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Robust Control Strategies for Microgrids: A Review

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***Abstract*—Microgrids consisting of photovoltaic (PV) power plants and wind farms have been widely accepted in power systems for reliability enhancement and power loss reduction. Microgrids are capable of providing voltage and frequency support, improving power quality, and achieving proper power-sharing. To achieve such goals and deal with the nonlinear behavior in such systems, appropriate robust control strategies are required to be adopted. This article presents a comprehensive review of robust control methods for microgrids, including AC, DC, and hybrid microgrids, with different topologies and different types of interconnection to conventional power systems based on recently published research studies. The main control objectives, along with proposed control methods, are comparatively discussed for different types of microgrids. Furthermore, several research gaps in this area related to the scalability, robustness assessment, and evaluation approach are discussed. Recommendations are made that can potentially open new research lines to enhance the effectiveness of robust controllers for AC, DC, and hybrid microgrids.**

***Index Terms*—AC microgrids, DC microgrids, distributed generations (DGs), hybrid microgrids, nonlinear control, renewable energy resources (RESs), robust control.**

I. Introduction

A. Motivation

THE population growth and urban and rural development have increased society's needs for more electricity. These days, environmental issues, as well as the huge cost of development of traditional power systems, have caused more tendency to use renewable energy sources (RESs), such as solar and wind, to generate more electricity. Despite many advantages of RESs, such as reducing carbon dioxide (CO_2) generation from power generation units, reducing power losses and voltage drop, delivering power to the new load centers that are geographically located far from power grids, the costs of investment, and maintenance of such energy sources are high [1]. Besides, the uncertainty of RESs and the nonlinear nature of generation facilities impose unprecedented changes on improving the control performance [2]–[5]. To deal with the above-mentioned drawbacks, it is mandatory to design and implement efficient and proper control techniques. Robust control techniques are the best solutions to overcome uncertainty, disturbance, and the nonlinear nature of RESs. With the increasing use of distributed generations (DGs), many good attempts are made to design robust controllers and implement various robust control algorithms. Such measures have been taken for both AC and DC microgrids, under islanded and grid-connected modes of operation [6]–[8]. A powerful robust controller/control algorithm should be capable of considering all parameters to efficiently stabilize the microgrid under different operating conditions.

In most of the research studies conducted in the field of robust control methods for the operation of AC, DC, and hybrid microgrids in power systems, it is tried to consider all the existing uncertainties [7], [8]. However, external disturbances have significant impacts on the accuracy and performance of the controllers. It is worth mentioning that there are various disturbances on microgrids, and such disturbances can be either internal or external factors that can directly affect the stability of microgrids. The main aim of some research studies was to stabilize the operation of microgrids by eliminating external disturbances (chattering) [9]. It is also noticed that most of the designed robust controllers in the past few years have better efficiencies and performance compared to the other controllers, such as conventional proportional-integral-derivative (PID) controllers.

B. Major Challenges in Microgrids Deployment

There are several challenges in AC, DC, and hybrid microgrids deployment in power systems, in which the most important one is energy balancing. Energy balancing in power systems requires a proper control structure. Such structures of microgrid control systems, e.g., hierarchical structure, run autonomously and intelligently to control and manage energy dispatch, and improve the reliability of power systems. Fig. 1 shows the hierarchical structure of a microgrid control system that operates based on three control levels, called primary, secondary, and tertiary control. Increasing the control level leads to a decrease in the

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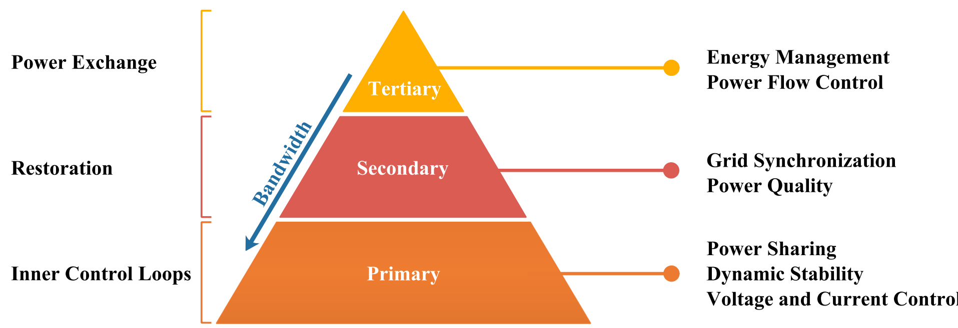

Fig. 1. Hierarchical structure of a microgrid control system.

bandwidth to properly decouple the dynamics of various levels. In fact, higher control levels require to be relatively an order of magnitude slower compared to the downstreaming levels.

