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SURVEY

Control Systems for Low-Inertia Power Grids: A Survey on Virtual Power Plants

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ABSTRACT Virtual Power Plants (VPPs) have emerged as a modern real-time energy management architecture that seeks to synergistically coordinate an aggregation of renewable and non-renewable generation systems to overcome some of the fundamental limitations of traditional power grids dominated by synchronous machines. In this survey paper, we review the different existing and emerging feedback control mechanisms and architectures used for the real-time operation of VPPs. In contrast to other works that have mostly focused on the optimal dispatch and economical aspects of VPPs in the hourly and daily time scales, in this paper we focus on the dynamic nature of the system during the faster sub-hourly time scales. The *virtual* (i.e., software-based) component of a VPP, combined with the *power plant* (i.e., physics-based) components of the power grid, make VPPs prominent examples of cyber-physical systems, where both continuous-time and discrete-time dynamics play critical roles in the stability and transient properties of the system. We elaborate on this interpretation of VPPs as hybrid dynamical systems, and we further discuss open research problems and potential research directions in feedback control systems that could contribute to the safe development and deployment of autonomous VPPs.

INDEX TERMS Smart grids, renewable energy, virtual power plant, feedback control, multi-agent hybrid dynamical systems.

I. INTRODUCTION

The accelerating effects of climate change have driven the scientific and engineering communities to invest an increasing amount of work and resources in the incorporation, modernization, and automation of low-carbon emission technologies in the electric power grid [1], [2], [3], [4]. Within such modernization efforts, the systematic introduction and implementation of Renewable Energy Sources (RESs) have become a priority to reduce the dependence on fossil-based generation and the emission of greenhouse gases [5]. These efforts have been further accelerated by recent technological and logistical advances that have made renewable generation more economically competitive, gaining a more dominant role in the power grid compared to traditional energy sources [6], [7], [8]. Indeed, as shown in Figure 1, by the year 2021, RESs accounted for 20% of all the electricity generated in the United States, compared to only 9% in the year 2011 [9]. This clearly increasing trend is expected to continue during the next decade [8], such that, by the year 2023, renewables will surpass natural gas to be the predominant source of electricity generation in the United States. Indeed, by the year 2050, renewables are expected to contribute more than 40% of the total electricity generation [10].

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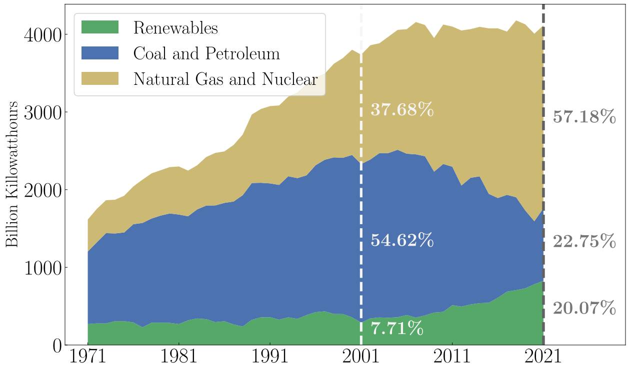


FIGURE 1. U.S. electricity generation from selected fuels and renewable sources. Figure generated from data reported by the U.S Energy Information Administration, *Monthly Energy Review*, Table 7.2a [9].

A. BACKGROUND

The increasing penetration of RESs in the power grid has the potential to significantly reduce the emission of greenhouse gases and to decentralize and personalize the generation of electricity. However, the effective integration of RES into the grid also demands new aggregation and coordination strategies, regulatory policies, and economic models to efficiently manage their inherently variable, heterogenous, and non-dispatchable nature [11]. Motivated by these challenges, *Virtual Power Plants* (VPPs) have emerged as a modern energy management paradigm that synergistically leverages the main advantages of renewables, non-renewables, energy storage systems, and controllable loads via bi-directional communication between devices and real-time feedback control. This paradigm could be instrumental for the solution of some of the most pressing challenges that arise in the integration of RESs to the power grid at the utility-scale, e.g., technical, economical, social, and regulatory, see [12, Sec 1.1], [13], [14]. Indeed, from a *technical perspective*, VPPs conceptualize the aggregation of multiple technologies through an *overarching communication and control framework* that makes use of distributed or co-located clusters of RESs to achieve cost savings, higher efficiency, and better environmental performance compared to traditional approaches [12], [14], [15], [16], [17]. In this way, VPPs can also be seen as mechanisms that act as an interface between the RES and the system operator [18]. By acting as a single virtual element, VPPs can also actively participate in the electricity market, provide ancillary services, and operate without geographical restrictions imposed on its distributed generators [19], [20]

The concept of a Virtual Power Plant was initially introduced in [21] under the term "*virtual utility*", describing a "*flexible collaboration of independent, market-driven entities that provide efficient energy services demanded by consumers without necessarily owning the corresponding assets*". Since then, the definition of a VPP has evolved to incorporate other technical aspects, including geographic considerations, coordination and communication protocols, enabling technologies, technical and economic objectives, operational modes, etc, see [22, Table 1] for a review of different characterizations of VPPs. However, while no single official definition of a VPP exists in the literature, a distinguishing feature in most characterizations of VPPs is their underlying "software-based" operation to aggregate and coordinate different heterogeneous distributed energy resources in order to achieve a common goal [22]. This level of coordination requires communication and real-time control technologies deployed in "the cloud", which, in turn, makes *digital* infrastructure and high-performance algorithms critical assets for the operation of VPPs. Moreover, the mixture of physics-based dynamics and digital elements in VPPs can lead to complex dynamic behaviors, including hybrid dynamics that involve continuous-time elements and discrete-time elements, [23], and which must be appropriately coordinated and controlled to preserve the stability of the system [24]. Incorporating elements with non-deterministic behaviors, e.g., highly intermittent renewable energy sources, can further enrich the behavior of VPPs, introducing myriads of additional challenges and opportunities for the purpose of control and optimization.

B. MOTIVATION AND TECHNICAL CHALLENGES

Feedback control techniques play a prominent role in guaranteeing stability, resilience, robustness, and transient performance in VPPs. For example, as shown recently in [12, Sec 3.3] and [25], a suitable design of the feedback control systems in each of the components of a VPP can harness the fast dynamic response of low-inertia generators to complement the transient response of conventional generators characterized by Synchronous Machines (SMs). In this way, they are able to meet performance requirements that are unattainable in traditional power systems that rely entirely on conventional generation. Similarly, new feedback control techniques are needed to efficiently coordinate VPPs with different energy resources having heterogeneous dynamic behaviors [26], [27], some of which might incorporate a high-level of volatility that calls for advanced forecasting and prediction mechanisms [28], [29]. The systematic integration of these mechanisms into highly dynamic feedback loops in VPPs could leverage recent progress made in the areas of data-assisted and data-enabled control [30], [31], [32], [33], [34], as well as more traditional adaptive and self-tuning methods with stability guarantees [35], [36], [37]. These techniques are becoming more and more relevant due to the increasing penetration of Inverter-Based Resources (IBRs) connected to the grid via a power inverter that decouples the mechanical dynamics of the generator from the dynamics of the power grid, thus facilitating the implementation of advanced control algorithms [4], [38], [39], [40]. These enabling technologies also open the door to modern nonlinear and non-smooth algorithms [41], [42] that can overcome some of the fundamental limitations of traditional linear control techniques such as

