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Epistemology of voltage control in DER-rich power system

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ABSTRACT

Despite the recent development of several scalable, robust, and resilient control approaches with superior convergence properties considering an increasing penetration of distributed energy resources (DERs), cognitive oversights often simplify several aspects of the cyber–physical power system in the controller development. Following the identification of the limitations of classical controller definitions, we justify alternative definitions of voltage control approaches classifiers considering three inter-disciplinary domains: (i) power system, (ii) optimization and decision-making, and (iii) networking and cyber-security, to develop a taxonomy for helping in real-world comparative performance analysis and deployability of these controllers. We observe that classical and introduced domain-based definitions together can better classify the control algorithms.

1. The need for controller classifications

The added operational complexity with increasing penetration of small-scale inverter-based clean distributed energy resources (DERs) necessitates the introduction of scalable, interoperable, and resilient control algorithms with practical implementation strategies to deploy in the real world. Given the noticeable impact of increased renewable penetration is felt on the power network voltage profile [1], we base our discussion in this paper on voltage control [2–4]. This newer algorithm development is facilitated by: (a) the advent of fast-acting advanced power-electronic converters facilitating the integration of DERs, (b) improved information and communication technologies (ICT), and (c) modern, resilient control schemes [5]. However, it is essential to classify these approaches based on their dynamical performance along with suitability in real-world deployment alongside traditional voltage control devices.

Four classical control/optimization approaches (despite the differences, we have used control and optimization synonymously), namely, (a) *local*, (b) *centralized*, (c) *decentralized*, and (d) *distributed*, has been introduced in the literature (see Fig. 1 for a detailed schematic diagram) based on requisite communication and coordination [3,6], and they are succinctly described herein:

Local approaches primarily rely on local measurements (limited to a particular node in the power network) and physical relationships among local measurements and control variables for decision-making. Once deployed, lack of coordination implies that these approaches often do not achieve performance optimality. Utilization of the measure–compute–control approach makes them primarily dynamic (information utilization) or feedback-based.

Centralized approaches require the power system states measured by the sensors placed within the power network to be communicated to a centralized unit — the advanced distribution management system (ADMS). Subsequently, the ADMS calculates control setpoints to be communicated to corresponding actuators throughout the power network, which makes these approaches primarily static.

Decentralized approaches necessitate the power network to be segregated into multiple clusters, where at least one of these clusters accumulates data from multiple power system nodes. The sensors communicate to the lead controller within a cluster for decision-making, making both sensing and decision-making cluster-specific. Centralized units in each cluster are weakly coupled and may not frequently communicate.

Distributed approaches are relatively newer approaches, wherein each controller is associated with a sensing agent, computing agent, and cyber agent. The computing agents associated with each controller can collectively utilize the measure–communicate–compute–deploy approach to solve the control problem, making them dynamic. If these approaches rely on multiple communicate–compute cycles before the control signal is deployable, these approaches become static (control

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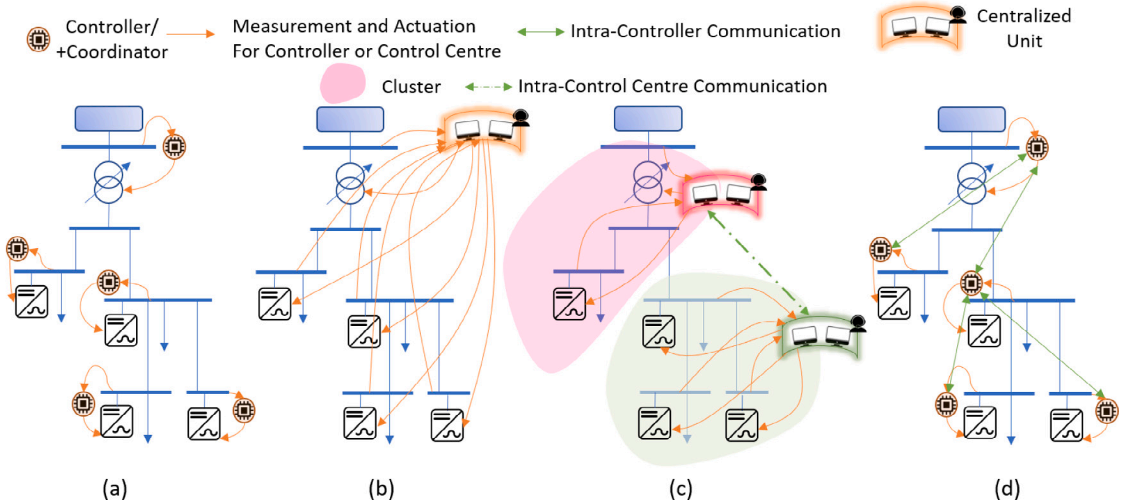

