Method and Taxonomy for Evaluation of Distributed Control Strategies for Distributed Energy Resources

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Abstract—Distributed control strategies applied to power distribution control problems are meant to offer robust and scalable integration of distributed energy resources. However, the term "distributed control" is often loosely applied to a variety of very different control strategies. This leads to problems in the design phase as well as with the performance evaluation of such systems. This paper develops a framework to assist the design and evaluation of distributed control strategies, supported by a rigorous taxonomy of control strategies and formal design criteria. The proposed framework and taxonomy are evaluated against the state of the art of control strategies as found in literature.

Index Terms—distributed energy resource, distributed control, classification, control architecture, smart grid.

I. INTRODUCTION

Evolutionary changes in the power system promoted by global efforts to replace fossil driven energy infrastructure with renewable energy sources as well as increasingly flexible demand [1]–[3] have started to influence how electrical grids are operated. A major factor driving this change in operation requirements is summarized by the term Distributed Energy Resources (DER), which includes controllable and variable distributed generation, storage, and controllable loads. These DER challenge grid operation due to higher coincidence of demand, renewable resource intermittency, and bidirectional power flows in the distribution grid resulting from embedded generation [4]–[6]. These changes cause challenges to power system operation, including problems with system stability, congestion, voltage as well as protection scheme [4]–[8]. However, as a large fraction of DER offers some extent of controllability, they can also contribute to resolving these challenges by means of active grid management [9]–[15].

Considering the increasing number of energy resources in the power system that will need to be controlled and coordinated, the complexity of a centralized control solution based on this traditional control paradigm is significant and does not scale well [16], [17]. The coordination of systems with a large number of heterogeneous and geographically dispersed active units requires new control paradigms, especially for the ones in power distribution grid, which is conventionally designed to be passive. Of the control solutions proposed in academic literature to address these new requirements, a significant fraction can be characterized as some form of distributed control [4], [18]–[22], [22]–[46]. Clearly, distributed control strategies proposed in [18]–[20] have different nature from the one in [4], but they use the same term “distributed control”. There has been a lack of systematic problem formulation as well as inconsistent interpretation of the design requirements and performance metrics. As a result, the value and performance of proposed solutions has proven difficult to assess and compare. A rigorous classification can be expected to contribute to control system design and evaluation, and thus eventually to an industrial maturing of solutions.

The terms “distributed system”, “distributed algorithm”, and “distributed control” are used in the domains of computer science, control and automation, and recently power system operation. However, the definitions are not consistent across domains. In general, distribution is a system property that describes the spatio-temporal conditions of system components.

In computer science, a distributed system is a collection of independent processes which appears to its users as a single coherent system [48]. The classification as a distributed system does not imply the use of a particular architecture for the implementation of its functionality; distributed systems may be hierarchical or not, be highly heterogeneous or be composed of identical processes. In non-hierarchical distributed systems such as peer-to-peer (P2P) systems, distributed algorithms are often employed in order to achieve a shared goal based on local decisions by individual communicating processes [49].

The use of the term distributed control in the domains of automation and control dates back to the 1970s [50], [51], where it has primarily been applied to hierarchical master-slave systems in industrial automation. More recently, distributed control has also been used to refer to distributed control algorithms such as [52] where a distributed algorithm is used to control a physical system [53].

Power systems have historically been designed with a central control strategy. As more instrumentation as well as controllable elements have been added to the grid, interactions with other domains such as computer science, automation and communication technology are becoming a necessity. Since all these domains use some form of distributed control, a single consistent definition cannot be extracted from the literature.

In this paper, a distributed control system consists of two aspects: Firstly, the spatial distribution of ICT infrastructure, i.e. the physical location of computing units and the physi-
cal communication links between these units. Secondly, the partition of software and (control) functionality between these physical locations which defines the way in which decisions are made, and which information needs to be exchanged between which locations in order to achieve the desired result.

