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ICT-Supported Scenario-Aware Adaptive Setting Method for Line Current Protection in Distribution Networks with High Proportion of Distributed Generation

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Abstract

INTRODUCTION: With the large-scale integration of distributed generators (DGs), distribution networks are gradually evolving into multi-source power supply systems. Although high-penetration DG integration improves system operational flexibility and power supply reliability, it changes fault current distribution characteristics and weakens the adaptability of conventional fixed-setting overcurrent protection. Under high DG penetration, wide-range DG output fluctuations and load demand variations may lead to protection miscoordination, maloperation, or failure to operate. OBJECTIVES: To address these challenges, this paper aims to develop an ICT-supported scenario-aware adaptive setting method for overcurrent protection in distribution networks with high DG penetration, so as to improve the adaptability, sensitivity, and reliability of line current protection under varying operating conditions. METHODS: The proposed method classifies operating states into typical scenarios according to load demand, DG output, and network topology. Refined protection settings are calculated offline for each scenario by considering the infeed and outfeed effects of DGs. Meanwhile, an information and communication technology (ICT) architecture composed of distribution terminals, intelligent electronic devices, communication networks, and edge computing units is introduced to collect real-time DG output, feeder current, switch status, and topology information. Based on these data, online operating scenario identification and adaptive switching of protection settings are realized. RESULTS: Simulation results show that the proposed method can adapt to different operating scenarios, including a low-load scenario with zero DG output, a high-load scenario, and a high-DG-output scenario with a load of 8 MW. For a fault at point k1, when the system switches from Scenario 1 to Scenario 3, the fault current measured by QF2 decreases to 1.93 kA, which is lower than the original Stage II protection setting of 1.98 kA under Scenario 1 and may lead to protection failure. After applying the proposed method, the Stage II setting of QF2 is adjusted to 1.39 kA, while the protection sensitivity coefficient remains greater than 1.3. In addition, when the load increases from 5 MW to 10 MW, the Stage III setting of QF21 is adjusted from 0.11 kA to 0.23 kA, thereby avoiding the risk of maloperation under heavy-load conditions. CONCLUSION: The proposed ICT-supported scenario-aware adaptive setting method can effectively respond to changes in DG output, load demand, and network topology. By enabling scenario-based setting calculation and online adaptive switching, the method improves the adaptability and reliability of overcurrent protection in active distribution networks with high DG penetration.

Keywords: high proportion of distributed generation, scenario self-adaptation, setting value switching, current protection

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1. Introduction

Driven by the "dual-carbon strategy", a new type of power system dominated by safe, efficient, and green low-carbon renewable energy is developing rapidly. The core value of this emerging power system lies in its ability to support the low-carbon transition of the energy system through efficient renewable energy accommodation mechanisms [1,2]. Distribution network protection serves as a critical line of defense for ensuring the safety and reliability of the power supply. Its primary function is to rapidly and accurately detect and isolate faults, thereby preventing equipment damage, casualties, and large-scale blackout accidents. However, with the high penetration of distributed generators, fluctuations in DG output together with variations in system load demand have rendered distribution network operating scenarios increasingly complex and uncertain. As a result, conventional protection settings based on fixed operating conditions can no longer simultaneously satisfy the requirements of sensitivity and selectivity [3-5].

At present, many scholars have investigated the impact of high-penetration distributed generator integration on protection performance. Existing studies on distribution network protection mainly adopt two approaches to improve protection reliability under high DG penetration scenarios. The first is the application of differential protection technology based on multi-terminal electrical information fusion, which enhances fault identification capability by exploiting the differences in electrical quantities measured at multiple points along the feeder [6,7]. The second is the development of adaptive relay protection schemes designed in accordance with the fluctuating characteristics of DG output, in which protection parameters are dynamically adjusted to match changes in operating conditions. However, in most existing adaptive protection strategies, the adaptive adjustment of protection settings is typically optimized only with respect to a single driving factor, such as DG output fluctuation, load variation, specific fault characteristics, or other limited sensing dimensions. References [8,9] realized fault type identification and dynamic switching of protection settings by extracting current sequence components. Considering the influence of DG integration, Reference [10] proposed an online setting calculation method combined with intelligent algorithms, in which protection settings are corrected in real time based on DG output forecast data. References [11,12] dynamically optimized the setting values of Stage II and Stage III protection through iterative calculation of the impact of DG parameters on fault current. In essence, the methods reported in the above studies perform local adaptive adjustment of protection settings for a specific protection scheme under conditions of limited perception of distribution network operating states, and are driven primarily by a single factor. Their main limitation is that scenario awareness remains relatively one-sided, without fully considering multidimensional operating characteristics such as large-scale fluctuations in load demand, the stochastic diversity of DG output, and the complex variability of network topology [13]. Meanwhile, adaptive settings based on a single condition are insufficient to cover the various complex operating conditions arising from the dynamic coupling between DG output and load demand in practical operation, which may still result in protection miscoordination, maloperation, or failure to operate under non-design scenarios. Moreover, most existing improvements to overcurrent protection rely on post-fault adaptive setting recalculation and dynamic adjustment. Such online decision-making methods, which determine whether protection should operate after a fault occurs, require a certain level of communication speed for data transmission, and the time consumed by protection logic evaluation inevitably affects the operating speed of protection.

