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An Overview of Inverter-based Resource Interconnection Standards

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Xue Lyu
Jing Xie

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Prepared for
Essential Grid Operations for Solar (EOS) Project

Pacific Northwest National Laboratory
Richland, Washington 99354

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1 Background

For the past century, electric power systems have primarily been bulk power systems consisting of generation, transmission, and distribution networks. Nowadays, the rapid expansion of distributed energy resources (DERs) has become the most significant change in modern power systems. The existing large, conventional synchronous machine resources are replaced via smaller-sized resources with diverse generation characteristics. With the increasing penetration of inverter-based resources (IBRs), it is important to develop interconnection standards that define performance and capability criteria for these IBRs. This is necessary to ensure the stable and reliable operation of power systems. This report summarizes the standards for IBRs interconnection.

2 IEEE Standards Development

As a global standards development organization, IEEE supports and advocates a set of standards development principles, executed by the IEEE Standards Association (IEEE SA). The life cycle of standards development is introduced in this section.

IEEE Standards are developed using a time-tested, effective, and trusted process [1]. This process is broken down into a six-stage life cycle, as shown in Fig. 1. The first step in beginning a standards development project in IEEE SA (whether an individual- or entity-based project) is the submission of the Project Authorization Request (PAR). Every PAR that is submitted must have a Standards Committee to oversee the project.

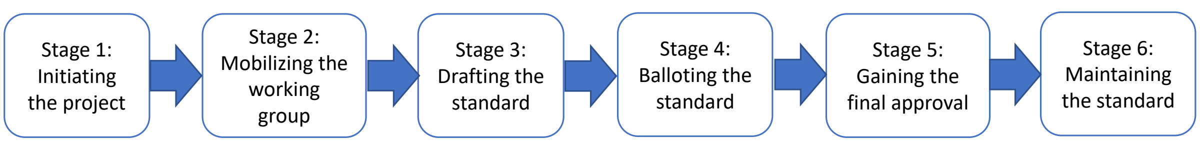

Fig 1 Standards development life cycle [1].

Once the IEEE SA Standards Board approves the request to develop a new standard, the Standards Committee follows IEEE SA's rules and processes to establish a Working Group (WG) to engage in the standards development activity. Working Groups are composed of individuals or entities (companies, organizations, non-profits, government agencies) who volunteer to participate in the development of the standard. These volunteer participants have an interest in a specific area of the development of the standard (e.g., producers, sellers, buyers, users and/or regulators of a particular material, product, process or service).

The third stage is the drafting stage. Once a draft standard has been reviewed, finalized, and approved by the Working Group, it is submitted to the Standards Committee for approval to move forward to the IEEE SA Ballot. Upon successful completion of the IEEE SA Ballot process, the draft standard is submitted to the Review Committee (RevCom). The balloted draft standard is reviewed by RevCom and then submitted to the IEEE SA Standards Board (IEEE SASB) for approval. After final approval by the IEEE SASB, the approved standard is published and made available for distribution and purchase.

It should be noted that standards are “living documents”, which may initially be published and iteratively modified, corrected, adjusted, and/or updated based on market conditions and other factors. Depending on where a standard is in its lifecycle, a standard may be accompanied by additional documents that are produced by its respective Working Group.

3 Overview of IEEE Std 1547, 2800, and 1729

The synchronous generator (SG) possesses inherent mechanical inertia and reliable frequency and voltage regulation capabilities. Consequently, SG-dominated power systems exhibit high resilience in supporting the grid under challenging scenarios. In contrast, renewable power sources are electronically interfaced and lack the ability to provide physical inertia. Additionally, their intermittent characteristics may lead to adverse consequences for the grid. To guide the interconnection of IBRs, IEEE has published relevant requirements on IBRs. For example, IEEE Std 1547 brought regulations for the interconnection and interoperability between utility electric power systems and distributed energy resources. IEEE Std 2800 is intended to apply to IBRs that connected to transmission and sub-transmission system. The scope of IEEE 1547 [2] and 2800 [3] series of standards, and 1729 Recommended Practice [4] are briefly introduced in this Section.