In this paper, the distributed nature of the supporting software and hardware infrastructure is considered out of scope; we will limit our focus to the architectural and algorithmic aspects of distributed control. To facilitate a systematic characterization of control strategies, we describe design criteria and performance metrics suitable for distinguishing distributed control algorithms in power systems. Next, we develop a taxonomy of control strategy types based on the above definition of distributed control. Finally, we evaluate the types according to the established criteria by analyzing distributed control strategies for providing system services as found in literature.

The paper is structured as follows: Section II presents an outline of a control strategy design process, together with design constraints and evaluation criteria. Section III contains the main contribution of the paper: a proposal for a classification of control algorithms based on their architecture. IV then validate the classification and performance metrics by analyzing control solutions in the field of smart grids. The paper is concluded in Section V.

II. DESIGN PROCESS AND EVALUATION CRITERIA

This section describes a distributed control applications design process including the definition of design elements, choice of evaluation criteria, as well as the assumed range of objectives and control domain.

A. Terminology

The following terms will be used throughout this paper: Distributed Energy Resource: In this paper, a narrower definition of DER is used to include only those DER which allow external control in order to provide flexibility.

Flexibility: The adjustable portion of the power or energy generated or consumed by a DER, constrained by technical limitations and the needs of the primary application.

Controlled Process: A continuously operating, dynamic process whose state is monitored and influenced by a control system.

Control Objective: The desired behaviour of a dynamic process, to be achieved by an associated control system.

Control Problem: A combined description of a dynamic process, its associated control objective, and a control system designed to achieve this objective.

Control Element: A physical, spatially located, computing unit which executes part of the control logic.

Control Architecture: The spatial distribution of the entities in a control system, including control elements, instrumentation, as well as the relations between those entities.

Control Strategy: A collection of design choices, combining a choice of control objectives with that of a control architecture and the design of control logic, or a control algorithm.

Control Layer: A functional level in a layered control architecture. Layered controls are often introduced to separate control loops which operate on different time scales and/or at different levels of abstraction from the physical system.

B. Conceptual design process

An iterative design process for distributed control algorithms in a smart grid context has been proposed in [54]. The iterative approach ensures that an algorithm under development is refined until it reaches maturity, i.e., the control objective is reached and design criteria are fulfilled.

External requirements and inherent system properties both contribute to the selection and prioritization of design criteria in top-down and bottom-up processes. The context and objectives of a control problem are identified early in the algorithm design process, defining the general requirements for a given system. A requirements analysis has to be performed to decide and prioritize technical design criteria, used for evaluating possible design choices. Certain features provided by the control architecture facilitate the design criteria. Therefore, it is beneficial to identify such relations and categorize the algorithms according to their architecture.

C. Fundamental constraints of a control problem

A control problem is constrained by 1) the control objectives, 2) the resources available for actuation, and 3) overall properties of the controlled process.

1) Control objectives: DERs are able to contribute to grid services by adjusting active or reactive power, including:

a) Power flow control and loss minimization [37], [41], [56]. This can be achieved solving an optimal power flow problem for losses, which may adjust voltage angles and magnitudes and aim at limiting reactive and active power flow. Both active and reactive power injections from different nodes in the grid may affect the power flow conditions.

b) Voltage and reactive power regulation [29], [57], [58]. The reactive power capability of inverter interfaced DERs can be utilized for reactive power regulation. In a resistive low voltage (LV) network, active power injection also significantly impacts grid voltage. By regulating the power injection, voltage magnitudes are kept in the allowed band.

c) Maximizing the utility of the resource operation [28], [29], [38], [59]. Examples include minimizing the overall charging cost of an EV fleet or optimizing the comfort vs. energy cost of residential buildings, etc.

d) Energy services: Up and down regulation to balance fluctuating production or to correct scheduling deviations [60]–[62], and to obtain a certain power profile at the point of common coupling [27], [31], [32], [63].

e) Power services: Services to achieve higher grid utilization by smoothing fast fluctuating active power production [44], [64], and by avoiding temporary grid overload (e.g., peak shaving and valley filling) [4], [28], [30], [54].

f) Primary frequency control [65].