To address the above issues, this paper proposes a scenario-adaptive setting method for distribution network overcurrent protection based on multidimensional operating feature perception. The proposed method first comprehensively considers key factors such as load level and DG output to construct a multidimensional operating feature space for the distribution network, thereby enabling a structured representation of complex operating states and, on this basis, dividing them into a finite number of typical operating scenarios. Building upon this framework, a protection setting method that takes into account both the fault current contribution and the infeed effect of distributed generators is established for different operating scenarios, and multiple groups of protection setting schemes are generated offline. Furthermore, by acquiring system operating information in real time, the current operating state can be identified online, and adaptive switching of protection settings can be achieved according to the "scenario–setting" mapping relationship, thereby enhancing the adaptability of protection to changes in operating conditions. Case study results demonstrate that the proposed method is feasible and effective under complex operating conditions.

Different from conventional adaptive protection methods that mainly focus on protection setting calculation, this paper further introduces an ICT-supported closed-loop protection concept of "measurement-communication-computation-execution". By establishing a multi-source data exchange mechanism among distribution terminals, intelligent electronic devices, and DG interconnection points, real-time information such as DG output, feeder current, switch status, and topology changes can be transmitted to edge computing units or substation-area protection controllers through fiber-optic private networks, 5G/wireless private networks, or fast communication channels based on IEC 61850. The current operating scenario can then be identified online, and the corresponding protection setting group can be rapidly matched. This cyber-physical coordination mechanism enables protection settings to move beyond offline static configuration and adaptively switch according to the real-time operating state of active distribution networks, thereby improving the sensing capability, response

capability, and engineering applicability of protection systems under high-penetration DG integration.
The remainder of this paper is organized as follows. Section 2 analyzes the impact of DG output fluctuations and large-scale load variations on overcurrent protection in distribution networks. Section 3 presents a protection strategy suitable for distribution networks with multiple DG integrations. Section 4 describes the scenario-adaptive overcurrent protection configuration procedure proposed in this paper. Section 5 provides case studies and analysis. Section 6 concludes the paper.

2. Impact of DG Output Fluctuation and Large-range Load Change on Distribution Network Current Protection

Considering that three-stage overcurrent protection is still widely adopted as the main protection scheme in distribution networks in China, this paper investigates the adaptability of staged overcurrent protection in the presence of DG integration, with particular emphasis on the impacts of DG output fluctuations and significant load demand variations, thereby providing a basis for subsequent studies on protection strategies.

2.1. Configuration of Step-type Current Protection in Distribution Network

Figure 1 is a schematic diagram of a 10kV distribution network system with DG integration.

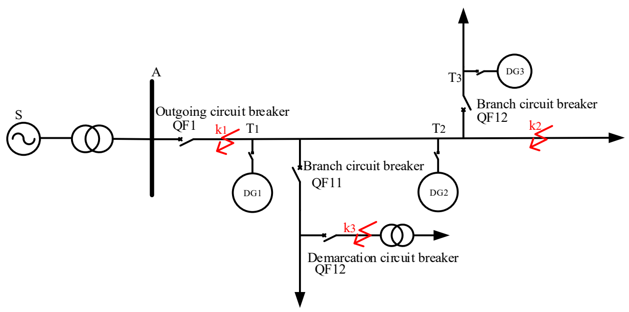

Figure 1. A Simple 10kV Distribution Grid Model with DG Integration

As shown in Figure 1, in the conventional staged overcurrent protection scheme of a typical distribution network, different protection stages exhibit different sensitivities to DG output variation and load fluctuation. The feeder outgoing Section I protection is only weakly affected by these factors, because its setting is primarily determined by the three-phase short-circuit current at the feeder outlet, to which DGs contribute relatively little. In contrast, protection elements such as feeder outgoing Section II, branch Section II, and interconnection boundary Section I are more susceptible to fluctuations in DG output. For protection elements, including feeder outgoing Section III, branch Section III, and interconnection boundary Section III, the combined effect of load variation and DG output fluctuation is more pronounced [14-16].
To better illustrate the problems of maloperation and failure to operate introduced by DG integration into conventional overcurrent protection of distribution networks, the protection configuration and setting scheme for a 10 kV distribution line without considering DG integration are presented in Table 1.

Table 1. Three-stage current protection configuration and tuning scheme

Protection Configuration		Current Setting Value/kA	Operating Time/s
Outlet QF1	I	6.18	0
	II	1.98	0.4
	III	0.97	0.6
Branch QF11	II	1.83	0.2
	III	0.20	0.4
Branch QF12	II	1.61	0.2
	III	0.10	0.4
Branch QF21	I	1.64	0
	III	0.15	0.2

2.2. Adaptability Analysis of Current Protection for Distribution Networks with High Proportion of DG Integration

With the continuous increase in the penetration level of inverter-based DGs, low-voltage ride-through capability is generally required to ensure the safe and stable operation of the system under fault conditions. During voltage disturbances, inverter-based DGs typically adopt a constant-current control strategy with reactive power priority, whereby the output current is limited to its maximum allowable range so as to support the voltage at the point of common coupling and enhance the continuity of power supply during faults. Under this control mode, an inverter-based DG can therefore be equivalently represented as a constant current source, with its current output upper limit generally ranging from 1.2 to 1.5 times the rated value [17].
Taking the simplified distribution feeder shown in Figure 1 as the study object, this paper investigates the variation characteristics of overcurrent protection performance under inverter-based DG integration. For a typical distribution network structure in which both the main feeder and branch feeders are connected with inverter-based DGs, the influence of DGs on the measured protection current and protection operating behavior is examined for different fault locations. After completing the protection coordination according to the setting method described in Section 2.1, a comparative analysis is carried out on the fault currents measured by each protection

device under two operating conditions: (1) varying DG output with constant load capacity, and (2) varying load demand with constant DG output.