3.1 IEEE 1547 Series of Standards for Distributed Resources Interconnection and Interoperability with the Grid

IEEE Standard 1547 (2003) [5] was the first in the series of standards developed concerning DERs interconnection. DER include distributed generators and energy storage systems [6]. IEEE 1547 focuses on the technical specifications for, and testing of, the interconnection, and not on the types of DER technologies—it is technology neutral. After undergoing an extensive revision process, Standard 1547-2018 [7] (IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces) went into effect as of August 2018. The standard provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection. It includes general requirements, responses to abnormal conditions, power quality, islanding, and test specifications and requirements for design, production, installation evaluation, commissioning, and periodic tests. The stated requirements are universally needed for interconnection of DER, including synchronous machines, induction machines, or power inverters/converters and will be sufficient for most installations. The criteria and requirements are applicable to all DER technologies interconnected to electric power systems (EPSs) at typical primary and/or secondary distribution voltages. Installation of DER on radial primary and secondary distribution systems is the main emphasis of this document, although installation of DERs on primary and secondary network distribution systems is considered. This standard is written considering that the DER is a 60 Hz source.

IEEE Std 1547 is the foundational, or root, standard of the IEEE 1547 series. There are additional complementary standards designed to expand upon or support the root standard.

- IEEE Std 1547.1–2005 [2] specifies the type, production, and commissioning tests that shall be performed to demonstrate that the interconnection functions and equipment of the distributed resources (DR) conform to IEEE Std 1547(TM).

- IEEE Std 1547.1–2020 [8] specifies the type, production, commissioning, and periodic tests and evaluations that shall be performed to confirm that the interconnection and interoperation functions of equipment and systems interconnecting DER with the EPS conform to IEEE Std 1547, as revised, corrected, or amended.

- IEEE Std 1547.2-2008 [9] provides background and rationale of the technical requirements of IEEE Std 1547-2003. It also provides tips, techniques, and rules of thumb, and it addresses topics related to distributed resource (DR) project implementation to enhance the user's understanding of how IEEE Std 1547-2003 may relate to those topics.

- IEEE Std 1547.3-2007 [10] addresses guidelines for monitoring, information exchange, and control for DER interconnections.

- IEEE Std 1547.4-2011 [11] provides approaches and good practices for the design, operation, and integration of microgrids, or DER island systems interconnected with the distribution grid.

- IEEE Std 1547.6-2011 [12] provides additional information in regard to interconnecting distributed resources with distribution secondary networks.

- IEEE Std 1547.7-2013 [13] addresses the criteria, scope and extent for engineering studies of the impact on area electric power systems of a distributed resource or aggregate distributed resource interconnected to an area electric power distribution system.

- IEEE Std 1547.8 [14] provides recommendations addressing DR interconnection system-level potential adverse effects, and, opportunities for EPS improvement, considering: the DR technology capabilities, interconnection technology capabilities, operations of the DR, operations of the area EPS, operations of the Local EPS, effects on power quality (voltage and frequency concerns), DR interconnection response to abnormal Area EPS conditions (e.g., voltage, frequency, faults), advanced capabilities of DR functions for supporting Area EPS operations, and, potential for DR to increase reliability and efficiency of electricity delivery and grid operations.

- IEEE 1547.9-2022 [15] provides information on, and examples of, how to apply IEEE Std 1547-2018 for the interconnection of energy storage distributed energy resources (ES DER). The guide's scope includes ES DER that are interfaced to an EPS via a power electronic interface (commonly referred to as a converter, inverter, or bidirectional inverter), capable of bidirectional active and reactive power flow, and capable of exporting active power to the EPS. this guide's scope includes ES DER that are capable of exporting active power to an EPS. The guide also considers energy storage-related topics that are not currently addressed or fully covered in IEEE Std 1547-2018 and sets a basis for future development of industry best practices for ES DER-specific interconnection requirements that could be considered in future revisions of IEEE Std 1547.

- IEEE 1547a-2020 [16] is anticipated to increase the deployment of DER with Category III capabilities that can provide the highest bulk system reliability, compared to DER that is capable of the lower Category II. This amendment allows for voltage trip clearing times