2) Controllable components: A large variety of DERs may contribute to the provision of a grid service. The number of DERs and their properties such as size and technical capability, affect how control strategies are designed. Inverter-coupled
energy resources are not bound to the physical constraints of rotating machinery and are therefore often able to adjust power output on demand \[5\]–\[7\], \[66\]. Controllable loads, in a demand response (DR) setup, allow power system services to be provided by exploiting flexibility in power consumption, for example by operating as “virtual” energy storage \[11\]–\[14\]. DERs are categorized according to their technical capabilities:

- **P source/sink**: DR (more specifically, thermostatic load with thermal storage \[65\], \[67\], \[68\]. EV charging and discharging \[47\], \[62\], \[69\], \[70\], energy storage charging and discharging \[20\], \[71\]. DG active power curtailment \[72\].
- **Q source**: reactive power from DGs \[57\], \[58\], \[72\], flexible AC transmission system (FACTS) devices \[59\], and other power electronic interfaced DERs (e.g., EV charging posts and energy storage) \[25\].

Apart from DERs, actions of On-load tap-changers (OLTC), Voltage regulators (VR) \[20\], \[73\], \[74\] can be coordinated with DERs in the control solutions. In addition, the ownership of the controllable components is a key factor affecting how the control system can be structured.

3) **Properties of controlled process**: In general, the choice of control strategy depend not only on the control objective but also on the characteristics of the control problem such as relative time scale, system size and inertia, relative scale of critical resources and localized sensitivity properties.

D. Criteria for design and evaluation of control strategies

In the design process, design criteria are both representation of requirements in the design phase and performance indicator in the evaluation phase. The design criteria of the power system control applications fall into two kinds: design constraints that determine required qualitative properties for a control algorithm to be considered functional within a specific context (Table I), and design metrics that provide a quantitative view of performance requirements (Table I). These design criteria offer a framework to reflect either regulatory, economic, or technical requirements of the control system. Each of them is defined and justified in the tables. As a key element of control strategy, control architecture significantly affects its characteristics. Therefore, we will elaborate how relevant criteria are scored for different architecture.

### III. Taxonomy of distributed control architectures

A classification of distributed control architecture into consistent types has to start by relating distributed with conventional centralized and fully decentralized architectures. Compared to fully decentralized architecture, a distributed architecture adds communication between control elements; with respect to centralized architecture, the autonomy of remote control elements is increased.

The first classification criterion is therefore based on the structure of control elements:

- **T1**: (C)entralized. One central control element collecting information from remote sites and deciding set-points for remote actuation; examples are \[56\], \[58\]–\[63\].
- **T2**: (D)istributed. Multiple control elements organized in a common architecture jointly responsible decomposing objectives and deciding actuation.
- **T3**: (Dec)entralized. A central (common) control objective is decentralized to independent local control elements; the local control elements only use local measurements and actuators; examples are \[57\], \[66\], \[74\].

In the following, Type 2 is further analyzed. If the roles of control elements in an architecture are symmetrical, no single control element imposes decisions on other control elements:

- **2.1 D-(V)ertical.** Decisions of one control element are imposed on other control element eliminating at least one

### TABLE I

| Constraint                        | ID   | Description                                                                 |
|-----------------------------------|------|-----------------------------------------------------------------------------|
| Information isolation and privacy | C-PRI| Specific requirements on the limits of disclosure of behavioural and operational data between parties. |
| Fairness                          | C-FAI| Access to infrastructure and contributions to infrastructure cost is fairly shared by (distributed to) all participants according to a given set of rules. |
| Market and regulatory compatibility| C-MAC| To offer a meaningful service the control algorithm has to be able to comply with an external market setup. |
| Transactive energy framework       | C-TEF| The coordination scheme of an algorithm has a public specification and its signals transparently encode value in exchange for resources in a manner aligned with a given operational and economic context. \[13\]. |
| Monitoring of control actions      | C-MCA| A consistent view of all control actions can be obtained from a single observation point in real time \[55\]. It is necessary for operation supervision and supervisory control. |
TABLE II
PERFORMANCE METRICS

