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"A Journey through Energy Systems Integration – Trending Grid Codes, Standards and IEC Collaboration"

Introduction

Our electrical world is changing. The journey we are on today parallels the era of Edison, Tesla and Westinghouse in the early race for electrification. Change abounds: energy from nature; Inverter-based technology; smart and smarter grids; decentralized power; and intercontinental interconnection. This new age of energy offers new choices and new challenges, all heavily influenced by the practices that evolved over the past century, institutionalized in standards, interconnection requirements, grid codes and technical regulatory policy. These standards drove the development of the electrical world as we know it and now they play an important role in its transformation. We would like to take you on a journey to the rapidly evolving standards world, both as a result of today's unprecedented technology development and an enabler to push the envelope even further.

Overview of Global Interconnection and Reliability Standards

IEC Standards

The IEC (International Electrotechnical Commission) is an international standards organization for the preparation and publication of International Standards for all electrical, electronic and related technologies. IEC standards work is carried out through technical committees (TCs) and subcommittees (SCs), with a wide range of topics from power generation, transmission and distribution to wind energy, solar energy and many others.

TC8: Technical Committee on System Aspects of Electrical Energy Supply

IEC TC8, in co-operation with other TC/SCs, develops standards with emphasis on overall system aspects of electricity supply, including grid integration and end-user connection. The two subcommittees under TC8, SC8A and SC8B, work to develop standards, specifications and technical reports on the grid integration of renewable energy and decentralized electrical energy systems.

SC8A, the Grid Integration of Renewable Energy Generation subcommittee, was established in July 2013, proposed by the China National Committee after the publication of an IEC white paper called *"Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage"*. The group's focus is on the system-wide effect of a high percentage of renewables. It covers grid integration standards for renewable energy, such as interconnection requirements and related grid compliance tests. It also includes standards or documents sharing best practices for planning, modeling, forecasting, assessment, control and protection, scheduling and dispatching of renewables, with a grid level perspective.

SC8A established ad-hoc group AHG3 to develop a roadmap to guide the activities of SC 8A over the next 3-5 years, a vital task. The purpose of the roadmap report is to give a succinct summary of the major challenges for grid integration of renewables and outline critical activities to address these challenges. The roadmap report addresses the wind and solar plant effect on the grid to ensure stable and reliable operation when renewable output has a significant impact on the electric system.

The main subjects of the roadmap report are areas that need future definition, development and/or coordination for seamless integration of renewable power plants. Renewable technology, particularly that of inverter-based resources, is continuing to rapidly evolve and penetration levels are climbing globally. As new technology develops, and penetration levels rise, gaps widen in the understanding of the state-of-the-art as well as how the latest technology is deployed. The roadmap addresses such gaps, including weak grid and special application issues like control interaction due to grid resonances, plant level coordination issues, as well as voltage and frequency control issues. The roadmap will be reviewed on a biannual basis to ensure that the tasks and priorities remain valid, and to identify any new concerns that may have arisen. JWG5 has been recently formed to coordinate on items that have been initiated by IEEE and CIGRE and will work on those that will be launched by SC8A. Such items include standardization needs related to weak AC grid interconnection and control stability, control interaction due to grid resonances and power system damping, fast frequency response and performance during balanced and unbalanced grid faults. Seven working groups are underway with participation of experts from 16 participating countries. By the end of 2018, there were five WG/JWGs established under SC8A. Besides AHG3 and JWG5, SC8A also has WG1 on vocabulary, WG2 on forecasting, and JWG4 on grid code compliance assessment.

A sister sub-committee to SC8A is a subcommittee focused on Decentralized Electrical Energy Systems, SC8B. SC8B focuses on preparing standards enabling the development of secure, reliable and cost-effective systems with decentralized management that are an alternative, complementary or a precursor to traditional large interconnected and highly centralized systems. The most contemporary concept that SC8B covers is general planning, design and control of microgrids. This group is also writing a roadmap report of decentralized energy to pave the way for future standards development in this space. Its WG4 is drafting two standards, IEC 63189 -1 and -2 covering functional requirements and applications of virtual power plants.

TC88: Technical Committee on Wind Energy Generation Systems

IEC TC88 has pioneering experience with international standardization in the field of wind energy generation systems. It covers wind turbines, on-shore and off-shore wind power plants, as well as their interaction with the electrical systems to which energy is supplied.

While the first TC88 standards were mainly focusing on mechanical parts and performance of wind turbines, the first standard dealing with electrical testing of grid connection of wind turbines was IEC 61400-21 published in 2001, focusing on power quality aspects. This standard was based on several national guidelines in the 1990s, mainly in Denmark and Germany. Due to the expansion of grid connection requirements, the 2nd edition published in 2008 and the 3rd edition expected in 2019 include the test and measurement of fault-ride-through capability and control performance of wind turbines.

