Small Commercial Inverter Laboratory Evaluations of UL 1741 SA Grid-Support Function Response Times

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Abstract — **Photovoltaic (PV) distributed energy resources (DER) have reached approximately 27 GW in the U.S., and the solar penetration rate continues to increase. This growth is expected to continue, causing challenges for grid operators who must maintain grid stability, reliability, and resiliency. To minimize adverse effects on the performance of electrical power system (EPS) with increasing levels of variable renewable generation, photovoltaic inverters must implement grid-support capabilities, allowing the DER to actively participate in grid support operations and remain connected during short-term voltage and frequency anomalies. These functions include voltage and frequency regulation features that adjust DER active and reactive power at the point of common coupling. To evaluate the risk of these functions conflicting with traditional distribution system voltage regulation equipment, researchers used several methods to quantify EPS-support function response times for autonomous voltage regulation functions (volt-var function). Based on this study, no adverse interactions between PV inverters with volt-var functions and load tap changing transformers or capacitor banks were discovered.**

Index Terms — **electrical power system, smart grid, voltage and frequency ride-through, voltage and frequency regulation, UL 1741, EPS support functions.**

I. Introduction

Recent studies indicate that the United States' solar generating capacity grew by 16% between 2014 and 2015, and forecasts suggest 16 GW_{dc} will come on-line in 2016 at an increase of 120% [1]. As more variable solar resources are implemented, solar energy displaces traditional electricity generation coming from centralized thermal generation and causes greater voltage swings on distribution circuits. Efforts to minimize adverse effects to the electrical power system (EPS) from this change in traditional generation can be realized by employing power converters with grid-support functions.

The California Public Utilities Commission (CPUC) Electric Tariff Rule 21 [2] has been aggressive in requiring new interconnection requirements for DERs to address EPS performance issues associated with the high penetration of solar DER. The Rule 21 tariff has been approved to allow distributed energy resources (DERs) to participate in voltage and frequency regulation in coordination with the area EPS. This proactive approach by the CPUC has initiated a revision to the UL 1741 certification standard [3] that not only reflects the requirements of the Rule 21 tariff, but also remains flexible to address other interconnection requirements documents like Hawaii Rule 14H [4]. The UL 1741 SA test procedure is designed to validate compliance with EPS support features in inverters and converters not yet covered by the broader IEEE 1547.1 [5], which includes all DER generators.

Evolutionary changes to the utility interconnection standard IEEE 1547 [6] are presently underway. However, because this is a consensus standard drafted by stakeholders including DER manufacturers, utilities, system integrators, consultants, academia and others, creating a major revision to the interconnection standard requires significant time to implement and is not expected until 2017 or 2018.

In both the UL 1741 SA and IEEE 1547 series update processes, many unanswered questions have been raised. One such question in the UL 1741 SA grid-support working group concerned the relationship and coordination of advanced grid-support DERs with classical protection systems and voltage regulation equipment. If, for example, the volt-var function operated extremely quickly, it would react to voltage regulating equipment transients, as when capacitor banks are actuated—potentially causing oscillations in the voltage profile due to conflicts in the voltage regulation schemes. Similarly, grid-support functions designed for protection, e.g., voltage and frequency ride-through, must allow protective equipment like reclosers to operate prior to DER tripping. With these concerns, standards development organizations (SDOs) are considering including the timing parameters of ramp time, time window, timeout period, and time delay from IEC TR 61850-90-7 [7] in the new standards to avoid equipment conflicts.

The orchestration of the new advanced inverter/DER functions with traditional voltage, frequency, and protection mechanisms is essential for grid operations and future adoption of PV. This paper investigates the experimental response of a small commercial (24 kW) inverter with an adjustable volt-var function as required by the UL 1741 SA grid-support test procedure. While response times will be manufacturer-specific, these results can guide discussions about DER influence on the EPS and risk of incompatibilities with existing utility equipment.

