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Momentary Cessation: Improving Dynamic Performance and Modeling of Utility-Scale Inverter Based Resources During Grid Disturbances

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Improving Dynamic Performance and Modeling of Utility-Scale PV Systems During Grid Disturbances

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Abstract

Sandia National Laboratories worked with NERC staff to provide stakeholder guidance in responding to a May 2018 NERC alert regarding dynamic performance and modeling issues for utility-scale inverter-based resources. The NERC alert resulted from event analyses for grid disturbances that occurred in southern California in August 2016 and October 2017. Those disturbances revealed the use of momentary cessation of transmission connected inverter-based generation- a short time period when they ceased to inject current into the grid, counter to desired transmission operation. The event analyses concluded that, in many cases, the Western Interconnection system models used to determine planning and operating criteria do not reflect the actual behavior of solar plants, resulting in overly optimistic planning assessments and substandard operational responses. This technical report summarizes the gaps between the models and actual performance that were observed at those times, and the guidance that Sandia and NERC provided to owners of solar PV power plants, transmission planners, transmission operators and planning/reliability coordinators to modify existing models to reflect that actual performance.

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TABLE OF CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

There has been increasing concern regarding the dynamic performance of utility scale inverter-based resources during grid disturbances. This particular issue was highlighted by the Blue Cut fire event in Southern California and documented by the subsequent North American Electric Reliability Corporation (NERC) report “1200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report” dated June 2017. The report outlines a multitude of technical details but focuses on two primary concerns: 1) utility scale inverter-based resources (especially solar PV) are unnecessarily reducing current output to the grid during fault conditions (termed momentary cessation), perpetuating the negative consequences of the fault, and 2) the interconnection system models used to determine planning and operating criteria do not reflect the actual behavior of the solar plants, resulting in overly optimistic planning assessments and substandard operational responses.

In close coordination with the Department of Energy’s Solar Energy Technologies Office (DOE/SETO), Sandia National Labs worked with NERC staff to provide stakeholder guidance in responding to the May 2018 NERC Alert titled “Loss of Solar Resources during Transmission Disturbances due to Inverter Settings – II”. The stakeholders included owner/operators of solar PV power plants, transmission planners, transmission operators and planning/reliability coordinators. This guidance was summarized by Sandia in an on-demand streaming webinar available on the NERC website. NERC’s Inverter-Based Resource Performance Task Force (IRPTF) provides an ongoing forum for broader engagement on inverter-based resource performance on the bulk power system.

NOMENCLATURE

Abbreviation	Definition
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BA	Balancing Authority
BES	Bulk Energy System
BPS	Bulk Power System
DOE	U.S. Department of Energy
GO	Generator Owner
HVRT	High Voltage Ride-Through
LVRT	Low Voltage Ride-Through
MVWG	WECC Modeling and Validation Working Group
NERC	North American Electric Reliability Corporation
PC	Planning Coordinator
POI	Point of Interconnection
PMU	Phasor Measurement Unit
PV	Photovoltaic
RC	Reliability Coordinator
RE	NERC Regional Entity
REMTF	WECC Renewable Energy Modeling Task Force
SETO	DOE Solar Energy Technologies Office
TP	Transmission Planner
TOP	Transmission Operator
VDL	Voltage Dependent Current Limit
WECC	Western Electricity Coordinating Council

1. INTRODUCTION AND BACKGROUND

On August 16, 2016, a number of transmission line faults occurred on the Southern California Edison (SCE) 500 kV system and Los Angeles Department of Water and Power 287 kV system as a result of the Blue Cut wild fire in the Cajon Pass [1]. Of the 15 faults caused by the fire, four of them resulted in significant loss of utility-scale solar PV generation. In the most significant event, approximately 1,200 MW of PV generation was lost despite the fact that all of the affected facilities remained energized. A similar incident occurred on October 9, 2017 as a result of the Canyon 2 wild fire east of Los Angeles [2]. Two faults, one on an SCE 220 kV line, and a second on an SCE 500 kV line, results in a loss of nearly 900 MW of PV generation. As with the Blue Cut incident, all of the affected solar PV plants remained energized.