Furthermore, new standards IEC 61400-21-2 for the test of wind power plants and IEC 61400-21-4 for test of electrical components and subsystems are under development, due to the increased grid connection requirements.

Although these test standards are driven by the rapidly growing share of wind in power systems, significant parts of the standards are generally valuable for other converter connected generation like solar PV (covered by IEC TC 82). The same can be said about development of modeling standards.

In 2015, TC 88 published the first standard IEC 61400-27-1 specifying generic models for wind turbines and a procedure to validate a wind turbine model based on tests according to IEC 61400-21-1. The next edition is expected in 2019 with IEC 61400-27-1 specifying models and IEC 61400-27-2 specifying procedures for model validation. The IEC 61400-27-1 models are included in IEC 61970-302 specifying how to exchange data for dynamic power system simulations using generic models. Finally, a technical report IEC 61400-21-3 about wind turbine harmonic models is expected to be published in 2019. An overview of the different IEC TC88 standards and their interaction with the grid connection requirements are shown in Figure 1.

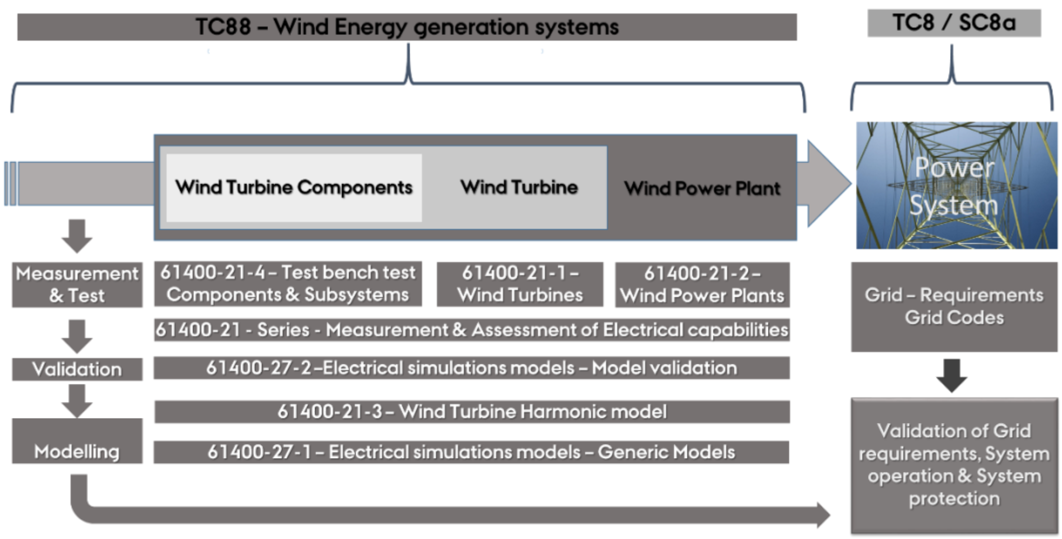

Figure 1: Overview of TC 88 - Grid connection related standards

Challenges for Distributed Energy Resource (DER) standards and grid codes

Standards and grid codes covering Distributed Energy Resources (DER) need to consider a very wide variety of requirements. In the past, a low penetration of DER allowed for a clear distinction between large transmission-connected plants and small units that are connected to the distribution grid. Big plants were responsible for system security, providing functions such as frequency control or fault ride through. Dedicated communication links to these plants also allow for fast and reliable two-way communication, enabling system operators to control these resources from the control room. Smaller DER units historically act autonomously as communication to the control room is very challenging due to the large number of

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units and higher communication costs, which needs to be kept in perspective as related to the investment per unit. In addition, requirements for small DER focus more on local effects like anti-islanding or voltage control at long feeder lines. Some of these requirements are even contradictory to the system requirements. For example, large plants should ride through a wide range of frequency deviations, while small DER often uses frequency deviations to detect an unintended islanding event and shut down immediately if the detected frequency is outside of a narrow band. With increasing penetration, DER becomes as relevant for system security as large plants. Therefore, new requirements for DER need to address both local effects as well as system wide responsibilities. As some of the requirements are contradictory, a fine line of compromise needs to be found for standards and grid codes of DER, balancing reliability needs, equipment capabilities and cost.

IEEE 1547

IEEE Standard 1547 is a series of standards, originally approved in 2003. It establishes criteria and requirements for interconnection and related testing of DER with aggregate capacity of 10 MVA or less, to Electric Power Systems (EPS) at typical primary and/or secondary distribution voltages.

