IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 4, Issue 2, December 2024
Impact Factor: 7.57

Design of Reliable Protection Schemes for Converter-Dominated Grids: A Review

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Abstract*: The growing presence of converter interfacing with generation resources, such as renewable energy systems, and HVDC transmission is greatly changing what we view as "the grid" today. Converter interfacing in a traditional sense means that the way faults behave on the system has changed and so have the ways in which fault currents interact with the protection systems of the system. Synchronous generators are being replaced by converters and thus traditional protection methods that were developed for synchronous generators are no longer sufficient to protect the grid. This comprehensive review paper examines both the challenges associated with developing reliable protection methods in converter interfaced systems and identifies state of the art solutions. It describes the different types of faults that occur in converter interfaced systems, discusses some of the issues with existing protection methods, presents examples of new or emerging protection technology, and provides an overview of future areas of study and potential standards development needed to support the rapidly evolving nature of our electric grid*

Keywords: Converter-dominated grid, protection schemes, inverter-based resources, fault current characteristics, adaptive protection, renewable energy integration, grid-forming converters

I. INTRODUCTION

Modern power grids are undergoing a fundamental shift due to the influence of environmental policies and technological innovation which is leading to an increased focus on the integration of renewable sources into the power generation mix. In particular, the rapid deployment of inverter based renewable energy sources such as solar and wind, battery energy storage systems, and high voltage direct current (HVDC) transmission links is transforming the electrical properties of power grids from traditional synchronous generator dominated systems to converter dominated systems. This conversion of the electrical properties of power grids fundamentally changes the electrical characteristics of faults occurring within them and thus creates new challenges for designing protection systems for these faults. Protection systems that have been developed and refined over the past few decades were specifically designed to address faults in systems containing synchronous generators. These systems were developed based upon a number of assumptions concerning fault currents, their magnitudes and directions, as well as the impedance characteristics between the fault location and the protection system's measurement points. These assumptions will not apply in converter dominated systems [3]. In addition to displacing synchronous machines that provide both inertia and fault current contribution to the power grid, the use of converter technology has introduced the possibility of fault response that can be controlled through the application of control strategies to each converter in the system. Each converter can also respond differently depending on its topology and the grid codes being enforced [4]. Studies conducted around the world have shown that there are many areas with instantaneous penetration levels of inverter based renewables approaching or exceeding 70% of total generation. This level of penetration fundamentally changes how grids behave and what protection systems need to do to maintain reliability. There are numerous examples of this trend; in the United States for example, states such as Hawaii and Texas, as well as portions of Europe have reached levels of inverter based renewable penetration at which traditional protection schemes developed for synchronous generator dominated systems may no longer be

DOI: 10.48175/IJARSCT-22800C

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adequate for protecting these future renewable power systems [6]. Therefore, a thorough review of protection philosophies and development of new protection methods that can ensure reliable operation in emerging converter dominated systems is required. The protection systems will have to adapt to lower fault current levels, bidirectional power flow, nonstandard fault signatures, and the potential for protection blindness or false tripping [7]. Additionally, the heterogeneity of the control systems used in different types of inverter based renewable energy sources further complicates the issue of protection coordination and standardization [8].

The objective of this review paper is to identify the protection challenges and solutions associated with converter dominated power grids and provide a synthesis of recent research and practical experience. The paper first identifies and characterizes fault behaviors in converter dominated systems, then identifies the protection challenges associated with those fault behaviors. Next, it discusses the limitations of traditional protection schemes and introduces a number of emerging protection technologies including adaptive protection, wide area protection systems, and machine learning based protection schemes. Finally, the paper identifies the research gaps and future directions for ensuring reliable protection in power grids during the on-going energy transition.

II. FAULT CHARACTERISTICS IN CONVERTER-DOMINATED GRIDS

Understanding fault characteristics in converter-dominated grids is fundamental to designing effective protection schemes. Unlike synchronous generators that provide fault currents determined primarily by electromagnetic transients and machine impedances, converter-interfaced sources exhibit fault responses governed by semiconductor device ratings, control algorithms, and grid code requirements [9].

