

Article

Research on the Optimal Transient Power Angle Control Strategy for New Energy Transmission Systems in Energy Storage Enhancement Areas

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Abstract

With the accelerated low-carbon transition of the global energy mix, offshore wind power (OWP) is one of the fastest-growing renewable resources and is often integrated with conventional thermal units into a bundled export transmission system. Under sudden large disturbances, the lack of inertia support makes rotor-angle instability prone to occur, which undermines sustainable operation. Battery energy storage systems (BESS) provide fast emergency power support, and an effective control strategy can enhance transient rotor-angle stability while improving operational sustainability. Accordingly, equivalent-circuit models of the regional export system are established for the before-fault, during-fault, and after-fault stages. Building on the extended equal area criterion (EEAC) and the low-voltage ride-through (LVRT) capability of OWP, the stabilizing mechanism of BESS participation is examined from the perspectives of optimal power and timing, thereby yielding an optimal BESS control strategy for improving transient rotor-angle stability in regional renewable export systems. Finally, a regional renewable export system is implemented in MATLAB/Simulink R2022b, where severe contingencies are imposed to validate the effectiveness of the proposed BESS control strategy.

Keywords: transient power angle stability; extended equal area criterion (EEAC); battery energy storage system (BESS); optimal control strategy; sustainable operation

1. Introduction

To address the increasingly stringent carbon-emission constraints arising from the sluggish transition of the global energy structure and the persistently high share of conventional fossil fuels, large-scale research and development programs on OWP have been comprehensively launched in major coastal countries and regions worldwide, driven by the temperature-control targets of the Paris Agreement and the renewable energy initiatives of the International Energy Agency [1,2]. With the increasing penetration of OWP, regional renewable generation is increasingly exported in a bundled scheme together with neighboring conventional thermal units. Nevertheless, the concentrated integration of OWP leaves the regional export system with limited inertia support, thereby compromising secure and stable operation [3–5]. The BESS, as an emergency control resource, is characterized by millisecond-level fast response capability and bidirectional power regulation, which renders it technically suitable for emergency transient rotor-angle control. Consequently,



Academic Editor: Shuhua Fang

Received: 26 December 2025

Revised: 2 February 2026

Accepted: 3 February 2026

Published: 5 February 2026

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investigating optimal control strategies for BESS participation in enhancing the transient rotor-angle stability of regional export systems is of considerable theoretical significance and practical value for mitigating instability risks under scenarios with high-penetration offshore wind integration.

At present, extensive research efforts have been devoted to transient stability control strategies involving BESS integration. In [6–9], the modeling of BESS at the electromechanical transient timescale was elaborated in detail, and its effectiveness in improving transient stability was verified using the power system analysis synthesis program (PSASP). In [10,11], electromagnetic transient models of the power conversion system were developed, and a unified master–slave power control strategy on the battery side and grid side was proposed, providing methodological support for electromechanical transient modeling of BESS plants. Using the damping torque method, ref. [12] analyzed the mechanism by which BESS enhances transient stability, indicating that a larger active power support from BESS leads to a more pronounced improvement in rotor-angle stability. Nevertheless, the underlying mechanism of transient rotor-angle support has not been sufficiently investigated, nor have storage capacity constraints been considered, both of which limit its practical relevance. In [13], coordinated control strategies combining BESS with generator tripping were proposed, effectively reducing the required amount of tripping. Although these studies examined BESS participation in transient rotor-angle stability from multiple perspectives, the considered scenarios generally excluded offshore wind and other renewable resources, thereby neglecting their impacts on system stability and constraining direct applicability to regional renewable power export systems.

In response, several studies have focused on bundled transmission scenarios involving new energy and conventional units. In [14–18], the influence of renewable penetration on regional rotor-angle stability was analyzed based on the extended equal area criterion (EEAC), and the interactions among wind power, thermal generation, and HVDC systems were investigated, while transient control of renewable units was not incorporated. In [7], the impact of renewable low-voltage ride-through control on the rotor-angle stability of regional export systems was studied, whereas the associated stability margin during fault transients was not further quantified. Moreover, when severe disturbances occur in regional export systems, emergency control actions are typically activated to ensure transient stability [8,19–23]. In [24], the effects of different generator tripping schemes on the rotor-angle stability of wind-thermal bundled AC/DC export systems were investigated, without invoking emergency resources such as BESS. In addition, the optimal timing of BESS participation in transient rotor-angle support was proposed in [25,26], yet its computational procedure was of high complexity. Another study simplified the derivation of optimal timing based on the approximate equivalence principle and further inferred the optimal control power accordingly [27]. Nevertheless, neither storage capacity constraints nor renewable transient control were considered, which departs from practical operating conditions.

The differences between this work and existing studies, in terms of the factors considered in both the system model and the BESS control strategy, are summarized in Table 1. Although the above studies have examined the capability of BESS to support transient rotor-angle stability, several limitations remain, as summarized below:

1. In the above studies, mechanism-level analysis of BESS participation in transient rotor-angle stabilization remains insufficient. The interaction between low-voltage ride-through (LVRT) and BESS support actions is rarely modeled, thereby masking the indirect role of turbine emergency control in shaping rotor-angle dynamics. Meanwhile, BESS capacity limits are often absent, with conclusions derived under ideal unconstrained assumptions that do not align with realistic operational constraints.

2. In the above studies, the transient BESS intervention problem is typically addressed from a single dimension, focusing on either optimal control timing or optimal control power. In concentrated renewable-export scenarios, callable BESS resources are inherently limited; however, timing-only optimization can overlook capacity ceilings. In addition, the mechanism for determining BESS control power in such export settings is rarely examined in depth, with control magnitudes often introduced through manual case settings, whereas joint consideration of both control timing and control power under limited BESS resources remains scarcely reported.

Table 1. Relationship between this paper and other studies.

Reference	Thermal Power Units	New Energy Units	LVRT Characteristics	Optimal Control Timing	Optimal Control Power
[6,7]	✓				✓
[27]	✓				✓
[25]	✓	✓		✓	
[14,24,26]	✓	✓			
This paper	✓	✓	✓	✓	✓

The “✓” indicates that the cited literature has addressed the relevant considerations.

In light of these considerations, this paper develops an optimal BESS-based emergency control framework for transient rotor-angle stabilization in regional export systems under severe disturbances, in which the optimal control power and control duration are jointly investigated under explicit BESS capacity constraints and renewable LVRT characteristics. In contrast to existing studies, this paper makes the following contributions:

1. Coupling between offshore wind turbine LVRT emergency actions and BESS support behavior is incorporated into the analysis framework. Based on this, a BESS-participating method is developed for transient rotor-angle support assessment. The results underpin the stable and sustainable operation of regional OWP bundled export systems.
2. A coordinated optimization framework is introduced during the design of the BESS transient rotor-angle support strategy. Specifically, the optimal intervention time and the optimal power command are determined simultaneously. Based on this framework, an optimal BESS control strategy is proposed for transient rotor-angle stability enhancement in regional renewable export systems, with security and economic performance considered together.

2. EEAC Theoretical Analysis

2.1. Multi-Machine System Equivalent Model

According to the EEAC method [25], the control targets for rotor-angle stability are uniformly the generators in the leading group. In this paper, the equivalent model assumes that the access point of the BESS is adjacent to the generator with the fastest rotor-angle instability speed in the leading group. The schematic diagram of the multi-machine system incorporating BESS is illustrated in Figure 1. By adopting the EEAC method, the multi-machine system is mapped into a single-machine equivalent for analysis through the complementary cluster center of inertia-relative motion (CCCOI-RM) transformation.