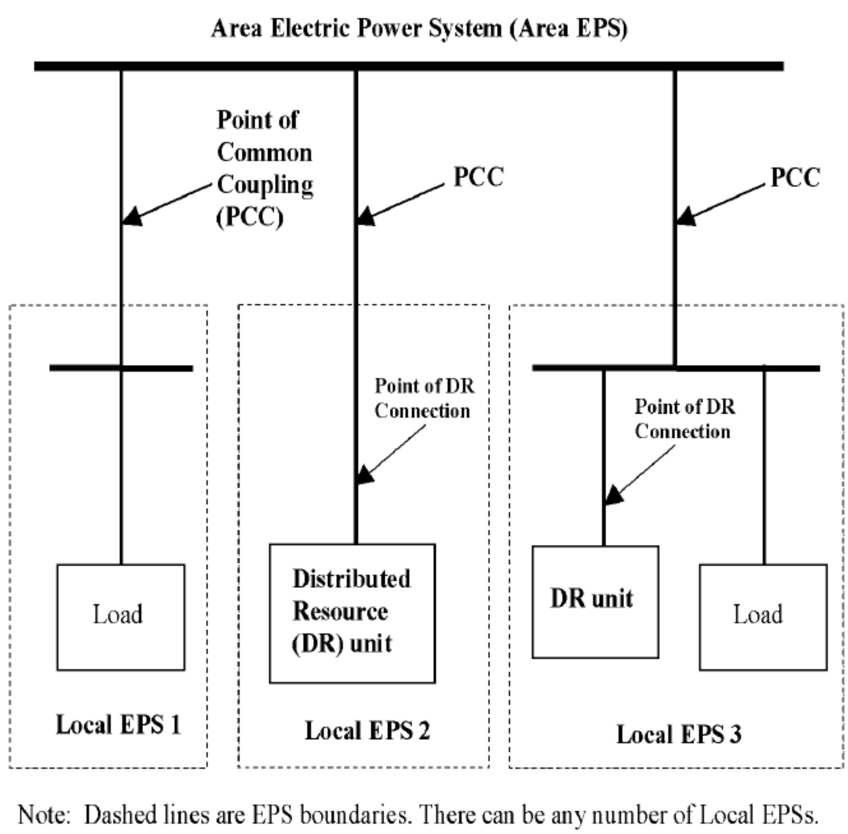

Figure 2: Relationship of interconnection terms

The first version of IEEE 1547 (IEEE 1547.1) was issued in 2005. It defined the conformance test regimens for DERs to confirm that components, subsystems, and/or systems intending to interconnect with the EPS complied with IEEE Std 1547-2003. In 2014, IEEE 1547.1 was amended to address issues that had arisen from experience gained from ever-increasing penetrations of DERs. It allowed DERs to participate in EPS voltage regulation and revised abnormal voltage and frequency protection thresholds and clearing times. IEEE 1547.1 was subsequently amended in 2015.

A full revision of the IEEE 1547 standard was issued in 2018 to address further DER expansion. It considered ongoing technological advancements, and addressed interoperability as deemed necessary to enable the development of the Smart Grid.

IEEE Std. 1547-2018 made a significant advancement in standardizing the interconnection and interoperability of DER connected to local distribution networks. IEEE Std. 1547-2018 addresses the "performance, operation, testing, safety considerations and maintenance of the interconnection." This includes general requirements, response to abnormal conditions, power quality, islanding, and other aspects. The requirements set forth in the standard "are universally needed for interconnection of DER, including synchronous machines, induction machines, or power inverters/converters." The IEEE P1547.11 project is exploring the testing and verification of these requirements as well.

IEEE Std. 1547-2018 defines performance requirements and capabilities, with default settings as well as ranges of adjustability. Utilities and state regulatory entities should evaluate and select appropriate performance categories and settings to suit their specific system characteristics. This involves coordination among these entities and Reliability Coordinators (RCs), Independent System Operators (ISOs), Transmission Operators (TOPs), Transmission Planners (TPs), and Planning Coordinators (PCs) on those issues pertaining to Bulk Power System (BPS) reliability and performance. The requirements set forth in IEEE Std. 1547-2018 foster this collaboration among the local utility and entities with a regional or wide-area view to ensure some uniformity in settings that impact the BPS.

Any existing rules, regulations, or utility interconnection requirements based on the IEEE Std. 1547-2003 should be updated to reflect the current requirements in IEEE Std. 1547-2018 reflecting appropriate selection of DER settings. Experiences around the world have proven that retroactive changes to installed resources can be extremely costly, complicated and impactful to a wide range of stakeholders. On the other hand, clearly defining DER settings in interconnection rules can improve efficiency, reduce costs, and maximize hosting capacity and efficient utilization of the existing network, as well as ensure the reliability of the local distribution systems and the BPS.