| Metric                  | ID  | Description                                                                 |
|-------------------------|-----|------------------------------------------------------------------------------|
| Responsiveness          | M RTS | The time between observation of a change and actuation in the process.        |
| Optimality and Accuracy | M OPT | Difference between a theoretically achievable global optimal/ideal outcome and the practically achieved outcome. |
| Resilience              | M RES | A measure of the capability to recover to stable system operation or adjust to changes due to disruptions or unexpected disturbances. |
| Scalability             | M SCA | Ability to continue meeting requirements while accommodating an increasing number of control elements. |
| Availability            | M AVA | The degree to which the control system is in a specified operable state.       |
| Maturity                | M MAT | Stage of development of the technology, which can be interpreted in terms of standardization, market adoption or available technical experience. |
| Ease of Integration     | M EOI | The ability of integration into existing workflows, processes and control systems. |
| Maintainability         | M MTY | The ease with which maintenance of a functional unit can be performed, which relates to the accessibility to control infrastructure, including direct and remote access. |
| Autonomy                | M AUT | Degree of independence with which a system can achieve its operating objectives without supervision or human intervention. |
| Operational transparency| M OTR | Extend to which a human operator can infer the rationale decisions, actions and behaviour of an automatic system. |

2.1 A D-V-(D)eterminate

A single control element (control center) concentrates data collection, analysis and control of all resources. This type of architecture is widely deployed in present day power systems and typically referred to as EMS or DMS. DERs directly react to control decisions derived from the EMS or DMS which has full process observability. Significant computing and communication resources are required at the central location which constitutes a single point of failure.

2.2 D-(H)orizontal

Different from T2.1 D-V, the responsibilities of control elements in this category are symmetrical, and the functions being executed in the control elements are similar. Examples are [33], [35], [39], [40]. The categories introduced so far are illustrated in Fig. 1 (centralized, distributed, and decentralized).

For the each of the distributed architecture types, two further subtypes are illustrated in Fig. 1. The distinction criteria here are specific to each type:

For T2.1 D-V the control decision can be based on hierarchical information collection as it is common in conventional distributed process control, or based on a negotiation process. The former case will be referred to as T2.1.A D-V-(D)eterminate; examples are [22], [23]. The latter will be referred to as T2.1.B D-V-(I)terative, as control decisions are made through iterative adjustments and information exchange between higher and lower level control elements. This is indicated by bi-directional arrows in the figure; examples are [28]–[30].

While control responsibility is symmetric among T2.2 D-H architectures, an algorithm or coordination mechanism may or may not require a centralization of at least one aspect of information exchange. This centralization introduces a ‘single point of failure’ that would not exist in a fully P2P architecture. In T2.2.A D-H-(C)entralized shared memory, a single entity is available to relay information among control elements as an essential part of the control algorithm (e.g. [33], [35]). In contrast T2.2.B D-H-(P)eer2peer represents only fully distributed P2P control architecture, as for example in [39], [40].

IV. ASSESSMENT OF DISTRIBUTED CONTROL ARCHITECTURES AND DER COORDINATION APPLICATIONS

This section assesses each distributed control architecture by alignment with the design criteria from Section II.

We first address the more common centralized and decentralized architectures to then discuss the distributed control architecture variants in detail as the main focus of this paper. The results are summarized in Table III which maps the properties of control architectures by category to the criteria discussed in Section II-D.

A. Type 1: Centralized Architecture

For a given control objective, e.g. loss minimization [56], [63], unit commitment [60], and up/down regulation [61], a single control element (control center) concentrates data collection, analysis and control of all resources. This type of architecture is widely deployed in present day power systems and typically referred to as EMS or DMS. DERs directly react to control decisions derived from the EMS or DMS which has full process observability. Significant computing and communication resources are required at the central location which constitutes a single point of failure.

