PNNL-30797

Response to Questionnaire of Grid Control Architecture Description Document

Mission Innovation, Innovation Challenge 1.
Task 5 – New Grid Control Architectures.
Subtask 5.1 – Collection of Available New Grid Control Architectures

December 2020

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U.S. DEPARTMENT OF ENERGY
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Mission Innovation, Innovation Challenge 1

Task 5 – New Grid Control Architectures

Subtask 5.1 – Collection of Available New Grid Control Architectures

Country: United States of America

Organization: Pacific Northwest National Laboratory

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When responding to the following questions please provide answers with descriptions of new grid control architectures that are being developed by smart grids research & development in your country. Please note that we are focusing on new or advanced grid control architectures in this exercise, and not on traditional power system controls.

1. For what purposes are new grid control architectures being developed in your country?

New grid control architectures are being developed in the U.S. for

- Managing complexity and untangling emergent ambiguity related to controls while reducing likelihood of unintended consequences,
- Facilitating high penetration of Distributed Energy Resources (DERs) in a standardized way,
- Enabling increased electrification without compromising reliability,
- Guiding integration and coordination of hybrid sensors and/or actuators,
- Controlling energy efficiency resources for maximizing benefits,
- Synchronization of sensors, communications and controls in a dynamic grid,
- Greater automation of grid controls,
- Optimization of grid operations.

The above-mentioned improvements will help enhance energy security, resilience and efficiency.

2. Please select from the list below the grid controls that are being addressed by smart grids research & development in your country.
(Try to describe briefly the technical approaches for the selected controls. What type of generation units are in charge of these controls? In which part of the system are these new controls being applied - DSO (MV-LV grid operators) and/or TSO (HV grid operators)?)

- **Automatic generation control**

Frequency control in power systems is classified based on the time it takes for the system to react to a disturbance. Primary frequency control acts in a time scale of few seconds and this control is usually decentralized. Secondary frequency control is a distributed control that is achieved through Automatic Generation Control (AGC) and operates in the scale of minutes to minimize the tie line flow deviation from the scheduled values for the control areas and therefore regulate the system-wide frequency. AGC in power networks is a closed-loop system where traditionally measurements from sensors in each area are fed (via the communication network) using the supervisory control and data acquisition (SCADA) systems to the control center which then generates the governor setpoints for the generators. Some of the recent research works investigate how Phasor Measurement Units (PMUs) can be used as inputs to the AGC system while overcoming challenges related to communication latency, data security etc.

- **Load frequency control**

Traditionally, the generator-side control [1] plays a dominant role in frequency regulation, wherein the generation is managed to follow the time-varying load. However, with the increasing integration of renewable energy, it becomes more challenging to maintain the power balance and the nominal frequency because of the increased volatility in non-dispatchable renewable generation. To address these challenges, load control has received considerable attention in the recent decade since controllable loads are ubiquitously distributed in power systems and can respond quickly to regulation signals or changes in frequency. Much research and demonstration effort has focused on frequency and voltage regulation provided by controllable loads, including electric vehicles, heating, ventilating, and air-conditioning systems, battery energy storage systems, and thermostatically controlled loads.

- **Market control (Day Ahead Market and Real Time Dispatch)**

The wholesale energy market plays the central role in the buying and reselling of wholesale power between the suppliers and the resellers. In the U.S. in the regional grids which have structured electricity markets, the processes have evolved over years to include day-ahead and intra-day markets. The day-ahead market helps in determining the unit commitment; however it is not enough to accommodate all of the uncertainty, variability and dynamics of the power systems. In order to accommodate the deviations from the day-ahead commitments and ensure reliable supply during the course of the operating day, there is also a Real Time Market (RTM). At present the wholesale market is not designed to coordinate generation from DER, and this is getting attention from the community. Research communities are also examining and proposing recommendations for future coordination and interactions between the Transmission System Operator (TSO), Distribution System Operator (DSO), DER owners, and aggregators in market and reliability contexts.

- **Excitation control, Automatic Voltage Regulator (AVR), and Power system stabilizer (PSS)**

The basic intent of adding a Power System Stabilizer (PSS) is to enhance damping to extend power transfer limits. The very nature of a PSS limits its effectiveness to small excursions about a steady state operating point. The small excursions about an operating point are typically the result of an electrical system that is lightly damped which can cause spontaneous growing oscillations, known as system modes of oscillation. Enhanced damping is required when a weak transmission condition exists along with a heavy transfer of load. A PSS works in conjunction with the excitation system of a synchronous machine to modify the torque angle of the shaft to increase damping. On new equipment, PSS may be software incorporated in digital automatic voltage regulators.

