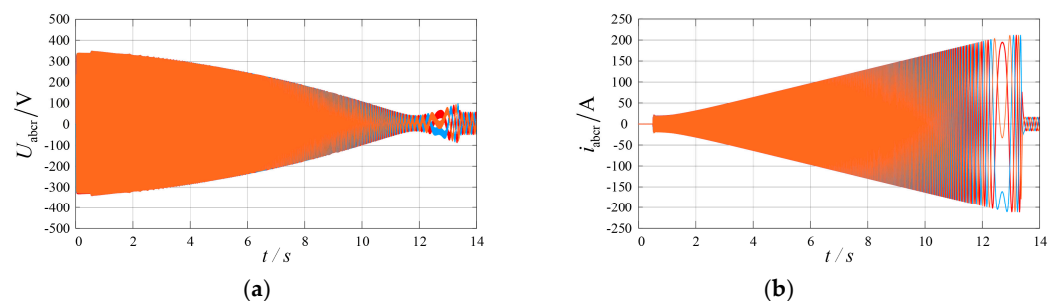


Figure 16. Simulation waveforms of the rotor-side three-phase voltages and currents: (a) rotor-side three-phase voltages; (b) rotor-side three-phase currents.

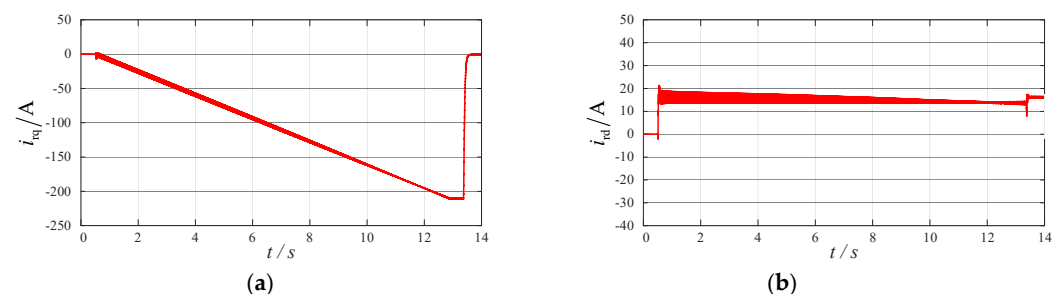


Figure 17. Simulation waveforms of the q -axis and d -axis components of the rotor-side current: (a) rotor current q -axis component; (b) rotor current d -axis component.

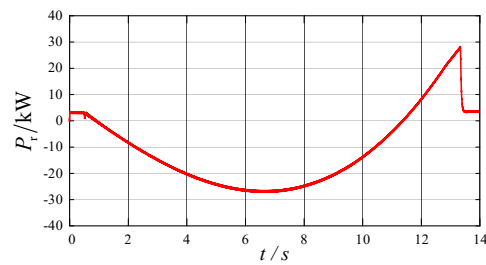


Figure 18. Simulation waveform of the active power exchanged between the AC side of the GSC and the grid.

After the pre-synchronization process is completed and the rotor-side breaker is closed, the machine begins to accelerate. Since the rotor speed is close to zero at the initial stage of startup, a large deviation exists between the actual speed and its reference value. The proposed soft-start control strategy effectively prevents the q -axis rotor-current reference from undergoing a step change after closing; instead, it increases gradually at a limited rate. Accordingly, under the action of the inner current loop, the q -axis rotor current i_{rq} smoothly tracks its reference and gradually increases. Since the stator active power is proportional to i_{rq} , the stator-side active power gradually increases and eventually reaches the rated power of -100 kW as i_{rq} increases, as shown in Figure 15, thereby causing the flywheel speed to increase smoothly. Throughout the entire process, the speed variation is smooth, without any abrupt acceleration or deceleration.

Figure 18 shows the waveform of the active power exchanged between the AC side of the GSC and the grid, which is used to characterize the active-power level transmitted from the rotor side through the back-to-back excitation converter. Under the condition that the DC-link voltage remains essentially stable, this active power can approximately reflect the active-power burden of the back-to-back excitation converter. It can be observed that, during startup, extending the time required for the speed outer-loop PI-regulator output to reach its limit enables the stator active power to build up slowly during the initial high-slip stage. Consequently, the active power flowing through the back-to-back excitation converter is effectively constrained. Its maximum value is approximately -27 kW, demonstrating that the proposed soft-start strategy can effectively prevent overload of the back-to-back excitation converter during flywheel acceleration.

