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Grid Support Functions Assessment of PV Inverters using Open-Source IEEE P1547.1 Test Package

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***Abstract*— Grid codes around the world are requiring grid-support functions (GSFs) and standardized interoperability interfaces for distributed energy resources (DERs) to address the rapid increase of renewable energy. However, these new GSFs need to be assessed to ensure the desired power and communication capabilities exist in the field. The IEEE 1547.1 standard outlines the conformance test procedures for DER devices and is currently undergoing a major revision to align it with IEEE 1547-2018. Once it is published (anticipated in mid-2020), GSFs in commercial PV inverters in USA and Canada will be certified to the IEEE 1547.1 conformance test procedures. Several international research laboratories are collaborating to develop a versatile open-source DER testing platform that performs automated testing of DER devices. This community of laboratories is developing open-source IEEE Std. 1547.1 test scripts to lower barriers to DER vendor internal equipment evaluations, ease product compliance testing at certification laboratories, and provide research institutions a tool to study DER behaviors. In this work, test scripts were used for test verification of GSFs, including limit active power, constant reactive power, active power-reactive power (watt-var), and prioritization of GSF response for several DER devices. Sample test results for these DER GSFs and test protocol recommendations are presented in this paper.**

Keywords*— interoperability, grid-support functions, DER testing, inverter, certification protocols, smart grid.

I. Introduction

The rapid increase of decentralized, variable renewable energy (RE) sources such as solar photovoltaic (PV) and wind systems in the electric power grid is offsetting the traditional, centralized electricity generation. These distributed energy resources (DERs) are mostly inverter-based, inertia-less systems that displace synchronous generator based thermal plants and impact power system operations and dynamics. Grid codes or interconnection standards around the world have been updated to include grid-support functions (GSFs) and interoperability requirements for DER devices [1]. These functions provide utility operators with new methods for voltage regulation, bulk system control, power system visibility, and other grid services. Therefore, both national and regional jurisdictions in North America have started to require GSFs (i.e., IEEE 1547 [2], CSA C22.3 No. 9 [3], CA Rule 21 [4], etc.).

DER vendors, grid operators, certification laboratories, and academic smart grid test laboratories need the ability to verify these new functionalities to ensure effective communication and power characteristics. A Nationally Recognized Test Laboratory (NRTL) certifies commercially available PV inverters in Canada and USA to conformance standards. IEEE Std. 1547.1 [5] defines the type testing procedures for conformance criteria to be certified to the DER advanced functions in IEEE Std. 1547 [6]. The IEEE 1547.1 standard went through a major revision between 2018-2020 to include the IEEE 1547-2018 GSFs and will be reflected in a revision of UL 1741, called Supplement B (SB), that will be used by NRTLs for certification purposes of DER inverters once published. Draft IEEE 1547.1/UL 1741 SB GSF test procedures typically include dozens, if not hundreds, of measurement points so, it is critical to automate the certification process to minimize certification costs, durations, and risk of human error.

The Smart Grid International Research Facility Network (SIRFN) is one Annex of an International Energy Association (IEA) Technology Collaboration Programme (TCP) called the International Smart Grid Action Network (ISGAN). SIRFN laboratories have been collaborating for years to create a versatile open-source DER testing and certification platform in collaboration with SunSpec Alliance, known as the SunSpec System Validation Platform (SVP) [7]. The SIRFN group has evaluated GSFs in multiple DER devices [5], [8], [9] and created test scripts for different test protocols, i.e., UL 1741 SA [8] and IEEE 1547.1. These evaluations have used the SVP that automates the test procedures by executing sequences of testing logic that change settings on the equipment under test (EUT), AC grid simulator, PV simulator, and data acquisition system using Python scripts [10]. The SVP saves the test results in the

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form of a manifest that contains the test log, raw data, a summary of results with pass/fail results, and Microsoft Excel/python plots of the results. The SIRFN group regularly assesses the versatility and effectiveness of upcoming grid codes and associated type test procedures from different jurisdictions and provides feedback to the standards development organizations for corrections and enhancements of the test procedures [5], [9].