- **Fault location, isolation, and service restoration (FLISR)**

  FLISR technologies and systems involve automated feeder switches and reclosers, line monitors, communication networks, distribution management systems (DMS), outage management systems (OMS), SCADA systems, grid analytics, models, and data processing tools. These technologies work in tandem to automate power restoration, reducing both the impact and length of power interruptions. FLISR applications can reduce the number of customers impacted by a fault by automatically isolating the trouble area and restoring service to remaining customers by transferring them to adjacent circuits. In addition, the fault isolation feature of the technology can help crews locate the trouble spots more quickly, resulting in shorter outage durations for the customers impacted by the faulted section. Recent research looks into various architectures of FLISR deployment [12, 13]. Another line of research looks at new distribution system restoration (DSR) algorithm which is an integral part of the FLISR application. One such work proposes an advanced algorithm that utilizes backup feeders and distributed generators (along with intentional islanding features) to restore critical loads [14].

- **Volt/VAr optimization**

  VVO is the capability to optimize the objectives such as VAr flow or power loss minimization, load reduction, etc. using optimization algorithms and control objectives, subject to various operating and system constraints through decentralized or centralized decision makings.

- **Distributed Energy Resources (DER) control**

  DER were initially considered to be those assets in a distribution system at a customer premises or a utility location that could generate electricity. Currently the definition has been expanded to include assets at either type of location that are capable of generation and/or flexible behavior and includes energy storage and responsive loads. One area of research proposes methodology for coordinating the support from DER-based inverters, which are grid-connected non-utility assets, by using a transactive energy approach.

  Currently, there are a growing number of jurisdictions requiring the use of smart inverters conforming to the IEEE 1547 revision or ISO/IEC smart inverter standards. These inverters are capable of being configured and controlled. Recent research focuses on how inverters can be controlled better to provide reactive power and real power voltage support.

- **Microgrid control**

  New dynamic control strategies, especially based on model-free control approaches, to support the primary frequency control are being researched.

For each of the selected or mentioned new grid control architectures please answer the following questions.

3. Name the various organizations that are directly involved in the delivery of the grid controls.

Figure 1 shows the generic as-is grid structure for electric power systems, represented in the form of an Entity Relationship (E-R) diagram [22]. Entity classes are representative of entire groups of organizations or entities and are represented by boxes with labels indicating their names [23]. For example, the "DO" entity class consists of all the distribution operators or utilities in the electric grid of the region being considered. Relationship between any pair of entity classes are groups of behaviors between them and are represented in the form of lines between the entity class boxes.

The industry structure model in Figure 1 shows from a high level the various organizations that are typically directly involved in the grid operations. The standard electrical infrastructure is on the right in the vertical stack of blue boxes. Primary grid operational entities are shown in green. Non-utility entities are shown in gray and red. Two sub-structures (microgrid and substation service area) are show in white boxes. Edge resource entity is shown in yellow and includes distribution-connected generation, storage and responsive loads.

In U.S. the Reliability Functional Model developed by the North American Electric Reliability Corporation (NERC) defines and describes a number of functions that must be performed in order to ensure reliability of the bulk electric system. Each function which is a set of tasks is assigned to a functional entity which is responsible for those tasks. In order to carry out the specific tasks the responsible entities deploy appropriate monitoring and control applications.

