Advanced real-time supervision and centralized control of distributed energy resources in smart grids

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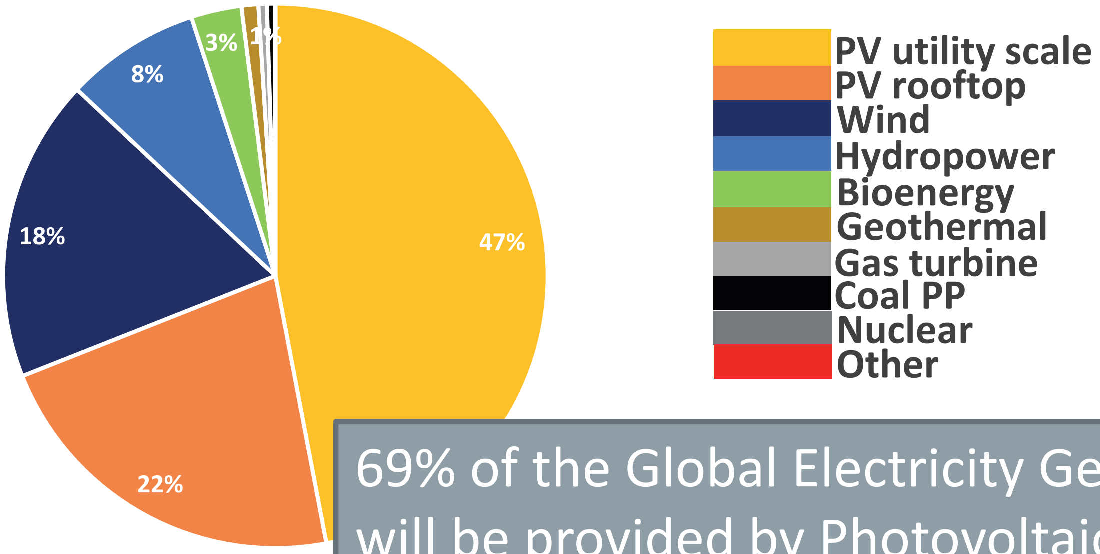
Introduction

- The century-old power grid remains the largest interconnected machine on Earth.
- Today's grid cannot meet the future expectations of the energy (R)evolution, mainly due to the high integration of renewables.
- Solar photovoltaic (PV) is entering a New Era as the global leader in renewable power offering competitively produced electricity.

55 571 TWh



69% of the Global Electricity Generation will be provided by Photovoltaics in 2050

Source: International Energy Agency (IEA), "Market Report Series: Renewables 2018", 2018

Key drivers

- European Climate Action and Energy Policy. European Union (EU) to become climate-neutral by 2050.
- Paris Agreement 2016 to reduce global warming <2°C.
- European Green Deal (EGD) energy policy for 2030 fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.

EU ≥ -55%
GHG emissions reduction

EU ≥ 32%
RES share target
(gross final consumption energy)

Large-scale electrification of end use sectors such as buildings, industry and transport, as well as gradual decarbonisation of the power sector, are key for the energy transition.

EU H2020 Programme GA No. 870620

Motivation

Main challenges:

- Future supply (renewable-powered grids) and increasing demand trends are affecting grid stability and reliability.
- The capacity of interconnected inverter-based technologies are increasing rapidly and challenge the operation of conventional power systems (centralized vs de-centralized supervision).

Opportunity:

- Modernize the distribution grid for increased distributed energy resources integrated in an optimal manner with real-time supervision and centralized control solutions.

Modernize the Grid (efficient and cost effective)
- Observability (supervision)
- Operational management (control)

Reinforce the grid
(not efficient and costly)

Scope

- Provide a conceptual overview of real-time supervision and control of distributed energy resources based on open-communication protocols, grid-edge IoT devices and cloud databases (unified and vendor independent solutions).

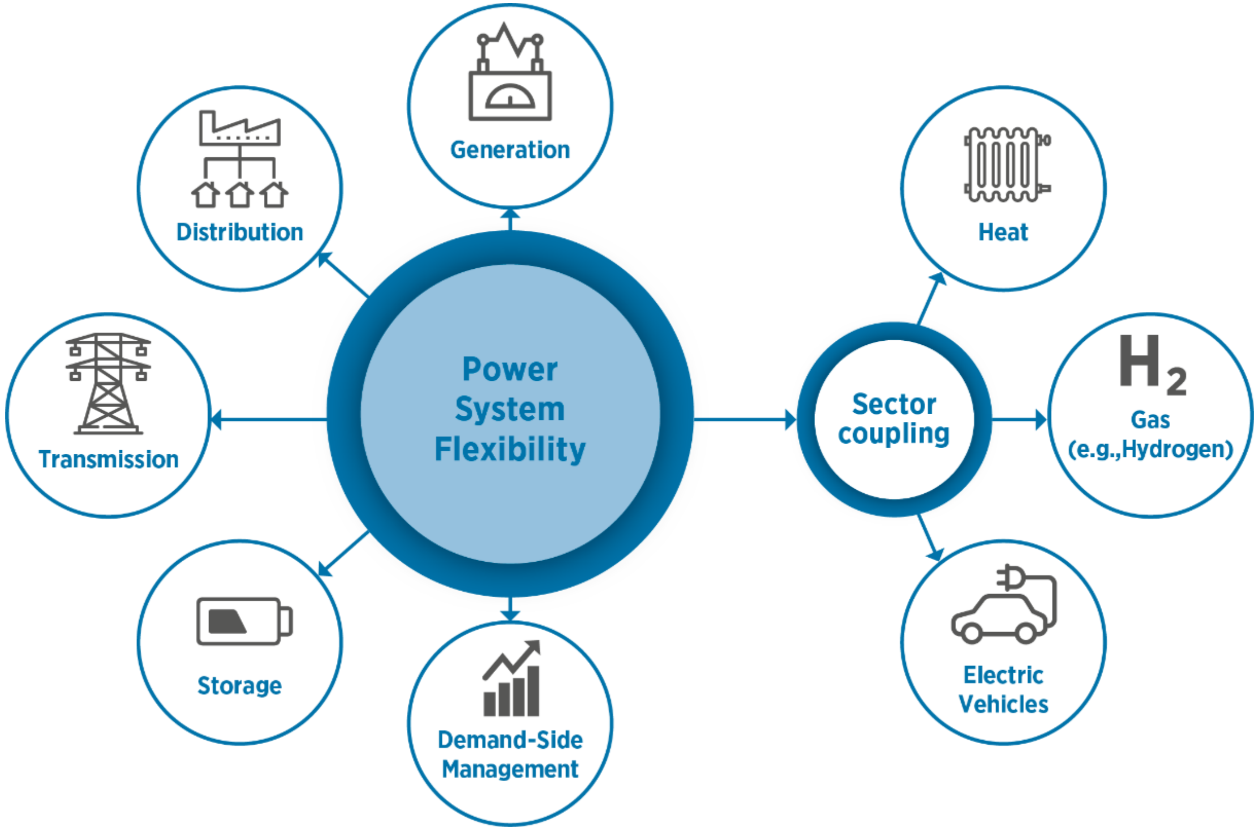
Demonstrate concept at University of Cyprus (UCY) nanogrid pilot with actual smart meters, PV and battery storage systems

