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Local Iterative Calculation Method and Fault Analysis of Short-Circuit Current in High-Voltage Grid with Large-Scale New Energy Equipment Integration

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Abstract: This paper delves into the critical issues of relay protection setting calculation in high-voltage power grids with large-scale integration of renewable energy sources, such as wind and solar power. By analyzing the topological structure of renewable energy systems, models of permanent magnet direct-drive wind turbines and photovoltaic power sources are established, with a particular focus on the short-circuit current characteristics of these renewable energy sources. Subsequently, a fault iterative method for short-circuit current calculation is proposed. This method effectively improves the accuracy of short-circuit current calculation by iteratively analyzing the fault region and considering the voltage-controlled current source characteristics of renewable energy sources. The paper also conducts in-depth research on various aspects of relay protection settings after the integration of renewable energy devices, including main transformer neutral grounding strategies, tie-line protection and reclosing principles, islanding prevention, and boundary backup protection management. By applying this method to a practical engineering case in G Province, China, the short-circuit current is calculated, and partial setting values are determined, demonstrating the ability of this method to enhance system safety and stability. This research provides valuable insights for operators of modern power systems.

Keywords: high-voltage grid; new energy; relay protection; settings calculation; short-circuit current calculation



Citation: Liu, Z.; Su, B.; Ji, Q.; Hu, Y. Local Iterative Calculation Method and Fault Analysis of Short-Circuit Current in High-Voltage Grid with Large-Scale New Energy Equipment Integration. *Sustainability* **2024**, *16*, 11144. <https://doi.org/10.3390/su162411144>

Academic Editor: Francesco Riganti Fulginei

Received: 15 September 2024

Revised: 13 November 2024

Accepted: 22 November 2024

Published: 19 December 2024



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1. Introduction

With the support of the Chinese government policies, new energy devices such as wind power and photovoltaic systems are being extensively integrated into the power grid. It is projected that by 2025, the G province of China will add approximately 18 million kilowatts of wind power and 10 million kilowatts of photovoltaic power. These additions of new energy devices provide green and renewable energy sources. However, as the proportion of clean energy generation increases, the power grid is facing higher requirements in terms of complexity and dynamics. This poses challenges to the traditional grid architecture and relay protection systems [1,2].

Among various faults that occur in power grid operation, short-circuits in different forms are the most common and also the most dangerous. Short-circuit current refers to the current flowing through the fault point when a short-circuit fault occurs in the power system. The magnitude and duration of the short-circuit current can result in thermal effects, electromagnetic effects, mechanical effects, and may even lead to equipment damage or accidents [3]. Accurate calculation of the short-circuit current can ensure the safety of power grid devices, improve grid stability, and optimize grid planning and design. Therefore, the short-circuit current is an important parameter in the planning, design, and operation of

power systems. New energy sources primarily include wind power, photovoltaics, and hydroelectric power [4]. Compared to traditional thermal power units, new energy sources have different generation modes, control methods, and output characteristics. These characteristics result in long duration of short-circuit currents, high harmonic content, and indeterminate current direction for the short-circuit currents of new energy sources [5,6]. In recent years, domestic and international scholars have conducted extensive research on short-circuit currents of new energy sources, achieving a series of significant results.

Reference [7] provides an overview of common fault types in transmission lines and various fault identification, classification, and localization algorithms. Reference [8] analyzes the impact of renewable energy integration into the power grid on fault currents, pointing out that the inclusion of distributed photovoltaic generation leads to prolonged fault clearance time. Reference [9] studies the calculation method of short-circuit current after the integration of voltage-source converters into the power grid, proposing a method of superimposing AC and DC components. References [10,11], respectively, provide short-circuit current calculation methods for current-controlled distributed power sources and modular multilevel converters (MMC) in multi-terminal DC (MTDC) grids. The setting and operating characteristics of relay protection are also affected by the integration of new energy sources. Reference [12], using photovoltaic power generation as an example, analyzes the impact of control strategies and voltage fluctuation of direct current buses on fault current characteristics. Reference [13] proposes a short-circuit current calculation method considering voltage distribution characteristics for doubly-fed asynchronous generator (DFIG) wind farms. Reference [14] summarizes the challenges faced by relay protection after large-scale wind power integration and analyzes the impact of wind power short-circuit current characteristics on collector line protection.

Currently, research on short-circuit currents of new energy sources has made certain progress, but there are still some limitations. In the current analysis and calculation of fault characteristics of new energy, the properties of new energy sources such as wind power and photovoltaics are often overlooked, and the characteristics of power output are not considered. This greatly affects the accuracy of short-circuit current calculation after faults and the performance of protection, and even endangers the safe operation of the system. The existing analytical expressions for short-circuit currents of new energy sources are mostly complex, leading to tedious calculations that are not convenient for engineering applications. Through analysis and summarization, the calculation process can be simplified, and computational efficiency can be improved. In this context, grid operators and researchers urgently need to reevaluate the existing relay protection mechanisms and attempt adjustments to adapt to the new requirements of the power system. This paper aims to reveal the key technical aspects of relay protection setting calculation after large-scale integration of new energy devices into high-voltage power grids. Under this new situation, relay protection setting technologies need to consider not only stability and security under traditional power generation methods but also the dynamic behavior of the power grid and changes in voltage stability caused by the integration of new energy devices [15–17].

This paper discusses the key technologies and engineering application examples of short-circuit current calculation and relay protection setting after the integration of large-scale new energy devices into high-voltage power grids. Section 2 of this paper establishes a topology model for new energy devices and summarizes the characteristics of short-circuit currents of new energy sources to ensure accurate simulation of their behaviors and characteristics. Section 3 analyzes the characteristics of short-circuit currents of new energy sources. Section 4 proposes a short-circuit current calculation method based on local iteration. Section 5 analyzes and summarizes the simplified calculation process of short-circuit currents in engineering, improving computational efficiency. By conducting in-depth research on the impact of short-circuit currents of new energy sources on relay protection, this paper proposes a method for improving relay protection setting. It aims to provide theoretical guidance and technical support to address the challenges in the new

power grid situation and promote the application and optimization of relay protection setting calculation in the scenario of large-scale integration of new energy.

2. New Energy Model

2.1. New Energy Topology

Currently, the widely used new energy generation in China mainly includes wind power and solar power, while the scale of biomass, geothermal, and ocean energy generation is relatively smaller, and their impact on the power grid is not as significant as the former. Therefore, this paper mainly investigates the impact of wind farms and solar power plants on the Ningdong power grid. Wind turbines can be divided into three types: fixed-speed wind turbines, doubly-fed variable-speed wind turbines, and permanent magnet direct-drive wind turbines. Currently, doubly-fed variable-speed wind turbines and permanent magnet direct-drive wind turbines are widely used in wind farms [18].

The impact of solar power plants on the power grid mainly includes abnormal islanding, power quality, grid stability, grid integration dispatch, regulatory supervision of electricity price subsidies, and grid integration safety. Solar power systems can be classified into standalone solar PV systems, grid-connected solar PV systems, and distributed solar PV systems. An individual solar power generation unit directly converts solar energy into electrical energy for immediate use by the loads. Generally, these units are equipped with batteries as energy storage devices to ensure sustainable power supply. Since the energy generated by solar PV systems cannot be directly absorbed by the power grid, the system involves multiple conversion steps such as boost voltage, DC/AC photovoltaic inverters, step-up transformers, and high-voltage distribution system transmission [19]. A typical structure of a new energy grid-connected system is shown in Figure 1.