Key findings by the NERC/WECC task force that was assembled to analyze these events included:

- Some inverters trip instantaneously and erroneously due to frequency measurements that are corrupted by transients generated by faults on the power system. Other inverters trip on reverse DC current that results from these same transients.
- The majority of the affected facilities contained inverters that momentarily cease output ("momentary cessation") for voltages outside the range of 0.9 to 1.1 pu.
- A portion of the inverters that momentarily ceased output were slow to return to their pre-disturbance power levels. Plant controllers imposed rate limits that in some cases delayed power recovery by up to two minutes after fault clearance.
- Many inverters contain default voltage and frequency protection setpoints that are based on the NERC PRC-024-2 "no trip" curves, rather than on the physical limitations of the inverters themselves.

Though none of these events resulted in loss of system stability (other spinning reserve absorbed the system load), dynamic planning models used in the Western Interconnection indicated that no utility-scale solar generation should have been lost for these disturbances, raising questions about the validity of the planning models. In addition, the post-fault recovery of some of the affected solar resources was unacceptably slow and not in agreement with the planning model analysis. As a result of these incidents, NERC issued a Level 2 Alert[1] on May 1, 2018, entitled "Loss of Solar Resources during Transmission Disturbances due to Inverter Settings – II" [4] to initiate actions by various NERC entities to address these modeling deficiencies and to change inverter and plant control setpoints to minimize the effects of the undesirable fault response.

[1] A Level 2 Alert recommends that specific action be taken by registered entities. A response from recipients, as defined in the alert, is required.

2. MAY 2018 NERC ALERT

The May 1, 2018 NERC Alert provided a number of industry recommendations and specific actions be undertaken by the various NERC registered entities:

1. Generator Owners (GO) were to work with their inverter suppliers to update their dynamic planning models, if necessary, to accurately represent the as-operated configuration of their facilities, with particular attention to momentary cessation and power recovery. Data sources for this task included inverter control and protection settings, inverter test reports, manufacturer simulation results, digital fault recorder data and PMU data. In addition, they were to work with their inverter suppliers to identify feasible changes to inverter and plant controls that could facilitate more desirable behavior during transmission system faults and in the post-fault recovery period (see Section 7, below). Dynamic planning model parameters for the current configuration and for a potential future configuration that incorporated these feasible improvements were to be provided to the affected Transmission Planner (TP) and Planning Coordinator (PC).
2. GOs were to work with their inverter and plant controller suppliers to reduce, to the maximum extent feasible, the post-fault recovery time by defeating up-ramp rate limitation in the post-fault period.
3. GOs were to work with their inverter suppliers to identify feasible inverter under- and overvoltage setpoint and time delay changes that could improve LVRT and HVRT capability. Updated setpoints were to be provided to the affected TP and PC.
4. For the affected GOs, they were to work with their inverter supplier to properly desensitize the reverse DC current fault detection logic to prevent nuisance tripping resulting from line voltage transients associated with transmission system fault.
5. GOs were to complete the NERC-provided data submission workbook that summarized their responses to the previous four recommended actions.
6. TPs, PCs, Transmission Operators (TOP), Reliability Coordinators (RC) and Balancing Authorities (BA) were to perform system reliability assessments with the updated model parameters provided by the GOs to identify potential risks to system stability. These studies were to address both the current configuration of the solar facilities as well the feasible control system upgrades identified by the GOs and their inverter suppliers. Results of these studies were to be provided to the relevant NERC Regional Entity (RE).

The scope of the NERC Alert was limited to Bulk Energy System (BES) solar PV resources, i.e., those facilities rated 75 MVA or higher and interconnected at transmission voltage. However, owners of non-BES solar generation facilities were encouraged to review control and protection setpoints with their inverter manufacturers and implement the same recommendations required of the BES facilities.

3. TIMELINE AND LOGISTICS OF NERC ALERT RESPONSES

Table 1 is a summary of responses NERC requested for each recommendation outlined in the Alert.

