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Review of Adaptive Setting Strategies for Transformer Differential Protection Aimed at Inverter Fault Ride-Through Control

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Abstract. In inverter-interfaced distributed generation (IIDG) systems equipped with fault ride-through (FRT) capability, this paper investigates adaptive protection-setting methods for transformer differential schemes. Due to FRT-induced changes in short-circuit currents, traditional differential protection relying on Kirchhoff's law and vector sum comparison suffers from reduced sensitivity, harmonic interference, and maloperation risks. Therefore, the paper presents the evolution of the field, contrasts in methodologies, and major technical approaches. Additionally, it examines influential research, with particular attention to wind, solar, and integrated microgrid scenarios. The results reveal that the differential protection technology has gone through three stages of development: traditional fixed settings, FRT adaptive adjustment, and intelligent adaptive collaborative control. This progress has driven the selection of methods, strategies, and system architectures, including trade-offs between centralized and decentralized control systems and adjustments in the level of automation in protection schemes. As a result, key technologies for achieving reliable protection include fault modeling, detection algorithms, and adaptive optimization.

Keywords: Transformer Differential Protection, Fault Ride-Through (FRT), Adaptive Setting, Inverter-Interfaced Distributed Generation (IIDG), Microgrid Protection

1. Introduction

The shift of global energy systems to low-carbon operation increasingly relies on the large-scale integration of wind, photovoltaic, and other inverter-interfaced distributed generation (IIDG). At the same time, mandatory fault ride-through (FRT) control ensures grid continuity during disturbances, yet it also modifies short-circuit currents formerly controlled by synchronous generators. As a result, fault currents decrease, transients become more complex, and system operation depends more on control. In high-IIDG environments, traditional differential protection loses sensitivity and is prone to harmonics and faults from distorted currents, making adaptive settings necessary. Recent studies have advanced FRT and differential protection for IIDG systems, addressing key challenges in stability, fault response, and adaptive control [1-3]. These works collectively highlight the need for methods that accommodate variable short-circuit currents, harmonic interference, and dynamic grid

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conditions. Traditional controls are not robust enough, highlighting the need for protection schemes that account for system inertia to prevent frequency collapse under varying loads and disturbances. Besides, rapid isolation methods require validation considering communication delays and inverter limitations. But existing approaches, including unified adaptive frameworks, model-data fusion, and cross-scenario trade-offs, remain insufficient because they poorly handle inverter dynamics and their interaction with conventional grid components. This paper reviews adaptive setting strategies for transformer differential protection under inverter FRT control, tracing the evolution from fixed to intelligent adaptive methods. In this context, it examines three strategic contrasts: model-driven versus data-driven, protection versus system stability priorities, and centralized versus distributed architectures. Besides, it highlights key engineering implementation pathways and potential future development directions.

2. Evolution of differential protection technology under inverter FRT conditions

2.1. Traditional differential protection stage

Transformer differential protection operates based on Kirchhoff's current law, detecting faults by comparing the vector sum of currents on both sides of the transformer. Key tasks include calculating short-circuit currents, compensating for current transformer ratio errors, and distinguishing inrush currents. The restraint coefficient, typically between 0.2 and 0.75, mitigates maloperations caused by external faults and transient unbalanced currents. The power-frequency differential protection method, formulated in the current complex plane, leverages its geometric properties to separate the magnitude and phase of fault currents while incorporating the restraint coefficient. Its evaluation criterion is as follows:

$$|\mathrm{I_R}+\mathrm{I_S}|>\mathrm{k}|\mathrm{I_R}-\mathrm{I_S}| \tag{1}$$

For scenarios involving distributed wind power integration, the minimum composite branch coefficient for each operating mode is derived using sequence network analysis and applied to the relevant distance protection section. The composite branch coefficient is given by [4]:

$$k_b = \frac{\frac{1}{k_{f(1)}}+\frac{1}{k_{f(2)}}+1+3k_{AC}}{\frac{1}{k_{b(1)}k_{f(1)}}+\frac{1}{k_{b(2)}k_{f(2)}}+\frac{1+3k_{AB}}{k_{b(0)}}} \tag{2}$$

This method also includes collector lines, transformer parameters, and turbine current limits. Node voltages are calculated using the voltage iteration method, followed by a Norton equivalent correction, ensuring accurate short-circuit current computation and providing both steady-state and transient current data essential for defining differential protection settings [5].