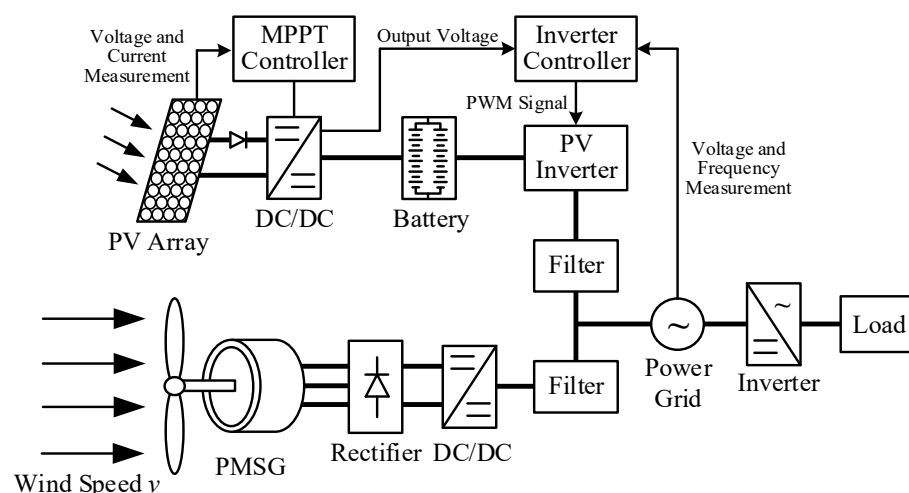


Figure 1. Schematic Diagram of New Energy Grid Connection System.

A typical simplified diagram of a centralized new energy station with a voltage level of 110 kV and above is shown in Figure 2 [20]. It includes the following components:

- (1) High-voltage outgoing lines: They are used to transmit power with a single circuit of either 220 kV or 110 kV. The outgoing lines are equipped with fiber-optic current differential, distance, and zero-sequence protection.
- (2) High-voltage busbar: It is equipped with busbar protection. In some stations, the busbar is omitted to save investment, and the main transformer high side shares the switchgear with the outgoing lines (line-transformer series configuration).
- (3) Main transformer: Generally, it adopts a two-winding configuration. The grounding method of the neutral point of the main transformer is set according to grid regulations, and complete protection systems are installed.
- (4) 35 kV busbar: It is equipped with busbar protection.

- (5) 35 kV sections: They operate normally in parallel and do not require independent sectionalized protection.
- (6) 35 kV equipment: Both the 35 kV busbar I and busbar II include collection lines, reactive power compensation (such as SVG), and on-site transformers connected to the neutral point with a small resistance grounding device. Due to space limitations, only a partial representation is shown. All 35 kV equipment is equipped with overcurrent and zero-sequence protection.
- (7) Power supply: The power supply is connected to the collection lines through distribution transformers. In the G province, the main forms of power supply are doubly-fed asynchronous wind turbines, permanent magnet direct-drive wind turbines, and photovoltaic arrays (other forms are not discussed in this paper). The protection of distribution transformers and power supplies is mostly set by equipment manufacturers.

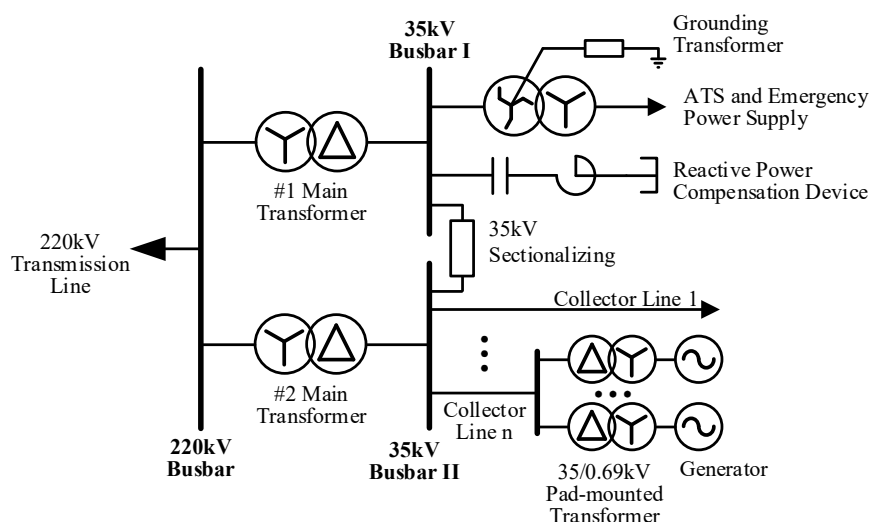


Figure 2. Topology Diagram of New Energy Station.

2.2. New Energy Connectary Simplified Model

The protection setting for new energy sources is determined based on the regulation range. For the power field, the main focus of setting is on the main transformer and the 35 kV equipment (specific details are omitted in this paper), and the topology model shown in Figure 2 should be adopted. As for the power grid, the setting is responsible for the main transformer's high-side busbar and outgoing lines. The station transformer connected to the neutral point, reactive power compensation, and other components can be removed from the model, leaving only the power source and related equipment. The modeling of new energy power sources has always been challenging, and it will be discussed below.

Existing literature mainly focuses on the actual control strategies for modeling new energy generators, providing valuable references for setting calculations. According to the regulations of Southern Power Grid in China, for a distributed power source equipped with current limiting capabilities, such as distributed photovoltaics and permanent magnet wind turbines, the short-circuit current provided after the integration of the distributed power source into the system can generally be calculated based on 1.2 to 1.5 times the rated current of the inverter, with specific overcurrent capability determined by the equipment specifications. For distributed power sources with no current limiting capabilities, the short-circuit current after grid integration should be calculated as per the specific equipment specifications [21].

Considering that the calculation of protection setting focuses on the most severe fault scenarios, which involve fault contingency analysis, similar to traditional generators, only the maximum and minimum short-circuit currents that the power source can provide need to be considered, without excessive concern for intermediate current values. This

is also one of the differences between protection setting calculations and other precise simulation calculations.

Therefore, based on the aforementioned three forms of power sources, they can be considered separately:

- (1) Permanent magnet direct-drive wind power and photovoltaic sources: Since inverters are used between the power source and the distribution transformer (involving AC/DC conversion), the inverters usually have overcurrent protection. A constant current source model can be used, and it is required that the equipment providers provide a formal parameter report specifying the maximum short-circuit current that the equipment can provide. If this information cannot be provided, the most conservative value recommended by the Southern Power Grid regulation, which is 1.5, should be adopted. In the event of a short circuit in the power grid, the power source only provides a constant positive-sequence current.
- (2) Doubly-fed asynchronous wind power source: It involves the stator, rotor, inverter, and robust devices, with complex control strategies and controversial modeling approaches. As it is essentially a rotating machine, it is not appropriate to completely ignore the negative-sequence effect by using a constant current source model. The author recommends using a similar model to the traditional generator with a constant voltage source (ignoring power supply voltage fluctuations), or combining the actual control strategies to iteratively calculate the relationship between machine terminal voltage and current (considering the efficiency of the iteration process).
- (3) For zero-sequence current, since the low voltage side of the main transformer is connected in a delta configuration, it can be assumed that the power source does not provide zero-sequence current to the main power grid. As for negative-sequence current, it is necessary to consult the inverter and control strategies to determine if there is a negative-sequence suppression function and to validate it using actual fault recorded waveform files.

