NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Performance of Distributed Energy Resources During and After System Disturbance

Voltage and Frequency Ride-Through Requirements

A report by the Integration of Variable Generation Task Force (Task 1-7)

December 2013

RELIABILITY | ACCOUNTABILITY

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Executive Summary

Overview

The amount of renewable energy resources interconnected to the electrical grid is predicted to grow rapidly in the future. Many of these renewable resources will be variable—such as wind generation and solar photovoltaic (PV) generation, which are referred to here as Variable Energy Resources (VERs). Some of these resources will be utility scale and interconnected to the bulk-power system (BPS) facilities, while other resources will be interconnected to subtransmission and distribution systems often behind customer metering facilities and not dispatched by the power system operator. Distributed energy resources (DERs) are generation resources that are distributed geographically and not centralized like traditional generation resources.

A large amount of distribution-connected generation may have significant effect on the reliability of the bulk power system. Existing interconnection requirements for DERs do not specifically take into account potential effects on bulk system reliability. Of particular concern to BPS reliability is the lack of disturbance tolerance, which entails voltage ride through (VRT) and frequency ride through (FRT) capability. Under high penetration scenarios, it is possible for a large amount of DERs to trip on voltage or frequency due to a transmission contingency, which could potentially affect bulk power system stability. The need for high frequency tolerance is being discussed as part of a current FERC stakeholder consultation on interconnection procedures for small generators[1] distribution-connected VERs. Like all other DERs, these resources are required to comply with IEEE Standard 1547, which at present does not contain any VRT or FRT stipulations. Instead, IEEE Standard 1547 requires DERs to disconnect from the grid within a short period of time after voltage or frequency fall outside a certain range. The results of the IEEE Standard P1547a ballot were announced in September of 2013, and the outcome was that VRT and FRT are now permitted, but not required.

This report discusses FRT and VRT potential requirements for VERs connected to distribution facilities, and the potential BPS reliability impacts if VERs do not remain interconnected, stable, and operational during and after normally expected momentary system disturbances. It reviews potentially inconsistent and conflicting requirements in existing standards for BPS-connected and distribution system-connected VERs. For illustration, it also provides example guidelines for suggested changes in the VRT and FRT requirements for distributed generation that may be necessary to maintain power system reliability. This report does not address reactive power capability or active/reactive control during steady state or transient conditions (e.g., current injection during the fault). Some of these related topics are discussed in other IVGTF reports. The IVGTF Task 1-3 report addresses performance of BPS-connected VERs during and after voltage or frequency disturbances. IVGTF Task 1-8 addresses potential reliability impacts of distributed resources.

Rapid Increase of Distributed Resources

This report focuses on BPS reliability considerations associated with the addition of a large number of DERs on the distribution system, and, in particular, with distributed wind and photovoltaic (PV) resources. Distributed PV deployment is already relatively high in some regions, such as urban areas in California where distribution-connected PV capacity approaches 3 GW. This trend is expected to continue or even accelerate in the future.

[1] See FERC Docket No. RM13-2-000.

Distribution-connected generation is growing fast in some areas due mostly to deployment of residential and commercial scale PV. The installed PV capacity reported by the Solar Electric Power Association (SEPA) was 7.7 GW at the end of 2012, with the capacity at the end of June 2013 reported at 10 GW. Of this amount, it is estimated that approximately 80 percent (8 GW) is installed on the distribution system.

For wind, at the end of 2012, the American Wind Energy Association (AWEA) reports the installed wind capacity in the US was 60 GW. Of this amount, it is estimated that approximately 5 to 10 percent (3 to 6 GW) is installed on the distribution system. Therefore, the total US VER capacity is currently approximately 70 GW, of which about 11 to 14 GW is installed on the distribution system, with distribution-connected PV growing at a faster rate than distribution-connected wind.

In Ontario, 2 GW of DER represents projects connected or underway.[2] Given Ontario is a 25 GW system; these penetration levels are quite significant. Current challenges exist mostly at the local distribution level with respect to power quality and coordination; though, IESO has noted connecting DER to distribution networks poses substantial challenges to operations as more DER is installed.

Recommendations

IVGTF 1-7 recommendations are summarized below. In addition to the recommendations, general guidelines are provided for illustration, recognizing that the need for specific requirements and any specific requirements themselves would have to be established through a stakeholder process when prudent, numerical examples are provided to clarify the intent and further substantiate the guidelines. The general guidelines are further described in Chapter 5 and 6 of this report.

The task force believes that NERC and other BPS stakeholders can play a constructive role in ensuring that the reliability implications due to lack of disturbance tolerance for distributed VER and other DERs are addressed. With this in scope, the following general recommendations are offered:

1. In the short-term, NERC should engage in current efforts to revise DER interconnection standards by providing information, raising awareness and encouraging the adoption of VRT and FRT for DERs. The initial focus should be on identifying the need for adopting minimum tolerance thresholds for VRT and FRT in the IEEE Standard 1547 and, then, establishing those minimums.

2. In the longer-term, NERC should establish a coordination mechanism with IEEE Standard 1547 to ensure that BPS reliability needs are factored into future DER interconnection standards revision efforts. To date, BPS stakeholders have participated only sporadically in the IEEE Standard 1547 process. As a result, VRT and FRT concepts receive limited consideration and may have been outweighed by distribution system protection concerns. This liaison process would be too late for the P1547a amendment, but it would be timely for the full revision to begin in December 2013.

[2] Ontario Power Authority (OPA): http://www.powerauthority.on.ca/sites/default/files/news/Q1-2013-Progress-Report.pdf
There almost 3GW of DER in total under contract with the OPA, but it is uncertain how much of the additional 1 GW will proceed at this time.

1. Introduction

The amount of renewable energy resources interconnected to the electrical grid is expected to grow rapidly in the future. Many of these renewable resources will be variable—such as wind and solar photovoltaic (PV) generation, which are referred to here as Variable Energy Resources (VERs). Some of these resources will be utility scale and interconnected to the bulk-power system (BPS), while other resources will be interconnected to subtransmission and distribution systems. A large portion of these VERs will be behind the meter and not dispatched by the power system operator. Currently, the total installed capacity of VERs exceeds 70 GW in the NERC footprint.

Distribution-connected PV generation is expected to grow very fast in some regions over the next decade. A large amount of distribution-connected generation or distributed energy resources (DERs) can have significant effect on the reliability of the bulk power system.[3] However, present interconnection standards applicable to DER do not address or take into account this potential impact. Of particular concern to bulk system reliability in North America is the lack of disturbance tolerance requirements for DERs, specifically voltage ride-through (VRT) and frequency ride-through (FRT). These concerns motivated IVGTF Task 1-7 activities produced this report.

In North America, VRT and FRT standards for both BPS-connected and distribution-connected generators are in a state of evolution. NERC Reliability Standard PRC-024-1 was recently approved as a relay setting requirement. The standard requires that generator voltage and frequency relays not be set to trip within the specified frequency and voltage performance envelopes, unless it is necessary to do so to protect equipment or meet one of several other exceptions. With respect to disturbance tolerance, DER interconnection standards are inconsistent with the direction in which bulk system standards are evolving.

IEEE Standard 1547 is the *de-facto* interconnection standard applicable to DERs in North America. Interconnection requirements applicable in Canada[4] are harmonized to a large extent with IEEE Standard 1547. IEEE standards are, by definition, voluntary; however, they may be made mandatory by regulatory authorities or by utilities to which interconnection is made. So, in practice, IEEE Standard 1547 is a requirement in most places but not universally in the NERC interconnections. Rather than VRT and FRT provisions, the existing IEEE Standard 1547 contains "must-trip" provisions for off-nominal voltage and frequency that raise the possibility of compounding transmission contingencies with sympathetic loss of significant amounts of distributed generation. These requirements were originally driven by safety and protection/control coordination of distribution systems, and did not consider the possibility of high penetration of DERs in the system. As DER capacity continues to increase, sympathetic DER tripping due to a BPS contingency could become significant enough to negatively impact bulk system reliability.

1.1 The Need for Disturbance Tolerance at the Bulk and Distribution System Levels

In order to ensure a high degree of reliability of the interconnected power system, it is imperative that bulk generation and transmission elements have a degree of disturbance tolerance. A principle of system protection is that elements should not be intentionally tripped unless it is necessary to clear a fault, to prevent equipment damage, or to preserve system stability. All other elements should remain connected to the grid and contribute to frequency and voltage recovery following the disturbance. Disturbance tolerance is a required element to

[3] S. Achilles, S. Schramm and J. Bebic, "Transmission System Performance Analysis for High Penetration Photovoltaics", Subcontract Report, NREL/SR-581-42300, February 2008. Access: http://www1.eere.energy.gov/solar/pdfs/42300.pdf

[4] CAN/CSA-C22.2 No. 257-06, Interconnecting Inverter-based Microdistributed Resources to Distribution Systems", 2006.

prevent cascading outages following voltage or frequency excursions that happen during normal system operation. This philosophy is reflected explicitly or indirectly in bulk-level grid codes or interconnection standards, including the recently approved NERC Reliability Standard PRC-024-1.

In contrast, with the expectation of disturbance tolerance for BPS-connected generators, IEEE Standard 1547 contains only must-trip requirements whereby DERs must disconnect within a short period of time when voltage or frequency fall outside a certain range. For example, a DER that experiences a voltage drop to 0.5 p.u. or lower would be required to trip within 10 cycles. This kind of voltage sag could occur over a fairly large area of the system during transmission system faults. While distribution facilities often have voltage regulation capability to offset voltage drops on the system, if the voltage drop is not countered this could exacerbate transmission contingencies and, in worst cases, contribute to a cascading outage if these contingencies are not studied and the effects properly mitigated per the TPL standards. Thus, under high penetration of DERs the existing provisions of the IEEE Standard 1547 could adversely affect bulk electric system reliability.

IEEE Standard 1547 must-trip requirements were in response to safety and protection/control coordination at the distribution systems level. When IEEE Standard 1547 was first developed, there were not large penetrations of DERs and BPS reliability was not a factor. It was not anticipated that distributed generation would be playing a significant role in power supply. In the near future, DER (especially PV) is expected to grow to the point that the must-trip requirements contained in IEEE Standard 1547 may play an important role in the transient behavior of the bulk power system following system disturbances.