As the rotor speed increases, the slip gradually decreases, and the frequencies of the three-phase rotor voltages and currents shown in Figure 16 decrease accordingly. When the rotor speed reaches the synchronous speed, the slip becomes zero, and the frequencies of the fundamental rotor voltage and current approach zero. Since the speed reference is set above the synchronous speed of 1500 r/min, the rotor current undergoes a commutation process when the speed exceeds the synchronous speed. After the machine speed exceeds the synchronous speed, the slip becomes negative, causing the sign of the rotor electrical frequency to change and resulting in a reversal of the phase sequence of the three-phase rotor currents. This is a normal electromagnetic phenomenon during the transition of the DFIM from subsynchronous to supersynchronous operation.

As the speed approaches the reference value of 1650 r/min, the output of the speed outer loop is no longer held at the limit value, and the rotor current begins to decrease and tends to stabilize. Accordingly, i_{rq} , the stator active power, and the power transmitted through the back-to-back excitation converter shown in Figure 18 decrease and eventually stabilize at the level required to compensate for the system losses. During startup, i_{rd} is mainly used to regulate the stator reactive power. Since the reactive-power reference remains at 0 kVar, i_{rd} does not exhibit significant fluctuations during the startup

process, indicating that decoupled control of active and reactive power can still be achieved throughout the startup process.

4.3. Simulation Verification of Startup Performance Under Different Operating Conditions

4.3.1. Simulation Verification Under Grid Disturbances

To further verify the performance of the proposed soft-start control strategy under grid-voltage disturbances, four disturbance conditions are considered in this subsection: a 10% increase or decrease in the grid-voltage magnitude and a 0.5 Hz increase or decrease in the grid frequency. In the simulation, each disturbance is applied from 0.25 s to 1 s. Since rotor-side closing occurs at 0.5 s, the disturbance interval covers the pre-synchronization process, the rotor-side closing instant, and the initial stage of soft start, thereby enabling a comprehensive evaluation of the soft-start control performance under grid-voltage disturbances.

First, the pre-synchronization performance under different grid-voltage disturbances is analyzed. Figure 19 shows the waveforms of the rotor-induced electromotive force and the fundamental output voltage of the excitation converter before and after rotor-side closing under the four disturbance conditions.

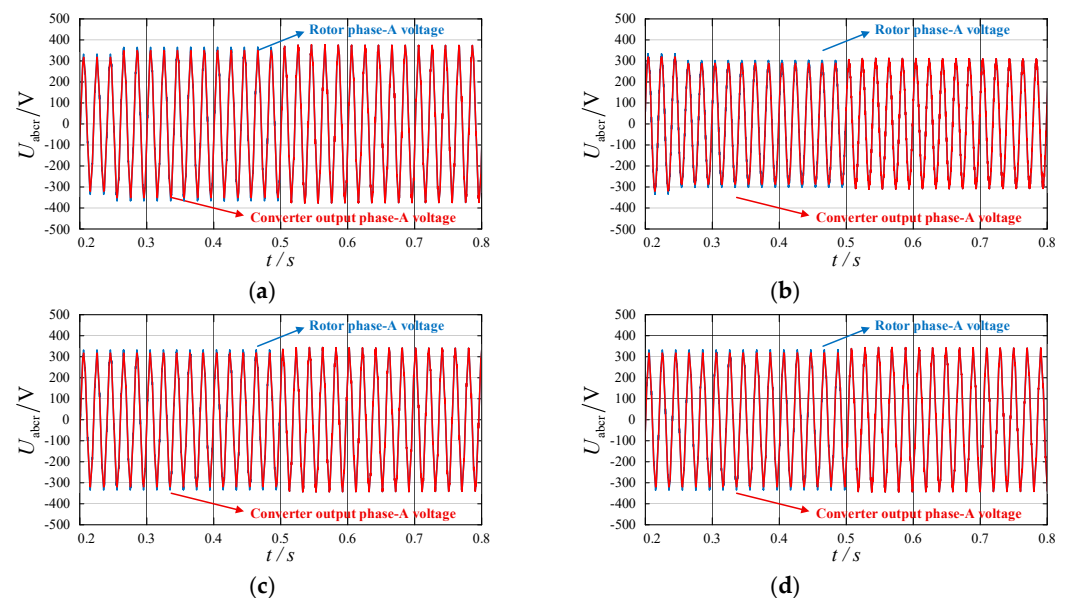


Figure 19. Rotor-side and excitation converter output fundamental voltage waveforms at the rotor-side closing instant under grid-voltage disturbances: (a) grid-voltage magnitude +10%; (b) grid-voltage magnitude −10%; (c) grid frequency +0.5 Hz; (d) grid frequency −0.5 Hz.