3. New Energy Short-Circuit Current Analysis

Different types of new energy power sources have different characteristics of short-circuit currents. Taking wind power and photovoltaic power, the two main power sources, as examples, we analyze their differences. This section mainly focuses on the short-circuit current characteristics of doubly fed induction generators (DFIGs) and photovoltaic power generation systems under different fault conditions. The short-circuit current of a wind turbine mainly depends on the type of the wind turbine, its operating state, and the type of fault. The short-circuit current of a doubly-fed wind turbine includes fundamental frequency components, attenuated DC components, and speed frequency components. The short-circuit current of a direct-drive wind turbine mainly includes fundamental frequency components and speed frequency components. The short-circuit current of a photovoltaic power system mainly depends on the type of photovoltaic modules, their operating state, and the type of fault. The short-circuit current of photovoltaic modules is directly proportional to the sunlight intensity and inversely proportional to the temperature. Other new energy power sources, such as energy storage systems and electric vehicles, also have their own characteristics in terms of short-circuit current. Compared to traditional power sources, new energy power sources have the following characteristics regarding short-circuit currents [22]:

- (1) Long duration of short-circuit current: The short-circuit current of new energy power sources can last for several seconds or even tens of seconds, which is much longer than the hundreds of milliseconds of traditional power sources.
- (2) High peak value of short-circuit current: The peak value of short-circuit current in new energy power sources can reach 5–10 times or even higher than the rated current.
- (3) Presence of DC component in short-circuit current: The short-circuit current of new energy power sources contains a DC component, which can introduce DC bias to power grid equipment and affect the safe operation of the equipment.

- (4) Rapid attenuation of short-circuit current: The short-circuit current of new energy power sources attenuates quickly and will rapidly decrease within a few hundred milliseconds after a short circuit occurs.

This chapter establishes corresponding mathematical models by analyzing the composition and variation patterns of short-circuit currents in DFIG and PV under different fault conditions (such as voltage drop degree and fault type). By comparing with actual fault recording data, a mapping relationship between short-circuit current analysis of new energy power sources and engineering practicality is established, and the expression of short-circuit current for engineering practicality of new energy power sources is summarized.

3.1. Wind Generators Short-Circuit Current Analysis

This paper investigates the relay protection setting calculation and optimization problem for high-voltage power grids with the integration of large-scale new energy devices, focusing on the analysis of a fault setting calculation model for new energy projects. The short-circuit current characteristics of different types of wind turbines are analyzed, with a particular emphasis on the most common Doubly Fed Induction Generator (DFIG) wind turbines. In DFIG fault analysis, due to the relatively small short-circuit current feed-out from the grid-side converter, only the stator short-circuit current is typically solved. Based on the extent of the post-fault terminal voltage drop, the short-circuit current analysis of DFIG can be divided into three scenarios: Crowbar operation, RSC (Rotor Side Converter) excitation control, and outer-loop control [23].

When the voltage drop is significant, the Crowbar resistance is activated to bypass the rotor impact current, effectively rendering the DFIG equivalent to an asynchronous machine. In this scenario, the short-circuit current of DFIG consists of fundamental frequency components, attenuated DC components, and speed frequency components. After the attenuation of the DC and speed frequency components, only the fundamental frequency component remains. The vector expression for the short-circuit current i_s is as follows:

$$i_s = \frac{(L_s L_r - L_m^2) \left[\frac{1}{\tau_{rc}} + j(\omega_1 - \omega_r) \right] L_r - R_{rc} L_m^2}{j\omega_1 (L_s L_r - L_m^2)^2 \left[\frac{1}{\tau_{rc}} + j(\omega_1 - \omega_r) \right]} u_s \quad (1)$$

where u_s is the post-fault stator voltage vector, L_s , L_r and L_m refer to the stator, rotor self-inductance, and mutual inductance, respectively; ω_1 is the synchronous speed; ω_r is the rotor speed; ω_{rc} is the equivalent rotor resistance after Crowbar operation; τ_{rc} is the rotor decay time constant, and $\tau_{rc} = (L_s L_r - L_m^2) / (L_r R_{rc})$.

From Equation (1), it can be observed that the steady-state short-circuit current I and the residual terminal voltage U exhibit a linear relationship under the condition of Crowbar operation, given by:

$$I = k_d U \quad (2)$$

where U is the grid-connected point voltage of the DFIG, and k_d is a proportional coefficient.

When the voltage drop is less significant, according to the requirements of LVRT (Low Voltage Ride Through), the RSC controls the stator short-circuit current by manipulating the rotor current, injecting reactive power to support the grid voltage. According to the wind power grid integration standard, the dynamic reactive power injected by the wind farm into the power system during a fault I_Q should satisfy Equation (3):

$$I_Q \geq K(0.9 - U)I_N \quad (3)$$

where K is the reactive power compensation coefficient, generally not less than 1.5; U is the normalized voltage at the grid connection point, $0.2 \leq U \leq 0.9$; I_N is the rated current of the wind farm.

For DFIG with d-axis voltage-oriented control, the following relation holds:

$$\begin{cases} i_{sd}^* = \sqrt{I_{s\max}^2 - (i_{sq}^*)^2} \\ i_{sq}^* = K(0.9 - U)I_N \end{cases} \quad (4)$$

where i_{sd}^* and i_{sq}^* represent the reference values of the stator d-axis and q-axis current, respectively, and $I_{s\max}$ is the maximum stator current limit.

In the steady-state of a fault, the actual current value follows the reference value, resulting in a stator short-circuit current given by:

$$i_{sdq} = i_{sd}^* + j i_{sq}^* \quad (5)$$

By performing coordinate transformation, the steady-state short-circuit current in the stationary three-phase coordinate system can be obtained.

In the case of extremely low voltage drop, the DFIG is controlled by an outer-loop. During this phase, the output current of DFIG does not change significantly and is generally taken as the rated value I_N .

Using actual fault waveform data of DFIG and selecting the stator current limit to be $I_{s\max} = 1.5I_N$, different sets of DFIG terminal current and voltage data can be obtained by adjusting the transient resistor value in the simulation. When the Crowbar is activated, an arbitrary set of DFIG terminal current and voltage data can be used to calculate the proportion coefficient k_d in Equation (2), which is found to be 3.73. With a stator current limit of $I_{s\max} = 1.5I_N$, the short-circuit current under RSC excitation control can be obtained. To more accurately characterize the fault characteristics of DFIG, the maximum current under Crowbar operation is taken as the stator current limit $I_{s\max}$ under RSC excitation control. From this, the critical voltage of Crowbar operation and RSC excitation control $U_b = 0.402$ p.u. Furthermore, applying the plotting method, the I-U characteristic curves of the DFIG waveform data and simulation data can be obtained, as shown in Figure 3, where the current and voltage are per-unit values.