Table 1. Summary of NERC Response Requests

Rec. #	Description	Provided By	Provided To	Due Date
1A	Update dynamic models for existing configuration or notify of no changes	GO	TP, PC, TOP,RC and BA	7/31/18
1B	Identify feasible disturbance recovery performance changes, provide updated dynamic models	GO	TP, PC	7/31/18
2	Modify plant-level ramp rate controls in post-disturbance period, if necessary	GO	N/A	ASAP
3	Identify feasible changes to inverter voltage trip settings, provide updated dynamic models	GO	TP, PC	7/31/18
4	Implement DC reverse current protection setting changes, if applicable	GO	N/A	ASAP
5	Complete data submission workbook	GO	TP, PC, TOP,RC and BA	7/31/18
6A	Provide notification of completion of system studies with models provided by GOs in Recommendation #1A	TP, PC, TOP,RC and BA	RE	12/7/18
6B	Approve or disapprove proposed changes from Recommendation #1B, provide notification of completion of system studies with updated models	TP, PC	RE	12/7/18

4. MOMENTARY CESSATION

As described in Section 1 of this report, some inverter types employ momentary cessation during under and/or overvoltage conditions at the inverter terminals. As an example, consider Figure 1, which shows the inverter response for an undervoltage condition. When the inverter terminal voltage drops below V_{mc}, active and/or reactive current is momentarily ceased. When terminal voltage returns to its normal range, current injection resumes after programmed or fixed delay time Δt_{sr}. Ramp rates on recovery may be limited by fixed or programmable setpoints in the inverter-level and/or plant-level controls as indicated over the time interval Δt_{rr}.

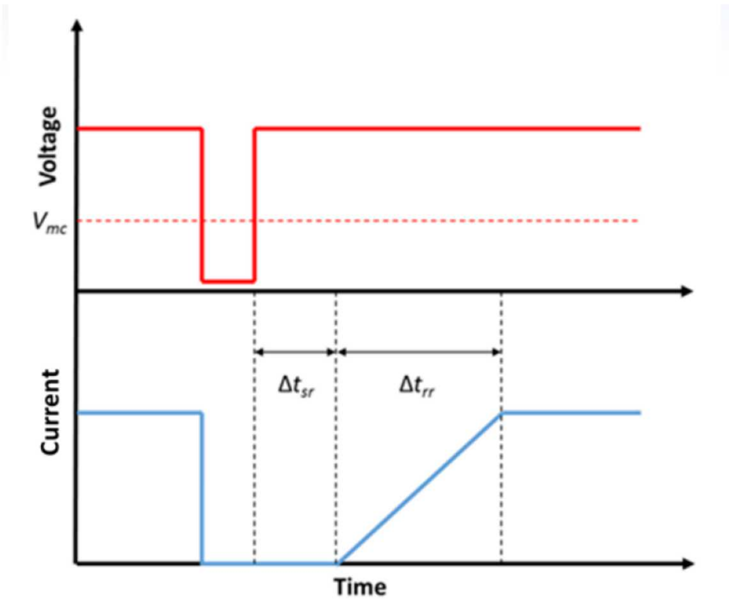

Figure 1. Momentary Cessation Example

Momentary cessation differs from "tripping" in that the inverters are still galvanically connected to the BES, and current injection is restored automatically via the inverter control logic. By contrast, a "tripped" inverter is electrically disconnected from the BES via a contactor or circuit breaker and requires either manual (either local or remote) or automatic reset action to restore current injection, but in either case well beyond the post-fault recovery period.

5. SECOND GENERATION GENERIC POSITIVE SEQUENCE DYNAMIC MODELS FOR SOLAR PHOTOVOLTAIC (PV) RESOURCES

Most transmission planners and coordinators in areas with significant solar resources have adopted the 2nd-generation generic positive sequence dynamic models available in planning tools such as PSS®E, PSLF and PowerWorld Simulator for use in their dynamics base cases. These models include three components:

1. Generator Model REGC_A: This model interacts with the phasor-domain network model by determining appropriate current injections based on active and reactive current commands.
2. Electrical Control Model REEC_A: The electrical control model produces active and reactive current commands for the RECG_A model based on external active and reactive power commands, the inverter terminal voltage and user-settable control flags.
3. Plant Controller Model REPC_A: This model generates inverter active and reactive power commands based on initial conditions from the solved power

flow case and conditions at a remote bus, typically the POI, including voltage, frequency and real and reactive power flows.

Connectivity and flow of signals between the three model components is shown in Figure 2.