IEEE P2800

The relatively new IEEE P2800 effort is developing a Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems. This standard "establishes the recommended interconnection capability and performance criteria" for these resources interconnecting at both the transmission and sub-transmission system. The standard, similar to IEEE Std. 1547-2018, will provide "recommendations on performance 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

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frequency conditions, dynamic voltage support under abnormal voltage conditions, power quality, negative sequence current injection, and system protection." The P2800 team has an aggressive schedule to complete this standard due to the gravity of its importance for North America. The plan is for approval and adoption by the end of 2021. In the meantime, utilities should be working to ensure that their interconnection requirements are adequately clear and encompassing to enable reliable operation and performance of inverter-based resources connecting the bulk power system.

The North American Electric Reliability Corporation (NERC)

NERC has two industry stakeholder groups that are helping drive reliability improvements and advanced capabilities across North America:

- The NERC Inverter-Based Resource Performance Task Force (IRPTF) has supported the analysis of large-scale disturbances involving solar PV resources, which has led to the identification of abnormal and undesired performance with the solar fleet. Working collaboratively with industry stakeholders, including the inverter manufacturers, many of these performance issues have been mitigated. The NERC IRPTF developed the NERC Reliability Guideline: BPS-Connected Inverter-Based Resource Performance, which specifies the recommended behavior and performance of inverter-based resources connected to the bulk power system. This guideline is also serving as valuable input to IEEE P2800.
- The NERC System Planning Impacts of Distributed Energy Resources Working Group (SPIDERWG) was recently formed to focus on DER from a transmission planning and system analysis perspective. NERC SPIDERWG is focusing on four key aspects of DER impacts to the BPS: modeling, verification, studies, and coordination. As the penetration of DER continues to grow across North America, transmission entities need to ensure they have the tools, capabilities, and study techniques to understand the impacts DER can have on the BPS. The NERC SPIDERWG is focused on developing recommended practices and guidelines on these topics to advance transmission planning studies considering rapidly growing penetrations of DER.

Key Standardization Challenges

A key aspect of standardization and regulation is ensuring a minimum level of performance and reliability while not being overly prescriptive, such that technology advancement can occur, as Figure 3 illustrates. Now more than ever, this consideration is at the forefront of standards development and grid code compliance. Standards are often written as "technology agnostic"; however, this has led to requirements that are not clear for newer technologies, which leaves uncertainty as to the intent and activities necessary to be compliant with the standards. There are opportunities to ensure the intent of codes and requirements remains neutral in terms of technology while still providing clarity and consistency regarding specific technologies. As technology continues to evolve, this needs to be a key consideration during standards development – clarity in requirements for specific technologies balanced with consistency in requirements across technologies.

In North America, the NERC Reliability Standards apply to those resources that meet the bulk electric system (BES) definitions – specifically, aggregated resources such as wind and solar plants larger than 75 MVA. However, most newly interconnecting resources do not meet this size threshold and therefore the NERC Standards do not apply. In these cases, it is paramount that the local utility requirements be leveraged for such resources. These requirements should ensure reliable operation and performance, covering everything from protection and control to performance and modeling.

As the penetration level of inverter-connected generation increases, new reliability issues are being experienced or are being forecast to occur.

- Active power-frequency control: The integrity of frequency response can be compromised at high instantaneous penetrations of wind power generation, especially in islanded networks. Monitoring and managing system inertia is one technique being used. Excessive rate-of-change of frequency following the largest contingency could result in cascaded tripping if generator units are not designed to ride through. Increasing the ride through requirement above the IEC limit of 0.5 Hz/sec is being considered in Ireland. Providing fast frequency support from wind plants is also under consideration.
- Reactive power-voltage control performance of BPS-connected inverter-based resources: The location of new inverter-based generation is typically different from the conventional plants they are displacing. As a result, even though the new transmission-connected plants provide reactive power and voltage control to meet grid codes, they may be insufficient to address local problems that result during various dispatch scenarios. Distribution connected plants may only be operating in a power factor control mode. The addition of grid connected reactive power sources, conversion of conventional units to synchronous condensers to provide the voltage support where it's needed, or modification to the control mode of distribution connected generation may be needed to ensure adequate voltage support.
- Low short circuit strength issues, appropriate modeling and study approaches, and effective solutions to address these issues: The short circuit ratio is a metric used to assess the voltage stiffness of the grid in a local area. Areas with a low short circuit ratio (< 3) are classified as weak networks. They typically require more detailed assessments to confirm voltage regulator stability, control interactions with other nearby devices and protective relay coordination, for example. Fault-induced delayed voltage recovery (FIDVR) is more of a problem in weaker grids.
- Sub-synchronous oscillations including resonance and control interactions (SSR/SSCI) between groups of power electronic resources and with the grid: Sub-synchronous torsional interaction (SSTI) is the interaction between the mechanical torsional masses in a turbine-generator unit. such as a wind turbine-generator and the wind turbine (hub and blades), and a power electronic device such as HVDC or FACTS. The power electronic device can exhibit negative damping to sub-synchronous frequencies. Sub-synchronous control interaction (SSCI) is the interaction between a power electronic device (e. g. Type 3 wind turbine-generator) and a series compensated transmission line. Specialized studies with electromagnetic transient (EMT) models are required in these cases.
- Aggregate modeling and impacts of DER on the bulk power system: Increasingly widespread penetration of DER, such as rooftop solar photovoltaic (PV) embedded in the distribution grids,

will require the emergence of an active distribution grid that will need to have improved observability and controllability for the transmission operators responsible for system security. Accurate aggregated models will need to be developed and added to transmission models to test the impact of ride-through capability.

