Grid Reliability Under High Levels of Renewables: Rethinking Protection and Control

A GUIDE FROM ESIG

Power systems that incorporate high levels of renewables constitute a major part of a comprehensive response to climate change. However, the change in the resource mix presents certain challenges for grid reliability. The major practices undergirding the stability of the grid were defined in an era in which synchronous generators—coal, gas, hydro, and nuclear generators with spinning masses—were the only game in town. As a result, protection schemes have been centered around their inherent characteristics, particularly their synchronous inertia and their high short-circuit currents in response to nearby transmission systems faults on the grid. Going forward, protection schemes for power systems combining synchronous generation with high levels of renewables will need to change, both accommodating inverter-based technologies and drawing upon the untapped design flexibility they offer.

A New Look at **Reliability**

The contributions of synchronous and non-synchronous resources to grid stability and system events differ in many respects. Reliability, therefore, has to be considered in light of the strengths and capabilities of the entire range of technologies available today and the direction of change in the future. This includes not just what's possible with commercially available inverter-based generation today, but what is technically possible—the broad spectrum of options that these technologies bring.

General objectives for grid reliability include tolerating design basis events, returning to acceptable conditions following a disturbance, and avoiding cascading failures. The most economic and reliable outcomes will follow from allowing and encouraging the evolution of new technology, particularly from inverter-based resources, that meets these objectives—without being prescriptive of the means by which the objectives are achieved.

This paper explores differences in tolerance to disturbances, responses to disturbances, and blackstart capability between a grid dominated by synchronous generation and a grid accommodating a diverse mix including substantial amounts of non-synchronous generation. Increased levels of non-synchronous generation are bringing changes to many facets of grid stability: how conditions under which frequency variations need actions are defined, what corrective actions are available when necessary, and the time required to respond.

Tolerance to Disturbances

Today's non-synchronous, inverter-based resources can provide better performance during disturbances that would cause synchronous machines to either lose synchronism or exhibit unacceptable oscillations. Inverter-based resources, such as wind and solar generation, tend to have superior transient stability characteristics, which has important practical implications. Export of power from remote locations in a grid (e.g., remote wind or fossil plants) will tend to have higher transfer limits with today's inverter-based generation compared to synchronous machines. More power can often be delivered with the same transmission infrastructure.

Response to Disturbances

Importance of frequency in a grid dominated by synchronous generation.

For disturbances—typically a loss of generation—on a grid in which synchronous generation predominates, changes in frequency serve to communicate to other generators that a disturbance has occurred and they should respond by adjusting their power level if they can do so. A key element of today's requirement for a minimum commitment of synchronous generation on the bulk power system stems from the design of most utility-scale inverters. Currently, these inverters are of the grid-following type, requiring an established grid frequency with a minimum system strength provided by synchronous generation. Reasons for this constraint include good current sharing and natural coordination between parallel inverters, good use of converter current ratings, and good transient stability.

However, the requirement of an established grid frequency is not an intrinsic characteristic of inverters but rather a function of their design at this point in time. To date, there has been little technical or economic motivation for the design of grid-forming inverters, which can establish grid frequency and voltage on their own. This is changing, as applications and operating conditions emerge in which the sole dependence on synchronous generation is problematic. Fortunately, proven concepts exist for addressing such issues. One class of these are the virtual synchronous machine controls that make inverters act like synchronous machines. It is an attractive and conceptually appealing idea, and the industry is capable of making inverters this way today. It would be a mistake to create rules or policy that entrench today's synchronous generators as the standard of performance; inverters offer degrees of design flexibility that present an opportunity to do better.

Role of inertia in extending response time.

The avoidance of blackouts requires a rapid response to reductions in system frequency. Traditionally, a high value has been placed on inertia because it extends the time frame within which corrective action can be taken. Reduced levels of inertia can be a concern in systems dominated by synchronous machines because when inertia is lower, system frequency drops faster during loss of generation or infeed events, leaving less time for frequency response.

However, inertia is just one tool. For effective responses to disturbances, the central need is not for inertia per se but for corrective action to be feasible within the time available. Inertia sets the initial rate of frequency decline: more inertia means more time for the system to employ frequency response. Since inertia is not a requirement in and of itself, but rather a mechanism to buy time while frequency support can act, the critical question is not "how do we ensure sufficient inertia?" but rather "how do we ensure reliability?"

Response time and frequency response with higher levels of non-synchronous generation.

Grid stability under higher levels of renewables involves approaches distinct from those used today for synchronous generation. Wind, solar, and storage are capable of providing fast frequency response, responses so rapid that they sometimes need to be slowed down to allow conventional resources to see the event and respond properly.

For example, much of the maladaptive behavior of the utility-scale solar plants in recent events in which solar plants failed to ride through certain transmission faults stemmed from overly aggressive response to measured frequency. Synchronous machine speed is often used as a proxy for system frequency. But inverters calculate frequency from measured local voltage waveforms, which can change instantly (unlike machine speed, which cannot). Attempts to measure and respond very rapidly to measured frequency changes can have unintended consequences. Extremely fast measurements based on voltage can be misleading or even meaningless. For example, in the Blue Cut event, inverters were set to block instantly for measured frequency substantially outside of nominal 60 Hz. This led to the unintended and incorrect tripping of multiple PV plants.