A. Converter Fault Current Contribution

Converters interfaced to a power system differ from synchronous generators in their fault current contribution. Synchronous generators inherently contribute fault current up to five to ten times their nominal current in the initial sub-transient time frame until they decay to lower values while the fault continues. The behavior of synchronous generators is due to the electromagnetic interaction of the rotor and stator; the magnitude of the fault current is dependent upon the time constants and reactance's of the machine. Converters interfacing to a power system through power electronics are restricted by the ratings of semiconductor devices which normally restricts the fault current contributed to be between one point two and two times the rated current to prevent the failure of the semiconductor device. Current limiting strategies activated by fault detectors operating in microseconds to milliseconds are typical for grid following converters used in renewable energy applications [12]. Current limiting strategies can include the use of several techniques such as instantaneous current clamping, voltage dependent current reduction, or converter blocking dependent on the type of fault detected and the design of the control strategy [13]. The IEEE Standard 2800-2022 requires fault current contributions from IBRs in transmission systems and specifies a minimum amount of reactive current to be injected into the grid during voltage sags to assist in the restoration of grid voltage [14][15]. The requirements specified in this standard are primarily based on balanced faults and positive sequence reactive current support, thus providing much flexibility in the fault current contribution from converters in response to unbalanced faults. Therefore, the fault current contribution from IBRs has a wide range of variability dependent upon the converter technology, the control strategy implementation, and the compliance strategies with grid codes utilized by each converter manufacturer [16]. Grid forming converters are an emerging technology capable of producing voltage sources that are similar to those produced by synchronous generators and could potentially offer better fault current contribution than grid following converters [17]. The North America Electric Reliability Corporation (NERC) and Electric Reliability Council of Texas (ERCOT) have published standards for the control of grid forming inverters specifically referencing their importance for battery energy storage systems in areas dominated by inverter-based resources [18]. Various grid forming control strategies, including but not limited to droop control, virtual synchronous machine control, and matching control have been proposed and implemented [19]. Although grid forming converters can produce fault current with controlled magnitude and phase angle, the practical realization of grid forming inverters also face the same semiconductor device limitations as other inverter technologies, therefore fault current management must be carefully managed to prevent damage to the inverter [20] [21].

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B. CURRENT LIMITING STRATEGIES AND THEIR IMPACT

The impact of the application of current limiting technology on the performance of protection systems in grid forming inverters is substantial. The research into current limiting methodologies has identified two primary classifications of current limiting as; direct current limitation techniques and indirect current limitation techniques. Each type of current limiting methodology presents different protection system limitations and challenges regarding fault detection and the coordination of protective relaying operations [22]. In general, a direct current limitation technique will provide a mechanism to limit the maximum output current from an inverter to a predetermined level by either modifying the PWM signal generation process or directly modifying the current at the output terminals of the inverter. On the other hand, an indirect current limitation technique modifies the reference signals used to determine the output current from an inverter to limit the output current indirectly. More recent research has provided the development of hybrid current limiting technologies that utilize combinations of direct and/or indirect current limiting methodologies to optimize both transient stability and compatibility with protective devices [24]. Research studies indicate that the choice of current limiting strategy is directly related to the determination of the critical clearing angle, which is critical for determining transient stability when faults occur in the system [25]. For example, using inductive virtual impedance-based limiters to limit the output current can improve the critical clearing angles, thus improving the transient stability against faults, while the use of capacitive virtual impedance-based limiters may decrease the critical clearing angles and subsequently reduce the stability margins [26]. The time-varying nature of the operation of current limiters also creates difficulties for protection algorithms that rely on steady-state assumptions of the fault currents. For example, during severe faults, current-reference limiters are generally the fastest acting current limiting methodologies and typically dominate the fault current limiting operation during the first few cycles of the fault, thus limiting the fault current to the predetermined maximum allowable limits, while virtual impedance limiters may become active during later phases of the fault and therefore introduce transients to the fault current that can create interference issues with conventional protection algorithms that rely on steady state assumptions of the fault current.

C. FAULT CURRENT WAVEFORM CHARACTERISTICS

Compared to fault currents generated by synchronous generators, the fault current waveforms of converter-interfaced power sources are distinctly different. While synchronous generator fault currents typically consist of well-defined sub-transient, transient and steady-state components (with predictable time constants and decay characteristics), and therefore resemble sinusoids with primary frequency predominance and minimal harmonic content [28], fault currents from converter-interfaced power sources can display varying degrees of waveform distortion based upon the converter configuration, modulation technique and control system response [29]. Converter control systems will typically shift between different operating regimes in response to fault conditions resulting in transient responses that may include discontinuity, higher order harmonics and inter-harmonics. Studies have identified typical fault current characteristics for IBRs including; sustained fault current magnitudes which are generally low because of the current limitation imposed by the inverter, transient responses ranging from approximately half cycle to 1 and 1/2 cycles duration prior to being limited by allowable inverter limits, and control determined angular relationships between voltage and current during faults [30]. Experimental studies and field measurements have demonstrated considerable variability in converter fault current waveforms among various manufacturers and technologies [31]. Some converter fault currents appear to be very clean and sinusoidal in nature (via advanced control techniques) while other converter fault currents exhibit significant amounts of harmonic distortion, asymmetry and/or intermittent current injections into the faulted circuit during severe depression of the voltage levels at which the converters are attempting to operate [32]. Such variability creates challenges for fault detection and classification algorithms that depend on sinusoidal waveforms or specific harmonic content for fault identification and classification.

