Test Case 3

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Name of the Test Case	Real-time supervision of a photovoltaic (PV) system and control of operational settings for centralized active power limitation and localized voltage regulation
Narrative	The integration of high shares of variable renewable energy (VRE) technologies, such as PV, is essential for decarbonizing and meeting the demands of future grids but introduces new grid operation challenges. In particular, the variability and uncertainty of solar electricity incurs serious stability and reliability issues in power system operations, rendering new power system flexibility options critical for ensuring balanced operation. To this end, the increasing amount of PV generation, especially at the distribution level, can create problems to the power system with a few of the reported consequences being rapidly varying voltage profiles and increased frequency swings that exceed design or regulated limits. This is the main reason why utility grids with large share deployment of distributed PV systems are fostering the transformation towards modern digitally-enhanced technologies that will enable the centralized observability and control of underlying distributed energy resources (DERs). In order to resolve these issues, programmable automation controllers (PACs) and PV system smart inverters have the interoperability capability to process signal operational set-points originating from centralized control and supervisory systems for immediate control and implementation of different autonomous control strategies (i.e. Fixed Power Factor, Volt-VAR, Volt-Watt and Frequency-Watt). In particular, intelligent edge devices such as PACs can be configured to act as a PV system power plant controller (PPC) and to pass signals that originate from centralized control and supervisory cloud-based systems to smart inverters for immediate controls (connection/disconnection of system and active power limitation). Regarding voltage regulation, the Volt-VAR mode is the most employed and discussed localized control strategy for smart inverters. This is because of the ease at which voltage regulation can be achieved by controlling the reactive power produced by the inverter. More specifically, the Volt-VAR mode provides dynamic reactive power output (absorption or injection) through responses to voltage measurements. The reactive power output follows a specified Volt-VAR response (characteristic curve) which typically would have a dead-band around the target voltage where no reactive power is injected or absorbed. In contrast to current practises of enabling localized smart inverter controls through manual methods and on-site visits, the localized Volt-VAR control strategy can be implemented by enabling the function and setting the characteristic curve points through

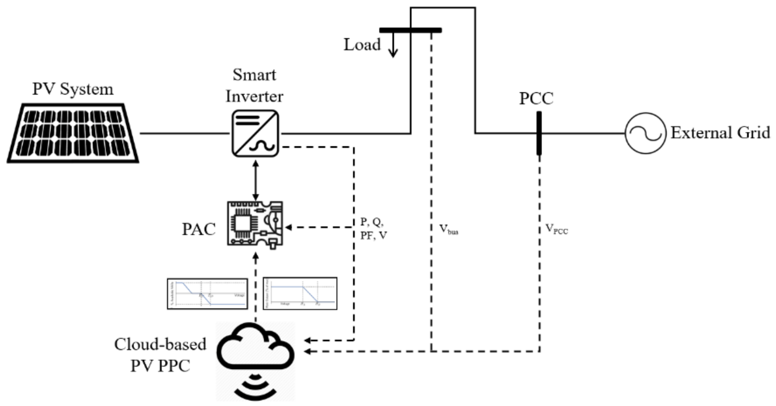
	the centralized control and supervisory cloud-based dashboard. The set-points are then transferred to the PAC that processes and relays the control function to the smart inverter (signalling responses based on SunSpec and IEC 61850). Another localized voltage regulation control mode is Volt-Watt. This control mode is applicable only to feeders with extreme over-voltage profiles and may also be enabled to operate in conjunction with the commonly applied Volt-VAR mode. Specifically, the rate of active power reduction is determined by the slope of the characteristic curve of set-points based on the voltage at the point of common coupling (PCC). To this end, this control strategy can be remotely enabled (configured at the centralized control and supervisory cloud-based dashboard) and set to the smart inverter (PAC processes control information and sets the control mode to the smart inverter) to provide active power reduction in case of voltage rises at the PCC, beyond National grid code levels. In the occurrence of fault communication conditions (loss of cloud connectivity) the PAC is set to remain/switch to the Volt-VAR autonomous control mode (fallback settings in the absence of cloud connectivity). The aim of this test case is to investigate coordinated real-time supervision and control strategies provided by cloud-based systems, PAC and SunSpec compliant smart inverters, for centralized active power limitation and localized voltage regulation.
Function(s) under Investigation (*FuI*) “the referenced specification of a function realized (operationalized) by the object under investigation”	PV system centralized active power limitation and enabling localized reactive and active power control for voltage regulation.
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test”	PV system connected to a smart inverter (SunSpec compliant) that can receive automated control signals through the use of a PAC. The PAC processes real-time signals (set-points for immediate and localized controls) originating from a centralized control and supervisory cloud-based system.
Domain under Investigation (*DuI*): “the relevant domains or sub-domains of test parameters and connectivity.”	• Electrical power system • Control • ICT
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	Design of a cloud-based PV PPC capable of providing automated ancillary services by taking advantage of the smart inverter abilities for immediate control (active power limitation) and to perform the Volt-VAR and Volt-Watt control modes for voltage regulation.
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	The SuT is composed of the following components: • PV system • Smart Inverter • PAC