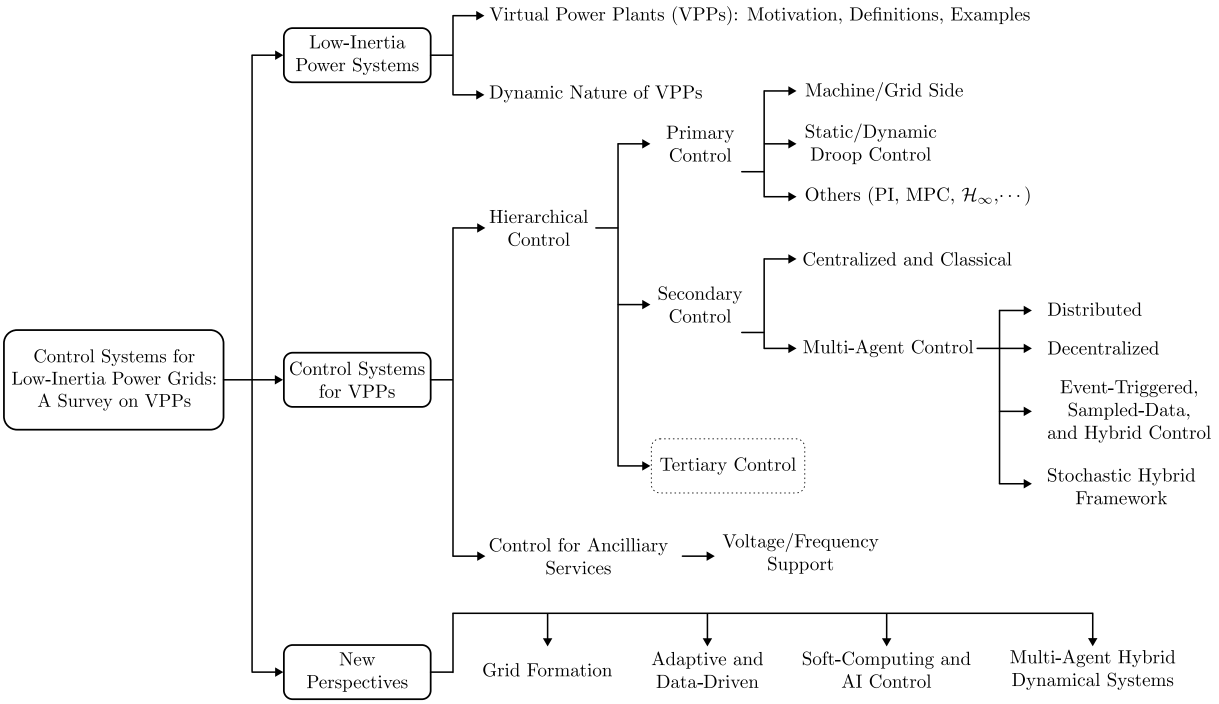


FIGURE 2. **Overall structure of the survey paper.**

proportional (integral) controllers (PI), linear quadratic regulators (LQR), pole placement methods, etc. Additionally, the decentralized and complex dynamic properties of these architectures call for new control and optimization algorithms able to efficiently handle the emergence of intricate feedback loops with multiple time scales [43], [44], intertwined dynamic behaviors that embed continuous-time and discrete-time dynamics [45], [46], switching cyber-physical infrastructure [47], [48], as well as the unavoidable stochastic nature of renewable generation [38], [40].

C. CONTRIBUTIONS AND PAPER ORGANIZATION

Motivated by the above challenges and opportunities, in this survey paper we present a review of the different feedback control techniques and algorithms commonly used in the context of VPPs. While existing survey papers have focused mostly on the hourly and daily time scales of VPPs (e.g., dispatch, pricing, etc) [49], [50], [51], frequency controllers for multi-area power systems [52] (e.g., automatic generation control, load frequency control, etc), and general control technologies of energy systems [53], we concentrate on the different control algorithms and dynamics used for regulation and reference tracking in the sub-hourly time-domain in VPPs, i.e., primary and secondary control for medium and fast time scales in energy systems comprised of multiple distributed energy resources, aggregated and controlled via software-based architectures. We review the different definitions and technical features that separate VPPs from traditional power grids, their main advantages and limitations in the context of feedback control, as well as the different opportunities for the implementation of novel algorithms that can overcome some of the existing challenges. Specifically, the following are the main contributions of this survey paper:

- We review the different definitions of VPPs that have been studied in the literature, and we provide a concise summary of the most common technical features that characterize a VPP.
- We present an up-to-date literature review on the control techniques for VPPs, with a focus on the fast and medium time scales of the system. We contextualize these techniques into different hierarchical structures and energy markets. Our review includes both traditional and modern control techniques.
- We provide a unifying modeling framework of VPPs based on the concept of multi-agent hybrid dynamical systems, which models networked systems that combine continuous-time dynamics (e.g., physics-based) and discrete-time dynamics (e.g., computational-based) using a common mathematical language.
- We identify and discuss different research problems and new perspectives in the area of feedback control for VPPs. We also contextualize these research directions with respect to up-to-date literature in control systems.

The overall structure of this survey paper is illustrated in Figure 2. In particular, the paper is organized as follows: In Section II, we introduce the concept of a VPP, and we discuss its main advantages and limitations as a possible solution to the technological challenges that arise in inverter-dominated power systems. In Section III, we review the different techniques and architectures used for the control

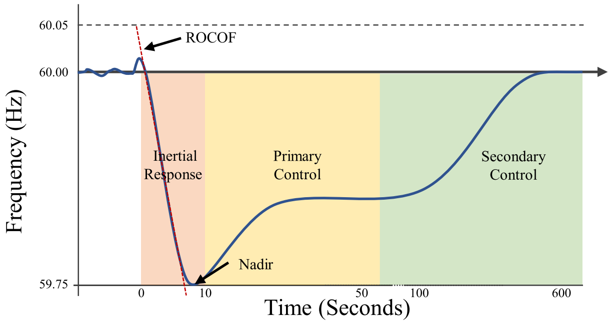


FIGURE 3. Typical frequency behavior after failure of a DER in a SM-dominated grid. Adapted from [56, pag.7].

and coordination of VPPs. In Section IV, we discuss some alternative approaches recently used to solve modern control problems in low-inertia power systems, as well as open research questions and future research directions. Finally, Section V ends with some conclusions.

II. LOW-INERTIA POWER SYSTEMS

The concept of inertia in power systems stems from the derivation of the power conversion between the mechanical energy of a rotating mass and the electric energy generated by a SM. This notion is usually captured by (simplified) models of ordinary differential equations (ODEs) of the form

$$H\dot{\omega} = -D\omega + p_m - p_e, \tag{1}$$

where p_m and p_e are the time-varying mechanical and electric power, respectively, H is the inertia, D is the damping factor, and ω is the time-varying mean angular speed [54]. In (1), a power imbalance leads to changes in the frequency of the grid, with a rate of change determined mostly by H. As shown in Figure 3, inertia plays an important role on the transient response of a SM-dominated power grid, effectively acting as a self-stabilizing mechanism. However, emerging and future power systems with higher penetration of RESs have low mechanical inertia compared to traditional generation systems [55], leading to fundamentally different control and coordination challenges, including:

- reduced stability and margins of robustness due to a higher Rate-Of-Change-Of-Frequency (ROCOF) and a lower Nadir,
- increased need for reliable frequency measurements,
- larger time delays when connected to additional communication and estimation pipelines, and
- unexpected dynamic behaviors that are not fully captured by traditional phasor-approximation models.

For a comprehensive review of the different challenges faced by low-inertia power systems, we refer the reader to [57], [58], [59], [60], [61], [62], [63], [64], [65], [66] and the references therein.

To tackle some of the above challenges, DERs, which include diesel engines, Energy Storage Systems (ESSs), local controllable loads, wind turbines, fuel cells, micro turbines, photovoltaic systems, and other RESs have been increasingly studied under the umbrella of Microgrids (MGs) [67], [68], [69]. These systems describe an aggregation of DERs that are able to operate either in islanded mode isolated from the bulk power system, or in a grid-connected fashion using a Point of Common Coupling (PCC) to the main grid [70]. The use of ESSs and local controllable loads further facilitates the balance of power in the grid via real-time control and/or shedding mechanisms [71]. In turn, having more controllable devices broadens the possibilities for the implementation of advanced feedback control algorithms to appropriately regulate, optimize, and coordinate the power grid. For recent reviews on state-of-the art feedback control techniques for MGs we refer the reader to [72], [73], [74] and the references therein.

A. VIRTUAL POWER PLANTS

VPPs emerged as system architectures designed to overcome some of the limitations of traditional MGs, including those related to the geographical proximity of the DERs that comprise the MG, as well as their ability to operate in islanded mode via a PCC switch that connects to the utility network [21]. This structure is illustrated in Figure 4. Multiple definitions of VPPs have been discussed in the literature [13], [18], [51], [75], [76], [77]. The most common characterizations describe VPPs as grid-tied systems comprised of multiple DERs, operating under a decentralized control scheme that seeks to emulate a single power plant by synergistically coordinating the multiple devices, using advanced communication and control systems, and seeking to achieve desired dynamic and static specifications. These transient and steady state specifications might be unachievable via traditional generation technologies due to fundamental physical limitations. Since the aggregation of DERs in VPPs can be virtual, i.e., based on software, VPPs can remove the physical and geographical constraints that emerge in MGs, allowing them to span larger geographical regions via advanced communication, coordination, and control technologies [13], [75]. It is important to note that VPPs are not the only existing approach that has been explored to solve the large-scale management of energy sources across large geographical areas. For instance, similar to some *large-scale* VPPs [78], Multi-Area Power Systems (MAPSs) [79, Ch. 2] are systems comprising different areas, each area having multiple energy sources localized in a specific geographical zone being responsible for meeting the local power demand, as well as for complying with scheduled interchanges of power with nearby areas [54]. However, the coordination of MAPSs is typically based on a centralized control structure [80], [81], [82], where a single entity is individually responsible for coordinating the operation of the multiple areas. This approach has been widely adopted in the past and it is still in use in modern energy systems [83], [84], [85]. Nevertheless, with the advent of new technologies and the increasing penetration of renewable energy

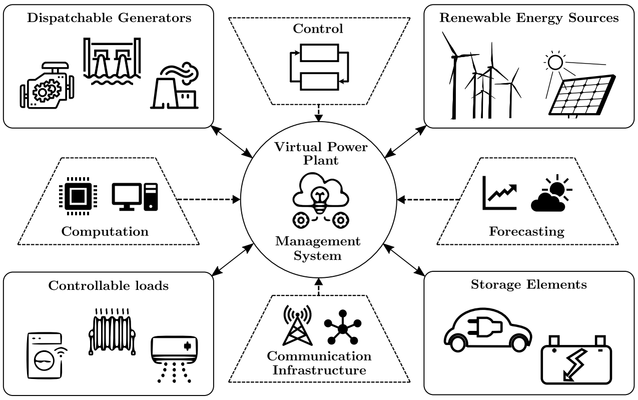


FIGURE 4. Schematic of the different components of a VPP.