Distributed energy resources

- Distributed energy resources (DERs) are small and medium-sized power sources connected to the distribution network, that can potentially provide services to the power system.
- The term 'DER' covers a wide range of technologies such as:
  - Solar photovoltaic (PV)
  - Battery storage
  - Demand response solutions (controllable loads, electric vehicles, power-to-heat, etc.)
- Integrating DER to the grid can provide increased flexibility to the power system. DER can be exposed to market signals and provide grid benefits by participating in the:
  - Electricity wholesale markets: Load shifting and peak shaving
  - Ancillary service market: Grid-supportive ancillary services and network congestion management

Distributed energy resource flexibility

- To effectively manage large-scale DER in future smart grids a number of flexibility sources need to be exploited in real-time and planned ahead of time.



Source: International Renewable Energy Agency (IRENA), "Power system flexibility for the energy transition", 2018

Distributed energy resource flexibility

- Integrating DER to the grid can provide increased flexibility to the power system.
- DER can be exposed to market signals and provide grid benefits by participating in the:
  - Electricity wholesale markets: Load shifting and peak shaving
  - Ancillary service market: Grid-supportive ancillary services and network congestion management
  - Capacity market: Improved generation capacity planning

DERs can generate or store energy, or manage consumption depending on type.

Distributed energy resource real-time supervision

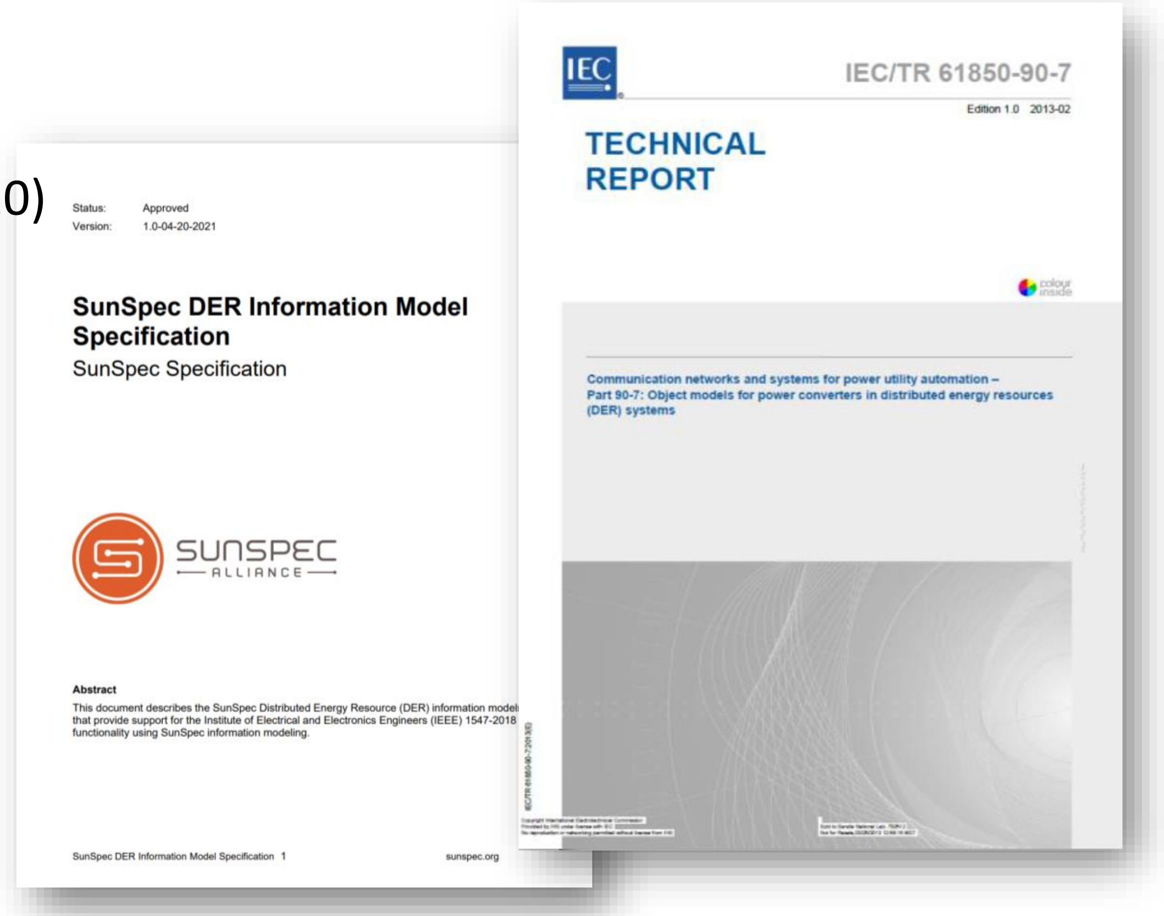
- The objective of real-time supervision is the safe and reliable operation of any DER system 24/7.
- In order to fulfil all required tasks for system operation, special tools like ‘Supervisory Control and Data Acquisition’ systems (SCADA) are used.
- Advances in grid-edge IoT controllers and cloud computing enable to more efficiently supervise DER and deliver the state quickly and reliably.
- In a cloud computing system, there are minimal hardware and software demands on users.

Smart controllers that stream data to cloud computing systems can provide an efficient and cost-effective way to integrate and supervise DER in the smart grid

Distributed energy resource interoperability

Connecting European Smart Grid Infrastructures

- Standardized interfaces and protocols for supervising and controlling DER in power grids are defined by the:
  - SunSpec Alliance (Modbus TCP)
  - IEC 61850 (IEC/TR 61850-80-7 and IEC 61850-7-420)


Status: Approved
Version: 1.0-04-20-2021

SunSpec DER Information Model Specification

SunSpec Specification

SUNSPEC ALLIANCE

Abstract

This document describes the SunSpec Distributed Energy Resource (DER) information model that provide support for the Institute of Electrical and Electronics Engineers (IEEE) 1547-2018 functionality using SunSpec information modeling.