The cautionary lesson is that faster isn't always better, especially when responding to measured frequency. Control and protection philosophy should be guided by "as fast as necessary," not "as fast as possible." In this case, the majority of the inverters were quickly modified to eliminate this particular problem—primarily by slowing down the protection so that frequency measurements were meaningful. The response of the industry to the event is representative of good practice that should be continued: (a) watch for unexpected behavior, (b) investigate and understand, (c) look for practical solutions. Making sure that protective functions on inverter-based resources are both understood and not unduly sensitive has become very important.

Distributed generation is also becoming a major factor in response to disturbances. Growth of distributed resources makes traditional under-frequency load shedding (UFLS) progressively more uncertain and less effective because the amount of load that was assumed when the load-shedding scheme was defined may increasingly be modified by embedded distributed generation. The disconnection of feeders with a significant amount of solar generation in response to dropping frequency is counter to grid reliability.

A strong case can be made that UFLS is reaching the end of its utility and that adopting rules and market strategies that are primarily aimed at preserving this particular facet of system practice is uneconomic. As system inertia declines, UFLS must act more quickly and be more precise in the amount of load interrupted in order to be effective. First, as you act more quickly, it becomes more challenging to measure frequency and meaningfully differentiate events that require UFLS from other transient disturbances. Second, the growth of distributed PV makes it difficult to know precisely how much load is being interrupted. Consequently, the efficacy of UFLS is declining, especially for the massive events for which it is typically targeted.

Much of the current thinking is geared toward maintaining minimum levels of inertia. But the economic consequences of trying to maintain higher levels of inertia than naturally occur with economic unit commitment will continue to become more onerous. One alternative to UFLS is the use of new protective schemes, which complement, and may gradually displace, traditional UFLS.

Protective Schemes for More Diverse Generation Mixes: **Remedial Action Schemes** and **Special Protection Schemes**

There is a range of dependence on remedial action schemes and special protection schemes (RAS/SPS) across the United States. These schemes augment conventional protective relays by use of additional computation and communications capabilities. For example, in the Western Interconnection, the system relies on a variety of specific schemes to allow acceptable response to some large disturbances. For many years, a scheme has been in place that responds to a trip of the Pacific DC Intertie by tripping generation hundreds of miles away. The sophistication of such schemes is growing, as both computation and communication get faster, cheaper, and more reliable.

Synchrophasors, which provide rapid simultaneous grid measurements, are one type of device introducing a host of new options. In the UK, these are being used to understand how and where the system is breaking up during extreme events, increasing the resilience of the system. They are also being considered in the development of protective relaying for identification and localization of grid faults—a problem made more difficult by the lower levels of short-circuit current delivered by inverter-based generation. Now that new generation resources are available that can respond much faster than traditional synchronous resources to disturbances, methods of response and control based on synchrophasors could become a new reality and a powerful tool.

Utility people are wary of RAS and SPS because these tend to be complex and their performance is highly dependent on system topology and operating condition. Consequently, these approaches may need to be armed for only specific operating conditions, and they will need to be monitored and updated as the grid topology changes. In addition, a number of significant institutional challenges need to be addressed: people who understand the schemes move on or the grid topology and generation locations change, and the scheme no longer works as intended. Customized hardware and software must be monitored, tuned, repaired, or replaced.

But the efficacy of a properly designed schemes can be high, potentially removing operating constraints for large operating cost savings and better market function. The investment in the systematic integration, development, and monitoring of RAS/SPS, including the institutional changes (and costs) needed to address these concerns, can yield major returns. A new generation of RAS/SPS will provide an important set of tools to system operation and planning, and synchrophasor applications extending into the distribution system can be expected to play an important part.

System **Restoration**

Today, system restoration plans nearly always rely on fossil and hydro synchronous generation. When configured to provide blackstart, these resources can start with no grid and be used to initiate energization. They are grid-forming resources and are the first step in system restoration.

Renewables are not currently part of system restoration plans because of the complexity of system restoration—as islands of load and generation are created, balanced, and interconnected—and because wind and solar generation are variable and (at present) not grid-forming. However, as more fossil generation retires and as some resources withdraw from offering blackstart services, it will soon be time to augment the traditional resources.

In the not-too-distant future, the penalty for leaving variable renewables and other inverter-based resources out of system restoration plans will prove to be economically untenable, as that would entail keeping fossil units around to provide this service when they would otherwise be retired. Bringing wind, solar, and battery storage into restoration planning will require new thinking and new functionality: (1) even without grid-forming inverters to provide blackstart, they can (and probably will need to) contribute to successful system restoration after local voltage and frequency are established by blackstart units; (2) by taking advantage of currently available frequency- and voltage-sensitive controls, these resources could add speed and security to the process; and (3) as future inverter designs are developed, wind, solar, and storage should be able to provide blackstart themselves.

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Reliability in the low-carbon grid will look different from reliability today in terms of tolerance to, communication about, and responses to disturbances. Alternatives to conventional inertia will need to be pursued in a near zero-inertia grid, a new generation of grid-forming inverters will need to be developed and applied, new protection schemes and the use of synchrophasors will need to be examined, and system restoration practices will need to be updated. All of this is possible and necessary to maintain the reliability of the grid as we transition to the new energy future.

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