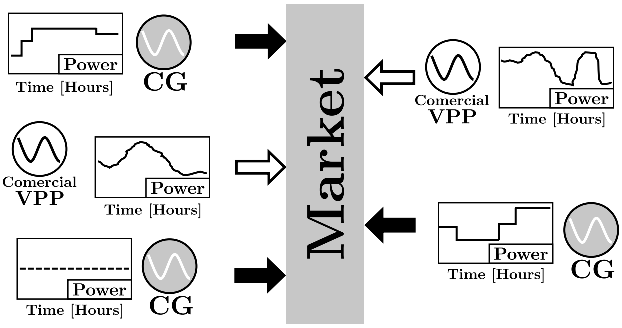


FIGURE 5. Commercial VPPs for market participation. Optimization and control problems are solved at slow time scales.

sources, VPPs have emerged as a more flexible, efficient, decentralized, and cost-effective alternative to traditional MAPSs [86]. In summary, VPPs usually exhibit the following salient features:

- They are formed by an aggregation of DERs with a communication infrastructure and a unified supervision and control system that can be implemented in a decentralized way.
- They operate mostly connected to the main power grid, as opposed to MGs, which are regularly operated in islanded mode.
- They can be connected to the main power grid through one or more PCC, specified and supervised by an Energy Management System (EMS).
- They can fully substitute a power plant in order to supply energy at the utility-level scale [87].
- Compared to traditional approaches [86], VPPs provide more flexibility and adaptability for the aggregation, coordination, and control of DERs.

The above features are not necessarily universal, and they should be taken only as a general guide. Indeed, recent works have also considered the aggregation of small MGs as VPP, arguing that these aggregations enable an optimal and more efficient power management in the grid, see [88], [89], and [90].

VPPs can also be categorized according to their market participation. For example, *Technical VPPs* focus on providing ancillary services to the Independent System Operator (ISO) or the Distribution System Operator (DSO) [18], [51], [91]. In contrast, *Commercial VPPs* have as main goal to optimize generation and demand (e.g., optimal dispatch) of electric power, which is usually achieved by solving optimization and control problems at slower time scales, see Figure 5. Other classifications of VPPs are presented in [92] using the notions of Virtual Power Plants for Load Control, Alternative Supply Virtual Plants, Virtual Mixed Asset Power Plants, and Wholesale Electric Power Plants.

Most of the existing literature on VPPs has focused on their commercial operation, characterizing their different scheduling techniques and operational constraints at slow time scales [49], or has broadly discussed the recent market, social and regulatory advances involved in their implementation [90]. However, less work has been devoted to the study of Technical VPPs that are in charge of providing ancillary services and general operational functionalities at faster time scales, such as guaranteeing the stability of the system, a property that is usually assumed *a priori* in order to solve quasi-static optimization problems related to voltage control, dispatch, and pricing [60], [93], to name just a few examples. Therefore, in this paper, we will focus mostly on Technical VPPs. To further study the above challenges, one needs to consider the *dynamical* properties of VPPs, which play an important role in the sub-hourly control strategies needed to achieve regulation and tracking at fast time scales.

B. DYNAMIC NATURE OF VIRTUAL POWER PLANTS

From a technical perspective, the aggregation of DERs and SMs in VPPs entails the synergistic coordination of different dynamic energy sources, while maintaining generation stability at the individual level. Therefore, to guarantee closed-loop stability, control techniques designed for operation at sub-hourly times must take into account the inherent heterogeneous dynamics of the multiple components of the VPP. This perspective contrasts with traditional slow-time scale control techniques that update the control signals at an hourly or daily rate, using only the steady-state characteristics of the DERs to solve an optimization problem for economic dispatch [89], [94].

While conventional generation based on SM with mechanical inertia provides suitable resilience properties to the grid, low-inertia VPPs may lack such intrinsic robustness, and therefore require dynamic control techniques that can emulate, compensate, or replace the role of inertia. The dynamic analysis of VPPs becomes even more crucial given the nonlinear dynamics of the IBRs that are used to facilitate their control. Here, the term IBR is applied to any power generating element with a power electronics unit as an interface to the grid. In the absence of inertial response, it becomes crucial to integrate the converter dynamics into the design of the control system of the VPPs [95]. Moreover, the dynamic model of the VPPs used for the purpose of feedback control will depend on the services that are offered to the ISO, or to

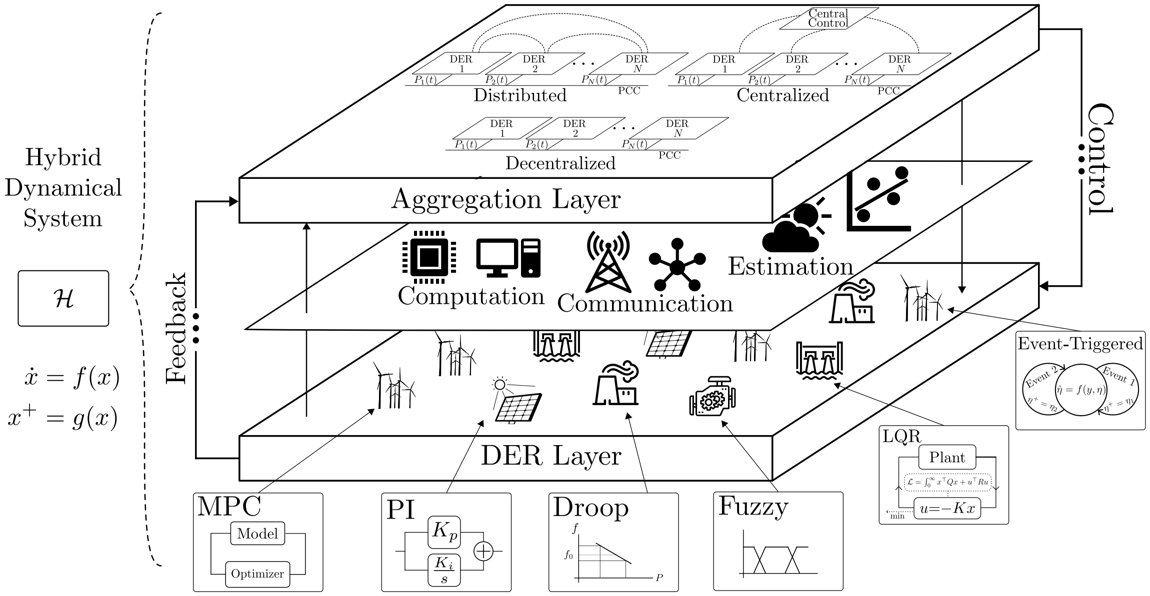


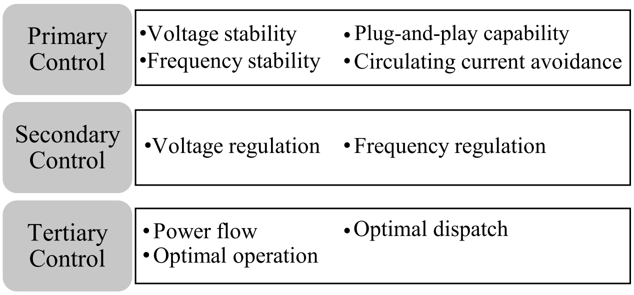
FIGURE 6. Control Framework of Virtual Power Plants. The integration of physical layers and digital layers leads to a closed-loop system with hybrid dynamics.

the coordination of several IBRs in a network. In this regard, the models fitting the time-scale of the stability analysis of a Technical VPP might differ from those used for the control of a Commercial VPP [38], [96]. To further emphasize the dynamic nature of VPPs, the concept of *Dynamic Virtual Power Plants* (DVPPs) was formalized in [40], where the authors also introduced a conceptual framework for prescribing strategies that do not necessarily comply with conventional hierarchical control structures for frequency and voltage regulation. The mathematical models used for the purpose of control design and analysis can be generated via first principles, and are usually further simplified to obtain linear models suitable for traditional multi-variable control theory for discrete-time, continuous-time, or hybrid dynamical systems [97]; see Figure 6. In this survey paper, we give particular attention to the roles of Wind Turbines (WTs), Photo-voltaic Generators (PVGs), and ESSs in VPPs, since these technologies have achieved higher maturity levels in terms of standardization [98], [99] and implementation [39], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110].