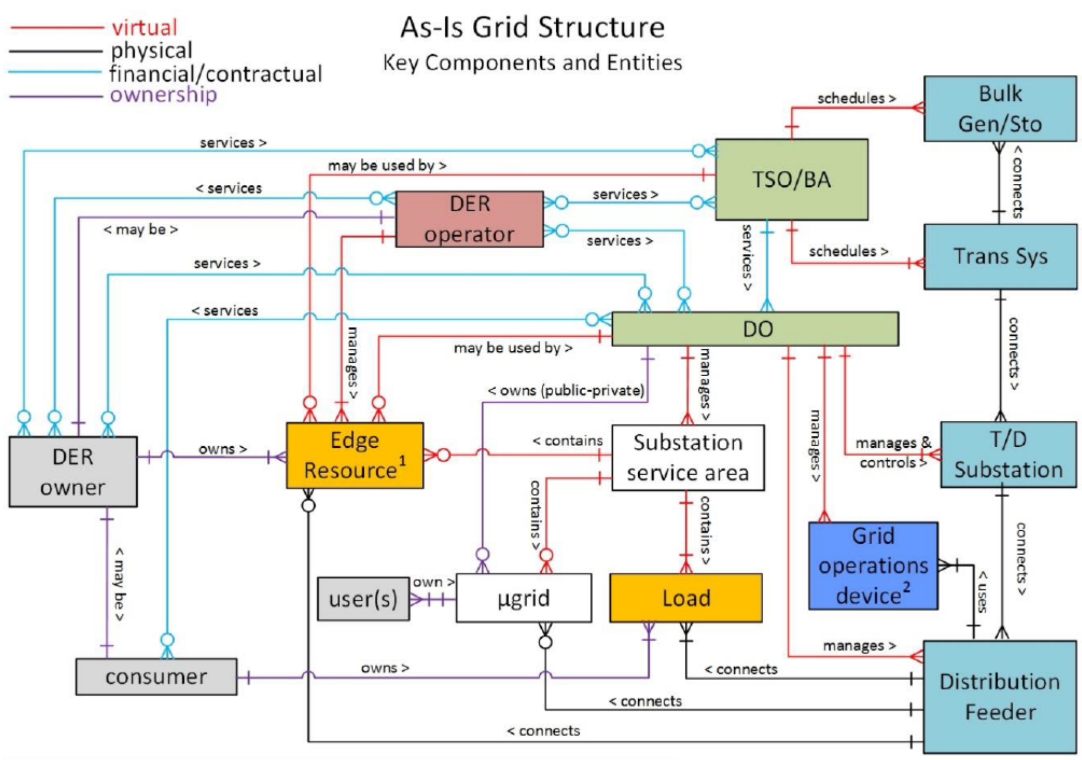


Figure 1: Existing Grid E-R Structure Diagram [22]

Industry structures of regional grids in U.S. can however vary widely based on the characteristics and the needs of the region. Therefore the approach adopted to perform the functions may differ and the control applications may differ as well. The very first step that can help understand the current system and the various controls involves developing an Industry Structure diagram which identifies the organizations that are involved in performing the different controls. Figure 6 provides an example. It presents the Industry Structure of Texas region with focus on Electric Reliability Council of Texas's

(ERCOT's) service area, and shows the various organizations that are working to deliver different functions of the electric grid.