It can be observed from Figure 19 that when the grid-voltage magnitude increases or decreases by 10%, or when the grid frequency increases or decreases by 0.5 Hz, the rotor-induced electromotive force varies accordingly with the grid voltage. After each disturbance is applied, the excitation converter output voltage can rapidly track the rotor-induced electromotive force following a brief regulation process and re-establish synchronization in terms of magnitude, phase, and frequency. This demonstrates that the proposed pre-synchronization control still exhibits satisfactory performance under grid-voltage disturbances.

To further verify the rotor-side closing-transient performance under grid-voltage disturbances, the absolute peak value of the three-phase rotor current, the three-phase rotor-current RMS value during the first electrical cycle after closing, the absolute peak values of the q -axis and d -axis rotor currents, and the DC-link voltage overshoot under the four disturbance conditions are summarized in Table 5.

Table 5. Comparison of closing-transient performance under grid disturbances.

Performance Index	Grid-Voltage Magnitude +10%	Grid-Voltage Magnitude −10%	Grid Frequency +0.5 Hz	Grid Frequency −0.5 Hz
Absolute peak of the rotor three-phase currents	23 A	19 A	21 A	21.2 A
First-cycle rotor-current RMS value	10.737 A	8.51 A	9.545 A	9.688 A
Absolute peak of the q -axis rotor-current component	7 A	6.2 A	6.5 A	6.7 A
Absolute peak of the d -axis rotor-current component	23 A	19 A	21 A	21.2 A
DC-link voltage overshoot	0.106%	0.091%	0.099%	0.093%

It can be seen from Table 5 that under grid-voltage disturbances, the peak values of the rotor current, the RMS values during the first electrical cycle, and the corresponding dq -axis components all remain at relatively low levels. Meanwhile, the DC-link voltage overshoot does not increase significantly. These results show no substantial differences from those obtained under steady-state conditions, indicating that the system maintains satisfactory closing-transient performance when disturbances occur in the grid-voltage magnitude and frequency.

After verifying the performance of the pre-synchronization control under grid-voltage disturbances, the performance of the soft-start control strategy under these disturbances is further analyzed. Figures 20–22 show the simulation waveforms of the rotor speed, stator-side active power, and active power exchanged between the AC side of the GSC and the grid, respectively, under grid-voltage disturbances. These waveforms are used to investigate the effects of the grid-voltage disturbances on the smooth increase in rotor speed, the variation in stator-side active power, and the overload protection of the back-to-back excitation converter.