In the following sections, we review different fast-time scale control techniques in VPPs, as well as some of their main advantages and limitations.

III. CONTROL SYSTEMS FOR VIRTUAL POWER PLANTS

The operation of DERs and loads in a VPP requires control schemes able to appropriately address the different dynamic requirements and objectives in the grid. These objectives include maintaining voltage and frequency stability and regulation, plug-and-play capabilities and fault management, optimal load shedding, synchronization, and real-time optimization, to name just a few [111], [112]. The objectives



Primary Control	•Voltage stability •Frequency stability	•Plug-and-play capability •Circulating current avoidance
Secondary Control	•Voltage regulation	•Frequency regulation
Tertiary Control	•Power flow •Optimal operation	•Optimal dispatch

FIGURE 7. Hierarchical control levels for VPPs in connected mode.

follow a hierarchical structure set by the different elements of the VPP, as well as local standards or guidelines, e.g., IEC/ISO62264 standards [113], or guidelines given by NERC in case of North America [56]. The hierarchical objectives can also define a hierarchical structure for the different control systems used in the VPP, see [75], [114], [115], and [116]. Other non-hierarchical control structures, particularly those focused on providing ancillary services, follow a transversal architecture that seeks to compress the time scales of the system. In the following, we describe in detail both classifications.

A. HIERARCHICAL CONTROL

The hierarchical nature of the operational objectives of the VPPs define also a hierarchical structure for the control systems. Figure 7 shows the three hierarchical operational objectives and control levels that are most commonly studied in the literature, [94], [117], [118], [119], [120], [121], [122]. This hierarchical architecture can also be used for the incorporation of other particular economic, technical, or environmental objectives, which set the participation of the VPP

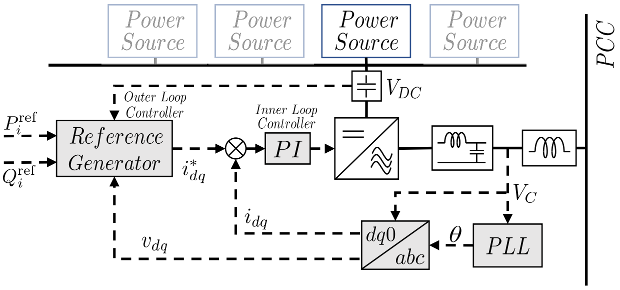


FIGURE 8. **Control scheme of a grid-side converter. Solid lines represent power connections, dashed lines represent signal connections.**

within a particular energy market. The economic objectives might be achieved via real-time pricing, critical-peak pricing, time-of-use rates, or incentive-based demand. The environmental objectives might include an operation of the grid with lower emissions to meet environmental targets set by regulatory schemes. Similarly, the technical objectives might include optimizing the network operation by minimizing power losses, regulating voltage and frequency variations, and improving power quality [13], [18], [51], [75], [76], [77].

The dynamic analysis of a VPP and its DERs usually employs models that explicitly incorporate power electronic interfaces [123]. The interconnection and operation of the resulting IBRs are standardized by, e.g., IEEE P2800 [124] or the Commission Regulation (EU) 2016/631 [125]. In the literature, they are usually modeled as voltage or current sources. The IBRs usually have one current control loop and one voltage control loop, constituting an additional level in the hierarchical control structure. Different works [93], [126], [127], [128] analyze the effect of the control system on the performance of the IBR under a sudden event. Hence, in this paper, we couple the objectives of the internal control loops of the converter with the traditional primary control (PC). In the following sections, we adopt the hierarchical structure of Figure 7 to review some of the control schemes commonly found in the literature at the primary and secondary level, as well as their applications in clusters of MGs and VPPs. In the case of control for MGs, we focus exclusively on the grid-tied or grid-connected operation since it is similar to the operation of a VPP. Since in this paper our focus is on the system's medium and fast time scales, we do not review results on tertiary control, economic dispatch, and market/pricing-based control.

1) PRIMARY CONTROL

The main role of Primary control (PC) is to guarantee voltage and frequency stability, as well as plug-and-play capabilities via control at fast time scales. To control independent DERs equipped with power electronic units, these energy resources are usually modeled as AC voltage sources with low-output impedance (in grid-forming operation), or as AC current sources with high parallel impedance (in grid-following or grid-feeding operation) [129], [130]. A detailed review of the power electronics hardware and the different topologies used to connect DERs can be found in [131], [132], and [133].

In Figure 8, we show a common control scheme for a grid-side converter unit with an inductor-capacitor-inductor (LCL) filter, which can also be substituted by purely inductive (L) or inductor-capacitor (LC) filters. In this scheme, the controller receives feedback from the network via a Phase-Locked Loop (PLL) (or another identification scheme [134]) that takes measurements from the PCC. Using these measurements, a synchronous reference frame control is applied to the system [97], [135]. Other approaches have also considered a stationary reference control or a natural frame control [136], [137]. The reference generator block has two objectives: 1) to act as the DC-link voltage control, and 2) to control the reactive power. The inputs P^{ref} and Q^{ref}, which set the active and reactive power, respectively, are usually generated by another control loop of the PC from information delivered by the Secondary control (SC) [127], [138]. The Power Source may correspond to another RES, a DC/DC converter unit, or even an AC grid with an HVDC coupling [139]. These elements are usually connected to another power electronics unit referred to as a machine-side converter. Such types of converters are generally controlled via Maximum Power Point Tracking (MPPT) schemes designed to optimize the power extracted during the operation of the system via model-free peak seeking schemes [140], [141]. Since grid-side and machine-side converters are the two main *controllable* elements of IBRs, we summarize the main objectives of both elements in Table 1. However, we note that other classifications also exist in the literature [142].

a: CONTROL OF MACHINE-SIDE CONVERTERS AND HETEROGENOUS RES IN VPPs

Different renewable power generation technologies can also be combined in what is called a *heterogenous RES*. For example, in [143], [144], [145], [146], [147], and [148] the authors proposed a novel MPPT controller for systems that incorporate wind and solar generation, as well as ESS. Specifically, in [143] the authors considered a control architecture based on an EMS for the power balance, and an Interline Unified power quality conditioner (IUPQC) to compensate disturbances. In [144], the authors introduced a coordination strategy for a WT equipped with a Model-Predictive Control (MPC), a PVG with an MPPT-based controller, and a Battery Storage Unity (BSU) with bi-directional control. Similarly, the work [145] presents an EMS that allows the smooth charge and discharge of a BSU and a Supercapacitor Bank (SCB). In [146], the authors considered a double integral sliding-mode based controller [149, Ch.14.1] for a WT and a PVG, achieving MPPT for both generators, DC-link voltage regulation, and smooth power transfer to the network. The sliding-mode controller is able to reject disturbances, but it might suffer from chattering, which can be detrimental for the mechanical components of the system. In [147], every feedback loop from the machine-side converter and the grid-side converter has a sliding-mode controller.

TABLE 1. **Common control objectives for converters in IBRs.**

Converter	Objective
Machine-side	• Harvest power • Ensure protection of RES
Grid-side	• Synchronize operation with the grid • Manage DC-link voltage • Regulate active power injection • Regulate reactive power injection • Guarantee high quality of the injected power

b: CONTROL OF GRID-SIDE CONVERTERS IN VPPs

To meet the objectives of the grid-side converter of the IBR, described in Table 1, the current control (i.e., the inner-loop in Figure 8) and the voltage control (i.e., the outer-loop in Figure 8) play critical roles. The current control is responsible for the power quality at the PCC, and also for maintaining the current within the admissible values at all times. On the other hand, the voltage control is designed for balancing the power flow. The design of these two controllers can be done independently or in tandem. However, their structure depends on the operating frame. As shown in Figure 8, under a $dq-$frame [97] it is common to implement a Proportional-Integral (PI) controller with transfer function given by $C(s) = K_p + \frac{K_i}{s}$, where $K_p, K_i \in \mathbb{R}_{>0}$ are tunable gains. In some cases, these controllers can be improved using cross-coupling terms and voltage feed-forward, as in [137].