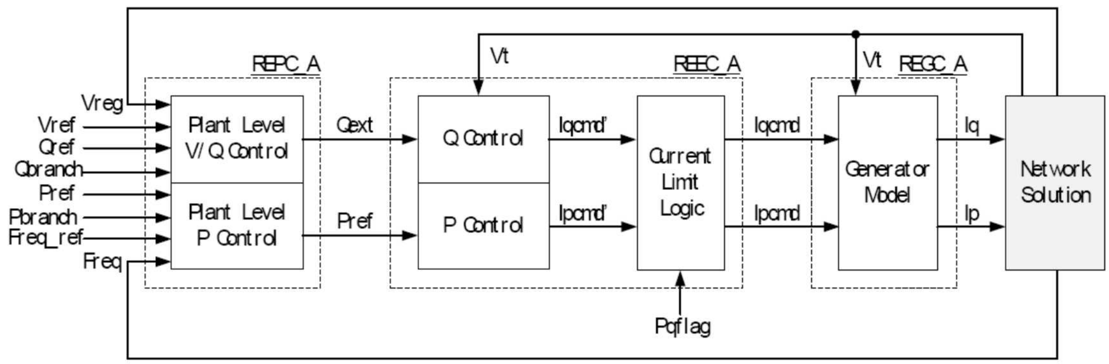

Figure 2. Model Connectivity for 2nd Generation Solar PV Dynamic Models

6. CAPTURING MOMENTARY CESSATION EFFECTS IN GENERIC DYNAMIC MODELS

During development of the 2nd generation solar PV dynamic models, which was led by the WECC Renewable Energy Modeling Task Force (REMTF) in the 2009 to 2014 time period, the use of momentary cessation during grid disturbances was not widely employed by the inverter industry in North America. Momentary cessation for distribution-connected inverters was introduced in 2015 in response to new requirements in California Rule 21 and Hawaii Rule 14H that addressed "smart inverter" functionality. Thus, the ability to explicitly model this behavior in the generic models was not anticipated. However, voltage dependent limits (VDL) on both active and reactive current commands do exist within the current REEC_A electrical control model. These limits are implemented via lookup tables that include up to four voltage-current pairs, and allow for a crude representation of momentary cessation.

The 2nd generation REEC_A model is shown in the block diagram of Figure 3, below. The source of this diagram is the PowerWorld Simulator modeling documentation, however, the same model is available in other bulk power system simulation tools. The parameters related to momentary cessation behavior are circled in red.

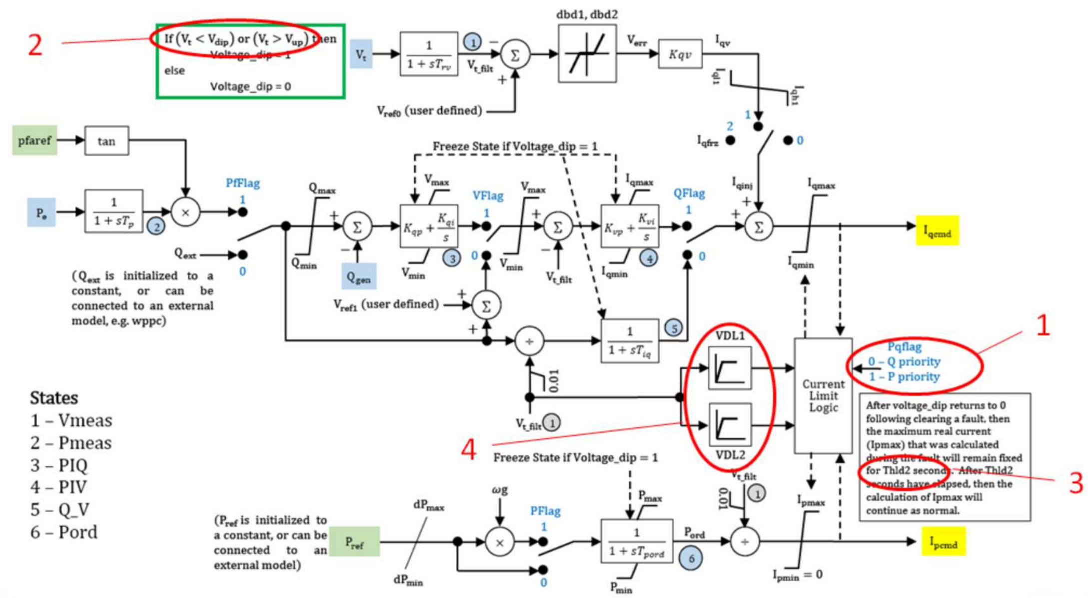

Figure 3. REEC_A Model Block Diagram (Source: PowerWorld Corporation)

