IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 24 November 2022, accepted 8 January 2023, date of publication 16 January 2023, date of current version 26 January 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3237576

SURVEY

Review of Wide-Area Controllers for Supporting Power System Stability

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This work was supported by the Chilean Council of Scientific and Technological Research (ANID) under Grant FONDECYT/1201676 and Grant FONDAP/15110019.

ABSTRACT Countries around the world are transitioning from conventional power systems dominated by synchronous generators towards low-carbon resources, characterized by high levels of converter-interfaced generators (CIGs). With this transformation, hundreds or even thousands of fast power electronic devices will be added to the grid as CIG penetration increases, thus making the system dynamic response progressively faster and more complex. This future scenario poses significant challenges in power system stability and control. To sustain power system stability in future power systems and achieve a seamless transition, we need to depart from current control practices based on decentralized and stand-alone local control actions and begin to explore new methods. A promising technology to overcome control complexities and underlying stability issues in future low-inertia power systems are wide area control (WAC). Within this technology, the control is no longer based on a purely localized tasks but rather a set of coordinated actions across wide areas in which interplant communication plays a key role. This paper presents the state of the art of existing research efforts in the field of WAC strategies for maintaining stability in large-scale low-inertia power systems of the future. We present different WAC solutions that have been put forward hitherto, we put these control strategies into context, classify them, and finally relate them to each other. We also raise open questions and challenges that need to be addressed in order to ensure a secure transition towards power systems dominated by CIGs.

INDEX TERMS Power system control, power system stability, time delays, telecommunication issues, wide-area measurement systems (WAMSs), wide-area power systems (WAPSs), wide-area control (WAC), power system control architecture, control techniques.

I. INTRODUCTION

The worldwide transition towards low-carbon electricity systems with high shares of converter-interfaced generators (CIGs) such as wind and solar power plants, is accelerating at a rapid pace. While some countries have already reached solar and/or wind power capacity beyond their own electricity demand [1], [2], [3], others like Ireland are targeting a 100% renewable-based electricity system in the future [4].

The ongoing energy transition is, however, not an easy task. Several technical challenges must still be overcome before these new generation technologies are widely deployed in power systems. One of the main deterrents to their massive deployment are the inherent dynamic behavior of CIGs and its significant differences with conventional generation facilities. Lack of inertial response [3], [5], [6], [7], low short circuit current capability [8], [9], [10], [11], and fast dynamics

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood.

within the electromagnetic timescale [12], [13], are among the key features of CIGs that will impact the stability of electricity systems in the future.

Increased levels of CIGs weaken power systems by decreasing rotational inertia and the short circuit levels in the grid. Operational and stability problems in weak low-inertia systems can manifest themselves in several ways. In steady state, low short circuit levels in busbars result in high values of dV/dP and dV/dQ, which in turn means that small disturbances in power flows can significantly change the network voltages [8], [11]. From a stability viewpoint, weak systems may experience extremely depressed voltages over wide network areas, which may challenge the voltage recovery after short-circuits. Severe voltage dips may also speed up the rotors of the nearby synchronous generators (SGs), which may lead to their loss of synchronism [20]. After major power imbalances, low inertia systems may exhibit steeper rates of change of frequency (RoCoF) and hence larger frequency excursions [5]. This may result in situations in which traditional protection schemes become too slow for preventing large frequency deviations which could lead to load shedding [7]. New stability phenomena such as converter-driven instability and electric resonance instability are also most likely to arise under weak grid conditions [12]. Moreover, unstable interactions between CIG controls with the grid and with the controls of other (nearby) power electronics-based devices are also to be expected in scenarios with high levels of converters [14]. Accordingly, future electricity systems dominated by CIGs will be less secure, faster, more complex, and more difficult to control than conventional systems dominated by synchronous machines.

Presently, the successful operation of electricity systems relies almost exclusively on a huge array of decentralized and uncoordinated control schemes that respond to local output feedbacks [16]. The objective is to use local information as much as possible for reducing communication requirements and thus allowing fast response times. While this simple approach has shown to be able to maintain stability in robust networks, it will not be tenable in weak power systems dominated by CIGs [16]. In these cases, several issues arise such as fast system dynamics in micro- or even nanosecond time-scales, complex control interactions, and unstable behaviors due to weak grid conditions, and will push power systems to their limits thereby forcing the exploration of new control methods that go far beyond those currently used.

The paradigm shift in energy supply towards electricity systems dominated by CIGs will require a gradual departure from the cornerstones that have sustained power systems control thus far. Although several control approaches may be theoretically conceivable to rise to the challenge, some recent works have recognized that high levels of CIGs will probably require a more global, coordinated, wide-area control (WAC) approach [15], [61], [214], [251]. In this case, the control actions undertaken by generators and other controllable network elements during contingencies are no longer a purely localized task but rather a set of coordinated system-wide collaborative efforts.

Over the past few years, the development of novel control strategies for supporting stability of power systems during abnormal conditions have been a very active research area. Nevertheless, most of these works have been focused on traditional decentralized controllers based on local measurements. More innovative strategies including WAC solutions have been less researched and discussed. To fill this gap, this paper presents the state-of-the-art of existing and emerging research efforts in the field of WAC strategies for sustaining stability in future electricity systems. We present different WAC solutions that have been put forward hitherto, even if they have been investigated more in theory than in practice. We put these control solutions into context, classify them according to different criteria, and relate them to each other.

The rest of this paper is organized as follows. Section II provides a theoretical background that summarizes the key concepts used for the categorization of the works to be reviewed. Section III presents a comprehensive review of WAC strategies that have studied for improving the stability of power systems, classifying them according to different categories and specific characteristics. Finally, concluding remarks and discussion regarding the results are given in Section IV.

II. THEORYTICAL BACKGROUND

A. CONTROL ARCHITECTURES

The successful operation of existing power systems relies on a huge array of control loops responsible for regulating key system quantities. The control organization utilizes architectures in which three levels can be distinguished: generation, transmission, and distribution. Depending on *where* the decisions are made as well as on the *number* of measurements that are utilized to make the control decisions, these control strategies can be roughly categorized as decentralized, centralized, distributed, and hierarchical [29], [31]. These factors also define the computational and communicational requirements of each strategy [27], [28].

1) DECENTRALIZED CONTROL

A decentralized control corresponds to the simplest control strategy in terms of communication requirements. Within this approach, decisions are made locally (within a certain area or by a single controllable device), without knowledge from the rest of the system [27], [29]. In traditional decentralized control architectures, individual controllers are spatially distributed, and each one has access to a specific subset of control signals obtained locally [30], [31], [32]. Since the amount of communicated and processed data is low, this approach usually results in fast control responses and low computational requirements.

Current operation of electricity systems relies mainly on decentralized controllers based on local measurements such as voltage regulators [27], power system stabilizers (PSS) [31], and governors of SGs [27]. Decentralized controls are used during both normal operation and contingencies [27],

[28]. Examples of decentralized controllers used to enhance system stability during contingencies are those implemented in flexible ac transmission system (FACTS) devices for damping system oscillations [35], [36], [37] or for supporting voltage stability [38], [39], [40], [41]. Current state-of-the-art controllers used in large-scale CIG power plants for supporting stability during contingencies are also implemented in a decentralized fashion using local measurements [42], [43].

Although less researched, decentralized controllers can also use remote signals [44], [45]. These strategies are typically designed offline in a coordinated manner with other controllable devices to avoid undesired interactions among them. Unlike traditional decentralized controllers, these schemes present some communication delays due to feedback signals coming from remote locations. Still, the amount of data that must be communicated and processed is significantly less than that of traditional centralized control schemes. In this paper, these controllers are referred to as decentralized controllers with remote signals (or remote signal-based decentralized controllers). When remote signals are included as an additional control loop to enhance the performance of a preexisting decentralized control, the resulting control is sometimes referred to as supplementary controller [49], [119], [138], [190], [255]. Typical examples of these controls are those used for damping interarea oscillations and local modes through PSSs in SGs [73], [108], [111], [112]. In these cases, each PSS receives a remote signal (e.g., generator speed or power) and returns a supplementary signal to the excitation system of the corresponding SG, usually modulated with a required phase compensation [46], [47], [48]. Note that early controllers for damping interarea oscillation were based on local signals only. However, many current PSSs use remote signals, thus falling into this category.

2) CENTRALIZED CONTROL

Centralized control strategies consist of a central control unit that manages power system components distributed across the network in a coordinated manner. In this case, the central unit collects information from different parts of the system, processes the data, defines the control actions and transmit them to spatially distributed controllable devices [28], [29], [31], [32]. Centralized control strategies usually require large amounts of data to be communicated and processed, which results in larger computational and communication requirements, compared to decentralized control strategies. Given their comparatively high communication requirements, centralized strategies are prone to suffer from significant communication delays, failures, and cyberattacks, among others [16], [27], [33], [34], [75].