On the other hand, under the stationary reference frame [150], the three-phase currents are transformed to alpha-beta currents, and a typical controller is given by a Proportional-Resonant (PR), which has transfer function of the form $C(s) = K_p + \frac{K_i s}{s^2+\omega^2}$, where ω is the resonance frequency of the controller [151]. Other works, have extended the PR controllers using repetitive control schemes [152], which are used to reject some of the harmonics of the resonance frequency.

Lastly, under the natural frame, where each individual phase current is controlled separately, the standard control techniques are Multiple-Input Multiple-Output (MIMO) PI control or a PR control. In addition to the previous schemes, hysteresis control, and dead-beat control are also common nonlinear control schemes that emerge in all three operating frames in the outer and inner loops. Hysteresis control usually makes use of logic modes and switching mechanisms, leading to a hybrid control system [42]. For a comprehensive study of these schemes, we refer the reader to [137].

c: STATIC DROOP CONTROL IN VPPs

DERs participating in the power exchange of the grid can support frequency stabilization. To achieve this task, the devices can be equipped with a frequency-droop (f/P) controller and a voltage-reactive power (V/Q) controller [153]. The standard static droop control for frequency and voltage stabilization has the form:

$$\begin{aligned} \omega_i &= -k_p(P_i^{\text{ref}} - P_i) + \omega_i^{\text{ref}}, \\ V_i &= -k_q(Q_i^{\text{ref}} - Q_i) + V_i^{\text{ref}}, \end{aligned} \qquad (2)$$

where k_p, k_q are tunable gains, ω_i, V_i are the measured frequency and the measured voltage amplitude of the i-th DER, respectively, while ω_i^{ref}, V_i^{ref} are the nominal frequency and nominal voltage amplitude of the network, respectively [154]. This static controller can also assist in the reduction of the *frequency nadir*, but not necessarily in the reduction of the ROCOF [136]. A well-known limitation of static droop control is that it might lead to emerging circulating currents among the DERs in smaller networks where the assumption of lossless lines does not hold [116]. This problem can be addressed by incorporating virtual impedance [155] in the traditional f/P-droop control. In [156], the authors improved the performance of the droop controller by adding a virtual damping that emulates the response of (1). In [157], the standard V/Q-droop is replaced by a $\dot{V}/Q$-droop scheme that incorporates integral control. Furthermore, [158] considers the incorporation of virtual impedance to improve performance. Other approaches, such as [159] consider consensus-based algorithms to dynamically update the value of k_q, taking into account the reactive power sharing in the network, see [160] for a comprehensive review on reactive power sharing. In [161], the authors incorporated a load change detection mechanism to correct deviations that emerge when traditional V/Q-droop control is used.

d: DYNAMIC DROOP CONTROL

The dynamic version of (2), called dynamic droop control [162], [163], usually takes the form

$$\begin{aligned} \frac{d\omega_i}{dt} &= -k_p(P_i^{\text{ref}} - P_i) + k_\omega(\omega_i^{\text{ref}} - \omega_i), \\ \frac{dV_i}{dt} &= -k_q(Q_i^{\text{ref}} - Q_i) + k_V(V_i^{\text{ref}} - V_i). \end{aligned} \qquad (3)$$

where k_ω, k_V are also tunable gains. The dynamic f/Q-droop control seeks to recover the structure of (1) by emulating inertia using dynamic damping. Variations of this approach have been studied in [164] under the so-called VISMA framework, in [165] using Virtual SMs, in [166] using Virtual Synchronous Generators, and in [167] via Synchronous Voltage Source Converters (VSCs). Dynamic droop control can improve transient and steady-state behavior compared to traditional static approaches. However, it might suffer from robustness issues under noisy measurements. To address some of the limitations of the standard static and dynamic droop controllers, in [168] the authors introduced the concept of iDroop control, which borrows ideas from traditional lead/lag feedback compensation. To further compensate for large disturbances, an angle-frequency droop controller based on the backstepping technique [149, Ch.14.3] was presented in [169]. Other recent approaches based on data-driven techniques and reinforcement learning have been investigated to tune the parameters of the controllers [170]. We will further discuss these techniques in Section IV-B.

e: OTHER PRIMARY CONTROL TECHNIQUES IN VPPs

Other control architectures typically used in VPPs take advantage of the VSC model, and do not necessarily have a droop-like structure for stabilization, or a P- or PI-type structure for the outer- and inner-loop of the inverter. Examples include robust state-feedback controllers designed via $\mathcal{H}_2$ or $\mathcal{H}_\infty$ tools [171], [172]. In [173], [174], [175], [176], and [177], sliding mode control was used to handle parameter uncertainty in the VSC. However, the advantages of this approach are hindered by the unavoidable chattering phenomena that emerges along the sliding surface in practical applications. Model Predictive Control MPC and other model-based control approaches for VPPs and MGs have also been studied in [178], [179], [180], [181], [182], [183], and [184]. However, the advantages given by the explicit satisfaction of constraints and the inherent optimality in the formulation of MPC techniques usually comes at the expense of high-computational requirements and having accurate plant models for the purpose of prediction. To dispense with some of these assumptions, Neural Networks (NNs) have also been incorporated in different MPC schemes in [185], [186], [187], [188], [189], and [190]. Similar approaches based on fuzzy control to approximate models and/or parameters were recently studied in [191], [192], [193], [194], [195], and [196].

The separation between PC and the internal control of the DER devices relies on a time-scale separation principle that allows to decouple the different control problems and schemes of the system, simplifying the analysis and design. This simplification can usually be formalized using singular perturbation tools [197]. However, it has been observed that feedback control schemes based on this explicit time-scale separation can lead to closed-loop systems with sub-optimal transient performance [136]. This observation highlights opportunities for the design and implementation of unifying control strategies that take into account the explicit control of the IBR, the PC, and even further up in the hierarchy [198].

2) SECONDARY CONTROL

The main goal of SC is to remove frequency and voltage deviations from the reference values of the VPP, which may result from the implementation of PC techniques [154], [199], [200]. In practice, secondary frequency regulation is also known with the name of Automatic Generation Control (AGC), which is often market-based; for more on AGC in the context of general interconnected power systems see [52]. Other functionalities of SC include power quality assurance, loss reduction, and reactive power sharing [201]. In this section, we leverage the similarities between the control objectives for MGs in grid-connected mode, and the control objectives of VPPs. Hence, we study SC techniques that are transversal to both and MGs (in grid-connected mode only), which, in general, tackle the problems of distributed IBRs.

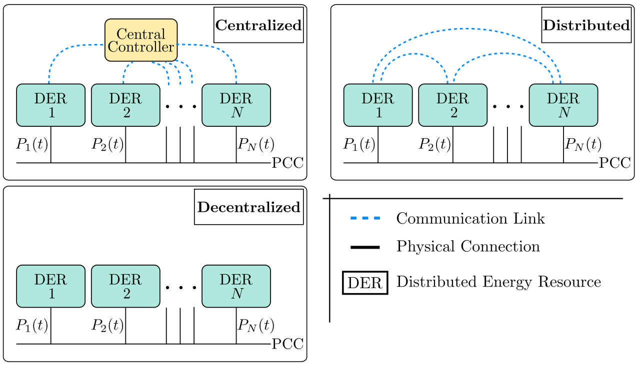


FIGURE 9. **Secondary control topologies classified according to their communication infrastructure.**

a: CENTRALIZED AND CLASSICAL CONTROL SCHEMES IN VPPs

Ideally, the main role of SC is to achieve zero frequency and voltage steady-state errors, while simultaneously guaranteeing stability and power delivery from the VPP to the grid. Letting $\mathcal{N} := \{1, 2, \ldots, N\}$ denote the set of labels for the DERs in the VPP, the main role of SC is to guarantee the satisfaction of the following limits:

$$\lim_{t \to t_f} \omega_i(t) = \omega^{\text{ref}}, \quad \lim_{t \to t_f} V_i(t) = V^{\text{ref}} \tag{4a}$$

$$\lim_{t \to t_f} \sum_{i \in \mathcal{N}} P_i(t) = P^{\text{ref}}, \quad \lim_{t \to t_f} \sum_{i \in \mathcal{N}} Q_i(t) = Q^{\text{ref}}, \tag{4b}$$

for all $i \in \mathcal{N}$, where ω_i and V_i represent frequency and voltage measurements, P_i and Q_i denote the active and reactive power currently generated by the i-th DER, $t_f \in \mathbb{R}_{>0}$ is a future (possibly unbounded) time, ω^{ref} and V^{ref} are frequency and voltage references, and P^{ref} and Q^{ref} are power references usually specified by the system operator of the grid to which the VPP is connected.