The results show that, when the load remains constant, and a three-phase short-circuit fault occurs at point k2, the short-circuit current detected at QF1 decreases as the DG output increases. At relatively low DG output levels, this variation is insufficient to affect normal protection operation. However, when the DG output increases further, the feeder outgoing Section II protection at QF1 may fail to operate because the measured current decreases under the influence of DG participation in fault current distribution. For a fault at point k3, QF12 detects the reverse fault current supplied by DG3. If no directional element is installed, this current may reach the operating threshold of Section III protection as the output of DG3 increases, thereby causing maloperation. Therefore, this paper assumes by default that all upstream protection devices are equipped with directional discrimination functions.

In summary, fluctuations in DG output together with large variations in load demand significantly increase the complexity and uncertainty of distribution network operating conditions. As a result, the conventional fixed-setting configuration of staged overcurrent protection can no longer effectively accommodate multiple operating scenarios and is prone to maloperation or failure to operate, thereby jeopardizing the safe and stable operation of the power system. It is therefore necessary to comprehensively consider the dynamic coupling between load demand and DG output, establish a mechanism for the adaptive adjustment of protection settings with changes in system states, and develop a scenario-based protection setting method supported by state awareness to meet the new protection requirements of distribution networks under high-penetration DG integration.

3. Protection Strategy for Distribution Networks with Multi-DG Integration

The operating state of a distribution network is not determined by a single factor, but rather by the combined influence of multiple factors, including distributed generator (DG) output, load variation, and network topology. Consequently, it exhibits strong diversity in operating conditions. In particular, DG output is inherently fluctuating, while load demand varies dynamically over time, causing the system to present different characteristics under different operating periods. Therefore, it is necessary to incorporate multidimensional operating information to systematically classify distribution network operating conditions, thereby providing a basis for hierarchical and scenario-based configuration of protection settings.

Based on the above considerations, this paper adopts an operating scenario modeling approach, in which key operating variables such as DG output level and load capacity are mapped into a unified multidimensional feature space. According to the proximity and distribution differences among these feature parameters, the operating states are clustered and aggregated into several typical scenarios. These scenarios are used to characterize the steady-state features of the system within specific operating ranges, thereby laying the foundation for targeted setting calculation and optimized configuration of protection parameters.

3.1. Analysis of Distribution Network Operating Characteristics and Scenario Classification

3.1.1. Data Selection

The operating state of the distribution network is influenced by multiple factors, including DG output, load scale and type, and network topology [18,19]. The summer output data of DG in a certain region is shown in Figure 2. Due to natural conditions and its own characteristics, DG power fluctuates randomly, which significantly affects the power flow distribution [20]. Loads also vary by region and user group. Figure 3 shows the load curve of a northern region.

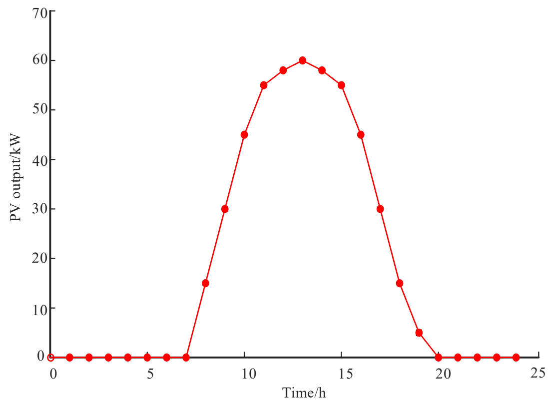

Figure 2. DG output curve in summer

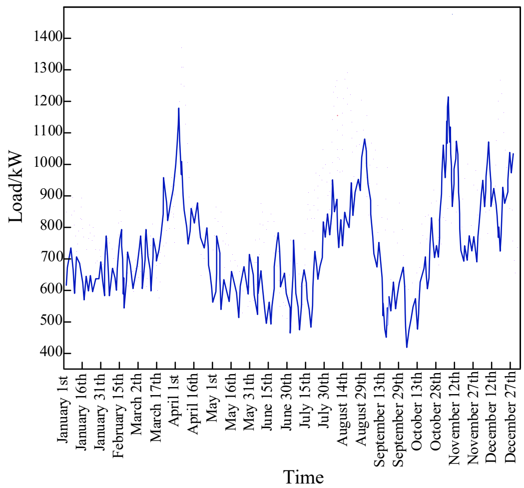

Figure 3. Load data of a certain northern region

Taking a photovoltaic (PV) power source as an example, its output power can be expressed as:

$$P_{DG}(t) = \eta g S_{pv} g G(t) \tag{1}$$

Where η is the conversion efficiency of the PV system, S_{pv} is the effective area of the module, and $G(t)$ is the solar irradiance intensity at time *t*. This expression indicates that the PV output is directly driven by external environmental variables, exhibiting significant temporal fluctuation characteristics.