	• Cloud-based database and SCADA platform
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT.	• Real-time signalling effectiveness of centralized control and supervisory cloud-based system for PV system active power limitation (active power limitation signals originating from the cloud are communicated to the PAC that acts as an edge device PPC. The PAC processes the signals and passes them to the inverter) • Volt-VAR and Volt-Watt localized control effectiveness for the provision of ancillary services (voltage regulation) from PV systems using smart inverter functionalities. The set-points of the characteristic curves are implemented at the cloud-based system dashboard and then relayed to the smart inverter via the PAC.
<u>Test criteria</u> *(TCR)* Formulation of criteria for each PoI based on properties of SuT; encompasses properties of test signals and output measures.	• Effectiveness of centralized control and supervisory cloud-based system to interoperate with on-site PPCs and smart inverters for real-time supervision and relaying of control set-points (immediate controls such as connection/disconnection, active power limitation and enabling control strategies) • Effectiveness of Volt-VAR localized control mode in controlling reactive power to regulate voltage (voltage levels within grid code limits at PCC) • Effectiveness of Volt-Watt localized control mode in controlling active power to regulate voltage (voltage levels within grid code limits at PCC)
Target Metrics *(TM)* Measures required to quantify each identified test criteria	• Voltage deviation • Active power curtailment • Reactive power injection/absorption • Interoperability of PV inverter with the centralized control signals originating from the control and supervision cloud-based (communication effectiveness and latency of response)
Variability Attributes *(VA)* controllable or uncontrollable factors and the required variability; ref. to PoI.	• PV inverter immediate control and active and reactive power set-points • Control methods • Interoperability methods • Voltage limit set-points • Rate of increase/decrease of reactive or active power injection/absorption and limitation, respectively
Quality Attributes *(QA)* threshold levels for test result quality as well as pass/fail criteria.	• Voltage staying within a specific range (±10%) • Control method reaction time latency (<3 seconds)

Qualification Strategy

The implementation plan to meet the Purpose of Investigation (PoI) is to first design and simulate the PV power plant providing ancillary services, through different control methods, using the EMTP software offline and investigate whether the voltage is maintained within the predefined limits. Subsequently, the control model designs will be transferred to the real time simulator (RTS) for high fidelity control hardware-in-the-loop (CHIL) validation and verification. Finally, the test case will be demonstrated on a test-bench PV system that includes a smart inverter and controller using a PAC that processes signals that originate from a centralized control and supervision cloud-based system.

Test Specification 3.01

Reference to Test Case	TC3
Title of Test	Cloud-based real-time supervision and voltage regulation ancillary services for PV systems
Test Rationale	Design and demonstration of a grid-edge PV PPC that processes real-time signals from a cloud-based system for centralized supervision and localized voltage regulation at the PCC
Specific Test System (graphical)	
Target measures	• Observability of PV system and smart meter data • Voltage regulation at PCC • Centralized active power limitation of smart inverters • PV system active and reactive power control
Input and output parameters	<u>Input parameters:</u> • Smart meter voltage at PCC • PV inverter Volt-Watt and Volt-VAR control characteristic curves <u>Output parameters:</u> • Immediate smart inverter connection/disconnection signal • Smart meter voltage, frequency, apparent, active and reactive power • PV system active and reactive power
Test Design	• Variation of PV system generated power • Implementation of different control methods
Initial system state	• Voltage close to 1 pu • Unregulated PV system operating at maximum power point (MPP) mode
Evolution of system state and test signals	• Measurement of increase/decrease of voltage at PCC • Increase/decrease of active and reactive power with respect to voltage magnitude
Other parameters	n/a
Temporal resolution	1 second
Source of uncertainty	• Uncertainty of smart meter voltage measurements (0.5%) • Uncertainty of smart inverter power measurements (1%)

Suspension criteria / Stopping criteria	• Abnormal over or under voltage conditions

