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Comprehensive Evaluation of Protection Strategies in Power Systems with High Inverter-Based Resources Integration

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Abstract. Inverter-based resources pose significant challenges to power systems, including the lack of electromechanical inertia, the inherently limited fault current contribution of power electronic interfaces, the harmonic injection due to their inherent switched behaviour and the strong dependence on active control loops that define their steady-state and dynamic operation. This paper presents a structured and implementation-oriented contribution to protection strategies of converter-dominated power systems. It subsequently synthesises recent advances in converter-aware protection concepts, emphasising strategies that enhance fault detectability, selectivity and robustness. Key implementation constraints, interoperability issues and interactions with grid-code requirements are highlighted, pointing to the need for validated, scalable and standards-compliant solutions capable of supporting reliable protection in future power systems.

Key words. Control, Converter, Electrical Faults, Inverter-Based Resources, Protection.

1. Introduction

Modern power systems are undergoing profound structural changes driven by the progressive replacement of synchronous generators with Inverter-Based Resources (IBRs). This transition, largely associated with the large-scale integration of renewable energy sources, fundamentally alters system dynamics by reducing inertia and modifying fault and frequency response characteristics. As a result, the massive integration of IBRs introduces significant challenges in terms of stability, protection, and control coordination.

Protection systems face increasing challenges due to the limited and tightly controlled fault currents produced by power electronic converters, which weaken the performance of conventional schemes [1]. Traditional Intelligent Electronic Devices (IED) could rely on fast voltage, current or impedance changes to isolate faults within a few cycles, well before synchronous-machine controls reacted. Today, converter controls operate on similar timescales, removing this separation and reducing the effectiveness of established protection principles. As a result, converters are likely to play a more active role during disturbances, creating a research landscape in which protection strategies may need to adapt to faster electromagnetic transients, greater system complexity and the need for coordinated, adaptive and communication-enabled fault management.

The literature presents a broad range of conventional approaches, including overcurrent and directional schemes [2], distance protection [3-4], differential protection [5-6], as well as techniques based on current and impedance variations [7-8]. Adaptive protection updates its settings automatically but depends on detailed system knowledge and costly communication infrastructures [9-11]. Collectively, these methods offer valuable capabilities yet remain constrained by network variability, communication demands, and limited adaptability to evolving system conditions.

As a possible way forward, these challenges can be addressed by enabling converters to proactively support fault detection, thereby contributing and improving the overall reliability of protection systems. Recent studies have explored the shift of converters in IBR dominated power systems from a passive operating mode to a proactive one, leveraging their control capabilities to assist protection functions during fault conditions.

Although protection issues in IBR-rich power systems have been widely studied, existing literature surveys rarely incorporate methods based on converter–protection coordination. Among the very few papers that do, the scope is typically narrow and the evaluation seldom provide structured or implementation-oriented insights [1]. [12] analyzes the role of converter control and communication in enabling effective protection in IBR-dominated networks, but it does not address advanced coordination mechanisms. This paper addresses these gaps by offering a robust and coherent taxonomy that connects protection behaviour with converter control characteristics, practical measurement and computational requirements as well as the realities of multi-inverter operation. A dedicated overview table and a graphical abstract further distinguish this work by unifying key method features, test conditions and operational implications. The discussion results in a contextualised practice-oriented understanding of protection behaviour in IBR-dominated power systems.

The paper is structured in five sections, including this introduction. Section 2 details protection requirements in power systems with high presence of IBRs. Section 3 proposes a classification of protection approaches that rely on converter control complementing the relay protection performance. Section 4 includes the implementation challenges and forthcoming developments that must be addressed, highlighting their practical relevance in contemporary power systems. Finally, section 5 presents the conclusions.

2. Protection Requirements in IBR-Dominated Power Systems

The transition towards power systems with high IBR penetrations imposes new operational conditions that redefine protection requirements. These arise from the distinct behaviour of converters during disturbances and from evolving regulatory obligations that set their required response.

A. Coordination with Converter Controls and Stability Support

Protection schemes must operate correctly despite the strong influence of converter control loops on electrical quantities during faults. Current-limiting behaviour, voltage control actions, and the operating mode of the converter (e.g., grid-following or grid-forming) can significantly alter the observed voltage and current waveforms, potentially masking conventional indicators of abnormal conditions.

Protection, therefore, requires compatibility with these internal dynamics, ensuring that fast control actions, such as current saturation, reactive current injection or voltage restoration, are not misinterpreted as signs of instability or equipment stress. This is particularly important in low-inertia or weak power systems, with high integration of IBRs, where converter controls dominate the system response and can cause rapid variations that challenge the dependability and security of traditional schemes.

