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Modeling and Simulation on the Hybrid Solution of Static Var Generator and Synchronous Condenser for Unlocking Power Output Limitation of Wind Farms Integrated into Weak Grid

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Abstract: The issues of low inertia, overvoltage, and wide-frequency oscillations in high-proportion renewable energy systems have become prominent, posing major challenges to renewable energy integration and threatening grid stability. Currently, many wind-rich areas ensure grid safety and stability by reducing wind farm output. To enhance the active power delivery capability of wind farms, this paper proposes a hybrid solution of a small synchronous condenser (SC) and static var generator (SVG) within wind farm stations to optimize reactive power and voltage at the point of grid connection. First, it was analyzed that the low short-circuit ratio (SCR) is a key factor affecting the stable operation of wind farms, and the sub-transient reactance of the SC can increase the SCR. Based on this, a method for configuring the capacity of the SC was developed. Next, simulation models for both the SC and the SVG were established, and their reactive power compensation capabilities were verified. The hybrid control approach combined the advantages of both devices, providing comprehensive voltage support across sub-transient, transient, and steady-state conditions for renewable energy stations. Furthermore, based on a practical 50.5 MW wind farm, which has been operating with a power delivery consistently limited to 60% of its capacity, a simulation model and scenarios were set up. A comparison of the simulation results shows that, with only the SVG in operation, the wind farm is prone to oscillations after a grid fault. However, after adopting the hybrid control of the SC and SVG, the wind farm operates stably. Therefore, installing a small SC within wind farms can effectively address the limitations of voltage stability and a low short-circuit ratio, thereby supporting higher levels of renewable energy integration.

Keywords: wind farms; synchronous condenser; short-circuit ratio; weak grid; static var generator; reactive power support; wind power delivery

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1. Introduction

With the global transition toward sustainable energy development, wind power, as a clean and renewable energy source, is becoming an increasingly prominent component of the global energy supply [1–3]. The large-scale integration of wind power and other renewable energy sources into the grid presents a number of challenges for power systems. Firstly, the SCR at renewable energy sites is decreasing, which consequently reduces the voltage support capability of the grid at the point of connection (PoC). Secondly, in

the event of a grid fault, there is a time delay in the reactive power response of wind turbine converters, which may result in a potential reactive power surplus immediately following fault clearance. This can result in transient overvoltage phenomena, which may compromise the safe and stable operation of grid-connected wind turbines [4]. Grid instability is frequently linked to low SCRs and weak power grids with high renewable energy penetration. This not only constrains the power output of wind farms but also undermines the cost-effectiveness and reliability of the power system. Consequently, strengthening a weak grid's SCRs and optimizing the reactive power support strategies for wind farms are vital to guaranteeing the stability of the power system and enhancing the integration of wind power.

The recurrent occurrence of significant incidents of wind turbines cascading off-grid has led to a consistent emphasis in analyses of past events on the issue of the insufficient dynamic reactive power compensation capability in wind farms. To enhance the reactive voltage support capability in wind power aggregated areas, the deployment of dynamic reactive power compensation devices has become a critical technical solution [5]. These technologies, which mainly include synchronous condensers (SCs), static var compensators (SVCs), and static var generators (SVGs), can effectively compensate for the power factor of wind farms, reduce transmission line losses, and enhance the transmission capacity and stability of the power grid.

The SC can be regarded as a large-capacity synchronous motor operating at no load, consuming only a small amount of active power to compensate for operational losses and overcome the damping torque of its rotating components. The SC is capable of rapidly absorbing or supplying substantial quantities of reactive power in response to fluctuations in voltage levels. Its key advantages include the capability to regulate reactive power in both directions with exceptional voltage regulation characteristics. However, it also presents certain limitations, such as a slower response speed and higher investment/operational costs [6,7].

Since the 1980s, with the significant advancements in power electronics technology, the traditional role of SCs in power systems has gradually supplanted modern static reactive power compensation devices, such as SVGs and SVCs, which provide more efficient and flexible reactive power support [8]. Despite the potential obsolescence of traditional SCs due to technological substitution and operational costs, they have once again become essential reactive power compensation devices in various scenarios, including classic high-voltage direct-current (HVDC) converter stations, power substations connected with high-capacity renewable generation infrastructure, and renewable energy plants.

The inherent randomness and intermittency of wind farms frequently result in complications such as voltage instability and increased line losses within the power grid. To address these issues, reactive power compensation devices are employed to improve the grid power quality, reduce grid losses, mitigate transient voltage fluctuations during grid faults, and enhance the operational stability and safety of the power grid. The majority of wind farms are often equipped with SVGs or SVCs for reactive power compensation. However, with the growing technical demands for renewable energy sources to provide essential inertia and short-circuit capacity support, SCs are being increasingly considered as an alternative for dynamic reactive power compensation in wind farms.

A substantial body of research has been conducted by numerous scholars on the response capabilities and excitation control of SCs. Igbinovia F.O. et al. [9] explored the key role of SCs in improving voltage stability in modern power systems and conducted a simulation study combining SCs with wind power generation. A. Nazir [10] highlighted the importance of the rapid reactive power response of SCs in HVDC systems for suppressing transient overvoltage caused by disturbances in DC systems, which greatly enhances grid

stability after wind farm integration. Chaobo Dai et al. [11] used electromagnetic transient digital simulation, combined with SC model data and typical parameters of excitation control systems, to systematically analyze the reactive power response speed of SCs in three dimensions: excitation regulation, grid voltage amplitude, and phase variation. Hadavi S. et al. [12] proposed a data-driven design method for SCs operating in weak grid and low-inertia systems, developing a high-order optimized excitation controller. The research results validated the controller's significant effectiveness in enhancing system stability after faults. To address the challenges posed by transient overvoltage, Mengyang Zhao [13] proposed an innovative method of using SCs for dynamic reactive power allocation to reduce the risk of transient overvoltage in DC sending systems, for which they established an optimization model. Hanhua Zhang [14], based on a case study of the Ningxia Mahuangshan Phase IV Wind Farm, simulated and verified the impact of SCs on the SCR of multiple renewable energy plants. The results showed that the operation of SCs significantly improved the minimum SCR at each node, thereby enhancing the grid's voltage support capability. Nair A.R. et al. [15] developed a coordinated control framework considering SCs for weak-grid systems integrated with renewable energy, developed a grid model, conducted linearized analysis, and proposed parameter optimization design guidelines. The simulations verified improvements in grid control and enhanced stability, but the authors did not analyze the increase in transmission capacity from a system perspective. Stiger, A. et al. [16] discussed the challenges currently faced by power systems, especially after the integration of large-scale renewable energy, where short-circuit contribution and inertia become more important. They also explored the impact of changes in system parameters, such as harmonic resonance and SCR, on power quality devices (such as SVC, STATCOM, HVDC, MSC, and harmonic filters). The study made a positive contribution to grid stability analysis. In summary, most studies on grid-connected wind farm systems with SCs focus on the enhancement of voltage support capability and the suppression of transient overvoltage, with few analyses on the improvement in wind farm transmission capacity after the deployment of SCs.

The objective of this study includes the following:

- To examine the mechanism of output limitation for wind farms connected to the weak grid by analyzing the SCR constraint in the grid code, as well as the relationship between the voltage and output power at the PoC.
- To quantify the benefits of enhancing the power output of wind farms connected to weak grids by simulating a 50.5 MW wind farm grid integration model using the hybrid solution combining a 10 Mvar SC and a 12 Mvar SVG.

The proposed hybrid solution combining an SC and SVG has the potential to effectively mitigate transient overvoltage issues, enhance the wind farm's voltage response to transient disturbances, and increase the power output of the wind farm.

The rest of this paper is organized as follows. The mechanism of the power output limitation of wind farms is introduced in Section 2. Section 3 gives general models of reactive power compensation devices in wind farms. Section 4 establishes a wind farm grid integration model with SCs and SVGs. In Section 5, simulation results are given to demonstrate the results of the power output of wind farms with SCs and SVGs, followed by discussions and conclusions.

2. Mechanism Analysis of Power Output Limitation in Wind Farms Connected to Weak Grid

Wind farms frequently encounter challenges associated with weak grids, such as low SCRs and an abnormal sensitivity to voltage fluctuations. When reactive power regulation is based exclusively on SVGs, wind farms may encounter transient overvoltage issues

during grid voltage faults. In order to ensure grid stability, the output of wind farms is frequently restricted, preventing them from fully achieving their generation potential. In wind farms, the SCR is a key parameter that measures the grid's voltage support capability, directly influencing grid integration and power delivery. The following section presents a comprehensive analysis of the mechanisms underlying system stability and output limitations in wind farms from the perspective of the SCR.

2.1. Short-Circuit Ratio

In order to facilitate the analysis of the system, a single-infeed AC equivalent system is constructed. The Thevenin equivalent method is typically employed to simplify the receiving-end AC grid into a model comprising an ideal voltage source and equivalent impedance, as shown in Figure 1, where U_N represents the rated voltage of the grid, P_d denotes the rated power of DC transmission, and S_{ac} represents the short-circuit capacity [17].

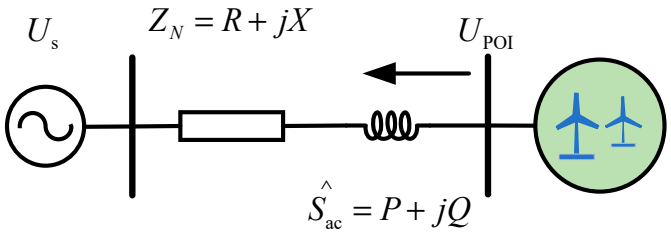


Figure 1. Single-feed AC equivalent system.

The SCR is employed to measure a system's ability to withstand voltage fluctuations in response to a fault. In the context of a wind farm, the SCR is defined as the ratio of the short-circuit capacity at the grid connection point to the rated capacity of the wind farm and reflects the wind farm's capability to support the grid during short-circuit faults. The expression for the SCR is described in the following equation:

$$K_{SCR} = \frac{S_{ac}}{P_N} = \frac{{U_{POC}}^2}{P_N \cdot |Z_N|}, \tag{1}$$

where K_{SCR} is the SCR, S_{ac} is the short-circuit capacity at the PoC, P_N is the rated capacity of the wind farm, U_{POC} is the voltage at the PoC, and Z_N is the equivalent impedance of the AC system.