Therefore, the division of typical scenarios requires collecting operational data under different working conditions, incorporating factors such as the randomness of DG output and load variations.

In this study, annual load and DG output profile data are selected for scenario classification. The use of long-term data helps optimize the temporal granularity of scenario partitioning and avoids frequent switching of protection settings caused by short-term fluctuations. Under the conventional setting-switching procedure of “withdrawal–update–reclosing,” excessively frequent operations may introduce the risk of protection blind zones. By contrast, clustering based on annual data makes it possible to extract the steady-state characteristics of typical scenarios. While maintaining adequate scenario coverage, this approach also suppresses intra-day and intra-seasonal fluctuations through temporal smoothing, thereby aligning the switching frequency of protection settings with the tolerance capability of protection devices.

3.1.2. Typical Scenario Classification and Real-Time State Awareness Techniques

Based on the multidimensional feature space constructed for distribution network operating states, the operating conditions can be classified into several sets of typical scenarios. Within each scenario, DG output range, load level, and power flow distribution exhibit relative consistency, thereby enabling the characterization of typical system features under different operating intervals. It should be noted that the core objective of scenario classification lies in the rational categorization of operating states through the integrated analysis of multidimensional features. Therefore, in practical applications, appropriate classification methods may be selected according to data scale and engineering requirements so as to effectively extract typical operating scenarios. Once the classification results of typical scenarios are obtained, the boundary ranges of DG output and load variation within each scenario can be further identified, thereby providing constraint conditions for protection setting calculation.

For typical operating modes of distribution networks with multiple DG integrations, feeder DG state identification techniques based on fast information exchange among distribution terminals can be employed to perceive the dynamic characteristics and regulation capability of DGs [21-23]. Specifically, an evaluation model of actual DG output can be established through real-time measurements, and output prediction intervals can then be constructed by incorporating the fluctuation characteristics of intermittent power sources. On this basis, multidimensional and multi-terminal scenario perception can be achieved through the identification of network topology as well as the operating states of DGs and the distribution network. Existing technologies are already capable of providing effective support for operating state monitoring.

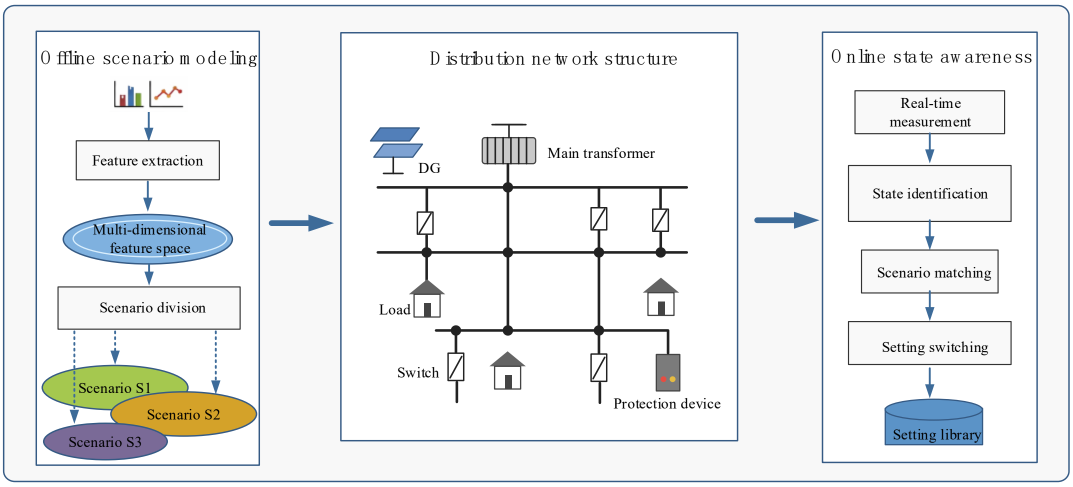

Figure 4. Scene Awareness Topology Diagram for Distribution Network State Estimation

To more clearly illustrate the relationship among distribution network operating state detection, network topology identification, and scenario awareness, this paper further presents a network topology diagram for distribution network operating state detection and scenario awareness, as shown in Figure 4. This diagram intuitively demonstrates the implementation logic of typical scenario division and operating state identification from three aspects: offline scenario modeling, online state awareness, and distribution network topology association.

3.1.3. ICT-Supported State Awareness and Setting Switching Architecture

To improve the real-time performance and reliability of scenario identification and setting switching, this paper establishes an ICT-supported architecture for protection in active distribution networks. The architecture consists of four layers: the sensing layer, the communication layer, the edge computing layer, and the execution layer.

The sensing layer is composed of feeder terminal units, distribution automation terminals, intelligent electronic devices, DG interconnection monitoring and control devices, and smart meters. It is responsible for collecting feeder current, voltage, switch status, DG output, load level, and operating information at the point of common coupling. The communication layer transmits multi-source measurement data through fiber-optic private networks, 5G/wireless private networks, or substation-area communication networks based on IEC 61850, providing real-time, synchronized, and traceable operating information for protection devices. The edge computing layer is deployed at substations, switching stations, or feeder automation master stations, and performs topology identification, operating scenario matching, abnormal data verification, and setting group selection. The execution layer consists of protection devices with multi-setting-zone storage and remote switching functions, which invoke the corresponding setting zone according to the scenario identification result issued by the edge computing unit, thereby realizing adaptive switching of protection settings.