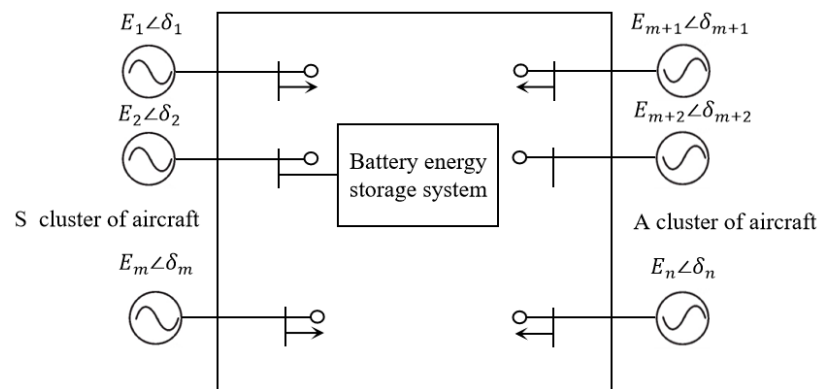


Figure 1. Schematic diagram of multi-machine system in consideration of BESS.

Based on the synchronous coordinate system, the equivalent power angle δ_S , δ_A angular velocity ω_S , ω_A as well as the rotational inertia M_S and M_A of the S-machine group (critical group) and the A-machine group (remaining group) are defined.

$$\begin{cases} \omega_S = \sum_{i=1}^m M_i \omega_i / M_S \\ \delta_S = \sum_{i=1}^m M_i \delta_i / M_S \\ M_S = \sum_{i=1}^m M_i \end{cases} \begin{cases} \omega_A = \sum_{j=m+1}^n M_j \omega_j / M_A \\ \delta_A = \sum_{j=m+1}^n M_j \delta_j / M_A \\ M_A = \sum_{j=m+1}^n M_j \end{cases} \quad (1)$$

where ω_i represents the rotor angular speed of the i th generator in the S-machine group, and δ_i denotes the rotor-angle of the i th generator in the S-machine group; ω_j represents the rotor angular speed of the j th generator in the A-machine group, and δ_j denotes the rotor-angle of the j th generator in the A-machine group.

Based on the above formula and combined with the knowledge of power system analysis, it can be derived that the rotor motion equations of the inertia center S and A are as follows:

$$\begin{cases} M_S \ddot{\delta}_S = \sum_{i \in S} [P_{m_i} - P_{e_i} - K_i (\delta_S - \delta_A)] \\ M_A \ddot{\delta}_A = \sum_{j \in A} [P_{m_j} - P_{e_j}] \end{cases} \quad (2)$$

where $\ddot{\delta}_S$ denotes the second derivative of the equivalent rotor-angle of the S-machine group, $\ddot{\delta}_A$ denotes the second derivative of the equivalent rotor-angle of the A-machine group, P_{m_i} represents the mechanical power of the i th generator in the S-machine group, P_{m_j} represents the mechanical power of the j th generator in the A-machine group, and P_e denotes the equivalent electromagnetic power of the single-machine equivalent system.

Further, performing the single-machine infinite-bus equivalent transformation yields:

$$M \ddot{\delta} = P_m - P_e \quad (3)$$

$$\begin{cases} \delta = \delta_S - \delta_A \\ M = M_S M_A / (M_S + M_A) \\ P_m = \frac{1}{M_S + M_A} \left(M_A \sum_{i \in S} P_{m_i} - M_S \sum_{j \in A} P_{m_j} \right) \\ P_e = \frac{1}{M_S + M_A} \left(M_A \sum_{i \in S} (P_{e_i} + K_e \delta) - M_S \sum_{j \in A} P_{e_j} \right) \end{cases} \quad (4)$$

Assuming the network is linear and ignoring the voltage and frequency characteristics of the load, the load admittance, and the transient reactance X'_d are incorporated into the network admittance matrix. The load nodes and tie nodes are eliminated, and only the generator terminal nodes are retained. P_{ei} and P_{ej} represent the electromagnetic power output of each generator in the S generator group and the A generator group, respectively. The formula is as follows:

$$\begin{cases} P_{ei} = E_i \sum_{k \in S} E_k G_{ik} + E_i \sum_{l \in A} E_l (B_{il} \sin \delta + G_{il} \cos \delta) \\ P_{ej} = E_j \sum_{l \in A} E_l G_{jl} + E_j \sum_{k \in S} E_k (B_{jk} \sin \delta + G_{jk} \cos \delta) \end{cases} \quad (5)$$

where E_i and E_j represent the magnitudes of the generator internal voltages after X'_d is applied, and $G + jB = Y$ is the element of the admittance matrix Y_{Bus} . Substituting (5) into (4) for the 4th equation, the electromagnetic power angle expression of the two-machine equivalent system considering energy storage is derived as follows:

$$P_e = P_C + P_{\max} \sin(\delta - \gamma) + P_\delta \delta \quad (6)$$

The coefficients in the formula are as follows:

$$\begin{cases} P_C = \frac{M_A}{M_A + M_S} \sum_{i \in S} \sum_{k \in S} E_i E_k G_{ik} - \frac{M_S}{M_A + M_S} \sum_{j \in A} \sum_{l \in A} E_j E_l G_{jl} \\ P_{\max} = (C^2 + D^2)^{1/2}; \gamma = -\tan^{-1}(C/D) \\ C = \frac{M_A - M_S}{M_A + M_S} \sum_{i \in S} \sum_{j \in A} E_i E_j G_{ij} \\ D = \frac{M_A - M_S}{M_A + M_S} \sum_{i \in S} \sum_{j \in A} E_i E_j B_{ij} \\ P_D = \frac{M_A}{M_A + M_S} \sum_{i \in S} K_{ei} \end{cases} \quad (7)$$

2.2. Calculation of the Effective Working Duration of the BESS

As illustrated in Figure 2, curves P_I , P_{II} and P_{III} denote the equivalent electromagnetic power under normal operation, during the fault, and after fault clearing, respectively, while the curve P_m represents the equivalent mechanical power. δ_0 , δ_c , and δ_d denote the rotor angles at fault inception, fault clearing, and BESS withdrawal, respectively. The system acceleration area during the fault is denoted by V_A , the decelerating area after fault clearing is denoted by V_B , and the additional decelerating area provided by BESS is denoted by V_C , while ΔP represents the additional decelerating area provided by the BESS-based emergency control strategy.

As shown in Figure 2, the analysis of the equivalent single-machine system's electromagnetic power–power angle operating trajectory: Assuming that a fault occurs at time t_0 (corresponding to power angle δ_0), during the fault period, the equivalent mechanical power is greater than the equivalent electromagnetic power, that is, $P_m > P_e$, the equivalent generator rotor accelerates, and the power angle increases; at time t_c (corresponding to power angle δ_c), after the fault is cleared, the equivalent mechanical power is less than the equivalent electromagnetic power, that is, $P_m < P_e$, the generator rotor begins to decelerate, and the power angle continues to increase but does not reach the maximum value. Assuming that at the time t_c (corresponding to power angle δ_c), emergency control of the energy storage measures is taken, and the control is ΔP_e , the equivalent generator rotor further

decelerates. If the maximum power angle δ is less than δ_d , the working point does not cross the unstable equilibrium point g (corresponding to power angle δ_d), then the power angle is stable; if the maximum power angle δ is greater than δ_d , even if the energy storage continues to be controlled, the deceleration area provided by the energy storage will not change. At this time, the emergency control of the energy storage should be exited, so the actual effective working time is the time period from δ_c to δ_d , which is $t_d - t_c$.

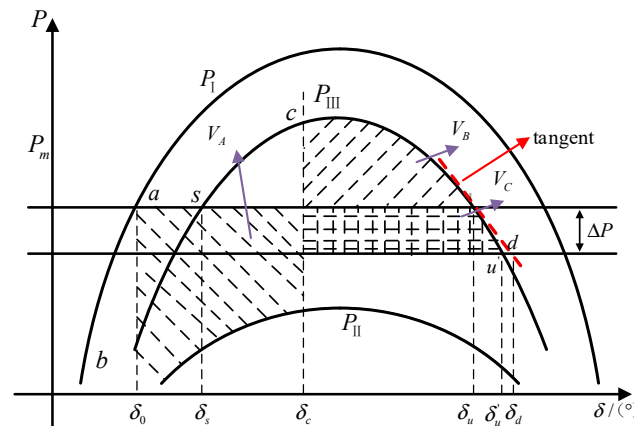


Figure 2. Equivalent electromagnetic power angle characteristics of an equivalent single machine system.