II. Grid-Support Inverter Functions

Spurred by the CA Rule 21 update, UL 1741 SA, and the IEEE 1547, full revision will include provisions for grid-support utility-interactive inverters to provide active and reactive power to assist the utility through multiple grid-support functions. The functions were developed for the power-

TABLE I
LOW-/HIGH-VOLTAGE RIDE-THROUGH SETTINGS THAT CORRESPOND TO ELECTRIC RULE 21

Region	Voltage at PCC (% Nominal Voltage)	Ride-Through Until (s)	Ride-Through Operating Mode	Maximum Trip Time (s)
High Voltage 2 (HV2)	V ≥ 120	No Ride Through	Not Applicable	0.16 sec.
High Voltage 1 (HV1)	110 < V < 120	12 sec.	Momentary Cessation within 0.16 Sec	13 sec.
Near Nominal (NN)	88 ≤ V ≤ 110	Indefinite	Continuous Operation	Not Applicable
Low Voltage 1 (LV1)	70 ≤ V < 88	20 sec.	Mandatory Operation	21 sec.
Low Voltage 2 (LV2)	50 ≤ V < 70	10 sec.	Mandatory Operation	11 sec.
Low Voltage 3 (LV3)	V < 50	1 sec.	Momentary Cessation within 0.16 Sec	1.5 sec.

electronic devices to minimize the adverse effects from variable renewable energy generation and other grid disturbances. Concise explanations of some of the voltage-regulating and voltage-monitoring functions follow.

A. Low-/High-Voltage Ride-Through

The interconnection standard in California now allows PV inverters to ride through events on the utility that previously caused the DER to cease energizing the utility. Based on the severity of the voltage sag or surge, there is a prescribed delay intended to allow the utility to stabilize prior to DER de-energization. The L/HVRT function is a departure from the previous UL 1741 / IEEE 1547 utility interactive requirements where only *must trip* levels and durations were assessed. Now the inverter *must stay connected* for a specific duration and then trip after the *must trip* time, as shown in Table I. Some low and high voltage regions require the equipment under test (EUT) to have a momentary cessation of power during the voltage anomaly when the inverter stops exporting current but returns to normal operation within 2 seconds of a voltage recovery.

B. Dynamic Volt-Var Operation

The volt-var (VV) function provides dynamic voltage-regulation response based on local or area EPS voltage. Either real or reactive power-prioritization behavior determines if the real power is reduced when the inverter reaches its VA limit. One example of the volt-var characteristic four-point curve is shown in Figure 1.

C. Specified Power Factor

The specified PF function sets the displacement angle as a response from a supervisory controller, local conditions, schedule, or other factors. It operates independent of voltage and frequency conditions at the point of common coupling (PCC). CPUC Electric Rule 21 requires an operating range of ±0.9 PF for <15 kW systems and ±0.85 PF for >15 kW systems, and power factor targets must be met for real power ranges of 20-100% of nameplate rating.

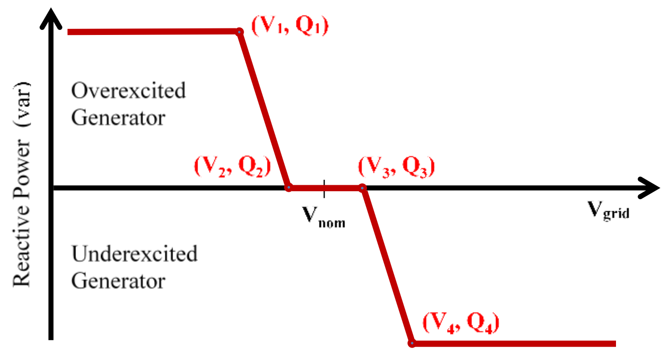

Fig. 1. Example Volt-var curve defined with 4 points. The deadband is between points 2 and 3.

III. VOLTAGE REGULATION EQUIPMENT AND RESPONSE TIMES

The potential conflict of the volt-var function with the implementation of typical distribution system voltage regulating equipment was investigated.