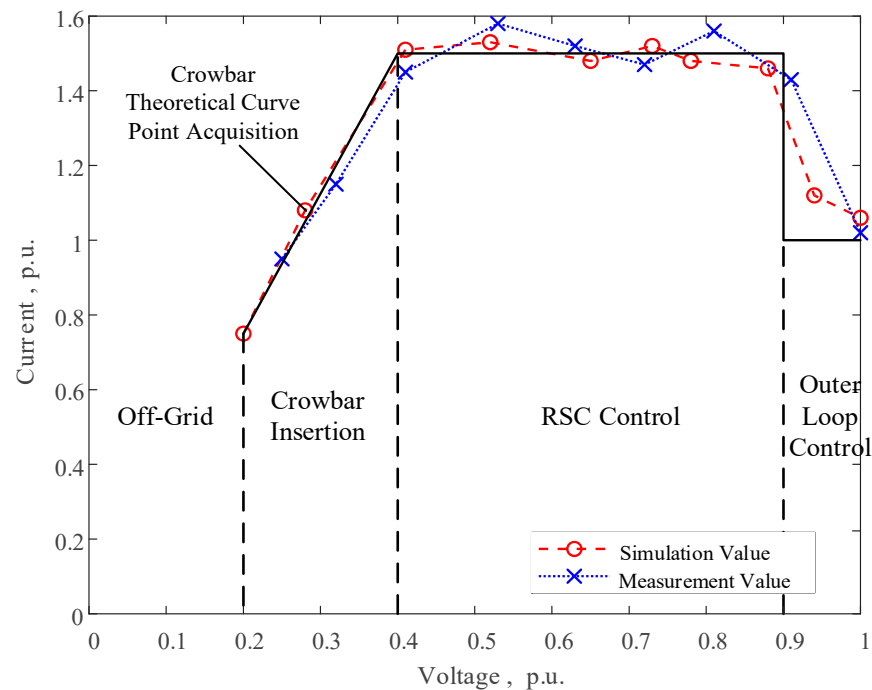


Figure 3. Current-Voltage Curve of DFIG.

As the measured values are extracted from actual fault waveform data in real power systems, there may be certain differences between the control strategies and parameters

of the new energy sources and those adopted in the simulations conducted in this study. Consequently, there exists a certain degree of error between the measured value curve and the theoretical curve.

From this, it can be deduced that the voltage-current mapping relationship for DFIG, which is suitable for practical engineering, can be expressed as:

$$I_{DFIG} = \begin{cases} 3.73UI_N & 0.2 \leq U \leq 0.402 \\ 1.5I_N & 0.402 < U \leq 0.9 \\ I_N & U > 0.9 \end{cases} \quad (6)$$

where I_{DFIG} represents the short-circuit current of DFIG under different voltage drop levels, and $U < 0.2$ denotes the case when the DFIG is disconnected from the grid.

3.2. PV Short-Circuit Current Analysis

For PV systems, when the grid-connected point voltage $U \geq 0.2$, the expression for the short-circuit current is similar to that of the Permanent Magnet Synchronous Generator (PMSG), and it will not be elaborated here. When the voltage $U < 0.2$, the PMSG allows disconnection from the grid, while the PV system needs to maintain continuous operation without disconnection for 150 ms and provide more reactive current to the grid [24]. According to the LVRT control requirements, the current command is modified as follows:

$$\begin{cases} i_d^* = 0 \\ i_q^* = 1.05I_N \end{cases} \quad (7)$$

Similarly, the Current-Voltage (I-U) characteristic curve of the PV system can be obtained, as shown in Figure 4.

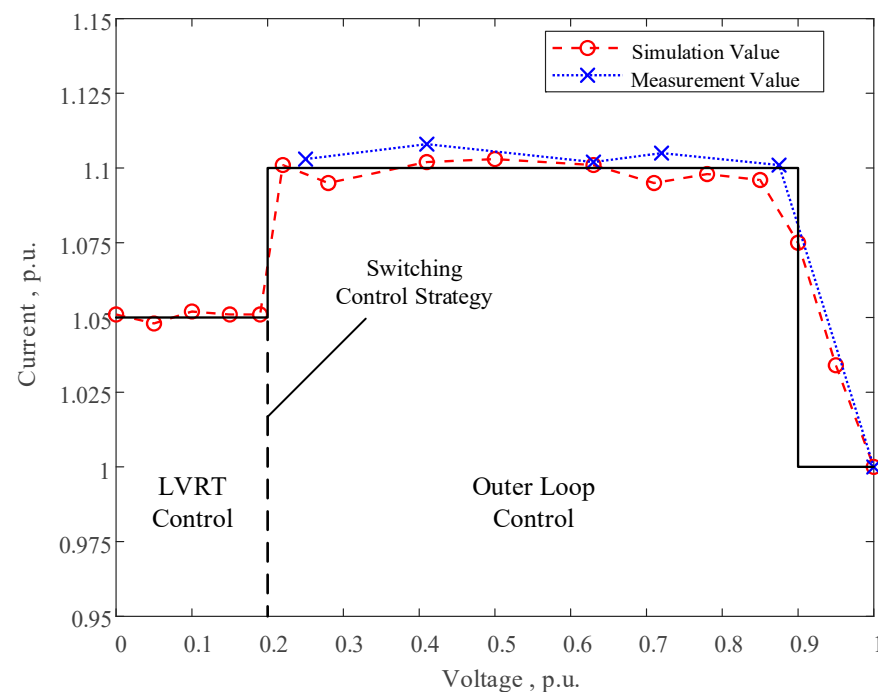


Figure 4. Current-Voltage Curve of PV.

From this, it can be inferred that the voltage-current mapping relationship for PV systems, which is suitable for practical engineering, can be expressed as:

$$I_{PV} = \begin{cases} 1.05I_N & U < 0.2 \\ 1.1I_N & 0.2 \leq U \leq 0.9 \\ I_N & U > 0.9 \end{cases} \quad (8)$$

where I_{PV} represents the short-circuit current of the PV system under different voltage drop levels.

4. Local Iteration Calculation Method of Short-Circuit Current

4.1. Traditional Short-Circuit Current Calculation Method

In traditional synchronous power networks, they can be decomposed into the normal operating network and the fault component network after a short-circuit fault occurs. Firstly, using power flow calculations, the voltages of each node under normal conditions are obtained, which represents the normal components. Then, all power sources are grounded, and a reverse power source is added at the fault location, directed from the short-circuit point to the ground. The fault components of the node voltages are calculated based on this setup. By adding the normal components and the fault components together, the voltage distribution of the network during a short-circuit fault can be determined, which further provides the current distribution across the entire network.

It should be noted that when performing power flow calculations in networks involving new energy sources, the output of the new energy sources is generally set to zero or treated as 1.2 times the maximum load current. Under this circumstance, the normal components of the node voltages can be calculated as:

$$U^{(0)} = [\dot{U}_1^{(0)} \dot{U}_2^{(0)} \cdots \dot{U}_f^{(0)} \cdots \dot{U}_n^{(0)}] \quad (9)$$

where f is the fault location, n is the total number of network nodes, and $\dot{U}_l^{(0)}$ ($l = 1, 2, \dots, f, \dots, n$) denotes the voltage of node l before the fault.