B. Type 3: Decentralized

Decentralized control algorithms for power system applications, such as droop-controlled units serving primary frequency control, are widely used in grid operation and unit control. Their design exploits inherent physical properties of the system, such as frequency being a global variable which reflects the power imbalance of the system. Aggregation is implicitly achieved by accumulation of the individual, independent efforts (see Fig. 2). Voltage support (such as [7], [57], [66], [70], [74]) and primary frequency control (e.g., [47], [65], [69]) are common objectives of such control algorithms. The decentralized control elements modulate the active and/or reactive power injection from DERs such as EVs [47], [69], [70], HVAC units [65] or

![Fig. 2. Realizations of a decentralized control architecture. The blue boxes are droop controllers. The arrows show the control loops. The curves and functions within the boxes indicate control trajectories.](image)
PV installations [57], [70] based on local measurements of grid state. For example, the algorithms in [57] provide power factor or reactive power set-points as a function of local voltage magnitude. In addition to DERs, active grid assets such as on-load tap-changers (OLTC), step voltage regulators (SVR), or static VAR compensators (SVC) often use autonomous local control [74].

In decentralized control algorithms, the control loop is closed locally and no internal information needs to be shared. Emergency actions and large-scale deployment is easy to realize using this type of control algorithm. The control performance is guaranteed as long as the physical properties of the controlled process do not change. However, since decisions are made based on only partial knowledge of the global state space, decentralized control may result in suboptimal decisions, and may even cause severe incidents such as system collapse [7]. Without system wide coordination, fair algorithms are difficult to design (e.g. [67]).

The following example illustrates the limitations of decentralized approaches. An OLTC controlling a medium voltage (MV) feeder cannot operate in an efficient manner without knowledge of the connected DERs and their operating states [74]. One approach is to find a trade-off between responsiveness and system observability (e.g., [67], [75]) (see Fig. 2b). Better control performance is achieved by advanced processing of the collected data (e.g., [67], [72], [75], [76]) and the controlled process model (e.g., [64], [71], [77], [79]). Control algorithms proposed in [64], [67], [71], [76]–[80] apply advanced heuristics to the control inputs (e.g. a virtual oscillator model in [77] or an adaptive neural network in [76]) instead of a predefined control trajectory.

### C. Type 2: Distributed Architecture

2.1A D(istributed)-V(ertical)-D(eterminate): A lot of dispatch applications use a vertically distributed architecture and communicate deterministic set-points between control elements in different levels (see Fig. 3). Their control architecture is usually aligned with the hierarchical physical distribution grid structure. The control objectives are assigned to different levels in the control hierarchy. Such architecture reduces the stress of the higher level control elements, both on exchanging and processing the in/out information, and on computation.

System level coordination functions are located on a higher level (e.g. coordination between a tap changer and other active assets in [20], [21]) between multiple voltage levels [22], [23], between the grid and DERs [19], [24], and among various kinds of DERs [25]). Regional and local problems are handled in lower level(s) of the hierarchy correspondingly. Explicit bidirectional message passing is essential to make the available resources on a lower level visible to a higher level. In addition, the local system states and control objectives are not passed to the higher level control element. To control the voltage and frequency in the power system, [25] proposes a multi-agent structure for active and reactive power flexibility dispatch. Four agents are proposed in the algorithm in a hierarchical order: central EMS agent, transmission agent, distribution agent, and DER controller. The operational control problem is solved by its responsible agent.

Since the information forwarded by lower levels is simplified and abstracted, the decision made in the high level may not derive system-wide optimal solutions with limited knowledge. For example, the set-points in the higher level are treated as part of the objective function at lower levels in [22], which cannot always be reached. In such case, suboptimal condition may occur. Abstraction of information in this control architecture also leads to lack of transparency on operational actions compared with centralized control solutions.

2.1B D(istributed)-V(ertical)-I(terative): Unlike 2.1A, in 2.1B control elements on different control levels negotiate the decisions. This allows lower level control elements more flexibility to decide on their contribution to the system; however, this approach sacrifices computational efficiency and optimality as illustrated in Fig. 4. A two level hierarchy is built in [4]: DER controllers handle the local control problem of deciding DER setpoints. The grid controller then negotiates with DER controllers to achieve a system wide solution.