2.2. Inverter grid connection and FRT stage

Large-scale integration of inverter-interfaced sources, such as photovoltaic and wind power, has altered short-circuit currents that were previously dominated by synchronous generators. As a result, fault currents now have lower magnitudes and decay more rapidly, and inverter control strategies strongly affect these currents. Accordingly, grid codes require inverters to provide fault ride-through (FRT) capability. During faults, inverters must remain online and inject reactive current to support voltage, tightly linking protection and control. Accordingly, this stage evaluates the effects of active

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current limiting, negative-sequence suppression, and fault harmonics on transformer differential protection. In particular, renewable hybrid microgrids employ DFIG wind turbines to coordinate demagnetizing current and virtual damping flux through rotor- and grid-side converters. External devices such as crowbar circuits, STATCOM, and energy storage further enhance FRT capability. Photovoltaic inverter controls also support low-voltage ride-through [1]. Meanwhile, single-phase PV grid-tied PWM inverters adopt an improved selective harmonic elimination (SHE) technique, solving switching angles offline and storing them in a segmented hybrid linear model. This reduces voltage total harmonic distortion (THD) and allows smaller L-C filters [6].

Based on these developments, differential protection for offshore wind DC converters is assessed using the sequence-component sensitivity formula:

$$K_s = \frac{4|1+qe^{j\theta}|}{1+q+4a} \tag{3}$$

Under asymmetrical faults, negative-sequence suppression, valve instantaneous blocking, and odd-order harmonics from current limiting reduce short-circuit currents, affecting both differential and restraint currents. Thus, conventional differential protection experiences reduced sensitivity and reliability [2].

2.3. Intelligent adaptive and cooperative control stage

High integration of inverter-based sources with FRT control has altered the magnitude and transient behavior of short-circuit currents. The correlation between protection settings, operating modes, and control strategies has become markedly stronger. Traditional fixed settings can no longer adapt to dynamic changes in load, generation, and fault conditions, hence requiring more flexible protection strategies. In this context, adaptive online settings based on real-time measurements have become essential, alongside protection-control cooperative mechanisms that ensure system stability and reliability under dynamic conditions.

At the wide-area protection level, an adaptive current differential scheme using a multi-agent architecture enables dynamic division of primary and backup protection zones. Relay agents adopt multicast communication to compute differential criteria, and a predictive self-healing mechanism suppresses maloperations, enhancing adaptability under varying conditions [7].

At the power electronics control level, a dual-loop active current-limiting strategy for modular multilevel converters (MMC) reconstructs voltage and current loops to regulate bridge-arm output voltage. This approach rapidly suppresses fault currents and improves submodule capacitor voltage distribution [8].

At the microgrid application level, a resilient community microgrid framework was developed for high renewable penetration. This framework reviews operating strategies and performance metrics, and analyzes adaptive control mechanisms in islanded and grid-connected/disconnected hybrid modes, highlighting how these mechanisms enhance reliability and efficiency of energy distribution under varying conditions. Furthermore, it proposes an integrated modeling approach for planning and operation, which considers diverse operational scenarios and constraints to improve overall system efficiency and reliability [9].

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3. Strategic differences and performance trade-offs of adaptive setting strategies

3.1. Model-driven versus data-driven approaches

Under inverter FRT conditions, adaptive settings for transformer differential protection fall into two categories. The model-driven method largely relies on physical mechanism modeling, emphasizing accuracy and interpretability. In contrast, the data-driven approach adapts dynamically via real-time data learning. The two methods differ in accuracy, generalization, and engineering feasibility.

In the model-driven approach, the voltage iteration method is used, integrating D-PMSG current characteristics under current limiting, wind farm node voltage equations, and Norton equivalent correction. This process provides precise calculation of internal topology parameters [2]. In addition, the power-frequency differential protection method based on the current complex plane decouples fault current amplitude, phase, and restraint coefficient, thereby enabling quantitative calculation of protection boundaries and restraint selection [10]. And the data-driven approach utilizes variational mode decomposition (VMD), the Hilbert-Huang transform, and a discrete Teager energy operator to extract sensitive modes from DC current, which are input into a stacked autoencoder neural network for high-precision classification of PG, PP, LG, LL, and LLLG faults [11].