In this architecture, long-term historical data are mainly used for offline scenario classification and setting group generation, whereas real-time measurements are used for online scenario identification and switching trigger. When the network topology changes, topology association verification should be performed first, and the corresponding setting group should be matched immediately. When the operating scenario changes only due to DG output fluctuation or load variation, time-window smoothing and threshold-based criteria are adopted to suppress frequent switching caused by transient fluctuations. Therefore, the proposed ICT architecture not only provides a real-time data basis for adaptive protection settings but also mitigates the impacts of communication delay, abnormal data, and excessive switching frequency on protection reliability.

3.2. Protection Setting Strategy Considering Scenario Adaptability

3.2.1. Protection Setting Calculation

As discussed in Section 2.1, the feeder outgoing circuit breaker Section I protection is insensitive to DG output fluctuations and therefore does not require resetting in response to changes in operating scenarios. Accordingly, this paper focuses on the analysis of Section II and Section III protection, which are more significantly affected by DG integration. When selecting DG output values for protection setting calculation under a specific scenario, the upper bound of DG output within that scenario is adopted if the DG contributes to the fault current measured at the protection location; conversely, if the DG exhibits an outfeed effect, the lower bound of DG output within that scenario is used. In the following, circuit breaker QF2 is taken as an example to illustrate the setting calculation procedure.

For the outgoing protection of QF2, both DG1 and DG2 produce an outfeed effect. Therefore, in the setting calculation, the minimum output values of DG1 and DG2 within the scenario set should be adopted. The setting formula for its Section II protection is given as follows:

$$I_{\mathrm{set}_{\mathrm{QF2}}}^{\mathrm{II}}=\frac{I_{\mathrm{kmin}}-\Delta I_{\mathrm{DG1}_{\mathrm{min}}}-\Delta I_{\mathrm{DG2}_{\mathrm{min}}}}{1.3} \quad (2)$$

In the formula: $I_{\mathrm{set}_{\mathrm{QF2}}}^{\mathrm{II}}$ denotes the Zone II setting value for protection device QF2; I_{kmin} represents the short-circuit current during a phase-to-phase fault at the end of the line where the protection device is installed; $\Delta I_{\mathrm{DG1}_{\mathrm{min}}}$ 、 $\Delta I_{\mathrm{DG2}_{\mathrm{min}}}$ are the fault currents flowing from DG1 and DG2 toward protection device QF2.

When the sum of the minimum DG output values in a given scenario is smaller than the load demand, the current remains positive. In this case, the protection settings should be determined based on the condition corresponding to the maximum forward current, and the minimum output values of all DGs within that scenario are therefore adopted:

$$I_{\mathrm{set}_{\mathrm{QF2}}}^{\mathrm{III}}=3(I_{\mathrm{Lmax}}-I_{\mathrm{DG1}_{\mathrm{min}}}-I_{\mathrm{DG2}_{\mathrm{min}}}) \quad (3)$$

In the formula: $I_{\mathrm{set}_{\mathrm{QF2}}}^{\mathrm{III}}$ denotes the Zone III setting value for protection device QF2; I_{Lmax} represents the maximum load current flowing through the local line; $I_{\mathrm{DG1}_{\mathrm{min}}}$, $I_{\mathrm{DG2}_{\mathrm{min}}}$ are the minimum output currents from DG1 and DG2 flowing toward the load direction of the protected line under normal operating conditions in a given scenario.

The time setting step for stage II protection in this paper is 0.2s, and the time setting step for stage III protection is 0.3s.

3.2.2. Protection Setting Switching

Due to the wide range of DG output and load demand fluctuations, as well as dynamic changes in network topology, the operating state of active distribution networks presents significant uncertainty. When the network topology undergoes structural changes, the protection device needs to immediately trigger setting group switching without time delay; when the operating state of the distribution network changes due to wide range changes in DG output and load demand, to avoid frequent switching of protection settings caused by random fluctuations such as instantaneous fluctuations as those in photovoltaic power generation affected by cloud shading, as well as the diurnal periodic changes in load., the switching strategy should have a certain time delay to judge whether it is an instantaneous fluctuation. At the same time, traditional protection setting switching needs to go through the process of “system de-energization-setting update-system re-energization”, and the risk of protection blind zones caused by frequent operations should also be minimized.