Except for energy balancing, there are other challenges in microgrids operation, which are as follows:

- decentralized structure of microgrids, which requires developing new controllers;
- accurate power-sharing for microgrids;
- optimization for control and operation of microgrids;
- voltage/frequency control of AC, DC, and hybrid microgrids;
- impact of external disturbances on control and operation of microgrids;
- uncertainties in energy supply and load demand;
- integration and interoperability of microgrids;
- stability issues in microgrids; and
- fast distributed current sharing in DC microgrids.

In detail, the above-mentioned challenges that arise in microgrids control can be related to different control layers, as follows:

1) Bidirectional Power Flow: While power distribution feeders were initially designed for unidirectional power flow, integration of DGs at low voltage levels can cause reverse power flows and lead to complications in protection coordination, undesirable power flow patterns, fault current distribution, and voltage control [10], [11]. The power flow control and protection are referred to as tertiary and primary control layers, respectively.

2) Stability Issues: Local oscillations may emerge from the interaction of the control systems of DGs, requiring a thorough small-disturbance stability analysis. Moreover, transient stability analysis is required to ensure a seamless transition between the grid-connected and stand-alone modes of operation in a microgrid [12]. Stability issues refer to the primary control layer.

3) Low Inertia: Unlike bulk power systems, where a high number of synchronous generators ensure relatively large inertia, microgrids might show low inertia characteristics, especially if there is significant sharing of power electronic-interfaced DGs. Although such an interface can enhance the system's dynamic performance, low inertia in the system can lead to severe frequency deviations in stand-alone operation if a proper control mechanism at the secondary control layer is not implemented [13]–[18].

4) Uncertainty: Due to their random input variations, power generation sources connected to microgrids produce randomly varying and fluctuating power, frequency, and voltage [19], [20]. Consumers, however, expect constant voltage and frequency. Therefore, it is a challenging task to provide smooth and steady power to consumers from power generation systems. Controllers at the secondary level via the primary level can deal with power, frequency, and voltage fluctuations.

5) Power Quality Issue: During a faulty condition, various DGs may face severe power quality issues in terms of undesirable voltage sags. In addition, the DC-link voltage, inverter, and DC/DC converter can also be affected [20]. This means that DGs should be transiently stable and have the ability to maintain fault ride-through capability. Furthermore, DGs must maintain grid code requirements [19]. Power quality issue is referred to as secondary control level.

If robust and efficient control methods are not adopted, such issues may cause serious consequences, and in the worst-case scenario, they may lead to power systems blackout. It should be noted that the above-mentioned issues affect the microgrid by itself, as well as power systems and consumers. Many research studies are available in terms of developing control approaches, optimization techniques, operation, etc. [21]–[24]. Also, different configurations for AC, DC, and hybrid microgrids are considered to increase their penetration into power systems considering the design complexity, the stability of the system, and performance [25]–[27].

A comprehensive review on centralized, decentralized, distributed, and hierarchical control schemes of microgrids, emphasizing their applicability and performances is performed in [28]. The adaptive and intelligent methods for microgrid control are introduced in [29], and the main focus is to use intelligent algorithms to automatically tune the control parameters, achieving stability and reliability under the stand-alone operation mode. The performance of the microgrid voltage controllers in the presence of unmodeled dynamics is investigated in [30]. Also, developments in the hierarchical control structure consisting of primary, secondary, and tertiary layers are reviewed in [31]. In addition, voltage and frequency issues in the microgrid with a large number of power electronics converters are discussed in grid-forming, grid-feeding, and grid-supporting scenarios originating from the industrial side. The controller is designed based on a linearized system model neglecting uncertainty. Linear system control is a well-developed field, but the system model is linearized at a given point. When a large disturbance occurs, the linearized model may be inaccurate. In principle, the nonlinear model is more accurate when the state variables vary in a wider range. It should be noted that in microgrids, at the primary control level, fast reactions, and therefore, linear controllers are needed, but at the higher control levels, it is mandatory to use nonlinear controllers. Although research studies are carried out in the area of AC, DC, and hybrid microgrids, there is no comprehensive and detailed review of robust control methods for the operation of such microgrids in power systems. Hence, this article aims at providing a comprehensive literature review on robust control techniques, mainly nonlinear approaches, for the operation of AC, DC, and hybrid microgrids in power systems. To the best of the authors' knowledge, the literature review in this field remains blank.