B. Requirements Imposed by Grid Codes and Compliance Obligations

Grid codes play a central role in defining protection needs in IBR-rich systems. Modern regulations require converters to remain connected and support the system during disturbances, a shift from the behaviour of legacy distributed generation. This is formalised in the EU-wide Requirements for Generators [13], which underpin national connection rules and are currently being updated to strengthen system stability and interoperability. National implementations specify detailed dynamic performance obligations [14], including functions that directly influence protection coordination, such as:

- Fault ride-through capabilities, preventing disconnection during defined voltage and frequency excursions.
- Reactive current injection during voltage dips, often with strict response times and performance criteria.
- Active power recovery profiles, preventing excessive ramping following fault clearance.
- Frequency support functions, including fast frequency response or synthetic inertia in some jurisdictions.

These requirements reflect the broader "new wave" of European grid-code activity that aims to maintain system stability as synchronous inertia declines and converter-driven phenomena become more prominent. A thorough analysis of the protection schemes currently implemented in countries such as Spain, Germany or United Kingdom is essential to determine how these schemes must be adapted to ensure reliable coordination with modern converter-interfaced generation

C. Adaptivity, Measurement Requirements and System-Level Coordination

The operating conditions of IBR-dominated power systems can change rapidly due to renewable variability, fluctuating system strength or changes in network topology [1]. Consequently, protection must incorporate adaptive elements or use richer measurement information than traditional schemes. This may involve synchrophasor-based data, high-resolution local measurements, or system-level signals that reflect the dynamic state of the network.

Coordination between protection devices also becomes more demanding when fault current contributions are limited and do not follow conventional magnitude- or angle-based patterns. Achieving selectivity may require new approaches that integrate dynamic thresholds, communication-assisted logic, or information on converter operating states. Such capabilities enable protection to maintain security and dependability even when system indicators vary rapidly or show limited discrimination.

3. Taxonomy of Protection Strategies Based on Converter Control

This section classifies the protection strategies that rely on converter-level control actions, focusing on their capability to enhance protection reliability in power systems with high penetrations of IBRs.

A. Active methods (A)

Active methods trigger specific converter actions upon fault detection to enhance protection sensitivity, directionality, and overall reliability.

1) *Signal Injection (SI).* The converters are controlled to inject specific signals, typically current harmonic upon fault detection, enabling protection devices to analyse the system response and thereby discriminate fault type or location with higher robustness, including harmonic overcurrent (HOCR), harmonic overcurrent directional (HOCDR) and related relay functions [15-23]. Besides, [24-25] inject tailored synthetic signals, such as off-nominal frequencies or controlled current components, to give conventional relays clearer and more dependable fault information in converter-dominated microgrids.
2) *Synchronous Machine Emulation (SM).* Converter controls are modified to emulate the dynamic behaviour and fault-current characteristics of synchronous machines, allowing protection systems to operate using familiar signatures and improving fault-ride-through coordination [26-29]. Although some papers do not explicitly state that they emulate a synchronous machine, their underlying objectives and implementation principles aim to reproduce the characteristic current response expected by protection schemes designed for synchronous machine-dominated systems [27,29].
3) *Adaptive Reference (AR*). These methods adjust the inverter's active/reactive power or current references during faults, enabling selective or coordinated protection [30-33]. In practice, the controller dynamically modifies its internal reference signals so that the converter exhibits a different fault response without altering any of the controller's parameters. This deliberate reshaping of the internal setpoints allows the device to shift its operating point within the control structure to better support protection functions while preserving the original control architecture.
4) *Parameter Modification (PM).* PM consists of altering the converter's internal control parameters, such as virtual impedance, gains, or dynamic constants, without changing its references or injecting new signals, thereby reshaping its inherent fault-time response. [34] show how modifying the converter's internal control parameters, directly alters its fault response and thereby influences distance-protection performance.

B. Passive Methods (P)

Passive methods tolerate the fault and rely on existing protection devices to operate, focusing on optimising the system intrinsic response and improving fault detectability without initiating any converter-driven intervention [35-36]. They analyse naturally occurring electrical quantities, such as voltage depressions, sequence components, or transient signatures, to infer fault conditions, rather than modifying the behaviour of the inverter or the grid. As a result, these schemes preserve the normal control priorities of IBRs and maintain simplicity. However, they may face inherent limitations when fault signals are weak or heavily distorted.