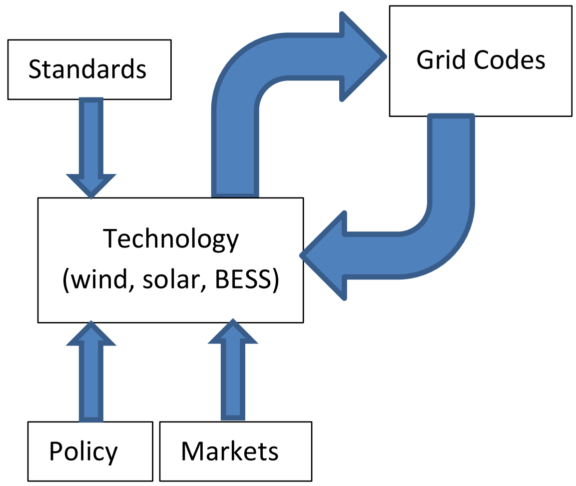

Figure 3: Aspects of codes, standards and policy on technology

Grid Code Trends

Grid codes are a massive subject of their own. A large portion of grid code changes occurring around the world are driven by renewable generation. We would like to point out trends in several representative regions that adopted new requirements resulting from growing inverter/converter-based penetration.

Grid Code Trends in Canada

In 2005, the Canadian Wind Association (CanWEA) noticed that the Canadian provinces were developing their own grid codes – largely in isolation. At the time, there was roughly 600 MW of installed wind capacity across Canada, but significant growth was expected. CanWEA worked with the transmission system operators to develop a minimum set of common interconnection requirements. The base code covered the following main areas:

- Frequency tolerance – continue to operate over a wide range of frequency.
- Voltage tolerance– Continuously operate within +/-10% of nominal voltage. Higher voltage ride through was considered a special case.
- Power control – be able to limit maximum power output and control ramp rates.
- Reactive power capability/control – provide 0.9 lagging and 0.95 leading at full power output. A portion should be dynamic, which differs for every province.
- Voltage control – be able to control the voltage at the point of interconnection.
- Frequency response – not a requirement now but may become one.
- Low Voltage Ride Through (LVRT) – ride through pre-defined low voltage envelope.

- Power system stabilizers – not a requirement.
- Data Provision – accurate stability models must be supplied.
- Operational monitoring – provide information to the TSO such as MW, MVar, wind speed, and site temperature. The wind plant must be capable of accepting TSO commands.

The Canadian provinces used the base code as a framework but developed their own unique grid code language over the next few years. Manitoba and Quebec, for example, adopted a unique requirement that ensures ride through for 4 Hz/second frequency variations. A temporary 900 MW limit on installed wind capacity was imposed in 2006 in Alberta so that that their grid code could be updated to include forecasting and wind power management (power limiting and ramp rate control). Currently, Canada has close to 13,000 MW of wind supplying between 2 and 12% of the provincial demands. While the provincial grid codes have ensured overall grid reliability so far, there are some notable trends:

- The grid codes are being expanded to include specific requirements for new technologies such as utility scale solar and battery energy storage.
- The provision of frequency control is becoming mandatory for all generators.
- Validated electromagnetic transient models are being requested in addition to traditional stability models.
- New wind facilities are being requested to be capable of providing a fast frequency or synthetic inertial response.

Grid code trends in China

At the beginning of 2017, China started to upgrade the grid code for wind power interconnection. The main purpose of this upgrade is to improve the behavior of wind power to support the grid and ensure system reliability, considering that the penetration of wind power will increase significantly in the next ten years. The new requirements refer only to the newly built wind plants, not retrofitting existing wind plants.

The grid operational behavior has been dramatically changed with the increasing penetration of renewable energy, and displacement of conventional synchronous generators. Several issues being addressed as a result follow:

- The absence of voltage and frequency regulation capability of renewable energy generators may cause a deterioration of the disturbance recovery capability of the bulk power system.
- Because of the lower voltage and frequency tolerance of wind and PV generation than conventional synchronous generators, large renewable generation outages may occur during Ultra High Voltage Direct Current (UHVDC) system blocking faults.
- The system stability modes are changing in a more complicated way because of the interactions between power electronics fed by renewable generation with UHVDC systems.