SunSpec DER Information Model Specification 1 sunspec.org

IEC

IEC/TR 61850-90-7

Edition 1.0 2013-02

TECHNICAL REPORT

Communication networks and systems for power utility automation – Part 90-7: Object models for power converters in distributed energy resources (DER) systems

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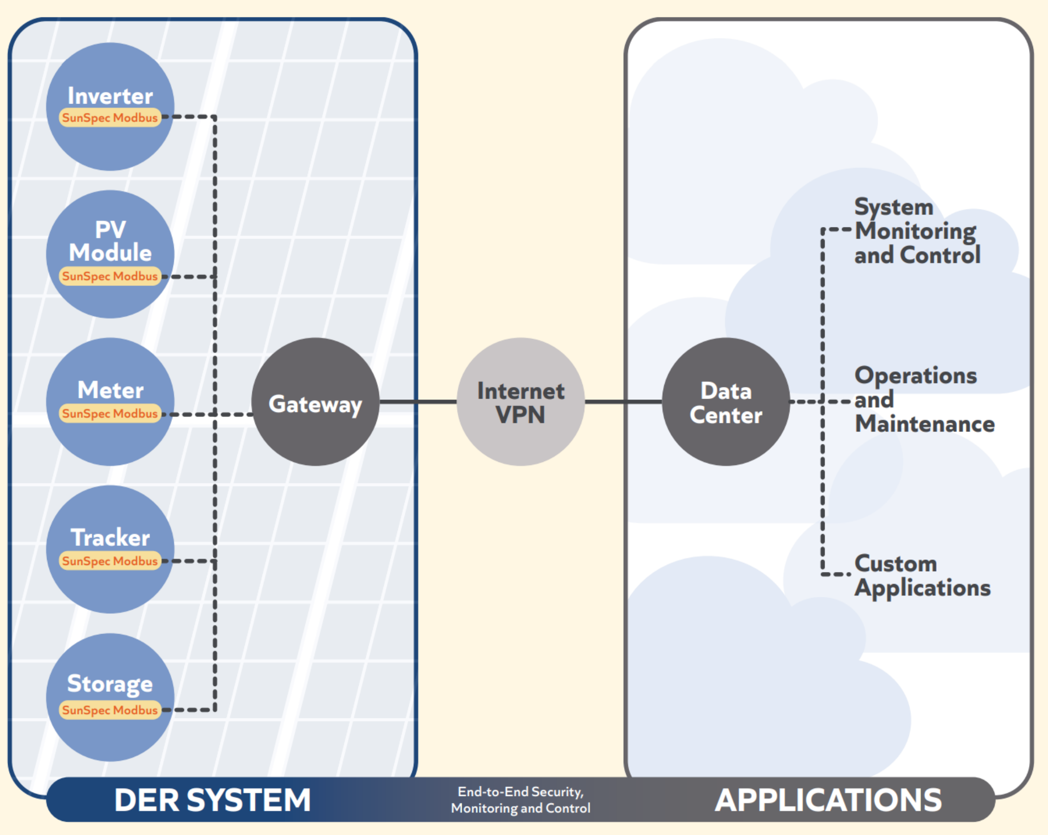
Distributed energy resource interoperability SunSpec

- SunSpec Modbus is an open standard, referenced in IEEE 1547-2018, that enables interoperability.
- Provides data structures for improved interoperability.
- Cost-effective since because the physical network interface exists in most DER devices (80% of DER support Modbus TCP).
- Client-server communication approach leveraging Modbus specifications.

Efficient migration for DER devices that support the Modbus specification

Distributed energy resource interoperability SunSpec

- SunSpec Modbus defines common parameters and settings for monitoring and controlling DERs.
- Information models include:
  - DER AC measurement
  - DER capacity
  - DER enter service
  - DER AC controls
  - DER VOLT-VAR
  - DER VOLT-WATT
  - DER Trip low Voltage and High Voltage
  - DER Frequency droop
  - DER storage capacity
  - DER DC measurement



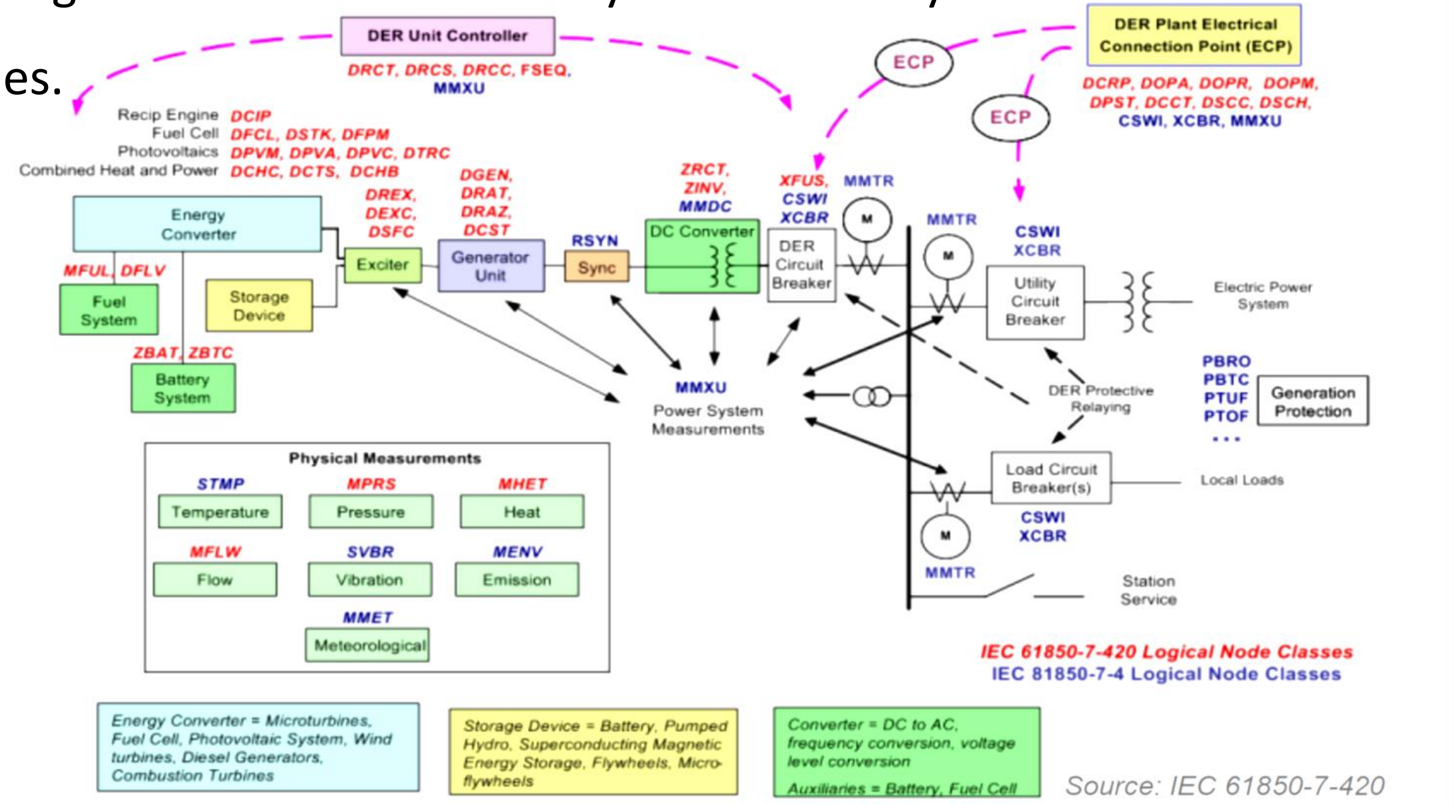
Source: SunSpec Alliance, "SunSpec Modbus interface", 2019