Specific recommendations regarding these parameters identified in the NERC Modeling Notification [5] are:

1. Ensure that model parameter *Pqflag* is set to reflect the actual active or reactive current priority during and immediately following voltage disturbance. This parameter is particularly important during low voltage events when the inverter reaches its current limit and must determine how to apportion its current between real power and reactive power injection.

2. Set model parameters V_{dip} and V_{up} to reflect the actual lower and upper thresholds of inverter terminal voltage at which momentary current cessation is triggered. V_{dip} is the parameter representing V_{mc} in Figure 1 (V_{up} is not shown in Figure 1). Some inverters may use a family of voltage versus time points to define the thresholds of momentary cessation instead of a single value. Since the REEC_A model only allows a single value, NERC recommended selecting the most conservative value for grid modeling purposes (i.e., the thresholds closest to nominal voltage).

3. Set model parameter *Thld2* to represent the actual delay in beginning active current recovery following terminal voltage recovery. *Thld2* is the parameter representing Δt_{sr} in Figure 1. The 2nd generation models do not accommodate recovery delay for reactive current, so Δt_{sr} in Figure 1 is effectively zero with regard to the reactive component of the inverter output current.

4. Set model parameter tables *VDL1* and *VDL2* to properly reflect the inverter's actual voltage-dependent active and reactive current limits. These parameters are used to drive appropriate current limits to zero during momentary cessation. An example is shown in Figure 4, below. For this particular inverter, its real

and reactive current limits are momentarily reduced from 1.15 pu and 1.45 pu, respectively, to zero when the inverter terminal voltage is less that 0.75 pu or greater than 1.1 pu.

- Low voltage threshold: 0.75 pu
- High voltage threshold: 1.1 pu

Table 2: VDL1 and VDL2 Settings			
VDL1		VDL2	
vq	iq	vp	ip
0.74	0	0.74	0
0.75	1.45	0.75	1.15
1.1	1.45	1.1	1.15
1.11	0	1.11	0

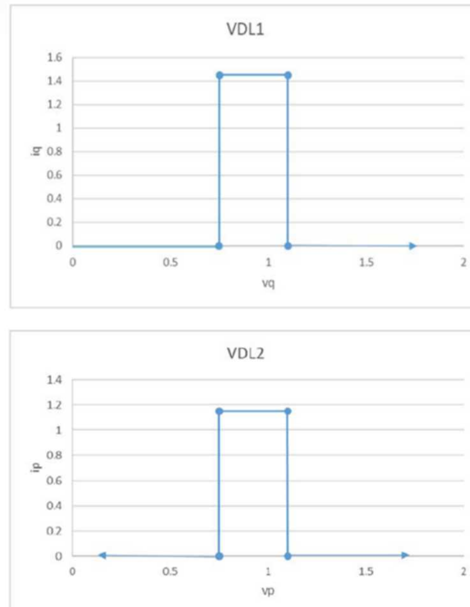

Figure 4. Example of Voltage Dependent Current Limits to Represent Momentary Cessation Behavior

The reader is referred to [5] for further guidance on appropriate table parameters for capturing these effects.

The REGC_A model, shown in Figure 5, also has certain parameters that affect momentary cessation behavior. These parameters are circled in red. Again, the source of this diagram is the PowerWorld Simulator modeling documentation, however, the same model is available in other simulation platforms.