At the same time, the multi-agent adaptive wide-area current differential protection system uses an expert system to divide primary and backup protection zones dynamically. In this setup, relay agents collaboratively compute the differential criterion through multicast communication, and a predictive self-healing mechanism enhances adaptability. These features enable adaptive protection under dynamic operating conditions [7].

3.2. Protection priority versus system stability priority

In inverter FRT scenarios, transformer differential protection must balance protection priorities with system stability priorities. Specifically, protection priority ensures equipment safety through rapid tripping, while system stability priority allows inverters to sustain FRT and grid operation. These two approaches weigh equipment safety against overall grid stability differently, directly shaping protection settings and system restoration. Moreover, FRT requirements highlight fault ride-through priority and the critical role of reactive current injection for voltage support, which is essential to maintain system stability during disturbances and keep voltage levels within acceptable limits [4].

Moreover, studies on power electronics integration indicate that protection-control coordination should prioritize system inertia and stability, thereby avoiding frequency collapse caused by rapid disconnection [12]. From a cyber-physical security perspective, rapid isolation stops fault or attack propagation, protecting equipment and the system, thus applying protection priority strategies [13]. Moreover, the unified power quality conditioner (UPQC) uses series and parallel compensation, achieving equipment protection priority while sustaining continuous grid operation [14].

3.3. Centralized setting versus distributed autonomy

Under inverter FRT control conditions, adaptive settings for transformer differential protection uses two primary architectures, namely centralized settings and distributed autonomy. In the case of centralized settings, they rely on central monitoring and communication networks, enabling global parameter optimization and coordination. By contrast, distributed autonomy employs local electrical measurements and intelligent agents to perform real-time adaptive decision-making.

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These architectures exhibit clear trade-offs in applicable scenarios, communication requirements, and system reliability. For instance, a multi-agent adaptive wide-area current differential protection system applies an expert system for dynamic division of primary and backup zones. Relay agents collaboratively compute differential criteria via a multicast protocol, and a predictive self-healing mechanism boosts adaptability, realizing distributed autonomy [6, 7]. Meanwhile, in multi-inverter grid-connected systems, centralized reliability assessment calculates indices such as SAIFI and SAIDI using ETAP software, providing a reference for network-wide protection planning [15]. Additionally, a local fault analysis method combines change detection filters with decision trees to achieve autonomous, fast detection and classification of differential and average current [16].

4. Implementation methods and technical pathways of adaptive setting strategies

4.1. Short-circuit current and fault modeling

Inverter grid-connected systems demonstrate complex short-circuit current characteristics, which demand precise modeling for transformer differential protection settings. To address this, physical modeling methods rely on electromagnetic transient simulation, power flow calculation, voltage iteration with inverters, and traveling wave analysis. These methods accurately characterize IIDG current-limiting behavior, internal topology structures, and asymmetrical fault responses, thereby providing the necessary electrical quantity foundation for adaptive protection.

In direct-drive wind farms, the voltage-iteration short-circuit method integrates D-PMSG current-limiting behavior with Norton equivalent corrections of node voltage equations, producing precise internal topology parameters [3]. For HVDC lines, the VS-DDTW traveling wave distance method employs variable-step derivative dynamic time warping to align heteronymous traveling waves, allowing rapid distinction between internal and external faults [17]. Besides, in distribution networks with IIDG, the asymmetrical fault short-circuit model uses the symmetrical component method, analyzing the impact of grounding resistance on fault quantities and proposing a suitable resistance selection scheme [3].

4.2. Fault detection and discrimination algorithms

High-proportion integration of inverter-interfaced power sources alters traditional overcurrent and differential protection. These protections are now more likely to malfunction due to current-limiting control and harmonic interference. Consequently, extracting features from electrical quantities is crucial to separate faults from inverter transients or harmonics. Key techniques include variational mode decomposition, change detection filters, and combining traveling-wave time-domain features with machine learning classifiers, enabling adaptive protection settings.