1.2 Organization of the Report

In this report, IVGTF Task 1-7 evaluates the possible exposure of negative reliability impact on the BPS due to the lack of VRT and FRT requirements for DERs and provides general guidelines for the revisions to IEEE Standard 1547 to minimize this negative impact. Chapter 3 describes the existing disturbance tolerance in North America, at the bulk and distribution system levels. Chapter 4 discusses the potential reliability impacts related to high penetration DER with limited disturbance tolerance, and describes how some jurisdictions are addressing this issue. Specifically, the BDEW[5] Medium Voltage Standard is discussed. Chapter 5 surveys the treatment of disturbance tolerance at the bulk system level in various jurisdictions, and describes the status of the recent NERC effort to adopt NERC-wide FRT and VRT requirements. The intention is to identify reasonable approaches that can be considered in the context of DER interconnection standards for North America. Finally, Chapter 6 summarizes technical guidelines offered to NERC and other stakeholders for consideration.

[5] BDEW (Bundesverband der Energie- und Wasserwirtschaft) is a German association of energy industries.

2. IEEE Standard 1547

This chapter describes the existing IEEE Standard 1547 requirements for DERs related to voltage and frequency disturbances. Comparisons to bulk-level disturbance tolerance and relay setting requirements are made to illustrate differences in the approach. The significance of these provisions with respect to BPS reliability is discussed in Chapter 2.

IEEE Standard 1547 has established maximum disconnect times for abnormal voltage and frequeny. The standard states that DERs must *cease to energize* within the thresholds shown in Table 1. The specified maximum clearing time includes both relay time and breaker time, so DERs must commit to tripping before the must-clear time is reached. DERs are required to monitor and react to all phases to which they are connected. Reset logic is not required per the standard. According to the standard, clearing time is the interval between the start of the abnormal condition and the DER ceasing to energize. A proposal for P1547.8[6] (Recommended Practice for Expanded Use of DER) states that the reset logic should be based on the voltage-time product, but this is not specified in IEEE Standard 1547. This particular topic is discussed in the IVGTF 1-3 report.[7]

Table 1: Voltage and Frequency Disconnect Requirement Contained in the Existing IEEE Standard 1547

Voltage Range (% Nominal)	Max. Clearing Time (sec) *
V < 50%	0.16
50% ≤ V < 88%	2.0
110% < V < 120%	1.0
V ≥ 120%	0.16

(*) Maximum clearing times for DER ≤ 30 kW; Default clearing times for DER > 30 kW

Frequency Range (Hz)	Max. Clearing Time (sec)
f > 60.5	0.16
f < 57.0 *	0.16
59.8 < f < 57.0 **	Adjustable between 0.16 and 300

(*) 59.3 Hz if DER ≤ 30 kW
(**) For DER > 30 KW

In addition to the trip and clear requirements described above, IEEE Standard 1547 requires that DERs cease to energize for faults in the area electric power system[8] and prior to circuit reclosing. A related requirement is that DERs must detect an islanding condition and cease to energize within two seconds of the formation of the island. The stated purpose of the trip requirements contained in the existing IEEE Standard 1547 concern “performance, operation, testing, safety considerations, and maintenance of the interconnection.” Effectively, DERs are responsible for providing primary or backup fault detection and primary or backup islanding detection.

Although it isn’t explicitly stated in IEEE Standard 1547, the voltage and frequency trip functions in Table 1 have become integral parts of the fault and islanding detection schemes for many DERs. This dependence on voltage and frequency trip functions for system protection has contributed to the reluctance of stakeholders to adopt ride-through provisions in IEEE Standard 1547. DER vendors have supported the concept of Table 1 because it simplifies production and certification. However, reliability of DER output with respect to BPS-level grid disturbances has not been a concern in the context of IEEE Standard 1547.

[6] http://grouper.ieee.org/groups/scc21/1547.8/1547.8_index.html
[7] http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/2012_IVGTF_Task_1-3.pdf
[8] "Area electric power system" is a term used in IEEE 1547.

Note that the standard allows for some adjustability on the voltage and frequency trip times for DER larger than 30 kW. However, changing trip times does not convey disturbance tolerance requirements because DERs could (and do) trip at any time prior to the threshold to comply with the standard. There is nothing that limits setting the DER tripping more sensitively than the thresholds described in Table 1. In fact, a vendor might intentionally do so in order to pass UL-1741[9] islanding tests that only ensure that the unit disconnects before two seconds in a balanced resonant test circuit. Many DERs use a scheme to force voltage and/or frequency out of bounds in the event of an island, and the time for this scheme to be effective depends on the trip bounds; therefore, a tighter setting is a clear way to improve anti-islanding compliance.

Figure 1 depicts the voltage disconnect requirement as a voltage versus time chart. The region in red represents the must trip-and-clear requirement. DERs may trip and clear anywhere inside the dashed line to comply with the standard. When accounting for practical design tolerances, DERs can be expected to trip in the regions indicated in brown, but tripping closer to the boundary is preferable to minimize the possibility of frequent nuisance tripping. While the IEEE Standard 1547 does not define a must-run voltage range, DERs are usually designed to operate continuously within the ANSI Range A or Range B (0.95 to 1.05 or 0.9167 to 1.0583 per-unit voltage (pu), respectively),[10] although it should be recognized that the ANSI operating ranges apply only to steady-state conditions and not to disturbances. Figure 1 depicts the ANSI Range A for reference.

Figure 1: IEEE Standard 1547 Voltage Sensitivity

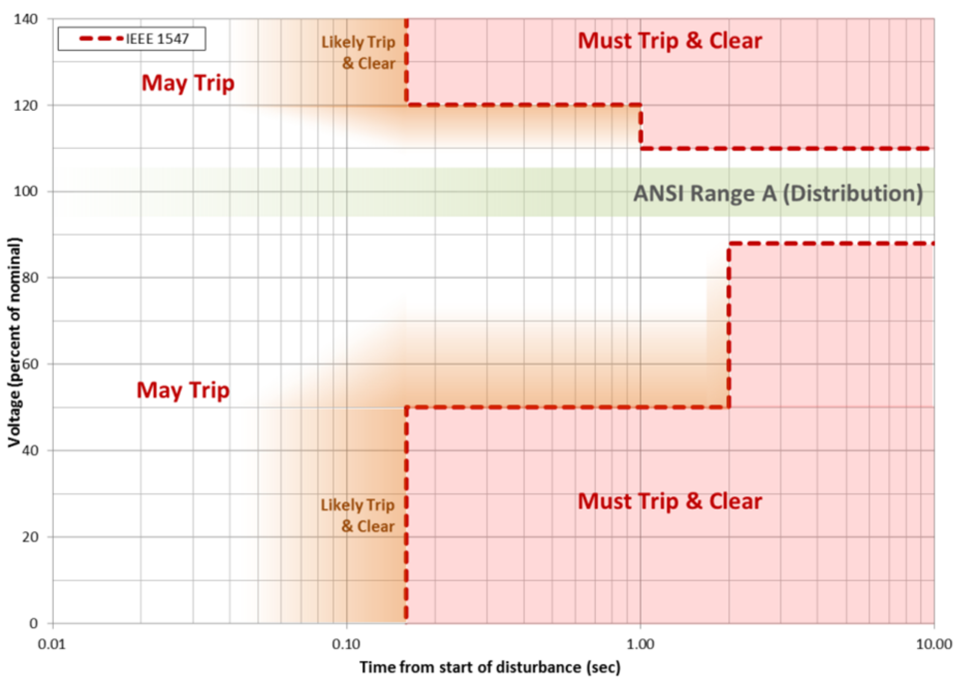


Figure 2 contrasts the IEEE Standard 1547 with the recently approved NERC PRC-024-1 relay setting standard,[11] the Hydro Quebec (HQ) VRT standard, and the LVRT requirement contained in FERC Order 661-A, which applies

[9] http://ulstandardsinfonet.ul.com/scopes/1741.html

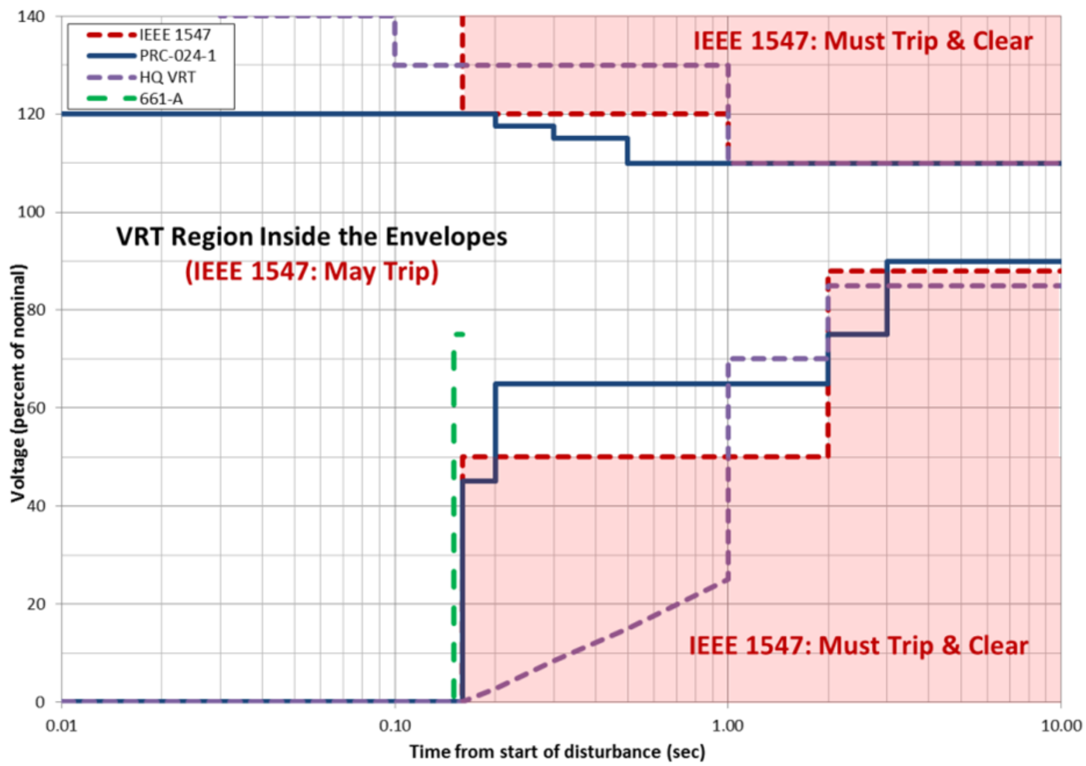
[10] ANSI C84.1, "Electric Power Systems and Equipment - Voltage Ranges"

[11] The NERC Standard PRC-024-1 only requires that voltage and frequency relays not be set to trip within the specified region, unless it is necessary to do so to protect equipment or meet one of several other exceptions. See Chapter 3 for additional discussion.

to wind plants larger than 20 MVA.[12] The area in which DERs may trip clearly conflicts with the notion of voltage tolerance conveyed by BES Reliability Standards.