The IEEE 1547.1 draft introduced type tests for new GSFs, which are novel for the DER industry; i.e., phase-angle change ride-through (PCRT), frequency-droop, limit active power, constant reactive power, watt-var, prioritization of DER function response, interoperability, etc. The SIRFN team is developing Python test scripts for these and currently assessing multiple residential and commercial-scale PV inverters for these functions using SVP, as commercial PV inverter vendors are updating their firmware to be compatible with these latest requirements. In addition, the team also developed the test scripts for volt-var, volt-watt, and constant power factor. This paper evaluates multiple DER (PV) inverters for four new tests from IEEE P1547.1 D9.9 standard; limit active power, constant reactive power, active power-reactive power (watt-var), and prioritization of GSF response. In prior work by this team, constant-power-factor, volt-var, volt-watt, and frequency-watt were evaluated [5], along with the phase-angle change ride-through (PCRT) function []. The paper also includes test results from different SIRFN laboratories with comments and findings for these functions.

II. System Validation Platform (SVP)

The SVP autonomously orchestrates interconnection and interoperability conformance tests for DER devices [10]. It automates the execution of tests/evaluations by communicating to laboratory equipment (e.g., grid simulator, PV simulator, and data acquisition system) as well as the (EUT) in a laboratory test setup, as shown in Fig. 1. In the SVP, the user defines the test by selecting the appropriate test script and associated parameters.

Based on the test requirement and EUT rating, the SVP configures all laboratory equipment. The SVP uses abstraction layers for all laboratory components, enabling the use of same test script at different laboratory testbeds by merely changing the equipment drivers for each testbed. The SIRFN group has developed a number of drivers for different kinds of grid simulators, PV simulator, data acquisition systems, and commercial EUTs, which are available in the open source GitHub repository [cite svp_energy_lab]. Currently seven SIRFN laboratories are actively using this SVP based structure for testing of DER inverters.

The Open SVP platform is available through GitHub for the laboratories to conduct similar DER testing [11]. The SIRFN group is also currently working on enhancing the capability of the test platform for new features, e.g., report generation, real-time plotting, etc. Ultimately, this open software tool will include all the test cases and procedures to target the full spectrum of the DER industry participants from DER vendors, universities, research institutions, certification laboratories and standards organizations to apply the same standardized testing methods at each stage of development.

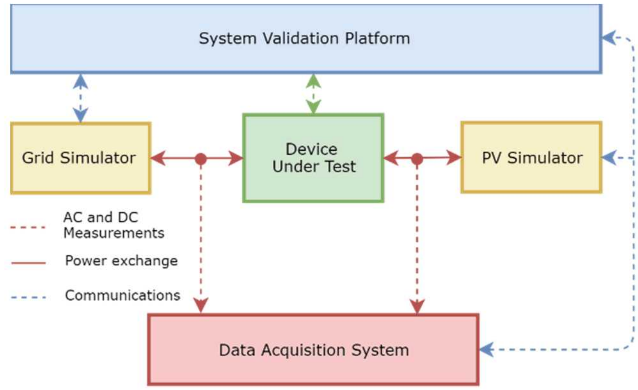

Fig. 1. SVP generic laboratory configuration.

III. Experimental Results

The SIRFN community has created the SVP test scripts to assess the GSFs from the draft IEEE 1547.1 (version 9.9) standard [12]. The test scripts are available on GitHub [13]. Experiments were conducted at different SIRFN laboratories using the open-source SVP to assess the GSFs. This paper presents the assessment of four (4) different commercial EUTs. These assessments were performed at four different SIRFN laboratories: CanmetENERGY in Canada, Sandia in USA, KERI in Korea, and AIST-FREA in Japan. Table I presents the specification of the different EUTs that were tested in this work. All the EUTs were tested for category B definition of IEEE 1547-2018. The detailed comparisons and findings of the test results and any issues with the SVP scripts and drivers are discussed below.