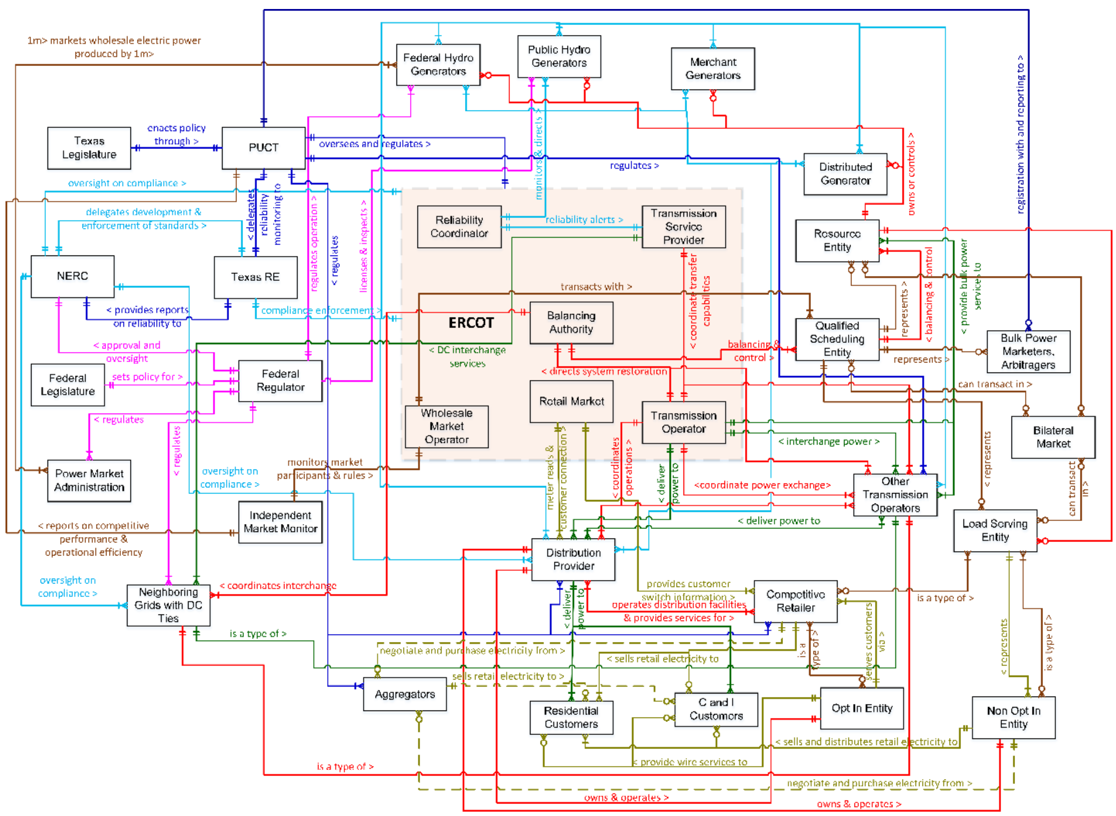


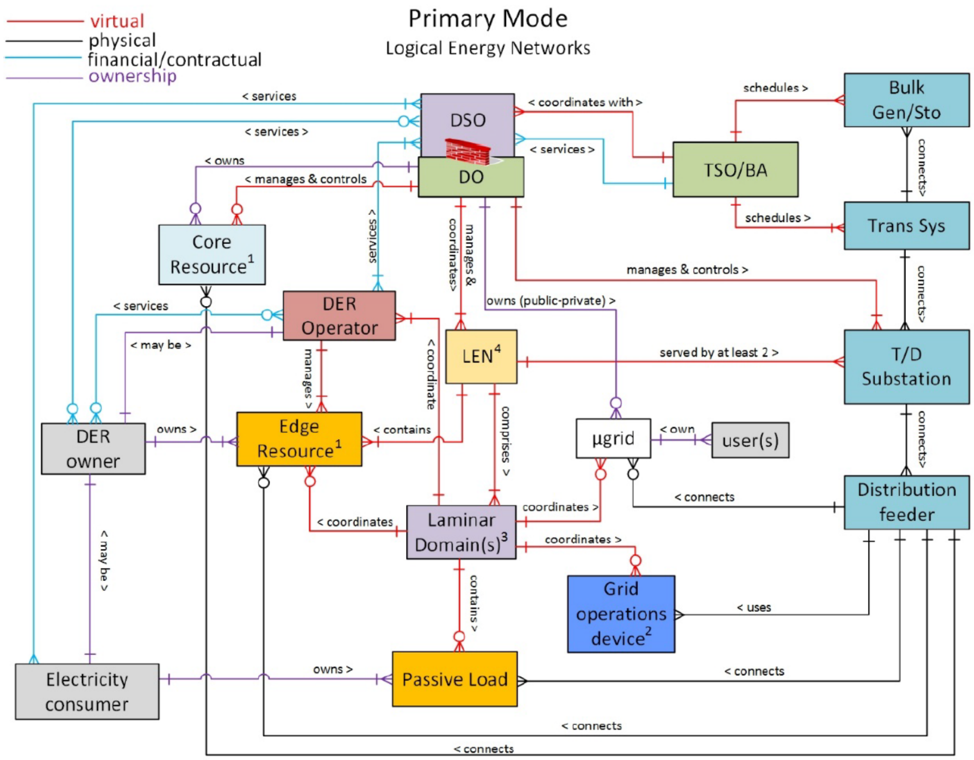
Figure 2: Industry Structure model of one of the regional grids in U.S. (focuses on the service territory of ERCOT) [23]

In the recent times, architecture for control of DER, grid connected inverters, distribution automation systems must allow for structured control of hybrid technologies by different entities besides the distribution utility, and, as well as direct control by the distribution utility. In addition to control via an external entity, control may be performed autonomously by any particular DER element or groups of DER elements may associate and operate as coordinated DER networks, either under supervision by an external entity or as an autonomous system. All of the above motivate the development of carefully designed decentralized or distributed architecture.

A distributed grid architecture is one in which the various decentralized elements cooperate to perform grid operation. The mechanism by which this cooperation occurs is coordination. Laminar Coordination Framework is a generator for coordination architectures for electric power systems via layered decomposition and allows to solve a wide class of optimization problems with multiple coupled constraints [22]. The resultant structures are called Laminar Coordination Networks. The methodology provides clean interface, avoids tier bypassing and separates roles and responsibilities for the various entities that are involved.