In current power systems, centralized control actions are used during normal operating conditions for system balancing purposes and also for contingencies. The most widely used example is the well-known automatic generation control (AGC), which can be used for both normal operating conditions and contingencies [50], [86]. Although some AGCs have been implemented using a decentralized control approach [51], most of them are based on centralized control structures [52], [53], [54].

3) DISTRIBUTED CONTROLS

Distributed control emerges as an intermediate alternative between centralized and decentralized control. Distributed controllers regulate a portion of the system, or even a single busbar, based on sensor signals from other subsystems or agents. These control strategies involve algorithms where each agent communicates with its neighbors without a high-level centralized entity in between [31], [32]. Compared to centralized control schemes, distributed controls require lower amounts of data to be communicated and thus less computational capacity, as only partial information of the system state is shared between agents. Examples of distributed control strategies can be found for addressing rotor-angle stability [56], [57], frequency stability [58], [59], inter-area oscillations [60], [61], and voltage stability [62]. Although these control strategies have been explored more in theory than in practice, they still provide useful insights and results for this review.

4) HIERARCHICAL CONTROL

Hierarchical control approaches are used for handling complex and large systems such as electric power systems. Hierarchical control strategies consist of single controllers that communicate with other controllers at a higher level in a hierarchical structure, eventually leading to a centralized controller [29], [31]. The controlled system is decomposed into smaller subsystems that are easier to handle. Usually, the control actions are carried out at each subsystem level. Then, a coordinating (central) unit is set at an upper level for adjusting the operating variables between the subsystems to meet control constraints, resulting in a more global control solution [29]. Hierarchical controls usually include a combination of decentralized and centralized controllers in different layers according to the control purposes [63]. Distributed architectures can also be included as part of a hierarchical strategy. In this architecture, the information exchange between the centralized control and the controlled objects is significantly reduced compared to a purely centralized control, thereby improving the reliability of the system [29].

Some authors categorize strategies that use centralized control signals coordinated with local measurements as hierarchical ones [64], [65], [66], [67], [68]. However, such classification contradicts the above definition, as no explicit hierarchical structure with different levels of communicational hierarchy nor explicit system partition into smaller subsystems can be identified. Thus, we will call these works non-explicit hierarchical structure controllers.

B. MEASUREMENT AND COMMUNICATION SYSTEMS

In present day electricity networks, Supervisory control and data acquisition (SCADA) systems are widely used to monitor and control main electrical infrastructures at both the transmission and distribution levels. These systems usually entail one (or more) central host computer linked to a number of remote terminal units (RTUs) and/or programmable logic controllers (PLCs) located at key network busbars [69], [70], [71]. RTUs are primarily stand-alone data acquisition and control units. Even though SCADA's update period can range between 1 and 3 seconds, measurements from the RTUs are not synchronized with each other and include a deadband to limit data transfer. Hence, high transmission delays and low precision are typical characteristics of SCADA [69], [70]. In terms of control, the update period of SCADA limits its application for fast and complex control actions, especially during contingencies [72], since real-time dynamics cannot be observed.

An alternative technology to RTUs are phasor measurement units (PMUs). A PMU is a device used to estimate the phase and magnitude of voltages, currents, and local frequency of the network busbar or line, reconstructing phasor quantities with synchronized time stamps, thus allowing synchronized real-time measurements of multiple remote points on the grid. Compared to traditional RTUs, PMUs are more accurate and faster (making up to 60 measurements per second), and have lower communication delays [73], [74].

The wide deployment of PMUs in power systems has resulted in the development of wide-area measurement systems (WAMS). WAMS can be used for estimating the state of a power system through synchronized system-wide phasor signals in combination with conventional measurements. The information measured by the PMUs - including the synchronized time stamps, is sent to a phasor data concentrator (PDC) through an Ethernet connection or a similar communication network. The PDC receives, parses, and sorts all the received data. Due to the large amount of information exchange, PDCs require high computational capacity and wideband communication, constraining that the number of PMUs associated with each PDC hardware [76].

Despite being considerably faster than SCADA systems, when using WAMS-based control systems for real-time applications, communication delays and/or failures may lead to instabilities or system blackouts. In fact, time-delay caused by transmission of global signals is one of the key factors influencing system stability and damping performance [78], [79], [80]. Usually, time-delays related to communications in WAMS vary from tens to several hundred milliseconds [78], [79], [81]. The exact value depends on the type of communication link, communication network length, network bandwidth, communication load, and transmission protocol, among other factors [79], [81]. Accordingly, time-delays should be properly considered when designing control schemes [80]. Although time-delays have traditionally been treated as constant [82], this may not always reflect the reality and such adoption impacts the communication latency of WAMS-based control systems [82]. In fact, [82], [83], [84] considered time-delays as a stochastic phenomenon, better capturing the effects of real WAMS delays.

C. CONTROL TECHNIQUES

In this section we classify the control techniques that have been put forward thus far, into different categories. Still, it is important to note that there is not a single widely accepted classification. In fact, a control technique can belong to more than one category since existing techniques are not intrinsically exclusive.

1) TRADITIONAL CONTROL

According to the classical control theory, there are fundamentally two types of controllers: 1) open loop control and 2) closed loop (feedback) control [29]. In power systems, traditional closed-loop control strategies are usually used. A closed loop control aims to maintain a controlled variable at a desired value (set point). To this end, it constantly measures the controlled variable, obtains the error between the current value and the set point, and uses that error to determine corrective actions on the actuators [85]. The actuator is the device that can influence the control variable of the process and perform the control actions based on the signal received by the control scheme [85].

Closed loop controllers in power systems are usually designed considering time and frequency domain performance indicators such as rise time, settling time, peak overshoot, gain and phase margin, and bandwidth. Historically, closed loop controllers were usually designed for locally-based control processes without optimized actions or robustness against uncertainty. Typical examples of such closed-loop controls are the speed control of the governor of prime movers of SGs (used for frequency regulation purposes), automatic voltage regulators (AVRs) for controlling the excitation of the machines (used for voltage regulation), and power system stabilizer (PSS) control loops, used as an additional feedback signal for damping rotor-angle swings among the system [86], [87], [88].

2) OPTIMAL CONTROL

Similar to the traditional control, an optimal control aims to maintain a controlled variable at a desired set point. The difference is that, to this end, it constantly determines the necessary control actions that satisfy some constraints while minimizing (or maximizing) some performance criterion [88], [89]. The optimization can be either performed in real time or offline. In the latter case, the parameters obtained from the optimization are fixed and do not change in time. Optimal controllers usually optimize a cost function that depends on state and control variables, resulting in a set of differential-algebraic equations that describe the minimization (or maximization) process. Thus, computational efforts for these strategies are usually very high, especially when the optimization is solved in real time [91].

When using optimal controls, the system state of all relevant variables must be available as a feedback signal. Moreover, in real time controllers the required variables must be transmitted from the point of measurement to the location of the datacenter where the optimization process is performed. Consequently, communication issues may arise.

An optimal control strategy widely adopted in most real-world power systems is the automatic generation control (AGC) [86]. AGC acts on the power output of selected generators to (i) perform load-frequency control (LFC) and (ii) to redispatch generation to minimize operating costs (also known as economic dispatch control (EDC)) [86]. In both cases, determining the optimal control actions demands high computational efforts so the actions are updated at most once every 5 minutes [86].

It is important to remark that within this category we are not including optimal controllers that consider uncertainty or use artificial intelligent techniques within the optimization. Both controllers are categorized as independent categories.

3) ROBUST CONTROL

While traditional and optimal controllers are usually designed for a specific operating condition or a limited set of them, robust controllers are designed to deal with uncertainty [29], [92]. The main objective is to ensure that the control actions work properly even for "worst-case" scenarios [93], meaning that they will not be optimal under normal circumstances [94].

Depending on the type of uncertainty involved, different mathematical techniques can be used for robust control applications including linear or nonlinear, parametric, or dynamic, structured, or unstructured [95]. Among the most popular ones are both dissipativity-based and H_∞-based methods.

Dissipativity-based methods can be applied in any system showing an energy decrease over time [96]. The concept of dissipativity is based on an input-output energy relationship. Roughly speaking, this means that the system absorbs more energy from the external world than the one that supplies [97]. In H_∞-based methods, the optimization consists of minimizing the H_∞ norm of the closed-loop transfer function [98], where the H_∞ norm can be physically interpreted as the maximum energy amplification across all input signals. This type of optimization problem is usually called *min-max* problem, in which the control seeks to minimize the worst-case scenario, i.e., when the closed-loop function has its peak.