Traditional SC strategies used for the control and coordination of MAPS and multi-MG systems, often rely on *centralized topologies* that require the measurements of all the DERs in the VPP to fulfill the control goals in (4), see [114], [202], [203]. For instance, [204] and [205] use cascades of fractional-order Proportional-Integral-Derivative (PID) controllers with parameters tuned through optimization-based techniques to obtain centralized controllers capable of reducing frequency deviations in multi-microgrid linear systems. Other existing approaches employ a centralized architecture and projected-gradient methods for energy distribution systems [206], [207], or consider Linear-Quadratic Regulator (LQR) controllers and energy storage devices [208] to satisfy the SC requirements. However, these approaches can conflict with the inherently distributed generation paradigm of VPPs. Moreover, since a central controller constitutes a common point of failure in the operation of the DERs, centralized implementations usually lack suitable robustness properties under the influence of disturbances affecting the communication interface or the controller computational node [209].

b: MULTI-AGENT CONTROL SCHEMES IN VPPs

To overcome the limitations and fragility of centralized techniques, several alternatives that leverage improvements in communication and measurement infrastructure have been proposed in the last two decades for *distributed* SC, e.g., [111], [201], [202], [210], [211], and [212]. Among the different distributed control approaches, most of the techniques are developed in the context of Multi-Agent Systems by leveraging tools from graph theory [213]. Using this formulation, each of the DERs in the VPP is modeled as an agent with individual physical dynamics and computational capabilities. Each agent can communicate with other neighboring agents to *cooperatively* fulfill the objectives in (4). Under this formulation, the i-th DER with state variable $\mathbf{x}_i \in \mathbb{R}^{n_i}$, capturing its relevant physical information (frequency dynamics, power dynamics, etc), and subject to a control input $\mathbf{u}_i \in \mathbb{R}^{m_i}$, can be modeled by the following continuous-time dynamical system

$$\begin{aligned}\dot{\mathbf{x}}_i &= A_i\mathbf{x}_i + B_i\mathbf{u}_i + D_i f_i\,(t, \mathbf{x}_i, \mathbf{u}_i)\\ \mathbf{y}_i &= C_i\mathbf{x}_i,\end{aligned}$$

where $A_i \in \mathbb{R}^{n_i\times n_i}$ and $B_i \in \mathbb{R}^{n_i\times m_i}$ describe the linear part of the dynamics, $D_i \in \{0, 1\}$ is used to indicate whether or not the nonlinear part of the dynamics $f_i : \mathbb{R}_{\geq 0}\times\mathbb{R}^{n_i}\times\mathbb{R}^{m_i} \to \mathbb{R}^{n_i}$ is to be considered for the control design, and $C_i \in \mathbb{R}^{l\times n_i}$ is a suitable matrix that "extracts" the output variables $\mathbf{y}_i \in \mathbb{R}^l$ to be synchronized to the reference values by the distributed SCs strategies.

In the context of VPPs, of particular interest are consensus-based distributed SC techniques, which implement control laws of the form

$$\mathbf{u}_i = -k_i(s)\sum_{j\in\mathcal{N}}\alpha_{ij}\left(\mathbf{y}_j(t) - \mathbf{y}_i(t)\right),$$

where $k_i(s)$ is a dynamic controller, and the coefficients $\alpha_{ij} \in \mathbb{R}_{\geq 0}$ for all $i, j \in \mathcal{N}$ are the elements of the adjacency matrix of a graph $\mathcal{G}$ representing the communication infrastructure. In this model, $\alpha_{ij} \neq 0$ whenever there is a communication link that allows the output variables $\mathbf{y}_i$ and $\mathbf{y}_j$ to be shared between the i-th and j-th DERs. These techniques have been shown to attain suitable robustness properties under communication delays, and have also gained widespread adoption due to their relatively simple implementation, see [214], [215], [216], [217], [218], [219], and [220].

Despite the stability and performance benefits that a distributed approach for SC can bring to the table, there are still some fundamental downsides in their implementation for complex or large-scale VPPs. Indeed, as the number of DERs in VPP increases, data transmission in the communication infrastructure used for control will likely grow, and the communication bandwidth will eventually be limited [221], [222]. Hence, multiple alternatives have emerged to reduce the message exchange frequency and to efficiently use the communication infrastructure while simultaneously maintaining system stability and performance. Among these alternatives, *decentralized* SC proposes to dispense with the usage of the communication infrastructure by making use of additional wash-out filters to complement PC [223], [224]. Other approaches are based on estimation methods implemented by a DER to predict the behavior of other DERs in the VPP [225], [226]. Nevertheless, the implementation of these methods will come at the expense of an increment in the local computational requirement of each DER. Moreover, additional elements and computational blocks can introduce disturbances in the form of estimation errors that can reduce the performance of the control strategies. Figure 9 shows a set of schemes comparing how centralized, distributed, and decentralized SC make use of the underlying communication infrastructure of the VPP. As depicted in the figure, the existence of an underlying communication infrastructure is fundamental for the practical realization of SC in both the centralized and distributed architectures. At the lowest level, this infrastructure is responsible for the transmission of references to local controllers at the DER level, as well as for the exchange of information between the different devices, such that regulation of frequency and voltage can be achieved at the VPP level. Aiming to study and standardize the communication and information requirements of VPPs, recent works have employed the IEC 68150 standard that defines communication protocols for intelligent electronic devices at electrical substations. For more information on the communication infrastructure needed for the implementation of VPPs, we refer the reader to references [115], [227], [228].

c: EVENT-TRIGGERED, SAMPLED-DATA, AND HYBRID CONTROL IN VPPs

As an alternative to traditional controllers that continuously update the values of the control signals, sampled-data and event-triggered control schemes can be used to mitigate the unnecessary usage of communication and computational resources. In sampled-data control, the plant is interconnected with the digital controller via a sampler/ zeroth-order hold mechanism [229]. On the other hand, in event-triggered control, the control action is updated only when a particular triggering condition is satisfied by the system [230], [231], [232]. For example, in [233], the authors proposed a method to redispatch IBRs according to a feedforward command signal which is constructed through active monitoring of significant power imbalances in the system.

A key challenge in the implementation of event-triggered control is to rule out the emergence of an infinite number of control updates in a finite period of time, a phenomenon known as Zeno behavior [23], [234], and which prevents the practical implementation of algorithms. To avoid this issue, the controllers should be designed to guarantee a minimum inter-event time between updates of the controller. This task is not trivial, and it has been shown that Zeno behavior can emerge even in the presence of arbitrary small disturbances if the event-triggering condition is not properly designed [234]. Works that addressed these issues in SC for MGs under disturbances were recently studied in [235]. Other approaches to avoid Zeno behavior involve the incorporation of time regularizations via periodic timers that enforce a short minimum inter-event time between execution times of the controller. All these algorithms have a common feature:

they combine continuous-time dynamics and discrete-time dynamics, leading to hybrid dynamical systems (HDS) [236], [237], [238], [239], which can be modeled in a unifying way via the following equations:

$$\mathbf{x} \in C, \quad \dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}), \tag{5a}$$

$$\mathbf{x} \in D, \quad \mathbf{x}^+ = g(\mathbf{x}, \mathbf{u}). \tag{5b}$$

In (5), the set C, called the flow set, describes the points in the space where the system is allowed to evolve according to the differential equation (5a). Similarly, the set D, called the jump set, describes the points in the space where the system can jump according to the recursion (5b) [23], [42]. This type of model has been used in the context of power systems and MG control in [235], [240], [241], [242], and [243]. VPPs, with their physical devices connected and controlled via software-based algorithms, can be seen as natural HDS. One of the main challenges of working with HDS of the form (5) is to guarantee that the mathematical model appropriately captures the behavior of the system under arbitrarily small disturbances, a property that is intrinsic to continuous-time ODEs [149, Ch. 3] and discrete-time recursions [244] with a continuous right-hand side, but which does not necessarily extend to systems with hybrid dynamics [23, Ch. 7] unless suitable conditions are imposed on the sets C and D. Stability and robustness analyses of hybrid controllers and hybrid closed-loop systems can be carried out by working with *hybrid time domains* to parameterize the evolution in time of the solutions of the system, see Figure 10. This feature makes the framework of [23] very appealing for the study of control and optimization techniques in VPPs, for which stability and robustness guarantees are desirable properties that are not easy to certify. Moreover, it has been shown that advanced hybrid controllers, such as reset control [245], [246], synergistic hybrid control [247], and switching control [248], can overcome fundamental transient and steady state limitations of traditional smooth linear controllers. The development and implementation of hybrid and nonsmooth controllers in VPPs offer exciting research opportunities to achieve performance levels that are unattainable via traditional techniques. For example, in [249] the authors showed that power grids with different rotational (low) inertia regimes could be modeled as hybrid systems switching between a finite number of discrete modes. Controllers for such systems can be systematically designed using Lyapunov-based methods [248].