When the open-circuit voltage is 1.0 pu, the SCR can be expressed as

$$K_{SCR} = \frac{S_{ac}}{P_N} = \frac{1}{P_N \cdot |Z_N|}, \tag{2}$$

Further, if the rated power (P_N) is used as the per-unit base value, i.e., P_N = 1 pu, the SCR can be expressed as

$$K_{SCR} = \frac{S_{ac}}{P_N} = \frac{{U_{POC}}^2}{P_N \cdot |Z_N|} = \frac{1}{|Z_N|}, \tag{3}$$

2.2. Critical Short-Circuit Ratio

The critical short-circuit ratio (CSCR) is a quantitative measure of the relationship between the SCR and voltage stability. It is typically defined as the minimum SCR required for the system to maintain voltage stability and avoid equipment overload. When the actual SCR falls below this critical value, the grid may not be able to maintain voltage stability during short-circuit faults, or the wind farm may not be able to provide sufficient reactive

support to sustain grid stability. Therefore, the critical SCR is closely related to the unstable conditions of the system during short-circuit faults.

By combining the maximum active power output (P_{max}) and using the definition of the SCR of the wind farm, the CSCR for the system can be calculated. This is the minimum SCR threshold at which the system can maintain stable operation under the current reactive power level and can be expressed as

$$K_{CSCR} = \frac{S_{ac}}{S_{max}} = \frac{S_{ac}}{|P_{max} + jQ|}, \quad (4)$$

where K_{CSCR} is the critical SCR, S_{max} is the maximum short-circuit capacity at the PoC, and P_{max} and Q are the maximum active power output and the corresponding reactive power of the wind farm, respectively.

Unlike the SCR, the CSCR for a single-infeed renewable plant is a parameter that is only related to the AC system side. Due to variations in system operating conditions, parameters such as P_{max}, Z_N, and U_{POC} change, and as a result, the precise value of the CSCR also varies.

2.3. Definition of a Weak Grid by SCR Levels

Weak grids are considered high-impedance connection points and have volatile voltage, and the SCR is a core concept in their definition. As shown in Table 1, there are different definitions of grid strength according to the SCR level.

Table 1. Grid strength according to SCR level [18].

Source	Very Weak	Weak	Strong
[19]	N.A.	SCR < 10	SCR > 20
[20]	SCR < 3	3 < SCR < 5	N.A.
[21]	SCR < 2	2 < SCR < 3	SCR > 3
[22]	N.A.	SCR < 6–10	SCR > 20–25
[23]	SCR = 1	N.A.	N.A.
[24]	N.A.	SCR = 6	N.A.

The New Zealand definition of a weak grid might lean toward SCR < 5 rather than a traditional value of 3, according to simulated results based on actual grids [25].

In China, according to [26–28], the SCR for renewable energy plants must meet specific requirements to ensure the stability and safety of the power system. Specifically, these plants should have sufficient inertia and short-circuit capacity support to maintain the voltage at the grid connection point within the specified range and ensure stable operation with an SCR not lower than 1.5. The classification standards for system strength are as follows:

- Strong system: the SCR is greater than 3.0;
- Weak system: the SCR is between 2.0 and 3.0;
- Very weak system: the SCR is lower than 2.0.

2.4. The Principle of Adding an SC to Increase the Short-Circuit Capacity Ratio

Consider a specific short-circuit point I_{ac} in the power system, where the effect of resistance can be neglected and the system can be represented by the circuit model shown in Figure 2. In this model, U_s represents the source voltage and X_T represents the transfer impedance of the network, i.e., the equivalent positive-sequence reactance between the source and the short-circuit point K. Additionally, X_L is defined as the system's equivalent positive-sequence reactance from the SC connection point to the short-circuit point K.

When the SC is integrated into the grid, it can be simplified as an inductive branch with a voltage source in parallel with the grid. In this simplified model, X_C represents the positive-sequence reactance of the SC.

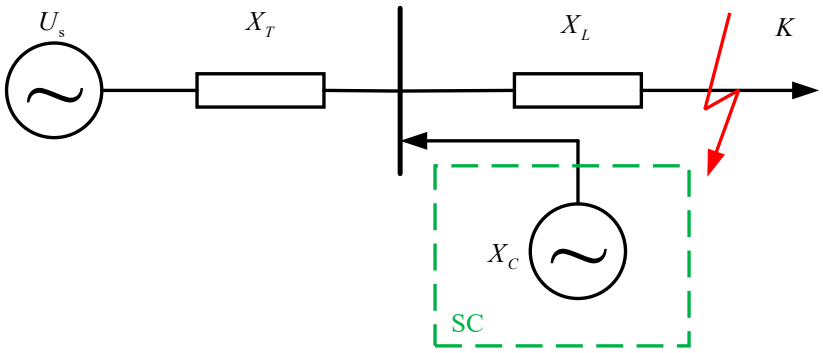


Figure 2. The system diagram after the SC is connected.

The integration of the SC into the grid has a significant impact on the short-circuit current at the fault point *K*. When the condenser is not connected, the short-circuit current is given by the following equation:

$$I_{ac} = \frac{I}{X_T + X_L}, \tag{5}$$

However, once the SC is connected to the grid, it introduces a new inductance X_C in parallel, and the short-circuit current calculation formula becomes

$$I'_{ac} = \frac{I}{X_T + X_L // X_C}, \tag{6}$$

Since the parallel reactance of X_L and X_C is smaller than the original reactance X_L, the new short-circuit current $I_{ac}{}'$ becomes bigger than I_{ac}. This indicates that the integration of the SC not only enhances the short-circuit current but also increases the system's short-circuit capacity, thereby improving the grid's ability to withstand short-circuit faults.

3. Modeling of Reactive Power Compensation Devices in Wind Farms

The most common reactive power compensation devices for wind farms are shunt capacitor banks, SVCs, SVGs, and SCs. This paper focused on analyzing the application of SVGs and SCs for reactive power compensation in wind farms and investigating how this hybrid configuration can contribute to the latter's efficient and stable operation.

3.1. SVG Operating Principle and Modeling

The SVG, also known as the static synchronous compensator (STATCOM), is a kind of reactive power dynamic compensation equipment used in power systems which uses power electronics technology to provide or absorb reactive power to improve the voltage stability and power quality of the power grid. SVGs can be classified based on different circuit structures, mainly including the types of voltage and current sources.

The voltage-source SVG is the most common type in practical applications, and it uses a voltage-source inverter as its core component. The DC side of this device has a large capacitor in parallel to ensure stable voltage during continuous charging and discharging or device commutation while the bridge side has a series inductor. This design enables the SVG to compensate for reactive power by adjusting the amplitude and phase of the inverter's output voltage or directly controlling the AC-side current, as shown in Figure 3.

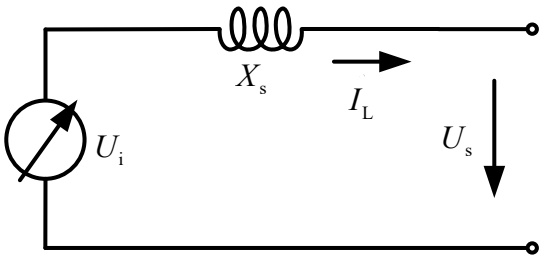


Figure 3. Equivalent circuit diagram of SVG.

The core of SVG control lies in the precise regulation of its converter, which is achieved by using a dq-axis current control method to independently adjust both active and reactive power. In the SVG control system, the direct-axis component of the three-phase current is adjusted to absorb active power, while the quadrature-axis component is regulated to output reactive power, achieving the decoupled control of active and reactive power. As shown in the control block diagram in Figure 4, the difference between the reference voltage (U_{ref}) at the PoC and the actual voltage (U) is processed with a PI controller to obtain the reactive current command. Similarly, the difference between the reference voltage ($U_{dc\text{ref}}$) of the DC-side capacitor and the actual voltage (U_{dc}) is processed with another PI controller to obtain the active current command. The D-axis and D-axis current, respectively, need a low-pass filter to suppress high-frequency noise. The ultimate goal of SVG control is to stabilize the voltage at the wind farm grid connection point through reactive compensation and ensure the stability of the converter's DC-side voltage [29].

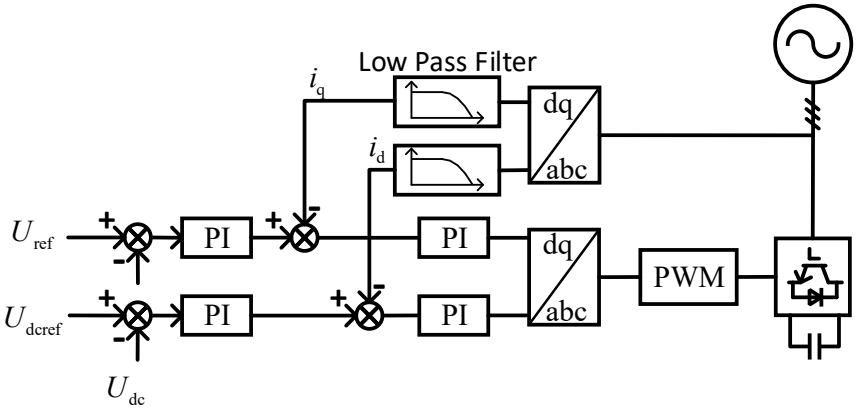


Figure 4. SVG control block diagram.

3.2. SC Operating Principle and Modeling

The SC is a special operating condition of a synchronous generator, primarily designed to provide reactive power to optimize the power factor of the power system and dynamically regulate system voltage. Small SCs play a key role in improving voltage stability within the power system by continuously adjusting the reactive power to dampen voltage fluctuations, accelerate voltage recovery after faults, and reduce the likelihood of commutation failures in DC transmission systems. In new models of SCs, greater emphasis is placed on dynamic reactive compensation, making them suitable for HVDC transmission projects, large-scale energy development areas, and centralized power reception areas, meeting the system's reactive power requirements under sub-transient and transient conditions.

During severe voltage dips, the excitation system of a small SC can quickly enter a transient forced excitation state to provide necessary reactive support, facilitating the rapid recovery of system voltage and DC power, preventing voltage collapse, and enhancing the stability and reliability of the power system. SCs are typically represented by their equivalent circuit model in power systems, as shown in Figure 5.