A special case of robust control are look-up table-based controllers, in which a look-up table serves as array of data that maps input values to output ones. In this approach, independent optimal controllers - one for a specific set of operating conditions, are designed. The obtained parameters are stored in the look-up table and used depending on the system operating condition. Despite being more robust than traditional optimal controllers, the performance of look-up table-based controllers is highly dependent on the number of operating points considered for its design [99].

4) INTELLIGENT CONTROL

Most controllers in power systems are designed using mathematical models of the underlying phenomena (e.g., state equations, transfer functions, or input/output descriptions), which can be derived from physical laws or experimental data. However, mathematical models are not always available, or the system under study may have limited observability thus making them unsuitable for real-time applications [100]. To overcome these issues, there is a different class of control techniques, called intelligent control, that employ artificial intelligence (AI)-based techniques to build the desired control strategy using a vast volume of information. Intelligent control systems are especially suitable when no mathematical model is available [101], when the existing model is too complex, or the system lacks the required observability.

TABLE 1. Number of WACS publications found.

Period	Publications
<2004	7
2005-2009	25
2010-2014	55
>2014	94
Total	181

An intelligent control system includes an engineering control and an information processing system with intelligent characteristics, that is usually designed based on the study of the human intelligent behavior and the rules of its control and information transfer process [29]. Examples of AI-based control techniques are controllers based on neural networks, evolutionary computation, machine learning, and intelligence agents; in addition to Bayesian control and fuzzy/neuro-fuzzy logic control. Artificial intelligence techniques can be used for defining the control actions in real time, or offline at the design stage [100]. In these strategies, data collection, storage, and analysis are critical and a non-trivial aspect [102].

Although intelligent strategies have been addressed more in theory than in practice, their potential for applications such as fault prediction, energy efficiency decision making, disaster recovery and stability enhancement, has been widely recognized in recent years [102].

III. CLASSIFICATION OF CONTROL STRATEGIES

In this section, we provide a comprehensive review of WAC strategies that have been put forward hitherto for ensuring or improving the stability of power systems during large contingencies. Control strategies focused on normal operating conditions are not further discussed. We address centralized, distributed, and hierarchical control solutions as well as decentralized controllers when they inherently include remote signals in their design.

The database of this review was set up with journal and conference papers from both *IEEE Xplore Digital Library* and *Elseviers' ScienceDirect*. The search criteria consisted of works that include in their abstract and/or title at least one of the following keywords: "rotor-angle", "transient", "frequency", "voltage", "stability", "converter", "inverter", "control strategies", "coordinated", "PMU", "WAC", "wide-area", "centralized", "distributed" and "hierarchical". Although inter-area oscillation damping controllers were not explicitly included as keywords in the search, a significant number of publications addressing this topic were still found and included in this review. Table 1 summarizes the total number of works included in the database. In total, 181 papers were found using the aforementioned search criteria ([44], [45], [49], [55], [56], [57], [58], [59], [60], [61], [62], [64], [65], [66], [67], [68], [73], [78], [80], [81], [90], [96], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138], [139], [140], [141], [142], [143], [144], [145], [146], [147], [148], [149], [150], [151], [152], [153], [154], [155], [156], [157], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], [170], [171], [172], [173], [174], [175], [176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186], [187], [188], [189], [190], [191], [192], [193], [194], [195], [196], [197], [198], [199], [200], [201], [202], [203], [204], [205], [206], [207], [208], [209], [210], [211], [212], [213], [214], [215], [216], [217], [218], [219], [220], [221], [222], [223], [224], [225], [226], [227], [228], [229], [230], [231], [232], [233], [234], [235], [236], [237], [238], [239], [240], [241], [242], [243], [244], [245], [246], [247], [248], [249], [250], [251], [252], [253], [254], [255], [256], [257], [258], [259], [260], [261], [262]). These works were classified based on the kind of stability they address according to [14], as shown in Table 2. From this table it can be seen that most works propose control strategies for damping inter-area oscillations (56.4%) and only few address two or more types of stabilities simultaneously, reaching only 17.1%.

Based on the reviewed works, there are essentially 5 recurrent features that allow us to advantageously characterize and classify each control strategy and draw useful insights: 1) type of control architecture, 2) communication issues, 3) type of controlled device, 4) type of control technique, and 5) characteristics of the simulated power system/test case. Next, we provide details on each of these features.

TABLE 2. Number of WACS publications according to addressed stability issue.

Stability issue	Details	Publications	Total
RA	RA	18.8%	28.2%
	RA + F	0.6%	
	RA + V	2.8%	
	RA + IA	5.0%	
	RA + F + V	1.1%	
F	F	8.8%	15.5%
	RA + F	0.6%	
	F + V	5.0%	
	RA + F + V	1.1%	
V	V	7.7%	16.6%
	RA + V	2.8%	
	F + V	5.0%	
	RA + F + V	1.1%	
IA	IA	47.5%	56.4%
	RA + IA	5.0%	
	F + IA	2.8%	
	RA + F + V	1.1%	

RA = Rotor-Angle, F = Frequency, V = Voltage,
IA = Inter-Area Oscillation.

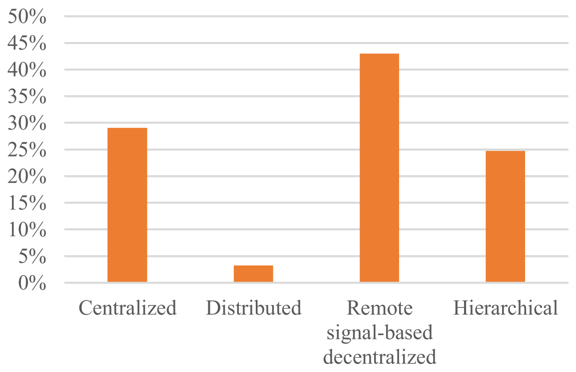

FIGURE 1. Percentage of works that address telecommunication issues according to their control architecture.

A. CONTROL ARCHITECTURE

Table 3 classifies the 181 papers according to their control architecture and the kind of stability being addressed. Figure 1 shows that most of the ongoing research efforts are focused on centralized and remote signal-based decentralized strategies, reaching a 35.9% and a 37.6% of the total amount of the reviewed papers, respectively. Hierarchical and distributed strategies have been less studied, reaching 19.3% and 8.3%, respectively.

1) REMOTE SIGNAL-BASED DECENTRALIZED CONTROL

Of the total of the reviewed works, most of them deal with decentralized controllers with remote signals, reaching 37.6% (66 papers). From these papers, 50 of them propose architectures for damping inter-area oscillations, [45], [61], [73], [96], [104], [108], [111], [112], [114], [118], [119], [121], [124], [129], [133], [134], [135], [138], [142], [144], [148], [156], [157], [162], [163], [164], [165], [167], [170], [173], [174], [175], [177], [185], [186], [187], [188], [189], [195], [198], [200], [208], [221], [228], [232], [240], [249], [255], [261], [262], 10 for improving rotor-angle stability [49], [107], [110], [120], [155], [172], [176], [190], [192], [217]; 1 voltage stability [230], and 7 addressed two or more types of stability [106], [128], [159], [197], [214], [220], [253]. Although some of these authors present their

TABLE 3. **Control architecture of WACS.**

Addressed stability	Centralized	Distributed	Remote signal-based decentralized	Hierarchical
RA	8.3%	2.8%	5.5%	2.2%
F	3.9%	2.8%	0.0%	2.2%
V	5.5%	0.6%	0.6%	1.1%
IA	8.8%	2.2%	27.6%	9.9%
RA + V	0.6%	0.0%	1.1%	1.1%
F + IA	1.1%	0.0%	0.0%	1.7%
F + V	4.4%	0.0%	0.6%	0.0%
RA + F	0.0%	0.0%	0.6%	0.0%
RA + IA	2.2%	0.0%	1.7%	1.1%
RA + F + V	1.1%	0.0%	0.0%	0.0%
Total	35.9%	8.3%	37.6%	19.3%

RA = Rotor-Angle, F = Frequency, V = Voltage,
IA = Inter-Area Oscillation.

works as centralized controllers, we classified them into this category because their controllers enhance the stability by controlling one device (SG and DFIG), without relying on a central controlling unit [128] and [167].

It is worth mentioning that most wide area damping controllers are usually designed for damping one specific oscillation mode. Nevertheless, when more than one oscillation mode needs to be damped, multiple WADCs can be simultaneously designed, as shown in [124], [165], [167], and [173].

2) CENTRALIZED CONTROL

The second group in importance by number of papers corresponds to centralized controllers, covering 65 papers of the total, reaching 35.9% of the total reviewed papers. Although most of these works propose centralized strategies to control the system as a single area, some of them control a particular grid area only [55].