D. SEQUENCE COMPONENT BEHAVIOR

The main difference between synchronous generators and converter interfaced sources are fault response characteristics due to the nature of the source. Unbalanced faults result in different types of fault current produced by synchronous generators based on their machine and connecting network sequence impedances. The negative sequence impedance of

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synchronous machines is relatively low; therefore, during unbalanced faults, significant negative sequence current will flow in the source [33]. Sequence component behavior of converter interfaced sources are controlled by algorithms versus impedances. In addition, most grid following converters have separate control loops for positive and negative sequences to control the magnitude and phase angle of each sequence separately [34]. There are two typical control methods used in IBRs during faults: Coupled Sequence Control (CSC) and Decoupled Sequence Control (DSC) [35]. Under the CSC method, there is no direct regulation of the negative sequence current by the controller and, as such, there may not be any negative sequence current flow during an unbalanced fault. Conversely, under DSC, both positive and negative sequence currents can be individually controlled and independently regulated, which reduces the potential for protection system misoperation [36]. While IEEE 2800-2022 requires negative sequence current generation from IBRs connected to transmission level power systems, performing EMT studies are essential to understand how IBRs respond to faults [37]. Studies have demonstrated that even if negative sequence current is required by grid codes, the maximum amount of negative sequence current that can be injected into the grid is limited due to the vector sum of the load current (if present), positive sequence reactive current, and negative sequence reactive current cannot exceed the maximum allowable current of the inverter [38]. As an example, when an IBR is operating at its rated capacity prior to a fault, it is likely that at least one phase will reach its maximum allowable current (approximately 120% of its rated current), which in turn limits the amount of negative sequence current that can be injected into the grid during an unbalanced fault [39]. The behavior of zero sequence current adds additional complexity to converter dominated systems. The ability of converters to generate zero sequence current is dependent on the type of converter and the grounding configuration [40]. Three phase three wire converters that do not have a neutral connection cannot generate zero sequence current; however, four wire converters or delta wye transformer configurations may allow for zero sequence current flow. Additionally, many grid connected converters utilize zero sequence blocking filters to prevent circulating current flow and mitigate common mode electromagnetic interference. Therefore, ground fault detection systems that measure zero sequence current will likely experience decreased sensitivity or may fail altogether in converter dominated systems [41].

III. CHALLENGES FOR CONVENTIONAL PROTECTION SCHEMES

The altered fault characteristics in converter-dominated grids expose fundamental limitations of conventional protection schemes that have reliably served synchronous generator-dominated systems for decades. Understanding these challenges is essential for developing effective protection solutions for emerging grid structures [42].

A. Overcurrent Protection Challenges

The use of overcurrent protection is the most commonly used protection method throughout the world's power systems. Overcurrent protection is based upon the detection of a current level that exceeds predetermined limits to indicate the occurrence of a fault condition [43]. To ensure effective operation of overcurrent protection, the fault current must be large enough to distinguish faults from the highest possible load currents, and there should be a reasonable amount of current differential between normal operation and a fault condition. Fault current contributions from converter-based renewable energy sources (IBRs) have been shown to greatly reduce the ability to rely on overcurrent protection as a means of protecting the system against faults [44]. Since converter fault current is generally limited to roughly twice rated current, the difference between fault current and maximum load current will be small enough to provide inadequate discrimination between faults and normal operating conditions for many distribution systems with high load diversity. Blinding of protection equipment occurs when the fault current is too small to cause the protective equipment to trip at its set point, thus preventing fault identification and removal [45]. The addition of distributed IBRs into power systems will introduce bidirectional fault current flow to the system, which will violate all previous assumptions made for the traditional coordinated operation of protective devices, and will cause sympathetic tripping of healthy feeder lines, or prevent the isolation of faulty sections [46]. A number of studies have shown that conventional protection methods developed for systems with high short circuit levels and one directional current flow are ineffective for microgrid systems with a high percentage of their generation coming from inverter-based distributed generation [47]. Depending upon how the microgrid is being operated, the nature of faults observed by protective relays will vary,

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depending on whether they observe low levels of current, current that flows in the opposite direction, and/or increased frequency, and therefore conventional protection methods may operate improperly [48].

B. Distance Protection Challenges

Distance protection, which operates based on impedance measurement to determine fault location, faces substantial challenges in converter-dominated networks [49]. Traditional distance relays calculate apparent impedance using voltage and current measurements, comparing the result against predefined zone characteristics to determine whether a fault is within the protected zone [50]. The low-magnitude and control-dependent nature of IBR fault currents can cause distance relay under reach or overreach [51]. Under reach occurs when the measured impedance appears larger than the actual fault impedance, potentially causing the relay to fail to trip for faults within its protection zone. Conversely, overreach happens when measured impedance appears smaller than actual, potentially causing tripping for faults outside the intended protection zone [52]. Recent research has proposed adaptive K-factor control schemes for IBRs to enhance distance relay operation during all fault types [53]. In these schemes, based on the fault type detected, the K-factor and thus the IBR current references are adjusted so that the apparent reactance measured by the distance relay's corresponding element equals the actual line replica reactance. Such methods aim to fulfill all fault ride-through requirements of IEEE Standard 2800-2022 and applicable grid codes while maintaining proper protection operation [54]. The phase angle relationship between fault current and voltage in IBR-dominated systems differs significantly from conventional systems, further complicating distance protection [55]. During balanced voltage sags, grid codes typically mandate predominantly reactive current injection to support voltage recovery, resulting in fault current nearly perpendicular to pre-fault current. This controlled phase relationship can cause measured impedance to deviate substantially from the actual fault impedance, potentially leading to protection misoperations [56].