Distributed energy resource interoperability IEC 61850

- The IEC 61850 is the most modern communication protocol in smart grids.
- Report client and Report Server communication approach:
  - There is no serial communication and no server-client
  - IEDs transfer information when new data is present
  - IEDs can also transfer/communicate with each other (not possible in traditional protocols)

Distributed energy resource interoperability IEC 61850

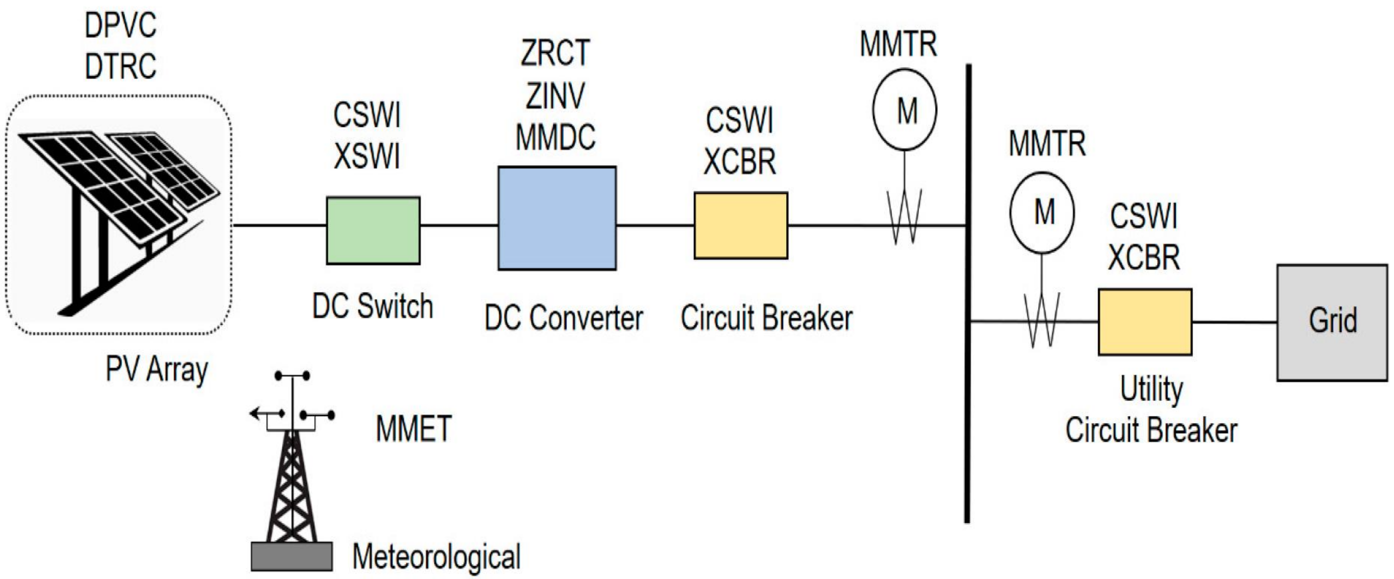
- The IEC 61850 mapping capability (plug and play interoperability).
- Mapping is done by importing/exporting the device ICD file to any automation system.
- High-level concept of DER logical nodes.



Source: IEC 61850-7-420:2021

Distributed energy resource interoperability IEC 61850

- IEC 61850-7-420 standard defines the general data model for DER.
- The standard describes the information model of the photovoltaic system including PV panels, conversion system, circuit breakers, protection devices, and metering devices.



Source: IEC 61850-7-420:2021

Distributed energy resource interoperability IEC 61850

- Logical nodes of PV system based on IEC 61850.

Name	Logical Node	Description
PV array	DPVC	PV array controller
	DTRC	PV tracking controller
DC Switch	CSWI	Switch controller
	XSWI	Circuit switch
DC Converter	ZRCT	Rectifier
	ZINV	Inverter
	MMDC	DC measurement
Circuit Breaker	CSQI	Switch controller
	XCBR	Circuit breaker
Metering	MMTR	Metering
Meteorological Tower	MMET	Meteorological information