From the 65 works reviewed, most of them present strategies to damp inter-area oscillations or to improve rotor-angle stability. Specifically, 16 papers address inter-area oscillations [78], [81], [115], [122], [125], [130], [151], [179], [182], [193], [199], [227], [236], [238], [241], [248] and 15 papers address rotor-angle stability [137], [139], [161], [166], [180], [204], [206], [207], [210], [213], [216], [218], [219], [231], [233]. From the remaining 34 papers, 7 address frequency stability issues [127], [146], [150], [168], [235], [237], [257] and 10 papers address voltage stability [55], [149], [152], [184], [191], [194], [201], [244], [245], [260]. The remaining papers (17 in total) propose strategies addressing two or more kind of stabilities [123], [131], [143], [154], [160], [183], [205], [209], [224], [225], [226], [229], [234], [239], [243], [246], [247].

3) DISTRIBUTED CONTROL

Distributed controllers by far, have been less studied, reaching only 15 works from the 181 papers. From these 15 works, 5 of them address rotor-angle stability [56], [57], [141], [215], [258]; 5 papers address frequency stability [58], [59], [212], [222], [256]; 4 papers address inter-area oscillations, [60], [61], [132], [151]; and only 1 paper addresses voltage instability issues [62]. It is worth mentioning that in [59] the authors present their work as a decentralized control scheme. However, as communication between different zones is required, we classified this work as distributed control. Similarly, the work presented in [132] is included within this category despite being presented as a hierarchical feedback controller.

4) HIERARCHICAL CONTROL

Hierarchical controllers total 35 works, from which 17 correspond to non-explicit hierarchical structure controllers. As before, the vast majority of hierarchical controllers are designed for damping inter-area oscillations [65], [67], [105], [109], [113], [116], [117], [126], [147], [151], [169], [171], [178], [181], [196], [211], [223], [250]. From the remaining 17 papers, 4 present control strategies for improving rotor-angle stability [90], [145], [153], [202], 4 for improving frequency stability [203], [242], [251], [252]; 2 papers address voltage stability [132], [254]; and 7 propose control strategies for addressing two or more types of stability [44], [64], [66], [68], [136], [140], [158]. Although the proposal in [242] is presented as a distributed control strategy, the proposal considers a centralized and a distributed signal in a hierarchical manner, thus we classified it as hierarchical architecture-based strategy.

B. COMMUNICATION ISSUES

A key issue when designing WAC is the impact of time delays resulting from the communication infrastructure. Delays in WAC are unavoidable in real-world large-scale power systems. The time-delays observed in such networks are time-varying and non-homogeneous [264]. Delays in real electricity systems may range from tens to hundreds of milliseconds or even more, depending on the communications technology being used [69], [70]. Several studies have shown that if the WAC is not designed considering the effects of time delays, the performance of the control may not be satisfactory or may even lead to power system instability [61], [67], [124]. In this sense, from the reviewed papers proposing WAC strategies for ensuring or improving power system stability, not all of them include key aspects related to communication networks. Furthermore, in theory, a WAC system can be based on fast-response PMU measurements (WAMS), or any other measurement system, such as SCADA. For each technology, different communications issues may appear. Still, from the reviewed papers, most works use WAMS-based controllers. Indeed, only reference [183] developed a SCADA-based control, in which a preventive-corrective demand response was performed. Although some of these works do not explicitly specify the requirements of the measurement system [58], [157], [179], [184], the proposed controllers rely on fast-response measurements and hence we include them within the group of PMU-based systems. Nevertheless, several publications do not specify the measurement system, nor the requirements for such measurement system, thus remaining unclear upon which platform the controls where designed (WAMS, SCADA, and/or another monitoring system) [120], [149], [159], [201], [203], [212], [213], [215], [216], [219], [222], [229], [243], [244], [254].

In this review article, we constrain telecommunication issues to those related to time-delays and loss of information. Within this group, we included papers that proposed time-delay compensation techniques, as well as papers that demonstrate a certain degree of robustness against time-delay issues and/or loss of communication. Considering both criteria, 93 papers (51.4% of the reviewed papers) consider telecommunication aspects, thus revealing that this is an active research area. Figure 1 presents the percentage of works that address telecommunication issues according to their control architecture. The figure shows that from the 93 papers considering telecommunication aspects, 43% use remote signal-based decentralized controllers, followed by centralized controllers with 29%, then by hierarchical controllers with 25%, and finally by distributed controllers, with only 3%. It is important to mention that, from all the proposals based on centralized controllers, only 42% of them consider telecommunication issues, despite being the architecture with the larger computational and communication requirements.

1) TIME-DELAY COMPENSATION TECHNIQUES

In this subsection, we classified papers addressing telecommunication issues according to the compensation technique being used. In this regard, the most common compensation techniques are Padé Approximation, Smith Predictor and Phase Shifting.

a: PADÉ APPROXIMATION

Time-delay compensation through the Padé approximant has been widely explored. This technique uses Taylor series expansion for transforming a time-delay system into a one without time-delayed outputs, thus allowing the subsequent use of conventional methods that do not consider time-delay [198]. The most common approach for this is to include time-delay compensators in the design stage of the controllers using Padé approximation techniques. This technique provides a finite-dimensional rational approximation of a dead-time for approximating dead-times in engineering systems. This approximation reduces a time-delayed system to one with a rational transfer function, thus allowing its use for stability analysis and design of controllers for delayed systems [265]. Most strategies rely on low-order Padé approximations [61], [67], [78], [119], [131], [145], [157], [186], [193], [199], [200], where first-order approximations are developed. Second-order approximations are considered in [73], [108], [123], [134], [135], [156], [169], [185], where [169] refers to a particularly modified second-order approximation. Although less used, higher-order strategies were also implemented in [117], [162] (third-order approximations), [177] (fourth-order approximation), and [234] (eighth-order approximation). In [122] the authors did not specify the order of the Padé approximation that was used.

b: SMITH PREDICTOR

Another strategy for addressing telecommunication issues through time-delay compensation is to design a delay-predictor control method to eliminate the negative effects of time-delays. In terms of control theory, the Smith predictor is one of the most popular dead-time compensation methods. In particular, the Smith predictor uses a model of the controlled process without delay, also known as the fast model, together with a model of the dead time, for predicting the future behavior of the system [266]. Therefore, the Smith predictor works to control a modified feedback variable (the predicted variable) instead of using the fast model by itself. In [65] and [250], a classical Smith predictor is used to preserve performance in presence of large remote-measurement time-delays. One of the drawbacks of this approach is its difficulty to ensure a minimum damping ratio of the closed loop poles when the open-loop plant is poorly damped. To overcome this issue, Watanabe and Ito proposed a modified Smith predictor scheme [267]. Nevertheless, this scheme may present numerical issues in systems with fast and stable eigenvalues. Consequently, [124] and [198] proposed a unified Smith predictor scheme, combining the advantages of both schemes and preventing stability issues.

c: PHASE SHIFTING

Despite the favorable results of the works presented so far for compensating time-delays, all these approaches have a common drawback: they assume the availability of a known (reduced) model of the system, which is not always the case. Some works address this issue through the implementation of phase compensator blocks, specifically designed to mitigate the negative effects of time-delays. This is done by compensating the phase lag induced on the control signals, without the need of a certain model of the grid. In [238], Prony method-based lead-lag blocks and a band-pass filter were designed to mitigate the negative effects of time-delay. While the objective of the first block is to compensate phase lag caused by time-delay, the second block aims at increasing the stability margin in the high frequency range. Similarly, in [223] the parameters of the filter and lead-lag blocks were adjusted according to an online-monitored oscillation mode with online Prony algorithm and online-monitored time-delay. A similar approach is followed in [115], where two different compensators are introduced along with a band-pass filter. The first compensator corresponds to the aforementioned lead/lag one, whereas the second compensator corresponds to a differential one that act as an alternative to provide a phase lead at a given frequency. Also, in [116] a damping controller with a phase lead compensation structure was designed. Another approach based on local lead-lag compensators is presented in [195], where the compensators are optimized considering these delays in the design stage. Finally, [188] presents a Simulink-designed lead-lag compensator.

Another phase shifting-based approach is developed in [81], where delay uncertainty is considered through an upper and a lower bound. The control input delay is addressed online through a phase-lag compensation. The control output delay is compensated with a damping controller based on Lyapunov–Krasovskii's (LK) functional delay-dependent stability criteria, which considers variable delay with packet drop. Other works computed the total latency in real-time, by subtracting the instant of measurement at the PMU from that of its arrival at the WADC. Then, the phase angle off-set is calculated to proceed with the compensation [109], [147], [255]. Similarly, a fuzzy-based controller is presented in [173], where an input signal was quantified by PMU data time tags and the coordinated universal time (UTC) at the controller location, with which output membership functions were shifted to compensate the time-delay. Time-delay computation is also included in [165], incorporating it as an input to the WADC parameter estimation.