A. Overview of Distribution System Voltage Regulation Equipment and Their Speed

Three common distribution system voltage regulation devices exist: substation transformer load tap changers (LTCs), substation and line voltage regulators, and switched capacitors. These devices are operated by local measurement and control units that sample pertinent system parameters at a high frequency and usually incorporate time-delay settings [8].

LTC and voltage regulators are transformers (either a single 3-phase gang-operated or three single-phase transformers) that include a movement on the secondary winding to switch between different tap positions to correct the downstream voltage. The regulator controls include several different control modes, voltage setpoints, reverse current settings, and remote voltage regulation [9]. Sequential mode is most common and it continually samples the voltage at a sub-second rate during the time delay. If the voltage remains out of band for the duration of the time delay setting, an appropriate tap change is activated. After the first tap change, all subsequent tap changes, if necessary, will use a shorter inter-tap time delay of around 2 seconds, allowing the sensing voltage to stabilize before continuing until the voltage returns to within band, resetting the timer [10]. For voltage regulators, the delays are typically 30 to 60 seconds.

Shunt capacitor banks can also be used to provide voltage regulation by connecting/disconnecting based on voltage measurements, power factor control, or seasonal control. Most switching capacitor delays are generally 60 to 120 seconds. After connecting or disconnecting, the capacitor control often includes a dead time (~5 minutes) when it cannot immediately change states again.

B. Impact of PV Variability on Voltage Regulation Equipment

Cecchi et al., Ari and Baghzouz, and Ravindra, et al. [11-13]) have demonstrated how PV variability and frequent changes in PV output can make the voltage regulation equipment continually change taps, creating additional degradation of the equipment. The number and frequency of PV fluctuations will determine the impact to the number of tap changes [13]. Slow oscillations in PV output will be leveled with the daily load variability, potentially even decreasing the number of tap changes [8], and fast oscillations will occur within the delay window of the regulation equipment. The number of voltage regulation equipment changes depends on the size of the PV system [15] and the position of the interconnection compared to the regulator [16]. PV systems distributed around the feeder will have significantly less variability than single-point irradiance variability, so distributed PV will have less impact on the voltage regulators [17]. To fully understand the complex interactions between load and PV through time, quasi-static-time-series (QSTS) simulation tools are needed [8, 19].

C. Impact of Advanced Inverters on Voltage Regulation Equipment

PV inverter reactive power (e.g., volt-var) functions can control the voltage locally [19] and provide some voltage regulation, reducing the number of tap changes on the voltage regulator. Equipment currently used for distribution system voltage regulation was designed to regulate voltage for the slow, daily variability of the aggregate feeder load; therefore, the time delays are set to intentionally slow (10s of seconds) grid response times to act only during sustained voltage excursions and not transient conditions. On the other hand, power electronics- based devices, such as PV inverters, operate on a very quick timeframe, so any PV advanced inverter functions will respond to regulate voltage much faster than existing distribution system equipment. Because the inverter will react first, the inverter controls must be coordinated with the existing distribution system controls; otherwise, the PV reactive power injections can create issues with the voltage regulation equipment [20, 21]. For example, if a PV system is interconnected near a voltage regulator that is set to regulate the voltage at 1.04 p.u., a VV-enabled inverter with a small VV deadband could be constantly absorbing reactive power to try to pull the voltage down.

By appropriately using the advanced inverter functions on PV inverters to regulate voltage, the distribution system PV hosting capacity can be significantly increased [22, 23]. The issue is how to determine the appropriate advanced inverter settings. Results in [24] show that poor volt-var settings can increase the number of tap changes significantly from the unity power factor case (>2 times the number of taps); whereas, by selecting the correct volt-var curve, the number of tap changes can be reduced by 20%. Methods have been proposed in [25, 26] to determine site specific inverter settings, but results show how those settings are highly dependent on the specific scenario analyzed.