For the fault component network, the node voltage equations can be written as:

$$\begin{bmatrix} \Delta \dot{U}_1 \\ \vdots \\ \Delta \dot{U}_f \\ \vdots \\ \Delta \dot{U}_g \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1f} & \cdots & Z_{1n} \\ \vdots & & \vdots & & \vdots \\ Z_{j1} & \cdots & Z_{jf} & \cdots & Z_{jn} \\ \vdots & & \vdots & & \vdots \\ Z_{n1} & \cdots & Z_{nf} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ -i_f \\ \vdots \\ 0 \end{bmatrix} \quad (10)$$

where Z_{ij} ($i, j = 1, 2, \dots, n$ and $i \neq j$) represent the mutual impedance between nodes i and j in the impedance matrix, z_{ii} is the self-impedance of node i , $\Delta \dot{U}_i$ is the voltage deviation of node i , and $\dot{I}_f$ is the injected fault current.

The calculation equation for the voltage deviation at the fault point is:

$$\Delta \dot{U}_f = -\dot{I}_f Z_{ff} \quad (11)$$

Taking into account the existence of the transition resistance in the fault component network, we have:

$$\Delta \dot{U}_f = -\dot{U}_f^{(0)} + \dot{I}_f z_f \quad (12)$$

where z_f is the transition resistance at fault point f .

By combining Equations (11) and (12), we can obtain the injected fault point current:

$$\dot{I}_f = \frac{\dot{U}_f^{(0)}}{Z_{ff} + z_f} \quad (13)$$

Since the fault network only contains excitations at the fault location, and the interconnection of various branches in the network can be characterized by z_{ff} , this method relies solely on Equation (13), enabling non-iterative calculation to obtain the fault current and consequently the fault components of the node voltages across the entire network. As a result, the node voltages of each node after the fault can be obtained as:

$$U^{(1)} = [\dot{U}_1^{(1)} \dot{U}_2^{(1)} \cdots \dot{U}_f^{(1)} \cdots \dot{U}_n^{(1)}] \quad (14)$$

4.2. Local Iteration of the Fault Area

The block diagram of the local iterative method for calculating the short-circuit current in a network with new energy sources is shown in Figure 5 [25].

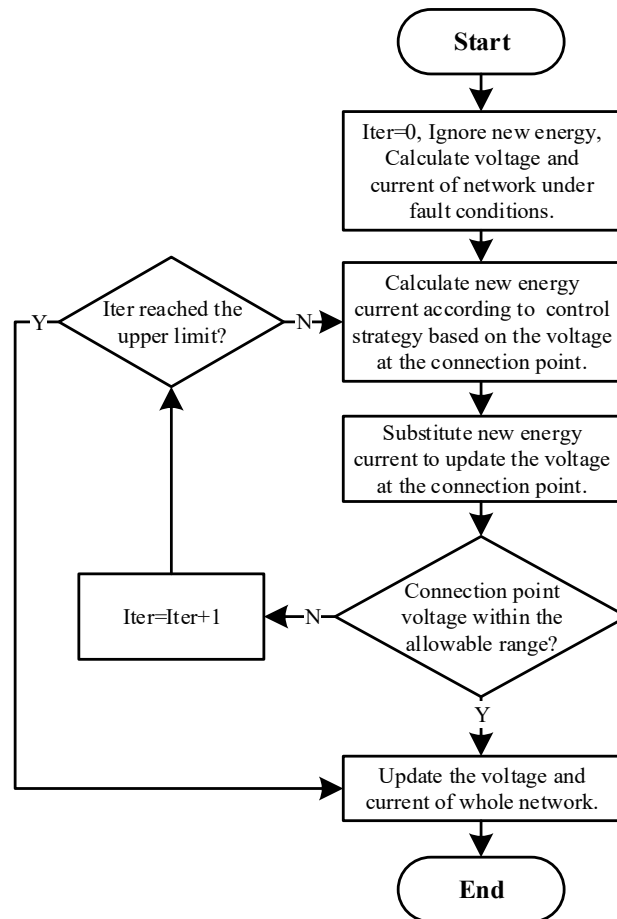


Figure 5. Block Diagram of DFIG Fault Iterative Calculation.

Firstly, by using the conventional short-circuit current calculation, the voltages of each node before and after the fault are obtained. Simultaneously, to eliminate the influence of initial voltage values on the partitioning, the ratio of the post-fault node voltages to the pre-fault voltages is calculated as the voltage drop coefficient for each node, as shown in Equation (15).

$$U^{*(1)} = [U_1^{*(1)} \quad U_2^{*(1)} \quad \cdots \quad U_f^{*(1)} \quad \cdots \quad U_n^{*(1)}] \quad (15)$$

where $U_l^{*(1)} (l = 1, 2, \dots, f, \dots, n)$ represents the voltage drop coefficient of node l .

A critical voltage threshold $U_{ref}^* \in (0, 1)$ is preset for a partition. If the voltage drop coefficient of a network node is lower than this threshold, i.e.,

$$U_l^{*(1)} < U_{ref}^* \quad (16)$$

then the node is retained and considered as a fault-relevant node, forming the node set S_0 . If the nodes in S_0 are interconnected, it is considered as the fault area node set S . If there are independent nodes in the node set S_0 (nodes not connected to any other nodes in S_0), in other words, if the mutual admittance between these nodes and any other nodes in S_0 is zero, then those independent nodes are removed, forming the fault area node set S .

Since the mapping relationship of new energy sources only changes when the grid-connected voltage is less than 0.9 p.u., the maximum value of the critical voltage threshold U_{ref}^* is set to 0.9 p.u.

To avoid excessively large iterative regions that affect computation time, the number of nodes in the fault area node set S needs to be limited. When the number of nodes in the fault area exceeds the predefined limit M_0 , the critical voltage threshold U_{ref}^* is reduced, and the fault area node set S is redefined. In order to ensure the computational speed of local iterations, M_0 generally does not exceed half of the total number of network nodes.

If there are no new energy source-connected nodes in the fault area node set S , there is no need to perform local iterations, and the node voltages and short-circuit currents of the entire network are obtained from the results of the conventional short-circuit current calculation.

If there are new energy source-connected nodes in the fault area node set S , local iterations in the fault area are required. First, the admittance matrix Y_S for the nodes in S is formed. Then, based on the node voltages $U_S^{(k)}$ in corresponding to the fault area nodes in $U^{(1)}$ (iteration count $k = 1$) and the type of new energy source power at these nodes, the output current of the new energy source power $I_{NE}^{(k)}$ is obtained using Equations (6) and (8). According to the treatment of new energy sources in conventional short-circuit current calculation, the correction amount of the injected current at the new energy source nodes is calculated as:

$$\Delta I_{NE}^{(k)} = \begin{cases} I_{NE}^{(k)} - 1.2I_{NE}^{(0)} & I_{NE,t} = 1.2I_{NE}^{(0)} \\ I_{NE}^{(k)} & I_{NE,t} = 0 \end{cases} \quad (17)$$

where $I_{NE,t}$ represents the injected current of the new energy source node in the conventional short-circuit current calculation, and $I_{NE}^{(0)}$ denotes the rated current of the new energy source power.