2) ADAPTIVE APPROACHES

Many practical applications require the implementation of an adaptive approach to face parameter variations due to time-delay uncertainties. In this subsection, we classified the papers addressing telecommunication issues with such a more complex, adaptive approach. This includes techniques mentioned in the previous subsection, but with an adaptive approach. Examples of such implementations are auto-tuning and self-tuning approaches. In [241], a time-dividing delay compensation strategy is presented. As the compensator for a specific delay is usually robust in a certain range, the strategy consists of dividing the random delay into several intervals and then designing compensators for each interval. This strategy reduces the conservativeness of the fixed compensation and avoids switching among a large number of predesigned controllers. Furthermore, authors in [174] present an adaptive proportional-plus-derivative method for compensating a wide range of time-delays in remote signals, based on an adaptive neuro-fuzzy controller. This method resulted to be similar to lead-lag compensation techniques, where the parameters are selected depending on a non-constant time-delay. A similar but simpler approach is proposed in [57], where a proportional-plus-derivative method is tuned following a time-dividing approach. Nevertheless, in this work only two time-ranges are defined and therefore it may result in a poor performance for critical delays. Works in [186] and [187] propose an adaptive delay compensator, which consists of a weighted combination of several Padé approximation-based compensators. Weights are adjusted based on the communication delay measured in real-time. Finally, [160] presents a delay-aware approach, in which the control design accommodates the knowledge of various delays of the PMUs. The control design employs a switching controller that switches between the nominal control and another one that accommodates drops if the delay exceeds a predefined threshold.

3) TIME-DELAY ROBUSTNESS

Other works addressing communication issues such as dead-time demonstrated to be robust against model uncertainties, despite not explicitly considering their impacts at the design stage. In particular, the results obtained in [49], [64], [66], [90], [129], [132], [137], [175], [211], [225], [230], [231], [239], [242], [245], [251], [252], [253], [257], and [262] showed only minor impacts on their performance when subjected to time-delays. Predictive control schemes presented in [62], [151], [152], [237], [249], and [260] also work well in the presence of time-delays.

Although the works presented in this subsection showed good performance in presence of delays, these results should be considered carefully, because they might be very dependent on the specific case being tested, and their robustness in general, cannot be guaranteed.

4) OTHERS

Besides the aforementioned time-delay compensation strategies, other delay-dependent design techniques have also been investigated. Works in [45], [80], and [148] presented Kalman filter-based strategies. In [45], a modified extended Kalman filter (MEKF)-based compensator method was proposed, where inter-area mode attributes such as signal frequency, phase, and damping factor were estimated in real time and then corrected using the total time-delay in the network. In [148], unknown time-delays are estimated using the extended Kalman filter algorithm and their estimates are then used to re-design the controller. In [80], a data-driven Kalman estimator is used as input for an enhanced time-delay compensator on for avoiding instabilities that are sometimes induced by other time compensation techniques.

Meanwhile, [166] presents a predictive control model where optimized stepped structural changes are carried out to drive rotor-angles to an acceptable equilibrium point. Within this strategy, an extra fixed time was considered between control actions, in order to avoid time-delay issues. In [104], a Lyapunov-based delay-margin (defined as the maximum time-delay under which a closed-loop system can remain stable) is introduced as an additional performance index for the synthesis of classical WADCs.

Another strategy is to design controllers considering the largest expected delay [164]. Such delays are expressed as multiplicative uncertainties and thus handled through a robust H_∞-norm of a complementary sensitivity function. In [142], an iterative algorithm is designed considering a range of time-delays, which are included in each step of the controller as part of the design process.

Some approaches based on emergency demand response (EDR)/emergency power boosting (EPB) strategies are designed with an extra power margin, in order to offset the impacts of time-delays [168], [207], [235]. In addition, several model-based strategies include both fixed or stochastic delays as part of the power system model in order to design delay-dependent WADCs through other diverse time-delay models, as in [126], [127], [128], [133], [153], [158], [163], and [172].

Finally, the approach followed in [55] addresses the desynchronization of measured data due to variable time-delays. To this end, voltage phasor signals are re-synchronized using a specially designed mechanism, allowing them to find a common delay. Thus, a synchronized array of voltage phasors can be obtained for subsequent control.

C. TYPE OF CONTROLLABLE DEVICE

In this paper, we refer to the actuators of a determined power system control approach as controllable devices.

Table 4 summarizes the main controllable devices used in the works considered in this review, as well as the kind of stability being addressed. From these works (181 papers), only 19 approaches were designed considering systems with high penetration of RES (around 10%) as presented in Figure 2. From Table 4, it can be noted that SGs are by far the most used devices (in 28.7% of the works). Other common devices are HVDC-links (16%), reactive power sources (14.4%), and inverter-based devices (14.4%). However, these controllers are mainly used to address inter-area oscillations and, to a lesser extent, rotor-angle stability. Load shedding and generation tripping enabling devices have also been widely studied (in 13.8% of the works). These devices have been mostly used to address voltage, rotor angle and frequency stability issues.

1) SYNCHRONOUS GENERATORS

SGs are one of the most common controllable devices used in WADCs, especially for addressing rotor angle transient stability and interarea oscillations. Most approaches include additional remote signals for feeding either the generators excitation system or a global-based PSS, or the governor system [55], [56], [57], [58], [60], [65], [73], [78], [90], [80], [105], [108], [110], [111], [112], [123], [125], [126], [128], [131], [132], [145], [147], [148], [153], [160], [162], [164], [169], [170], [171], [172], [177], [185], [188], [196], [197], [198], [200], [208], [211], [217], [240], [241], [245], [249], [255]. The work in [230] differs from the others because it uses an additional hardware to increase the excitation levels of the generator through an ultracapacitor-based device. Another novel approach is proposed in [215], where one generator is selected as the *leader* and the others are *followers*, forcing their rotor angle speeds to move to a desired value in a distributed manner. Reference [216] presents a fast-valving technique, where a tracking agent tracks generators rotor angle to determine power system instability. In [180] a novel technique is proposed to optimize the mechanical input of SGs using a center-of-inertia (COI)-based stability criterion. In [206], a novel, transient-stability-oriented, preventive control action in the form of generation rescheduling was presented.

2) HVDC-LINK

High voltage direct current (HVDC) transmission is generally used to interconnect regional grids. One of their major advantages is the ability of quickly setting the power transmitted, which in turn influences the operating characteristics of the electric networks. Hence, plenty of control strategies have been developed with HVDC-links as main controllable devices, especially for addressing transient rotor-angle stability and inter-area oscillations issues. Most works rely purely on HVDC-links, as in [49], [106], [107], [115], [121], [133], [138], [142], [154], [155], [159], [161], [175], [182], [187], [213], [221], [222], [238], and [254]. However, in practical large-scale interconnected systems, there are usually various interarea oscillation modes with various oscillation shapes that act together and endanger the stable and secure operation of power systems. In such cases, a simple HVDC-based WADC may not be sufficient to provide an effective damping characteristic to surpass the instability issues of the grid [130]. Thus, some strategies involve additional controllable devices. Works in [143], [146], [192], and [223] design control strategies that act on both the transmitted power of HVDC-links and the output power of SGs in a coordinated manner. Works in [168] and [235], propose combined strategies that use HVDC-link power modulation and an emergency demand response approach. Furthermore, [130] and [190] addressed instability issues through the implementation of FACTS devices simultaneously with HVDCs. In [137], a coordinated control strategy is proposed for a voltage source converter (VSC)-HVDC-based grid and offshore wind farms connected by the DC grids.

3) INVERTER-BASED DEVICES

In recent years, control strategies that use inverter-based devices have gained interest due to both, its fast-acting capability and its growing integration in power systems. In particular, inverter-based technologies have been widely used as a mean for an increased integration of renewable energy in power grids [103]. Among these technologies are solar and wind power plants, battery energy storage systems (BESS) and electric vehicles (EV). FACTS devices are also based on inverters, nevertheless they are not exclusively considered in this category because, in this context, they are mostly used as reactive power sources, which is considered as a separate category.

Energy storage-based devices can be utilized to improve power supply reliability. Major advantages of these devices are their rapid dynamic response and the smoothly adjustable output. This aspect is addressed in [61], [150], [214]. In [199], a centralized controller utilizes superconducting magnetic energy storage (SMES) systems to quickly supply and absorb active and reactive power simultaneously. In [127], a novel frequency stabilization method is proposed, where EVs are

TABLE 4. Controllable devices of WACS.