Source: IEC 61850-7-420:2021

Comparison of IEC 61850 and SunSpec

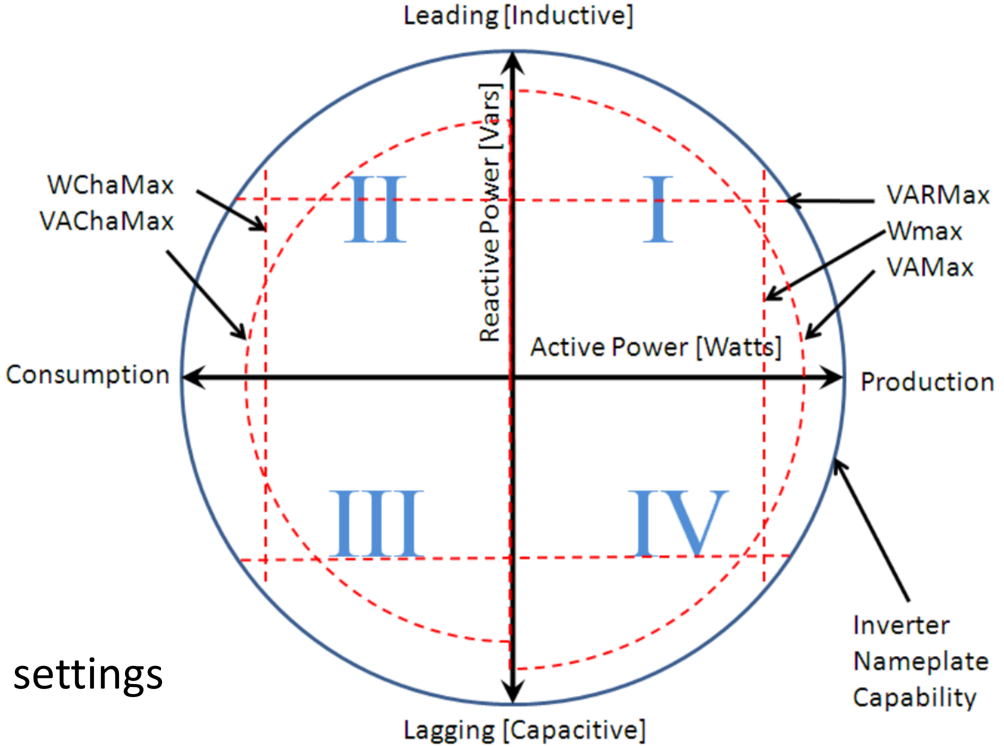
- Information models
  - Similar approaches for the information/data models
- Communication protocols
  - IEC 61850 communication is based on MMS over TCP/IP
  - SunSpec communication is based on Modbus (RTU or TCP/IP)

SunSpec control models overview
Data models

- SunSpec data models and Modbus register mappings support of programmed, scheduled and autonomous inverter control operations.
- Many control points are specified in terms of percent of a fundamental setting or nameplate Rating.
- For many supervisory and control registers a scale factor (SF) register is provided to allow higher resolution.

SunSpec control models overview
Basic settings

- SunSpec Basic Settings block provides information on how to modify the operating limits of an inverter (compared to the defined nameplate ratings).
- Nameplate and operational settings definitions.

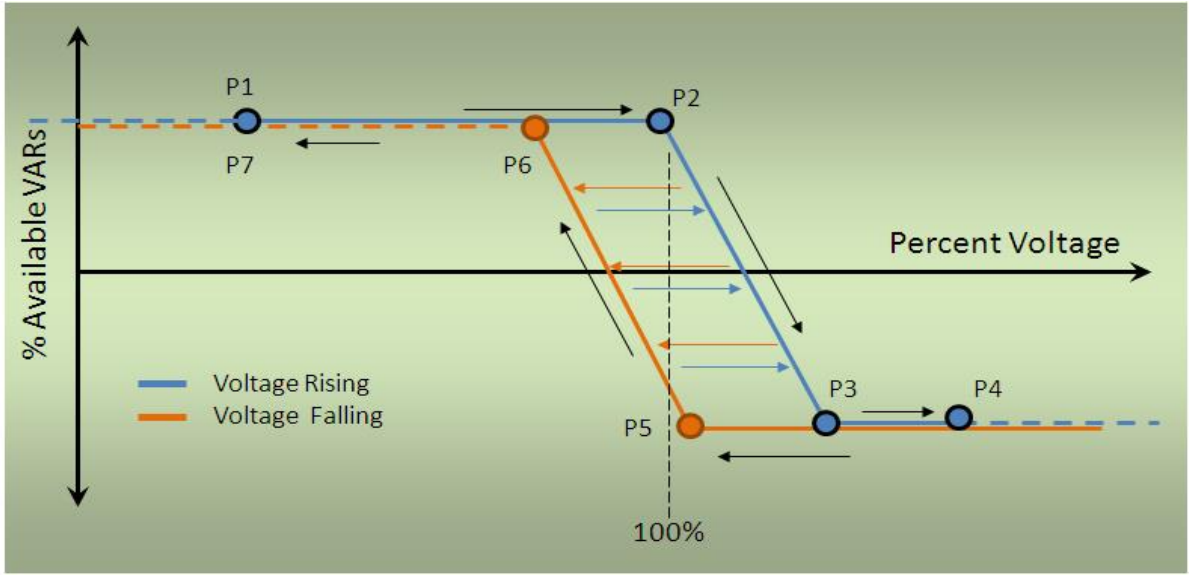


Example of nameplate and operational settings

Source: SunSpec Alliance, "Inverter Control Models SunSpec Alliance Specification", 2013

SunSpec control models overview
Volt-VAR Arrays

- The Volt-VAr function provides the mechanism to control reactive power based on the local voltage.
- One or more Volt-Var arrays can be defined (pairs of voltage levels and corresponding VAr levels).
- The voltage is in percent of VRef (PCC Voltage).
- The VAr setting depends on the DeptRef which selects percent of available VARs (VArAval), percent of maximum available VARs (VArMax).



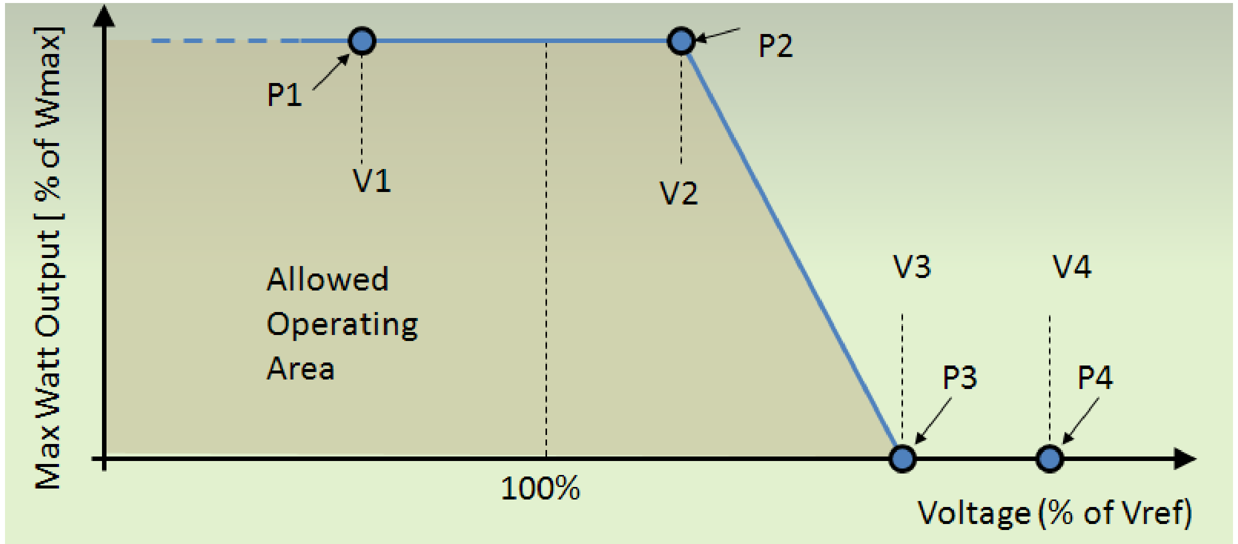
Example of Volt-VAr curve and definitions