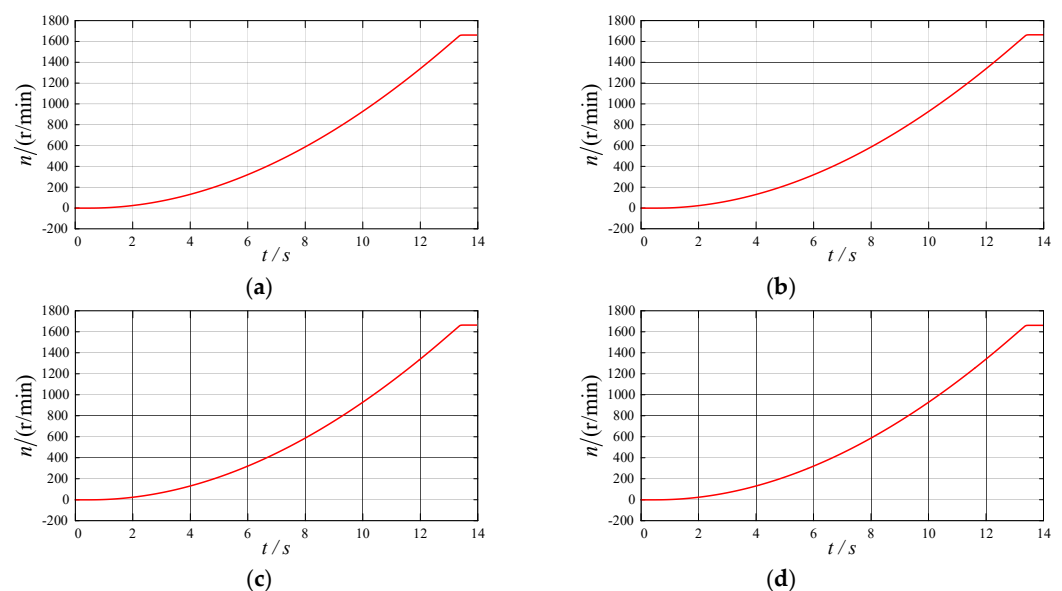


Figure 20. Simulation waveforms of the rotor speed under grid-voltage disturbances: (a) grid-voltage magnitude +10%; (b) grid-voltage magnitude −10%; (c) grid frequency +0.5 Hz; (d) grid frequency −0.5 Hz.

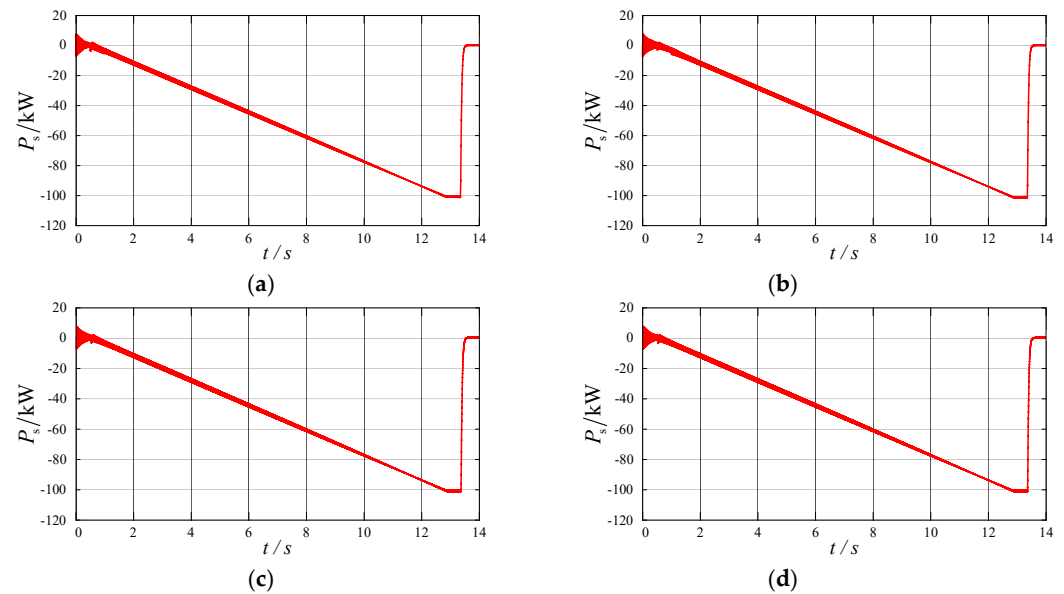


Figure 21. Simulation waveforms of the stator-side active power under grid-voltage disturbances: (a) grid-voltage magnitude +10%; (b) grid-voltage magnitude -10%; (c) grid frequency +0.5 Hz; (d) grid frequency -0.5 Hz.