Addressed stability	HVDC-Links	Reactive power sources	Synch. generators	Load shedding and gen. tripping	Protections	Demand-side management	Inverter-based devices	Multi-element approach
RA	4.4%	1.7%	6.6%	2.8%	3.3%	0.0%	0.0%	0.0%
F	2.2%	0.0%	0.6%	1.1%	0.0%	1.7%	1.7%	1.7%
V	0.6%	1.1%	1.7%	3.9%	0.0%	0.0%	0.0%	0.6%
IA	6.6%	10.5%	17.1%	0.0%	0.0%	0.0%	9.4%	3.9%
RA + V	0.0%	0.6%	0.6%	0.6%	0.0%	0.0%	0.6%	0.6%
F + IA	0.6%	0.0%	0.6%	0.0%	0.0%	0.6%	1.1%	0.0%
F + V	0.6%	0.0%	0.0%	4.4%	0.0%	0.0%	0.0%	0.0%
RA + F	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%
RA + IA	1.1%	0.6%	1.7%	0.0%	0.6%	0.0%	1.1%	0.0%
RA + F + V	0.0%	0.0%	0.0%	1.1%	0.0%	0.0%	0.0%	0.0%
Total	16.0%	14.4%	28.7%	13.8%	3.9%	2.2%	14.4%	6.6%

RA = Rotor-Angle, F = Frequency, V = Voltage, IA = Inter-Area Oscillation.

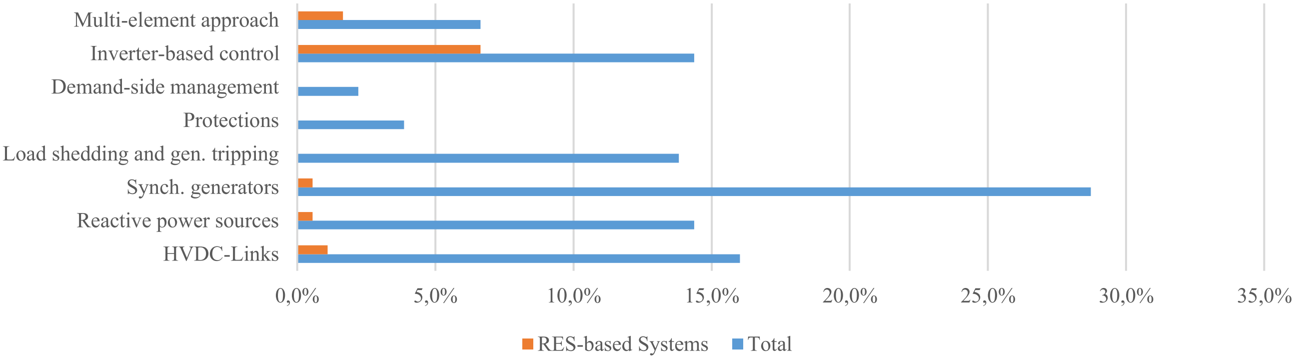

FIGURE 2. Percentage of reviewed strategies according to their controllable devices and RES-based systems addressment.

used as storage systems for primary and secondary frequency control, thus suppressing fluctuations in the system frequency.

Several studies have reported improvements of system stability when acting over doubly fed induction generator (DFIG)-based wind turbines, due to the ability of independent active and reactive power controls. This options lead to the possibility of power system stabilization through additional control signals for the control loops of DFIGs [66], [129], [165], [167], [178], [193], [195]. Combined strategies are developed in [45] and [67], where wide-area power oscillation dampers (POD) are implemented in both DFIGs and FACTS, as well as in DFIGs and PSS of synchronous generators, respectively. Though scarce, full-converter wind turbines have also been studied for this purpose, as presented in [220]. Works in [68] and [117] proposed a control strategy involving variable speed wind energy conversion systems (VS-WECS) along with SGs and FACTS devices.

WACS specially designed with PV systems as controllable devices for stability enhancement have also been proposed in [156], [157], and [186]. Other approaches have been proposed for enhancing power system stability by controlling *unspecific* inverter-based renewable-based generation units. Specifically, in [109], [114], and [212], control actions utilize the high frequency converter of VSC to modulate real and reactive power in an effective manner through programmable power electronic interfaces. A different strategy is proposed in [96], [158], and [253], where instability issues are addressed through an adequate control of virtual SGs (VSG). In [96], a wide-area control approach of power systems with high penetration of renewable-based DERs is proposed. However, in this work it was assumed that every DER is designed as a VSG, which is an unrealistic scenario.

4) REACTIVE POWER SOURCES

With the development of smart-grid technologies, different kinds of reactive power compensation-based stabilizers have been proposed and applied for addressing stability issues [181]. In most cases, Static VAR compensator (SVC)-based approaches have been proposed, using the capability of SVCs of providing fast-acting reactive power [104], [118], [119], [124], [134], [135],

[140], [174], [176], [181], [236], [250]. Furthermore, other FACTS-based approaches use thyristor controlled series capacitor (TCSC) [136], [144], [163]; static synchronous series compensator (SSSC) [173]; unified power flow control (UPFC) [179]; and static synchronous compensators (STATCOM) [120], [189]. Some approaches have also considered more than one type of FACTS device simultaneously, such as in [122] and [248], where both SVC and TCSC are considered within the control strategy. Some strategies are also designed for generalized FACTS devices, without specifying one in particular. This is the case of [141], where shunt FACTS devices were considered at the design stage.

Additionally, [149] proposed a combined control strategy which included on-line tap changer (OLTC) schemes and capacitor banks simultaneously. Finally, some works proposed using a wide-area-based control of three or more reactive power-based actuators simultaneously, as in [194], in which AVR, OLTC, and shunt reactors and capacitors were considered. Another example is [81] which considered distributed generators (DGs), SVCs, and SSSCs as acting devices.

5) LOAD SHEDDING AND GENERATION TRIPPING

Load shedding and generation tripping have become a popular option to avoid major blackouts in power systems after power imbalances or generation desynchronization. Several works have proposed control schemes following this approach. In most cases, a purely load shedding scheme is performed, such as in [62], [183], [184], [191], [201], [205]. [224], [225], [226], [229], [237], [239], [243], [244], [246], [247], [257], and [259]. Approaches using purely generation tripping schemes are less common, such as [204], [207], [219]. In [233], a strategy based on the combined action of both load-shedding and generation-tripping schemes is presented. Other works combined load shedding and generation tripping with other approaches in order to increase the effectiveness of the control. In [209], load shedding and generation tripping schemes are implemented simultaneously with a controlled islanding approach. In [166], load shedding and generator tripping is combined with auxiliary capacitance shifting. Finally, work in [152] proposes a load shedding approach together with OLTC schemes and AVR adjustment of SGs.

6) PROTECTION

To maintain the stability of power systems, some approaches rely specifically on protection actions such as for changing the topology of the grid or isolating a particular element of the system. In particular, multi-agent frameworks are proposed in [202] and [258], where intelligent agents coordinate protection devices to isolate the faulted part from the rest of the system before a critical clearing time, thus increasing the transient stability margin of the system. Controlled islanding approaches were proposed in [139], [210], [218], and [234]. In these schemes, the network is split into stable islands to avoid disturbances propagation. The protections are coordinated based on stability characteristics. A special protection scheme (SPS) was designed in [231] as a preventive on-line security assessment tool which accurately determines the stability limits of a multi-machine transmission network and then determines if the automatic arming signal should be enabled/issued for the next given contingency.

7) DEMAND-SIDE MANAGEMENT

Demand-side management (DSM) is a strategy in which continuous fast-acting distributed-load participate in system control of smart grids. Though scarce, some works follow this approach by controlling aggregated loads in order to vary the demanded power and therefore to enhance the frequency stability and/or the oscillation damping ratio of the system. In [59], a DSM approach was specifically designed to manage thermostatically controllable loads. Additionally, [242] focused on a leader-following communication protocol for load aggregators that uses a centralized pinner (leader) and multiple load aggregators (followers). Both [64] and [256] proposed an optimal load control (OLC) scheme, where the decisions are made in an optimal manner. In [64], the proposal minimizes the number of consumers subjected to a decrease in power demand due to power balance requirements and frequency regulation over the network. Nevertheless, such an approach is not able to restore the frequency to its rated value, an aspect that is addressed in [256] using a centralized approach.

8) MULTI-ELEMENT APPROACH

To fully exploit the capability of existing grid elements, several strategies are designed for controlling multiple elements simultaneously. The approaches proposed in [251] and [252] design a hierarchical structure which contains three main components, a central supervisor (CS), regional data aggregators, and local controllers (LCs). Every local controller is equipped with an undefined fast-frequency-response-provider. When an event occurs, every LC uses the information received from the CS and determines whether it should respond and with how much power. Artificial intelligence (AI)-based, multi-agent systems (MAS) as power system control strategies were presented in [203] and [260]. The principle of distributed AI was implemented through a constant or periodic message exchange between agents, which can be represented by various (unspecific) power system components, including local controllers available in the electric system. While the approach in [260] is purely preventive, the one in [203] developed both a preventive approach based on a deep learning strategy and a corrective one based on MAS. In [228], an active power modulation-based scheme that can be implemented in multiple active power-actuators is proposed. The scheme is tested on both the PSS of SGs and HVDC-links. Similarly, a generic approach to control existing elements is adopted in [151]. The approach was tested on both, the PSS of SGs and also on TCSCs. Authors in [44] designed a global control scheme capable of handling a mixture of continuous and discrete, dynamic and static control actions, including advanced controllers like FACTS devices.