Game theory (e.g., [26], [27]) and optimization decomposition methods (e.g., [4], [28], [30]) are used to decompose optimization problems, and iterate the values of auxiliary vari-
The central entity which may introduce a single point of failure may limit the scalability. In this context, the central entity and may limit the scalability. In this context, the central entity which may limit the scalability.

Exchanges between all available control elements are avoided, so that the communication effort scales linearly with the number of control elements. However, bottlenecks exist at the level control element has more knowledge of the system, and therefore has more weight on directing the values of auxiliary variables. The applications applying this control architecture generally do not have quick response time, e.g., 1 hour is used as time interval in [4], [26]–[29]. Limited exchanges of information keep individuals away from revealing their behaviors to others, but also introduce difficulties on observing and understanding the behaviors of the whole system.

2.2.A D(istributed)-H(orizontal)-C(entralized shared memory): An optimization problem can also be decomposed to symmetrical sub-problems, i.e., equal responsibilities of control elements on decision making (see Fig. 5 and Fig. 6). For example, in [31], a distributed model predictive control (D-MPC) algorithm is proposed on solving congestion problem at the point of common coupling (PCC). Instead of a centralized dispatch element, multiple DER control elements are designed for scheduling the consumption for individuals and sharing the efforts on not over-passing the capacity limit. A similar setup can be found in [32], which presents a distributed control algorithm for the coordination of multiple wind turbines in order to supply a certain amount of power to the system.

Most applications in this category are motivated by a system-wide problem which requires a response from all connected units within a section of grid, such as in the case of peak shaving [33], [34] or power flow limitation [31], [32], [35], [36]. In these cases, the behaviour of each unit is impacted by all other ones.

A concentrated data repository/processor collects and processes the data without manipulating the data with its own objective. In some cases (e.g., [31], [32]), the information exchanges between all available control elements are avoided, so that the communication effort scales linearly with the number of control elements. However, bottlenecks exist at the central entity which may introduce a single point of failure and may limit the scalability.

The D-H-C architecture is applied in many game-theoretic applications (e.g. [33]–[36]). In this context, the central entity serves as a data processor or bid pool which collects information from all players and returns information, typically a price, depending on the outcome.

2.2.B D(istributed)-H(orizontal)-P(eer-to-peer): The control architecture of this category is fully distributed, such that all information exchanges between control elements are through P2P communication (see Fig. 6). In some applications, graph theory is applied to reduce the number of communication links among control elements without losing much coordinating efficiency. For example, a distributed optimal power flow algorithm using the alternating direction method of multipliers (ADMM) for a three phase system was proposed in [41]: The distribution grid is divided into several regions and power flow calculations are performed locally for each region. Only control elements associated with neighboring regions communicate with each other, exchanging information about the voltage vector of interconnection buses between regions. Similar applications can be found in [37], [40], the communication topology in [38] is designed according to a N-1 criterion using graph theory with redundant communication, such that an optimal dispatch is still available if one control element / communication link fails. The control objectives in these applications are to dispatch active or reactive power from DERs to maintain voltage levels (e.g. [40]–[42]), to minimize grid losses (e.g. [42], [43]), or to maximize the resource utilization (e.g. [37], [38], [43]). Control time scales range from few minutes to one hour. Some algorithms (e.g. [81]) may not guarantee convergence under all circumstances.

In this control architecture, all control elements are able to operate autonomously and communicate with others to obtain sufficient knowledge to support their decision making. In the proposed algorithms such as [40]–[42], there is no single point in this architecture where an overview of control actions, the state of the control system, and the state of the physical grid can be observed.

D. Hybrid Architectures

In real-world solutions, a control problem can often be reformulated into several vertically layered control problems.
The layer separation can employ time scale separation or other concerns. Each layer then can employ a different one of control patterns outlined above, forming a hybrid architecture.