d: STOCHASTIC HYBRID SYSTEMS FRAMEWORK IN VPPs

The dynamic operation and control of VPPs are heavily influenced by the behavior of the loads and the RESs, which, in general, are time-varying and non-deterministic [250]. While the stochastic load behavior in power systems is usually approximated via Gaussian processes [251], [252], it has been argued that this approach might not be ideal in VPPs, where the number of individual loads is small compared to traditional grids, thus reducing the applicability of the central limit theorem to justify Gaussian system-level approximations. Indeed, in [250] the authors argue that an appropriate characterization of the load behavior in microgrids should be based on large-signal transient events occurring at random intervals. This behavior naturally leads to dynamical systems with stochastic "jumps". General systems exhibiting these features are called stochastic hybrid dynamical systems (SHDS) [253], and similarly to (5) they can be written as

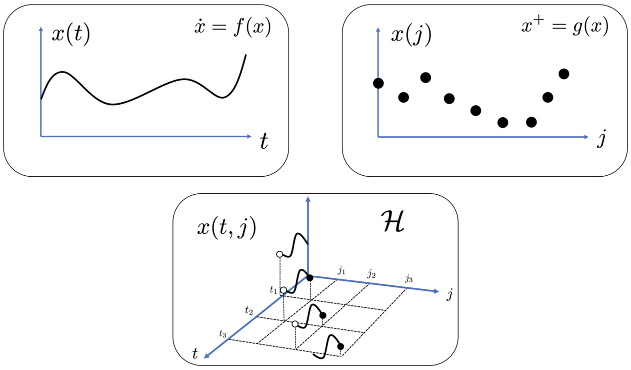


FIGURE 10. **Mathematical time domains of solutions of continuous-time, discrete-time, and hybrid dynamical systems. For VPPs with explicit modeling of continuous-time dynamics (e.g., physics) and discrete-time dynamics (e.g., digital elements), hybrid systems offer a suitable mathematical framework for the purpose of analysis and design of control and optimization algorithms.**

$$\mathbf{x} \in C, \quad d\mathbf{x} = f(\mathbf{x}) + B(\mathbf{x})d\mathbf{w} \tag{6a}$$

$$\mathbf{x} \in D, \quad \mathbf{x}^+ = g(\mathbf{x}, \nu^+), \tag{6b}$$

where (6a) describes a stochastic differential equation driven by Brownian motion, and (6b) corresponds to a difference equation with ν acting as a place holder for a sequence of i.i.d. random inputs defined in the same probability space as w. As shown in [254], models of the form (6) are fairly general and they cover a variety of stochastic hybrid systems that commonly emerge in engineering systems. Most of the existing results in VPPs using stochastic models have focused on economic dispatch problems [255], [256]. However, as the set of analytical tools for the study of SHDS of the form (6) is further developed, we expect to see more realistic mathematical models of VPPs that incorporate the natural stochastic and non-smooth behaviors in the fast dynamics of the closed-loop system.

B. CONTROL FOR ANCILLARY SERVICES MARKETS

In the previous section, we discussed the different modeling and control frameworks that emerge in the hierarchical control structure described in Figure 7, with an emphasis on Primary Control and Secondary Control. In this section, we briefly review other non-hierarchical control structures for VPPs and grid-connected MGs, which typically emerge in the context of ancillary services. Such services are fundamental to maintain the stability and integrity of the power grid. They might include frequency control at primary, secondary, or tertiary level, voltage support, compensation of active power losses, black start, system coordination, and balance group management, among others [257].

The fast transient properties of the DERs generate new opportunities to provide different services like voltage or frequency support in either nominal or emergency operation of the grid [258], [259]. However, such services should be provided while avoiding injecting oscillations in the system due to low inertia [60]. For example, in [26] the authors propose a novel multivariable control method to provide fast frequency and voltage control. The approach employs an optimal adaptive control strategy that is able to manage internal constraints in the devices, additionally handling temporal variability related to weather and external disturbances. In [25], DERs are coordinated to achieve two of the main goals of the System Operator (SO): Frequency Containment Reserve (FCR) and Fast Frequency Response (FFR). In this work, the controllers of the devices are synergistically designed to achieve a prescribed dynamic performance via model matching at high and low frequencies, overcoming some of the fundamental limitations of traditional generation mechanisms. An LQR-based FFR controller with tunable virtual inertia was designed in [260]. In [261], a control strategy for Doubly Fed Induction Generator (DFIG)-based WTs is implemented. Even though this control is applied to the rotor current controller of the WT, it is able to provide Low-Voltage Ride-Through capabilities (LVRT), which are important for the resilience of the grid. In [262], the authors introduced a multi-stage voltage support optimization method to stabilize voltage, current, and power. In [263], a new algorithm is introduced to provide the maximum positive sequence voltage boost during a fault of the grid, while simultaneously minimizing voltage unbalance. The problem of coordinating a group of MGs to provide ancillary services is thoroughly review in [264], highlighting the different existing architectures, as well as some of the most common communication protocols. The concept of Active Distribution Grid (ADG) is studied in [265] in the context of ancillary services for frequency control. In the context of voltage support, ADGs are also studied in [266] and [267].

IV. NEW PERSPECTIVES FOR VPPs

In this section, we discuss some of the research areas and open problems that emerge in the control of VPPs.

A. GRID FORMATION IN VPPs

The increasing number of RESs connected to the grid will eventually lead to power systems with frequency and voltage signals that are not mainly driven by SMs, but rather by DERs [138], [268]. In this grid-forming scenario, DERs should also support the stability properties of the grid during both nominal and emergency operations. In grid-forming mode, DERs have been studied as Virtual Synchronous Generator (VSG) for which a variety of control techniques have been proposed in the see [269].

For VPPs, the grid-formation perspective has been inspired by works on MG control operating in islanded mode. A comprehensive review of PC techniques for islanded MGs is presented in [270]. In [271], it was shown that wind energy plants equipped with doubly fed induction generators can achieve excellent grid forming and grid supporting capabilities using stator flux control with droops for frequency and magnitude. The idea of adaptive dynamic participation factors was presented in [272] to design grid-forming controller for dynamic virtual power plants. The approach can be used to achieve voltage or frequency control, and it can update the parameters of the controller in real-time to cope with potentially time-varying capacity limits in the devices. In [273], the authors introduced an FFR controller based on MPC for the coordination of multiple DERs. Compared to previous techniques, the approach is shown to reduce the frequency nadir and ROCOF. Recent works have also studied the application of reinforcement learning techniques to adjust the power set points of each DER in a MG, aiming to maintain the frequency in acceptable operational ranges [274]. The control policy was trained using data generated from simulations that incorporate disturbances at arbitrary buses in the system, thus providing appealing robustness guarantees. Finally, a grid-forming framework for VPPs with online tunable inertia was presented in [275]. The approach incorporates a real-time optimization method to update the parameters of the inverters in an online fashion.

B. ADAPTIVE AND DATA-ENABLED METHODS IN VPPs

The growing penetration of DERs into the power grid calls for novel control methodologies able to address the fragility and lack of robustness that can emerge in power systems with low inertia. As a potential solution to some of these challenges, the framework of VPPs could further benefit from recent advances in control, optimization, and learning algorithms [276], [277]. Model-free and adaptive control techniques can be particularly useful in systems with high levels of uncertainty and might require real-time re-tuning of parameters based on the current operating conditions of the generators and the grid, see for example [49], [278]. For these types of adaptive dynamics, which usually rely on ‘‘exploration vs exploitation’’ paradigms, safety mechanisms are critical to guarantee that the exploration always takes place in admissible operational regions [279], [280]. Such safety mechanisms can be designed via projections [278], barrier functions [281], safety filters [282], or switching dynamics [283], to name just a few examples. For decentralized implementations, it will be fundamental to design robust coordination techniques able to appropriately handle these constraints, as well as delays, asynchronous communications, infrequent measurements, and distributed data used for the design of data-enabled controllers. Recent works have shed light on how to appropriately allocate data in multi-agent data-driven control systems via cooperative persistence of excitation conditions [33], [284], [285]. Recent advances in adaptive strategies for VPPs based on robust control were presented in [26]. A controller for VPPs based on the solution of real-time optimization problems was also studied in [219]. We note that many traditional learning-based and adaptive techniques have been shown to exhibit prohibitively slow rates of convergence that difficult their implementation in practical applications. Recent works on nonsmooth feedback control have been able to accelerate these rates of convergence, and in some cases achieve finite-time [286] or fixed-time [287] (practical) convergence, see [288]. The development, analysis, and implementation of adaptive, fast, and safe control algorithms for VPPs remain an active area of research [289], [290].