The rest of the article is organized as follows. Section II describes an overview of robust control methods for microgrids. Sections III and IV provide comprehensive and detailed reviews of robust control methods for microgrids and multi-microgrids, respectively. A summary of the reviewed research studies, research gaps, and discussions is given in Section V. Section VI provides the recommendations for future research. Finally, Section VII indicates the conclusions of this article.

II. An Overview of Robust Control Methods for Microgrids

As mentioned, the decentralized and hybrid structures of microgrids, accurate power-sharing, voltage and frequency control, and stability are the major challenges in the operation of AC, DC, and hybrid microgrids.

To control the voltage and/or frequency in microgrids, several attempts are made. In [32], a robust PID controller based on Cohen–Coon (CC) tuning method is developed to control the AC voltage in AC microgrids. An observer controller is proposed in [33] for secondary AC voltage and frequency control in autonomous AC microgrids to overcome possible limitations in this regard. A dynamic event-triggered robust secondary frequency control for islanded AC microgrid is proposed in [34] to overcome the uncertainty in the energy supply of RESs. To synchronize hybrid microgrids and control the frequency, a multiagent asynchronously compensated (MAAC) control method is presented in [35]. In [36], a virtual inertia controller is developed to deal with the large frequency fluctuations while controlling AC microgrids and improve their stability. An integrated hybrid microcontroller frequency control based on Kharitonov theory (KT) is proposed in [37] while considering the time delay of communication channels and uncertainties in the system's parameters. In [38], the direct droop control method for frequency control of islanded microgrids is presented. A fully distributed secondary control (DSC) method aiming at restoring the AC voltage and frequency in islanded AC microgrids is developed in [39]. Controlling the secondary frequency considering the clock drift phenomenon and its impacts on the secondary frequency are investigated in [40]. A centralized controller for accurate DC voltage regulation in DC microgrids considering the uncertainty in the system's parameters is proposed in [41]. To control the frequency and AC voltage of a DC microgrid, a control method using a consensus-based control scheme is studied in [42]. A robust DSC method using active disturbance rejection control (ADRC) to restore the AC voltage of an islanded microgrid is presented in [43]. A nonlinear input-to-state stability (ISS) Lyapunov-based controller to stabilize the DC voltage of the DC microgrid and provide the frequency support to AC grids in grid-connected mode is proposed in [44]. In [45], a nonlinear and finite DSC method to coordinate all DGs in AC microgrids and control the AC voltage and frequency is proposed. A robust nonlinear decentralized control scheme for islanded DC microgrids to achieve the desired voltage at the DC bus, as well as maintain power balance, is developed in [46]. In addition, a nonlinear robust fractional-order control (NRFOC) scheme for hybrid energy storage systems (HESSs) is proposed in [47] that has a better performance compared to the PID controllers.

To achieve an accurate power-sharing for microgrids, several research studies are conducted. A two-layer hierarchical controller to solve the power-sharing of grid-connected spatially concentrated AC microgrids is developed in [48]. In [49], a robust secondary control strategy based on high and low levels for islanded microgrids is proposed. An improved two-layer hierarchical control strategy for a three-phase four-wire microgrid under unbalanced and nonlinear load conditions using a four-leg power converter is investigated in [50]. In addition, a two-layer distributed controller for islanded microgrids is developed in [51] to control the output power of distributed energy resources (DERs), such as photovoltaic (PV) and battery energy storage systems (BESSs). The concept of power-sharing among power converters in microgrids can be extended to high-voltage applications, and hence, applying a method to solve the power flow problem in hybrid AC/DC grids is required [52]. The H_∞ control method is used as a robust scheme to control microgrids. A robust H_∞ control method for regulating the AC voltage and frequency in AC microgrids in the presence of unmodeled dynamics is proposed in [53]. Controlling the DC voltage based on the nonfragile H_∞ method in off-grid microgrids within the scenario of energy internet (EI) is investigated in [54]. A voltage and current robust controller with three degrees of freedom is introduced in [55]. A control method for adjusting the AC voltage and frequency of a microgrid in grid-connected mode using H_∞ robust controller is investigated in [56]. In [57], an H_∞ multivariable robust controller for adjusting the initial frequency in stand-alone microgrids is proposed.