IV. EPS Support Function Performance Evaluation

Sandia National Laboratories has been working with UL and inverter manufacturers to quantify the performance of grid-support functions in a controlled laboratory setting. For these evaluations, the functions were programmed through a manufacturer-provided graphical user interface that communicated Modbus to the equipment under test (EUT) over a TCP/IP connection. All of the assessments were implemented with default ramp rates. The focus of this paper is on the response times of volt-var (VV) to simulated utility voltage anomalies that vary in magnitude and duration.

A. Dynamic Volt-Var Operation

The VV autonomous function can be remotely enabled and the parameters can be adjusted through communications. This function is designed to respond autonomously to a change in line voltage outside a predetermined deadband value between points 2 and 3 in Figure 1 (above).

The range of VV slopes has been widely debated during the development of the UL 1741 SA volt-var test procedure. For these tests, the inverter was configured with an aggressive volt-var curve to maximize the response time of the function. To do this, the reactive power transitioned from 0 to the maximum EUT rating when the grid voltage exited the deadband, i.e., $V_1 = V_2 = 0.99$ p.u and $V_3 = V_4 = 1.01$ p.u. Figure 2 shows the curve where the reactive power is set to maximum outside of the deadband.

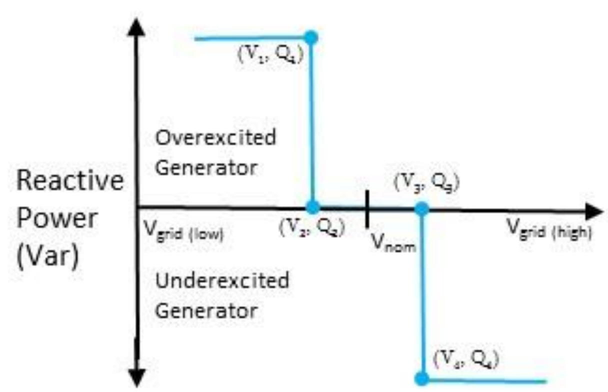

Fig. 2. Aggressive volt-var curve used for the experiments with $V_1 = V_2$ and $V_3 = V_4$.

Because the function responds to a change in voltage, concern has been expressed by stakeholders that the function will respond to capacitor banks and other short term voltage fluctuations. For this reason, function characterization evaluations have begun at Sandia National Laboratories.

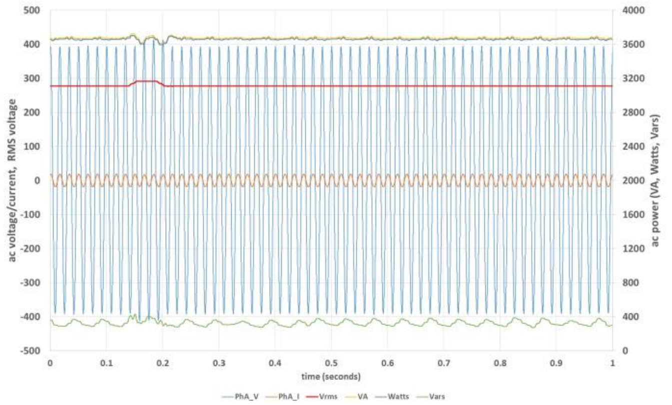

Fig. 3 Volt-var response to 3 cycle voltage surge. The reactive power is absorbed by the inverter.

Voltage deviations were conducted for 3 cycles, 30 cycles, and 300 cycles using an Ametek RS180 ac grid simulator to determine the response time of the EUT. Figure 3 shows that the real and reactive inverter power does not change during a 3 cycle, 1.05 p.u. voltage surge. For a 30-cycle voltage surge to 1.05 p.u., the volt-var function sinks reactive power, but the response happens after the voltage surge event as shown in Figure 4. While the EUT did not have a programmed delay in the volt-var response, it does have a default 1-second minimum ramp rate to reach 95% of programmed reactive power; therefore, the change in reactive power takes ~1 sec to reach full reactive power output.