Distribution and transmission voltages are closely related but are not the same. BPS reliability requirements are expressed in terms of transmission voltages. Determining specific distribution voltage limits that correspond to the transmission voltage limits requires additional analysis. Distribution and transmission voltages are both shown in this document to illustrate the reliability concern.

Figure 2: IEEE Standard 1547 Voltage Sensitivity Compared to Selected Bulk Level VRT Requirements



A similar argument can be made about the frequency disconnect requirement contained in the IEEE Standard 1547. Figure 3 shows the frequency must-trip-and-clear regions outside the dashed red lines, as applicable to DERs smaller than 30 kW. For DER larger than 30 kW, the high frequency must-trip region is the same, but the low frequency must-trip region is adjustable within the range of 57 to 59.8 Hz and 0.16 to 300 seconds. This adjustability range is represented by the area shaded brown. Extending the maximum must-trip time does not establish a requirement for better disturbance tolerance. The must-trip requirement leaves a narrow practical frequency region within which a DER may operate without tripping.

[12] Order 661-A states that wind plants must ride-through for faults down to zero volts for up to 9 cycles and stay connected during the voltage recovery period. The voltage recovery period is not defined.

Figure 3: IEEE Standard 1547 Frequency Sensitivity

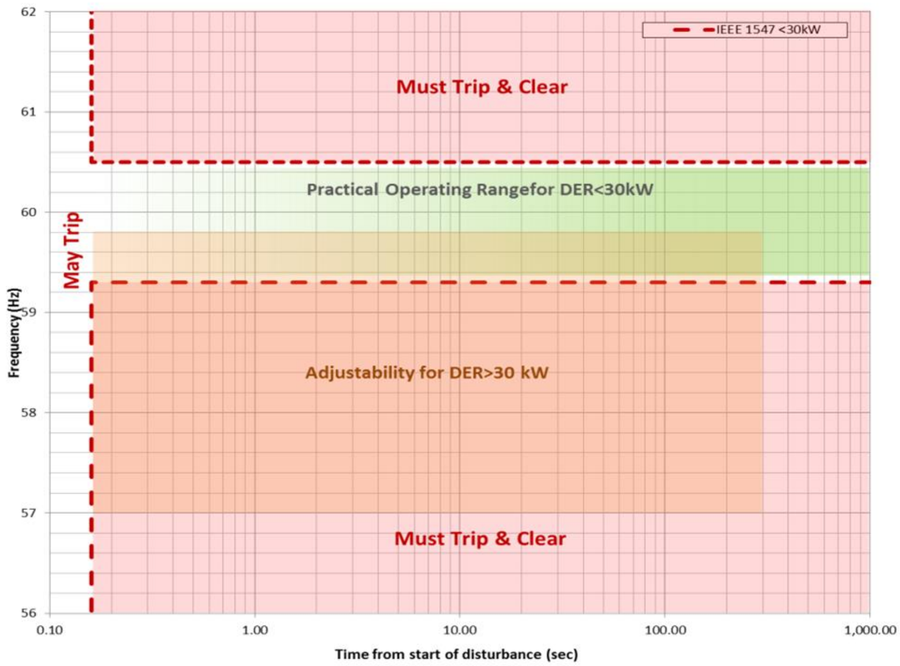
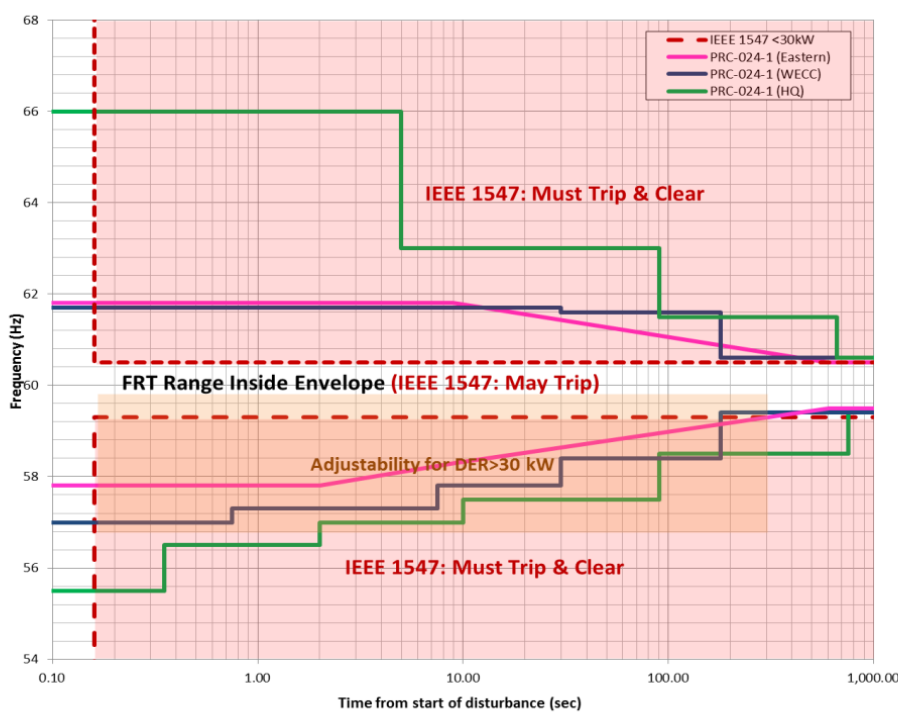


Figure 4 compares the IEEE Standard 1547 requirements with the recently approved NERC Standard PRC-024-1 applicable to frequency relay settings for BPS-connected generator protection.[13] This clearly shows that the IEEE Standard 1547 is not compatible with the notion of frequency ride-through.

Figure 4: IEEE Standard 1547 Frequency Must-Trip Compared to Selected Bulk Level FRT Requirements



13 The NERC Standard PRC-024-1 only requires that voltage and frequency relays not be set to trip within the specified region, unless it is necessary to do so to protect equipment or meet one of several other exceptions. See Chapter 3 for additional discussion.

3. Potential System Reliability Impacts

When DER levels in a given region can be significantly high, the concern is that BPS disturbances that would otherwise have negligible impact may challenge the IEEE Standard 1547 trip thresholds and, thus, become compounded by sympathetic tripping of a significant amount of DERs. In worst cases, this could lead to an increased exposure to system instability, under-frequency load shedding or cascading outages over large areas of the interconnected system. As noted in IEEE Standard 1547, the frequency and voltage trip settings were designed to protect distribution circuits and potential BPS system impacts were not the primary consideration. In most North American power systems, and especially in the Eastern Interconnection, DER penetration is low in most jurisdictions. However, DER penetration on some systems is increasing and has the potential to grow rapidly in the future. With this in mind, potential reliability issues need to be addressed proactively by updating and enhancing standards when gaps are identified. Revising standards and other interconnection requirements on the front-end is generally preferable to implementing costly retrofits to legacy equipment in the future.[14] Certain entities in Europe--particularly Germany where penetration levels on the distribution system are very high compared to the North American systems--have recognized this reliability exposure and have taken steps in the form of revised interconnection standards for DERs.

This chapter illustrates bulk power system reliability issues that can arise with the existing IEEE Standard 1547 trip thresholds, in a high penetration DER situation. Detailed studies have not been conducted to fully quantify the possible impacts; however, examples are provided based on assessments of DER deployment scenarios and operating experience.

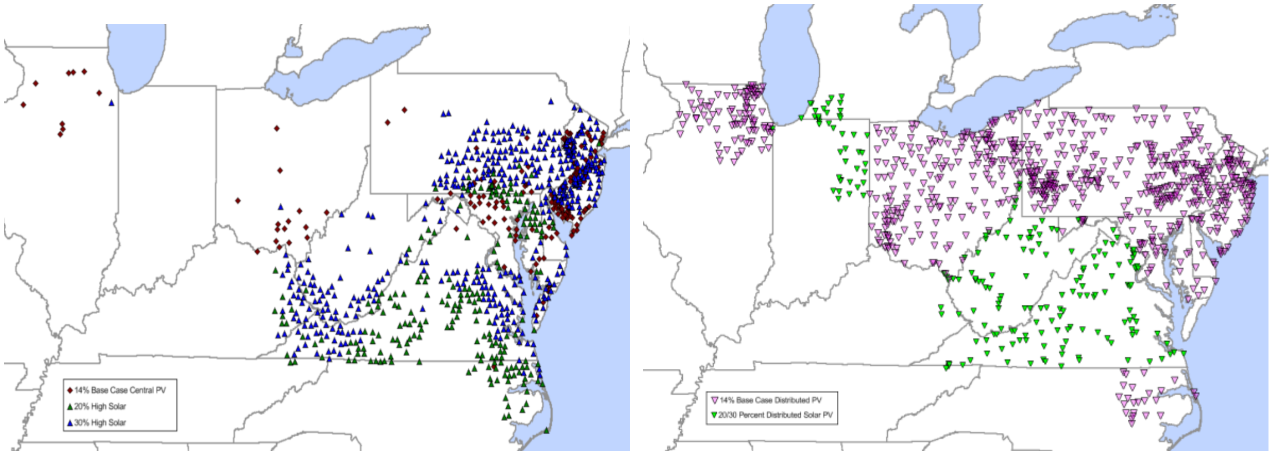
3.1 Voltage Tolerance

As of January 2012, approximately 4,800 MW of wind and 205 MW of solar generation are interconnected on PJM transmission (primarily) system. PJM has approximately 22,680 MW of wind projects and 1,650 MW of solar projects in the interconnection queue. A PJM Renewable Integration Study[15] illustrates that for the 2026 time frame, various scenarios estimate distributed solar PV to be about 4,100 MW in the base case and 34,710 MW in a high-solar penetration scenario case. The range in the scenarios is dependent on a number of factors, but is primarily attributed to the range of uncertainty in the timing and aggressiveness of respective state renewable portfolio standards. Figure 5 below shows expected locations of central and distributed solar resources in a high penetration scenario.