Using the droop control method is another technique to control microgrids. The droop control approach is also employed for controlling converters in high-voltage and high-power applications in [58]. In [58], an improved droop-based control strategy is proposed to achieve accurate power-sharing in power systems with both conventional power sources and DERs. In [59], the stability issue of an islanded microgrid with inverter-based DGs in the low-frequency range controlled using the droop control method is investigated. A distributed finite-time control scheme based on droop for BESS-based microgrid is proposed in [60]. In [61], a droop-based controller for decentralized power-sharing in DC microgrids is developed to address the large-signal stability problem. Also, an improved droop-based control scheme for microgrids is investigated in [62] to solve the stability problem and increase the accuracy of power-sharing in grid-connected microgrids.

Another efficient technique to control microgrids is the sliding-mode control (SMC) scheme. In [63], a multifunctional control structure based on SMC, Lyapunov function, and fractional order sliding-mode controller (FOSMC) for a multi-DER microgrid is developed to control the AC voltage and improve power dispatch and stability of the system. A fully decentralized second-order SMC method to control the DC voltage of converters in DC microgrids is developed in [64]. SMC scheme is employed in [65] to improve the dynamic performance of microgrids against large disturbances. A multi-agent fixed-time control strategy based on the SMC scheme is proposed in [66] for the energy balance of BESSs and PV systems in grid-connected mode. In addition, the SMC scheme is employed in [67] to balance the power generation and consumption for a marine vessel system with different DGs as an islanded microgrid. In [68], an SMC-based control approach is employed to control the AC voltage and frequency in an islanded AC microgrid with arbitrary topology.

Except for the above-mentioned methods, the backstepping control method is another commonly used technique to control microgrids in power systems. In [69], an integral backstepping control (IBC) method for DC microgrids is introduced that includes RESs and HESSs aiming at merging several sources on a typical DC bus. In [70], an augmented backstepping control method is proposed to control the AC voltage in islanded microgrids under faulty conditions and external disturbances. A fully robust backstepping control scheme is investigated in [71] to control the DC voltage of PV systems in islanded DC microgrids considering the system's dynamics and uncertainties.

Kalman filtering and fuzzy logic are the other methods to control microgrids. A Kalman-based controller to stabilize the DC microgrid system with constant power loads (CPLs), RESs, and HESSs is proposed in [72]. A nonfragile fuzzy control method is employed in [73] to control the DC current in islanded DC microgrids. In addition, an approach based on linear programming (LP) and Chebyshev theorem is proposed in [74] to regulate the DC voltage in islanded DC microgrids.

In other research studies, robust control methods for voltage and frequency regulation, as well as power quality improvement and proper power-sharing, in multi-microgrids, are proposed. In [75], a two-stage optimal scheduling for hybrid multimicrogrids is investigated. A nonlinear fixed-structure control strategy for a transformer-like interlink converter, called transfverter, is proposed in [76] for regulating both the AC voltage and the DC voltage in hybrid AC/DC microgrids. In [77], a nonlinear state feedback control strategy is proposed for accurate power-sharing for hybrid microgrids. An optimal control strategy for grid-connected microgrids for optimal power dispatch is investigated in [78]. In addition, an optimized two-stage energy-sharing control scheme for grid-connected microgrids is proposed in [79].

In [80], an optimized information gap decision theory (IGDT) method based on augmented Lagrangian relaxation (LR)-based algorithm for optimal power dispatch in grid-connected microgrids is proposed. A semidefinite programming (SDP)-based control scheme for regulating the AC voltage and frequency in islanded microgrids is proposed in [81]. In order to regulate the AC voltage and achieve accurate power-sharing in islanded microgrids, a Takagi–Sugeno (TS) fuzzy control is proposed in [82]. It is shown in [83] that the active damping control method is capable of regulating the frequency in islanded microgrids. In [84], the DC voltage regulation and power-sharing control in islanded microgrids are performed using optimal control. In [85], the frequency-superimposed coordinated control method is used to achieve accurate power-sharing in islanded microgrids. In order to regulate the AC voltage and frequency in islanded microgrids, a bialternate sum matrix control and nonlinear ecological systems-based control methods are investigated in [86] and [87], respectively. A three-phase, improved-magnitude, phase-locked loop (3IMPLL) control scheme for accurate power-sharing in islanded microgrids is proposed in [88].

Considering power quality improvement, a critic neural networks (NN)-based adaptive dynamic programming (ADP) control method and also an affinely adjustable alternating direction method of multipliers (ADMM) control strategy are presented in [89] and [90] for islanded and grid-connected microgrids, respectively. In addition to the above-mentioned methods, model predictive-based robust control methods for the tertiary control level are employed to coordinate energy management among microgrids [91], [92], faster operation of microgrids [93], and minimizing the energy cost drawn from power grids and increasing self-consumption of local RESs [94].