Other works propose schemes to control specific elements simultaneously, such as PSS, FACTS controllers and HVDC systems [232], [261], [262]; PSS, DFIG, PV, and SVC [116]; and PSS, DFIG, PV, SVC, and HVDC [113].

D. CONTROL TECHNIQUES

In terms of control techniques, a wide variety of WACs with different control techniques have been proposed in recent years. In this section, the reviewed papers will be classified according to the categorization set out in Section II-C, which are traditional control, optimal control, robust control, intelligent control. Papers that do not clearly fit on one of these categories will be presented as Miscellaneous.

1) TRADITIONAL CONTROL

The use of traditional feedback controllers is still an active research area. Several works modify traditional control strategies of common system elements by including an additional loop to their control system using wide-area signals to enhance the control performance of power systems. Among these works are [55], [108], [110], [111], [112], [115], [119], [120], [121], [228], [230], [241], [245], [250], and [255]. Traditional PI and PID controllers have also been studied, as presented in [56], [106], [107], and [118]. In [259], a bus selection method was proposed, where additional active/reactive power is injected or consumed to enhance the stability of the system. Although never mentioned, such power would be injected (or consumed) using a control loop of an existing controllable element.

It is important to mention that none of these strategies specify the optimization process at the design or tuning stage of the controller. Although the work in [118] indicates that there is an optimization process involved, it uses heuristic tuning techniques, specifically the Zeigler-Nichols tuning method.

2) OPTIMAL CONTROL

Today, several control strategies are designed following an optimal control approach. Most common approaches consist of MPC [62], [148], [149], [150], [151], [152] and LQR/LQG-based controls. Most approaches from the latter group follow an LQR optimization process or similar [44], [60], [64], [68], [90], [117], [153], [154], [158], [159], [160], [220], [254]. Nevertheless, such optimizations assume a noiseless and fully observable system, which is unrealistic in real-world power systems, even with WACS. To cope with this issue, [80], [155], [156], [157], [162] propose an LQG approach that considers Gaussian noise in system variables as well as in the output, and assumes that the full system state may not be observable. The work in [235] relies on simpler optimization methods due to real-time computation time constrains, driving a real-time optimization process by converting the system's non-linear constraints into a linear matrix inequality.

As stated previously, traditional controllers can be optimally tuned, thus leading to an optimal control. The tuning law of PID controller parameters presented in [114] are obtained using the theory of adaptive interaction, following a minimization of the feedback error of the controller. The tuning of the control system in [105] is also presented as an optimization process. Nevertheless, the optimization technique is not presented. Similarly, [109] also omits the optimization method. They only mention that an optimization-based tuning process is driven without providing further details.

Several other optimal approaches have also been researched, mostly to address nonlinear systems. Non-linear bang-bang optimal controllers are presented in [161] and [213]. An optimization-based algorithm is proposed in [238] that uses a hybrid stochastic programming method. Here they also omit details on the optimization, and they only mention that such an optimization could be performed combined with AI-based algorithms. In [164], the control-design problem is formulated into a general parameter-constrained nonlinear programming problem, which was solved using a sequential quadratic programming (SQP) method. Such an optimization technique is also used by [224] for a load shedding selection based on a post contingency system state. A nonlinear Nelder and Mead simplex method based on geometrical considerations is used in [165] and [167], which is interfaced with PSCAD/EMTDC to formulate the optimization function to be minimized. A novel nonlinear optimization process is designed in [166], in which the total cost over all admissible control actions is minimized considering a structural change metric (control cost) and a signal metric (state cost). In [256], a primal-dual algorithm is proposed to solve the Lagrangian dual of the optimization problem of the controller. In [168], a classical optimization problem designed to reduce control cost under the premise of restraining the frequency deviation within the stable constraint is formulated.

Optimal load shedding approaches have also been developed, where an optimization procedure is carried out to determine the optimal amount, location and timing of the load shedding, as in [244] and [246].

Finally, the work in [251] presents a hierarchical wide-area fast frequency response scheme. Here, decisions are made by a central supervisor in an optimal manner, which assigns priorities for each system resource to perform corrective actions. Still, the optimization process is not described. A similar approach is also followed by the same authors in [252].

3) ROBUST CONTROL

Most robust WADCs found in the literature are designed under the H_∞-based robust control theory [81], [122], [123], [124], [125], [126], [127], [128], [131], [132], [133], [134]. In addition, the work in [73] proposes a combined optimization design process on the basis of the spectral abscissa, complex stability radius, and H_∞ norm minimization to reduce the controller order which in turn reduces the optimization complexity in large-scale power systems. In [130], a multi-objective mixed H_2/H_∞ output-feedback control with regional pole-placement constraints was proposed. The work in [262] proposes a LMI-based mixed H2/H∞ control with partial state feedback and regional pole placement constraints. In [135], a two-input single-output (TISO) controller is introduced. The model has two degrees of freedom: A robust controller first designed to ensure that the system can be stabilized in the case of a communication failure and then another controller to add an additional degree of freedom to minimize the infinity norm of the closed loop system and shape the control loop.

Lyapunov stability-based control theory and its branches have also been widely researched among WADCs. Several methods to obtain Lyapunov functions were proposed with the aim of maximizing the rate of energy dissipation during contingencies [57], [96], [136], [137], [138], [140], [141], [142], [163], [214], [218], [221], [248]. The work in [104] proposed a residue method for designing phase-compensation parameters combined with a Lyapunov stability criterion and linear matrix inequalities (LMI). The method calculates the delay margin and determines the gain of the WADC based on a tradeoff between damping performance and delay margin.

Sliding mode control has also been object of research for WACSs. It is a variable structure control method which is not affected by parameter variations that enter in the control channel [49]. In particular, [49], [143], and [146] followed this approach, of which [143], and [146] employed a combined control design of sliding mode control and backstepping method.

Regarding robust control, a diversity of other approaches have also been developed. The work presented in [129] proposes a combined approach that uses both H_∞-based and energy-based control. Specifically, a wide-area damping controller for DFIGs that combines a line mode potential energy (LMPE) method with an extended state observer (ESO)-H_∞ control was developed. In [67], a robust controller based on small-gain theory is presented, which ensures the input-output stability on the basis of the individual stability of two subsystems by themselves. The work in [169] designed a fixed-order WADC considering power system operation uncertainties based on the solution of the Riccati equation. Additional novel and robust approaches specially developed for controlling specific power system elements are presented in [58], [144], [145], and [147]. The method presented in [219] uses off-line time domain analysis to build look-up tables with the required generator trip arming. Another look-up table-based approach is presented in [231], where adaptive look-up tables are generated to take corrective tripping measures based on previously calculated stability margins during contingencies.

Finally, the robust approach presented in [113] is meant to be general enough to be applied to any local controller used in power systems. This approach also uses an additional loop for traditional controllers used in power systems.

4) INTELLIGENT CONTROL

AI as a design tool for optimal and/or robust wide-area controllers of power systems has gained increased interest over the past years. The main advantages of these approaches are their capability to handle vast volumes of information and to define a control a system even if its mathematical model is partially or fully unavailable.

Fuzzy-logic control (FLC) is a rule-driven nonlinear control strategy that copes with uncertainty and variability of the input. It also provides the capability of introducing expert knowledge in control rules. Several works implement this technique, such as [170], [173], [176]. Fuzzy-logic control variations such as Takagi-Sugeno fuzzy model control based approaches [45], [171], [172] have also been researched. In these approaches, the local dynamic of each fuzzy rule is expressed by linear system models. Unlike other AI-based approaches, FLC cannot learn from data, which could reduce its performance in specific cases. Hence, [174] proposes a hybrid neuro-fuzzy approach that integrates the capabilities of fuzzy-logic and neural networks to surpass such issues.

Evolutionary-based intelligent optimization methods have also been widely studied for WACS design, including genetic algorithms [78], [177], [240]; plant growth simulation [181]; multi-objective evolution [183], [184]; customized differential evolution [185], [189]; Jaya algorithm [188]; and a modified imperialistic competition [191]. The work in [180] also performs evolutionary computation, although no further details are given regarding the evolutionary algorithm used.