When the operating state of a distribution network shifts due to variations in DG output and load demand, scenario identification based solely on instantaneous measurements is highly susceptible to random photovoltaic fluctuations and periodic load variations, which may lead to frequent switching of protection settings. Considering that the conventional setting-switching process involves procedures such as withdrawal, updating, and reclosing, excessively frequent operations may further increase the risk of protection blind zones. To address this issue, this paper extracts long-term steady-state operating characteristics through time-scale smoothing while ensuring effective scenario coverage and combines them with short-term monitoring data to accomplish dynamic scenario identification. In this way, a balance between the stability and real-time performance of protection setting switching can be achieved. According to the above setting method, a total of L groups of protection settings are ultimately obtained. In addition, the cluster centers corresponding to each operating scenario set, together with the maximum and minimum load currents flowing through the protection device within each scenario, are stored in the protection device, based on which the following criterion for protection setting switching is established:

$$\begin{cases} \Delta I_1 \Delta I_2 > 0 \\ I_{QF}(t_3) < K_1 I_{QF\min} \end{cases} \text{or} \begin{cases} \Delta I_1 \Delta I_2 > 0 \\ I_{QF}(t_3) > K_2 I_{QF\max} \end{cases} \tag{4}$$

In the formula: $I_{QF}(t_3)$ denotes the magnitude of the current flowing through protection device QF at time t_3, and its value is sampled once every 24 h. And $\Delta I_1 = I_{QF}(t_2) - I_{QF}(t_1)$, $\Delta I_2 = I_{QF}(t_3) - I_{QF}(t_2)$, $I_{QF\min}$ and $I_{QF\max}$ represent the minimum and maximum load currents, respectively, flowing through the protection device under the current operating scenario set. K_1 and K_2 are auxiliary coefficients introduced to account for measurement and modeling uncertainties, and are assigned values of 0.9 and 1.1, respectively.

When the current magnitude measured at the protection installation point exhibits a continuous decreasing or increasing trend, and the current magnitude at time t_3 exceeds the minimum or maximum load current range of the current operating scenario set, it is determined that the distribution network operating scenario set has changed, and the protection device should accordingly update its settings.

4. Scenario-Adaptive Overcurrent Protection Configuration Scheme

Based on the above protection setting calculation and switching criteria, the overall implementation procedure of the proposed ICT-supported scenario-aware adaptive current protection method is summarized in Figure 5.

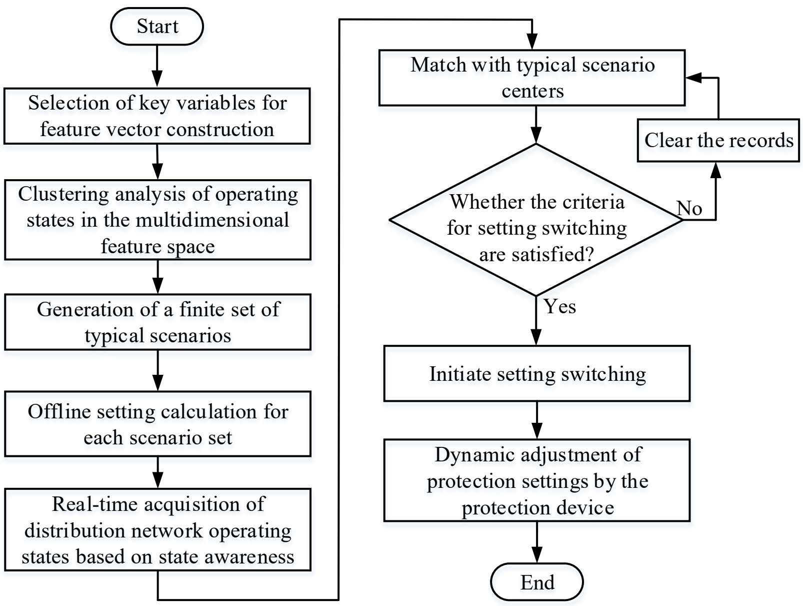

Figure 5. Flowchart of current protection configuration considering scene adaptability

First, based on historical operating data as well as key information such as load level, DG output, and network topology, the operating states of the distribution network are analyzed, and a finite number of typical operating scenarios are extracted, thereby providing the basis for scenario-specific configuration of protection settings under different operating conditions. Second, for each typical scenario, the infeed and outfeed effects of distributed generators on the current measured by protection devices are comprehensively taken into account, and the settings of protection at all stages are determined offline to form protection setting schemes corresponding to different operating scenarios. Furthermore, during system operation, the current operating state of the distribution network is identified online through real-time acquisition of operating information, and the corresponding typical scenario is determined. When a change in the operating scenario is detected, the protection device invokes the corresponding setting according to the pre-established mapping relationship between scenarios and protection settings, thereby achieving adaptive adjustment of protection configuration

5. Case Study

To verify the effectiveness of the proposed method, a typical 10 kV distribution network with multiple DG integrations is established in PSCAD/EMTDC, as shown in Figure 6. Considering the impacts of DG output fluctuations and load level variations on the operating state of the distribution network under high-penetration DG integration, several representative typical operating scenarios were designed to reflect the influence of changes in system operating conditions on protection configuration under different scenarios.

5.1. Simulation Analysis of Protection Action Characteristics Under Different Scenarios

Considering the impacts of distributed generator output fluctuations and load variations on the operating state of distribution networks, three representative typical operating scenarios are selected to comprehensively evaluate the adaptability of the proposed protection scheme under different operating conditions. These three scenarios differ in terms of DG output range and load capacity. Scenario 1 represents a conventional distribution network, with a low load level of 5 MW and zero DG output. Scenario 2 corresponds to a high-load condition of 10 MW with relatively low DG output. Scenario 3 represents a lower load level of 8 MW with high DG output. The specific data are shown in Table 2.