The least squares method is used to fit the fault curve P_{III} , P_C , P_{max} , γ , which are related to the network structure parameters and generator parameters [12]. The values of δ_c , ω_c corresponding to the moment of fault clearance.

$$P_{III} = P_C + P_{max} \sin(\delta - \gamma) \quad (8)$$

By combining Formulas (4) and (8), we can obtain:

$$\delta_d = \pi - \arcsin \frac{P_m - \Delta P - P_e - P_C}{P_{max}} + \gamma \quad (9)$$

By combining Formulas (3), (5), and (8), we can obtain:

$$M\ddot{\delta} = P_m - [P_C + P_{max} \sin(\delta - \gamma) + P_D\delta] \quad (10)$$

Substituting the initial values, we have $\delta|_{t=t_c} = \delta_c$, $\omega|_{t=t_c} = \omega_c$, and thus obtaining:

$$t_d - t_c = \int_{\delta_c}^{\delta_d} \left(\omega_c^2 + \frac{2}{M} \left\{ (P_m - P_C)(\delta - \delta_c) + P_{max} [\cos(\delta - \gamma) - \cos(\delta_c - \gamma)] - \frac{1}{2} P_D (\delta^2 - \delta_c^2) \right\} \right)^{-1/2} d\delta \quad (11)$$

As shown in Formula (11), after a system fault, solving δ_c and δ_d alone enables the calculation of the optimal duration for BESS to support transient rotor-angle stability.

3. Typical System for Centralized Transmission of Regional OWP New Energy

3.1. Structure of BESS-Integrated OWP New Energy Centralized Transmission System

The typical system structure of regional new energy centralized alternating current (AC) transmission is shown in Figure 3. OWP is delivered to the onshore grid via a VSC-HVDC transmission system and then exported in a bundled manner together with neighboring conventional thermal units, with BESS plants integrated at the point of interconnection.

To facilitate theoretical analysis and derivation, the following assumptions are adopted:

Assumption 1. Conventional synchronous generators are represented by the second-order classical model, while the effects of turbine governors are neglected during the transient process.

Assumption 2. In the equivalent circuit modeling, the resistances of transmission lines and transformers are neglected, and only reactance effects are taken into account.

Assumption 3. The active power output of offshore wind farms is assumed to recover instantaneously after fault clearing, such that the influence of its gradual recovery on the accelerating area is neglected.

Assumption 4. The fault clearing instant is assumed to coincide with the initiation instant of the emergency control action.

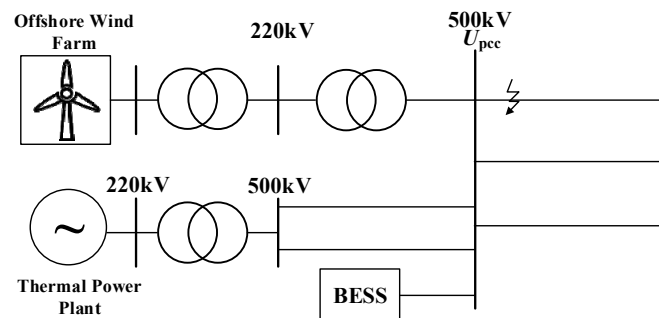


Figure 3. Model of a regional offshore wind-thermal bundled power transmission system with energy storage.

3.2. Equivalent Circuit of the Typical System for Centralized Transmission of Regional OWP New Energy with Integrated Energy Storage

The equivalent circuit of the system after the regional new energy is connected is shown in Figure 4.

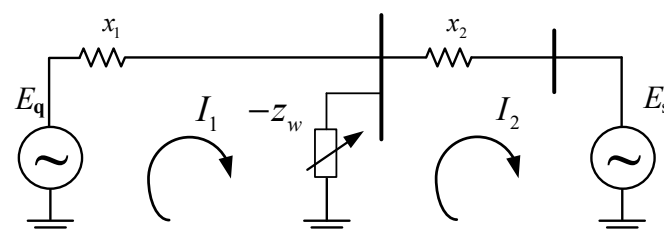


Figure 4. Simplified Model of Regional New Energy Centralized AC Transmission System.

Before renewable energy is integrated into the system, the electromagnetic power angle equation of traditional generating units is given as follows:

$$P_e = \frac{E_q E_s}{x_1 + x_2} \sin \delta \quad (12)$$

where E_q represents the transient electromotive force of the traditional generator; E_s is infinite bus potential; X_1 and X_2 are, respectively, the equivalent line impedances from the traditional unit to the grid connection point and from the grid connection point to the infinite bus. δ is the Angle between the electromotive force inside the generator and the vector of the receiving end system.

After considering the regional new energy access, the loop current equation can be written according to Figure 4. The expression of the loop current I_1 obtained through solving Formula (2):

$$\dot{I}_1 = \frac{\dot{E}_q}{jx_1 + (-Z_w)/jx_2} - \frac{\dot{E}_s}{j(x_1 + x_2) + \frac{jx_1 \cdot jx_2}{-Z_w}} \quad (13)$$

Since the energy storage capacity is much lower than the OWP capacity, the OWP and energy storage are equivalent to a negative impedance $-Z_w$ together.

The external output characteristics of OWP mainly include active power P_w , reactive power Q_w and terminal voltage u_w . In addition, the external characteristics of OWP are mainly determined by its operating mode and control strategy. Common operating modes include constant power factor mode and constant voltage mode, and there are various control strategies. Moreover, from the measured data of low-voltage ride-through, it can be known that different models of OWP from different manufacturers exhibit significantly different power output characteristics. For the convenience of research, this paper adopts the method from reference [28] to equivalently represent the wind farm in the wind-fire tie system with a set of variable negative resistance $-r_w$ and negative reactance $-x_w$ before, during, and after the fault. BESS is also equivalent in this way.

$$r_w = \frac{u_w^2}{P_w} \quad (14)$$

$$x_w = \frac{u_w^2}{Q_w} \quad (15)$$

Based on Equation (8), the electromagnetic power–power angle equation of the traditional generating units in the region for the typical structure of the regional concentrated AC power transmission system proposed in Figure 1 is Equation (16):

$$P_e = \dot{E}_q \cdot \dot{I}^* = \frac{E_q^2}{|Z_{11}|} \sin \alpha_{11} + \frac{E_q E_s}{|Z_{12}|} \sin(\delta - \alpha_{12}) \quad (16)$$

Define Z_{11} and Z_{12} as the self-impedance of the traditional unit and the mutual impedance with respect to the receiving-end system, they, respectively, are as follows:

$$\begin{cases} Z_{11} = jx_1 + \frac{(-Z_w) \cdot jx_2}{-Z_w + jx_2} = |Z_{11}| \angle (\pi - \alpha_{11}) \\ Z_{12} = j(x_1 + x_2) + \frac{jx_1 \cdot jx_2}{-Z_w} = |Z_{12}| \angle (\pi - \alpha_{12}) \end{cases} \quad (17)$$

where α_{11} and α_{12} are the self-impedance angle and mutual impedance angle, respectively.

As shown in Figure 5, by comparing the electromagnetic power-to-power Angle curves of traditional units before and after the integration of new energy, it can be known that the power Angle curve of traditional units shifts downward to the right as the power of new energy increases.

In other words, under the condition that the output of traditional units remains unchanged, the increase in the power of new energy transmitted in the region will reduce the static stability limit of the output of traditional units.

3.3. Short-Circuit Ratio Calculation of Regional OWP

3.3.1. Definition of Short-Circuit Ratio (SCR)

In the typical system for centralized transmission of regional OWP new energy, due to the combined effects of the growing number of power electronic devices integrated into the

AC grid along with renewable energy grid connection and the expansion of grid capacity, the grid strength of the AC system declines, and the coupling degree between devices is consequently intensified [29]. Therefore, the system strength after OWP integration into the grid can well reflect the risk of transient instability caused by the connection of power electronic devices to the AC grid. For this reason, in engineering practice, the definition of short-circuit ratio (SCR) is commonly adopted to characterize the relative strength of power electronic device integration into the AC system. The ratio of the system's three-phase short-circuit capacity to the rated active power of the exported energy is adopted as SCR to characterize grid strength, based on which the SCR of a standalone wind farm is calculated.