Fig. 1. Examples of Voltage Control Architectures: (a) Local, (b) Centralized, (c) Decentralized, (d) Distributed.

action generated based on static measurement information). The nodal aspects shown in Fig. 1(d) can be symbolic, i.e., a node could represent a cluster as in Fig. 1(c). However, the controllers are tightly coupled and participate together in the decision-making. The coordinators are a part of controllers to identify the power system topology in facilitating controller operation.

2. Insufficiency of classical controller definitions

Despite such an extensive classification, researchers often look at these classical approach definitions as the logical extension of one another (comparing definitions in [3,7,8]), and therefore, clear distinctions between these control approaches are widely debated. As an example, from the detailed reviews on classical distributed and decentralized control approaches in distribution power systems in [5–9], we observed existence of implementation diversity even within these approaches. For example, among two examples provided in [5] for distributed optimization, one is feedback-based, which actively relies on the power system itself. Reliance on 'measure–communicate–update–deploy' in this approach makes it less reliant on communication and is shown to perform well under delay, communication failure, model errors, etc. The other example is also a duality-based approach and uses multiple 'communicate–update' cycles for the set-point generation, requiring a fast-communication link. Both of these approaches also have significantly different controller dynamics.

Furthermore, majority of the control approaches can seldom be classified by one particular architecture in actual deployment. For example, in the implementation of local approaches, the controllers are expected to respond to predefined rules (droop-based, rule-based, optimization-based) without actively utilizing any communication. However, these rules are expected to change depending on loading conditions, topology changes in the system, etc., and are expected to be provided from a centralized place. The distinction between decentralized and distributed algorithm is also subtle with symbolic definition, which makes us question the necessity of pluralism in existing controller definitions. Even within distributed approaches, if a power system node chooses among clusters, there will be concern about appropriate data management. Individual controllers in a decentralized approach can also choose among the clusters to enable resiliency. The taxonomy presented in [9] addresses some of these complexities with hybrid approaches, but if the controllers operate in multiple time-horizon, classification can become extremely cumbersome.

In this paper, we adhere to the classical definitions provided in [3]. Alternatively, it is also imminent that the evolving cyber-power system

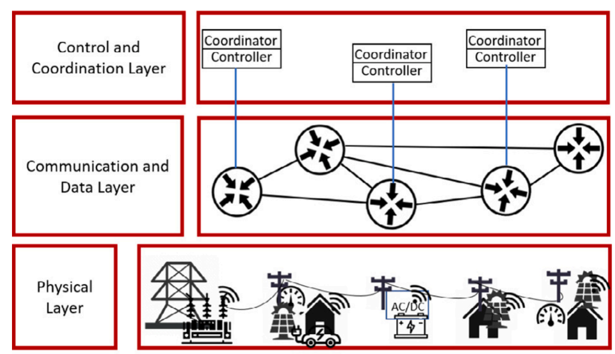

Fig. 2. An overview of the typical real-world distributed control architecture implementation used for voltage control.

relies on three domain-related aspects, namely, (i) power system domain, (ii) cyber domain, and (iii) decision-making-related domains, and the controllers could also be classified with these alternative domain-based aspects. It is important to understand whether both of these definitions (classical and domain-based approaches) are epistemological extensions or whether the alternative definitions would help us perform a real-world performance analysis of the control algorithms.