C. Comparative Analysis and Graphical Summary

In order to improve the clarity and accessibility of the proposed taxonomy, Table I summarises each reference, indicating its classification, converter type (grid-following: GFL or grid-forming: GFM), communication requirements (COM), application domain (microgrid: MG or power system: PS) and computational cost (COMP COST), where "+" denotes low cost and "-" high cost. It also specifies whether the scheme suits radial (RAD) or ring networks, and lists the test-system conditions, including voltage level, fault resistance, detection time, and any noise analysis performed. Table I significantly strengthens the structure of the taxonomy by providing a unified comparison framework that allows readers to quickly identify methodological patterns, technical assumptions, and contextual constraints across studies, highlighting gaps in the literature, such as techniques that have only been validated on specific converter types, or methods that have not yet been tested across different network topologies or noise conditions.

Finally, Fig. 1 depicts graphical abstract offering a concise visual overview of the method categories and their main characteristics. By combining both the table and the graphical abstract, the taxonomy becomes more accessible, enabling readers to navigate the complexity of protection strategies for IBR-dominated systems with greater ease and precision.

4. Discussion, Practical Challenges and Future Needs

Active protection methods introduce targeted converter actions to improve sensitivity, directionality and reliability, but their practical application faces several challenges. Their performance depends strongly on converter bandwidth, PLL behaviour and control-loop stability, which may constrain the magnitude or speed of the injected signals or reference adjustments. Interactions with grid-code requirements, particularly limits on current injection, negative-sequence content and voltage-support duties, also restrict the applicability of many schemes.

SI-type methods rely on actively injecting synthetic signals, to enhance fault visibility. However, injected harmonics can unintentionally enter inverter control loops and interact with inner controllers, altering dynamic behaviour or reducing stability margins. Some approaches also assume prior knowledge of the grid impedance at specific frequencies, even though this parameter is difficult to measure accurately and can vary significantly

Table I. - Overview of protection strategies based on converter control and test conditions.

REF	TYPE	GFL/ GFM	COM.	COM. COST	MG/PS	RAD/ RING	VOLT (kV)	RF (Ω)	DET. TIME (s)	NOI.
[15]	SI + OCR	-	No	+	Islanded MG	Radial	0.38	0-3.6	0.11-0.285	No
[16]	SI + HDOCR	-	No	-	Islanded MG	Radial	12.47	0-15	0.035-4.406	No
[17]	SI + pattern based directional relay	Both	Yes	--	Islanded MG	Both	12.47	10-40	58.33	No
[18]	SI + HDOCR	-	No	-	Islanded Grid MG	Both	12.47	0-1-3	0.923-2.18	Yes 35dB
[19]	SI + HDOCR	-	No	-	Islanded MG	Radial	12.47	0.1-15	0.219-1.356	No
[20]	SI + HOCR	Both	No	+	Islanded MG	Radial	11	0.1-66	0.6 - 0.82	No
[21]	SI + Harmonic Current Voltage Directional Relay	-	No	-	Islanded MG	Both	12.47	0.1-10	0.839-1.229	No
[22]	SI + Directional Relay+ Backup: Harmonic Impedance Protection	-	Yes/ No	-	Active PS	Radial	10.5	0.1-100	60 ms	No
[23]	SI + Distance Relay	-	No	-	PS	Both	12.47	0-20	-	Yes 70dB
[24]	SI + Differential Relay	Both	Yes	+	Islanded MG	Radial	12.47	-	-	No
[25]	SI: impedance measuring + current injection + OCR	Both	No	-	Islanded MG	Ring	0.80 DC	0.001-0.5	10 ms	No
[26]	SM: sequence currents shaping	-	No	--	PS	Mesh PS	138	10-20	-	No
[27]	SM: Sequence based current control emulates synchronous generator's angle behaviour	-	No	-	PS	-	230	0-50	0.015	No
[28]	SM: Virtual impedance control for current angle-based relay	-	No	--	Islanded Grid MG	Both	12.47	10-50	20-40 ms	No
[29]	SM: Dual-sequence current control emulating SG sequence angle	-	No	--	IEEE 14-Bus	Mesh PS	138	0.01-100	-	No
[30]	AR: Current limiter for distributed generation and fuse-reclosing	-	No	--	IEEE 13-Bus	Radial PS	4.16	0.01-11.5	<5 ms	No
[31]	AR: reference currents adjustment	-	No	-	Offshore PS	Radial	66	0.1	< 15 ms	No
[32]	AR: Active phase control eliminating operating to fault current phase difference	-	No	-	PS	-	35	10-100	50 ms	No
[33]	AR: Power reference injection + sequence analysis	-	No	+	PS	-	500	0-200	160 ms	No
[34]	PM: Dual-sequence current control (GFL)/virtual impedance-based control (GFM) + Distance Relay	Both	No	++	Islanded MG + PS	Mesh PS	275	2-6	0.025-1.653	No
[35]	Passive: Fault current limiter + OCR + Undervoltage Relay	-	No	+	LVDC PS	Radial PS	0.75 DC	0	< 3 ms	No
[36]	Passive: Current derivative measurement	-	No	-	LVDC PS	-	0.35 DC	Low-23.3	87.5 us	No