TABLE I. EUT Specifications

Laboratory	Phase	Rated Power [kW]	Nominal Phase Voltage [V]	Nominal Frequency [Hz]
AIST	3-ph	50	277	60
CANMET	1-ph	6	120	60
KERI	3-ph	12	277	60
SANDIA	3-ph	24	277	60

A. *Test for limit active power*

This test verifies the EUT's capability to limit the active power while confirming the EUT prioritizes the volt-watt mode and frequency-droop over active power limiting. For the entire test, the DC source is programmed for nominal output power. This test is done for three different EUT power limit command (66%, 33% and zero). Fig. 2 presents the steady-state applied-measured voltage and frequency and the corresponding target and output active power (response) at the different steps of the test following the IEEE P1547.1 D9.9 standard [12]. The figure also includes the target value which is calculated here based on the commanded AC voltage magnitude and frequency. However, to pass the test according to the standard, the results can be within a band of 0.075 pu from the target value. It should be mentioned that this test was conducted for only 66% power level at AIST.

For the steps D and E, the EUT at KERI does not change the output active power when subjected to all frequency variations.

The EUT at CanmetENERGY reduces the active power to 43.9%, 11.6% and 0% when the frequency is 61 Hz for operation at the 66%, 33% and 0% power levels respectively. The EUT at AIST reduces the active power to 24.9% when the frequency is 61 Hz for operation with 66% power level. However, none of the EUTs increase the active power when the frequency is 59 Hz. Therefore, no EUT follows the frequency-active power droop characteristic for frequency values lower than the nominal frequency.

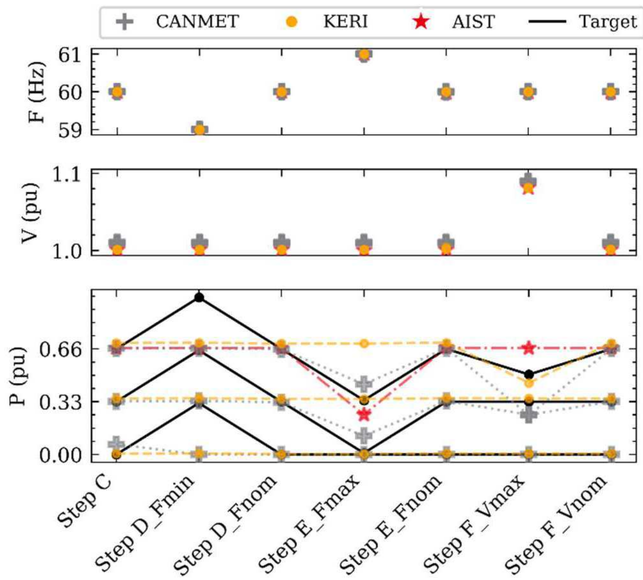

Fig. 2. Test results for limit active power.

For Step F, when the voltage is increased to 1.08 pu, the EUT at CanmetENERGY reduces its active power to 25%, 25% and 0% for 66%, 33% and 0% power limit operations respectively. The power curtailment is higher because the AC side applied voltage was higher than the target value. For the same voltage variation, the EUT at KERI reduces its active power to 44.7% for 66% active power level test. This EUT also does not change the active power for 33% and 0% power level test. The EUT at AIST does not respond to the voltage variation while operating at 66% power level test.

B. Test for constant reactive power (var) mode

This test verifies the EUT's operation at a constant reactive power setting while operating at different active power levels and subjected to AC voltage variations. The test analyzed the response of EUT for four different constant reactive power values at ±100% and ±50% of Q_{rated}. For each of the test at constant reactive power value, the EUT is subjected to first an active power perturbation of P_{min} and then, to a voltage variation at rated power operation. The voltage variation includes minimum and maximum voltage value and in addition for three phase EUT, two unbalance voltage scenarios.

Fig. 3 shows reactive power response for operation at ±50% of Q_{rated} of the EUTs from different laboratories. It presents the steady state reactive power response for each of the test steps from the standard. To pass the test, the results can be within a band of 7.5% of apparent power nameplate from the target value according to the standard. Since the single-phase EUT from CanmetENERGY is not subjected to voltage unbalance scenarios, therefore, it does not have test output values for steps M to Q. The output reactive power of the EUTs from CanmetENERGY and KERI follow the reactive power commands as shown in Fig. 3. Even it is also found that these EUTs are also following the ±100% of Q_{rated} command/programme value by curtailing its active power value.