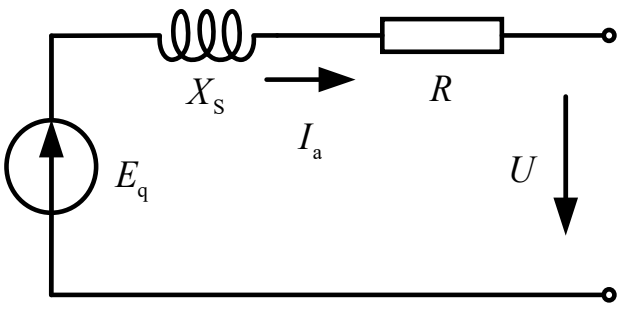


Figure 5. Equivalent circuit diagram of SC.

The reactive power output of an SC is primarily achieved by adjusting its excitation state. In an idealized machine model, taking a generator as an example, the voltage equation of the SC can be expressed as

$$\dot{E}_q = \dot{U} + j\dot{I}_a X_s, \tag{7}$$

where $\dot{E}_q$ represents the excitation electromotive force, $\dot{U}$ is the terminal voltage, $\dot{I}_a$ is the stator current, and X_s is the synchronous reactance.

The operational states of an SC can be categorized into three basic conditions: normal excitation, over-excitation, and under-excitation, as depicted in Figure 6. In the normal excitation state, the SC operates at no load, neither generating nor absorbing reactive power. Under over-excitation, the terminal voltage leads the stator current phasor, causing the condenser to operate in lagging-phase mode and thus supply reactive power as a continuously adjustable reactive power source. Conversely, in the under-excitation state, the terminal voltage lags behind the stator current, leading the condenser to operate in leading-phase mode, absorb reactive power, and act as a reactive load to balance the system's surplus reactive power. These states collectively form the theoretical basis for the SC's role in reactive power regulation within a power system.

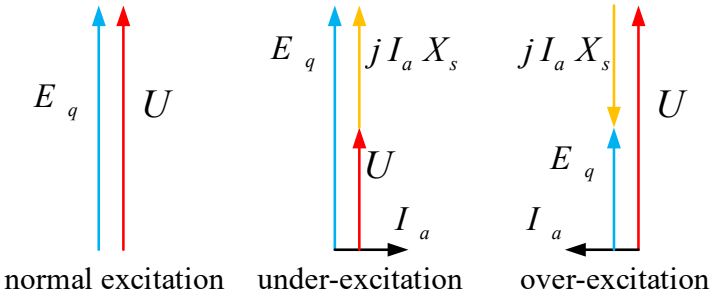


Figure 6. Vector diagram of SC excitation principle.

Under steady-state conditions, SC's control is achieved with adjustments in high-voltage bus voltage and reactive power, while transient conditions are controlled with a voltage closed-loop system that performs rapid excitation or de-excitation, extending the conventional generator control model to accommodate system bus voltage. The control diagram, shown in Figure 7, includes two PI controllers used to adjust reactive power and voltage errors. The input signals to the controller are processed by the PI controllers and combined with steady-state and transient control signals, and the control parameters of the SC are adjusted to generate the final output control signal.

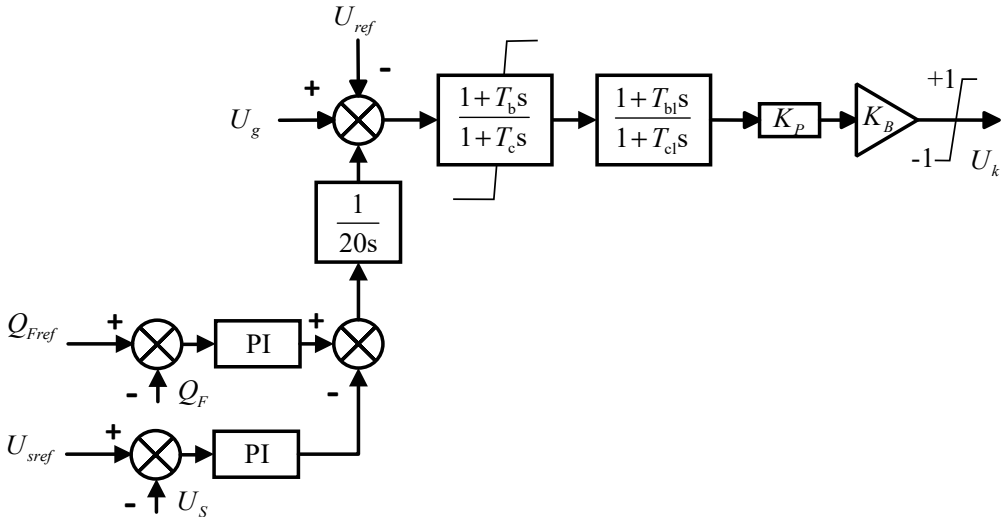


Figure 7. Control block diagram of an SC.

3.3. Hybrid Solution of SVG and SC

3.3.1. SVG Individual Operating Mode

The real-time monitoring of 35 kV bus voltage U can be performed in the following manner: when 0.95 pu < U < 1.01 pu, the SVG operates in constant reactive power mode with the objective of reducing the probability of abnormal oscillations in the voltage of the wind power aggregation system. To ensure that the SVG is capable of providing the requisite reactive power to support the voltage at the grid connection point, it is necessary to maintain a certain reactive power margin during the regulation process. This margin is set at 50% of the total reactive power capacity, which is defined as the optimal dynamic reactive power reserve point for the SVG.

When U < 0.95 pu or U > 1.01 pu, the SVG will transition to a constant-voltage control mode with 1.0 U as the constant value. The SVG is capable of adopting a constant-voltage control mode with slope characteristics for voltage regulation.

3.3.2. SC Individual Operating Mode

The SC is configured for constant-voltage control, leveraging its rapid transient response capability to regulate the 35 kV bus voltage. In particular, when the voltage declines, the SC rapidly provides a substantial quantity of reactive power support to stabilize the bus voltage of the rectifier station due to its forced excitation characteristics. Conversely, when the voltage increases, the SC instantaneously absorbs a considerable amount of reactive power from the system, thereby reducing the 35 kV bus voltage.

3.3.3. Coordination Controller Operating Mode

The flowchart of the coordination controller is shown in Figure 8. The AVC substation receives the grid dispatch instructions from the AVC master station and sends the given reactive power to the coordination controller. The coordination controller monitors the 35 kV bus voltage, compares the real-time voltage with the reference value of 35 kV, calculates the deviation, and determines the required reactive power compensation through a PI controller. This value is then added to the reactive power sent from the AVC substation, yielding the final reactive power compensation, which is reasonably distributed through a reactive power allocation scheme. The allocated reactive power is sent to devices such as the SVG and SC to complete the reactive power compensation. The system assesses whether the state is stable by comparing the real-time voltage with the reference value.

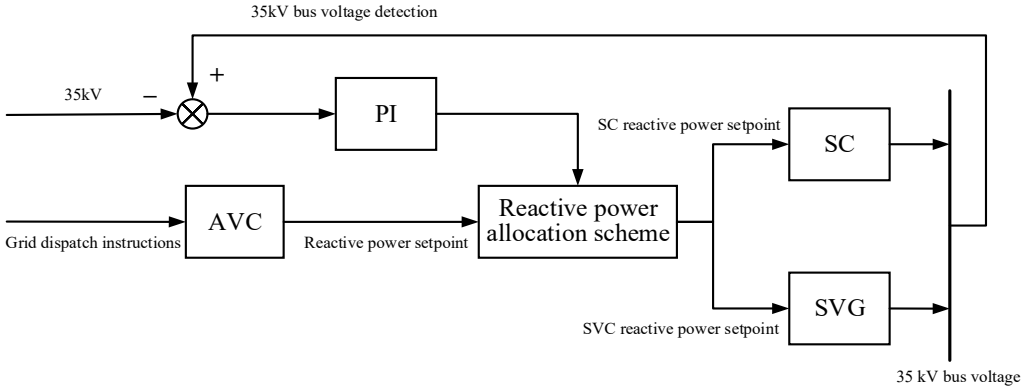


Figure 8. Coordination controller flowchart.

The coordination controller adopts a dual-layer control mode with an inner voltage control loop and an outer reactive power control loop (as shown in Figure 8). The reactive power compensation value calculated from the voltage control loop is added to the reactive power setpoint from the AVC substation. The final reactive power compensation is then reasonably distributed to the SVG and SC, ensuring effective reactive power compensation.

3.4. Capacity Configuration of Reactive Power Compensation Devices in Wind Farms

3.4.1. Capacity Configuration of SVGs in Wind Farms

In general, the reactive power configuration capacity of SVGs in wind farms is set to 20% of the plant capacity. Additionally, the configuration of capacity may be conducted in accordance with the following steps:

- Identify the components of reactive power loss: the reactive power loss of a wind farm can mainly be divided into four principal components: the turbine-side 690 to 35 kV transformer, the collection lines, the main transformer, and the outgoing lines.
- Collect data: collect wind speed data from the wind farm and calculate the active power output at each moment by using the wind–power curve.
- Calculate the SVG capacity: based on the components of reactive power loss and the collected data, the required reactive power compensation capacity can be calculated.

3.4.2. Capacity Configuration of SCs in Wind Farms

In the context of practical power system design, it is essential to ensure that the capacity of SCs is appropriately sized in order to meet the system's required SCR. The capacity of an SC can typically be determined by calculating the difference between the desired SCR and the wind turbine terminal SCR, which is referred to as ΔSCR. This method is employed to ascertain the requisite capacity of the SC. However, since SCs are usually connected to the grid through a step-up transformer, it is essential to consider their impedance characteristics and connection to the transformer during the back-calculation process.

The process of determining the capacity of an SC can be divided into the following steps:

1. Calculate the ΔSCR

For the convenience of calculation, the formula for calculating the SCR can be adjusted as follows:

$$K_{\mathrm{SCR}} = \frac{\sqrt{3} \cdot \frac{1}{X_{\Sigma}^{*}}}{\frac{P_{\max}}{S_{\mathrm{b}}}} \tag{8}$$

where $P_{\max}$ is the maximum power of the fan, S_{b} is the short-circuit capacity, and X_{Σ}^{*} is the sum of the per-unit impedance values of the system being sought.

The capacity of the SC is determined by the inverse calculation of the SCR difference ΔSCR, which is the difference between the expected SCR and the SCR before the introduction of SC.

2. Calculate the SC per-unit impedance

First, based on the parameters of the known SC model, calculate the per-unit impedance by using the following formula:

$$X_{SC}^{*} = X_{d}^{''} \cdot \frac{S_b}{S_{SC}{}'} \tag{9}$$

where $X_{d}^{''}$ is the SC's sub-transient reactance, S_b is the system's short-circuit capacity (MVA), and $S_{SC}{}'$ is the required capacity of the SC.