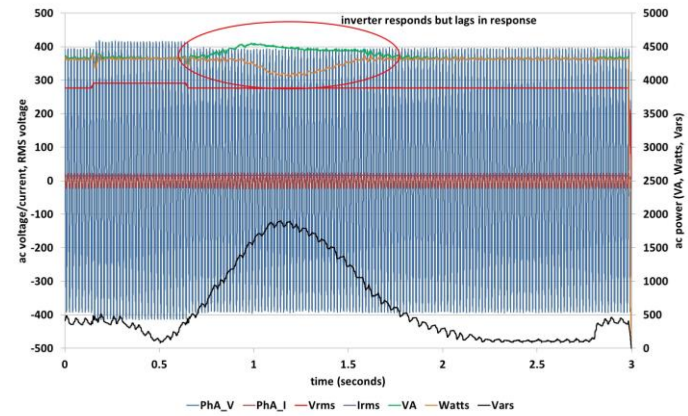

Fig. 4. Volt-var response to 30-cycle voltage surge. The reactive power is absorbed by the inverter.

Another waveform was captured in Figure 5, but this time with a voltage sag long enough to ensure that the reactive power output from the EUT reaches the programmed maximum reactive power limit. The waveform in Figure 5 shows the volt-var function fully engaged and the inverter delivering the maximum programmed reactive power in an attempt to address

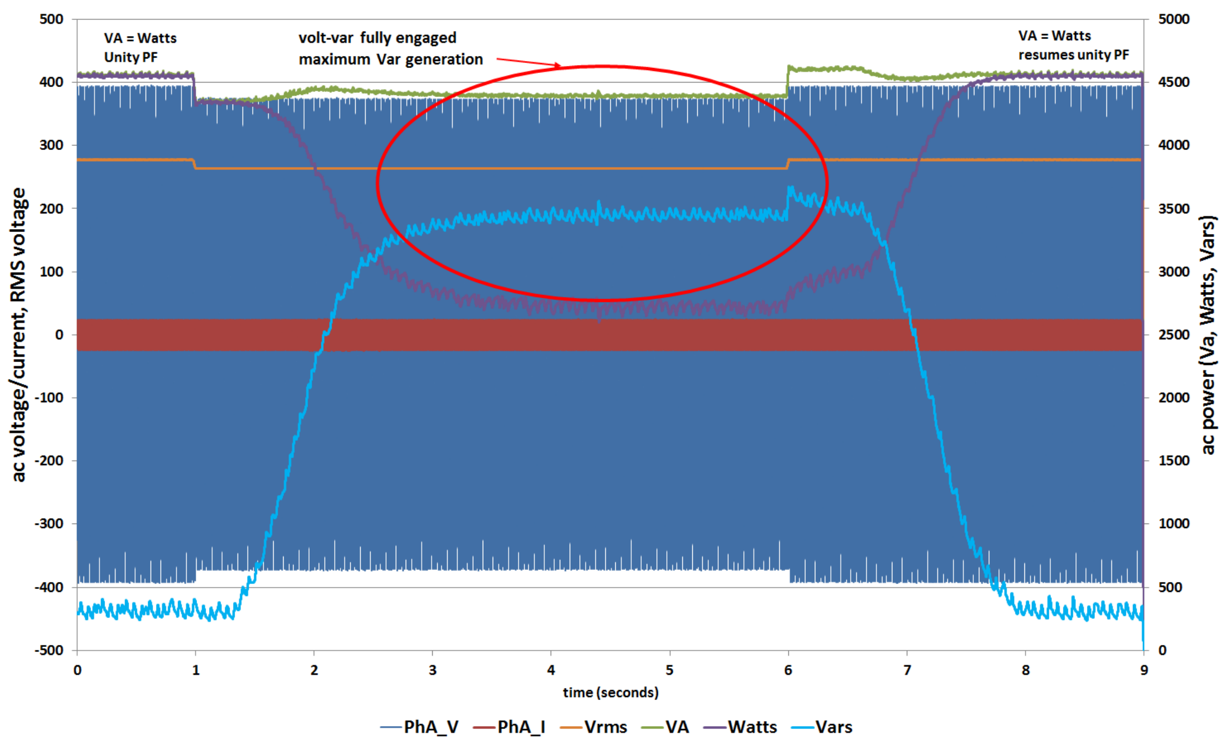

Fig. 5. Volt-var response to 5-second voltage sag to 95% of nominal line voltage. The reactive power is sourced by the inverter.

the under voltage condition. These waveforms provide an example of the potential capabilities of the volt-var function if the parameters of the functions were set to respond aggressively. The response to voltage variations will vary between inverter manufacturers.