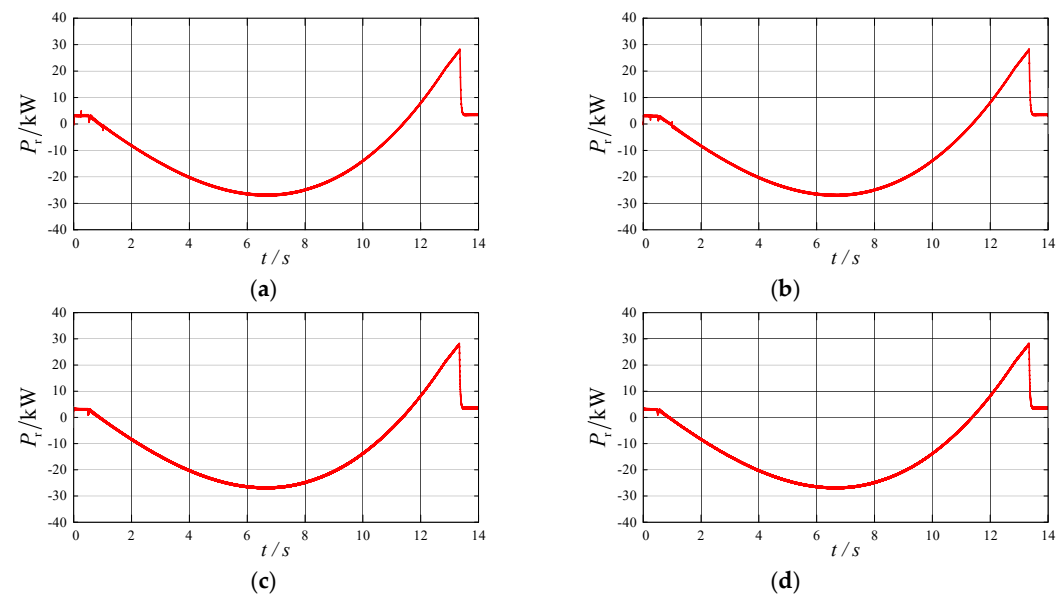


Figure 22. Simulation waveforms of the active power exchanged between the AC side of the GSC and the grid under grid-voltage disturbances: (a) grid-voltage magnitude +10%; (b) grid-voltage magnitude -10%; (c) grid frequency +0.5 Hz; (d) grid frequency -0.5 Hz.

It can be observed from Figures 20–22 that the variations in the rotor speed and power are essentially consistent under the four grid-voltage disturbance conditions. In all cases, the rotor speed increases smoothly and eventually stabilizes near the reference value, without any abrupt speed variations during the grid-voltage disturbances. The stator-side active power gradually increases to the rated value and exhibits no significant oscillations or transients either at the rotor-side closing instant or during the disturbances. In addition, under all four grid-voltage disturbance conditions, the active power exchanged between the AC side of the GSC and the grid remains within the allowable range, and no overload occurs in the back-to-back excitation converter. These results demonstrate that the proposed soft-start control strategy still exhibits satisfactory performance under disturbances in the grid-voltage magnitude and frequency.

4.3.2. Simulation Verification Under Different Speed References

To further verify the performance of the proposed soft-start control strategy under different speed references, simulation analyses are conducted with speed references of 1500 r/min and 1350 r/min. Together with the previously considered case of 1650 r/min, these operating conditions cover supersynchronous, synchronous, and subsynchronous operation, thereby enabling the verification of the control performance in different steady-state speed regions.

Since the pre-synchronization control is completed before the RSC is connected to the rotor winding, and the input signals of the speed-loop and current-loop PI regulators are blocked during this stage, the speed reference does not directly participate in the pre-synchronization regulation. Therefore, the pre-synchronization performance is not analyzed repeatedly here; instead, the analysis focuses on the startup process after rotor-side closing. Figures 23–25 show the simulation waveforms of the rotor speed, stator-side active power, and active power exchanged between the AC side of the GSC and the grid, respectively, under different speed references.

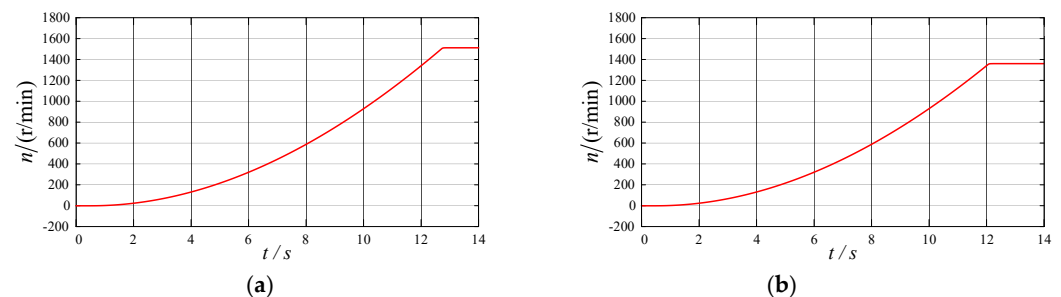


Figure 23. Simulation waveforms of the rotor speed under different speed references: (a) speed reference of 1500 r/min; (b) speed reference of 1350 r/min.