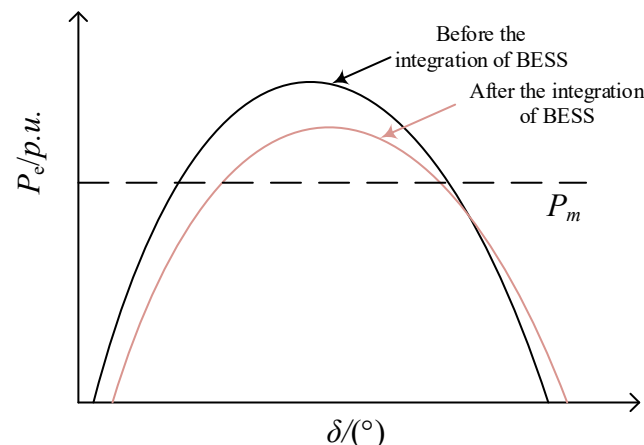


Figure 5. System power angles before and after the integration of BESS.

The interconnection of an individual wind farm to an AC system is commonly simplified using the Thevenin equivalent method, in which the system is represented as an ideal voltage source in series with an equivalent resistance. Take the receiving system as an example, as shown in Figure 6.

$$K_{SCR1} = \frac{S_N}{P_N} = \frac{U_N^2 / Z_{eq1}}{P_N} \quad (18)$$

where $Z_{eq1} = Z_W + Z_X$. Z_W represents the equivalent reactance of the transmission lines for the wind farm. Z_X denotes the equivalent reactance of the bundled system transmission line; S_N denotes the three-phase short-circuit capacity of the system; P_N denotes the active power exported by the renewable energy system; and U_N denotes the rated voltage at the wind turbine point of interconnection. K_{SCR1} denotes the system SCR in the scenario where only the wind farm is integrated into the grid.

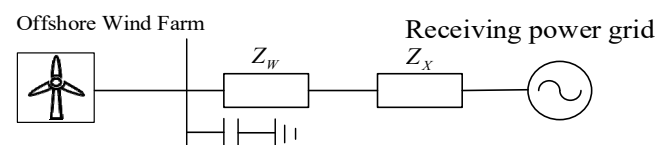


Figure 6. Sketch map of a grid-connected individual wind farm.

3.3.2. System for Centralized Transmission of Regional OWP New Energy

The Thevenin equivalent method for a standalone wind farm is extended to the bundled wind–thermal generation system, which can likewise be simplified as an equivalent voltage source in series with an equivalent resistance. Figure 7 illustrates the schematic of the centralized transmission of regional OWP connected to the receiving-end grid.

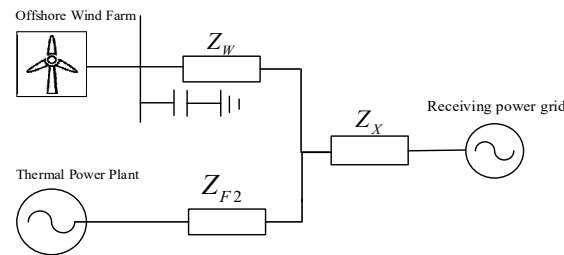


Figure 7. System for Centralized Transmission of Regional OWP New Energy.

Considering that thermal generating units in the system for centralized transmission of regional OWP can provide short-circuit current in a manner similar to the AC grid, thereby increasing the short-circuit capacity of the AC system, the thermal units are incorporated into the receiving-end grid. By paralleling their impedance with that of the receiving-end grid, the SCR calculation formula for the renewable wind farm is obtained as follows:

$$K_{SCR2} = \frac{S_N}{P_N} = \frac{U_N^2 / Z_{eq2}}{P_N} \quad (19)$$

where $Z_{eq2} = Z_W + Z_X // Z_{F2}$, Z_{eq2} represents the impedance of the wind-thermal bundled system; Z_{F2} represents the sum of the synchronous generator reactance and the line impedance. In general, after thermal generation is integrated, the system network is further reinforced due to the increase in transmitted power, which may also lead to a reduction in the equivalent system impedance; K_{SCR2} denotes the SCR of the system for centralized transmission of regional OWP.

3.3.3. Definition of the SCR for the BESS-Integrated Regional OWP New Energy Centralized Transmission System

Based on the above analysis, conventional thermal generating units can be incorporated into the receiving-end grid. Therefore, in calculating the SCR of a bundled offshore wind regional export system with BESS, the BESS and offshore wind subsystems are primarily decoupled for separate analysis, as illustrated in Figures 8 and 9.

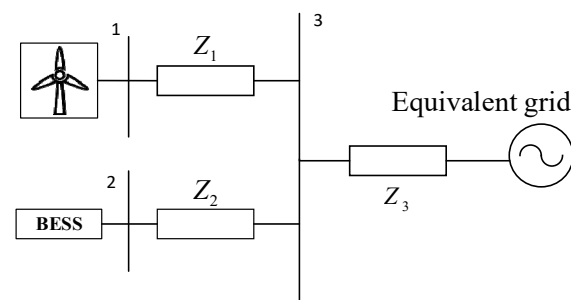


Figure 8. BESS-integrated regional OWP new energy centralized transmission system.

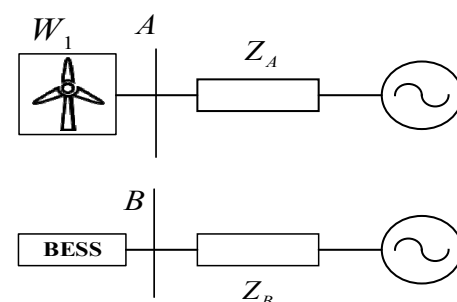


Figure 9. Decoupling system of BESS-integrated regional OWP new energy centralized transmission system.

In Figure 8, Z_1 denotes the equivalent impedance from the wind farm to the point of interconnection, Z_2 denotes the equivalent impedance from the BESS to the point of interconnection, and Z_3 denotes the equivalent system impedance excluding the wind farm and BESS.

In Figure 9, Z_A denotes the equivalent impedance of the equivalent wind-farm-only system A after decoupling the BESS from the wind farm, while Z_B denotes the equivalent impedance of the equivalent BESS-only system B after decoupling the BESS from the wind farm. As shown in Figure 9, the BESS and OWP were decoupled [30]. At this point, the calculation formula for the SCR is (20) and (21):

$$\begin{cases} K_{SCRW} = \frac{2}{S_G} / \left[\left(\frac{n_1}{S_{A1}} + \frac{n_2}{S_{A2}} \right) (1 + m) \right] \\ K_{SCRBESS} = \frac{2}{S_G} / \left[\left(\frac{n_1}{S_{A1}} + \frac{n_2}{S_{A2}} \right) (1 - m) \right] \end{cases} \quad (20)$$

$$m = \sqrt{1 - (1 - g^2) \cdot \frac{4n_1n_2}{S_{A1}S_{A2}} / \left(\frac{n_1}{S_{A1}} + \frac{n_2}{S_{A2}} \right)^2} \quad (21)$$

where $g = \sqrt{S_{A1}S_{A2}/S_{A3}^2}$. K_{SCRW} denotes the SCR of the equivalent offshore wind farm only system after decoupling; $K_{SCRBESS}$ denotes the SCR of the equivalent BESS-only system after decoupling; S_G denotes the rated capacity of a single wind turbine; n_1 denotes the number of wind turbines in the wind farm; n_2 denotes the equivalent number of wind turbines corresponding to the BESS capacity; S_{A1} denotes the AC short-circuit capacity at the wind–BESS point of interconnection 1; S_{A2} denotes the AC short-circuit capacity at the wind–BESS point of interconnection 2; g denotes the wind–BESS coupling coefficient; m denotes the wind–BESS short-circuit capacity correlation coefficient; S_{A3} denotes the AC short-circuit capacity at the wind–BESS collector bus 3.

4. Analysis of the Mechanism of BESS Participation in Enhancing System Transient Rotor-Angle Stability

Since both the power and time for energy storage to enhance transient power angle stability can affect its enhancement capacity [31], this paper analyzes each of these two aspects one by one to explore the optimal control strategy for energy storage to enhance transient power angle stability.