[14] The type of retrofitting likely depended on the specific installation. It could either be resetting adjustable parameters or replacing equipment.

[15] http://www.pjm.com/committees-and-groups/task-forces/irtf.aspx

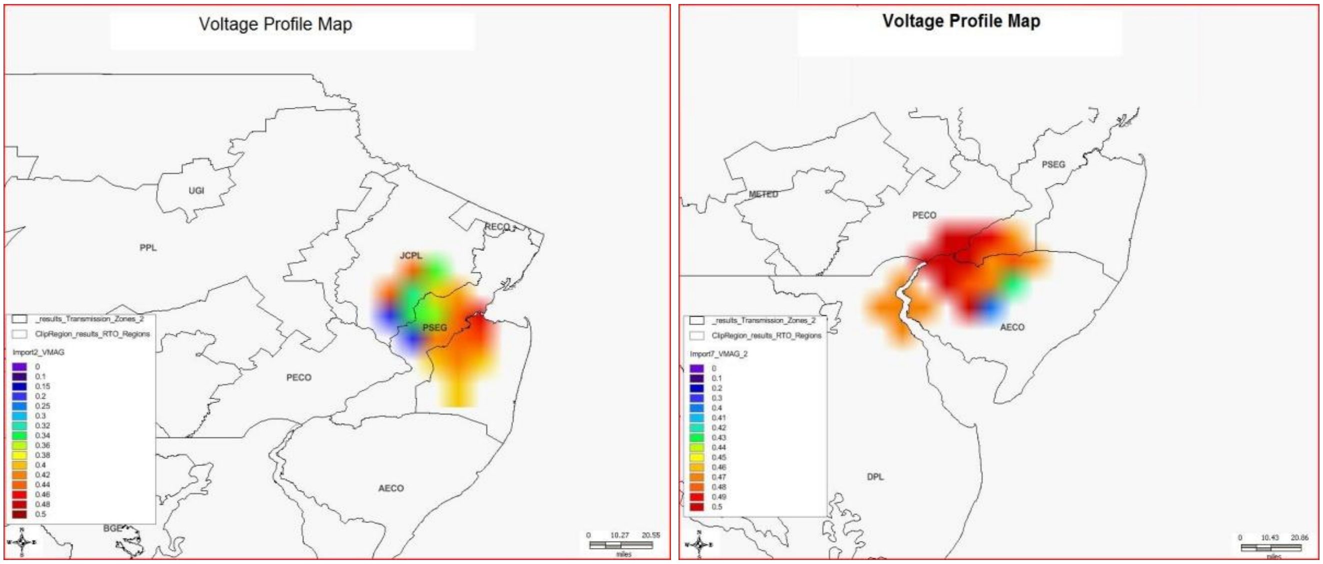
Figure 5: High Solar Generation Scenarios used in PJM Renewable Integration Study



According to the existing IEEE Standard 1547, DERs that experience voltage drop to 0.5 pu or lower at their interconnection point are required to trip within ten cycles (0.16 seconds). This kind of voltage sag would not be uncommon over a fairly large area of the system during transmission system faults[16]. In addition, since the DER trip requirement in IEEE Standard 1547 is a maximum trip and clear time, trip must be initiated before the clearing time. Figure 6 below shows the extent of voltage depression below 50% of nominal for BPS faults at various EHV locations. In the shaded areas, DERs connected to distribution circuits served from that portion of the transmission system are likely to trip on under voltage within ten cycles. It should be noted that, in this case, the fault is not on the distribution system, the distribution protective system is not required to clear the fault, and the possibility of a localized islanding situation does not exist. Yet, if the penetration of DERs in this region is high enough, a transmission contingency would be compounded which can potentially increase the probability of a cascading disturbance if not studied and properly mitigated. The Hawaiian Electric companies (Hawaiian Electric, Maui Electric, and Hawaii Electric Light) all have DER penetration levels that already affect the local bulk power system reliability. For this reason the DER frequency trip settings have been adjusted to the maximum duration/lowest frequency settings available. Voltage setting requirements are under evaluation.

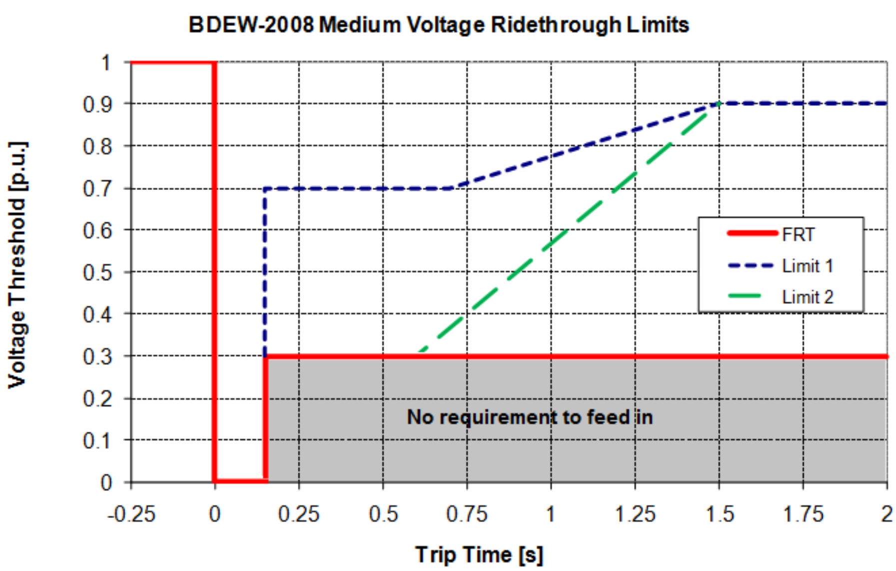
[16] Distribution and transmission voltages are closely related but are not the same. BPS reliability requirements are expressed in terms of transmission voltages. Determining specific distribution voltage limits that correspond to the transmission voltage limits requires additional analysis. Distribution and transmission voltages are both shown in this document to illustrate the reliability concern.

Figure 6: Voltage Contours of Voltages during Faults on Two Different Transmission Buses



The bulk system reliability issue described above has been recognized and is being addressed by reliability organizations in Europe. A German association of energy industries (BDEW) issued a recommendation for generator interconnection at medium voltage (i.e., distribution-level voltages) that is more in line with grid codes for interconnection with the BPS. Figure 7, taken from Technical Guideline of BDEW for Generating Plants Connected to Medium-Voltage Network[17] (published June 2008), shows the existing requirement for DER connected at Medium Voltage (10 kV to 60 kV) to remain connected without instability for voltage drops to zero at the interconnection point for 150 milliseconds.[18]

Figure 7: Borderlines of the Voltage Profile of a Type-2 Generating Plant at the Network Connection Point



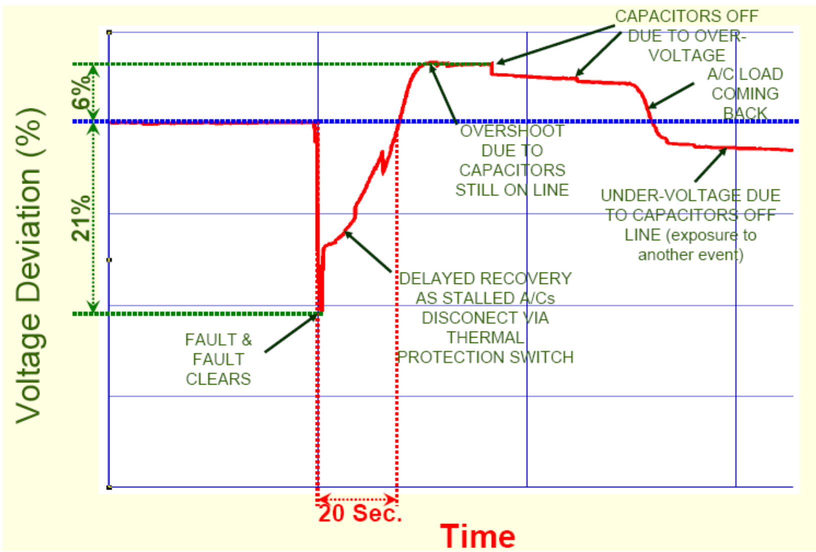
[17] BDEW (2008) Generating Plants Connected to the Medium-Voltage Network, June 2008 issue.
http://www.bdew.de/bdew.nsf/id/DE_7B6ERD_NetzCodes_und_Richtlinien/$file/BDEW_RL_EA-am-MS-Netz_engl.pdf

[18] Limit 2 is the overall requirement. Generators that are unable to meet Limit 2 may be allowed a lower requirement, down to Limit 1, if allowed by the system operator.

Adoption of this guideline was justified by reliability exposure similar to the scenario described above. Since the standard was adopted in April 2011, PV capacity in Germany has increased by more than 50% to 35 GW. Other jurisdictions have followed suit.

Fault induced voltage recovery (FIDVR) could also be exacerbated by under-voltage DER tripping. Figure 8 shows a typical FIDVR event. By definition, a FIDVR event lasts beyond fault clearing, possibly 10 to 20 seconds, and can be followed by high voltage due to switching of shunt devices as well as load tripping. With high penetration of DER in a load area, shunt capacitors and reactors configuration may be such that FIDVR could happen more frequently or more severely. DER tripping during the fault as well as during the FIDVR event would cause net load in the load area to increase, which can further delay voltage recovery and cause additional loss of load. For this reason, it would be advisable to consider longer voltage ride-through tolerance at a higher voltage (e.g., 70%).