After obtaining $\Delta I_{NE}^{(k)}$, the correction amount of the node voltages $\Delta U_S^{(k)}$ in the fault area is iteratively solved within the fault area using the node admittance matrix, as follows:

$$Y_S \Delta U_S^{(k)} = \Delta I_S^{(k)} \quad (18)$$

where $\Delta I_S^{(k)}$ is a column vector of the injected currents of the fault area nodes, $\Delta I_{NE}^{(k)}$ represents the current value at the corresponding new energy source node in $\Delta I_S^{(k)}$, and the current value for non-new energy source nodes is zero.

Thus, the node voltages in the fault area after the $k + 1$ iteration are calculated as:

$$U_S^{(k+1)} = U_S^{(1)} + \Delta U_S^{(k)} \quad (19)$$

where $U_S^{(1)}$ represents the node voltages in the fault area corresponding to $U^{(1)}$ obtained from the conventional short-circuit current calculation.

The iterative process continues within the fault area until the correction amount of the node voltages $\Delta U_s^{(k)}$ satisfies the convergence condition or the iteration count k exceeds the maximum iteration count:

$$(|\Delta U_s^{(k)} - \Delta U_s^{(k-1)}| < \varepsilon) \parallel (k > K_0) \quad (20)$$

where K_0 is the maximum iteration count.

Since the correction amount in the first iteration has the largest magnitude, the subsequent changes will gradually decrease. To ensure the computational speed of local iterations, K_0 generally does not exceed 10.

The final node voltages with the consideration of the voltage-controlled current source characteristics of the new energy sources U_f are obtained by adding the correction amount of the fault area node voltages $\Delta U_s^{(k)}$ to the corresponding node voltages $U^{(1)}$.

For new energy transmission lines, if the grid connected node belongs to the fault area node, the short-circuit current of the node is:

$$\Delta I_{fNE} = I_{NE}^{(k+1)} \quad (21)$$

where $I_{NE}^{(k+1)}$ represents the output current of the new energy source obtained from the fault area node voltages $U_s^{(k+1)}$ corresponding to the new energy source node.

If the new energy grid connected node does not belong to the fault area node, the short-circuit current of the node is:

$$I_{fNE} = 1.2I_{NE}^{(0)} \quad (22)$$

For short-circuit currents in lines not directly connected to the new energy source power, they can be calculated using the following equation:

$$\dot{I}_{ij} = \frac{\dot{U}_i - \dot{U}_j}{z_{ij}} \quad (23)$$

where $\dot{I}_{ij}$ represents the current in the line between nodes i and j , $\dot{U}_i$ and $\dot{U}_j$ are the voltages at nodes i and j , and z_{ij} denotes the line impedance between nodes i and j .

From this, the short-circuit currents I_f for the entire network can be obtained.

5. Compilation of Revital Protective Project Examples

To verify the correctness and practicality of the aforementioned calculation method, this paper takes a 220 kV PV power station in Province G as an example to conduct a case study on relay protection setting engineering. The characteristics of this power station are its large PV capacity and complex grid structure. This section will first introduce the basic parameters of this case study, including the topological structure, grid parameters, and PV equivalent source parameters. Subsequently, the short-circuit current calculation will be performed based on the aforementioned method, followed by an analysis of the calculation results. Finally, relay protection setting will be carried out based on the calculation results, and boundary protection will be recorded.

5.1. Topological Parameters

Taking the 220 kV PV power station in Province G as an example, the station is connected to the main grid 220 kV LP station through the 220 kV B-line (positive sequence impedance of 6.8 Ω). The basic parameters include the equivalent positive and zero sequence reactances of the main grid in both big and small modes, the length and the positive and zero sequence reactances of the interconnection line (B-line), as well as the capacity of the B#1 main transformer and the positive and zero sequence reactances. Refer

to Figure 6, where the reactances are given in per unit (p.u.), and the base capacity is 100 MVA.

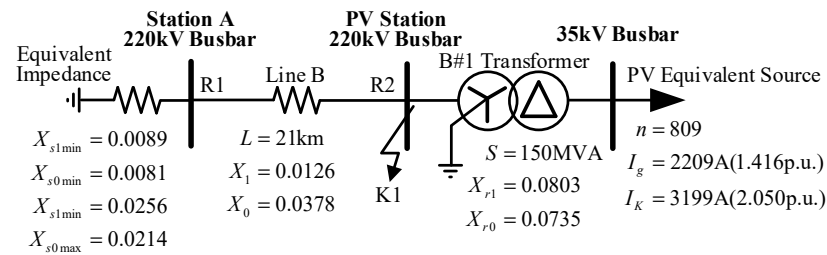


Figure 6. G Province New Energy Station Parameters.

PV equivalent source parameters: The rated voltage of the grid-side inverter $u_N = 0.8$ kV, with a rated current $I_e = 126.3$ A and a maximum output current $I_k = 182.91$ A per unit. There are 809 units connected through collection lines to the 35 kV bus. Therefore, the equivalent source rated current, converted to the 35 kV voltage level, is calculated as $I_E = nI_e \times u_N/u_H = 809 \times 182.91 \times 0.8/37 = 2209$ A, and the maximum short-circuit current I_k is calculated in a similar manner. The overload ratio $K = I_k/I_E = 1.45$. Hence, when a fault occurs in the grid, the PV power source provides a constant current of no more than 3199 A.

5.2. Short Circuit Calculation

Based on the calculation method proposed earlier, the short-circuit calculation is performed on the PV power station B shown in Figure 6. The calculation for the A-phase fault at K1 point under big mode is presented, while other modes, locations, and fault types are omitted in this paper. Considering the influence of the PV power output angle on the short-circuit current, two extreme cases, $\varphi = \pm 90^\circ$, are calculated separately.

$$\begin{aligned} Z_{ff(1)} &= Z_{ff(2)} = jX_{s1min} + jX_1 = j0.0215 \\ Z_{ff(0)} &= j(X_{s0min} + X_0) \parallel X_{T0} = j0.0283 \\ Z_{fj} &= j0.0215, I_j = 2.05 \end{aligned} \quad (24)$$

When φ is set to 90° , substituting the above equation into Equation (1) and combining it with the single-phase-to-ground boundary conditions, the positive-sequence fault current at the fault point is:

$$\begin{aligned} I_{fa(m)} &= \frac{V_f^{(0)} + \sum_{j \in H} Z_{fj}(I_j \angle -\omega)}{Z_{ff(1)} + Z_{ff(2)} + Z_{ff(0)}} \\ &= \frac{1 + j0.0215 \times 2.05 \angle -90^\circ}{j(0.0215 \times 2 + 0.0283)} = 14.65 \angle -90^\circ \end{aligned} \quad (25)$$

Distribution of currents on both sides of the fault point:

- (1) Positive sequence: The PV side maintains a constant current source amplitude, while the remaining current is supplied by the main grid side.
- (2) Negative sequence: Supplied entirely by the main grid side.
- (3) Zero sequence: Distributed inversely proportional to the zero sequence impedances on both sides, with no zero sequence at the low side of the PV main transformer.

Refer to Figure 7 for specific values.