4.1. Before the Electrical Failure Occurred

Based on Formulas (14) and (15) and the above analysis, the following conclusions can be drawn regarding the equivalent characteristics of the battery energy storage system (BESS) during the transient process: During the transient period, when the BESS participates in transient rotor-angle stability support, its active power absorption behavior can be equivalently regarded as a positive resistance r_c . It should be clarified that the “two components” referred to here are the equivalent positive resistance r_c derived from the BESS and the original impedance of the system. The combination of these two components can be regarded as an integrated equivalent impedance.

It is worth noting that before a system fault occurs, the BESS does not participate in the enhancement of transient rotor-angle stability. In this state, the BESS is equivalent to an infinite resistance, which means it has no impact on the original impedance characteristics of the system. However, once the fault occurs and the BESS is activated to absorb active power for stability support, it is equivalent to the positive resistance r_c . Thus, the integrated equivalent impedance formed by the equivalent positive resistance r_c and the original

system impedance is eventually equivalent to a negative impedance Z_w . The equivalent circuit of the system under this working condition is shown in Figure 10.

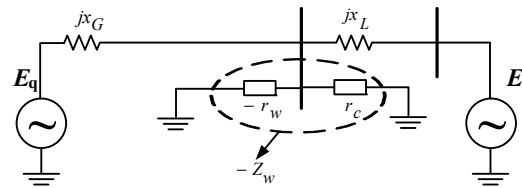


Figure 10. The system circuit before the fault occurred.

The phase angles α_{11} between the self-impedance Z_{11} , mutual impedance Z_{12} and the self-impedance is, respectively:

$$Z_{11} = jx_G + jx_L // -Z_w = \frac{Z_w X_L^2}{Z_w^2 + X_L^2} + j \left[x_G - \frac{Z_w^2 X_L}{Z_w^2 + X_L^2} \right] \quad (22)$$

$$Z_{12} = jx_G + jx_L + \frac{jx_G \cdot jx_L}{-Z_w} = \frac{x_G x_L}{Z_w} + j(x_G + x_L) \quad (23)$$

$$\alpha_{11} = \arctan X_G \left(X_L^2 + Z_w^2 \right) - Z_w^2 X_L / \left(X_L^2 + Z_w^2 \right)^2 \quad (24)$$

When r_w is positive, the other system parameters and circuit parameters of the remaining systems are also positive, resulting in $\alpha_{11} < 0$. From this, it can be known that the first part of the Formula (24) is negative, causing the power characteristic curve to shift downward. From this, it can be concluded that the appearance of r_w , namely the intervention of the offshore wind farm, reduces the amplitude of the electromagnetic power.

4.2. During the Electrical Failure

During the fault period, based on Formulas (14) and (15), the offshore wind farm is equivalent to $-r_w$ and $-x_w$ in parallel. The system circuit is shown in Figure 11.

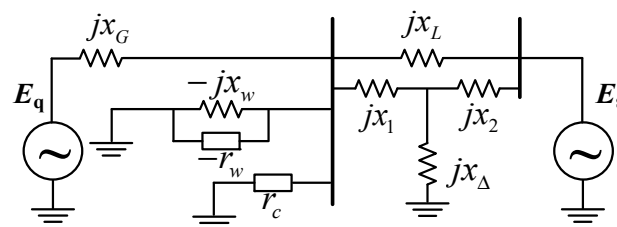


Figure 11. System circuit during a fault.

Under normal system operation, the new energy station operates in a constant power factor state, only supplying active power to the system, and the reactive power output is zero. When a system failure occurs, during the transient period, the new energy station enters the LVRT state. The new energy station supplies reactive power to the system to support the system voltage, and the remaining capacity is used to meet the active power requirements. Therefore, the active power will be limited to a relatively low level. After the fault ends, the new energy station exits the transient ride-through control, and the reactive power directly returns to the level before the fault. The active power usually slowly recovers to the level before the fault at a fixed slope [17]. The power dynamic characteristics of renewable energy under low voltage ride-through (LVRT) control are specifically illustrated in Figure 12.

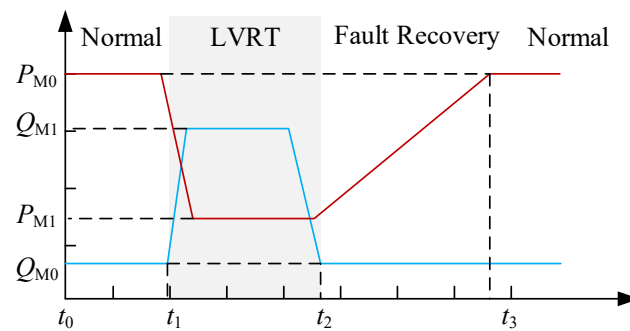


Figure 12. Power dynamic characteristics of renewable energy under LVRT control ride-through.

During the electrical failure, the self-impedance Z_{11} , mutual impedance Z_{12} , the expressions of α_{11} and α_{12} , respectively, given as follows:

$$\begin{aligned} Z_{11} &= jx_G + (-r_w) // -jx_w // jx_1 // jx_L // r_C \\ &= \frac{\frac{1}{r_C} - \frac{1}{r_w}}{\left(\frac{1}{r_C} - \frac{1}{r_w}\right)^2 + \left(\frac{1}{x_w} - \frac{1}{x_L} - \frac{1}{x_1}\right)^2} \\ &\quad + j \left[x_G - \frac{\frac{1}{x_w} - \frac{1}{x_L} - \frac{1}{x_1}}{\left(\frac{1}{r_C} - \frac{1}{r_w}\right)^2 + \left(\frac{1}{x_w} - \frac{1}{x_L} - \frac{1}{x_1}\right)^2} \right] \end{aligned} \quad (25)$$

$$\begin{aligned} Z_{12} &= j(x_G + x_L) + \frac{jx_G \cdot jx_L}{(-jx_w) // (-r_w) // r_C // jx_1} \\ &= -x_G x_L \left(\frac{1}{r_C} - \frac{1}{r_w} \right) + j \left[(x_G + x_L) - x_G x_L \left(\frac{1}{x_w} - \frac{1}{x_1} \right) \right] \end{aligned} \quad (26)$$

$$\alpha_{11} = \arctan \left(\frac{x_G \left[\left(\frac{1}{r_C} - \frac{1}{r_w} \right)^2 + \left(\frac{1}{x_w} - \frac{1}{x_L} - \frac{1}{x_1} \right)^2 \right] - \left(\frac{1}{x_w} - \frac{1}{x_L} - \frac{1}{x_1} \right)}{\frac{1}{r_C} - \frac{1}{r_w}} \right) \quad (27)$$

$$\alpha_{12} = \arctan \frac{(x_G + x_L) - x_G x_L \left(\frac{1}{x_w} - \frac{1}{x_1} \right)}{-x_G x_L \left(\frac{1}{r_C} - \frac{1}{r_w} \right)} \quad (28)$$

As shown in Formula (27), it can be seen that the value of x_w is generally much larger than x_L , and it can be easily proven that $\alpha_{11} > 0$. In addition, since the denominator is larger than the numerator, it is almost zero. Therefore, the first term in Formula (16) is approximately zero and has little effect on the electromagnetic power angle curve. In addition, when considering transient emergency control in OWP, the second part under the square root of Formula (26) decreases, the modulus of Z_{12} decreases, the denominator part in Formula (28) decreases, and α_{12} increases. In other words, when the OWP implements transient emergency control, the electromagnetic power angle curve of the conventional thermal units shifts upward, which in turn reduces the system's acceleration area S_a during the fault period. During the transient process, the smaller the active power output of the new energy, the greater the reactive power support output. During the fault period, the acceleration area will be smaller, and the impact on the transient stability of the system will be greater. By comparing and analyzing the electromagnetic power–power angle curves of traditional units that consider transient control in the transient process of new energy, the results are shown in Figure 13.