Figure 8: Typical FIDVR event following a 230 kV Transmission Fault in Southern California[19]



3.2 Frequency Tolerance

Sudden changes in generation or load (such as that resulting from a large generating unit trip) result in system frequencies deviating from their normal ranges. Over a short control period, system frequency regulation controls like generator governors and Automatic Generation Control (AGC) would restore system frequency to within its normal range. However, if additional generation or load trips due to this frequency disturbance, it has a potential to amplify the disturbance and adversely affect system reliability. Therefore, to preserve system reliability, it is desirable for generators connected to the electric system to ride through such frequency disturbances, remain interconnected and stable, and continue operating close to their pre-disturbance levels. Overly sensitive frequency DER sensitivity could result in a frequency disturbance becoming compounded due to DER tripping, which delays frequency recovery and possibly leads to further under-frequency load shedding.

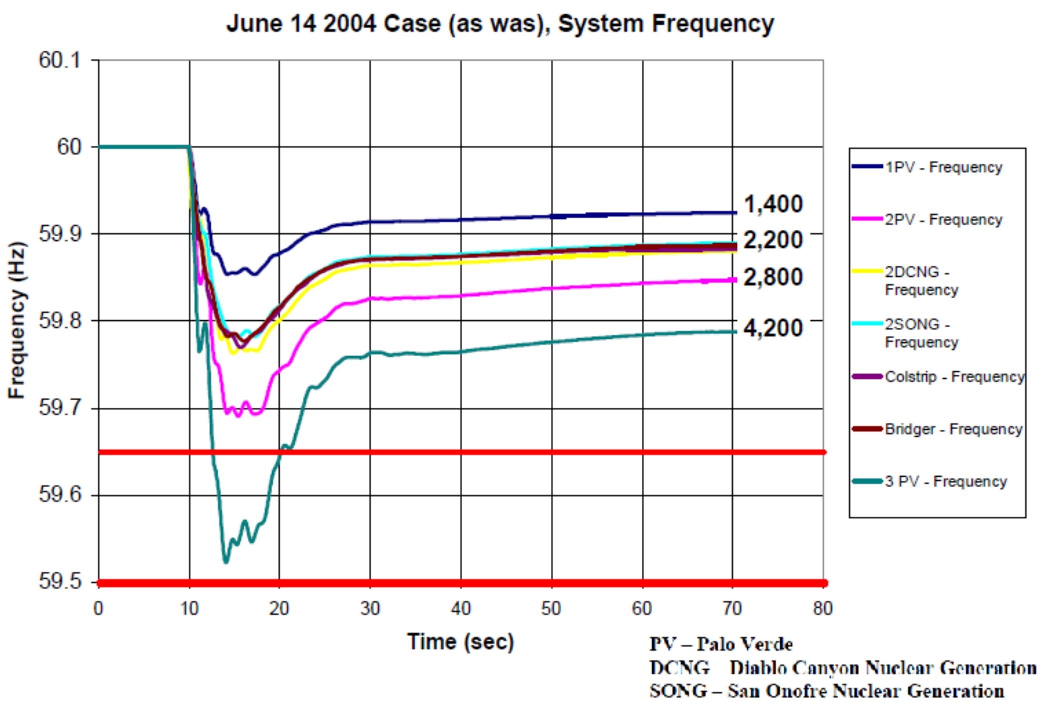
As discussed in the previous chapter, IEEE Standard 1547 requires DER to disconnect within 160 ms when frequency is above 60.5Hz, or below 59.8Hz (upper range of adjustability for DER >30 kW). In the Western Interconnection, a generation contingency of 2,000 MW could cause frequency to decrease to near or below 59.8

[19] NERC publication: "A Technical Reference Paper Fault-Induced Delayed Voltage Recovery", V1.2, June 2009

Hz for several seconds (Figure 9). A survey of the Western Interconnection generation contingencies for the time period of 1994 to 2004 shows that this level of generation loss happens roughly once a year.[20] For the same generation loss, frequency dip would be greater in a smaller interconnection and during light load periods. In a high penetration DER scenario, the possibility of significant DER tripping on under-frequency would impact the level of reserves required to ensure adequate frequency recovery.

As DER grows, tripping at frequencies not coordinated with system protection, and which are reached by contingencies, essentially increases the size of potential contingencies. To further complicate matters, the actual amount of MW from variable DER is difficult to determine in real time as it is not generally monitored; therefore, challenging to include as a consideration in operating reserves. Loss of DER during low-voltage transmission events will result in a net load increase, which will exacerbate low-voltage conditions and potentially result in collapse.

Figure 9: Western Interconnection Frequency for Various levels of Generation Loss[21]



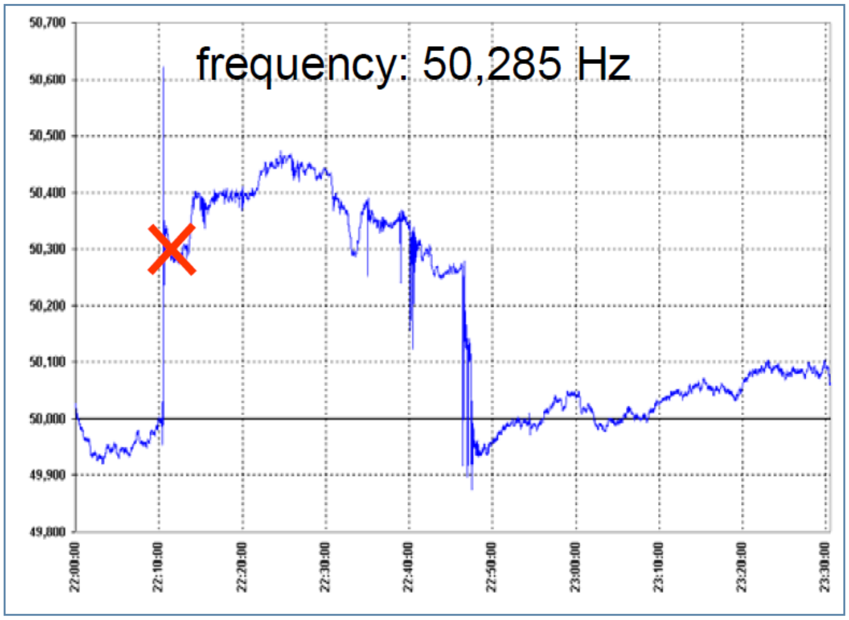
Under certain conditions, high frequency could also pose a reliability risk, and this has been recognized in Europe. In Germany, the applicable standard DIN V VDE V 0126-1-1:2006-02 requires that DER disconnect within 0.2 seconds when frequency reaches 50.2 Hz. Several other European countries use this standard as well. During the 2006 UCTE[22] event, frequency in the Eastern portion of the system rose above 50.2 Hz (Figure 10). With the amount of DERs in the system today, the generation loss could have threatened the stability of the grid.

[20] White Paper Frequency Response Standard Reserve Issues Task Force, November 24, 2005.

[21] N. Miller and Z. Ye., *Report on Distributed Generation Penetration Study*, NREL Technical Report NREL/SR-560-34715, 2003. Access:www.nrel.gov/docs/fy03osti/34715.pdf

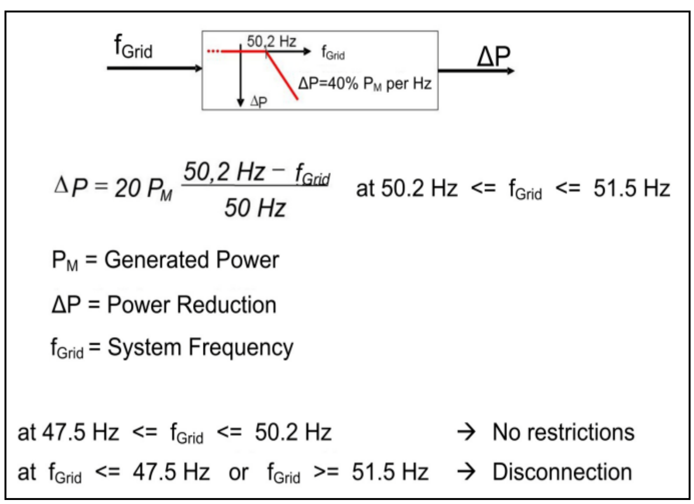
[22] Union for the Coordination of the Transmission of Electricity (Europe): https://www.entsoe.eu/index.php?id=102

Figure 10: High Frequency in Eastern Portion of the UCTE System Following the Nov. 2006 Breakup[23]



Recent efforts to address this reliability exposure, known as the 50.2 Hz problem, led to the adoption of requirements such as the BDEW high frequency droop, depicted in Figure 11. The concept is DER output power will, in aggregate, be reduced in proportion to frequency and then return as frequency is restored rather than drop to zero. Concurrently to adoption of this requirement, a DER retrofitting campaign was undertaken to address the reliability exposure of the existing DER capacity.[24] A similar retrofitting program was required in Spain to address wind generation low voltage ride-through.

Figure 11: Germany's (BDEW) Solution to Address Challenges—NERC is Proposing the Same



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[23] www.vde.com/de/fnn/arbeitsgebiete/tab/documents/dr_grebe_50-2-hz-problem.pdf

[24] [ECOFYS 2011] Boemer, Burges, Zolotarev, Lehner, Wajant, Fürst, Brohm, Kumm: Overview of German Grid Issues and Retrofit of German Photovoltaic Power Plants for the Prevention of Frequency Stability Problems in Abnormal System Conditions of the ENTSO-E Region Continental Europe. In: Proceedings of the 1st International Workshop on Integration of Solar Power into Power Systems. Aarhus, Denmark, 24 October 2011: http://www.ecofys.com/files/files/ecofys_2011_paper_on_frequency_stability_challenge.pdf

The need to address high frequency DER tripping was raised as part of FERC's Small Generator Interconnection Procedure (SGIP) Notice of Proposed Rulemaking Docket No. RM13-2-000. This issue was also discussed in the context of IEEE Standard P1547a proceedings. A high frequency droop characteristic similar to the BDEW requirement described above has been proposed as an option, but not yet mandated.