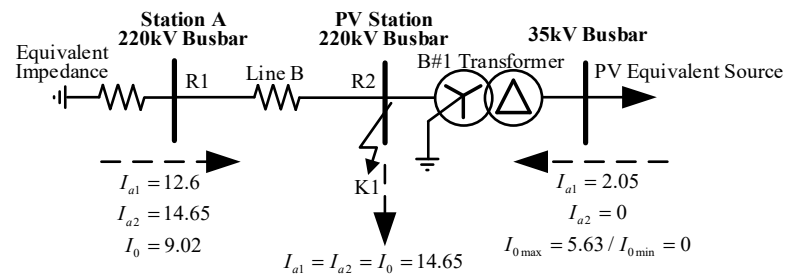


Figure 7. G Province New Energy Station Short-circuit Fault Current Distribution.

Using the same method, the calculations are performed for the PV power source with φ set to -90° and for the shutdown case, as shown in Table 1. The data in the table reveals several regularities:

- (1) φ at 90° and -90° respectively enhance and diminish the fault current at the fault point, while having the opposite effect on the positive-sequence current on the main grid side.
- (2) Treating the shutdown of the PV power source as the most extreme case may not be appropriate. It is recommended that the setting software for relay calculations considers both the φ at 90° and -90° cases, as well as the three scenarios of the PV power source shutdown.

Table 1. Short-circuit Current Comparison.

Short-Circuit Current/A	PV Outage	$\varphi = 90^\circ$	$\varphi = -90^\circ$
Fault Point $I_a(1, 2, 0)$	14.03	14.65	13.42
Grid Side I_{a1}	14.03	12.60	15.47
Grid Side I_{a2}	14.03	14.65	13.42
Grid Side I_0	8.64	9.02	8.26
PV Side I_{a1}	0	2.05	2.05
PV Side I_{a2}	0	0	0
PV Side I_0 (High Voltage Side of Main Transformer)	5.39	5.63	5.16

Note: 1, 2, 0 represent sequence components.

5.3. Partial Setting of Protective Devices

Based on the aforementioned short-circuit calculation results, the settings of the protection devices for the interconnection line shown in Figure 6 will be determined in this section. Following the content described earlier, the parameters such as distance, zero sequence, and operating mode for the protections R1 and R2 will be set.

- (1) Setting the distance for the first section between protections R1 and R2:

$$Z_{dzI} = K_k Z_L = 0.5 \times 6.8 = 3.4\Omega \quad (26)$$

- (2) Setting the distance for sections II and III for protection R2, as well as the corresponding delay times and time limits:

$$\begin{aligned} Z_{dzII} &= K_{1m} Z_L = 1.5 \times 6.8 = 10.2\Omega \\ Z_{dzIII} &= K'_{1m} Z_L = 2 \times 6.8 = 13.6\Omega \end{aligned} \quad (27)$$

The maximum time limits for sections II and III are 1.5 s and 3.3 s, respectively. Considering the coordination with R2, the delay times for sections II and III can be set to 1.8 s and 3.6 s, respectively.

- (3) The setting for the penultimate section of the zero sequence protection for R2 should be determined based on sensitivity at the line end, with a time limit of no more than

2.8 s. The end section of the zero sequence should be set to avoid high impedance and should not exceed 300 A, with a time limit of 6.5 s.

- (4) Both protections R1 and R2 are set to single restraint.

5.4. Recording of Boundary Protection

Due to various factors such as different management units, the backup protection at the network boundary can be a risk area for over-tripping of the network-wide protection. To improve the coordination performance between new energy sources and the main power grid protection system, the following recommendations are proposed for enhancing the management of boundary backup protection.

- (1) The main power grid should provide clear information on the grounding method at the neutral point of the main transformer, the equivalent impedances for positive and zero sequence under different modes of the external main power grid, and the settings and time limits for each side of the main transformer (such as the requirements for coordination between the interconnection line distance protection and the main transformer distance protection, and between the high-voltage side zero sequence protection of the main transformer and the zero sequence protection of the interconnection line).
- (2) The calculated settings for the power grid (such as the settings for the main transformer and the 35 kV equipment) should be submitted for record to the power grid. The power grid operator should review the settings, focusing on whether they meet the limit requirements, especially for the settings related to tripping the high-voltage side switch of the main transformer, such as protection and grounding transformer protection.

Based on the above suggestions, the boundary protection of the 220 kV PV power station shown in Figure 6 will be recorded and reviewed, paying close attention to the following aspects:

- (1) Whether the arrangement of the neutral point of the main transformer complies with the requirements of the main grid.
- (2) Whether the distance and overcurrent protection settings for the high-voltage side of the main transformer meet the limit requirements or coordinate with the interconnection line. For example, the delay time for the overcurrent protection should not exceed 5 s, and the time limit for the zero sequence overcurrent protection should be no less than 6.8 s.
- (3) Whether the trip output of the grounding transformer involves tripping the high-voltage side of the main transformer and whether the settings are reasonable.
- (4) Whether the deblocking, islanding prevention, and backup timing within the station comply with the requirements for synchronous reclosing coordination with the interconnection line.

5.5. Comparison of Short-Circuit Current Calculation Time

The proposed short-circuit current calculation method effectively reduces the calculation scope and improves computational efficiency by performing local iterations on the fault region. By setting appropriate convergence criteria, the desired accuracy can be achieved within a small number of iterations.

Taking the iterative process in Section 4.2 as an example, when the step size of the short-circuit current I_f is set to 0.1, approximately 10 iterations are required. In each iteration, an average of about 9 inner loops are needed to meet the convergence criteria. Based on MATLAB R2022a simulation results, when the iteration accuracy ε reaches 0.1%, the entire iterative process takes only tens of milliseconds. It should be noted that the above time consumption is based on the simplified scenario in Section 4.2, which includes only 3 PV units. In actual large-scale new energy power stations, the number of units often exceeds 50. Table 2 presents the simulation time for different numbers of units and step

sizes. The results show that even when the number of units increases and the step size decreases, the proposed iterative process for obtaining the short-circuit current at the new energy grid connection point can still maintain high computational efficiency.

Table 2. Iteraton Time in Different Simulation Scenarios.

Number of Renewable Energy Units	Step Size	Iteration Time/s
20	0.10	2.045
50	0.10	12.122
50	0.05	18.157
50	0.01	28.415
80	0.10	26.784

6. Conclusions

This study investigates the relay protection setting calculation and optimization problem for high-voltage power grids with the integration of large-scale new energy devices, with a focus on the analysis of a fault setting calculation model for new energy projects. The short-circuit current characteristics of new energy power sources are summarized, and models for permanent magnet direct-drive wind turbines and photovoltaic power sources are established, laying the foundation for accurate simulation of the behavior and characteristics of new energy devices. The voltage-current mapping relationships for DFIG (Doubly Fed Induction Generator) and PV (Photovoltaic) systems that are suitable for practical engineering are analyzed based on the summarized short-circuit current characteristics of new energy power sources. The traditional relay protection setting methods are optimized, and a new short-circuit current calculation method based on fault iteration is proposed to adapt to the changes in the grid structure after the integration of new energy sources, thereby improving calculation efficiency and accuracy. The proposed method is validated using a practical engineering example of a large-capacity new energy power station in G province, China. The protection configuration, parameter selection, system arrangement, and revision of the setting calculation principles are computed, providing a new solution for the setting calculation of new power system. It not only ensures the normal and stable operation of the power grid but also contributes to the efficiency and performance improvement of the new energy devices. Therefore, this research has significant practical implications for the development of the power grid industry and the effective utilization of new energy resources. Future work can focus on studying the short-circuit current characteristics of new energy power sources under multiple fault scenarios and the impact of renewable energy integration on the stability of the relay protection system, further enhancing the stability of the system.