3. Towards an extended classification: An epistemology

Based on the hierarchical architecture shown in Fig. 2, the three associated domain-related aspects can be invoked to develop the taxonomy shown in Fig. 3. The developed taxonomy could suitably incorporate the one presented in [9] while helping us sub-classifying controllers identified based on classical definitions. Details in regards to domain-specific aspects are given as follows:

For the *power system domain*, we observe limitations of certain algorithms to specific application types (due to limited availability of required information), and the type of model selected impacts both the convergence rate and quality of the solution. The power system domain could be subdivided into power system model and application type. The difficulty in the implementation of AC-OPF through an existing first-order distributed algorithm is imminent. Power flow models are not explicitly needed for local algorithms. Also, the underlying applications and their complexity also dictate controller performance.

The *algorithmic part or the decision-making domain* requires information about the frequency of data exchange from the power system

		Local Approaches	Centralized Approaches	Decentralized Approaches	Distributed Approaches
Power Domain	Power System Model	Not Needed (Needed for Hybrid Approaches)	Branch (Power/Current) Flow, Bus (Power/Current) Injection, AC-OPF	Branch (Power/Current) Flow, Bus (Power/Current) Injection, AC-OPF	Branch (Power/Current) Flow, Bus (Power/Current) Injection
	Application Type	Loss Minimization, Voltage Profile improvement, Minimal active power curtailment	Loss Minimization, Voltage Profile improvement, Minimal active power curtailment, Conservation Voltage Reduction	Loss Minimization, Voltage Profile improvement, Minimal active power curtailment, Conservation Voltage Reduction	Loss Minimization, Voltage Profile improvement, Minimal active power curtailment, Conservation Voltage Reduction
Cyber Domain	Implementation Type	Not Needed	Centralized Location	Holonic, Hierarchical, Static Clusters	Federated, P2P
	Communication	Sporadic (Operating Point Update)	Frequent	Frequent and Sporadic	Frequent and Sporadic
Decision-Making Domain	Iterative Data Exchange	Dynamic Method	Static Method	Static Method	Static Method, Dynamic Method
	Algorithm Type	Droop-based, Optimization Based, Rule Based	Mathematical Optimization, Heuristic Approaches	Mathematical Optimization, Heuristic Approaches	Concensus based Method, Distributed Dual Method

Fig. 3. Taxonomy of Different Control Approaches: Classical to Extended Definition.

and the type of algorithm being utilized. This domain aspect could be subdivided into the frequency of data collection from the power system and the type of algorithm being implemented. As discussed earlier, certain algorithms actively utilize the power system and ensure that the generated control action is not detrimental to the system. These methods are 'dynamic' and are primarily used in local and distributed approaches. Alternatively, another set of methods calculates the feasible control action before deployment, and these are called 'static'. In the algorithm type end, certain algorithms can use approximated power system model but will be able to correct the approximation error iteratively. Certain algorithms are only possible to be deployed in specific approaches.

The *cyber model* includes the frequency of needed communication, frequency of model exchange, and database management, and these are captured through implementation type and requisite communication. Methods such as holonic, hierarchical, static clusters, federated, and P2P are various ways of database management and hence dictate the implementation. The frequency of communication needed can be time-decomposable defining 'frequent' and 'sporadic' communication. Here, frequent communication implies the one requiring faster communication links. Sporadic communication implies the requirement is limited to a slower time scale, which is primarily used for set-point update, model update, etc. Notably, operation in the slower time scale doesn't imply algorithms would require a slower communication channel, addressing the challenges related to hybrid approaches.