3.3 System Restoration

System restoration after a major event is another issue that requires attention in the case of high penetration DER scenarios. Bulk power system restoration is a controlled procedure whereby generation restart is coordinated with network restoration. In contrast, DER restart is automatic. According to IEEE Standard 1547, DERs must wait 5 minutes to restart automatically after disconnecting due to off-nominal voltage and frequency, provided that frequency and voltage have been restored within tolerance. To minimize energy loss, restart usually occurs very close to the 5 minute interval. There is no provision for staggered restart to avoid possible problems during a system recovery. In a high penetration During November 2006 European Blackout,[25] approximately 8,000 MW of mainly distribution connected wind turbines auto-restarted despite the fact that the system was still islanded and the frequency was at 50.3 Hz.[26] As a result, frequency went higher to about 50.45 Hz, causing significant overloads of facilities and nearly causing a collapse of the system by tripping generation on over-frequency. Automatic reconnection is already a large concern for restoration from potential island-wide outages for the Oahu, Maui, and Hawaii Island grids due to the large amount of distributed solar PV.

[25] *Final Report on the disturbances of 4 November 2006:* https://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/Final-Report-20070130.pdf

[26] Europe operates at a nominal 50 Hz.

4. Summary of VRT and FRT Requirements Grid Codes Applicable to BES-Connected Generators

The reliability of the bulk power system depends on most generators remaining connected in the event of a system fault. At the bulk system level, the expectation is that generators will remain connected during a disturbance and contribute to restoration of voltage and frequency as soon as possible. If even a few large generators fail to ride through a disturbance, the power system risks a cascading failure and blackout. Historically, this disturbance tolerance capability for conventional generators was considered inherent, rather than required by standards.

During the initial phase of large-scale VER deployment, there were no specific requirements for any generators to ride through faults. VERs were significantly smaller than conventional generators and could be distribution-connected. DER also added a complication to distribution circuit protection schemes. The dynamic response of inverter-based VERs was poorly understood or, in the case of induction-based wind generators, was known to be detrimental to voltage recovery. For these and other reasons, VERs were designed to quickly disconnect from the grid after a voltage or frequency disturbance. As the potential for large-scale integration of VERs became apparent, VER (wind) specific VRT/FRT requirements were incorporated into grid codes. Today, disturbance tolerance standards are still evolving. There are efforts to harmonize requirements so that they can be applied to all generators, not just VERs. Due to the rapid increase in distribution-connected VERs, there are initiatives in several countries aimed at reconciling disturbance tolerance with standards for distribution-connected generators, which is the subject of this report.

This chapter describes disturbance tolerance standards in North America and around the world, with the purpose of identifying technical elements that could be applied to distributed generation as well.

4.1 Voltage and Frequency Tolerance Requirements in North America

In North America, there are several regional standards that address disturbance tolerance of transmission-connected generators. These are discussed below.

FERC Order 661A contains a low voltage ride-through (LVRT) requirement that applies only to FERC-jurisdictional (US only) wind generators larger than 20 MVA. FERC Order 661-A states:

> "Wind generating plants are required to remain in service during three-phase faults with normal clearing (which is a time period of approximately 4–9 cycles) and single line to ground faults with delayed clearing, and subsequent post-fault voltage recovery to pre-fault voltage unless clearing the fault effectively disconnects the generator from the system. The clearing time requirement for a three-phase fault will be specific to the wind generating plant substation location, as determined by and documented by the transmission provider. The maximum clearing time the wind generating plant shall be required to withstand for a three-phase fault shall be 9 cycles after which, if the fault remains following the location-specific normal clearing time for three-phase faults, the wind generating plant may disconnect from the transmission system. A wind generating plant shall remain interconnected during such a fault on the transmission system for a voltage level as low as zero volts, as measured at the high voltage side of the wind GSU."

ERCOT, WECC, the Quebec Interconnection, and other Canadian provinces have also established disturbance tolerance standards that apply within their own jurisdiction. In the case of WECC, the disturbance tolerance standard only addresses low voltage ride-through. In regions where there are no explicit FRT requirements

(Eastern Interconnection and WECC, for example), new generators are expected to remain connected within the envelope defined by the off-nominal frequency programs applicable within the interconnection. BPS Reliability Standards apply to transmission-connected plants and generating units above a certain size.[27]

NERC initiated a project to include FRT and VRT as part of NERC Reliability Standard PRC-024.[28] The final version of the Standard approved by the NERC Board of Trustees in March 2013 addresses frequency and voltage relay settings, but does not establish an explicit disturbance tolerance requirement for generators. According to the standard, generators are allowed to trip for reasons other than voltage or frequency relay action, including impending or actual loss of stability, as needed for fault clearing or as part of a special protection scheme, and documented regulatory or equipment limitations. While the standard is a relay setting standard, generator performance enhancements are expected as a result.

Figures 12 and 13 describe the “no-trip zone” for voltage and frequency contained in the NERC Reliability Standard PRC-024-1. The no-trip zone described in the NERC Reliability Standard PRC-024 applies to generator voltage and frequency protection relays. The time dimension is the cumulative time that the value (voltage or frequency) is more severe than that given value (e.g., voltage less than value for LVRT, greater value for HVRT). That is, the requirement does not establish continuous generator must-run ranges. For example, if voltage dips no lower than 0.8 pu, the corresponding relay must have an intentional delay no shorter than three seconds. Note that the frequency no-trip zone is defined differently among NERC interconnections, but the voltage no-trip zone is the same across the NERC footprint.

[27] NERC BES Definition: Generating resource(s) with gross individual nameplate rating greater than 20 MVA or gross plant/facility aggregate nameplate rating greater than 75 MVA including the generator terminals through the high-side of the step-up transformer(s) connected at a voltage of 100 kV or above.

[28] See http://www.nerc.com/filez/standards/Generator-Verification-Project-2007-09.html

Figure 12: NERC Standard PRC-024-1 Generator Voltage Relay Setting Requirement

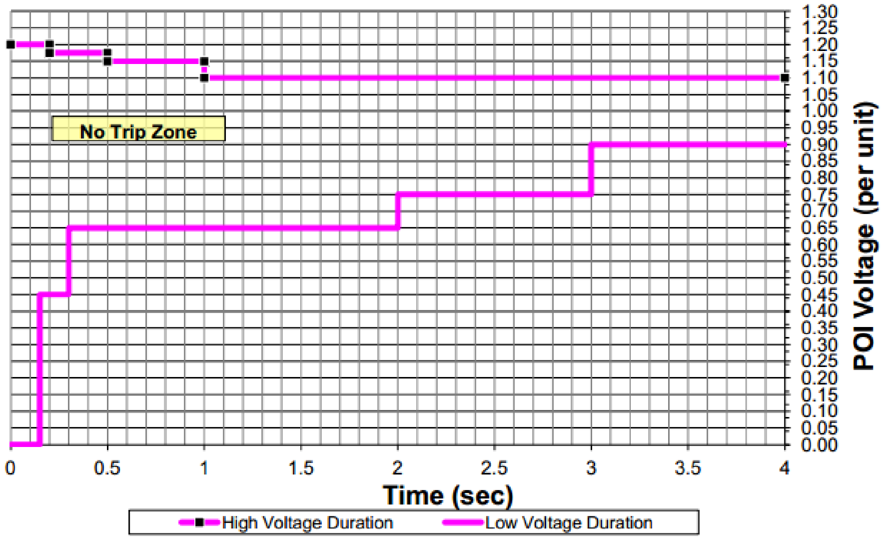
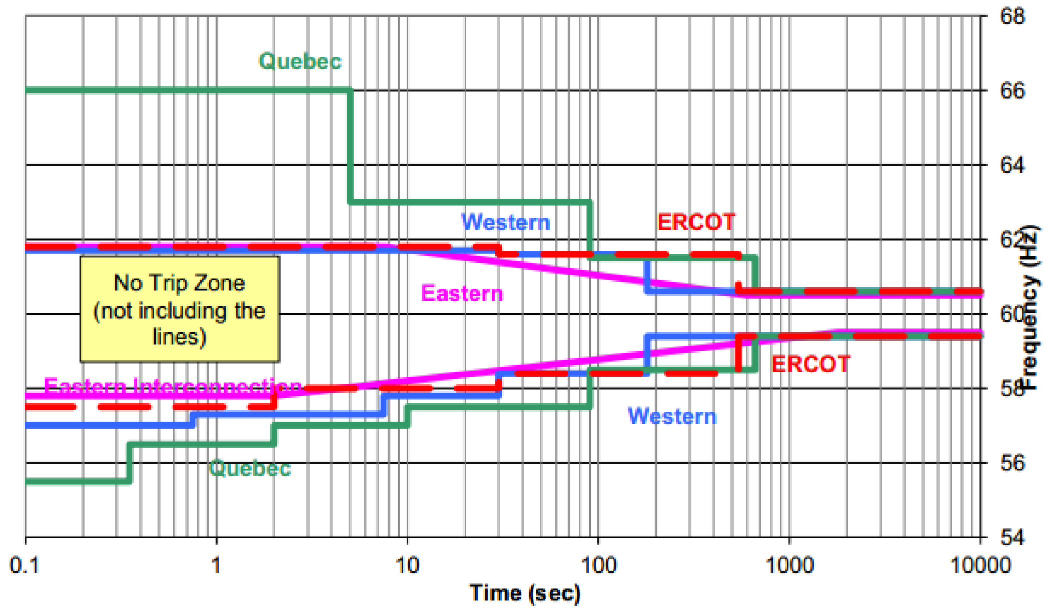


Figure 13: NERC Standard PRC-024 – Generator Frequency Relay Setting Requirement



NERC Reliability Standard PRC-024-1 contains several clarifications that are useful to properly interpret the standard. It states that "Voltages in the curve assume minimum fundamental frequency phase-to-ground or phase-to-phase voltage for the low voltage duration curve and the greater of maximum RMS or crest phase-to-phase voltage for the high voltage duration curve." It clarifies that the curves apply to voltage excursions regardless of the type of initiating event, and lists several baseline assumptions to be used when evaluating protective relay settings. NERC Standard PRC-024 voltage relay standard applies at the point of interconnection.