Several new technical requirements are still under consideration during the development of the grid code. This includes high voltage ride through capability with a 500-millisecond duration of 1.3pu system over-voltage at the point of connection; inertial response; and primary frequency regulation capability with 6% headroom of rated power, with a response time of 12 seconds, which is faster than conventional generation. These new required functions of wind turbines (and wind plants) normally do not require additional hardware installations but may be achieved by re-adjusting the controls or software settings, which incurs very minor incremental cost.

The situation in the Australia National Electricity Market (NEM)

In 2018, new generator technical standards came into effect, which included several new and modified requirements for large generating systems. In particular, the changes introduced additional requirements to ride through successive disturbances, modified requirements for reactive current injection (with distinct requirements for synchronous and asynchronous generating systems), as well as other key changes relating to active power and frequency control capability. This was the NEM's most detailed review of generator technical requirements since 2006-07, when changes were first made to accommodate grid-scale asynchronous generating systems.

Additionally, in 2017-18, system strength impact assessment rules and guidelines were introduced in the NEM to ensure adequate assessment of asynchronous generator performance in weak networks, including associated provisions for connecting generators to remediate any resulting adverse system strength impact, as illustrated in Figure 4. The assessment of system strength and weak grid phenomena is undertaken to identify whether there is an adverse impact on the ability of the power system to maintain stability and is based on detailed wide-network modelling using EMT analysis techniques using PSCAD.

Substantively, wind and solar resources are connecting to weakly interconnected fringe areas of the grid, remote from synchronous machines, resulting in these key challenges:

- In areas where synchronous generators have traditionally been located, there is an increasing need to manage high voltages on the extra high-voltage (EHV) transmission system network through line switching and out-of-merit generator dispatch during light-load conditions;
- In areas where asynchronous generators are proposing to connect, single contingency risks as well as prior planned or unplanned outages are resulting in significant constraints on asynchronous plants due to potential control system instability in these circumstances, as well as an emerging need to limit generation to mitigate spinning reserve requirements.

Added to this, recent events have demonstrated the significant effects of withdrawal of primary frequency response capabilities in the NEM and highlighted the need for greater emphasis on modelling of frequency control systems and establishment of DER performance requirements.