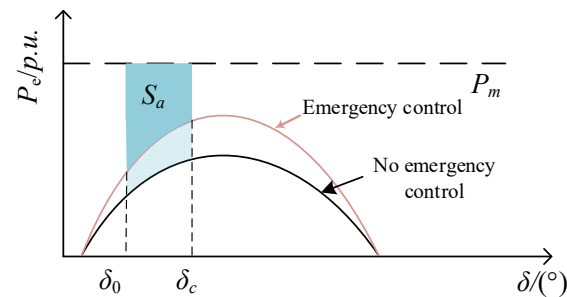


Figure 13. The influence of wind power transient control on the transient acceleration area of traditional units.

4.3. After the Electrical Failure Occurred

Suppose one of the three circuits in the system fails. After the system fails, the BESS participates in the transient power angle support when the fault is removed, changing the modulus and phase angle of the mutual impedance, thereby altering the electromagnetic power angle curve. To analyze how BESS can enhance the transient power angle stability of the system, this paper plots the equivalent circuits of the system after fault removal and conducts an analysis in combination with the EEAC rule. The equivalent circuit of the system after fault removal is shown in Figure 14.

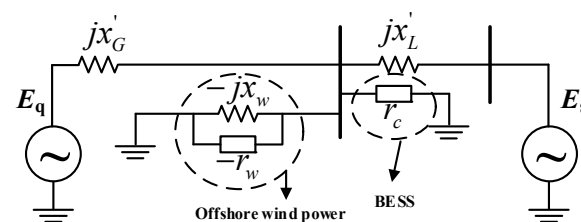


Figure 14. Schematic diagram of energy storage, power station connected to the system after fault clearing.

After the fault is removed, the wind farm exits the LVRT state, restores active power, and reduces reactive power. Therefore, a set of variable negative resistance $-r_w$ and negative reactance $-x_w$ are used for equivalence.

To analyze the mechanism of transient power Angle support provided by energy storage, Formula (17) is further derived into Formulas (29) and (30).

$$|Z_{12}| = \sqrt{\left(x_G x'_L \left(\frac{1}{r_c} - \frac{1}{r_w}\right)\right)^2 + \left(x_G + x'_L + \frac{x_G x'_L}{x_w}\right)^2} \quad (29)$$

$$\alpha_{12} = \pi - \arctan\left(\frac{x_G + x'_L - \frac{x_G x'_L}{x_w}}{x_G x'_L \left(\frac{1}{r_c} - \frac{1}{r_w}\right)}\right) \quad (30)$$

At the same time, based on the EEAC rule, the electromagnetic power Angle curve when the energy storage provides transient power Angle support is drawn, as shown in Figure 15.

When the energy storage absorbs active power, the Z_{12} and α_{12} The modulus value increases. After the fault is removed, to P'_{III} , the energy storage absorbs active power, causing the electromagnetic power angle curve to shift downward to the right. Moreover, the smaller the active power absorbed by the energy storage, the greater the amplitude of its movement, and the larger the power Angle at stability. The system stability margin is compressed, which is not conducive to system stability. Therefore, it is necessary to make the BESS absorb the maximum possible active power to minimize the power Angle at

stability. At the same time, to ensure the safety of the energy storage equipment, Transient power Angle support should be provided at a current not exceeding 1.5 times the rated current. If the system suffers a severe failure and the wind power needs to take emergency curtailment measures, the Z_{12} and α_{12} modulus value will decrease, the fault recovery curve will move upward to the left to P_{III}' , and the power Angle will decrease to δ_s'' when the system returns to stability. In conclusion, under the premise of ensuring the safety of energy storage power stations, they should provide the maximum active power as much as possible to participate in the improvement of transient power angle stability.

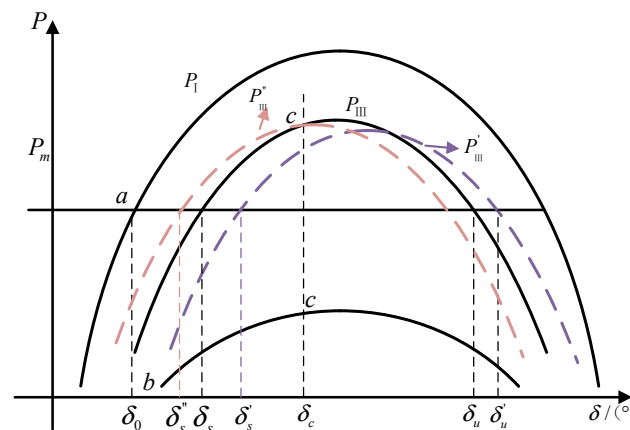


Figure 15. Power angle characteristic curves of energy storage with different powers.

In fact, when the power of the energy storage participating in the improvement of the system's transient power Angle stability is constant, when the working time of the energy storage in the emergency control process reaches a certain threshold and can provide sufficient deceleration energy, the operating point can not exceed the unstable equilibrium point and gradually approach a new operating point. On this basis, even if the working time of the energy storage is extended, it only affects the power Angle swing speed. And it does not affect the stability of the power Angle itself. Therefore, when the power of the energy storage participating in the transient power angular branch is constant, the maximum additional deceleration area it provides is also fixed. If the working time of the energy storage is too short, it cannot provide sufficient deceleration energy to stabilize the system. Thus, it is necessary to find its optimal working time. After the fault is removed, the active energy absorbed by the energy storage is equivalently reflected in the reduction in mechanical power, and the additional deceleration area is approximately equivalent to a trapezoid V_c , as shown in Figure 16. The maximum active power absorbed by the energy storage can be obtained by measuring the data $\Delta P_{\max}$ at the grid connection point. At this time, it can be calculated according to the expression of the slope of the hypotenuse $k = \frac{\Delta P}{\delta_u - \delta_d}$, which greatly reduces the computational complexity. The corresponding moment δ_d is t_d , the corresponding time δ_c is t_c , when the energy storage connection time is greater than t_d , the additional acceleration area provided by it will not increase.

The EEAC criterion is affected by communication delays, practical actuation delays, and measurement accuracy. Moreover, since BESS operates as a continuous emergency control resource, inherent limitations arise when applying the EEAC criterion to continuous control actions. Ultimately, to eliminate systematic errors, in practical engineering applications, the time for energy storage to participate in emergency power control is usually multiplied by a certain margin coefficient: $T_{work} = \mu(t_d - t_c)$.

In conclusion, under the premise of ensuring the safety of BESS, they should provide the maximum active power as much as possible to enhance the stability of the transient

power Angle, and exit in a timely manner after providing sufficient deceleration area to avoid affecting the stability of the system.

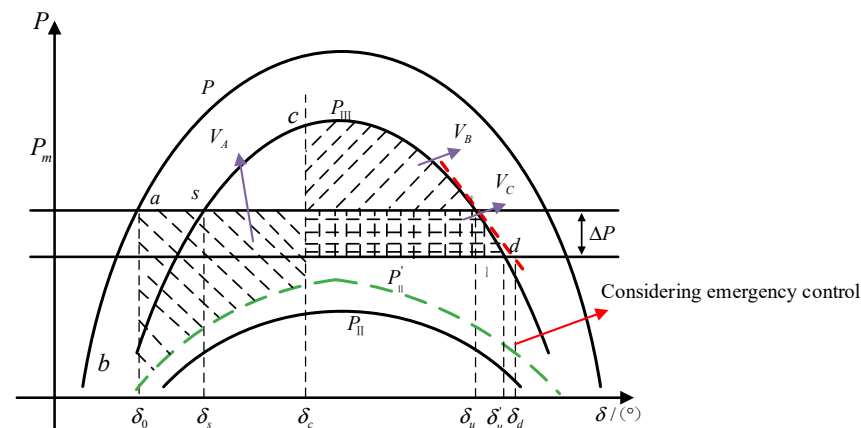


Figure 16. Power angle characteristic curve of energy storage participating in transient stability emergency control.