Source: SunSpec Alliance, "Inverter Control Models SunSpec Alliance Specification", 2013

SunSpec control models overview
Volt-Watt Arrays

- The Volt-Watt function provides the mechanism to control active power based on the local voltage.
- One or more Volt-Watt arrays can be defined (pairs of voltage levels and corresponding watt levels)
- The voltage is in percent of VRef (PCC Voltage).
- The watt setting is 0% to 100% of the maximum available watts (WMax).

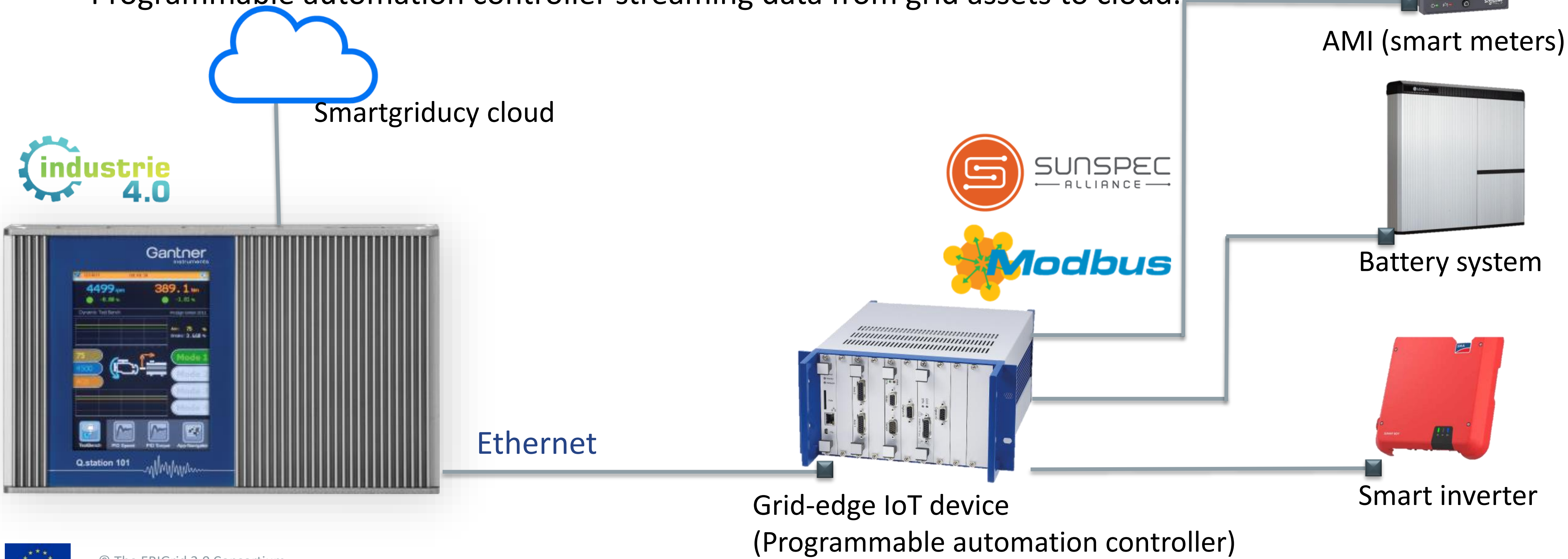
Example of Volt-Watt curve and definitions



Source: SunSpec Alliance, "Inverter Control Models SunSpec Alliance Specification", 2013

Test Case – UCY nanogrid pilot

- Vendor-independent system for dynamic and accurate DER supervision and control (SunSpec).
- Programmable automation controller streaming data from grid assets to cloud.



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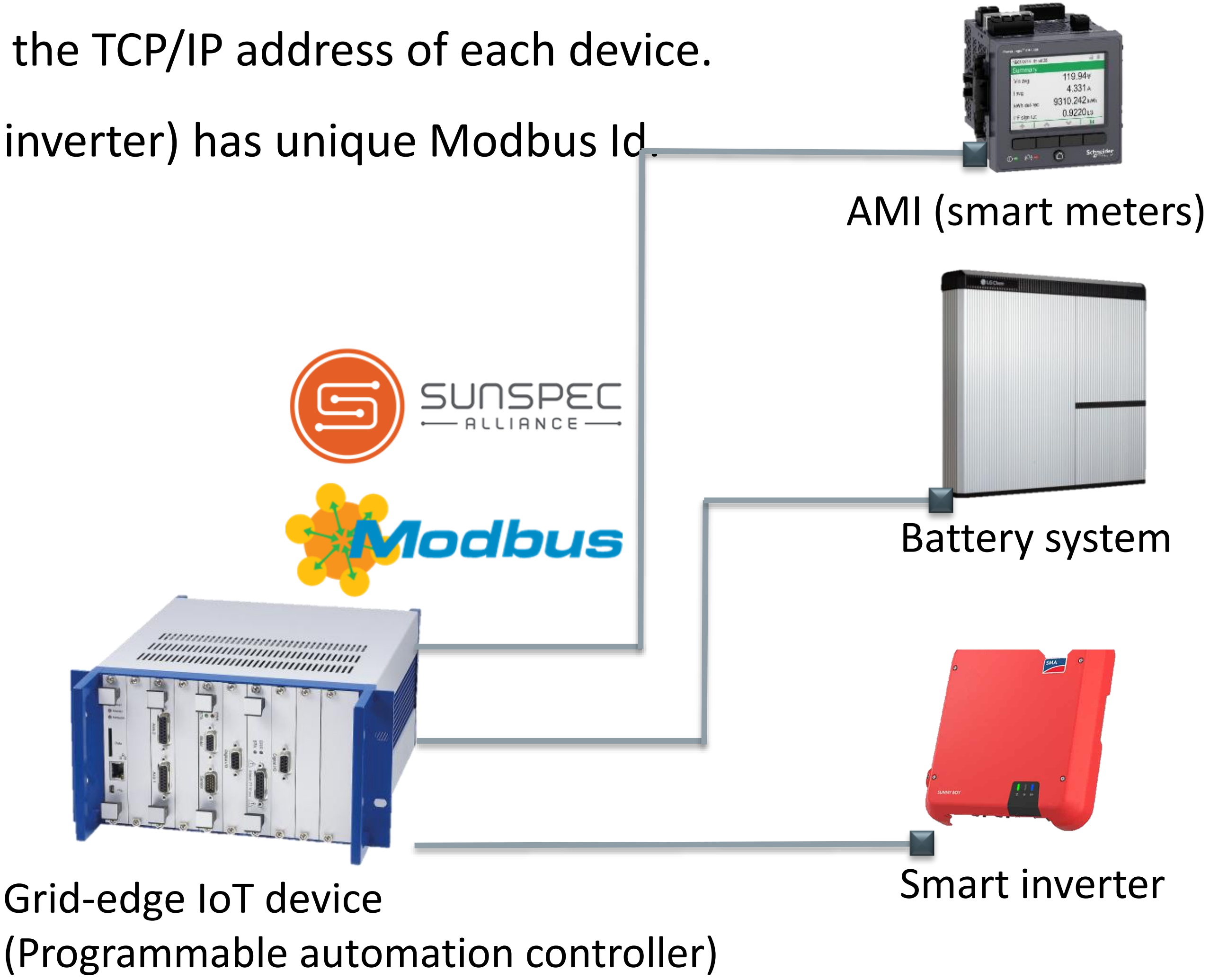
Test Case – UCY nanogrid pilot
Network TCP/IP configuration