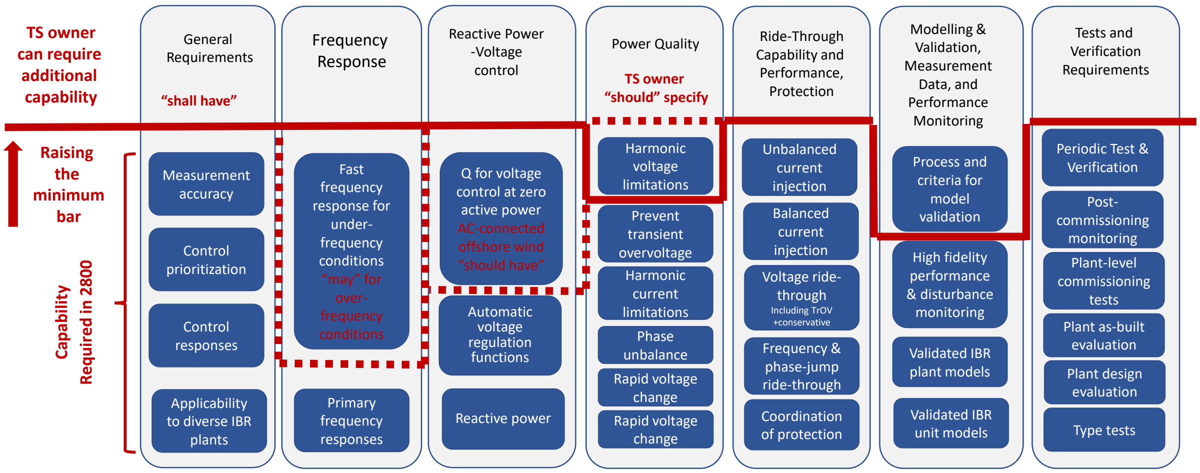

Fig 2 IEEE 2800-2022 technical minimum capability requirements [17].

inside the ride-through capability regions of Category III capable DER to achieve safe and reliable coordination of DER ride-through with prevailing distribution protection objectives and practices. The amendment can also lead to increased deployment of DER that address integration issues such as power quality and distribution grid or substation overloads caused by DER tripping in local Area EPS that have very high levels of DER penetration.

3.2 IEEE 2800 Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems

IEEE 2800-2022 [3] establishes the minimum requirements for the interconnection, capability, and lifetime performance of IBRs interconnecting with transmission and sub-transmission systems. The performance requirements for reliable integration of inverter-based resources into the bulk power system, including, but not limited to, voltage and frequency ride-through, active power control, reactive power control, dynamic active power support under abnormal frequency conditions, dynamic voltage support under abnormal voltage conditions, power quality, negative sequence current injection, and system. This standard also applies to isolated inverter-based resources that are interconnected to an ac transmission system via dedicated voltage source converter high-voltage direct current (VSC-HVDC) transmission facilities; in these cases, the standard applies to the combination of the isolated IBRs and the VSC-HVDC facility, and not to an isolated inverter-based resource (IBR) on its own. IEEE 2800 applies to all IBRs (including grid-forming ones), but was designed with conventional grid-following IBRs. Fig. 2 illustrates the specific requirements that are within and outside of the scope of 2800 in relation to international leading practices.

P2800.1 [18] specifies the test equipment, test conditions and test and verification methods for type tests, production tests, facility design and as-built evaluations and commissioning tests to be performed to demonstrate the interconnection capabilities and functions for equipment connected with transmission electric power systems. Included in the test and verification procedures are all performance and functional requirements for reliable integration of inverter-based resources into the power grid, including, but not limited to, voltage and frequency ride-through performance, reactive power control, power quality, and dynamic voltage support under abnormal voltage conditions. This guide may also specify verification procedures for generic steady-state short-circuit models for fault analysis, as well as, generic, fundamental frequency, stability-type models (root-mean-square (RMS) with positive-sequence and possibly negative-sequence representation) of inverter-based resources interconnecting with transmission electric power systems for bulk system stability studies and/or proprietary time-domain (electromagnetic transient) models for verification of interconnection requirements of composite systems (facilities) at the point of interconnection.

P2800.2 [19] defines recommended practices for test and verification procedures that should be used to confirm plant-level conformance of IBRs interconnecting with bulk power systems in compliance with IEEE Std 2800. This recommended practice complements the IEEE 2800 test and verification framework with specifications for the equipment, conditions, tests, modeling methods, and other verification procedures that should be used to demonstrate conformance with IEEE P2800 technical minimum requirements for interconnection, capability, and performance of applicable IBRs.