C. Directional Protection Challenges

Directional elements in protective relays determine the direction of power or current flow to provide selectivity in protection schemes [57]. These elements typically rely on voltage and current phase angle relationships or sequence component comparisons to establish fault direction. However, the control-determined phase relationships in IBR fault currents undermine the fundamental assumptions of directional elements [58]. Memory-polarized zero-sequence directional protective relay elements, commonly used for ground fault protection, face challenges due to the absence or limited magnitude of zero-sequence currents from IBRs [59]. The lack of zero-sequence current contribution from three-wire converters can prevent proper polarization of directional elements, leading to incorrect fault direction determination or complete failure to operate [60]. Negative-sequence-based directional protection also experiences difficulties in converter-dominated grids [61]. The variable and often minimal negative-sequence current contribution from IBRs during unbalanced faults can prevent reliable direction determination. Furthermore, the independent control of positive and negative-sequence components in modern IBR control systems means that traditional relationships between sequence components may not hold, potentially causing directional element misoperations [62]. Permissive overreaching transfer tripping (POTT) and directional comparison blocking (DCB) schemes, which rely on directional elements at both ends of a protected line, may experience reliability issues when one or both terminals are connected to IBR generation [63]. The reduced fault current and altered phase relationships can prevent proper coordination between the protection zones, potentially resulting in delayed tripping or failure to trip for faults within the protected zone.

D. Differential Protection Considerations

Line current differential protection, which compares currents at both ends of a protected zone, generally performs better in converter-dominated grids compared to impedance-based schemes because it does not rely on specific fault current magnitudes or phase relationships [64]. However, current differential protection requires communication channels between relay terminals and may still experience challenges related to current transformer (CT) saturation during transient conditions or synchronization errors in time-stamping of measurements [65]. The initial transient response of IBR fault currents, which can last between half to one and a half cycles before stabilization, may cause temporary differential current that could be misinterpreted as an internal fault [66]. Modern differential relays incorporate algorithms to distinguish between fault conditions and transient phenomena, but the unique transient characteristics of IBR fault currents may require adaptive thresholds or enhanced filtering techniques [67].

IV. ADAPTIVE PROTECTION SCHEMES

Adaptive protection represents a promising approach to address the challenges posed by converter-dominated grids by automatically adjusting protection settings based on system operating conditions, network topology, or generation dispatch [68]. The fundamental principle of adaptive protection is to maintain optimal protection performance across diverse operating scenarios by modifying protection parameters in real-time or near-real-time [69].

A. Setting Group Approaches

The simplest form of adaptive protection employs multiple predetermined setting groups that are selected based on system conditions [70]. Modern digital relays typically support multiple setting groups that can be activated through supervisory control and data acquisition (SCADA) commands, communication protocols, or local logic based on measured quantities [71]. For systems with IBR penetration, setting groups can be configured for different operating modes such as grid-connected operation with various levels of IBR output, islanded operation, or mixed operation with both synchronous generation and IBRs [72]. Research on microgrids has demonstrated adaptive overcurrent protection techniques where protection relay settings are updated to required trip values according to the state of the microgrid, accounting for changes in fault current contribution from distributed generators [73]. The challenge with setting group approaches lies in determining appropriate switching criteria and ensuring timely group selection without introducing protection security risks during transitional periods [74]. Furthermore, the number of possible system states in large interconnected networks with numerous IBR installations may exceed practical setting group capabilities, requiring more sophisticated adaptation mechanisms [75].

B. Real-Time Adaptive Algorithms

Advanced adaptive protection schemes employ real-time calculation of protection settings based on current system conditions [76]. These approaches utilize measurements from multiple locations, often facilitated by phasor measurement units (PMUs) or synchro phasor technology, to continuously update protection parameters [77]. For overcurrent protection in distribution systems with IBRs, adaptive algorithms can adjust pickup settings and time-current characteristics based on online assessment of available fault current at each protective device location [78]. Researchers have proposed adaptive protection schemes that combine current-based and voltage-based logic to enhance fault detection and relay response, addressing the impact of IBR momentary cessation modes on protection systems [79]. These schemes ensure rapid, accurate, and adaptive protection under diverse fault scenarios, thereby improving system reliability and operational resilience [80].