5. Simulation Analysis

5.1. Parameter Settings

To verify the effectiveness of the above strategies, this paper establishes a simulation system for the centralized transmission of regional offshore wind power (OWP) new energy integrated with a battery energy storage system (BESS). A wind-thermal bundled transmission scenario is adopted, with a capacity ratio of wind power to thermal power of 1:1.5. Specifically, the total capacity of wind power is 1200 MW, which is aggregated by 4 equivalent offshore wind farm clusters. Each wind farm cluster is equipped with 60 offshore wind turbines with a single-unit capacity of 5 MW, and the wind speed is set to fluctuate randomly around 11 m/s; the total capacity of thermal power is 1800 MW, and both wind power and thermal power are modeled by equivalent aggregation. In the actual BESS-integrated regional OWP new energy centralized transmission system, thermal power units can provide short-circuit current and enhance system stability. Therefore, this paper focuses on the short-circuit ratio (SCR) on the offshore wind farm side, and the system SCR is set to 2.0. The BESS capacity is configured as 10% of the system's transmission capacity.

This paper designs multiple sets of simulation experiments to verify the effect of energy storage on enhancing the transient power Angle stability of the regional new energy transmission system.

5.2. Necessity Analysis of Optimal Control Power for BESS

To explore the influence of different active power outputs on the system power Angle when energy storage participates in emergency power support, this study sets up three control scenarios for simulation: no BESS participation, energy storage output at 70% of the rated power, and BESS output at 25% of the rated power. Furthermore, a three-phase ground short-circuit fault with a duration of 0.2 s is initiated at the position one-quarter of the distance from the point of common coupling (PCC) on one of the three transmission lines shown in Figure 1. The variations in the system rotor-angle under three scenarios are illustrated in Figure 17. In this picture, P_N represents active power.

As shown in Figure 17, when no energy storage is involved in emergency power control, the system's power Angle swing is the largest and the recovery to stability is the slowest. In combination with Figure 17, when the energy storage outputs at 25% of the rated power, the system power Angle increases compared to the initial value when it returns to stability, and the system stability margin is compressed. When the energy storage

operates at 70% of the rated power, the system's power Angle recovers the fastest and can return to the initial value, which is consistent with the conclusion drawn from the analysis in Figure 17. In summary, when the BESS participates in enhancing the system's transient rotor-angle stability, it should maximize the absorption of active power to improve the system's transient rotor-angle stability.

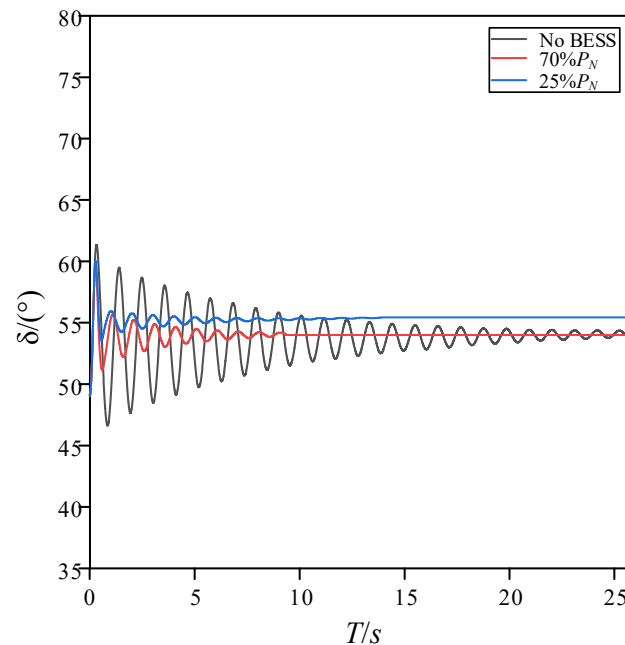


Figure 17. Power angle curves under different energy storage power schemes.

5.3. Necessity Analysis of Transient Emergency Control for Renewable Energy Units

For renewable energy units such as offshore wind power (OWP) farms, they should switch to the low-voltage ride-through (LVRT) mode and implement emergency control when a short-circuit fault occurs in the system. Meanwhile, if a severe fault, such as a three-phase ground fault, occurs in the system, generator tripping is required if necessary. To verify the impact of emergency control measures implemented by renewable energy units on the system's transient rotor-angle stability after a fault, the simulations are configured as follows in this paper:

Suppose at time $t = 0$ s, a severe three-phase ground short-circuit fault occurs in one of the three transmission lines of the system near the connection point, with a fault duration of 0.2 s. Wind power takes and does not take emergency control measures, respectively. The variations in the system rotor-angle and the point of common coupling (PCC) voltage are illustrated in Figures 18 and 19, respectively.

As shown in Figures 18 and 19, when a serious fault occurs, if wind power does not participate in emergency control, the system power Angle will gradually oscillate after the fault is removed, and eventually power Angle instability will occur. When wind power units take emergency shutdown measures, due to the provision of additional acceleration area, the system power Angle will gradually stabilize. However, the power Angle of the second pendulum of thermal power units still has 68.8° , and the overall oscillation amplitude is relatively large. Further analysis of Figure 19 reveals that during the system's transient process, the voltage at the grid connection point drops below 0.2 (p.u.). At this point, in accordance with the requirements of the low-voltage ride-through curve of the wind turbine, after emergency control of wind power is implemented, energy storage should be considered for improving the transient power Angle stability.

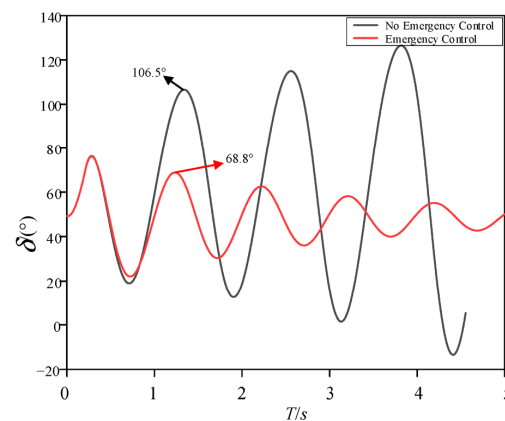


Figure 18. Power angle curves with and without wind turbine emergency control.

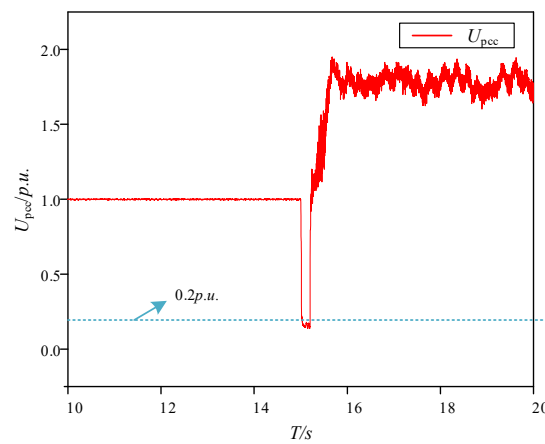


Figure 19. The voltage at the connection point of OWP when there is no emergency shutdown.

5.4. Necessity Analysis of Optimal Control Time for BESS

The BESS should participate in enhancing the system's transient rotor-angle stability with its maximum active power. To verify the existence of an optimal control time for the BESS under this condition, this paper configures the simulations as follows.

Suppose at time $t = 0$ s, a severe three-phase ground short-circuit fault occurs in one of the three transmission lines of the system near the connection point, and the duration of the fault is 0.2 s. After the wind power adopts emergency control, the optimal working time T_{work} of the energy storage under the most controlled conditions is calculated by the numerical integration method to be approximately 1.05 s. To verify the validity of the calculation results, the BESS operation times are set at 0.3 s, 1.05 s and 2.8 s. The differences in generator power angles of the BESS under three different working conditions were compared. The simulation results are shown in Figures 20 and 21.