4.2 Voltage and Frequency Tolerance Requirements in Other Grid Codes

The discussion about international standards is largely derived from the Australian Energy Market Operator report, “Wind Integration: International Experience, WP2: Review of Grid Codes,” Ecar Ltd., 2nd October 2011. Table 2, taken from the ECAR report, lists a number of grid codes from around the world that contain VRT and FRT provisions for generators. The pertinent documents are accessible through the hyperlinks.

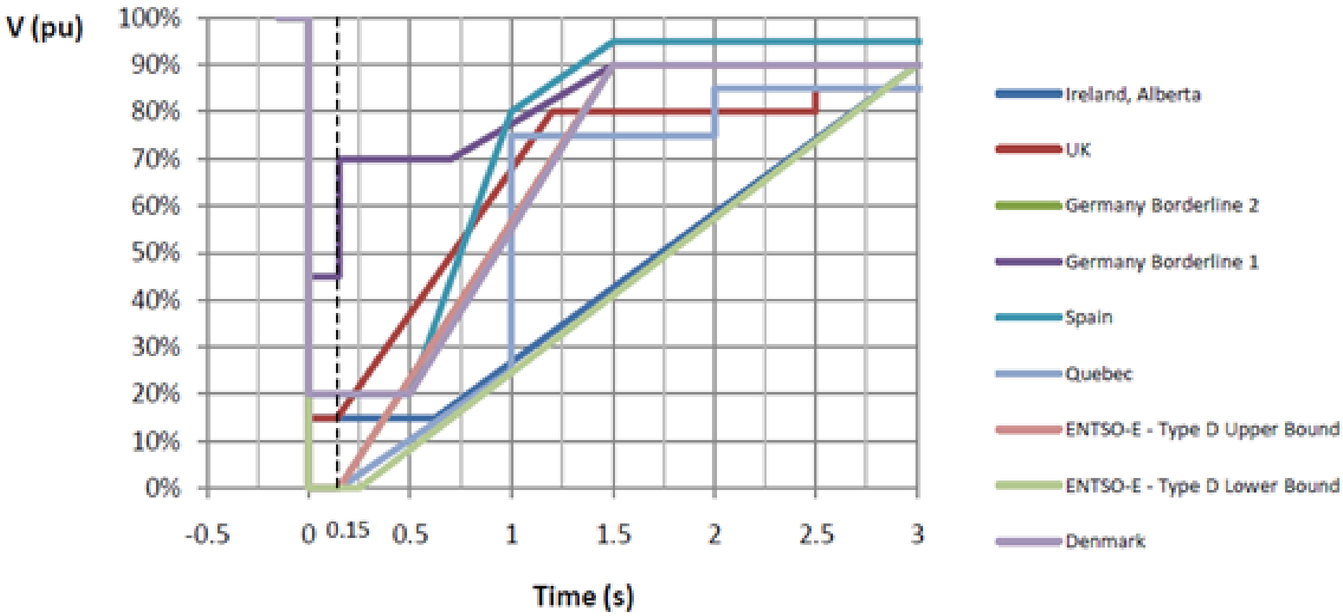
Table 2: Survey of VRT-Related Grid Codes[29]

Region	Issuer	Document
Ireland	EirGrid	Grid Code version 3.5, 15th March 2011
UK	National Grid Electricity Transmission	The Grid Code, Issue 4, Revision 11, 16th March 2012
Germany	VDN 50 Hz Transmission Transpower (Tennet) FGW	Transmission Code 2007 Netzanschluss- und Netzzugangsregeln, May 2008 Grid Code for high and extra high voltage, 1st April 2009 Technical Guidelines for Power Generating Units, Part 4, Demands on modeling and validating simulation models of the electrical characteristics of power generating units and systems, revision 5, 23.03.2010
Denmark	Energinet.dk	Technical regulation 3.2.5 for wind power plants with a power output greater than 11 kW, 30.9.2010
Spain	Ministry of Industry, Commerce and Tourism	P. O. 12.2, Installations connected to the transmission system, minimum requirements for design, operation and safety and commissioning, Nov 2009, unofficial translation
Canada	Alberta Electric System Operator Hydro Québec Trans Énergie Ontario IESO	Wind power facility technical requirements, November 15 2004 Transmission Provider Technical Requirements for the Connection of Power Plants to the Hydro Québec Transmission System, February 2009 Market Rules, Chapter 4, Grid Connection Requirements –Appendices, March 6, 2010
Europe	ENTSO-E	Draft Requirements for Grid Connection Applicable to all Generators, 22 March 2011

Most grid codes specify VRT requirements using voltage functions versus time. Figure 14 depicts the requirements from the various grid codes in Table 2. For each particular profile, if the voltage at the grid connection point remains above the corresponding line, the generator must remain connected to the power system.

[29] Table extracted from http://www.aemo.com.au/planning/0400-0050.pdf.

Figure 14: Voltage Ride-Through Requirements in Selected Grid Codes

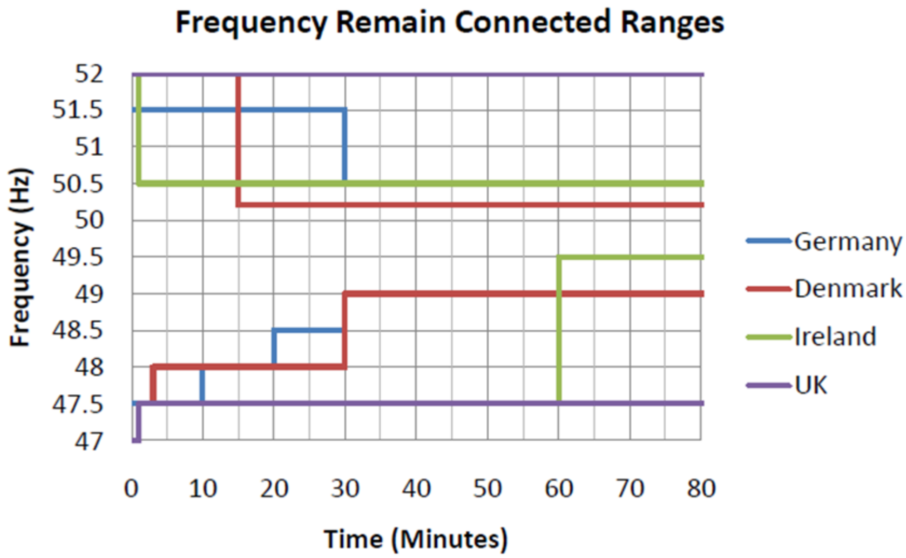


While the voltage versus time profile is a feature common to many grid codes, the type of fault to which it applies is not consistent. For Ireland's, the United Kingdom's, Denmark's and Alberta's requirements (and those specified in the ENTSO-E draft), the profile applies to symmetrical or unbalanced faults on any or all phases. In the grid codes of Spain and Quebec, there are reduced requirements for some types of faults. For example, in the Spanish grid code, a three-phase symmetrical fault resulting in a voltage of 20% of nominal at the grid connection point must be withstood for 500 ms; however, a generator must only remain connected for two-phase-to-ground faults with a voltage drop to 60% of nominal.

Note that the draft ENTSO-E requirements define two voltage/time profiles. One represents the most severe profile the TSO can require at its discretion (ENTSO-E Type D Lower Bound), depending on system needs; the other defines the minimum requirement (ENTSO-E Type D Upper Bound). The German transmission code also defines two profiles (Germany Borderline 1 and Germany Borderline 2). If a generator cannot meet the requirement defined by Germany Borderline 2, it may be possible to negotiate a requirement between the two curves with two conditions: a minimum reactive current feed-in during the fault can be guaranteed and resynchronization time is decreased.

Many grid codes contain FRT requirements for generators, as shown in Figure 15 below. Some grid codes also specify the rates of change of frequencies that generators must withstand. Similar to the VRT standards, some grid codes require specific control capability during a frequency disturbance. A typical requirement is reduction of active power during high frequency. This type of requirement is included in Germany, Ireland, UK and ERCOT grid codes, and is typically specified as a percent reduction of power output per Hz above a certain threshold above nominal frequency. Capability to increase power production for low frequency is included in some grid codes (Denmark, Ireland); however, deployment of this capability in actual operating practice is uncommon because it requires spilling "free" available power. Some jurisdictions like Quebec also require provision of synthetic inertia for inverter-based wind power plants. While this type of frequency droop control is outside the scope of IVGTF 1-7, the task force believes that high frequency droop is a feature that should be considered instead of a fixed high frequency cut-off.

Figure 15: Frequency Ride-Through Requirements in Selected Grid Codes



5. Summary of NERC IVGTF 1-7 Recommendations

In North America, IEEE Standard 1547 is the *de facto* standard for DER interconnection.[30] The lack of voltage and frequency disturbance ride through requirements in IEEE Standard 1547 has the potential to adversely affect the reliability of the BPS under conditions of relatively high DER penetration levels expected in the future. While NERC's authority is solely to ensure bulk-power system reliability, the task force concludes that large amounts of distribution-connected resources, in aggregate, can pose risks to the reliability of the bulk power system.

To mitigate these potential impacts, IVGTF Task 1-7 recommends that the voltage and frequency disturbance trip levels in IEEE Standard 1547 be revised and explicit disturbance tolerance requirements be adopted. This section summarizes the IVGTF 1-7 task force's guidance for future efforts to update DER interconnection requirements.

Two general recommendations for NERC actions are provided followed by several suggested general guidelines for consideration by the IEEE 1547 participants, recognizing that specific requirements would have to be established through a stakeholder process. The recommendations offered are motivated by the relatively rapid deployment of distribution-connected VERs in some areas, particularly PV; however, they are intended to apply to other DER as well.