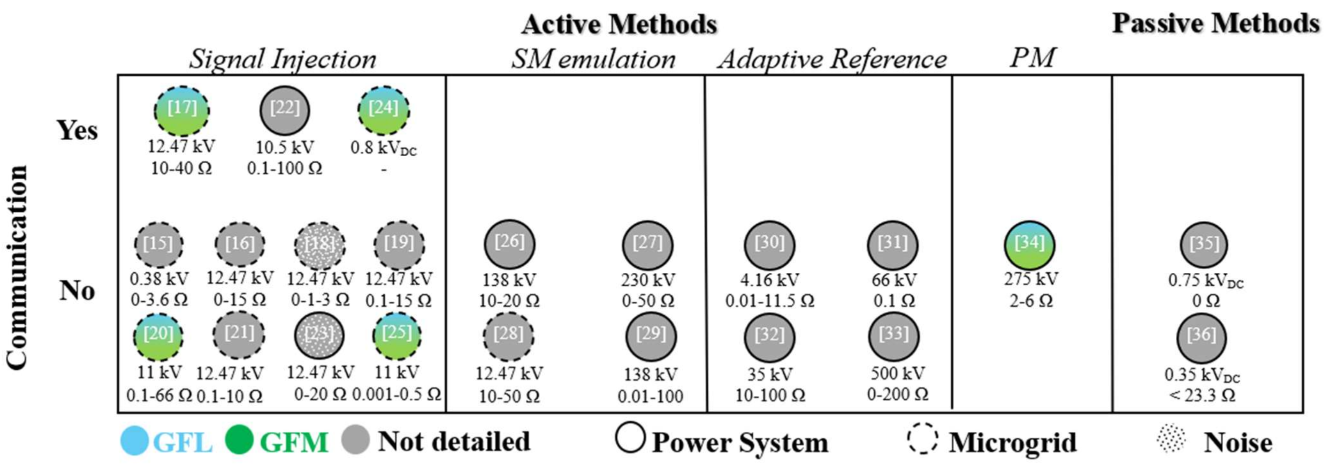

Fig. 1. Graphical abstract.

with operating conditions. As a result, the effectiveness of both SI and SM techniques remains highly sensitive to network strength, topology, and real-time operating states, while measurement noise, parameter uncertainty, and delays can further impair discrimination in weak or IBR-dominated systems.

Implementation complexity is another key barrier: multi-harmonic analyses, adaptive parameter updates or high sampling rates may exceed the computational capabilities of commercial relays or converter controllers. Coordination with legacy protection remains limited, and interoperability issues may arise when multiple converters apply different active strategies simultaneously. More extensive EMT-based validation, real-time hardware-in-the-loop testing and multi-vendor studies are needed, together with improved guidelines to ensure compatibility with emerging GFM controls and evolving connection codes.

Passive methods remain simpler and inherently compatible with existing relays, but their performance is ultimately constrained by the limited fault signatures available in highly IBR-dominated power systems. In this field, future research areas for these methods should study the possibility of implementing advanced diagnostic tools in real-time, such as time-frequency domain analysis with artificial intelligence-based condition monitoring and protection methods.

5. Conclusions

The proposed taxonomy offers a structured and mechanistic framework for classifying protection–oriented converter interactions, distinguishing clearly between SI, SM, AR, PM and purely passive schemes. Active approaches offer enhanced sensitivity and discrimination but introduce implementation, coordination and compliance challenges. Passive methods remain simpler and fully compatible with existing relays, yet their effectiveness is limited by the reduced fault signatures inherent to IBRs.

Unlike broader classifications, the paper captures how each method influences the converter's internal control loops, the level of intervention required, and the resulting computational burden, enabling consistent comparison across diverse protection philosophies. This taxonomy also provides practical advantages: it separates methods that actively synthesize new electrical signatures from those that reshape internal references or emulate synchronous behaviour, highlights implementation complexity, and clarifies which approaches integrate directly with relays versus those that reformulate the converter's dynamic response. As a result, it serves as a more granular and engineer-oriented framework that enhances comparability, reveals trade-offs, and supports systematic evaluation of emerging protection solutions.

Overall, further work is required to achieve robust, interoperable and standardised protection solutions capable of supporting reliable operation in future power systems with high presence of IBRs.

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