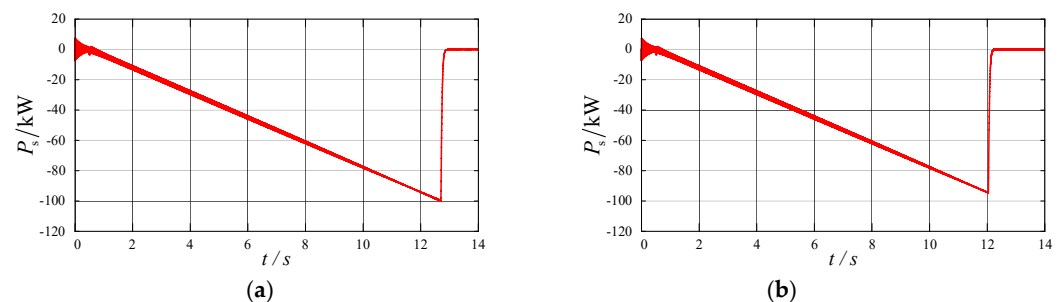


Figure 24. Simulation waveforms of the stator-side active power under different speed references: (a) speed reference of 1500 r/min; (b) speed reference of 1350 r/min.

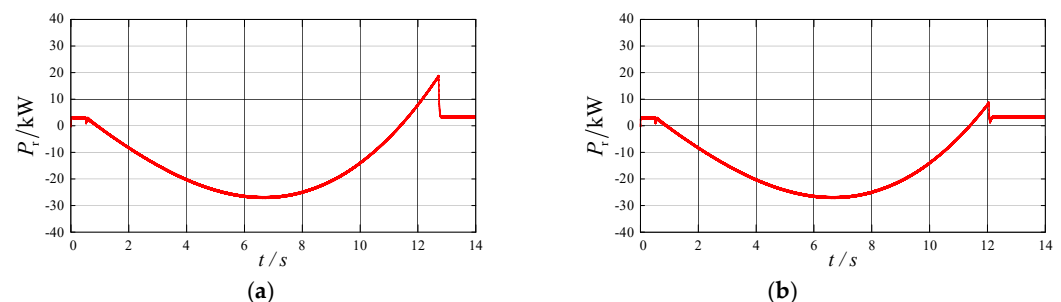


Figure 25. Simulation waveforms of the active power exchanged between the AC side of the GSC and the grid under different speed references: (a) speed reference of 1500 r/min; (b) speed reference of 1350 r/min.

It can be seen from Figures 23–25 that when the speed references are set to 1500 r/min and 1350 r/min, the rotor speed increases smoothly and eventually stabilizes near the corresponding reference value, without any abrupt speed variations during startup. Under both operating conditions, the stator-side active power gradually increases and then rapidly decreases after the rotor speed reaches the reference value, which is consistent with the preceding analysis. Moreover, the active power exchanged between the AC side of the GSC and the grid remains within the allowable range in both cases, indicating that the back-to-back excitation converter does not experience overload. These results demonstrate that the proposed soft-start control strategy also exhibits satisfactory performance when the target speed corresponds to synchronous or subsynchronous operation.

5. Hardware-in-the-Loop Verification

To further verify the correctness of the theoretical analysis and MATLAB/Simulink simulation results, a HIL experimental platform was established using PLECS and the RTBOX real-time simulator developed by Plexim. The complete system model of the active-support equipment, the rotor-side circuit breaker, and the corresponding pre-synchronization and soft-start control blocks were developed in PLECS and deployed to RTBOX for real-time execution. RTBOX was used to simulate the system switching behavior and dynamic responses in real time, the host monitoring system was used for model deployment, parameter configuration, and operating-state monitoring, and an oscilloscope was used for real-time waveform observation and data acquisition. Therefore, the HIL experiments were conducted to verify the feasibility of implementing the proposed pre-synchronization and soft-start control strategies under real-time discrete computation and to examine whether the startup dynamic performance remained consistent with the theoretical analysis and simulation results. The relevant circuit parameters were kept consistent with those described in Section 4, and the experimental platform is shown in Figure 26.