Mapping to Research Infrastructure

Experiment Specification 3.01.01

Reference to Test Specification	*TC3*
Title of Experiment	Simulating the effectiveness of PV power plant controls for voltage regulation
Research Infrastructure	UCY-FOSS DER-Grid Smart Facility
Experiment Realisation	The voltage regulation control methods proposed in Test Specification 22.01 (Volt-Watt and Volt-VAR operation of smart inverters) will be evaluated on a typical low voltage (LV) feeder (DER-Grid Smart Facility of UCY-FOSS). The LV feeder includes loads (fixed uncontrollable) and a grid-connected PV system (AC-coupled via a smart inverter). The feeder and localized voltage regulation controls will be digitally mapped and simulated using the EMTP software.
Experiment Setup (concrete lab equipment)	• PV system with smart inverter (SMA SB 3.0 PV inverter) • Smart meter (Schneider PM8000) • EMTP software
Experimental Design and Justification	The LV feeder at the UCY-FOSS DER-Grid Smart Facility will be digitally mapped using the EMTP software. The feeder includes loads, a grid-connected PV system (coupled to the grid via a smart inverter), a smart meter (grid measurements at the PCC) and a PAC (grid-edge PPC device). The localized voltage regulation controls will be modeled as a PV system PPC block configured as: • PI controller for reactive power control • Controller based on Volt-VAR curve settings • Controller based on Volt-Watt curve settings The effectiveness of the proposed control methods to regulate the voltage at the PCC of the simulated grid will be evaluated by applying a step change in the voltage and analyzing the output response of the modelled PV system PPC block. Finally, the performance of the implemented controls will be assessed by applying actual consumption and generation data-sets acquired at the feeder over a yearly period (1-minute resolution consumption and generation data).
Precision of equipment and measurement uncertainty	• Uncertainty of smart meter voltage and power measurements (0.5%) • Uncertainty of smart inverter active and reactive power measurements (1%)
Storage of experiment data	Csv

Experiment Specification 3.01.02

Reference to Test Specification	*TC3*
Title of Experiment	Centralized cloud-based PPC for real-time supervision and control of PV systems
Research Infrastructure	UCY-FOSS DER-Grid Smart Facility
Experiment Realisation	Real-time supervision (streaming of high-resolution smart meter and PV system data) and centralized control methods proposed in Test Specification 22.01 (immediate controls such as connection/disconnection, active power limitation and enabling control strategies) will be demonstrated using a cloud-based SCADA platform. The PAC installed at the feeder will stream high-resolution data (1-second) acquired from the smart meter and PV system inverter to the cloud database. The implemented cloud-based dashboards will provide the interface for visualizing in real-time the acquired data and to provide centralized control functionalities (relaying control signals for immediate smart inverter active power limitation and enabling Volt-VAR or Volt-Watt operational modes).
Experiment Setup (concrete lab equipment)	• PV system with smart inverter (SMA SB 3.0 PV inverter) • Smart meter (Schneider PM8000) • PAC (Gantner Instruments Q.Station XT) • RTS CHIL testbed (Typhoon HIL 604)
Experimental Design and Justification	The experiment entails the configuration of a PAC, installed at the DER-Grid Smart Facility feeder, to acquire and stream in real-time data from the smart meter and PV system inverter. Data acquisition will be implemented using the vendor-specific and SunSpec Modbus registers. The data streams created and stored at the PAC will be setup for real-time streaming to a centralized cloud database. Accordingly, an online cloud-based platform comprising of different dashboards will be designed in order to demonstrate the proposed observability and interoperability concepts. More specifically, a SCADA dashboard will be created to act as the supervision interface and exhibit in real-time the measurements streamed from the underlying assets of the feeder (smart meter and inverter). Moreover, a PPC control dashboard will be developed in order to provide the user interoperability interface for enabling the PV system control signaling (set-points for immediate and localized controls). The effectiveness of the centralized supervision and control methods will be demonstrated by enabling remotely the implemented control modes of the smart inverter through the cloud-based system. Finally, the functional response and latency of the cloud-based supervision and control system will be further verified in a CHIL approach using a RTS testbed. The RTS testbed will be utilized in order to vary the grid condition settings (varying in real-time the reference voltage at the PCC of the feeder via SunSpec Modbus over TCP/IP and analyzing the response of the controller).
Precision of equipment and measurement uncertainty	• Uncertainty of smart meter voltage and power measurements (0.5%) • Uncertainty of smart inverter active and reactive power measurements (1%)
Storage of experiment data	Csv