Logical Energy Networks (LEN), on the other hand, are structures for the virtualization of distribution systems to access the latent capacity of DER for resilience purposes. LEN is a distribution level virtual structure specified and enforced through coordination and control processes. It is a portion of a distribution system that is segmented in a way that is roughly analogous to bulk system Balancing Areas. LENs operate autonomously when needed and are globally coordinated normally via Laminar Coordination networks. Both laminar coordination framework and LEN structures help in defining architectural design for newer grid controls which may be heavily dependent on sensors and communication networks.

Figure 2 shows the revised grid E-R model for a LEN structured grid. In this grid structure distribution systems are virtualized into LENs coordinated via Laminar Networks and managed using the total DSO role set to interface with TSO. This approach requires distributed intelligence at the distribution grid level, and benefits from silo-to-layer conversion of sensing, communications, and control into a platform model where sensing and communications become an infrastructure layer supporting many decoupled applications. No tier bypassing exists.



4. What are the components, and their various inputs and outputs? What are the high-level functions of the components, and their interrelationships? (Please provide a diagram if possible[1], and any reference to technical documents, reports or papers.)

For responding to this question, we have provided two perspectives – architectural and technological perspectives as summarized below.

Architectural Perspective [22]:

Grid architecture provides a set of methodologies for analyzing and understanding the structures of the electric grid to enable superior decision-making, and among other outcomes, reduce the risk of poor functionality and stranded assets. The objective is to modify existing grid structure and specify new grid structure to achieve better coordination and decoupling of applications. Use of layering concepts to define the platform structure leads to reduction of brittleness and enhancement of configurability, functional flexibility and functional extensibility, all of which help in enhancing the operational resilience. Figure 3 shows layering concepts to define a platform structure for resilient electric distribution operations that treats sensing and communications as an infrastructure layer.

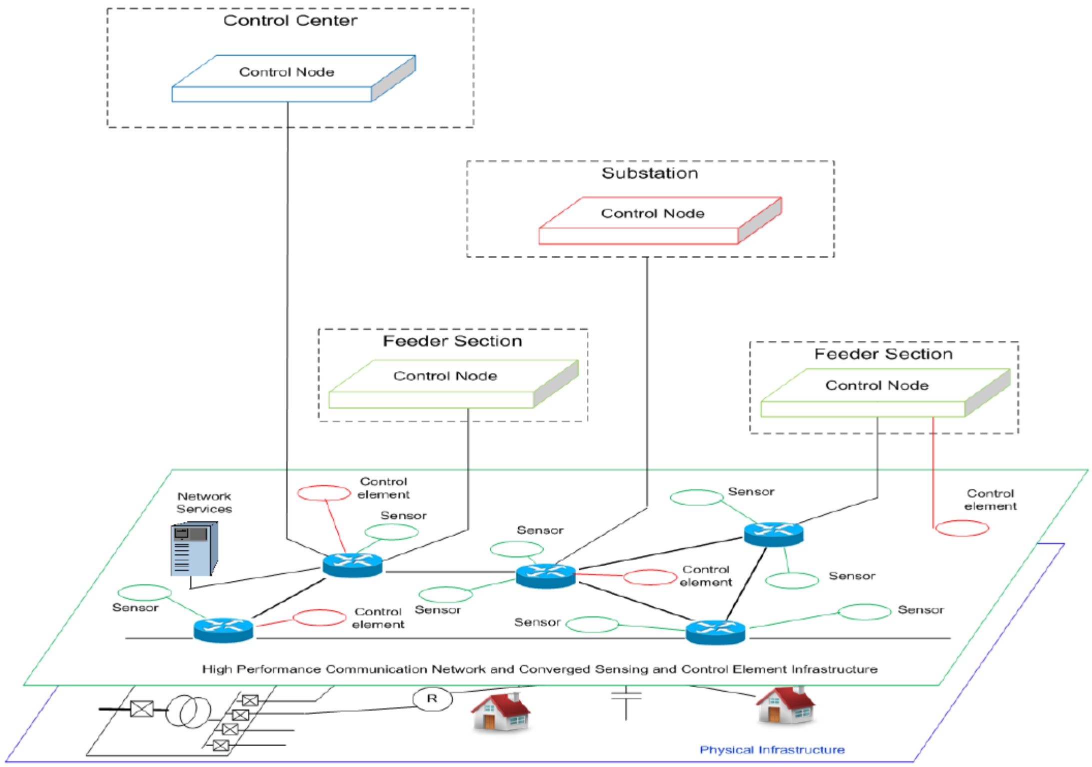


Figure 3: Layering and consequent decoupling of applications [22]

Technological perspective:

In this technological perspective we have reviewed a number of recent research works to determine what new controls are being proposed, what application category they belong to and what their high-level purposes are. They are listed in Table 1.