As observed from the proposed taxonomy, classifications under the domain-related aspects are not uniform across classical definitions. Therefore, classical and domain-based aspects must be invoked together for appropriate controller categorization and are not necessarily in opposition to one another. Instead, a pluralistic variety would help us identify the causality behind algorithmic behavior and the comparative benefits of the approaches; hence they are an epistemological extension of one another. One can rely on time-decomposability for performance analysis, where control architecture in each time-scale can be different. Performance at different time-scale can be knotted together for overall architecture and implementation.

Identified taxonomy will be better able to identify requisite communication medium [10], requisite interoperability with multi-vendor devices, standard protocols to be deployed, specific vulnerabilities in the communication medium, possible implications of those vulnerabilities on the algorithm, and the measures needed to circumvent these vulnerabilities [11]. Future work will involve the development of metrics and test cases for realistic comparison of existing or new control algorithms in a benchmark co-simulation environment, duly considering the implications of the ICT.

CRediT authorship contribution statement

Subir Majumder: Conceptualization, Methodology, Investigation, Writing – original draft. **Niloy Patari:** Writing – review & editing, Investigation. **Anurag K. Srivastava:** Writing – review & editing, Investigation, Supervision. **Priyank Srivastava:** Writing – review & editing. **Anuradha M. Annaswamy:** Investigation, Writing – editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] Essential Evergy Newsletter, Breaking the duck curve. https://www.essentialenergy.com.au/media-centre/newsletter/newsletter-3-breaking-the-duck-curve (accessed: 05-09-2022).

[2] H. Sun, Q. Guo, J. Qi, V. Ajjarapu, R. Bravo, J. Chow, Z. Li, R. Moghe, E. Nasr-Azadani, U. Tamrakar, et al., Review of challenges and research opportunities for voltage control in smart grids, IEEE Trans. Power Syst. 34 (4) (2019) 2790–2801.

[3] K.E. Antoniadou-Plytaria, I.N. Kouveliotis-Lysikatos, P.S. Georgilakis, N.D. Hatziargyriou, Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research, IEEE Trans. Smart Grid 8 (6) (2017) 2999–3008.

[4] D.K. Molzahn, F. Dörfler, H. Sandberg, S.H. Low, S. Chakrabarti, R. Baldick, J. Lavaei, A survey of distributed optimization and control algorithms for electric power systems, IEEE Trans. Smart Grid 8 (6) (2017) 2941–2962.
[5] N. Patari, V. Venkataramanan, A. Srivastava, D.K. Molzahn, N. Li, A. Annaswamy, Distributed optimization in distribution systems: Use cases, limitations, and research needs, IEEE Trans. Power Syst. 37 (5) (2021) 3469–3481.
[6] A. Vosughi, A. Tamimi, A.B. King, S. Majumder, A.K. Srivasava, Cyber-physical vulnerability and resiliency analysis for DER integration: A review, challenges and research needs, Renew. Sustain. Energy Rev. 168 (2022) 112794.
[7] A. Kargarian, J. Mohammadi, J. Guo, S. Chakrabarti, M. Barati, G. Hug, S. Kar, R. Baldick, Toward distributed/decentralized DC optimal power flow implementation in future electric power systems, IEEE Trans. Smart Grid 9 (4) (2018) 2574–2594.
[8] S. Howell, Y. Rezgui, J.-L. Hippolyte, B. Jayan, H. Li, Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources, Renew. Sust. Energy Rev. 77 (2017) 193–214.
[9] X. Han, K. Heussen, O. Gehrke, H.W. Bindner, B. Kroposki, Taxonomy for evaluation of distributed control strategies for distributed energy resources, IEEE Trans. Smart Grid 9 (5) (2017) 5185–5195.
[10] J. Gao, Y. Xiao, J. Liu, W. Liang, C.P. Chen, A survey of communication/networking in smart grids, Future Gener. Comput. Syst. 28 (2) (2012) 391–404.
[11] C.-C. Sun, A. Hahn, C.-C. Liu, Cyber security of a power grid: State-of-the-art, Int. J. Electr. Power Energy Syst. 99 (2018) 45–56.