3. Perform a back-calculation based on the SCR formula

By using the definition of the SCR, derive the required SC capacity (S_{SC}) based on the desired ΔSCR. The back-calculation formula can be inferred from Formulas (8) and (9) as follows:

$$S_{SC} = X_{d}^{''} \cdot \frac{S_b}{X_{SC}^{*}} = X_{d}^{''} \cdot \frac{S_b}{\frac{\sqrt{3}}{\frac{\Delta SCR}{\frac{P}{S_b}}} - X_{TSC}^{*}} \tag{10}$$

where ΔSCR is the difference between the desired and actual SCRs, P is the total power of the wind farm (MW), S_b is the short-circuit capacity (MVA), and X_{TSC}^{*} is the per-unit impedance of the step-up transformer on the SC side.

4. Plan the capacity of the SC

Based on the results of the above calculation, determine the initial capacity of the SC. Based on this value, select the appropriate model and capacity of the SC to ensure it meets the system's SCR requirements and reactive power regulation capability.

Throughout the calculation process, it is crucial to ensure that the technical parameters of the selected SC are aligned with the overall reactive power demands and SCR requirements of the wind farm, thereby achieving optimal reactive power compensation and maintaining system stability.

4. Wind Farm Grid Integration Model with SCs and SVGs

This study focuses on an actual wind farm located in northern China. The original wind farm is equipped with an SVG, as shown in the black dashed box in the grid integration system in Figure 9. This system includes an SVG with a capacity of 12 MVA. The total installed capacity of the wind farm is 50.5 MW, consisting of seven wind turbines with a unit capacity of 4 MW each and five wind turbines with a unit capacity of 4.5 MW each. To enhance the active power delivery capability of the wind farm, this paper proposes the installation of a 10 MVA SC within the wind farm, as shown in the modified wind farm system diagram with the green dashed box in Figure 9.

The wind turbine terminal voltage is 690 V and is connected to a 35 kV substation with a step-up transformer. The generated wind power is then transmitted through a 4 km 35 kV transmission line and further stepped up to 110 kV with the main transformer. Finally, wind power is delivered to the upper transmission grid through a 40 km 110 kV transmission line, achieving grid integration.

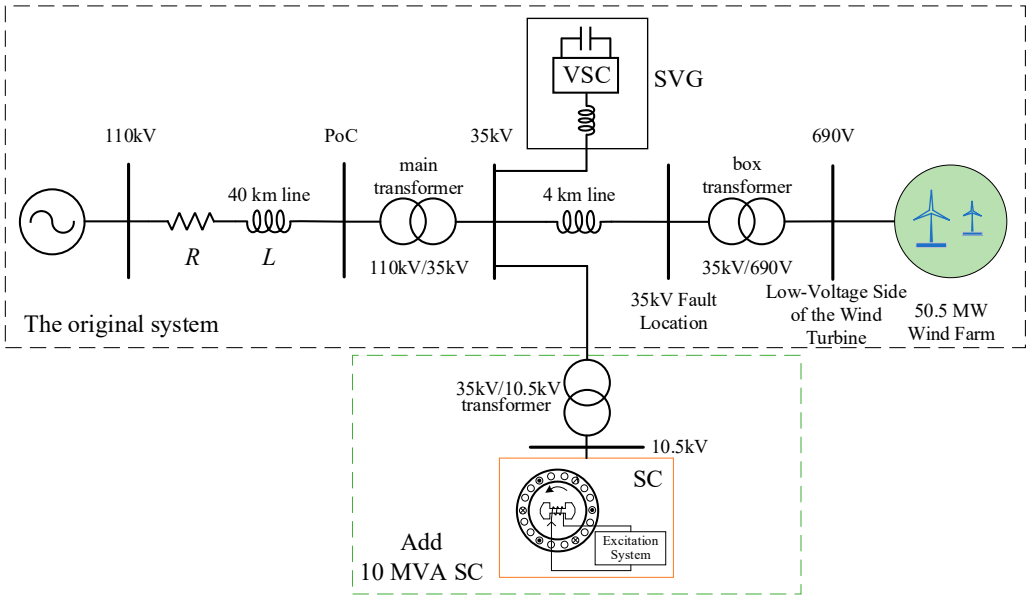


Figure 9. Wind farm system diagram.

4.1. Model of a Wind Farm with SCs and SVGs

Based on the wind farm configuration mentioned above, a detailed transient simulation model was developed in the MATLAB Simulink environment to simulate the dynamic behavior and response of the wind farm under various operational conditions. To ensure the model's applicability and real-time performance in practical applications, it was encapsulated for precise simulation on the Opal-RT OP5600 real-time simulation platform. The real-time simulation results closely match the simulation results from Simulink, confirming the accuracy and reliability of the model, as illustrated in Figure 10. The model demonstrates the complete electrical power delivery path from the wind turbines to the PoC.

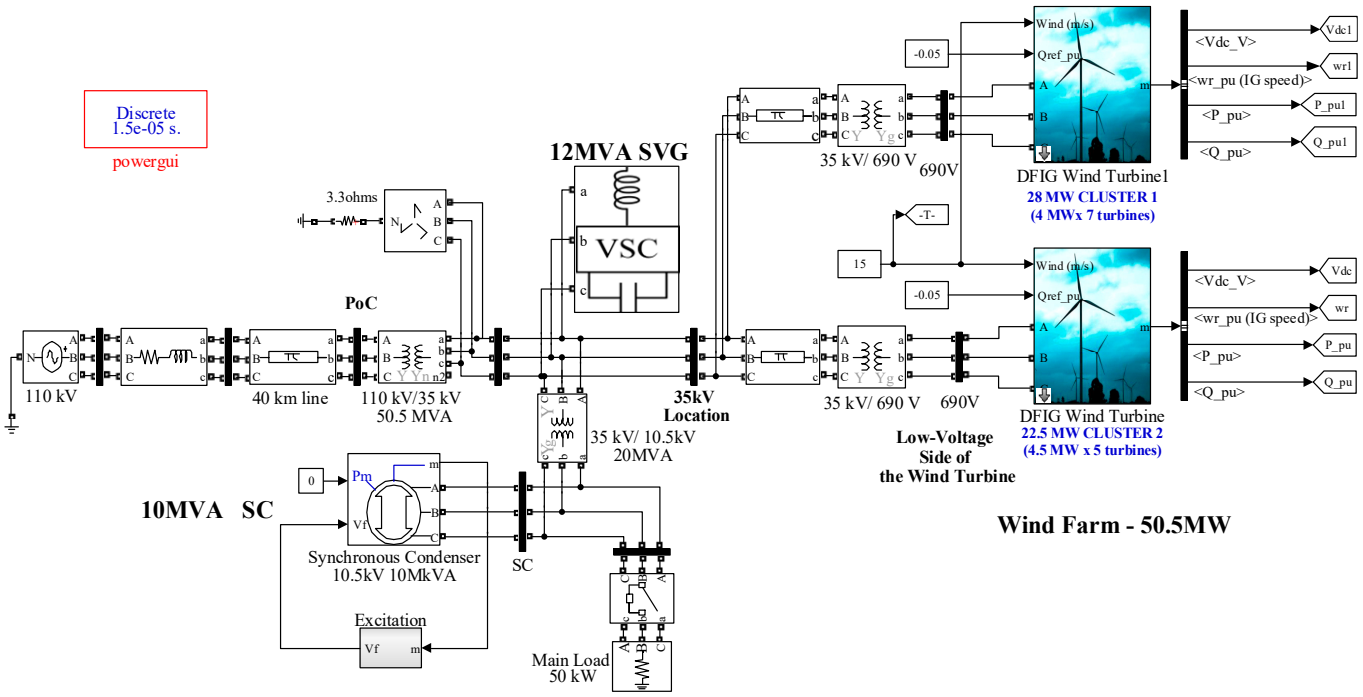


Figure 10. Wind farm grid integration model.

The terminal voltage of the wind turbine generator is 690 V, which is then stepped up to 35 kV with a step-up transformer. The node operates as a PV node, supplying active power while maintaining the node voltage. The SVG, which serves as a reactive power compensation device on the 35 kV bus, is capable of dynamically adjusting reactive power and functions as a PQ node, playing a critical role in maintaining the stability of the 35 kV bus voltage. The SC has a terminal voltage of 10.5 kV, which is also stepped up to 35 kV with a step-up transformer, and functions as a PQ node, thereby further enhancing the system's reactive power regulation capability. The internal electrical lines of the 35 kV wind farm are connected to the main transformer, which steps the voltage up to 110 kV.

Finally, the wind farm is connected to the PoC through a 40 km high-voltage transmission line. The PoC serves as the system's slack bus, ensuring power balance and voltage stability.

4.2. Short-Circuit Ratio Calculation

When a fault occurs at 35 kV, the base capacity of S_b = 100 MVA is used with the three reference voltages of V_{b1} = 110 kV, V_{b2} = 35 kV, and V_{b3} = 10.5 kV. The per-unit impedance of each component is calculated as shown in Table 2. By using the SCR equation in (3), the SCR at the 35 kV location was computed, both before and after the installation of the SVG and the SC, as detailed in Table 3.

Table 2. Impedance parameters for each component.

Component	Impedance *Z* (p.u.)
System impedance L	0.571
40 km line X1	0.135
Main transformer T1	0.208
SC-side transformer T2	0.525
SC	1.200
SVG	0.942

Table 3. Short-circuit ratio at 35 kV for different scenarios.

Short-Circuit Ratio K_{SCR}	35 kV Location
Original	2.750
Only with SVG	2.870
Only with SC	4.738
With SC and SVG	4.859

The analysis based on the SCR calculations revealed the following insights:

- The SCR on the 35 kV side of the wind turbines is less than three, indicating that the system is classified as a weak grid.
- The deployment of a 10 MVA SC can significantly improve the system's SCR, increasing it by 1.988 compared with the baseline. In contrast, a 12 MVA SVG can only increase the SCR by 0.12.
- The SC is more effective than the SVG in enhancing the system's short-circuit capacity, showing a distinct advantage in stabilizing transient voltage support.