3.3 IEEE 1729-2014 IEEE Recommended Practice for Electric Power Distribution System Analysis

The aim of 1729 is to expand the use of IEEE power distribution test feeders into a broader space of software developers, software users, and researchers. The need for new distribution software functionality evolves quickly in areas such as distributed resource modeling, load response to voltage and frequency, reliability improvement, neutral-earth voltage, harmonics, active controls, interoperability, etc. By leveraging and expanding the set of test feeders, more attention can focus on providing the new functionality. The scope of the recommended practice includes steady-state, event-based, probabilistic, stochastic, and dynamic analysis of medium-voltage (up to 35 kV) electric utility power distribution systems. Industrial and commercial power distribution systems, harmonic analysis, and electromagnetic transient analysis are all excluded. Now there is an active PAR for renewal and there has been a dedicated WG for IEEE 1729 [20]. The purpose is to focus research attention on areas where legitimate needs exist, to identify methods that should not be used in software products, and to provide guidance on the application of new analysis methods to electric utility distribution systems.

4 Typical Grid Connection Requirements and IBRs Requirements

Grid connection requirements for IBRs encompass both technical and non-technical considerations, as shown in Fig. 3. Technical concerns primarily involve frequency and voltage requirements. Frequency requirements include inertial response, primary frequency response, and frequency deviation specifications, particularly critical for grids with high IBR penetration. Voltage requirements emphasize maintaining a stable voltage profile at the point of common coupling (PCC), requiring IBRs to provide voltage support, especially during grid faults. It is required that IBRs should possess ride-through capabilities during these faults. Additionally, technical requirements encompass aspects like harmonics, damping, control interaction, islanding prevention, and black start procedures, are included in these standards. Non-technical requirements, particularly testing specifications, are essential during the IBR design phase.

In addition to grid-connection requirements, IEEE standards also address specific demands for IBRs. These include power quality requirements like harmonic current limitations, phase unbalance, rapid voltage control, and flicker limitations. Additionally, they cover general require-

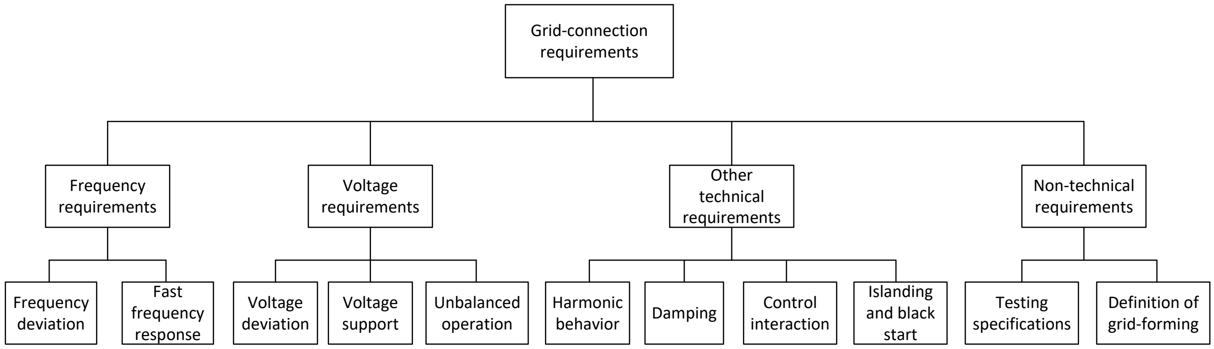

Fig 3 Grid-connection requirements for IBRs [21].

ments such as measurement accuracy, control response, and applicability to diverse IBR plants. The standards also outline tests and verification requirements, which include post-commissioning monitoring, plant-level evaluation and modeling, commission tests, and type tests.

With increasing attention being given to grid-forming (GFM) inverters, NERC has released its "White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems" [22]. This paper outlines a comprehensive functional specification that transmission service providers can integrate into their interconnection requirements for defining GFM. It also establishes a series of testing procedures for transmission planners to include in their interconnection modeling and studies, specifically for assessing GFM capability in interconnected projects. The paper strongly advocates that all new battery energy storage projects for interconnection should inherently possess GFM capability and that this capability should be the default setting.

5 Conclusion

With the continued increase of wind, solar, and other IBRs in the power grid, the responsibility for meeting grid demands and load demands is shifting to these renewable energy sources. For example, IBRs are expected to provide a variety of power system support functions, including voltage regulation through active/reactive power control, frequency regulation through active power control, and voltage ride-through capability. In this report, the IEEE Std 1847, 2800 and 1729 are introduced. While certain definitions are still under discussion, it is evident that future trends indicate the inevitability of a high-penetration IBR or even a 100% IBR power system. Based on this, the working groups are continuously striving to develop and update interconnection requirements to describe the characteristics of power systems and to ensure the reliable operation of modern power systems and the future power systems dominated by IBRs.

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