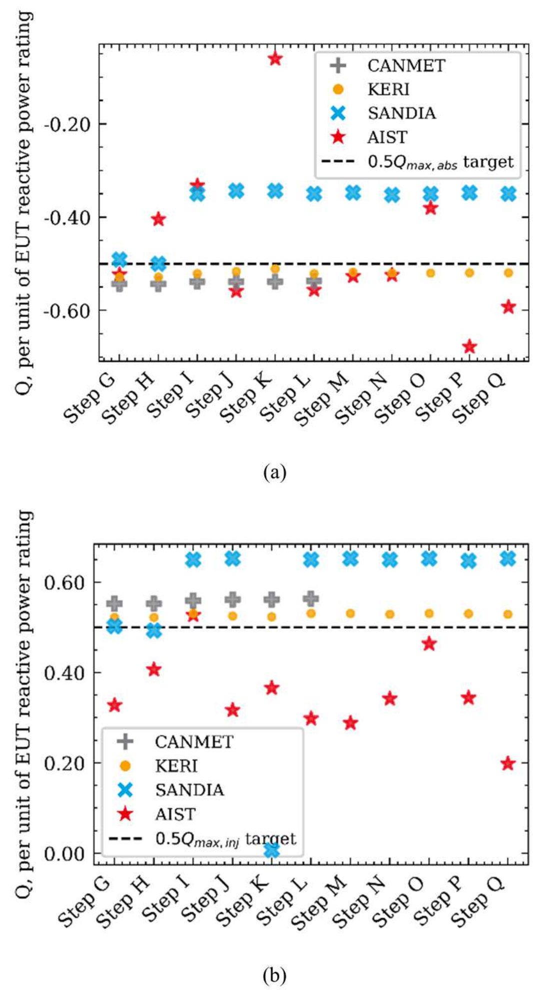

Fig. 3. Test results for constant reactive power. (a) 0.5 of max absorbtion, (b) 0.5 of max injection

C. Test for active power-reactive power mode (watt-var)

This test verifies the EUT's reactive power response with variation of output active power. The test verifies the watt-var operation of the EUT by analyzing three different characteristic curves. This test is conducted by applying different values of available active power to the EUT and observing the reactive power response.