III. Robust Control Methods for Microgrids

A. State-Space Control Methods

Robust PID controllers are mainly designed to control the voltage in microgrids and achieve a fast transient response and zero steady-state error. Among the most common tuning methods, including Chien–Hrones–Reswick (CHR), CC, and Wang–Juang–Chan, the CC-based PID controller shows a better performance according to [32]. In [33], an SMC-based distributed controller, along with an extended state observer, is proposed for a multiagent system in which DGs are affected by measurement noise. In [34], a secondary controller is proposed to control the frequency through a dynamic event-triggered scheme in an islanded AC microgrid. The proposed controller also controls the uncertainties coming from RESs. The lack of existence of power grids in an islanded microgrid makes the frequency control more challenging as none of the agents is grid forming. A few sets of literature take the communication delays into account in multiagent systems making the proposed controllers more practical and realistic [35]. In some control techniques, the phased locked loop (PLL) is deployed to estimate the frequency. However, using PLL can cause large fluctuations in the frequency. To combat such adverse effects and improve the frequency profile, a virtual inertia controller is designed in [36] using a robust H_∞ controller based on the linear fractional transformation technique. In [37], a control scheme is presented based on the KT to analyze the impact of communication channels' time delay and uncertainty in frequency control. In [38], a robust droop controller and an SMC-based controller for the primary and secondary levels, respectively, in an islanded AC microgrid, are presented.

One of the important challenges is to design a completely distributed secondary robust controller for voltage and frequency in islanded microgrids. A multiagent consensus-based control strategy is proposed in [39] to design a robust and adaptive secondary AC voltage and frequency control scheme for such networks. To provide a certain degree of robustness, the designed controller should consider the model uncertainty, parameter changes, and unmodeled dynamics. Due to the well-distributed control, each DG unit only needs its own information and a limited number of neighbors (depending on the control scheme), which helps to reduce bandwidth and minimize communication costs, and increases the reliability and flexibility of the microgrid. The performance of a distributed controller that can be affected by minor parameters, such as clock drift, is discussed in [40]. Although distributed controllers have recently attracted attention, centralized controllers are still being used for accurate voltage regulation in microgrids affected by DGs' uncertainties. In [41], a robust centralized controller for a DC microgrid impacted by parametric uncertainty and disturbances is proposed. A secondary control scheme, called stochastic consensus-based control approach, is proposed in [42] for islanded microgrids considering the system and communication noises. This method results in high accuracy in the estimation process, less complexity, and low computational burden for frequency and voltage restoration. Compared to existing methods, the proposed scheme can achieve mean-square synchronization for voltage and frequency restoration of DGs.

In order to minimize the amount of information exchanged among different agents in the grid, a secondary control scheme is presented in [43] that only needs information from nearby DGs through a scattered communication patch. In the proposed scheme, the ADRC technique is applied, which can partially eliminate model uncertainty, as well as unknown disturbances. An ISS Lyapunov-based nonlinear controller for a DC microgrid is proposed in [44]. The controller ensures the efficient integration of RESs and stable operation of the DC microgrid providing ancillary services to AC grids. The improved performance of the proposed controller is shown and compared with the classic proportional-integral (PI) controller under CPLs. In [45], a consensus-based secondary control scheme is proposed for chattering-free power-sharing, as well as AC voltage/frequency restoration control, using Lipchitz-continuous secondary control scheme. Also, improvements are shown in terms of the transient overshoot and convergence speed through a cumulative distribution function. A robust decentralized nonlinear controller is introduced in [46] to achieve the desired voltage at the DC bus and maintain the power balance in an islanded DC grid to which a PV unit, a fuel cell system, and a BESS, are connected along with DC loads. In this article, the parametric uncertainties are merged as unknown control inputs that are then, estimated through adaptation laws. The inherent characteristic of the employed adaptive partial feedback linearization scheme in noise decoupling makes the controller robust against external perturbations. An NRFOC approach is proposed for HESSs in electric vehicles (EVs) in [47]. The proposed NRFOC is capable of handling nonlinearities and model uncertainties through a FOPID controller as an additional input. The control cost is also compared with PID control, feedback linearization control, and SMC methods.