The most common layering in power systems is the distinction of primary (I.), secondary (II.), and tertiary (III.) control layers. Here, the control problem is mathematically decomposed into a cascade, where each layer encapsulates certain disturbances while defining specific behaviour providing inputs to the next layer [82]. In conventional power system control, the layering is (I.-Dec., II.-Centralized, III.-Centralized), but many alternative architectural realizations of this basic layering have been proposed [18]. In [43] a hybrid architecture mixing a centralized with a decentralized pattern for the coordination of PV inverters. Decentralized control elements are used for an inner control loop performing fast voltage support, while a centralized controller provides global coordination of the active power flow at the PCC. A similar approach is proposed in [45], [46] combines D-V-D with a decentralized pattern in order to enable the efficient aggregation of flexibility while considering both global and local constraints.

The driver for layering different control patterns is typically the need to meet several design criteria that cannot be achieved in a desirable performance by a single integrated algorithm. The layering is thereby not necessarily driven by a cascaded control problem, but may be simply addressing another aspect of the control problem, thus meeting other design constraints. For example in the control strategy proposed by [19], [83] a D-V-D pattern is employed for the voltage control, which is complemented with a D-H-P pattern layered above to building up the control hierarchy; this combination achieves a much higher resilience of the overall control architecture while providing optimal control performance.

E. Demonstration and projects

Over the last several years, a variety of distributed control strategies have been implemented in a number of smart grid demonstration projects. A number of projects representing the above categories are discussed in the following.

A centralized approach (Type I) was proposed in the Cell Control Pilot project (CCPP) [84] that each control problem deals with a certain grid service with dedicated resources. A successful DR project, Olympic Peninsula project [85], uses a centralized architecture (Type I) to mobilize the flexibility from 112 customers responding to price signals. SmartGrid City [86] project is a similar one by demonstrating a large-scale prototype energy management program in a centralized architecture (Type I), involving more than 20 thousand smart meter. The Irvine Smart Grid Demonstration (ISGD) project [87] demonstrates a complete distribution automation solution in 12 kV distribution feeders.

In the meanwhile, efforts are also put in distributed control solutions featured by certain design requirements. EcoGrid EU [88] provides a full scale smart grid demonstration utilizing PowerMatcher platform [89] on the Danish island of Bornholm with 50% renewable penetration. Two thousand residential customers have been equipped with intelligent controlled DER units to respond to a real-time price signal reflecting the energy imbalance between production and consumption. The aggregated DR behavior is learned by the market, so that the desired behavior can be achieved in an iterative process (T2.1.A D-V-I). ELECTRA programme [90] aims at developing new approaches for distributed regional and pan-European voltage and frequency control using the Web-of-Cell (WoC) concept (T2.2.B D-H-P), in which cells are arbitrary control area of the grid organized on its own and communicate with each other for fully distributed collaboration [91]. DREAM project [92] proposed a control framework, in which distributed optimization (T2.1.B D-V-I) is applied in a multi-agent environment to demonstrate its advance on information isolation. Congestion management and voltage control are considered to be demonstrated in the project. Grid4EU project [93] aims at demonstrating advanced smart grid solutions with wide replication and scalability potential for Europe, one of which is a hierarchical control (T2.1.A D-V-D) strategies for load break switches in the field.

V. Discussion and Conclusion

In this paper, a taxonomy and design criteria are provided as an assistance to design, select, and evaluate control strategies for DER applications, especially control architectures as a key element of it. We focus on the distributed nature of the control architecture and develop a taxonomy for the categorization of different control strategies. Such a taxonomy can be used to establish a clear distinction between different approaches, which helps the design and evaluation of distributed control systems.

Furthermore, this paper discusses how the design criteria are related to the characteristics of control architectures by analyzing specific control strategies applied to DER units connected to a power distribution grid. For each type of architecture, a number of control problems and their related criteria are presented to support the characterization of control architectures.

To allow a thorough quantitative design, analysis, and evaluation of control algorithms, future work includes developing benchmark models, scenarios including the physical configuration and the control support infrastructure, and service/control problem specifications.

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