C. AI & SOFT COMPUTING-BASED CONTROL OF VPPs

The development of computationally efficient data-driven prediction and decision-making methods for VPPs has seen increasing interest during the last years. Such methods, commonly referred to in the literature as soft-computing or "artificial intelligence" (AI)-based methods [291], are being increasingly incorporated into feedback control loops in energy systems [292], [293]. For example, machine learning (ML), the leading exponent of data-driven techniques in practical applications, has been incorporated into VPPs for the purpose of forecasting [28] and optimization [29]. Similarly, deep-learning techniques were studied in [294] and [295] for the solution of optimal market participation problems in VPPs. A comprehensive survey paper on machine-learning applications for VPP (mostly focused on tertiary control) is presented in [29]. As mentioned in [29, pp. 15], the high demand for labeled data to train ML models represents an important limitation for ML techniques in VPPs with a high number of components. These scalability issues could be addressed via transfer learning methods, or by clustering similar components and using a common ML model for the purpose of prediction. A comprehensive review of ML models for forecasting in VPPs is presented in [296]. Deep-learning methods have also been used to improve the performance of VPPs in frequency regulation markets [295]. In that work, it was shown that, in certain scenarios, deep learning can reduce the uncertainty related to the components of the VPP, including those inherent to wind turbines, distributed generators, energy storage devices, and electric vehicles, leading to a more effective participation in ancillary service markets. Other data-driven techniques, such as reinforcement learning (RL), have also received increasing interest during the last years [297]. In particular, as mentioned in [297], frequency regulation and voltage control techniques based on RL could serve as viable alternatives to model-based methods in settings where the models of the system are unavailable or too complex. In the context of VPPs, RL methods have been mostly focused on economic dispatch [298], demand response [299], and pricing problems [300]. Novel RL techniques for frequency regulation in VPPs have been recently studied in [301] and [302]. Adversarial training of RL schemes were recently studied in [303] to improve the robustness properties of controllers in power grids. Overall, the systematic incorporation of AI-based techniques in the control and operation of VPPs, with stability, robustness, and transient guarantees, is still in its infancy.

D. VPPs AS COORDINATED MULTI-AGENT HYBRID DYNAMICAL SYSTEMS

While the idea behind a VPPs is to create "software-based" clusters of DERs to achieve higher flexibility and efficiency in the grid, the physics-based dynamics of the generators controlled by this software will necessarily lead to closed-loop systems that combine continuous-time and discrete-time dynamics. Indeed, temporal dynamics of DERs are usually modeled as ordinary (or partial) differential equations derived from first principles. On the other hand, control, communication and coordination algorithms implemented over digital infrastructure will necessarily be characterized by discrete-time recursive algorithms. The interaction between physical and digital components naturally leads to cyber-physical systems with hybrid dynamics [304], [305]. Moreover, since VPPs are also decentralized architectures, their overall dynamics can be modeled as *multi-agent hybrid dynamical systems* (MA-HDS) [306]. Such systems can exhibit intricate behaviors that do not emerge in standard purely continuous-time and purely discrete-time systems, or in single-agent hybrid systems of the form (5). In fact, when multiple individual hybrid systems are interconnected, the emerging behavior of the new networked (hybrid) system can be drastically different from the behavior of the individual components due to, among others, the asynchrony of the jumps, the presence of delays in the communication network, and the emergence of new feedback loops with dynamic behaviors highly dependent on the communication topology of the network, see Figure 11. In some situations, this can lead to instability of decentralized implementations of controllers designed under a synchrony assumption. For example, in [307] the authors showed that standard multi-variable discrete-time controllers can be destabilized under arbitrarily small disturbances once they are implemented over decentralized cyber-physical infrastructure. This instability issues usually do not emerge in continuous-time models of VPPs, see [308]. A solution to this problem was proposed in [307] using *pre-jump sampling control* (PJSC), which makes use of decentralized local sampling mechanisms and synchronization techniques implemented by each of the agents to guarantee robust stability properties of overall network [309]. PJSC is inspired by zero-cross detection mechanisms widely used for the simulation of systems with boundary decisions that are sets of measure zero. Extensions of PJSC to game theoretic problems have also been considered in [310] and [311]. Multi-agent hybrid controllers have also been studied in [312] to implement event-triggered strategies in energy internet systems. In [313], the authors showed that coordinated distributed control can improve the short-term transient

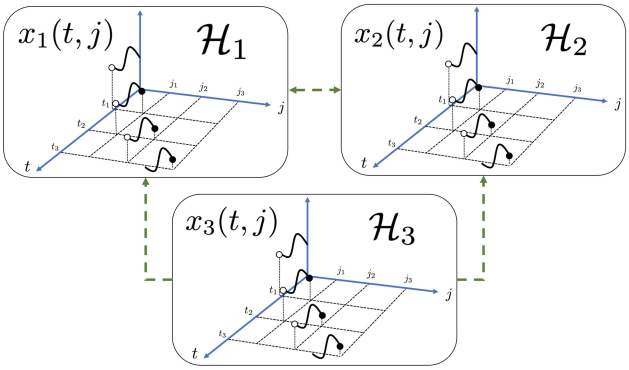


FIGURE 11. VPPs can be seen as multi-agent interconnected hybrid systems exhibiting complex dynamic behaviors that significantly differ from those emerging from their individual components.

performance of VPPs. The approach incorporated stochastic disturbances acting on the loads, wind speed, and solar irradiance. For a survey on multi-agent control of modern power systems we refer the reader to [314].

V. CONCLUSION

VPPs are modern energy management systems that aim to tackle the multidisciplinary nature of some of the challenges that arise from the integration of RESs into the power grid. In this survey paper, we reviewed the main challenges that emerge in power systems with high penetration of renewables, and we surveyed the different emerging models, control techniques, and hierarchical architectures that are most commonly used for the real-time operation of VPPs. In particular, we focused on the dynamic nature of the different components that comprise a VPP in the sub-hourly time scales. The software-based component of a VPP, combined with the physics- based components of the power grid, make VPPs prominent examples of cyber-physical systems, where both continuous-time and discrete-time dynamics play prominent roles in the stability and transient properties of the system. We discussed this interpretation, as well as several open research problems and potential research directions that could contribute to the development and deployment of autonomous VPPs.

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ACRONYMS

ADG	Active Distribution Grid.
AGC	Automatic Generation Control.
BSU	Battery Storage Unity.
DER	Distributed Energy Resource.
DSO	Distribution System Operator.
EMS	Energy Management System.
ESS	Energy Storage System.
FCR	Frequency Containment Reserve.
FFR	Fast Frequency Response.
IBR	Inverter-Based Resource.
ISO	Independent System Operator.
LQR	Linear-Quadratic Regulator.
MAPS	Multi-Area Power System.
MG	Microgrid.
MIMO	Multiple-Input Multiple-Output.
MPC	Model-Predictive Control.
MPPT	Maximum Power Point Tracking.
NN	Neural Network.
PC	Primary control.
PCC	Point of Common Coupling.
PI	Proportional-Integral.
PID	Proportional-Integral-Derivative.
PLL	Phase-Locked Loop.
PR	Proportional-Resonant.
PVG	Photo-voltaic Generator.
RES	Renewable Energy Source.
ROCOF	Rate-Of-Change-Of-Frequency.
SC	Secondary control.
SCB	Supercapacitor Bank.
SM	Synchronous Machine.
SO	System Operator.
VPP	Virtual Power Plant.
VSC	Voltage Source Converter.
VSG	Virtual Synchronous Generator.
WT	Wind Turbine.

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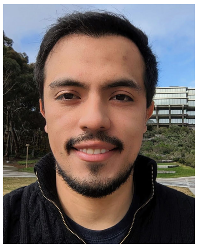

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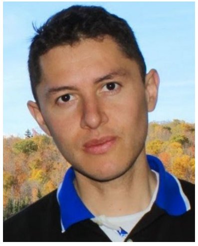

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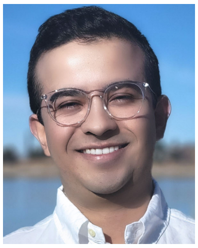

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