B. Hierarchical Control Methods

A hierarchical robust power-sharing scheme is presented in [48], considering two layers of control. The secondary control level, where DGs exchange information, acts slower than the primary level of control, where the set-points are tracked. Another two-level distributed control scheme is presented in [49], where the higher level controller shares the power accurately among power resources while minimizing the voltage and frequency deviations from reference values. The lower level control adjusts the magnitude and angle of the inverter output voltage, enabling it to track the reference power. A hierarchical distributed control technique for an islanded microgrid is proposed in [50] that controls the frequency and mitigates harmonics at the primary layer while the active power-sharing is performed at the secondary layer. The proposed controller is capable of controlling active and reactive power accurately. A two-layer distributed control scheme is introduced in [51] for an islanded microgrid to regulate the output power of DERs. As the proposed control scheme solely relies on limited aperiodic communications, the cost of communication on the cyber networks can be greatly reduced using delayed communication. This control method is used where the communication infrastructure is distributed and suffers from time delays and bandwidth limitations.

C. H_∞-Based Control Methods

In [53], an H_∞-based robust control technique is proposed, and its effectiveness is evaluated under unbalanced and nonlinear loads in a microgrid. In [54], a nonfragile robust H_∞ control within the scenario of EI in an islanded microgrid is used to adjust the DC bus voltage while the system is robust against external disturbances and modeling uncertainties. The state equations are presented by a class of nonlinear stochastic differential equations while the parametric uncertainties are merged in coefficients. A cascaded voltage/current robust control strategy is introduced in [55] with an emphasis on improving the power quality delivered to loads from DGs. Designed via the H_∞, the proposed controller possesses three degrees of freedom. To achieve the set goals and design a robust controller, one needs to choose the most appropriate weight functions. An H_∞ robust controller for regulating the AC voltage and frequency in a microgrid is evaluated in [56] under different loading conditions, and its performance is compared with the droop control. In this method, a multilevel control method, including a droop control loop, voltage control loop, current control loop, and control loop for inductance–capacitance–inductance filter and coupling circuit, is proposed. Also, the incorporation of the harmony search algorithm (HSA) leads to a better adjustment. A multivariable H_∞-based controller is proposed in [57] to mainly adjust the frequency in a PV-diesel hybrid power system operating in stand-alone mode. The controller is designed using linear matrix inequalities (LMIs). Uncertainties in the state-of-charge (SoC) of supercapacitors are considered using μ-analysis. It is shown that the proposed H_∞ controller maintains stability in the presence of disturbances and SoC uncertainties.

D. Droop-Based Control Methods

In [58], an improved droop-based control strategy for the integration of RESs to the medium- and high-voltage buses in power systems is proposed. To achieve proper power-sharing, the proposed method uses DC voltage-droop, AC voltage-droop, and frequency-droop controllers simultaneously along with optimal tuning of the PI controllers. In [59], a robust two degrees of freedom decentralized droop controller is proposed, which is a combination of a conventional droop and a robust transient droop function. To mitigate low-frequency oscillations, robust

D-stability analysis is performed incorporating Kharitonov's stability concept. In [60], a droop-based control is applied to a small-scale system that is made up of heterogeneous BESSs. The proposed technique is fully distributed through a sparse communication network. The distributed control method is based on a hierarchical control structure that can achieve energy level balance and active/reactive power dispatch, as well as voltage/frequency synchronization. Neglecting the global information, this controller is capable of greatly reducing the computational and communication load compared to the centralized methods and also showing robustness. To address concerns about the stability of a self-disciplined microgrid that allows plug and play for different DGs, a droop-based decentralized controller is presented for DC microgrids considering the large-signal stability in [61]. In the proposed scheme, a nonlinear disturbance observer (NDO) is used to estimate the interactions among different agents. The uncertainty of the parameters is compensated by the NDO and makes the system robust against the parametric uncertainties.

A combination of secondary communication-based control and droop control can be suitable for maintaining a constant voltage and frequency at point of common coupling (PCC) along with the power-sharing among DGs. However, this can be threatened by slow dynamic operation and communication errors. An improved droop-based control is suggested in [62] to improve the dynamic behavior and enhance the power-sharing accuracy in autonomous microgrids. Compared to a conventional droop controller, the proposed controller provides a faster response. This is due to the fact that it does not require low-pass filters. This method performs power-sharing effectively. However, it suffers from the line impedance variation. To reduce such deviations, as well as to optimize then the voltage and frequency setting, an improved *dq* secondary controller is suggested.