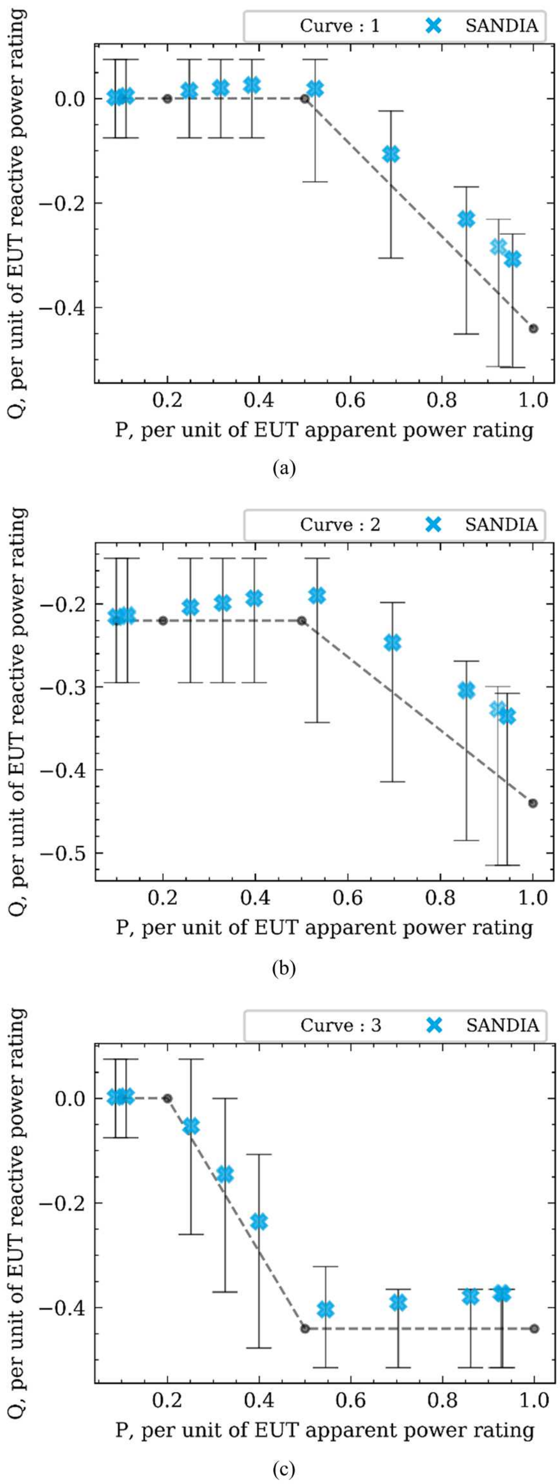

Fig. 4. Test results for watt-var function. (a) characteristic 1, (b) characteristic 2, (c) characteristic 3

The watt-var function is only available in the EUT from Sandia. Fig. 4 presents the watt-var test results for the three different characteristic curves. The ideal watt-var curves are shown by the dotted lines in the figure. Overall, the test results reveal that the EUT remains within the passing band provided by the Annex C of IEEE P1547.1 D9.9 test criteria formulas. The pass-fail band for watt-var function is defined by the equations below, where MRA stands for minimum required accuracy.

$$Q_{min} = Q(P_{meas} + 1.5 \times MRA(P)) - 1.5 \times MRA(Q) \quad (1)$$

$$Q_{max} = Q(P_{meas} - 1.5 \times MRA(P)) + 1.5 \times MRA(Q) \quad (2)$$

In the IEEE 1547.1 draft, the test requires the curve evaluation sequence to be executed at 20% and 66% of rated EUT power. Since the available DC power is the input variable for the experiments, this curtailment will not expose the characteristics of the WV curve. Instead, it is recommended that the test sequence replace step AA with three sweeps of the WV curve without any active power limitation while using the available DC power as the control variable.

D. Test for prioritization of DER responses

The purpose of this test is to verify the EUT's operation and prioritization with multiple voltage and frequency regulation functions enabled when it is subjected to AC side voltage and frequency variations. The EUT shall prioritize the response of the functions correctly.

This test is conducted by keeping both frequency-watt and volt-watt functions enabled and operating the EUT with active power limit signal to 50% of P_{rated}. This test analyzes the EUT's active power and reactive power response for each scenario of voltage regulation functions, i.e., volt-var, constant var, constant power factor, and watt-var. The expected response (for the 8 steps) from the EUT are outlined in Table 39 of IEEE 1547.1 D9.9 for category B DER. The test results for the following sections are obtained at CanmetENERGY and KERI.

Volt-var (VV)

Fig. 5 presents the prioritization test results with volt-var function for all the 8 steps. It shows the EUTs' response when it is subjected to voltage and frequency variation, per the Table 39 of the standard. Both the EUTs follow the target reactive power values corresponding to the different voltage and frequency values.

The active power output of the EUT from KERI is not affected by the frequency variation during the whole test. It only responds to the voltage variation, therefore reduces the output active power accordingly in Steps 2 to 5. The EUT from CanmetENERGY reduces its output active power for over voltage conditions in Steps 2 to 5. However, the grid simulator was applying higher voltage than the commanded value of 1.09 pu value as seen in Fig. 5, therefore it resulted in higher active power curtailment with the volt-watt function. While operating in this region (of Steps 2 to 5), when the frequency changed to 60.33 Hz, the EUT reduces the output power further following the frequency-watt or droop function. But this EUT does not respond to under frequency condition as seen in Steps 6 and 8 of Fig. 5.