It is therefore evident that the installation of an SC is crucial to enhance the stability and reliability of the wind farm grid integration system, particularly in the event of grid faults. Its rapid response and substantial reactive power output provide more effective voltage support for the system. Furthermore, in the context of analyzing the optimal capacity configuration of SC in a complex power grid system, the integration of AI-based

algorithms can be integrated with the previously mentioned SC capacity configuration. The application of deep learning techniques to historical data and real-time operating conditions enables the optimization of SC capacity selection. This approach not only provides more precise and rational capacity parameters in response to the dynamic changes in the grid and load demands but also effectively predicts potential fault scenarios and overload risks. This enables real-time adjustments to the SC capacity, enhancing the grid's adaptability and stability [30,31].

4.3. Comparison of Reactive Power Capabilities of the SC and SVG

During a sudden voltage-drop fault on the grid side, the reactive power compensation curves for the system with either the SVG or the SC operated individually are shown in Figure 11. The blue and black lines represent the reactive power compensation with only the SC and the SVG, respectively. The comparative analysis revealed that when the grid voltage drops from 1.0 pu to 0.2 pu, the reactive power compensation provided by the SC is five to eight times greater than that provided by the SVG alone.

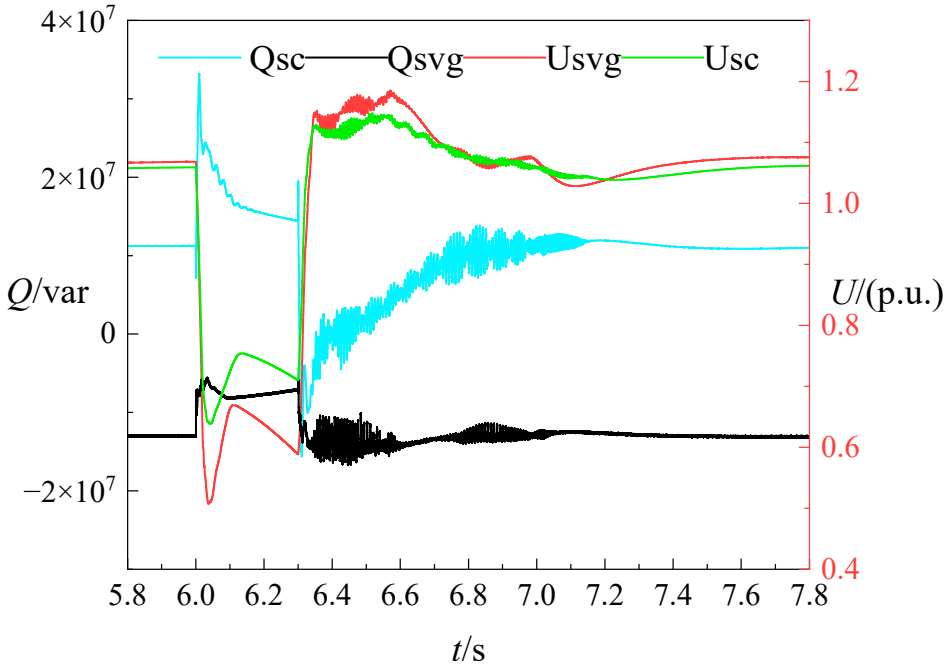


Figure 11. Comparison of reactive power output of an SVG and an SC.

The SC demonstrates remarkable resilience in the face of grid faults, exhibiting a superior performance in both the immediate aftermath and in the subsequent recovery phase. When compared with the SVG, the SC is uniquely capable of autonomously responding to reactive power demands and providing substantial short-term overload currents, thereby markedly enhancing the fault ride-through capability. During grid faults, the SC rapidly injects reactive power, effectively supporting transient voltage stability, improving the system's ability to handle short-circuit currents, and thereby increasing the overall stability and safety of the upper power system.

5. Simulation Results of Power Output of Wind Farms with SCs and SVGs

In modern wind farm operations, SVGs play a crucial role in reactive power compensation, significantly impacting grid stability and power quality. However, during grid faults, SVGs can occasionally result in an excess of reactive power, leading to transient increases in bus voltages that may threaten the stability of wind turbines and potentially

trigger disconnection protection. To mitigate the risk of disconnection, grid operators must implement safety control strategies, such as shedding a portion of the wind turbines or reducing wind power output. To this end, simulation analyses were conducted to examine the dynamic behavior of the test wind farm grid integration system with and without the deployment of an SC.

5.1. Simulation of a Wind Farm at Full Power Output with Only an SVG

A simulation analysis was conducted to examine the impact of a sudden bus voltage drop during a grid fault in the context of wind farm integration. In the simulation, the wind farm was set to operate at full capacity during the fault, maintaining an output power of 50.5 MW. Simultaneously, the SVG was utilized for reactive power compensation to support grid integration and operated in power factor mode to stabilize the grid voltage.

In the simulation, a grid voltage drop was generated from 1.0 pu to 0.2 pu at 4.0 s, with a recovery to 1.0 pu at 4.3 s. Prior to the fault, the voltage at the PoC was stable within the range of 1 ± 5% pu, and the power factor was stable at one, indicating an efficient and balanced system operation, as illustrated in Figures 12–14.

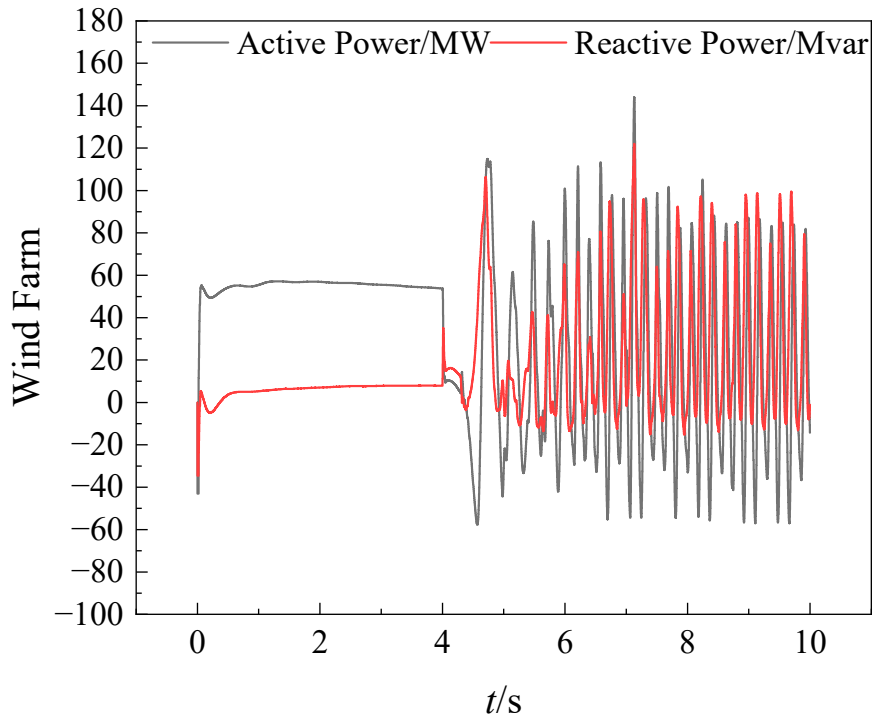


Figure 12. Active and reactive power of a wind farm at full power output with only an SVG.

Following the occurrence of the fault, due to the bus voltage drop, the wind turbines entered low-voltage ride-through (LVRT) mode. In this mode, the SVG increased its reactive power output with the aim of raising the bus voltage to a safe level. However, upon the clearance of the fault, the accumulation of excess reactive power within the system resulted in a sudden and significant transient increase in voltage at the wind turbine connection point, which may have exceeded the high-voltage tolerance limit of the turbines. This phenomenon could potentially trigger the protection mechanisms of wind turbines, leading to their disconnection from the grid and causing severe voltage oscillations at the PoC.

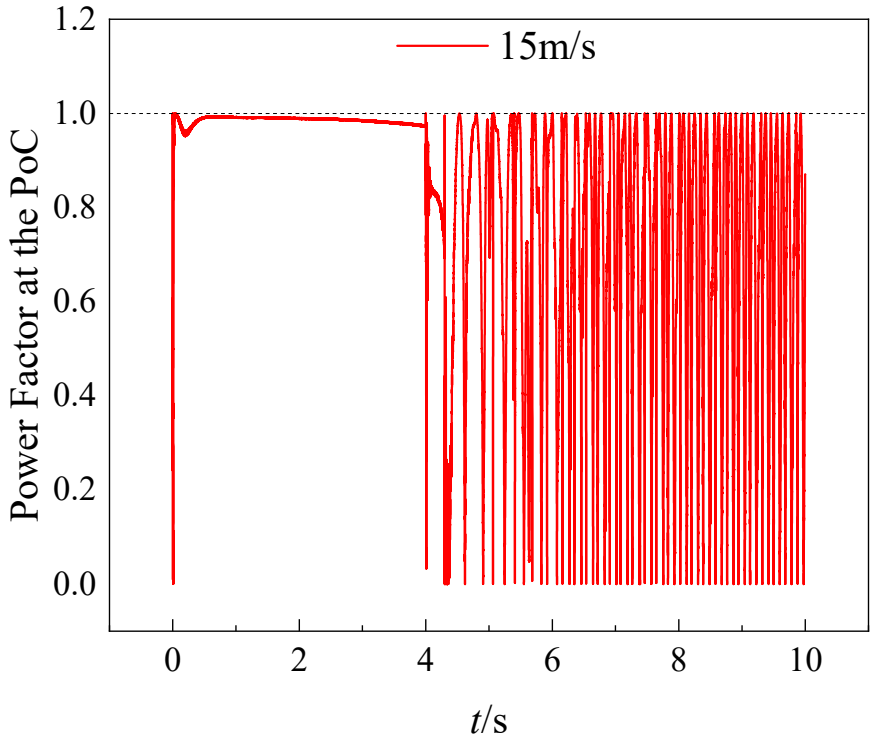


Figure 13. Power factor at the PoC of a wind farm at full power output with only an SVG.