- Network configuration at controller by mapping the TCP/IP address of each device.
- Each DER (smart meter, battery inverter and PV inverter) has unique Modbus Id.



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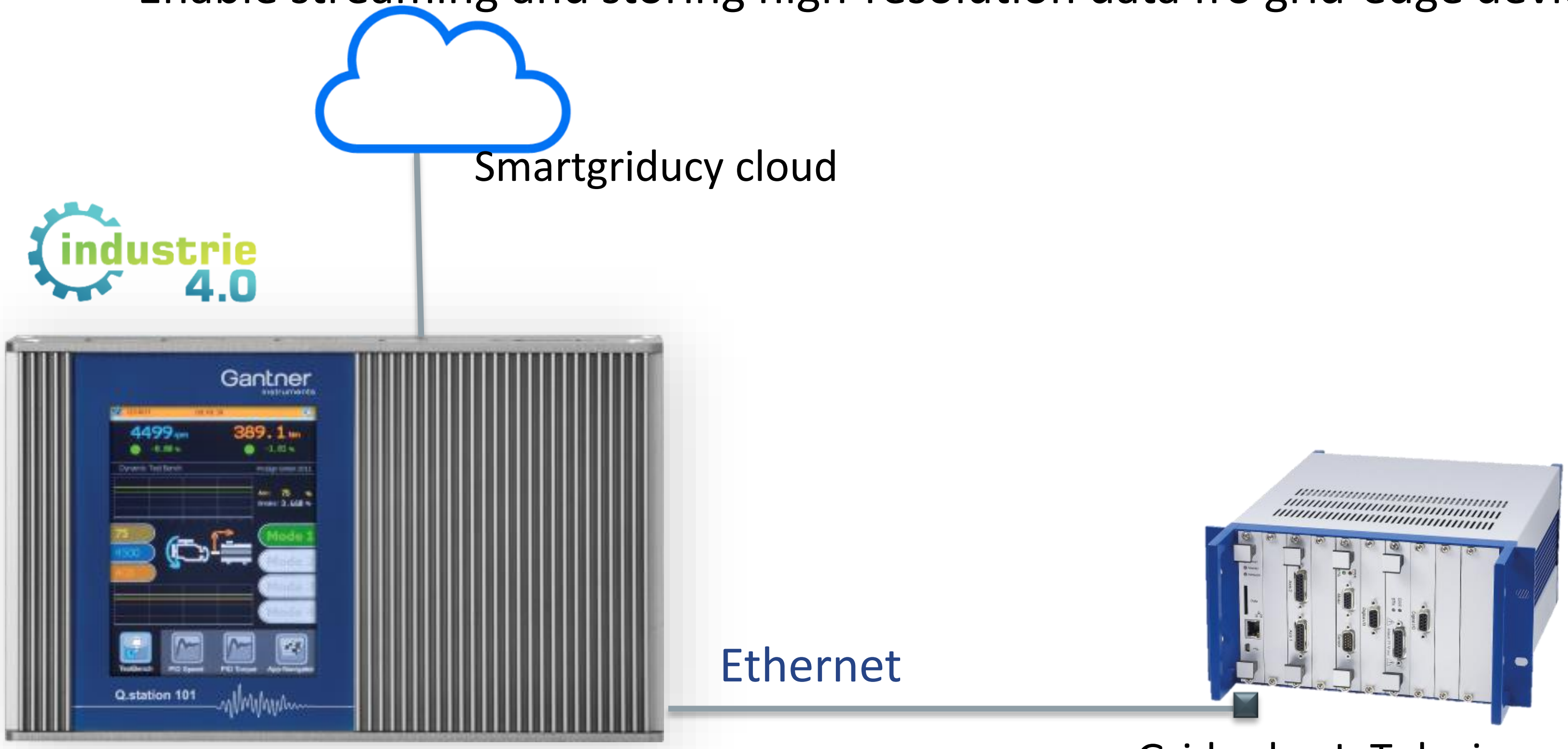
Test Case – UCY nanogrid pilot
Controller-to-cloud connection

- Configuration of controller-to-cloud connection using secure network port 443.
- Enable streaming and storing high-resolution data fro grid-edge device to cloud.



Test Case – UCY nanogrid pilot
PV system AC measurements

- SunSpec Modbus allocation Table (Inverter Integer Map).
- Configuration of main AC monitoring parameters from smart inverter.

Register	Description	Type
40188	AC current (A), in A×10^{A_SF} (40192).	Read Only
40200	Active power (W), in W×10^{W_SF} (40201).	Read Only
40202	Power frequency (Hz), in Hz×10^{Hz_SF} (40203).	Read Only

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

Test Case – UCY nanogrid pilot
PV system AC measurements

- SunSpec Modbus allocation Table (Inverter Integer Map).
- Configuration of main AC monitoring parameters from smart inverter.