E. Sliding Mode Control-Based Control Methods

To enhance the power-sharing and stability of the system, an efficient decentralized robust power/current/AC voltage/frequency control strategy is presented in [63], and its performance is evaluated under unbalanced loads. Three separate controllers are designed based on the SMC, Lyapunov function theory, and FOSMC in order to improve power-sharing and regulate voltage and active/reactive power. In [64], a decentralized second-order SMC-based control method is applied to boost converters in a DC microgrid to regulate the DC voltage. The proposed controller generates continuous inputs that can be used as duty cycles for boost converters. The effectiveness of the proposed scheme is evaluated under unknown load demand and modeling uncertainties. A robust control algorithm for multifunctional grid-tied inverters under an unbalanced loading condition is proposed in [65] by incorporating the instantaneous power theory. A positive fundamental components estimator (PFCE) is used to estimate the undesired components of the load current, such as harmonics, reactive power, and negative sequence component. An efficient SMC method is also used as a DC bus regulator. In addition to injecting active power, the algorithm allows the multifunctional grid-tied inverter to manage reactive power, reduce harmonics, and balance the load. In the proposed algorithm, the weighted average voltage converges to the weighted average of the reference voltage in the microgrid. A second-order SMC method is used, which may lead to an increase in power losses. To solve this problem, in addition to the second-order SMC method, a third-order SMC method is also recommended, which continuously receives the control signal that can be used as a duty cycle. The distributed multiagent fixed-time control strategy presented in [66] regulates the AC voltage, frequency, charge balance, and reactive power in a microgrid considering communication delays. A fixed-time SMC method balances the charge mode using a fixed-time observer. Based on the distributed control system model, it restores the frequency, adjusts the average voltage to its nominal value, and achieves an accurate power-sharing. This strategy ensures robustness to load changes, as well as intermittencies in the PV system. A nonlinear SMC method is tested on a shipboard microgrid proposed in [67] to control the secondary load frequency. A combination of the sine cosine algorithm (SCA) and the wavelet mutation (WM), called SCAWM, is used to optimize the performance of the proposed controller and reduce the complexities. Robust control of an islanded AC microgrid with arbitrary topology is discussed in [68]. Using the second-order SMC-based control approach and AC voltage measurement, without the need for communication networks among DGs, the asymptotic stability of the system is ensured.

F. Backstepping-Based Control Methods

An IBC method is proposed in [69] for a DC microgrid, and its performance is compared with other control schemes. The controller is designed to adjust the DC bus voltage for wind, PV, and HESSs. A backstepping-based fault-tolerant control algorithm is introduced in [70] for an islanded microgrid. The proposed controller robustly regulates the AC voltage of the microgrid irrespective of the faults and disturbances and improves the reliability of the system. As opposed to many droop and nondroop control strategies requiring a precise model of the system, the nonlinear backstepping-based control method proposed in [71] takes the uncertainties and dynamics into account using a disturbance observer. Also, local quantities measurement leads to faster response in tracking the reference values.

G. Other Approaches

In [72], the cubature Kalman filter (CKF) approach is used to stabilize a DC microgrid with CPLs, DGs, and BESSs. This method uses CKF and LMI to optimize the power buffer design. The proposed model does not require Jacobian and Hessian matrices, leading to a less computational burden. Also, the robustness of the method is evaluated against uncertainties. The stability of a DC microgrid is assessed through a robust nonfragile fuzzy control method in [73]. The proposed technique takes the parametric uncertainties, CPL characteristics, and inaccuracies in models into account. By incorporating the exponential stability analysis and TS fuzzy modeling, rapid stabilization is achieved. Additionally, using the Lyapunov-based approach leads to better accuracy in terms of considering nonlinearities in the system. DC microgrid stability analysis can be more challenging when constant DC power loads are being fed due to their destabilizing effects on the system. The method presented in [74] is an efficient robust controller combined with an LP approach and Chebyshev theorem to solve the problem of LMI optimization that can reduce the destabilizing effects of CPLs.

IV. Robust Control Methods for Multi-Microgrids

An optimal two-stage robust scheduling for hybrid multimicrogrids is proposed in [75]. In this method, in addition to the uncertainties in the source-load, the tie-line disconnection uncertainties are also taken into account that improves the robustness of the method. Stiff voltage sources pose a challenge for interlink converters in hybrid microgrids. In [76], a transfverter is proposed that acts as a transformer and converter linking AC and DC grids together. The transfverter, the same as a transformer and converter, can reflect the voltage stability of the other side. This article proposes a robust control structure for interlink converters that are optimized for all of the three modes of a hybrid AC/DC microgrid, including balanced, AC dominant, and DC dominant. A new design based on the concept of state feedback control is presented in [77] that can be applied to bidirectional interlink converters in hybrid microgrids. The method uses Lie derivatives for linearization and considers model/parametric uncertainties. It is also shown that using approximate parameters, the nonlinear model of the interlink converter can be represented by two separate subsystems. Accordingly, a high-gain PI observer and a virtual state feedback controller are designed to control each subsystem.