In DC microgrid applications, the fault detection scheme applies variational mode decomposition to break down the derivative of the differential current into intrinsic mode functions. Then, the Hilbert-Huang transform then extracts instantaneous amplitude and frequency, while sensitive modes are selected using a weighted kurtosis index. Discrete Teager energy is incorporated to enable rapid identification of PG, PP, LG, LL, and LLLG faults [11]. The change detection filter processes average and differential current components, identifies change points, extracts half-cycle features, and feeds them into a decision tree classifier, achieving fast discrimination between internal and external faults on HVDC lines [16]. Meanwhile, the improved selective harmonic elimination PWM technique stores switching angles in a segmented hybrid linear model, effectively reducing voltage THD and providing clean signals for feature extraction [6].

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4.3. Adaptive setting and optimization strategies

Transformer differential protection can be adjusted online under inverter FRT control using adaptive setting and optimization methods. In this process, global optimization algorithms, adaptive control rules, and intelligent agent collaboration coordinate protection parameters with inverter control in real time, enhancing overall system robustness.

In practices, dual-loop active current-limiting control based on energy difference reconstructs the bridge-arm voltage reference, achieving dual-variable regulation during MMC DC faults [8]. At the same time, the multi-agent adaptive wide-area current differential protection system dynamically divides primary and backup protection zones through an expert system. Relay agents use multicast communication to perform predictive self-healing, allowing real-time adjustments and improving protection reliability during faults [7]. For multi-inverter grid-connected systems, ETAP software evaluates reliability and optimizes layout, boosting indices like SAIFI and SAIDI [15]. Besides, the resilient community microgrid framework integrates adaptive operation strategies and performance metrics, providing systematic support for protection settings [9].

4.4. Modeling methods and field validation

In adaptive strategies for transformer differential protection under inverter FRT control, modeling and field validation form the complete bridge from theoretical analysis to engineering application. Validation techniques include electromagnetic transient simulation, hardware-in-the-loop testing, and on-site short-circuit tests, which assess protection performance under complex transients and real operating conditions.

For instance, the 220 kV offshore wind power flexible DC demonstration project used the RTDS real-time simulation system to evaluate internal and external fault scenarios. This demonstrated the adaptability of converter transformer differential protection under wind turbine full-load and outage, negative-sequence suppression, and instantaneous blocking [2]. Meanwhile, under FRT conditions, multiple simulation methods for DFIG, photovoltaic, and hybrid microgrid strategies were systematically reviewed. These methods encompassed both electromagnetic transient (EMT) and digital simulations, alongside discussions of protection performance metrics against national grid codes [1]. In addition, for grounding resistance selection in distribution networks with IIDG, digital simulations using symmetrical component modeling and fault analysis verified feasibility [3].

5. Conclusion

This paper examines adaptive setting strategies for transformer differential protection under inverter FRT control. It reviews technological evolution, strategic differences, and method pathways. These elements establish a cognitive framework for the field. The results show that development in this area is driven by policy guidance, high-proportion IIDG integration, and the need for grid security and stability. Progress has unfolded through three stages: traditional differential protection, the impact of inverter FRT, and intelligent adaptive cooperative control. Three major insights have emerged, including two academic schools (model-driven and data-driven), the trade-off between protection priority and system stability, and the architectural split between centralized settings and distributed autonomy. In addition, four key technical pathways are identified, providing theoretical support for upgrading and adapting transformer main protection in modern power systems.

However, this review mainly addresses core results from mainstream grid-connection scenarios, such as wind and photovoltaic systems, while coverage of niche or unusual connection types

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remains limited. In addition, field-measured validation is not comprehensive, and some practical cases do not fully capture protection performance under complex operating conditions, including AC-DC hybrid microgrids and combined photovoltaic-storage systems. Future research should target specific scenarios, including AC-DC hybrid microgrids and combined photovoltaic-storage systems, to expand literature coverage. It should also advance the integration of model-driven and data-driven methods, enhancing the precision and adaptability of setting strategies. Meanwhile, engineering validation of protection-control cooperative strategies must be strengthened to ensure effectiveness and reliability in real-world applications, and full-condition field tests will help refine the practical evaluation system.

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