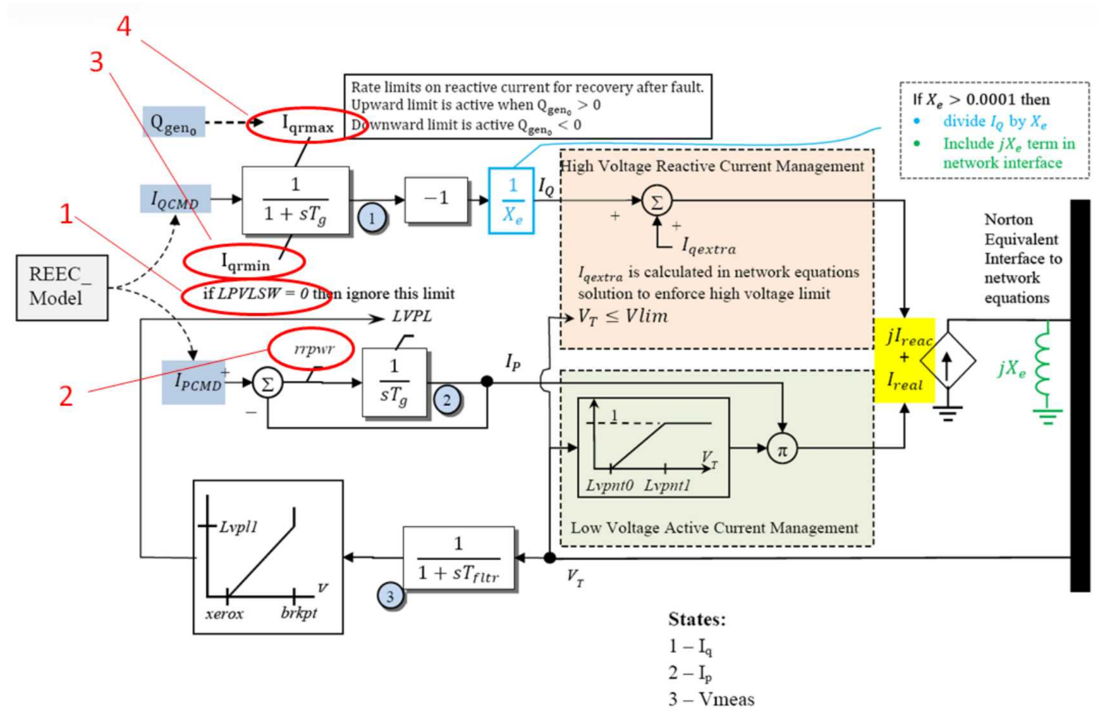

Figure 5. REGC_A Model Block Diagram (Source: PowerWorld Corporation)

Specific recommendations regarding the RECG_A model parameters identified in the NERC Modeling Notification [5] are:

1. Set model parameter *LVPLSW* to zero to prevent the *VLD1* and *VLD2* settings in the REEC_A model from being overridden.
2. Set model parameter *rrpwr* to the active current recovery rate following an event that invokes momentary cessation.
3. Set the model parameter I_{qrmax} to limit the upward reactive current ramp rate.
4. Set the model parameter I_{qrmin} to limit the downward reactive current ramp rate.

The WECC Modeling and Validation Working Group (MVWG) is currently revising all three model components shown in Figure 2, and future versions will include expanded VDL tables capable of more accurately representing the momentary cessation algorithms currently employed by most major North American inverter manufacturers.

7. DESIRED SOLAR PV RESOURCE RESPONSE TO BULK POWER SYSTEM VOLTAGE DISTURBANCES

An important element of the May 2018 NERC Alert was providing quantitative guidance to GOs and their equipment (inverter and plant controller) suppliers on what is considered desirable response of BES solar resources to transmission system faults. The Alert addressed this in three areas:

1. Momentary Cessation: While momentary cessation is presently required by some jurisdictions for distribution-connected solar resources, the complete elimination of momentary cessation is the most desirable option for BES facilities. Where hardware limitations prevent its elimination, reducing the low voltage threshold and increasing high voltage threshold where momentary cessation is initiated to the maximum extent feasible is next best. The shortest feasible delay in recovery (Δt_{sr} in Figure 1) is most desirable, ideally less than three line cycles.

2. Post-Fault Active Power Recovery: While some BES resources have interconnection agreements that restrict power ramp rates for balancing purposes, these ramp rate limitations do not apply in the post-fault recovery time. The desired response of the solar resource during post-fault recovery is no less than 100% of pre-fault power per second.