Constant power factor (CPF)

Fig. 6 presents the prioritization test results with constant power factor function. The same voltage and frequency variation profile is applied to the EUT like the previous section of volt-var. The reactive power is calculated from the active power (*P*) and power factor (*pf*), given by,

$$Q(P) = P\sqrt{\left(\frac{1}{pf^2} - 1\right)} \tag{3}$$

The EUT from CanmetENERGY produces very low active power output for Steps 2 to 5, unexpectedly. However, it responds to the *pf* command to steps 1 and 7. Again, as the EUT does not respond to under frequency event, therefore, it does not follow the targets for Steps 6 and 8. The EUT of KERI follows the target values with voltage variations while operating at rated frequency. However, it does not respond to the frequency-watt or droop function for the entire test.

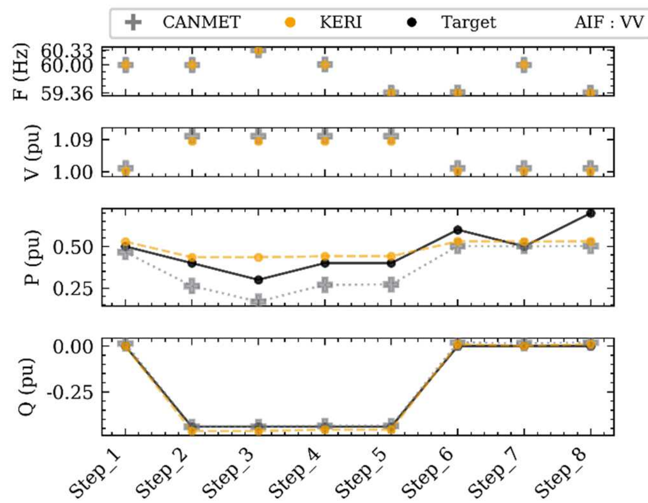

Fig. 5. Test results for priotization with volt-var function.

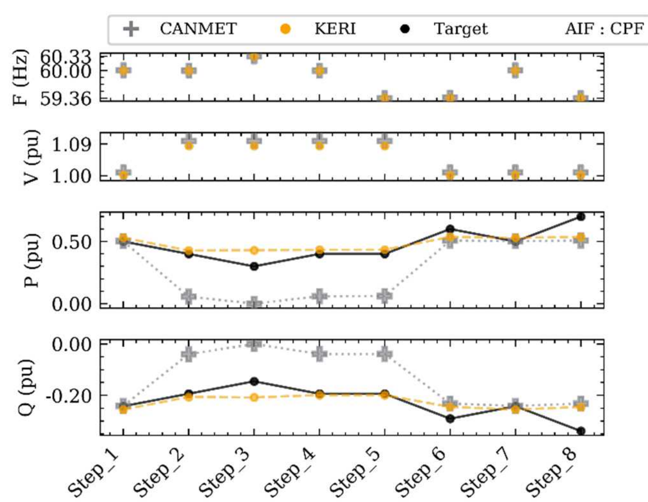

Fig. 6. Test Results for priotization with constant function.

Constant reactive power (CRP)

Fig. 7 presents the prioritization test results with constant reactive power function when the same voltage and frequency variation profile is applied to the EUT. The EUT from CanmetENERGY again goes to low active power output for Steps 2 to 5, unexpectedly. In addition, it stops injection of power for Step 3. This needs further investigation. However, it maintains the constant reactive power command (within the error band of 0.075 pu from the target value) for all steps except Step 3 when the EUT stopped injection of power. Again, as the EUT does not respond to under frequency event, it does not follow the active power targets for Steps 6 and 8. The EUT of KERI follows the target values with voltage variations while operating at rated frequency. It does not respond to the frequency-watt or droop function for the test (Step 3, 6 and 8).

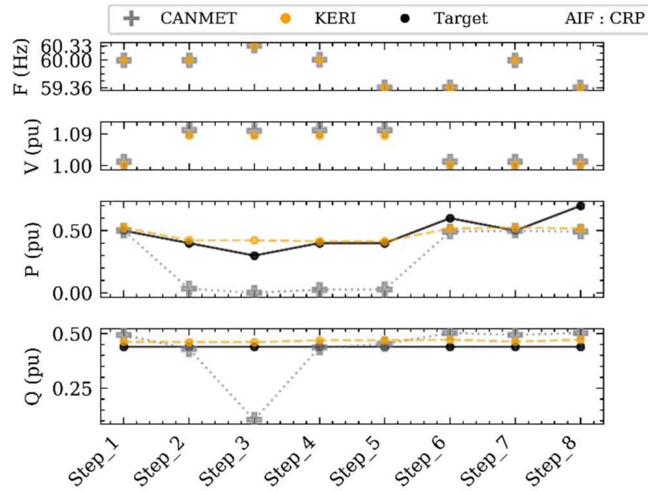

Fig. 7. Test Results for priotization with constant reactive power function.