The peak and valley values of the K oscillation of the curve in the figure is defined as X_{max}^k and X_{min}^k , respectively, and the power angle value is X_{bal} . The coefficient γ^k is defined to evaluate the transient stability regulation ability of the energy storage power station, as shown in Formula (31). The larger the γ^k , the stronger the stability of the energy storage power station and the better the transient stability regulation effect. The γ^k values of the first four oscillations are shown in Table 2.

$$\gamma^k = \frac{x_{\text{tbl}}^k}{|x_{\text{max}}^k - x_{\text{min}}^k|} \quad (31)$$

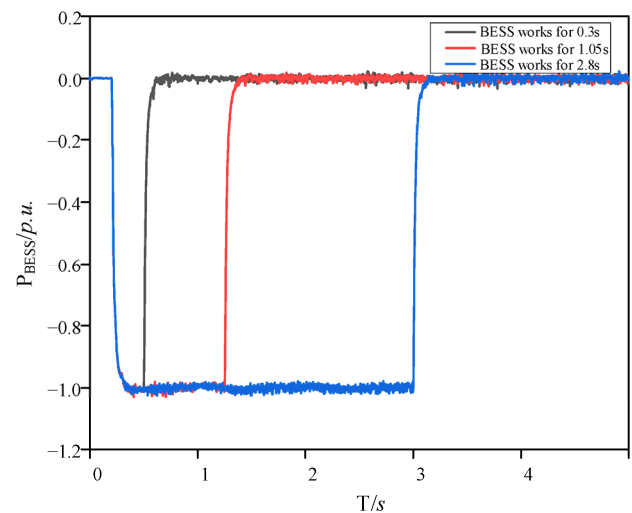


Figure 20. The active power output curves of the BESS under different working hours.

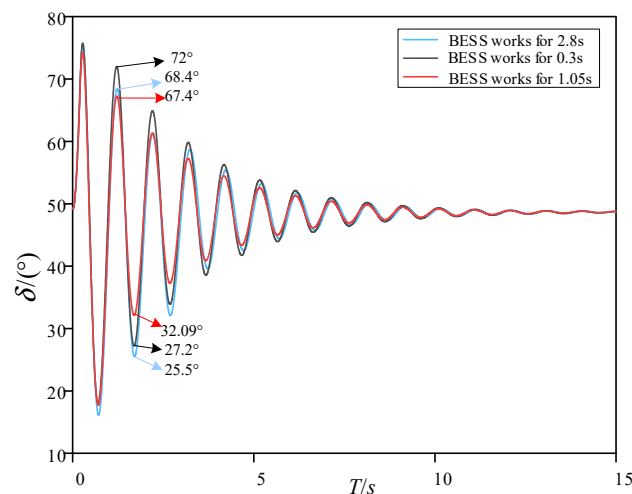


Figure 21. Power angle curves of energy storage with different working times at $K_{SCR} = 2.0$.

Table 2. Values of energy storage with different participation times.

$T_{work} k$	1	2	3	4
0.3 s	0.847	1.089	1.574	2.292
1.05 s	1.137	2.016	2.980	3.255
2.8 s	0.819	1.136	1.665	2.551

As shown in Figure 21, the emergency control of the BESS can be completed within 100 ms. It can be seen from Figure 21, combined with Table 2, that the energy storage working time is optimal when it is 1.05 s. When the energy storage working time is 0.3 s, it cannot provide sufficient deceleration area to make the system power Angle quickly return to stability. When the working time of energy storage is 2.8 s, compared with that, the long-term operation of energy storage will cause system instability due to the lack of inertial support from the power grid. In summary, the energy storage control strategy proposed in this paper proves to be highly effective.

5.5. Analysis of the Impact of Different SCRs on System Transient Stability

The lower the grid strength of the system, the more unstable the system becomes. To further analyze the impact of SCRs on system transient stability, this paper reduces the system SCR to 1.8 by modifying the impedance Z_3 shown in Figure 3. Subsequently, the

same fault is applied to the corresponding location in the simulation system described in Section 5.4, and the simulation results are illustrated in Figure 22.

As shown in Figure 21, the optimal control time of the BESS is 1.0 s, which is shorter than that of the system with an SCR of 2.0. This is because, by increasing Z_3 , this paper shifts the system's electromagnetic power angle curve in the steady state to the upper left corner, thereby shortening the duration of this optimal control. In addition, by comparing Figures 21 and 22, it can be observed that when the SCR is 2.0, the steady-state power angle of the system is 47.5° ; when the SCR is 1.8, the steady-state power angle of the system is 55.03° . The difference between the two is 7.53° . A decrease in the SCR indicates that the system's stability margin is compressed, which in turn leads to an increase in the power angle during the stable operation of the system. Furthermore, after the fault is cleared and the system returns to stability again, the power angle of the system with an SCR of 2.0 stabilizes at 49° , while that of the system with an SCR of 1.8 stabilizes at 60.12° , with a difference of 11.12° between the two. As can be seen from Formula (19), this paper reduces the system's SCR by increasing Z_3 , after the fault is cleared, Z_3 increases again, further compressing the system's stability margin.

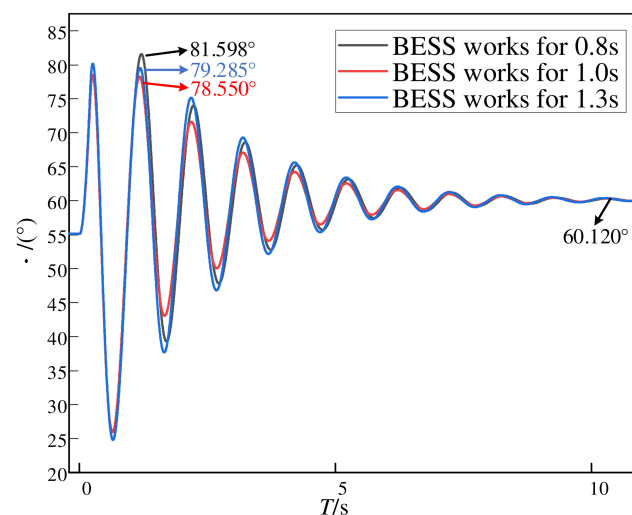


Figure 22. Power angle curves of energy storage with different working times at $K_{SCR} = 1.8$.

6. Conclusions

This paper establishes an equivalent model of a regional OWP concentrated export system with a BESS and reveals the key mechanism by which OWP integration affects transient stability. In addition, based on the EEAC method, the accelerating and decelerating areas during the transient process are evaluated, and an optimal control strategy is developed for BESS participation in transient stability support. The main conclusions are summarized as follows.

1. Under severe faults that lead to transient rotor-angle instability, the OWP enters the LVRT state. In this state, active power reduction and reactive power injection reduce the accelerating area effectively. If OWP emergency power control is not considered and BESS is the only emergency resource, rotor-angle stability is difficult to restore. Therefore, the OWP's LVRT characteristics should be included when assessing the stabilizing contribution of BESS under severe disturbances.
2. This paper further proposes an optimal control strategy for BESS participation in transient rotor-angle stability enhancement of regional renewable export systems. The strategy is characterized by the coupled determination of optimal control power and optimal control timing. Based on the EEAC, both quantities are derived with OWP's

LVRT characteristics incorporated, and the effectiveness of the strategy is validated through time–domain simulations.

Although the proposed method yields encouraging results, the case study only considers the most severe fault scenario and neglects the influence of OWP active-power recovery speed on the decelerating area. Future work will investigate how different OWP recovery speeds coordinate with BESS actions and how such coordination affects the enhancement of transient rotor-angle stability. Additionally, future research can combine the optimal strategy proposed in this paper with machine learning to realize adaptive control based on real-time data while simulating the impact of uncertain factors such as wind speed fluctuations; extend the research scenario to multi-energy hybrid systems including photovoltaic and hydrogen energy to explore the cooperative optimization strategy of the battery energy storage system (BESS) under multi-energy coupling scenarios and improve the adaptability of the method in complex energy systems.

Author Contributions: Conceptualization, F.T.; Methodology, Y.L. and F.T.; Software, Y.L.; Validation, Z.L. and L.Z.; Formal analysis, Y.L. and Z.L.; Investigation, L.Z.; Writing—original draft, Y.L.; Writing—review and editing, F.T.; Visualization, Z.L.; Supervision, F.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Key Science and Technology Project of China Southern Power Grid Co., Ltd. (GDKJXM20222431).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Yuming Liu and Zining Liu are employed by Electric Power Research Institute, China Southern Power Grid (CSG). The authors declare that this study received funding from the Key Science and Technology Project of China Southern Power Grid Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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