Distance protection can be adapted by modifying zone reach settings and characteristic angles based on real-time system impedance calculations that account for IBR fault current contributions [81]. Adaptive units based on weight calculation for online seen impedance have been developed to adjust trip characteristics of distance relays using local information, avoiding incorrect operation due to intermittent operation of wind farms [82].

C. Communication-Assisted Adaptive Protection

Wide-area measurement systems (WAMS) and communication infrastructure enable sophisticated adaptive protection schemes that leverage system-wide information [83]. These schemes can coordinate protection across multiple devices, adjust settings based on global system state, and implement backup protection strategies when primary protection may be compromised by IBR characteristics [84]. Pilot protection schemes that rely on communication between protective devices at different locations generally provide more robust performance in IBR-dominated systems compared to non-pilot schemes [85]. Phase comparison protection and line current differential protection, which compare quantities at both ends of protected elements through communication channels, maintain reliability even with reduced fault current magnitudes [86]. However, communication-assisted schemes introduce dependencies on communication system reliability, latency, and cybersecurity [87]. Protection systems must incorporate fallback modes or degraded operation

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ISSN: 2581-9429 Volume 4, Issue 2, December 2024 Impact Factor: 7.57

strategies for scenarios where communication is unavailable or compromised. The increasing prevalence of IEC 61850-based substation automation and communication protocols provides standardized frameworks for implementing communication-assisted adaptive protection, though challenges remain in ensuring interoperability across multi-vendor environments [88].

V. EMERGING PROTECTION TECHNOLOGIES

Beyond adaptive protection, several emerging technologies show promise for addressing protection challenges in converter-dominated grids. These technologies leverage advanced signal processing, pattern recognition, and data-driven approaches to overcome limitations of conventional protection principles [89].

A. Signal Processing-Based Protection

High-frequency transient-based protection methods utilize the unique frequency components present during fault initiation to detect and classify faults independently of fault current magnitude [90]. Traveling wave protection analyzes the propagation of electromagnetic waves initiated by fault events, providing extremely fast fault detection and accurate fault location without dependence on steady-state fault current characteristics [91]. These ultra-fast protection schemes operate on timescales less than the response time of IBR control systems, making them theoretically unaffected by control-induced fault current variations [92]. Wavelet transform-based methods extract transient signal features for fault detection in microgrids, requiring short time windows and therefore being less affected by inverter control system dynamics [93]. However, signal processing-based protection schemes require high-sampling-rate data acquisition systems and sophisticated processing algorithms [94]. They may also be sensitive to measurement noise, communication channel bandwidth limitations, and electromagnetic interference in substations. Practical implementation requires careful consideration of data acquisition infrastructure and computational resources available in protective relay platforms [95].

B. Machine Learning and Artificial Intelligence Applications

Machine learning techniques have emerged as powerful tools for power system protection, offering capabilities to handle the complexity and variability introduced by IBRs [96]. The application of ML in protection and disturbance management has grown substantially, with research addressing fault detection, classification, location, and protection coordination [97]. Artificial neural networks (ANNs) have been proposed for fault detection and classification in systems with high IBR penetration [98]. These networks can be trained on diverse fault scenarios encompassing various IBR operating conditions, control strategies, and system configurations, potentially providing robust fault identification that adapts to IBR characteristics [99]. Adaptive neuro-fuzzy inference systems (ANFIS) have been developed for detecting and classifying faults within wind farms and other IBR installations [100]. Support vector machines (SVMs) and decision tree-based algorithms offer alternative ML approaches for protection applications [101]. Two-level SVM classifiers have been utilized for accurate fault identification in microgrids, using root mean square (RMS) values of both voltage and current as input data [102]. Deep learning algorithms, particularly long short-term memory (LSTM) networks, can capture temporal patterns in protection-relevant signals without requiring extensive feature engineering [103]. Despite promising research results, several challenges hinder widespread deployment of ML-based protection schemes [104]. Training data requirements are substantial, necessitating comprehensive datasets that capture the full range of fault scenarios, IBR behaviors, and system conditions [105]. The black-box nature of many ML models raises concerns about explainability and trustworthiness in safety-critical protection applications [106]. Regulatory and standardization frameworks have not yet established clear guidelines for validation and deployment of ML-based protection systems [107]. Recent scoping reviews have identified that while ML models often demonstrate high accuracy on simulated datasets, their performance under real-world conditions remains insufficiently validated [108]. The existing literature is fragmented, with inconsistencies in methodological rigor, dataset quality, and evaluation metrics [109]. Bridging the gap between research demonstrations and field deployments requires addressing these validation challenges and developing industry-accepted testing procedures [110].

C. Hybrid Protection Approaches

Recognizing that no single protection technology provides complete solutions for all challenges in converter-dominated grids, hybrid approaches that combine multiple protection principles show considerable promise [111]. These schemes leverage the complementary strengths of different protection methods while compensating for individual weaknesses.