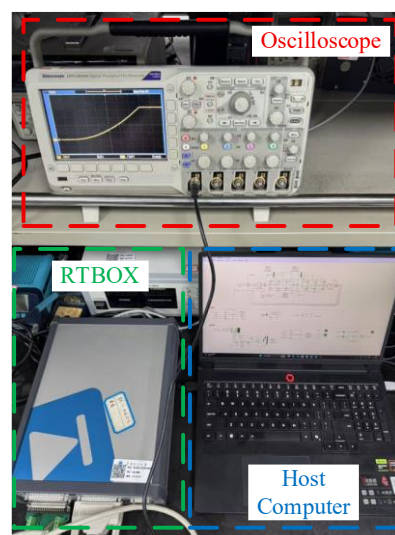


Figure 26. HIL experimental platform.

Figures 27–30 present the HIL experimental waveforms during the motor startup process, with the oscilloscope time base set to 2 s/div.

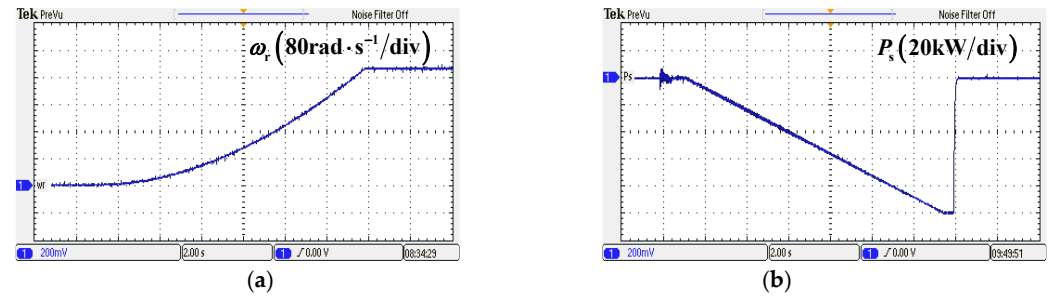


Figure 27. Experimental waveforms of rotor speed and stator active power: (a) rotor speed; (b) stator active power.

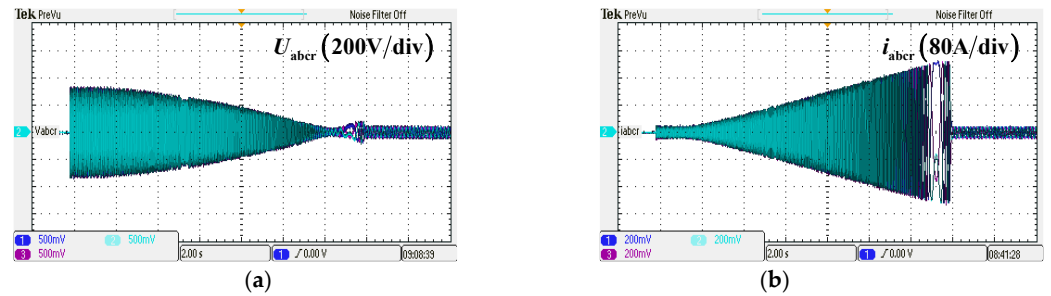


Figure 28. Experimental waveforms of the rotor-side three-phase voltages and currents: (a) rotor-side three-phase voltages; (b) rotor-side three-phase currents.

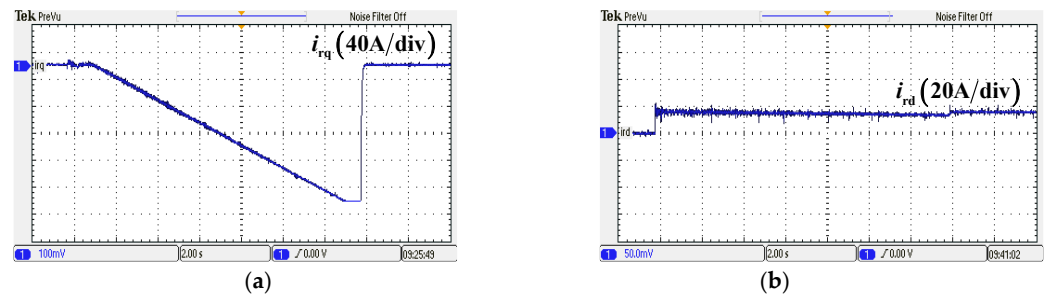


Figure 29. Experimental waveforms of the q -axis and d -axis components of the rotor-side current: (a) rotor current q -axis component; (b) rotor current d -axis component.