Table 1: Application categories and purposes of new controls proposed in recent years

Reference number	Application Category	Purpose
[1]	Inverter Control	Showcase the viability of operating a 100% inverter based system with only PLL based 'grid following' control architectures, when the actual Thevenin impedance is still relatively small.
[2]	DER control	Presents a model-free control design on the DERs in a decentralized fashion to improve the dynamic performance of the power systems. The design does not require information about the transmission network,

		synchronous generators, loads, and DER models, and only requires the measurements of the DER states, and the voltage magnitudes of their terminal buses.
[3]	DER control (non-utility)	Develops a framework that coordinates the support from DER-based inverters, which are grid-connected non-utility assets, by using a transactive energy approach.
[4]	Microgrid Control	Proposes a new dynamic control strategy, based on model-free control (MFC) approach, to support the primary frequency control of such islanded microgrids.
[5]	Inverter Control	Develops a controller for a grid-forming inverter that is capable of operating as either a GFM or grid-feeding source that can improve the operation of a microgrid during on-off grid transitions by using a novel synchronization approach. It avoids use of a phase-locked loop (PLL) and the inverter is able to synchronize with the grid with self-generated voltage and frequency which prevents the inverter from replicating any grid voltage disturbances in its output. Note output signal is compensation angle which is the phase angle difference between the battery voltage and the grid voltage.
[6]	Frequency Regulation using EV	Presents field demonstration of a fleet of 29 mixed-use bi-directional EVs actively participating in the California Independent System Operator (CAISO) market for frequency regulation. The inputs were the projected EV utilization, initial SOCs, projected MCPs, and weather conditions and a real-time charge controller provided individual dispatch signals to EVs.
[7]	Secondary frequency control	Presents a distributed control scheme for achieving secondary frequency control in AC microgrids comprised of distribution lines with equal/unequal resistance to reactance ratio. However the input signals are the DER setpoints and the active power injections, and the output signal is a new DER setpoint. A ratio-consensus algorithm in which each control node computes the average frequency error as an intermediate signal in a distributed manner.
[8]	DERMS	Presents a hardware-in-the-loop (HIL) simulation to evaluate the performance of voltage regulation of Data-Enhanced Hierarchical Control (DEHC) which uses an advanced distribution management system (ADMS) for grid operations to control legacy and grid-edge devices. It coordinates with distributed energy management systems (DERMS) to manage high penetrations of photovoltaics (PV) on a utility distribution system.
[9]	Microgrid control	Presents a microgrid power flow control for islanded microgrids consisting of photovoltaic (PV) system, battery energy storage system (BESS) and diesel generator to ensure automatic coordination among the microgrid units.
[10]	Balancing	Decentralized real-time pricing scheme that is dependent on system frequency and gives every connected agent the ability to balance local needs while stabilizing the global system.

Table 2 looks at the proposed controls, and classifies them based on their structures, input signals and output signals. Three types of structures have been considered in these referenced works, and they are centralized, distributed and decentralized. Each row in the table corresponds to one of the types of the mentioned structures. Electrical quantities like voltage, frequency, current and power, as well as protection settings and price have been used as input and output signals. Each column in the table corresponds to the considered control signals. For each reference the structure, input signal and output signal are identified and marked in the relevant row and column using the reference number within bracket, along with ‘i’ for input, ‘o’ for output or ‘i-o’ for input and output. In some of these works multiple controls are proposed, so the specific control is indicated by mentioning the name of the system. For example in reference number 9, control for both PV and BESS have been proposed so the specific system whose control is listed has been indicated using the terms ‘(BESS)’ and ‘(PV)’ at the appropriate places.

Table 2: Table showing inputs and outputs of controls described in recent published research works; i: input, o: output, i-o: input and output

Structure / Control	Voltage	Frequency	Current	Power	Protection Settings / setpoints	Price
Centralized	[8]i, [9]i (BESS)	[9]i (PV control), [9]o (BESS)		[9]i (BESS)	[8]o	
Distributed	[10]i (SIVOM device)		[10]i (SIVOM device)	[3]o, [7]i (active)	[7]i-o (setpoints)	[3]i
Decentralized	[1]i, [2]i-o (mag. only), [5]i (start-up and islanded)	[1]i, [4]i-o, [10]i (frequency)	[1]o	[2]o (active), [5]i (grid connected)		

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