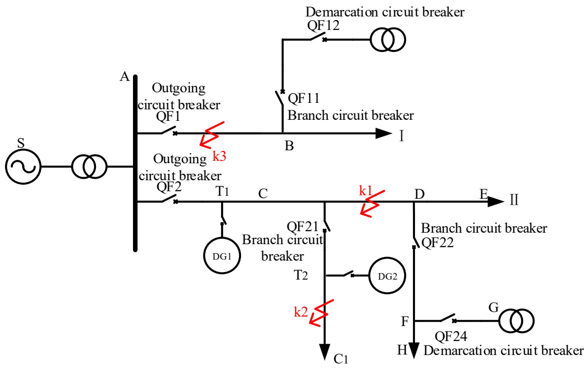

Figure 6. Including DG access 10kV simulation model

Table 2. Set running parameters in different scenarios

Scenario	DG1 Output Range	DG2 Output Range	Total Line Load Capacity/MW
1	0%	0%	5
2	0%~30%	50%~90%	10
3	70%~80%	90%~100%	8

In this paper, a three-phase short-circuit fault occurring at location k1 at 0.2 s and the normal operating conditions under different scenarios are taken as examples. The operating characteristics of the outgoing protection QF2 and the branch protection QF21 are analyzed to demonstrate that the protection settings should be switched accordingly when the operating condition changes. The measured currents and operation status at the protection installation locations under different scenarios are shown in Table 3.

Table 3. Set running parameters in a different scenario

Fault Location	Protection Device	Stage Configuration	Proposed Method Setting/kA	Fault Measured Current /kA	Normal Operating Current /kA	Protection Operation Status
Scenario 1	QF2	Stage II	1.98	2.80	/	Failure to operate

	QF21	Stage III	0.11	/	0.093	/
Scenario 2	QF21	Stage III	0.23	/	0.13	/
Scenario 3	QF2	Stage II	1.39	1.93	/	Maloperation

The fault current waveforms measured by protection QF2 under Scenario 1 and Scenario 3 for a fault at location k1 are compared in Figure 7. The load current waveforms measured by protection QF21 during normal operation under Scenario 1 and Scenario 2 are shown in Figure 8.

As shown in Figure 7, when a fault occurs at the same location under different operating scenarios, the fault currents measured by protection QF2 differ significantly. Assume that the distribution network is initially operating under Scenario 1. When the DG output undergoes a significant increase, the system operating condition shifts to Scenario 3. According to the setting method proposed in this paper, and taking into account the outfeed effect of DGs, the fault current decreases to 1.93 kA, which is already lower than the Stage II setting of protection QF2 under Scenario 1, i.e., 1.98 kA. If the protection device continues to use the original setting without timely switching, QF2 will fail to respond correctly to the fault, i.e., failure to operate. After recalculation using the setting method proposed in Section 3.2.1, which accounts for the influence of DG output, the protection setting corresponding to Scenario 3 is adjusted to 1.39 kA. Once the setting update is completed, the protection can operate reliably, and the sensitivity factor satisfies the requirement of being greater than 1.3.

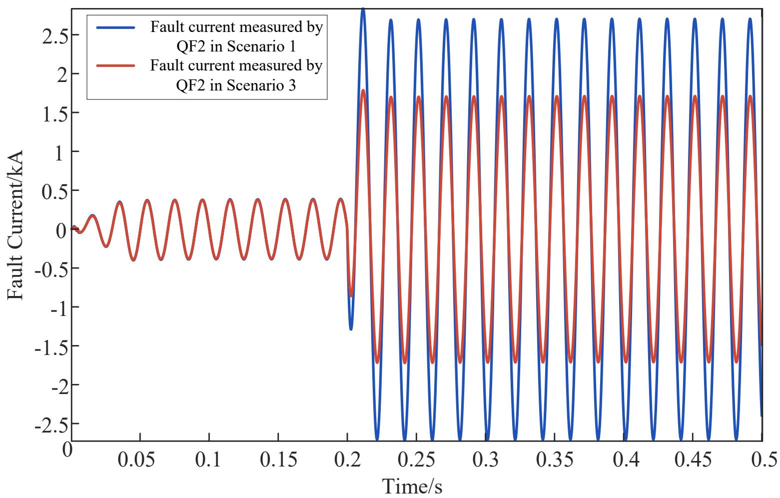

Figure 7. Fault current measured by protection QF2 for a fault at location k1 in Scenario 1 and Scenario 3

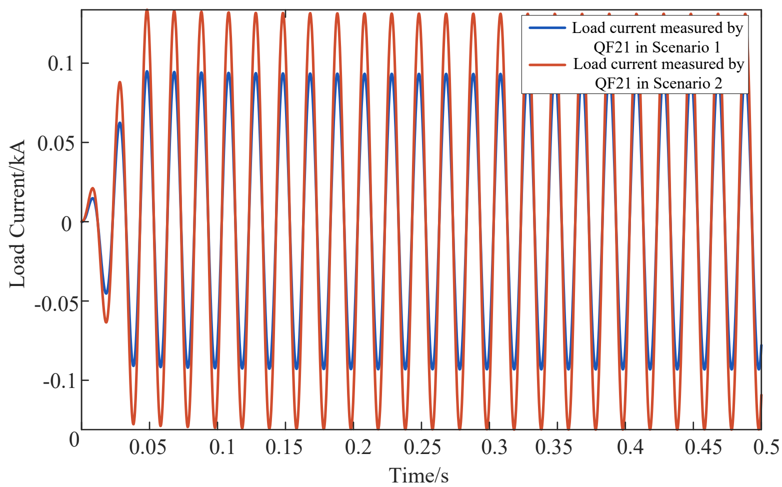

Figure 8. Load current measured by protection QF21 during normal operation in Scenario 1 and Scenario 2

Similarly, as shown in Figure 8, the load currents measured in Scenario 1 and Scenario 2 also differ, which may lead to a decrease in protection sensitivity. When the load level of the distribution network increases substantially from 5 MW in Scenario 1 to 10 MW in Scenario 2, the load current under normal operating conditions in Scenario 2 already exceeds the Stage III setting of 0.11 kA corresponding to Scenario 1. Under such circumstances, if the original scenario setting is still used without updating, protection QF21 will fail to operate.