Register	Description	Type
40204	Apparent power (VA), in VA×10^{VA_SF} (40205).	Read Only
40206	Reactive power (VAr), in VAr×10^{VAr_SF} (40207).	Read Only
40208	Displacement power factor cos ϕ (PF) ×10^{PF_SF} (40209).	Read Only

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

Test Case – UCY nanogrid pilot
PV system DC measurements

- SunSpec Modbus allocation Table (Inverter Integer Map).
- Configuration of main DC monitoring parameters from smart inverter.

Register	Description	Type
40217	DC power (DCW), in W×10^{DCW_SF} (40218).	Read Only

Test Case – UCY nanogrid pilot
PV system Connection Control

- SunSpec Modbus allocation Table IC 123 (Immediate Inverter Controls).
- Configuration of parameters for immediate connection control of smart inverter.

Register	Description	Type
40348	Connection control (Conn): 0 = Not connected 1 = Connected	Write Only

Smart inverter

Grid-edge IoT device
(Programmable automation controller)

Test Case – UCY nanogrid pilot
PV system Active Power Control

- SunSpec Modbus allocation Table IC 123 (Immediate Inverter Controls).
- Configuration of parameters for active power control of smart inverter (percentile set-points).

Register	Description	Type
40348	Set power to default value (WMaxLimPct), in % of $\mathrm{WMax} \times 10^{\mathrm{WMaxLimPct\_SF}}$ (40367)	Write Only
40353	Choking (WMaxLim_Ena): 1 = Activated	Read / Write

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

Test Case – UCY nanogrid pilot
PV system Power Factor Control

- SunSpec Modbus allocation Table IC 123 (Immediate Inverter Controls).
- Configuration of parameters for power factor control of smart inverter.

Register	Description	Type
40354	Set power factor to a certain value (OutPFSet) $\times 10^{\text{OutPFSet\_SF}}$ (40368)	Write Only
40358	Fixed power factor (OutPFSet_Ena): 1 = Activated	Read / Write

Smart inverter

Grid-edge IoT device
(Programmable automation controller)

Test Case – UCY nanogrid pilot
PV system Reactive Power Control

- SunSpec Modbus allocation Table IC 123 (Immediate Inverter Controls).
- Configuration of parameters for reactive power control of smart inverter.

Register	Description	Type
40359	Reactive power (VArWMaxPct), in % of WMax×10^{VArPct_SF} (40369)	Write Only
40365	Mode of the percentile reactive power limitation (VArPct_Mod): 1 = in % of Wmax	Read / Write
40366	Control of the reactive power limitation (VArPct_Ena): 1 = Activated	Read / Write

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

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Test Case – UCY nanogrid pilot
PV system Advanced Control

- SunSpec Modbus allocation Table IC 126 (Static Volt-VAr Arrays)
- Configuration of parameters Volt-VAr control of smart inverter

Register	Description	Type
40398	Index of the active curve (ActCrv): 0 = No curve active (deactivated) 1 = Curve 1 active	Read / Write
40399	Volt-VAR control active (ModEna): Bit 0 = Activated	Read / Write

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

Test Case – UCY nanogrid pilot PV system Advanced Control

- SunSpec Modbus allocation Table IC 126 (Static Volt-VAr Arrays)
- Configuration of all Volt-VAR control points of smart inverter. Repeated block for all curve points.

Register	Description	Type
40410	Point 1 volt (V1), in % of VRef$\times 0^{V_SF}$ (40405)	Read / Write
40411	Point 1 VAr (VAr1) $\times 10^{DeptRef\_SF}$ (40406)	Read / Write
	Repeated for all defined curve points.	

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

EU H2020 Programme GA No. 870620

Test Case – UCY nanogrid pilot PV system Advanced Control

- SunSpec Modbus allocation Table IC 132 (Static Volt-Watt Arrays)
- Configuration of parameters Volt-Watt control of smart inverter

Register	Description	Type
40558	Index of the active curve (ActCrv): 1 = Curve 1 active	Read / Write
40559	Volt-watt control active (ModEna): Bit 0 = Activated	Read / Write

Smart inverter

Grid-edge IoT device
(Programmable automation controller)

Test Case – UCY nanogrid pilot
PV system Advanced Control

- SunSpec Modbus allocation Table IC 132 (Static Volt-Watt Arrays)
- Configuration of all Volt-VAR control points of smart inverter. Repeated block for all curve points.

Register	Description	Type
40570	Point 1 volt (V1), in % of VRef$\times 10^{V_SF}$ (40565)	Read / Write
40571	Point 1 watt (W1), in % of DeptRef$\times 10^{DeptRef_SF}$ (40566)	Read / Write
	Repeated for all defined curve points	

Grid-edge IoT device
(Programmable automation controller)

Smart inverter

Test Case – UCY nanogrid pilot
Battery storage Monitoring

- SunSpec Modbus allocation Table IC 124 (Basic Storage Controls)
- Monitor state of charge and internal voltage of battery storage

Register	Description	Type
40378	Current available energy (ChaState), in % of AhrRtg×$10^{\text{ChaState\_SF}}$ (40392)	Read / Write
40380	Battery internal voltage (InBatV), in V×$10^{\text{InBatV\_SF}}$ (40394)	Read / Write

Grid-edge IoT device
(Programmable automation controller)

Battery

EU H2020 Programme GA No. 870620

Test Case – UCY nanogrid pilot
Battery storage Charge / Discharge

- SunSpec Modbus allocation Table IC 124 (Basic Storage Controls)
- Configuration of parameters for charge / discharge of battery storage

Register	Description	Type
40372	Set value for maximum charging active power (WChaMax), in $W \times 10^{WChaMax\_SF}$ (40388).	Read / Write
40375	Activation of the storage control mode (StorCtl_Mod): Bit 0 = Battery charging Bit 1 = Battery discharging	Read / Write

Grid-edge IoT device
(Programmable automation controller)

Battery

Conclusion

- Real-time supervision and control of DER is a requirement in future smart grids.
- With cost-effective IoT devices, open-communication protocols and cloud computing it is possible to achieve real-time management at grid-edge.
- Main communication protocols include:
  - IEC 61850 communication is based on MMS over TCP/IP
  - SunSpec communication is based on Modbus (RTU or TCP/IP)
- SunSpec data models and Modbus register mappings support of programmed, scheduled and autonomous inverter-based DER functions.
- Proof-of-concept demonstrated at UCY nanogrid pilot.