For example, combining traditional overcurrent protection with voltage-based protection can improve fault detection sensitivity in low-fault-current conditions [112]. When fault current magnitude is insufficient for reliable overcurrent detection, voltage magnitude and phase angle deviations can provide additional discrimination criteria. Adaptive schemes that combine current-based and voltage-based logic have been demonstrated to enhance fault detection and relay response under diverse fault scenarios in IBR-dominated distribution networks [113].

Multi-agent protection systems represent another hybrid approach, where autonomous intelligent agents coordinate protection decisions across distributed protective devices [114]. Each agent monitors local conditions and communicates with neighboring agents to achieve system-wide protection coordination. This decentralized architecture provides resilience to communication failures and computational scalability for large networks with numerous IBR installations [115].

The integration of synchronized measurement technology, such as PMUs, with conventional protection enables hybrid schemes that utilize both local measurements and wide-area information [116]. During normal conditions or minor disturbances, conventional protection based on local measurements provides fast primary protection. For complex fault scenarios or conditions where local protection may be compromised by IBR characteristics, wide-area backup protection utilizing synchronized measurements across multiple locations provides additional security [117].

VI. GRID CODE REQUIREMENTS AND STANDARDIZATION

The development of comprehensive grid code requirements and standardization efforts plays a crucial role in ensuring reliable protection in converter-dominated grids [118]. Grid codes establish technical requirements that IBRs must meet for grid connection, including fault ride-through (FRT) capabilities, voltage support during faults, and reactive power injection requirements [119].

A. Fault Ride-Through Requirements

IEEE Standard 2800-2022 establishes requirements for IBRs connected to transmission systems, specifying performance during voltage and frequency disturbances [120]. The standard mandates that IBRs remain connected during certain fault conditions and provide positive-sequence reactive current injection proportional to voltage deviation to support grid voltage recovery [121]. Specific requirements are defined for balanced three-phase faults, with additional considerations for unbalanced faults. The European Network Code for Requirements for Grid Connection of Generators (NC RfG) and similar international grid codes establish comparable FRT requirements, though specific technical parameters may differ across regions [122]. Coordination between different grid codes and regional requirements remains a challenge for IBR manufacturers serving global markets [123]. Grid-forming converter requirements are evolving rapidly as system operators recognize their importance for stability in high-IBR scenarios [124]. NERC's white paper on grid-forming functional specifications for battery energy storage systems provides detailed recommendations for GFM capabilities including frequency response, voltage control, fault current contribution, and black start capabilities [125]. ERCOT has been particularly active in developing GFM requirements, recognizing the critical role these resources will play in maintaining reliability as IBR penetration increases [126].

B. Protection-Oriented Requirements

While most grid codes focus primarily on FRT performance and voltage support, protection-oriented requirements specifically addressing protection system compatibility are emerging [127]. These include requirements for minimum and maximum fault current contribution levels, negative-sequence current injection during unbalanced faults, and coordination with protective relay settings [128]. The German grid code (VDE-AR-N 4120) has been noted for including relatively detailed technical requirements that support protection system operation [129]. However, challenges remain in balancing prescriptive requirements that ensure protection compatibility with flexible requirements that allow innovation in IBR control strategies [130]. Research and industry collaboration are advancing toward standardized IBR models for protection studies [131]. Generic models that capture essential fault current characteristics while abstracting manufacturer-specific control details enable protection engineers to conduct coordination studies without requiring detailed proprietary information. The development and validation of such models requires cooperation between IBR manufacturers, utilities, and standards development organizations [132].

C. Testing and Validation Requirements

Comprehensive testing and validation procedures are essential to verify that IBRs comply with grid code requirements and behave as expected during fault conditions [133]. Type testing, commissioning tests, and periodic verification tests establish conformity with technical specifications. However, testing IBR fault response presents unique challenges compared to conventional synchronous generator testing [134]. Many grid codes now require manufacturers to demonstrate FRT performance through laboratory testing or field measurements [135]. Testing protocols must account for the diversity of fault types, voltage depression levels, and system conditions that IBRs may encounter. Dynamic simulation models validated against test data provide essential tools for protection studies, but model accuracy depends on the fidelity of control system representation [136]. The gap between laboratory testing conditions and actual field performance remains a concern [137]. Real grid faults may involve voltage unbalance, harmonic distortion, frequency deviations, and other complexities not fully captured in standardized test procedures. Field experience and disturbance monitoring data are gradually improving understanding of IBR behavior during actual grid events, informing refinements to testing requirements and model validation procedures [138].

VII. CASE STUDIES AND FIELD EXPERIENCE

Analysis of actual field events and case studies provides valuable insights into protection performance in systems with significant IBR penetration, validating theoretical understanding and identifying practical challenges not always evident in simulation studies [139].