5.2. Comparative Analysis with Existing Protection Methods

This paper further compares the conventional staged overcurrent protection scheme with the proposed method under Scenario 3 for short-circuit faults occurring at different locations. The protection settings adopted by the conventional staged overcurrent protection scheme in practical engineering are listed in Table 4. The electrical measurements at each protection installation point, together with the corresponding protection operating results, are presented in Table 5.

Table 4. Current setting values of stage-type current protection in existing distribution networks

Scenario	Protection Device	Zone I Setting	Protection Setting /kA Zone II Setting	Zone III Setting
1	Main Feeder QF2	8	3	1.2
	Lateral QF21	\	2.7	0.4

Table 5. Protection action conditions when phase-to-phase short-circuit faults occur at different locations in operating Scenario 3

Scenario	Fault Type	Fault Location	Protection Device	Zone Setting	Existing Setting /kA	Proposed Setting/kA	Measured Current/kA
K1	QF2	II III	3 1.2	1.39 0.93	1.93	×	√
	QF21	II III	2.7 0.4	1.28 0.16	/	—	—
K2	QF2	II III	3 1.2	1.39 0.93	1.52	■	■
	QF21	II III	2.7 0.4	1.28 0.16	1.92	×	√

Note: √ indicates that the operation conditions are met and correct tripping occurs; ■ denotes the setting value is reached but the operation time criterion is not satisfied, resulting in no operation; — represents breakers not involved in the fault scenario; × signifies protection failure to operate.

The results presented in Table 3 indicate that, under conditions of large DG output fluctuations, when two-phase short-circuit faults occur at different locations in the system, both QF2 and QF21 in the original protection scheme exhibit unreliable operation of Section II protection. This demonstrates that the conventional fixed-setting configuration of staged overcurrent protection has limited adaptability to multi-scenario operating conditions and is therefore unable to satisfy the protection requirements of distribution networks with high DG penetration. In contrast, the scenario-adaptive setting switching method proposed in this paper can dynamically adjust protection parameters according to changes in operating conditions, thereby effectively mitigating the problems of protection failure to operate and incorrect operation that are likely to arise under wide-range DG output variations and large load fluctuations.

6. Conclusion

To address the difficulty of adapting conventional overcurrent protection settings to multiple operating scenarios under high-penetration distributed generator integration, this paper proposes an adaptive protection method based on operating scenario classification and online setting switching. By comprehensively considering variations in DG output levels and load conditions, the operating states of the distribution network are classified into several typical steady-state scenarios, and the corresponding protection settings for each scenario are determined offline, thereby alleviating the protection miscoordination problem encountered by conventional fixed-setting methods under multiple operating modes. Furthermore, by incorporating state awareness techniques to acquire DG output and load information in real time, operating scenario identification and protection setting switching are achieved through a hierarchical time-window scheme and threshold-based criteria. The proposed method is validated using overcurrent protection under two-phase short-circuit faults as an example. The results show that the proposed method can effectively reduce the risks of protection failure to operate and incorrect operation under conditions of high DG output and significant load variation, thereby improving the correctness and reliability of protection operation. These findings demonstrate that the proposed method can effectively meet the practical requirements of distribution network protection configuration under high-penetration DG integration.

This study mainly focuses on overcurrent protection and verifies the feasibility of the proposed method. The same fundamental idea of scenario classification and adaptive setting can also be extended to other protection types and fault conditions. Future work may further investigate scenario clustering based on actual operating data and integrate online topology identification and edge computing technologies to further enhance the engineering applicability of the proposed adaptive protection method.

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Author Contribution

Conceptualization, Dongfang Wang and Xudong Ouyang; methodology, Xudong Song; software, Xudong Song; validation, Dongfang Wang, Xudong Ouyang and Xudong Song; formal analysis, Dongfang Wang; in-vestigation, Xudong Ouyang; resources, Yongjun Liu; data curation, Shuiyuan Liu; writing-original draft preparation, Yanpeng Feng; writing-review and editing, Dongfang Wang , Xudong Ouyang, Xudong Song, Yongjun Liu, Shuiyuan Liu, Yanpeng Feng, Yangyang Dai; visualization, Yongjun Liu, Shuiyuan Liu, Yanpeng Feng, Yangyang Dai; supervision, Dongfang Wang; project administration, Xudong Ouyang and Xudong Song; funding acquisition, Xudong Song. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data used to support the findings of this study are included within the article.

Ethics Statement

Not applicable.

Conflict of interest statement

The authors have no relevant financial or non-financial interests to disclose.

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