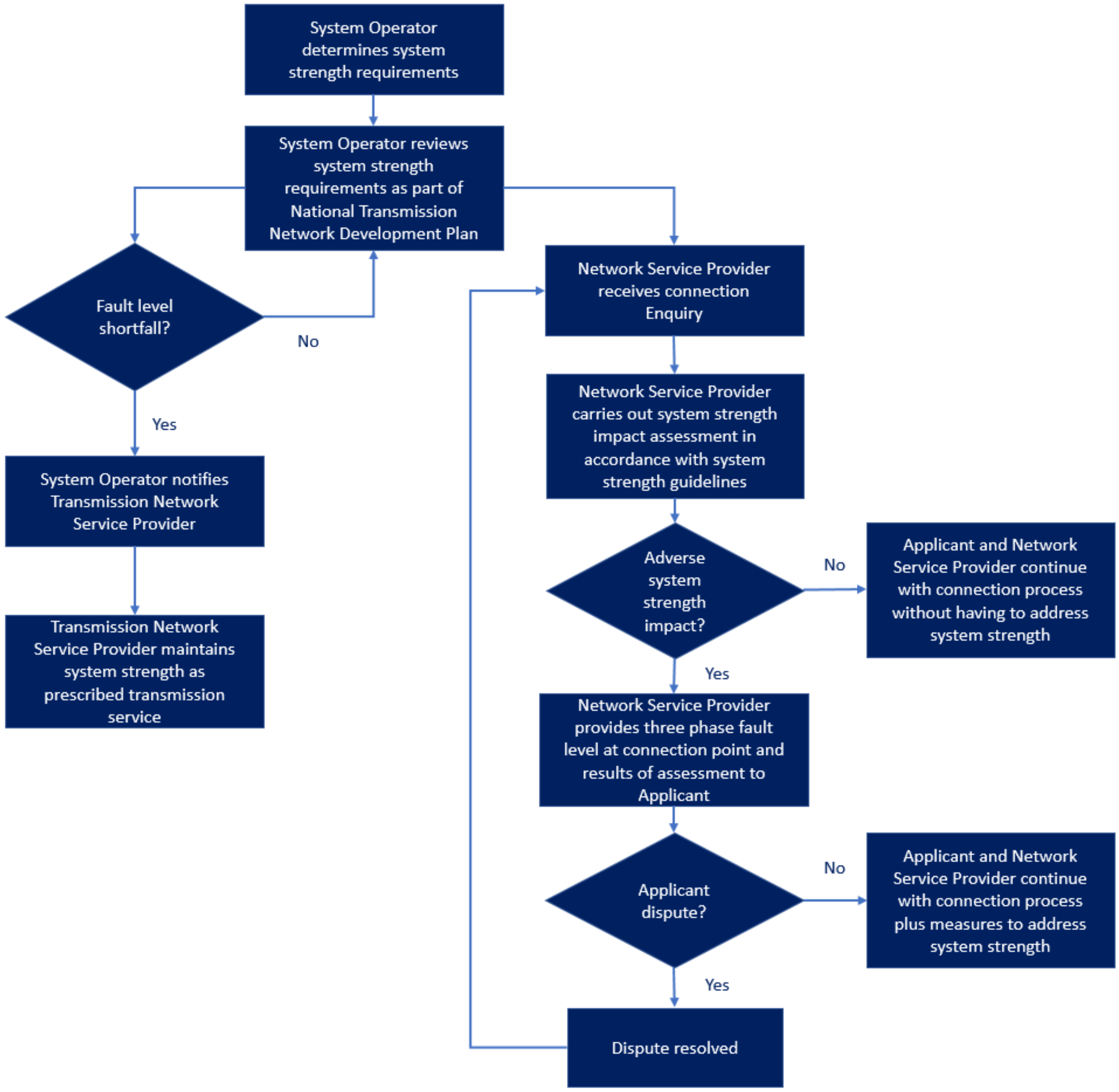

Figure 4: System strength framework within the NEM

Stakeholders' Roles and Collaboration in Standards Development

Roles of industry stakeholders in standards development process

As the NERC IRPTF has shown, regulators working collaboratively with industry stakeholders, equipment manufacturers, and other industry experts has led to rapid progress and understanding of rapidly evolving technologies and capabilities. The integration of inverter-based resources has many challenges as well as many opportunities. Understanding the balance between these is critical. It is important for policymakers and regulators to stay informed about key issues and the various means by which these issues can be addressed. Grid codes, interconnection requirements and standards should continue to evolve as generation, transmission, and distribution technologies evolve. In some cases, the standards applicable to one area may be suitable for others as well; however, in other cases, applying standards from one area to another without considering the context of their contents can and has led to significant industry challenges.

Universities and research institutes play an important role in the development of standards. They help bridge the gap between research and applied science, at the time when the technology and methods are mature enough to be standardized. The participation of universities makes it possible to build a solid analytical base, which helps justify the content and increase the credibility of the standards. As opposed to industry stakeholders, universities do not have direct commercial interests in the standards, and therefore they often play the role of independent moderator, acting as members and conveners of working groups. Their participation in the development of standards is also very useful to the universities, who can use the industry collaboration and the standards to improve the education process and direct research to better benefit technology development.

Harmonization and collaboration are crucial in standardization

When developing system-level integration standards or grid codes, there should be a balance among the needs of grid operators for reliable service, the needs of customers for minimal costs, and the needs of society for a sustainable future, as Figure 5 points out. Requirements should be no more specific than they need to be to avoid over-designed equipment and reduced efficiency, but should be specific enough to maintain adequate system reliability. All three of these needs are rapidly changing. Market design and system requirements should promote performance needs so that any provider using any technology can support the grid on an equal cost-sensitive playing field.

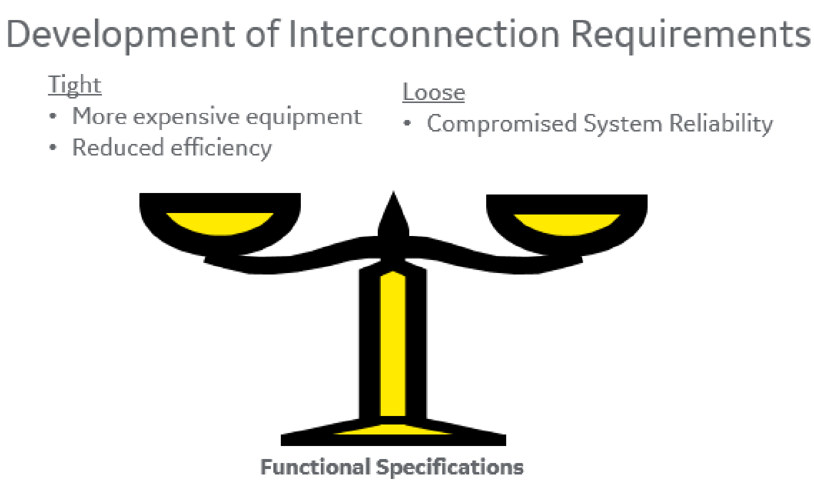

Figure 5: Development of interconnection requirements is a balance of functionality vs. cost

Grid codes may be developed at the national level or at the grid company level. They may be developed over time based on experience gained locally or by leveraging experience from other areas of the world. The early grid codes for wind were flexible and allowed for early adoption of the technology based on lower penetration levels. As reliability issues were discovered, the grid codes were tightened. This

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approach has led to wide-spread adoption of wind but has also created a difficult time for manufacturers to adopt a wide range of specific requirements. IEC has suggested that the time is right to develop an international framework document to assist in writing more consistent grid codes.