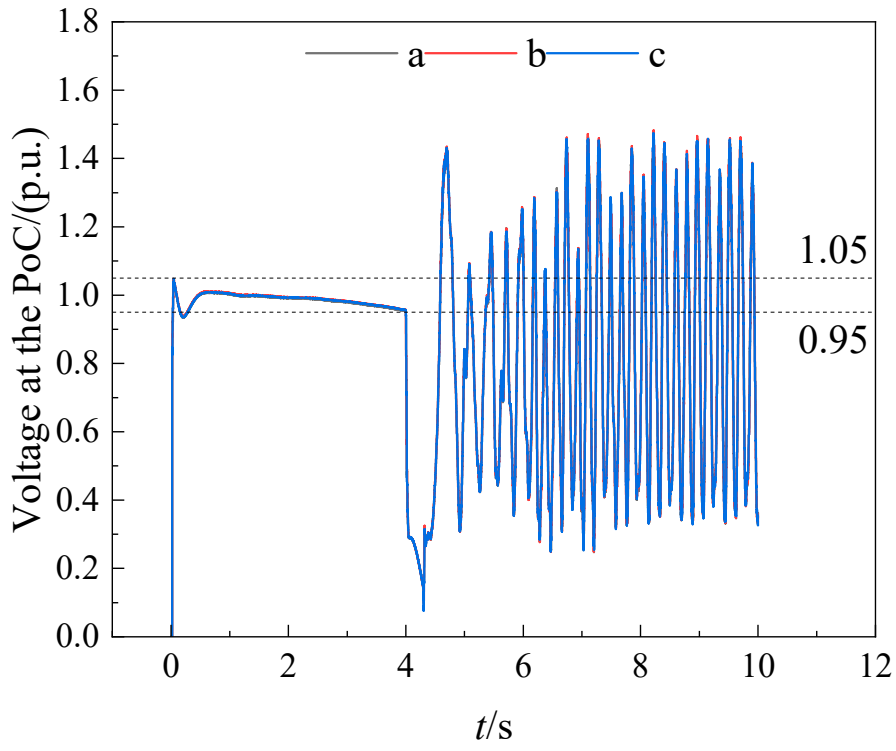


Figure 14. Voltage at the PoC of wind farm at full power output with only SVG.

During grid faults, the transient voltage increase at the wind turbine connection point represents a critical factor contributing to the risk of disconnection. To effectively mitigate this risk, common strategies include disconnecting some wind turbines or reducing the wind power output to decrease the system's reactive power demand, thereby maintaining voltage stability.

5.2. Simulation of a Wind Farm at Limited Power Output with Only an SVG

The simulated wind farm is a real wind farm located in Zhangjiakou, Hebei Province, China. When the wind farm operates at full power output, the voltage at the PoC exceeds the limits during grid recovery from a transient fault, resulting in severe oscillations within the system. This outcome aligns with the simulation results under the full power output conditions at a wind speed of 15 m/s, as shown in Figure 15. Based on operational experience, the utility currently mandates that the wind farm is to operate at no more than 60% of its rated power output, which corresponds to approximately 33 MW.

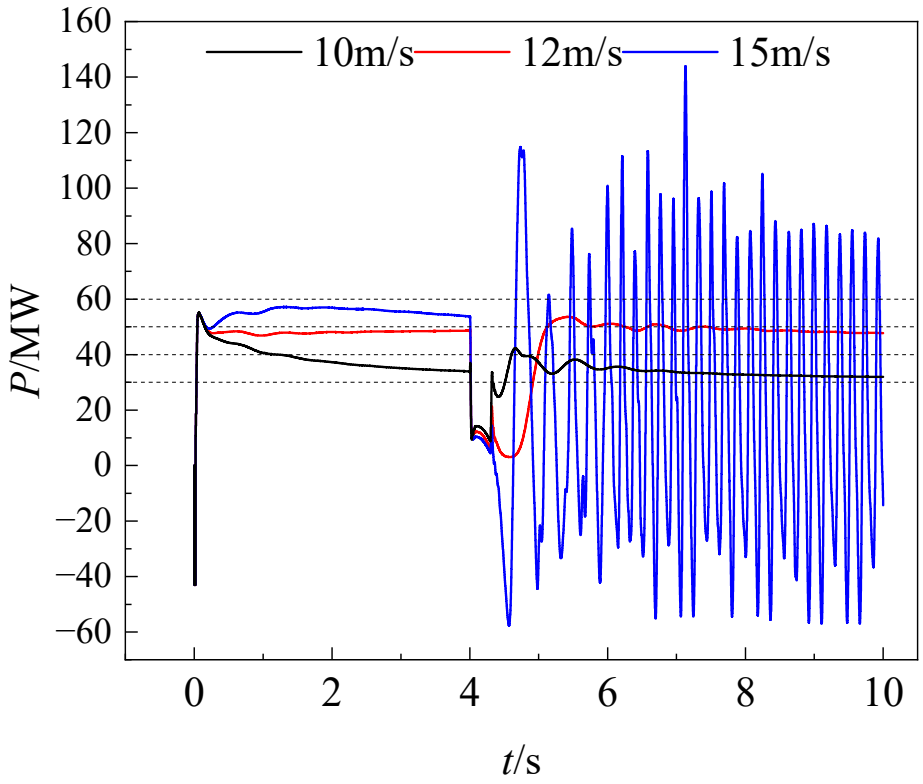


Figure 15. Active power output of wind farm with different wind speeds.

With the wind power output constrained to 33 MW based on the original parameters, the SVG, as a reactive power compensation device, quickly responded to grid faults. It adjusted the power factor at the grid connection point to one to compensate for the reactive power deficit in the grid. This adjustment facilitated the rapid recovery of the connection point voltage, restoring it to a stable level within $1 \pm 5\%$ pu, thereby ensuring the continued stable operation of the system.

According to Figures 12, 16 and 17, during a sudden voltage-drop fault in the grid, if the wind turbines continue to operate at full output, they face the risk of disconnection. Consequently, while the implementation of SVG control strategies ensures the stability and reliability of the grid, it necessitates sacrificing a portion of wind power output, significantly limiting the system's delivery capacity.

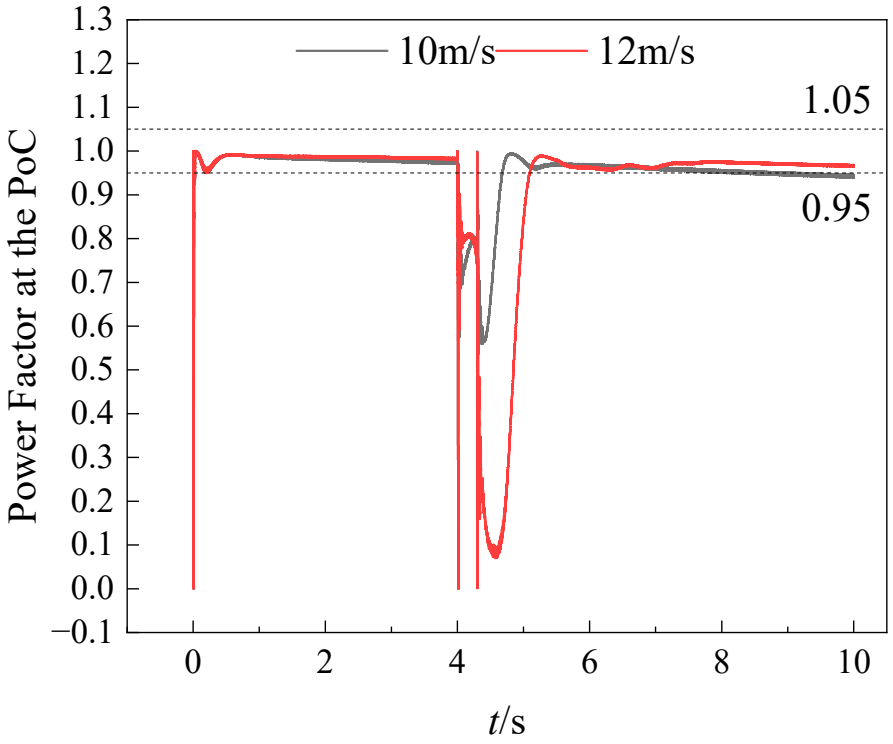


Figure 16. Power factor at the PoC of a wind farm at limited power output with only an SVG.

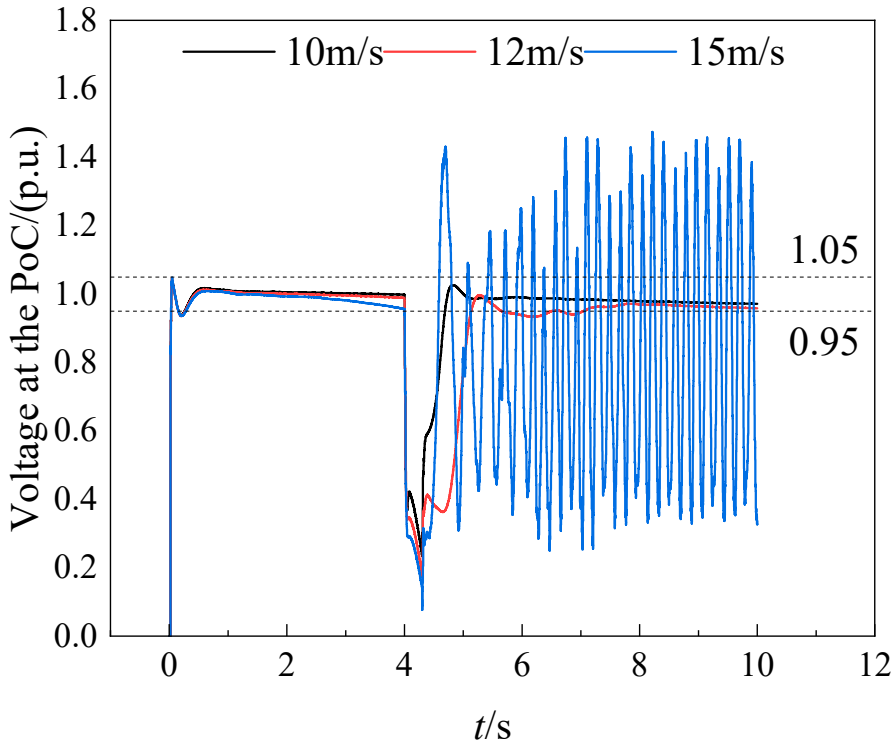


Figure 17. Voltage at the PoC of a wind farm at limited power output with only an SVG.

5.3. Simulation of a Wind Farm at Full Power Output with Both an SC and an SVG

A hybrid solution involving the deployment of an SC was adopted to ensure the wind farm's stability while optimizing its operation and enhancing the system's delivery capacity.

A simulation analysis was conducted to evaluate the impact of bus voltage drops during grid faults on wind farm integration. In the simulation scenario, the wind farm

maintained full output at 50.5 MW during a fault, while the SVG operated in power factor mode to stabilize the grid voltage.