Author Contributions: Conceptualization, Z.L. and B.S.; methodology, Z.L.; software, B.S.; validation, Q.J.; writing—original draft preparation, Q.J.; writing—review and editing, Y.H.; visualization, Q.J.; All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the fund: Research on standardized collection and analysis of experimental data based on multiple sources (Project Number: 2023-4-1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Alam, M.S.; Al-Ismail, F.S.; Salem, A.; Abido, M.A. High-level penetration of renewable energy sources into grid utility: Challenges and solutions. *IEEE Access* **2020**, *8*, 190277–190299. [\[CrossRef\]](#)
2. Ahmed, S.D.; Al-Ismail, F.S.; Shafiullah, M.; Al-Sulaiman, F.A.; El-Amin, I.M. Grid integration challenges of wind energy: A review. *IEEE Access* **2020**, *8*, 10857–10878. [\[CrossRef\]](#)
3. Fang, Y.P.; Sansavini, G.; Zio, E. An optimization-based framework for the identification of vulnerabilities in electric power grids exposed to natural hazards. *Risk Anal.* **2019**, *39*, 1949–1969. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Chen, Y.; Xu, P.; Chu, Y.; Li, W.; Wu, Y.; Ni, L.; Bao, Y.; Wang, K. Short-term electrical load forecasting using the Support Vector Regression (SVR) model to calculate the demand response baseline for office buildings. *Appl. Energy* **2017**, *195*, 659–670. [\[CrossRef\]](#)
5. Connolly, D.; Lund, H.; Mathiesen, B.V.; Leahy, M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl. Energy* **2010**, *87*, 1059–1082. [\[CrossRef\]](#)
6. Zhang, C.; Wei, H.; Zhao, J.; Liu, T.; Zhu, T.; Zhang, K. Short-term wind speed forecasting using empirical mode decomposition and feature selection. *Renew. Energy* **2016**, *96*, 727–737. [\[CrossRef\]](#)
7. Mukherjee, A.; Kundu, P.K.; Das, A. Transmission line faults in power system and the different algorithms for identification, classification and localization: A brief review of methods. *J. Inst. Eng. India Ser. B* **2021**, *102*, 855–877. [\[CrossRef\]](#)
8. Alcala-Gonzalez, D.; García del Toro, E.M.; Más-López, M.I.; Pindado, S. Effect of distributed photovoltaic generation on short-circuit currents and fault detection in distribution networks: A practical case study. *Appl. Sci.* **2021**, *11*, 405. [\[CrossRef\]](#)
9. Zhou, N.; Wu, J.; Wang, Q. Three-phase short-circuit current calculation of power systems with high penetration of VSC-based renewable energy. *Energies* **2018**, *11*, 537. [\[CrossRef\]](#)
10. Kim, I. A calculation method for the short-circuit current contribution of current-control inverter-based distributed generation sources at balanced conditions. *Electr. Power Syst. Res.* **2021**, *190*, 106839. [\[CrossRef\]](#)
11. Luo, Y.; He, J.; Li, M.; Zhang, D.; Zhang, Y.; Song, Y.; Nie, M. Analytical calculation of transient short-circuit currents for MMC-based MTDC grids. *IEEE Trans. Ind. Electron.* **2021**, *69*, 7500–7511. [\[CrossRef\]](#)
12. Liu, H.; Xu, K.; Zhang, Z.; Liu, W.; Ao, J. Research on theoretical calculation methods of photovoltaic power short-circuit current and influencing factors of its fault characteristics. *Energies* **2019**, *12*, 316. [\[CrossRef\]](#)
13. Pan, W.; Liu, M.; Zhao, K.; Zhang, Y.; Liu, T. A practical short-circuit current calculation method for DFIG-based wind farm considering voltage distribution. *IEEE Access* **2019**, *7*, 31774–31781. [\[CrossRef\]](#)
14. Wei, X.; Yang, J. Progress in research on relay protection of the power system with large-scale wind power access. *J. Electrotechnol. Electr. Eng. Manag.* **2023**, *6*, 26–29.
15. Hossain, J.; Pota, H.R. *Robust Control for Grid Voltage Stability: High Penetration of Renewable Energy*; Power Systems; Springer: Berlin/Heidelberg, Germany, 2014.
16. Hosseinzadeh, N.; Aziz, A.; Mahmud, A.; Gargoom, A.; Rabbani, M. Voltage stability of power systems with renewable-energy inverter-based generators: A review. *Electronics* **2021**, *10*, 115. [\[CrossRef\]](#)
17. Boričić, A.; Torres JL, R.; Popov, M. Fundamental study on the influence of dynamic load and distributed energy resources on power system short-term voltage stability. *Int. J. Electr. Power Energy Syst.* **2021**, *131*, 107141. [\[CrossRef\]](#)
18. Vargas, S.A.; Esteves, G.R.T.; Maçaira, P.M.; Bastos, B.Q.; Oliveira, F.L.C.; Souza, R.C. Wind power generation: A review and a research agenda. *J. Clean. Prod.* **2019**, *218*, 850–870. [\[CrossRef\]](#)
19. Gomes IS, F.; Perez, Y.; Suomalainen, E. Coupling small batteries and PV generation: A review. *Renew. Sustain. Energy Rev.* **2020**, *126*, 109835. [\[CrossRef\]](#)
20. Ellabban, O.; Abu-Rub, H.; Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. *Renew. Sustain. Energy Rev.* **2014**, *39*, 748–764. [\[CrossRef\]](#)
21. Schuman, S.; Lin, A. China's Renewable Energy Law and its impact on renewable power in China: Progress, challenges and recommendations for improving implementation. *Energy Policy* **2012**, *51*, 89–109. [\[CrossRef\]](#)
22. Zhang, C.; Zeng, J.; Zhao, W.; Zhong, G.; Zhang, W.; Li, W.; Dai, M. Fault characteristics of full power inverted sources and its short-circuit current calculation model. *J. Eng.* **2017**, *2017*, 2471–2476. [\[CrossRef\]](#)
23. Jiang, D.; Yu, W.; Wang, J.; Zhong, G.; Zhou, Z. Dynamic analysis of DFIG fault detection and its suppression using sliding mode control. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *11*, 643–656. [\[CrossRef\]](#)
24. Song, J.; Cheah-Mane, M.; Prieto-Araujo, E.; Gomis-Bellmunt, O. Short-circuit analysis of grid-connected PV power plants considering inverter limits. *Int. J. Electr. Power Energy Syst.* **2023**, *149*, 109045. [\[CrossRef\]](#)
25. El Mountassir, O.; Stewart, B.G.; Reid, A.J.; McMeekin, S.G. Quantification of the performance of iterative and non-iterative computational methods of locating partial discharges using RF measurement techniques. *Electr. Power Syst. Res.* **2017**, *143*, 110–120. [\[CrossRef\]](#)

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