Summary/Moving Forward

In the end, interconnection requirements, grid codes and standards have a great deal of influence over how the power system is built, how it operates and how it performs. As technology develops, these requirements may serve as an enabler to unlock the best available performance of certain functions, such as frequency response or ride-through of disturbances. However, if overprescribed or immune to costs of implementation, they can also inhibit the very function they are trying to enable. Standards also highly impact the penetration of generation technologies, since cost of capability and compliance are closely linked. If the technology is too expensive for investors, it won't be installed or deployed, no matter how beneficial it may be for system reliability. A key factor in determining how this plays out is the coordination between generation and transmission infrastructure as we re-orient grids to new forms of generation (including rapidly emerging battery energy storage plants as illustrated in Figure 6), and tune-up controllers to react with lightning speed.

There are many groups, task forces and drafting teams discussing similar challenges and risks in parallel, well beyond what was mentioned in this article. The interest and sharing of knowledge in these many forums are at an all-time high and monumentally important. However, the level of dialogue opens the risk of diversion, and there is much greater need to focus on harmonization of requirements. Requirements developed by organizations like IEEE and IEC influence grid codes and regulatory requirements, and vice versa. Poorly harmonized or conflicting requirements cause very costly development and deployment of equipment, which again feeds back to the technology mix and reliability discussion. Development of standards needs subject matter experts to participate and collaborate to get it right. There are many possible paths to resolving the new era of stability and reliability challenges posed by new technology. These paths have the potential to open and enable further groundbreaking capabilities (refer to the first article on grid forming!), but only if the requirements are balanced with solid investment and incentive structure to back it up. Technology development is an iterative journey of new requirements pushing the envelope and the policy supporting it. Grid planners and operators, manufacturers, generation owners, regulating bodies, public commissions and universities all have a unique perspective and a critical role to play. All need to contribute. Your knowledge and expertise are needed in the intensely dynamic world of standards. Get involved!

Figure 6: The world's largest Li-ion battery installed in South Australia, 100MW/129MWHr

For Further Reading

M. Leblanc, L. Evans, P. Gardner, N. Scott, and S. Whittaker, "Canadian Grid Code for Wind Development - Review and Recommendations," https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/2006-075_%2528TR%2529_411-INTERC_Leblanc_Evans_Gardner_Soctt_Wittaker_e.pdf

J. O'Sullivan, Y. Coughlan, S. Rourke, N. Kamaluddin, "Achieving the Highest Levels of Wind Integration-A System Operator Perspective," IEEE Transactions on Sustainable Energy, vol. 3, no. 4, pp. 819-826, Oct. 2012.

G. Irwin, A. Jindal, A. Isaacs, "Subsynchronous Control Interactions Between Type 3 Wind Turbines and Series Compensated AC Transmission Systems," IEEE Power and Energy Society General Meeting, 2011.

IEC White Paper: Grid Integration of Large-Capacity Renewable Energy Sources and Use of Large Capacity Electrical Energy Storage, October 26, 2018 https://www.iec.ch/whitepaper/gridintegration/

NERC Reliability Guideline: Integrating Inverter-Based Resources into Low Short Circuit System Strength Systems, December 2017 https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Item_4a._Integrating%20_Inverter-Based_Resources_into_Low_Short_Circuit_Strength_Systems_-_2017-11-08-FINAL.pdf

"Final Report – Queensland and South Australia System Separation on 25 August 2018", Australia Electricity Market Operator, January 10, 2019 https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2018/Qld---SA-Separation-25-August-2018-Incident-Report.pdf

Authors

Jason MacDowell is with GE Energy Consulting in Schenectady, NY, USA;
Yingying Wang is with Arizona State University in Tempe, AZ, USA;
Ryan Quint is with the North American Electric Reliability Corporation (NERC) in Portland, OR, USA;
Yongning Chi is with the China Electric Power Research Institute (CEPRI) in Beijing, China;
Bernie Ernst is with the Fraunhofer Institute in Kassel, Germany;
Steven Saylors is with Vestas in Portland, OR, USA;
David Jacobson is with Manitoba Hydro in Winnipeg, Manitoba, Canada;
Björn Andresen is with Aarhus University in Aarhus, Denmark
Poul Ejnar Sørensen is with the Technical University of Denmark (DTU) in Copenhagen, Denmark;
Raphael Portales is with ABB in Madrid, Spain;
Dan Brake is with ARESCA in Norwich, VT, USA;
Bob Zavadil is with Enernex in Knoxville, TN, USA;
Luke Robinson is with Australia Electricity Market Operator in Melbourne, Australia;