E. *Evaluation of time response*

The assessment of the grid support functions in the previous sections were done based on the steady state measurement value. The IEEE 1547.1 D9.9 standard also requires verification of the response time for GSFs. This verification process for one of the GSFs are discussed below.

The standard requires assessment of the open loop time response. The general idea is that by testing the open loop response; one is indirectly testing the close loop response. The Annex I information section of IEEE Std. 1547 explains this correlation and why using an AC test source and open loop response in the criteria is the preferred method for testing voltage and frequency regulation functions.

Fig. 8 shows time domain response for the active power–reactive power (watt-var) function. The figure also includes a zoomed version of the output reactive power to show the transitions between two operating points. In this zoomed figure, $TR_{initial}$ is the beginning of a perturbation, TR_1 is the first time response, and TR_2 is the last time response (or time for steady state response). The value corresponding to red dashed line (--) represents the expected reactive power (y) value after an elapsed time of TR_1, given by,

$$Y_{Target} = 90\ \% * \left(Y_{final} - Y_{initial}\right) + Y_{initial} \tag{4}$$

The EUT is considered to pass the first time response criteria if it exceeds this Y_{Target} value following a reference value change. This evaluation should also consider the minimum required accuracy (MRA) of time variable. The MRA for time is available from Table 3 of IEEE 1547-2018 standard. Therefore, the Y_{Target} value should be achieved by a maximum time of TR_1 - MRA_{time} as shown in Fig. 8.

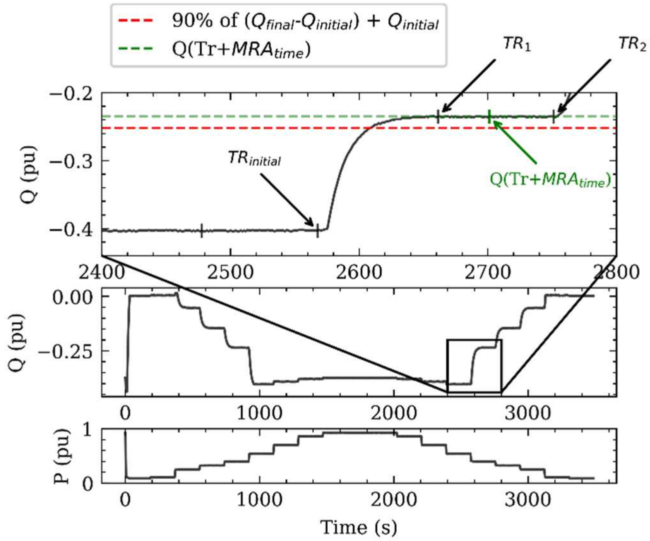

Fig. 8. Open loop time response of WV curve no.1.

IV. Conclusions

To enable greater penetration of renewable energy resources in the distribution grid level, grid codes and interconnection standards are requiring DERs to include grid support functions and communication capabilities for their interoperation. The international research laboratories under the SIRFN are working on developing an open-source test software package including both an open-source GSF validation platform and associated test scripts for multiple certification standards. This community developed the test scripts for validating multiple grid support functions from the draft IEEE 1547.1 standard. Several residential/commercial PV inverters were assessed at different international laboratories for several new functions, i.e., limit active power, constant reactive power, active power-reactive power (watt-var), and prioritization of GSF response. A performance comparison of different EUTs is presented in the paper. The commercial products are already equipped with these new grid support functions thus can meet the requirements to certain extent. None of the EUTs respond to under frequency droop characteristic. Eventually the manufacturers will update their DER products to meet all the grid support function requirements of IEEE 1547-2018.

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