Another widely AI approach for designing WACS is swarm intelligence (SI). SI simulates the collective behavior of artificial self-organized systems to solve complex mathematical problems. These algorithms represent nature-based phenomena, such as bacterial foraging algorithm [192]; firefly algorithm [116], [193]; particle swarm optimization (PSO) [194], [195], [196], [198], [199]; hierarchical structure poly-PSO [201]; mean variance mapping optimization [197]; and grey wolf optimization [61], [200].

Dynamic programming-based algorithms are developed in [66], [179], [182], [186], [187], and [190]. A coordinated control framework using an approximate dynamic programming (ADP) technique is proposed in [66] and [182]. Other heuristic dynamic programming (HDP) algorithms are developed in [179] and [190]. Furthermore, [186] and [187] presented a goal representation HDP (GrHDP), which improves the classical HDP approach by adding an additional neural network to automatically build an adaptive internal reward signal for improving the relation between the system state and the control action. The work in [175] combined a supervisory fuzzy-logic module with a GrHDP approach to adjust its learning rate in real-time when encountering a communication failure. Works in [178] and [211] propose an adaptive critic design (ACD)-based techniques to handle the reinforcement learning approach used on the design stage of the controller.

Other AI-based WACS design approaches include decision tree-based schemes [59], [204], [208]; support vector machines [205], [206], online sequential extreme learning machine [207]; and multi-agent systems [202], [203], [210], [216], [257], [258], [260]. Other neural networks-based AI approaches were introduced in [209], [212], and [261]. In [209], an artificial neural networks-scheme was proposed for transient stability prediction. In [212], an actor-critic neural network-scheme was proposed. Finally, in [261] two AI-based strategies were designed based on deep neural network and deep reinforcement learning.

5) MISCELLANEOUS

There are several other approaches that were not clearly classifiable according to the proposed categories. The work in [65] presented a two-level control framework, where the wide-area level is used to enhance each local controller performance by compensating the interactions among generators and inter-area oscillations. A Lyapunov exponent (LE)-based framework for transient instability prediction and mitigation using wide area measurement systems data was presented in [139]. Other control methods based on consensus theory were proposed in [215] and [222]. Distributed pinning control was implemented in [242], which is a feedback control strategy for consensus and synchronization of complex networked systems. A non-optimized adaptive VSG with variable inertia according to COI measurements was presented in [253]. According to multivariable inverse system theory, an inverse-system method-based approach was designed in [217], which controls a selected element of the system in a closed-loop situation according to wide-area COI measurements. A networked predictive control based on a generalized predictive control was proposed in [249]. A scheme based on a block relative gain and a block generalized dynamic relative gain to design decentralized controllers through a systematic analytical procedure was proposed in [232]. A similar approach to [224] (where an SQP-based optimal approach was followed for a load shedding selection based on post contingency state of the system) was presented in [225]. Instead of SQP, a novel algorithm without an optimization process based on a voltage stability risk index, was used.

Several controllers have been designed and/or tuned based on a Prony analysis for estimating frequency, amplitude, phase, and damping component of a signal. A Prony-based oscillation identification approach was developed in [236], where a set of remedial actions were designed to take corrective actions before the oscillations become critical. Both Prony-based and mode-free adaptive control schemes were implemented in [223], which leads to an adaptive approach. In addition, a hierarchized combined strategy was proposed in [227], where a central unit analyzes PMU signals using Multi-Prony method grouped by specially designed offline and online rules. Then local controllers were designed as lead/lag compensators using the signals from the central unit as input.

Several works also proposed load shedding and element tripping schemes without an optimization stage. For those cases, the classification according to our categories is not direct. Such non-optimal schemes were presented in [229], [233], [234], [237], [239], [243], and [247]. In [226], several performance indices were used for performing load shedding. Despite stating that the load shedding location is decided optimally, no optimization methodology is presented and thus how (and more importantly, which of) the indices are used in an optimal manner is not clear.

TABLE 5. Simulated power systems.

Addressed stability	Small-medium scale test model	Small-medium scale real power system model	Large scale power system	Field test
RA	9.4%	8.3%	1.1%	0.0%
F	6.6%	2.2%	0.0%	0.0%
V	3.9%	3.9%	0.0%	0.0%
IA	23.8%	21.5%	1.1%	0.6%
RA + V	1.1%	1.7%	0.0%	0.0%
F + IA	1.7%	1.1%	0.0%	0.0%
F + V	2.8%	1.7%	0.6%	0.0%
RA + F	0.6%	0.0%	0.0%	0.0%
RA + IA	1.7%	3.3%	0.6%	0.0%
RA + F + V	0.0%	1.1%	0.0%	0.0%
Total	51.4%	44.8%	3.3%	0.6%

RA = Rotor-Angle, F = Frequency, V = Voltage,
IA = Inter-Area Oscillation.

E. SIMULATED POWER SYSTEMS

In stability studies it is of utmost importance to consider a proper model of real-world power systems, as the non-linear dynamic behavior and complexity of power system can directly impact the performance of the designed controllers. In fact, a controller that is designed based on simplified and linearized models of a power system may perform well when controlling simple, linear models, but poorly when controlling more complex, non-linear real systems. In this sense, Table 5 shows that only 7 works validated their WAC using full dynamic models of large-scale power systems, whereas 93 of them used simplified test systems and 81 used reduced/simplified models of real-world power systems. In this study, we classified the dynamic models used in the case studies in four categories: 1) Real world field tests, 2) Large scale power system model, with at least 150 busbars, 3) Small-medium scale models based on real power systems, and 4) small-medium scale models based on test systems.

Among the works that considered complex large-scale power systems or field tests are [49], [121], [155], [164], [223], [225], and [234].

In [49], the proposed strategy is validated using a large-scale model of the China State power grid. The grid consisted of 22,503 buses, 2,120 generators and 14 HVDC links. The work in [121] is tested on a high-fidelity model of the Western Electricity Coordinating Council (WECC) power system using the GE Positive Sequence Load Flow (PSLF) software as simulation platform. The WECC model was adapted from a 31,419-buses, 4,063-generators model, specifically developed and validated by WECC. In [155], system's stability is investigated using a high-fidelity future Great Britain system model in PowerFactory, which consist of 5,328 busbars, 7,801 transmission lines, and 220 synchronous generators. The approach in [164] was tested on a practical 437-machine, 2,791-node power system, based on the interconnected Northern and the Northeastern power grids of China. The proposed scheme in [225] was tested on both New England 39-bus system and a practical 246-bus model of the Indian system. Work in [234], was tested on a practical model of the Iran National Power Grid, were an inter-area oscillation damping control scheme was simulated through a 450-generators model.

Field testing was also carried out in [223], where WADC-HVDC strategy field tests were conducted gradually on the China Southern Grid.

IV. CONCLUSIONS

Significant efforts have been made to develop wide-area control strategies to overcome traditional stability challenges of power systems dominated by SGs in recent years. The issues addressed include interarea oscillations, rotor angle, voltage, and/or frequency stability. However, none of the reviewed works propose control strategies that are specially designed to address the control complexities and underlying (new) stability challenges that weak low-inertia power systems with high levels of RES will experience. In this context, key factors that need to be considered in the control design are actuation delays due to signal processing; possible instabilities due to current limitation of the converters; unstable, fast, dynamic interactions due to the coupling between the converters and the grid; and the high dependency of RES dynamic performance on system strength and on their control structure and parameters.

Regarding the kind of stability being addressed, most of the reviewed works propose control strategies that improve one kind of stability, rather than proposing unified approached in which the stability of the system is considered as a whole. Although system stability has been usually classified into different categories, stability is basically a single problem. While classification of system stability is an effective and convenient means to deal with the complexities of the problem, the overall stability of the system should always be held paramount. In this context, only 17.1% of the reviewed papers addressed two or more types of stabilities. However, most of these works propose control strategies for improving the stability of conventional power systems dominated by SGs and therefore their proposals may not be suitable for low-inertia networks.

Another topic of interest for the design of WAC strategies for real-world power systems is the consideration of communication issues such as time-delays and loss of information. This review revealed that, despite acknowledged as a key aspect, almost half of the works that develop WAC strategies do not consider such issues. While the rapid integration of PMUs in power systems offers new opportunities for the development of more complex and powerful WAC strategies, communication issues may become critical and therefore further research efforts must be done to anticipate their impact.

In conclusion, this review shows that most WAC strategies proposed are validated using simplified or linearized models of power systems. We only found 7 works that validated their proposals using full dynamic models of large-scale power systems. This is a huge research gap, since in those cases the proposed performance may not be valid or have the same performance, when validated in realistic-size large-scale dynamic models of power systems.

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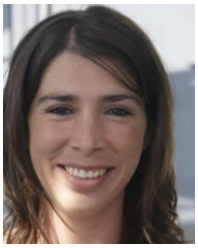

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