B. Component Interaction with Volt-Var Operation

Different devices and grid operations can cause voltage fluctuations. One event that can cause a short, high voltage spike is energizing of a capacitor bank. When a capacitor is initially energized, a transient charging current will flow and, depending on the impedance of circuit and the significance of the current flow, this can cause a voltage perturbation. To determine if the voltage surge from the capacitor bank would invoke the volt-var function, a 50 kvar capacitor surge waveform was captured at Sandia National Laboratories' Distributed Energy Technologies Laboratory (shown in Figure 6). The current surge causes a voltage perturbation relative to the impedance of the circuit and the capacitance of the capacitor bank. From this experiment and other measurements of capacitor bank operations (that also occur in the time frame of <10 ms [27]), one can conclude that this particular EUT would be deconflicted with capacitor bank operations since the EUT requires at 3 cycles to respond. Furthermore, most inverter manufacturers use more than 1 cycle (often 5 or 10 cycles) to calculate the rms grid voltage so the reactive power response will be dampened with the inherent smoothing from the voltage calculation.

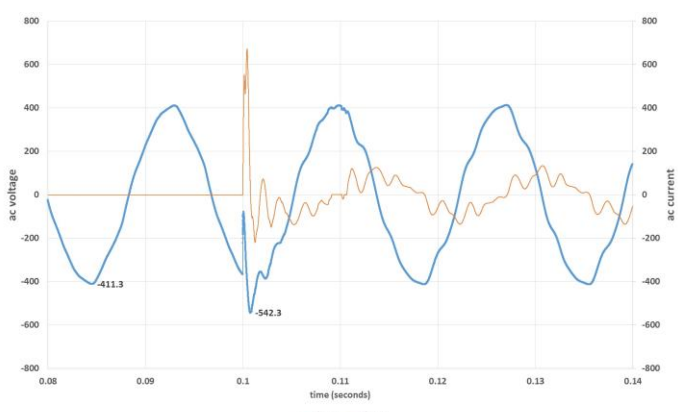

Fig. 6. Capacitor induced ac voltage transient (blue). This configuration results in a ~130% temporary overvoltage for ~3 ms.

Because LTC operations do not experience significant voltage overshoot, the tap occurs in 30-200 ms, and there are 2-sec delays between successive taps [28]. PV inverters with VV functions will not respond with significant reactive power injection/absorption during the LTC operation or initiate oscillatory feedback between the PV inverters and LTC devices.

V. Conclusion

The penetration of photovoltaic distributed energy resources has the potential to increase by an order of magnitude by 2030 [29]. Challenges to this growth range from coordination schemes for high levels of variable DER and load to the financial challenges encountered when providing reactive power capabilities reduces fiscally-lucrative active power generation. By implementing and properly using inverters with utility support functions to reduce the effects of hosting a high level of variable DER and to minimize the activation of existing voltage regulation equipment, high PV penetrations will invariably be achieved..

The experimental results presented in this report show that the volt-var function would ***not*** respond to voltage transients caused by capacitor banks or LTCs. Analysis of the VV function demonstrated that the dynamic change in reactive power would combat a voltage anomaly outside the volt-var deadband and would reach steady-state after 1 sec. Capacitor banks and LTCs response times are faster than the analyzed autonomous voltage regulating function and therefore will not result in significant reactive power injection from VV-enabled inverters during the voltage transient; and there will be no conflict between the grid-support functions and traditional voltage regulation equipment.

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