One of the challenges is that, while high penetration of DERs can have an impact on bulk system reliability, NERC Reliability Standards that require relays on BES generators to be set to allow voltage and frequency ride through do not directly apply. The task force believes that NERC and other BPS stakeholders can play a constructive role in ensuring that the reliability implications due to lack of disturbance tolerance for distributed VER and other DERs are addressed. The following general recommendations are offered:

1. In the short-term, NERC should engage in current efforts to revise DER interconnection standards by providing information, supporting the efforts of IEEE with transmission reliability subject-matter experts, raising industry, regulator, and policy maker awareness, and encouraging the consideration of the explicit VRT and FRT for DERs. The initial focus should be on potential ways to adopt minimum tolerance thresholds for VRT and FRT in the IEEE Standard 1547 while balancing against other important distribution issues such as safety and protection/coordination.

2. In the longer-term, NERC should establish a coordination mechanism with IEEE Standard 1547 to ensure that BPS reliability needs are factored into future DER interconnection standards revision efforts. To date, BPS stakeholders have participated only sporadically in the IEEE Standard 1547 process. As a result, VRT and FRT concepts receive limited consideration, and may have been outweighed by distribution system protection concerns. This liaison process would be timely for the full revision to begin later in 2013 or early 2014.

The task force also offers the following general guidelines on VRT and FRT specifications for distributed VERs and other DERs, for consideration in the P1547a process or future IEEE Standard 1547 revision. It is assumed that VRT and FRT requirements would have to co-exist with revised "must trip" provisions needed to address safety and protection/coordination issues in distribution systems.

[30] Other international organizations have also adopted the IEEE standard.

1. The revised IEEE Standard 1547 should allow for different methods of meeting the functional requirements of fault detection (clause 4.2.1), reclosing coordination (clause 4.2.2) and unintended islanding detection (clause 4.4.1). At present, DERs meeting those functional requirements would still have to trip on voltage (clause 4.2.3) and frequency (clause 4.2.4) excursions. Removing those linkages would help pave the way for VRT and FRT requirements. The IVGTF recognizes that these alternative methods are more expensive, require more engineering effort, and in some cases require further technical development. However, the increasing level of DER and the potential impact on the BPS justifies the effort.

2. The revised IEEE Standard 1547 should include explicit low and high VRT requirements. Likewise, the revised IEEE Standard 1547 should include explicit low and high FRT requirements. These requirements should be expressed as voltage versus cumulative time and frequency versus cumulative time requirements.[31,32]

3. Must-trip voltage thresholds in the existing IEEE Standard 1547 should be extended to accommodate an effective VRT envelope without overlap (Figure 16).

   a. As an example, the following table and figure describe a possible approach to implement low voltage ride-through down to 50 percent voltage for 10 cycles (160 ms), within the existing IEEE Standard 1547 framework.

   b. Zero voltage ride-through is not required for BPS reliability. A ride-through level down to approximately 50 percent voltage would provide adequate tolerance during transmission faults.

   c. A ride through period longer than shown in Table 3--possibly greater than 10 seconds--at higher voltage level (e.g., down to 70% voltage) may be needed to avoid compounding fault-induced delayed voltage recovery (FIDVR).

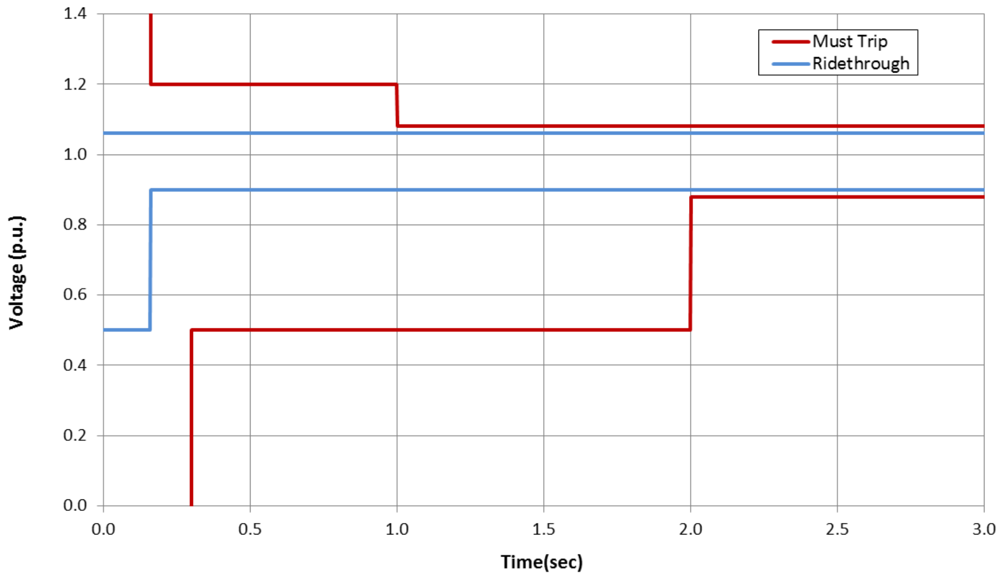
Table 3: Proposed changes to IEEE Standard 1547 to include VRT down to 50% voltage

Voltage Range (% of nominal voltage)	Minimum Ride-through time(s)	Maximum Clearing time(s)
V < 50	-	0.30
50 ≤ V < 88	0.16	2.00
88 ≤ V < 90	0.16	-
90 ≤ V < 108	No tripping	-
108 ≤ V < 110	-	-
110 < V < 120	-	1.00
V > 120	-	0.16

[31] Cumulative time represents time duration since crossing the high voltage threshold.

[32] Distribution and transmission voltages are closely related but are not the same. BPS reliability requirements are expressed in terms of transmission voltages. Determining specific distribution voltage limits that correspond to the transmission voltage limits requires additional analysis. Distribution and transmission voltages are both shown in this document to illustrate the reliability concern.

Figure 16: IVGTF 1-7 Recommended Ride-Through and Must-Trip Requirements for DER



4. Must-trip frequency thresholds in the existing IEEE Standard 1547 should be extended to accommodate an effective FRT envelope without overlap.

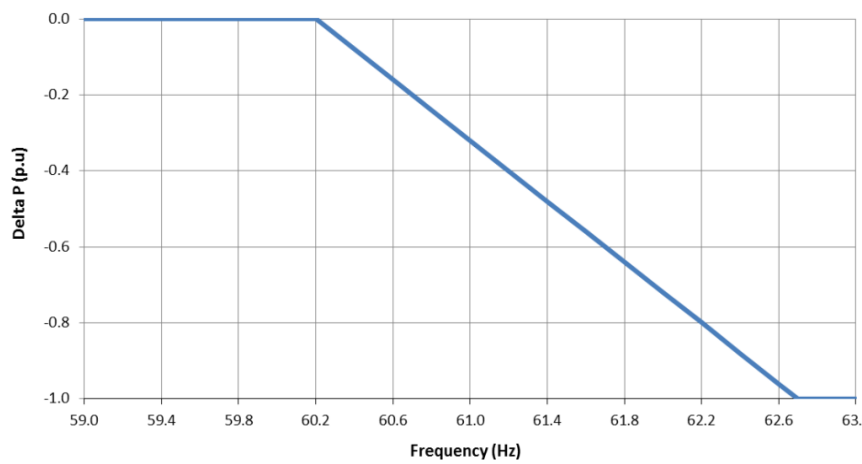
    a. Table 4 shows a possible approach to implement frequency ride through down to 57 Hz for 10 seconds, within the existing IEEE 1547 framework.

    b. The longer low frequency ride through period is needed to prevent tripping at least until all UFLS stages have deployed and frequency begins to recover from a generation loss event.

    c. Considering that frequency affects an entire interconnection, the standard should not require all DERs to disconnect at the same high frequency level. Sudden disconnection of large amount of DERs on high frequency caused by temporary over-generation, load tripping, or during a breakup event could cause frequency instability. Instead, the standard should require a gradual reduction of aggregated DER output when frequency exceeds a certain threshold. The following table and figure illustrate a possible approach to specify a high frequency droop characteristic in place of the current high frequency trip point. A droop characteristic could be programmed into the controls for each DER or it could be achieved at the fleet level by, for example, randomizing high frequency cut-off times within a frequency range above a suitable threshold. Both achieve the same objective, but the fleet approach may be more sensible based on cost considerations.

Table 4: Proposed changes to IEEE Standard 1547 to include FRT for 10 secs		
Frequency Range (% of base voltage)	**Minimum Ride-through time(s)**	**Maximum Clearing time(s)**
f ≤ 57.0	-	0.16
57.0 < f ≤ 58.5	-	300
58.5 < f ≤ 59.5	10	-
59.5 < f ≤ 60.5	No tripping	-
60.5 < f ≤ 61.0	10	-
61.0 < f ≤ 61.5	-	300
f > 61.5	-	0.16
60.2 <f ≤ 61.5	Droop Characteristic	

Figure 17: Example of frequency roll-off characteristic for DER fleet, with 40% droop above 60.2 Hz



5. The time dimension of the VRT/FRT curves and tables described above is meant to represent cumulative time elapsed since the onset of a disturbance event that result in temporary excursions of voltage and/or frequency. The VRT/FRT envelopes should not establish must-run ranges for generators (i.e., they should not prevent intentional shutdown of a DER for reasons other than grid voltage and frequency disturbances, such as normal shutdown of PV at night or by operator action.)

6. The prospective disturbance tolerance standard should provide a default VRT and FRT envelope, but should allow for the time and frequency/voltage magnitudes to be adjustable, within certain limits, for coordination with local protection, in coordination with the distribution system operator.

7. FRT and VRT requirements should cover all DERs that are normally grid connected, regardless of size or technology. However, a range of thresholds could be considered based on technology differences (e.g., inverter versus rotating machines), as some European grid codes do. In general, focusing requirements on the truly functional needs of the grid tends to eliminate the need to have technology-specific requirements.

8. The restarting of DERs during system restoration should be considered during the development of DER interconnection requirements. While the restoration situation in North America is somewhat mitigated at present by the sequential nature in which distribution feeders will likely be reenergized after a major blackout, reliability impacts of DERs should consider the automatic restarting of DERs. Failure to consider and mitigate these impacts could lead to further instability during a disturbance.

Appendix I: Assessment Preparation

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