A. Field Event Analysis

Several documented field events have illustrated protection challenges in converter-dominated systems. One notable case involved a solar generation facility connected through a dedicated transmission line experiencing a phase-to-phase fault [140]. The relay waveforms captured during the event showed dissimilar fault current characteristics supplied by the integrated system with synchronous generators versus the solar facility with IBRs [141]. The synchronous sources provided expected high-magnitude short-circuit currents, while the solar facility's fault current was limited to approximately twice rated current with control-determined phase relationships [142]. In another case, the impact of IBR momentary cessation on distribution system protection was observed [143]. When IBRs temporarily cease generation during severe voltage depressions, the sudden loss of fault current contribution can affect protection coordination and potentially prevent proper fault clearing. This phenomenon highlights the importance of considering all possible IBR operating modes, including protective functions that may disconnect generation, when designing protection schemes [144]. Utility experiences in regions with high renewable penetration have documented instances of protection miscoordination attributable to variable IBR fault current contribution [145]. Distribution systems originally protected with time-current coordinated overcurrent devices have required comprehensive protection studies and setting revisions as distributed solar and wind generation capacity increased. Some utilities have implemented multiple protection setting groups or time-scheduled protection adaptations to maintain coordination across varying generation and load conditions [146].

B. Microgrid Protection Implementation

Microgrids with high IBR penetration provide controlled environments for testing and validating protection concepts applicable to larger converter-dominated systems [147]. Several demonstration projects and commercial microgrids have implemented novel protection approaches specifically designed for IBR-dominated operation [148]. A solar-plus-storage microgrid project implementing protection schemes for both grid-connected and islanded operation demonstrates practical considerations for IBR protection [149]. The protection architecture utilizes a combination of traditional time-overcurrent coordination for grid-tied operation and modified schemes compensating for limited fault current in islanded mode. Programmable automation controllers provide centralized protection coordination, communicating with distributed protective devices through standardized protocols [150]. The deployment of grid-forming battery energy storage systems in islanded microgrids has provided operational experience with GFM protection characteristics [151]. These systems must balance providing adequate fault current for protection operation with protecting converter hardware through current limiting. Field data indicates that well-designed GFM control can maintain stable fault current contribution for protection purposes while managing transient overloads through coordinated control actions [152].

VIII. FUTURE RESEARCH DIRECTIONS

Despite significant recent progress in understanding and addressing protection challenges in converter-dominated grids, substantial research gaps remain. Identifying and pursuing these research directions is essential for developing comprehensive protection solutions that will ensure grid reliability as IBR penetration continues increasing [153].

A. Standardization of IBR Fault Behavior

A critical need exists for greater standardization and consistency in IBR fault current characteristics across manufacturers and technologies [154]. While grid codes specify minimum performance requirements, significant variability remains in how different IBRs respond to faults, particularly for unbalanced fault conditions and transient behavior immediately following fault inception [155]. Research toward developing standardized control strategies that ensure predictable and protection-compatible fault responses while still allowing innovation in normal operating performance would benefit the industry [156]. This includes developing consensus on appropriate negative-sequence current injection strategies, current limiting approaches that balance converter protection with grid protection needs, and transient response characteristics during fault onset and clearing [157]. Enhanced collaboration between IBR manufacturers, protection equipment vendors, and system operators is needed to establish mutually acceptable fault behavior standards [158]. Industry working groups and standards development organizations provide forums for such collaboration, but achieving consensus requires balancing sometimes conflicting priorities of cost, performance, protection reliability, and design flexibility [159].

B. Advanced Protection Algorithms

Continued development of advanced protection algorithms specifically designed for converter-dominated grids represents a high-priority research area [160]. This includes refining adaptive protection techniques to handle rapid changes in system conditions, developing robust ML-based protection that can be validated for safety-critical deployment, and creating hybrid protection schemes that leverage complementary strengths of multiple approaches [161]. Research is needed to develop protection algorithms that explicitly account for IBR control system dynamics and their interaction with grid conditions [162]. Current protection algorithms often treat IBRs as static impedances or current sources, but more sophisticated representations that incorporate control system response could enable more accurate fault detection and classification [163]. Ultra-high-speed protection techniques operating faster than IBR control system response times show promise but require further development for practical deployment [164]. Traveling wave-based protection and high-frequency transient analysis methods need enhancement to handle noise, measurement accuracy limitations, and coordination with conventional protection for comprehensive fault coverage [165].

C. System-Level Protection Coordination

As IBR penetration increases, protection must be considered at the system level rather than as a collection of independent device settings [166]. Research into holistic protection coordination frameworks that simultaneously optimize protection across all devices in a network while accounting for IBR characteristics and operational variability is needed [167]. Wide-area protection and control systems that leverage communication infrastructure and synchronized measurements offer potential for adaptive system-level protection [168]. However, research must address communication reliability requirements, cybersecurity vulnerabilities, and degraded operation strategies for communication failures before widespread deployment can be realized [169]. The interaction between protection systems and IBR control systems requires deeper investigation [170]. Coordinated design of protection schemes and IBR control could potentially improve both protection reliability and overall system performance, but achieving such coordination in multi-vendor environments with proprietary control systems presents substantial challenges [171].