During the simulation, the grid voltage dropped from 1.0 pu to 0.2 pu at 4 s and recovered to 1.0 pu at 4.3 s. Prior to the fault, the bus voltage at the wind turbine side was stable at 0.95 pu, with a power factor of one, indicating efficient and balanced system operation.

After the fault occurred, the drop in bus voltage caused the wind turbines to enter LVRT mode, and the SVG increased the reactive power output to increase the bus voltage to a safe level. Compared with the simulations without the SC, the results show that by employing this device, the bus voltage successfully recovered to 1.0 pu and the wind farm maintained a full output, ensuring the continuous and stable operation of the system, as shown in Figures 18–21.

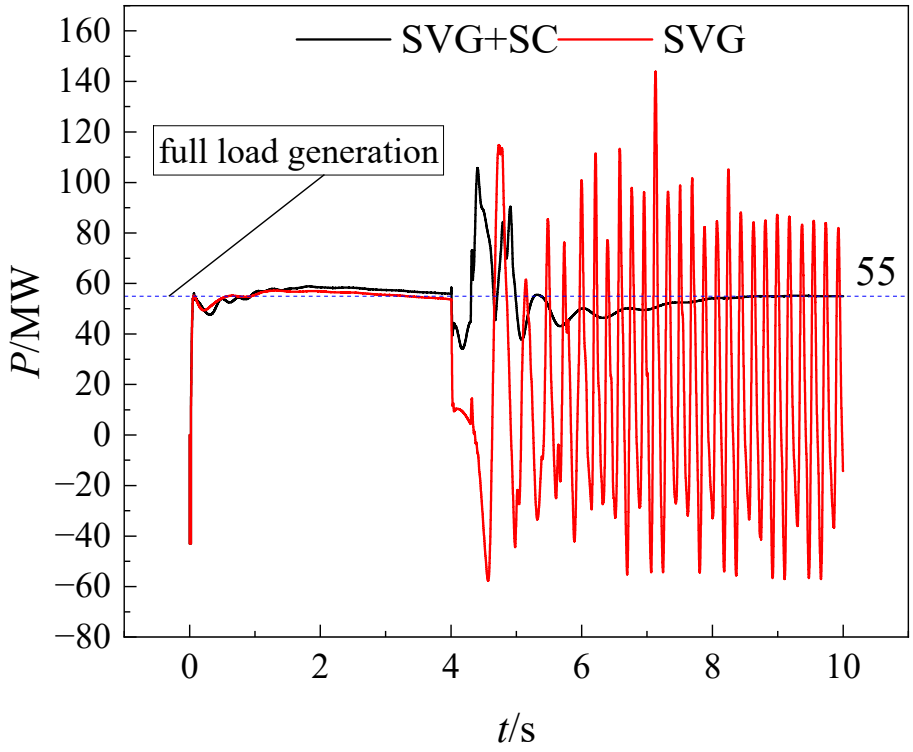


Figure 18. Comparison of wind farm output before and after SC deployment.

This simulation demonstrates that the effective configuration of reactive power compensation devices and SCs can markedly mitigate transient voltage fluctuations at the bus during grid faults. This hybrid solution can also ensure the stability of wind farm integration and enhance the system's delivery capacity. However, regarding the implementation, maintenance, and operational costs of synchronous condensers (SCs) and static var generators (SVGs), the unit kVar reactive power operating cost of SC is approximately 10 times higher than that of an SVG. Therefore, from a cost perspective, SC does not currently offer a significant cost advantage. However, in terms of increasing the power output of wind farms, the cost can be recouped in about one year.

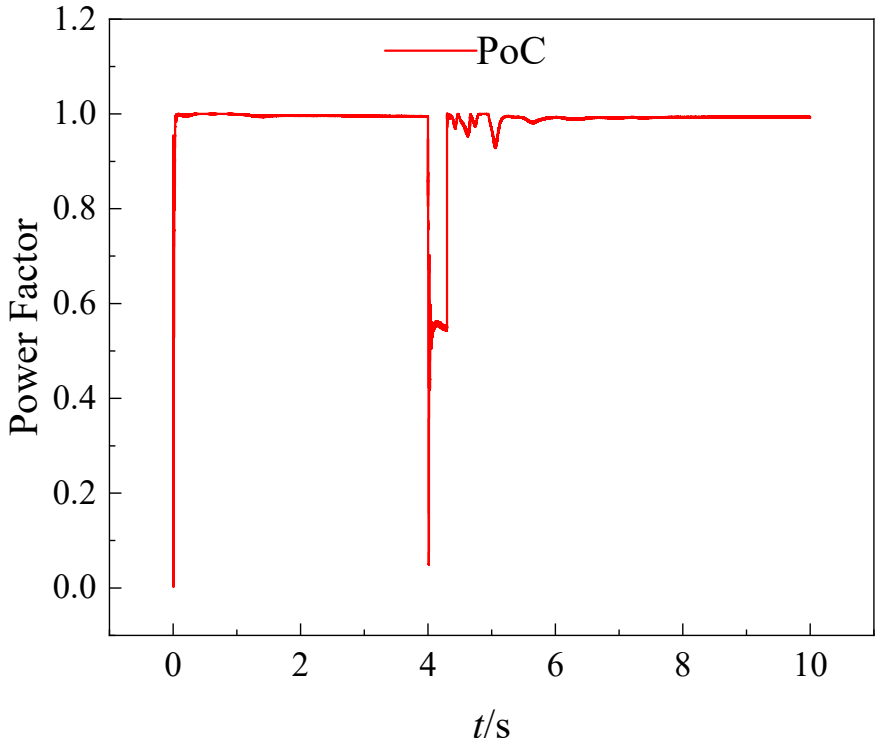


Figure 19. Power factor after SC deployment.

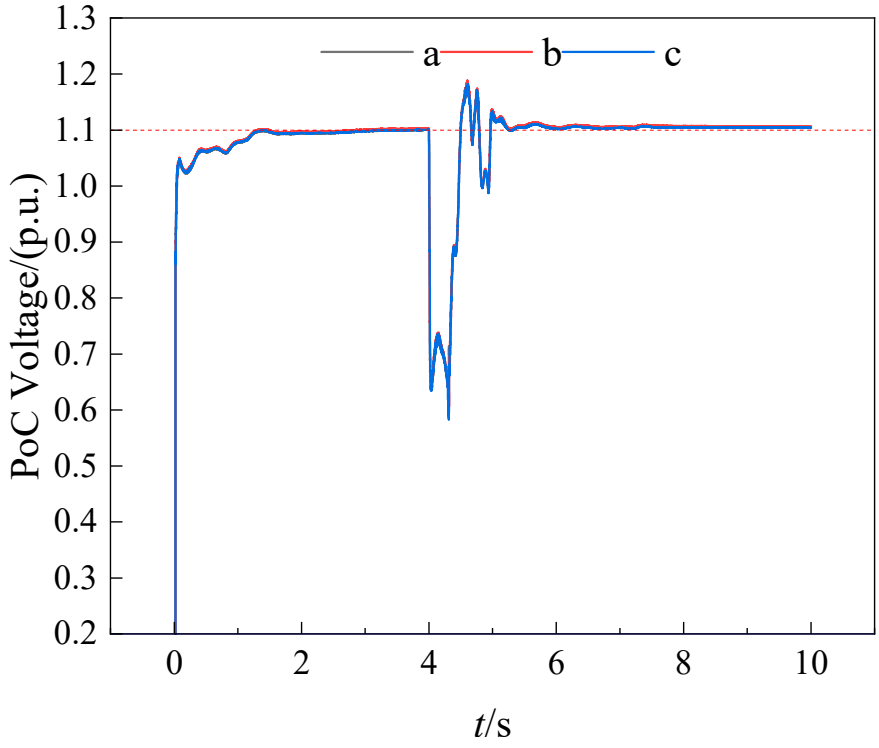


Figure 20. PoC voltage after SC deployment.

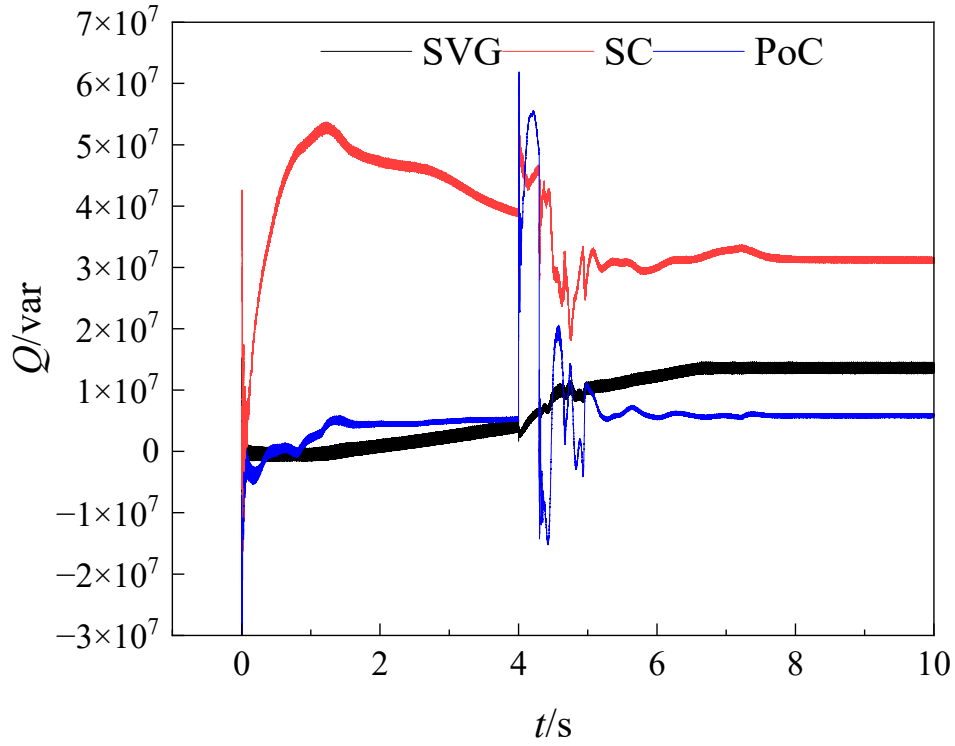


Figure 21. Comparison of reactive power contributions of the SC and SVG at the PoC.