3. Over and Under Voltage Protection: A finding of the Blue Cut and Canyon 2 event analyses was that many inverters had default over and under voltage setpoints and time delays that were tailored to the "no trip zone" of Attachment 2 to NERC Standard PRC-024-2 [9] (see Figure 6). This is a fundamental misapplication of PRC-024-2. First, PRC-024-02 applies at the high side of the solar facility substation transformer, not at the inverter terminals. In addition, the standard only requires that tripping not occur for voltages and time durations within the No-Trip Zone – it specifically does not require tripping when outside that zone. The desirable voltage pickup and time delay settings for an inverter within in a BES facility are those that provide the most robust LVRT and HVRT performance consistent with the physical limitations of the inverter hardware.

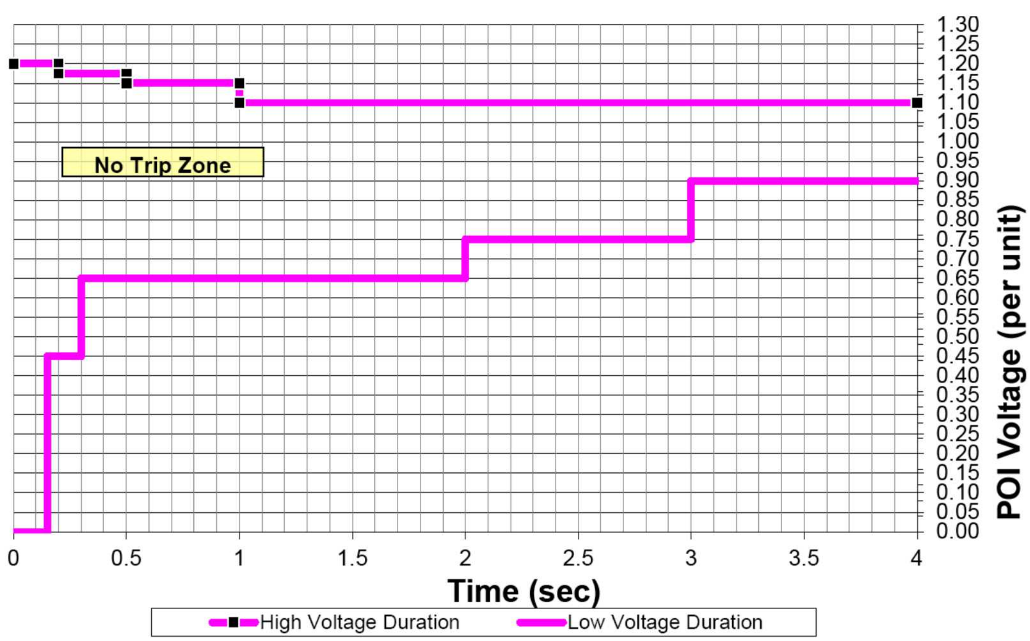

Figure 6. Voltage "No Trip" Zone from NERC PRC-024-2

8. CONCLUSIONS

The May 2018 NERC Level 2 Alert resulted from event analyses for grid disturbances that occurred in southern California in August 2016 and October 2017. The event analyses revealed undesirable fault response from a number of BES utility-scale solar generating resources that resulted in an unexpected loss of significant levels of generation. Further, the Western Interconnection system models used to determine planning and operating criteria were determined to be inaccurate with respect to the actual behavior of many solar plants, resulting in overly optimistic planning assessments.

Since the two disturbances that triggered the NERC Alert, two additional events in southern California have occurred with similar outcomes [11]. On April 20, 2018, a failed splice resulted in a phase-to-phase fault on an SCE 500 kV line in the Angeles National Forest, with a net reduction of 877 MW of BPS-connected solar generation. On May 11, 2018, a flashed insulator resulted in a phase-to-ground fault on another SCE 500 kV line near Palmdale. 711 MW of BPS-connected generation was subsequently lost. Momentary cessation and overly tight undervoltage trip settings were found to be major contributors to the loss of generation in those events, as well.

NERC continues to work with the affected GOs to implement the control and protection setting changes recommended in the Alert. As of the publishing date of this report, the reliability assessments to be performed by the TPs and PCs are ongoing, and conclusions with respect to the impacts that the setting changes may have are expected to be made public in the coming months.

In addition to specific GO, TP, and PC engagement to fully address the Alert, this and broader inverter-based resource performance assessment is being carried out by NERC's Inverter-Based Resource Performance Task Force (IRPTF) [12] which is expected to inform the performance requirements specified in IEEE P2800.

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