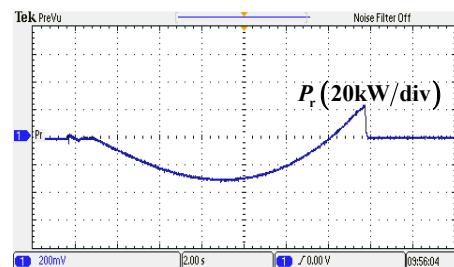


Figure 30. Experimental waveform of the active power exchanged between the AC side of the GSC and the grid.

It can be seen from Figures 27–30 that, under the proposed control strategy, the motor speed increases smoothly and eventually stabilizes at the reference value. The stator-side active power, three-phase rotor currents, dq -axis rotor currents, and rotor-side active power vary continuously, and their overall trends are essentially consistent with the MATLAB/Simulink simulation results. This indicates that effective coordination among the pre-synchronization control, rotor-side closing, and subsequent soft-start control can be achieved under real-time operating conditions.

During the rotor-side closing process, no significant inrush current is observed in the experimental waveforms, indicating that the proposed pre-synchronization control can still effectively reduce the voltage deviation before closing under real-time discrete computation. Meanwhile, the rotor-side active power remains within the allowable range of the converter throughout the startup process, and no significant oscillations occur in either the motor speed or the stator-side active power. These results demonstrate that the proposed soft-start control can simultaneously achieve smooth acceleration and prevent overload of the back-to-back excitation converter.

Compared with the simulation results, the HIL experimental waveforms exhibit certain high-frequency ripples and local fluctuations, which are mainly attributable to real-time discrete computation, signal sampling, and the switching process. However, these effects do not significantly influence the overall startup process of the system. The above results demonstrate that the proposed pre-synchronization and soft-start control strategies are not only effective in the theoretical analysis and simulations but also maintain satisfactory dynamic performance in a real-time execution environment, thereby further verifying the feasibility of the proposed control strategy.

6. Conclusions

Targeting the operational characteristics of the active-support equipment, this paper proposes a virtual-impedance-based pre-synchronization method and a corresponding complete soft-start control strategy. By establishing a virtual-impedance model between the rotor-induced electromotive force and the excitation converter output voltage, the voltage deviation between the two sides is converted into a virtual current, and its d -axis and q -axis components are used to compensate for the phase and magnitude deviations, thereby reducing the inrush current generated during rotor-side closing. Throughout the entire soft-start process, the RSC maintains a speed–current dual-loop control structure. By blocking and unblocking the input signals of the PI regulators, coordinated transitions among pre-synchronization, rotor-side closing, and subsequent acceleration are achieved. Meanwhile, by limiting the magnitude and rate of change of the speed outer-loop PI-regulator output signal, the electromagnetic torque and stator active power are gradually established, thereby preventing overload of the back-to-back excitation converter.

Simulation and experimental results verify that the proposed pre-synchronization method can effectively reduce the deviation between the rotor-induced electromotive force and the excitation converter output voltage before closing and significantly suppress the inrush current generated at the instant of rotor-side closing. Compared with the case without pre-synchronization control, the absolute peak value of the three-phase rotor current is reduced from 157 A to 21 A, the rotor-current RMS value during the first electrical cycle after closing is reduced from 91.287 A to 9.614 A, and the DC-link voltage overshoot is reduced from 2.81% to 0.078%, corresponding to reductions of 86.62%, 89.47%, and 97.22%, respectively. During the subsequent startup process, the motor speed increases smoothly to the reference value, while the power flowing through the back-to-back excitation converter remains within the allowable range.

In addition, under disturbances in the grid-voltage magnitude and frequency and under different speed references, the proposed strategy can still successfully complete the pre-synchronization process and maintain a smooth startup process, demonstrating satisfactory performance under grid-voltage disturbances and different target-speed conditions.

In summary, the proposed control strategy simultaneously achieves rotor-side closing-inrush suppression, smooth motor acceleration, and overload protection of the excitation converter, thereby satisfying the startup performance requirements of such active-support equipment.

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