D. Validation and Testing Methodologies

Development of comprehensive validation and testing methodologies for protection systems in converter-dominated grids is essential [172]. This includes establishing standardized test scenarios, performance metrics, and acceptance criteria for evaluating protection scheme effectiveness across the range of operating conditions and fault types encountered in actual systems [173]. Hardware-in-the-loop (HIL) testing platforms that integrate actual protection relays with real-time simulation of converter-dominated power systems provide valuable validation tools [174]. Expanding HIL testing capabilities to encompass detailed IBR control system models, multi-manufacturer interoperability testing, and stressed system conditions would strengthen confidence in protection system performance before field deployment [175]. Field validation through controlled testing on actual power systems or comprehensive disturbance data analysis is crucial for verifying that protection performs as intended in real-world conditions [176]. Developing safe and effective procedures for field testing without compromising system reliability requires careful planning and coordination between system operators, protection engineers, and IBR operators [177].

E. Cybersecurity Considerations

As protection systems increasingly rely on digital communication, data analytics, and software-based algorithms, cybersecurity becomes a critical consideration [178]. Research into secure protection architectures that maintain reliability even under cyber-attack, anomaly detection methods that identify compromised protection data or control signals, and secure communication protocols for protection-critical information exchange is needed [179]. The use of ML-based protection introduces additional cybersecurity considerations, as adversarial attacks on ML models could potentially compromise protection decision-making [180]. Developing robust ML algorithms resistant to adversarial manipulation and establishing security validation requirements for AI-based protection systems represents an important research frontier [181].

IX. CONCLUSION

Converter-dominated grids represent a major paradigm shift in the history of power system, significantly changing many characteristics that protection systems have been relying on for decades. This paper presents a comprehensive overview of the challenges posed by the integration of IBRs into the existing conventional protection systems; and it reviews the last generation of solutions under development to mitigate those challenges. The limited fault currents (and dependent to the level of control) generated by IBRs make impossible the use of all the traditional protection methods based on the over-currents detection, impedance measurement and directional elements. Additionally, the variety of control schemes and the manufacturer-specific ways to manage faults during the operation of converters add complexity to the planning and coordination of protections. In fact, field experience shows that problems related to the protection of grids with high penetration of renewables are already present in the operational environment. Therefore, adaptive protection schemes capable of modifying their configuration depending on the environmental conditions seem to be a good solution to maintain the dependability of the protections in environments characterized by different levels of penetration of IBRs and operating modes. Although communication assisted protections with wide-area measurements have the potential of increasing the dependability of the protections thanks to the possibility of making decisions based on the analysis of information available from multiple locations; they also have the disadvantage of introducing new vulnerabilities due to the dependence on communication infrastructures. Additional tools for mitigating the protection challenges posed by IBRs can be provided by some emerging technologies such as advanced signal processing techniques, machine learning and hybrid protection schemes; however, before they can be used in practice, they need to be extensively validated. Standardization of the fault behaviors of IBRs, and therefore of their compatibility with protection systems, is progressing at the international level; although the establishment of common rules between various stakeholders with different objectives and the definition of valid tests to check the compliance with those rules are still active areas of study. The introduction of the requirement for grid-forming capability of converters is an important step toward the creation of IBRs able to provide more conventional fault current characteristics than other converters while preserving the benefits of using power electronic devices. In the future, research must continue to develop standardization of IBR fault behaviors, design of protection algorithms specifically targeted to converter-based systems, framework for coordinating the protections at the system level, valid test procedures for checking the compliance of protection systems with those standards and methodologies for protecting those systems against cyber threats. For the successful completion of the energy transition and, in particular, the integration of large quantities of renewable sources, it is essential that the collaborative effort between researchers, manufactures of equipment, system operators and developers of standards continues in the next decade. Ensuring the dependability of the protections in the converter dominated grids will be crucial both to maintain the dependability of the power system and to allow the integration of large quantities of renewable sources that are essential to fight climate change. As demonstrated by the recent progresses reported in this paper and the numerous technologies under development, the protection challenges posed by IBRs are real but solvable. Therefore, it will be essential to continue to invest time and money in this critical area to enable the accelerated transformation of the power systems expected in the next ten years.

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ISSN: 2581-9429 Volume 4, Issue 2, December 2024 Impact Factor: 7.57

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ISSN: 2581-9429 Volume 4, Issue 2, December 2024 Impact Factor: 7.57

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Volume 4, Issue 2, December 2024
Impact Factor: 7.57

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