6. Discussion

Transient voltage fluctuations at the wind farm connection point represent a significant challenge to system stability during grid faults. This study effectively illustrates the vital function of the SC–SVG configuration in maintaining grid voltage stability. The following key findings are presented:

- Modeling and validation: Models for both SCs and SVGs were developed, and their reactive power compensation effectiveness was validated with simulations. The results substantiated that both devices provide indispensable reactive power support, thereby exerting a pivotal influence on grid stability.
- SCR analysis: The calculation of the SCR demonstrated the considerable influence of the SC on enhancing the system's short-circuit capacity. With the introduction of the SC, the SCR exhibited a notable increase of 1.988. In contrast, the SVG contributed a mere 0.12 increase, which serves to underscore the SC's greater potential for reinforcing system stability.
- Comparative simulation of reactive power capabilities: simulations comparing the reactive power capabilities of an SVG and an SC revealed that, in the event of grid faults or load fluctuations, the SC exhibited rapid response characteristics and advantages in large-scale reactive power supply, thereby providing a more robust safeguard for grid dynamic stability.
- Enhancement of output and delivery capacity of wind farm: The simulation results indicate that the wind farm's power output should be limited to 60% in order to avoid instability following the clearance of a grid fault. However, the installation of a small SC allows the wind farm's power output to reach 100%. This outcome not only validates the practical benefits of SCs in enhancing the adequacy of wind farm grid integration but also underscores their practical value for improving overall grid stability.

7. Conclusions

This paper proposes a hybrid solution of small SCs and SVGs in wind farm substations to optimize reactive power and voltage level at the point of grid connection. The main conclusions of this study are as follows: (1) The low short-circuit ratio (SCR) is a key factor affecting the stable operation of wind farms in weak grids, and the sub-transient reactance of the SC could largely increase the SCR. (2) The developed hybrid control approach combines the advantages of both SCs and SVGs, which could provide comprehensive voltage support across sub-transient, transient, and steady-state conditions for renewable energy stations. (3) The comparison of the simulation results shows that a hybrid solution of SCs and SVGs could improve the output power capacity of wind farms in weak power grids by 40% in this case.

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References

1. Jiménez, R.P.; Platero, C.A.; Sánchez, M.E.; Barneto, E.R. Synchronous Condenser for European Grid Code Compliance: A Case Study of a PV Power Plant in Spain. *IEEE Access* **2023**, *11*, 54713–54723. [CrossRef]
2. Samaranayake, L.; Ugalde-Loo, C.E.; Adeuyi, O.D.; Licari, J.; Ekanayake, J.B. Multi-Terminal DC Grid with Wind Power Injection. *Wind* **2022**, *2*, 17–36. [CrossRef]
3. Kulkarni, S.S.; Wang, L.; Venetsanos, D. Managing Technology Transfer Challenges in the Renewable Energy Sector Within the European Union. *Wind* **2022**, *2*, 150–174. [CrossRef]
4. Yang, H.; Liu, H.; Ding, Z.H.; Sun, Z.L.; Liu, C.; Cai, G.W.; Zhang, G.L. Optimization Configuration of Two-Stage Synchronous Condenser Considering Short-Circuit Ratio Improvement and Transient Overvoltage Suppression in High-Proportion Wind Power Connected Grid. *Power Syst. Technol.* **2024**, *48*, 540–552. [CrossRef]
5. Jiang, H. Design and Application of Reactive Power Optimization Control Strategies for Wind Farms. *Electr. Power Technol.* **2023**, 6–8. [CrossRef]
6. Chubraeva, L.; Timofeev, S. Modern Reactive Power Generators. In Proceedings of the International Conference on Actual Problem of Electromechanics and Electrotechnology (APEET), Yekaterinburg, Russia, 13–16 November 2017; IOP: Bristol, UK, 2017. [CrossRef]
7. Zhang, M.; Xu, M.; Zhang, J.; Hao, W.; Hu, Y.; Liu, J.; Zhang, R. Research on Voltage Control Strategy Optimization of Wind Farm Cluster. In Proceedings of the Asia Conference on Geological Research and Environmental Technology (GRET), Kamakura City, Japan, 10–11 October 2020; IOP: Bristol, UK, 2020. [CrossRef]
8. Zhou, Z.; Mastoi, M.S.; Wang, D.; Haris, M. Control Strategy of DFIG and SVG Cooperating to Regulate Grid Voltage of Wind Power Integration Point. *Electr. Power Syst. Res.* **2023**, *214*, 108862. [CrossRef]
9. Igbinovia, F.O.; Fandi, G.; Muller, Z.; Tlusty, J. Reputation of the Synchronous Condenser Technology in Modern Power Grid. In Proceedings of the International Conference on Power System Technology (POWERCON), Guangzhou, China, 6–8 November 2018; IEEE: Piscataway, NJ, USA, 2018.
10. Nazir, A. Comparison of Synchronous Condenser and Static Var Compensator on Voltage Stability of HVDC Transmission System. Master's Thesis, North China Electric Power University, Baoding, China, 2019. [CrossRef]

11. Dai, Z.B.; Yang, Z.C.; Zhao, G.L.; Duan, F.W.; Yang, Y.X. Simulation Analysis of Synchronous Condenser Response Speed. *Electr. Power Capacit. React. Power Compens.* **2023**, *44*, 8–14+37. [CrossRef]
12. Hadavi, S.; Rathnayake, D.B.; Jayasinghe, G.; Mehrizi-Sani, A.; Bahrani, B. A Robust Exciter Controller Design for Synchronous Condensers in Weak Grids. *IEEE Trans. Power Syst.* **2022**, *37*, 1857–1867. [CrossRef]
13. Zhao, M.Y. Study on Configuration Method of Synchronous Condenser to Suppress Transient Overvoltage of Wind Farms under DC Disturbances. Master's Thesis, Nanjing Normal University, Nanjing, China, 2021. [CrossRef]
14. Zhang, H.H.; Li, H.Q.; Zhou, L.; Ma, X.; Gu, Y.J. Analysis of Factors Affecting Short-Circuit Ratio in New Energy Multi-Site. *Ningxia Electr. Power* **2022**, *5*, 27–34. [CrossRef]
15. Nair, A.R.; Patel, S.; Kamalasadan, S.; Smith, M.; Siddiqui, S. Parametrically Optimized Synchronous Condenser Coordinated Control Framework to Enhance Bulk Grid Stability with Renewables. *IEEE Trans. Ind. Appl.* **2024**, *60*, 5737–5750. [CrossRef]
16. Stiger, A.; Rivas, R.A.; Halonen, M. Synchronous Condensers Contribution to Inertia and Short Circuit Current in Cooperation with STATCOM. In Proceedings of the IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia 2019), Bangkok, Thailand, 19–23 March 2019; pp. 955–959. [CrossRef]
17. Sun, R.P. Study on Short-Circuit Ratio Calculation Method Based on Simulation Data and Thevenin Equivalent Parameter Identification. Master's Thesis, Zhejiang University, Hangzhou, China, 2023. [CrossRef]
18. Vilmann, B.; Randewijk, P.J.; Jóhannsson, H.; Hjerrild, J.; Khalil, A. Frequency and Voltage Compliance Capabilities of Grid-Forming Wind Turbines in Offshore Wind Farms in Weak AC Grids. *Electronics* **2023**, *12*, 1114. [CrossRef]
19. Bindner, H. *Power Control for Wind Turbines in Weak Grids: Concepts Development*; Forskningscenter Risø: Roskilde, Denmark, 1999; p. 40.
20. *CIGRE Connection of Wind Farms to Weak AC Networks*; Technical Report No. B4.62, Reference 671; CIGRE: Paris, France, 2016.
21. IEEE Working Group 15.05.05 (HVDC Interaction with low SCR AC Systems). *CIGRE Guide for Planning DC Links Terminating at AC Systems Locations Having Low Short-Circuit Capacities (Part I: AC/DC Interaction Phenomena)*; Technical Report No. 14.07; AC/DC System Interaction; CIGRE Working Group: Paris, France, 1992.
22. Etxegarai, A.; Eguia, P.; Torres, E.; Fernandez, E. Impact of wind power in isolated power systems. In Proceedings of the Mediterranean Electrotechnical Conference—MELECON, Hammamet, Tunisia, 25–28 March 2012; pp. 63–66.
23. Fu, R.; Li, L.; Wang, X.; Lv, X. Critical SCR for the stability of VSC connected to weak grid. In Proceedings of the IEEE Power and Energy Society General Meeting, Montreal, QC, Canada, 2–6 August 2020.
24. Chawda, G.S.; Shaik, A.G. Power Quality Mitigation in Weak AC Grid with Low X/R Ratios Using Distribution Static Compensator Controlled by LMF Algorithm. In Proceedings of the 2020 IEEE Region 10 Symposium (TENSYMP), Dhaka, Bangladesh, 5–7 June 2020; pp. 44–47.
25. Goud, R.D.; Rayudu, R.; Mantha, V.; Moore, C. Impact of Short-Circuit Ratio on Grid Integration of Wind Farms—A New Zealand Perspective. In Proceedings of the 2nd International Conference on Large-Scale Grid Integration of Renewable Energy, New Delhi, India, 4–6 September 2019.
26. *GB 38755-2019*; Guidelines for Safety and Stability of Power Systems. Standardization Administration of China: Beijing, China, 2019.
27. *GB/T 40594-2021*; Guidelines for Coordinated Technical Standards of Power Systems and Resources. Standardization Administration of China: Beijing, China, 2021.
28. *GB/T 40581-2021*; Code for Safety and Stability Calculations of Power Systems. Standardization Administration of China: Beijing, China, 2021.
29. Guo, C.; Guan, K.; Guo, Y.H. Research on Reactive Power Compensation of Direct-Drive Wind Farms by SVG. *Electr. Power Capacit. React. Power Compens.* **2017**, *38*, 67–70+77. [CrossRef]
30. Srinivasan, S.; Kumarasamy, S.; Andreadakis, Z.E.; Lind, P.G. Artificial Intelligence and Mathematical Models of Power Grids Driven by Renewable Energy Sources: A Survey. *Energies* **2023**, *16*, 5383. [CrossRef]
31. Zhao, L.; Wang, Z.; Li, Y.; Wang, X.; Hu, Z.; Xiao, Y. Two-Stage Optimal Configuration Strategy of Distributed Synchronous Condensers at the Sending End of Large-Scale Wind Power Generation Bases. *Energies* **2024**, *17*, 4748. [CrossRef]

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