In [78], a robust optimal control strategy for BESSs within grid-connected microgrids is presented. It is shown that the proposed method guarantees the highest economic benefit for the system even under the worst-case net demand prediction error conditions. A two-stage power-sharing framework is presented in [79] for prosumer-based microgrids with RESs, multiple HESSs, and load shifting. In this article, both the uncertainties of market prices and the PV energy forecasting are considered. The proposed algorithm continuously optimizes the energy schedule and also predicts errors. A robust optimization scheme for multi-microgrids active distribution grids is provided in [80]. The model is designed to take the uncertainties in the market price, RESs, and loads into account. In this proposed method, a fully distributed model is presented that does not require a central controller. An optimized IGDT method is also used to model uncertainties. Finally, the central hybrid robust optimization model is split using an augmented LR-based algorithm and a heuristic approach. A robust control strategy for an islanded multi-microgrids is proposed in [81] using a decoupling algorithm for DGs with arbitrary topology. There is also a fixed control structure and a new SDP-based approach used for compensatory design to ensure the level of decoupling of the microgrid channels considering the uncertainties. A fuzzy-based decentralized control strategy for multiagent islanded microgrids is proposed in [82] considering the system dynamics and uncertainties. The TS fuzzy approach is applied to achieve stability and optimal performance of microgrids. The control method is combined with a convex optimization problem and LMI formulation. An approach to mitigate the resonance phenomena in islanded multi-microgrids is provided in [83]. In addition, a detailed scheme is developed to assess the dynamics behavior of DGs. The proposed model shows that the resonant characteristics of islanded microgrids cause variable frequency behavior due to the complex resonance at harmonic and subharmonic frequencies. To avoid such resonances, a damping method based on a robust distributed observer is proposed that can enhance the stability of microgrids. The proposed method is robust against changes in system and load parameters and can reconstruct undesirable resonance disorders without knowing the system parameters and frequencies.

A distributed control scheme is discussed in [84] for multiagent DC microgrids. In addition to adjusting the DC-link voltage, the proposed scheme shares the power among different agents while the uncertainties in the load demand, power generation, and modeling are all taken into account. It also prioritizes the use of resources. A coordinated robust control technique for microgrids is presented in [85] by introducing the concept of virtual frequency. In the proposed method, the low-voltage virtual frequency is injected into the main DC grid. The proposed technique dispatches the power among BESSs within the grid through interactions between a master controller and slave control units without using any virtual resistance in the network. A robust stability analysis is presented in [86] based on the bialternate sum matrix approach to identify the stable region of microgrids considering the parametric uncertainty. The main advantage of this method is the less computational time compared to other techniques. In order to evaluate the robustness and stability of microgrids with mixed DERs, i.e., inverter-based and synchronous generator-based, in [87], a robust control method based on concepts derived from ecological systems is studied. The best possible configurations of microgrids are determined based on how the interactions and interconnections among subsystems affect the stability of the system.

A 3IMPLL control algorithm is presented in [88] that provides improved steady-state performance, as well as fast dynamic response. This control algorithm can reduce unbalanced components from input signals. The proposed control method adjusts microgrids' AC voltage and frequency, and maximum power is achieved through the converters. There is also a synchronous reluctance generator (SyRG)-based pico-hydro system that feeds the nonlinear load. The converter can meet nonlinear load current conditions. The control method is capable of harmonics elimination, reactive power compensation, and load balancing. A critic NN-based ADP robust control strategy for multiplayer linear systems with input disturbances is proposed in [89]. This controller is combined with a reinforcement learning method. Compared to the traditional SMC-based control strategy, this method generates a continuous-time control signal while preventing disturbances. This algorithm is mainly presented to solve the Hamilton–Jacobi equations, along with reducing the complexity of the calculations and preventing approximate errors. The discussion of coordination for the use of prosumer-owned DERs by not violating power grid constraints is a challenging task. However, such coordination is difficult due to the uncertainty of PV units and prosumer loads, as well as their distributed nature. To solve the mentioned problems, an affinely adjustable robust approach based on the ADMM algorithm is proposed in [90]. This approach is more flexible to predict deviations.

V. Summary and Discussions

Fig. 2 illustrates the flowchart of robust control strategies for microgrids. The majority of the robust controllers for microgrids

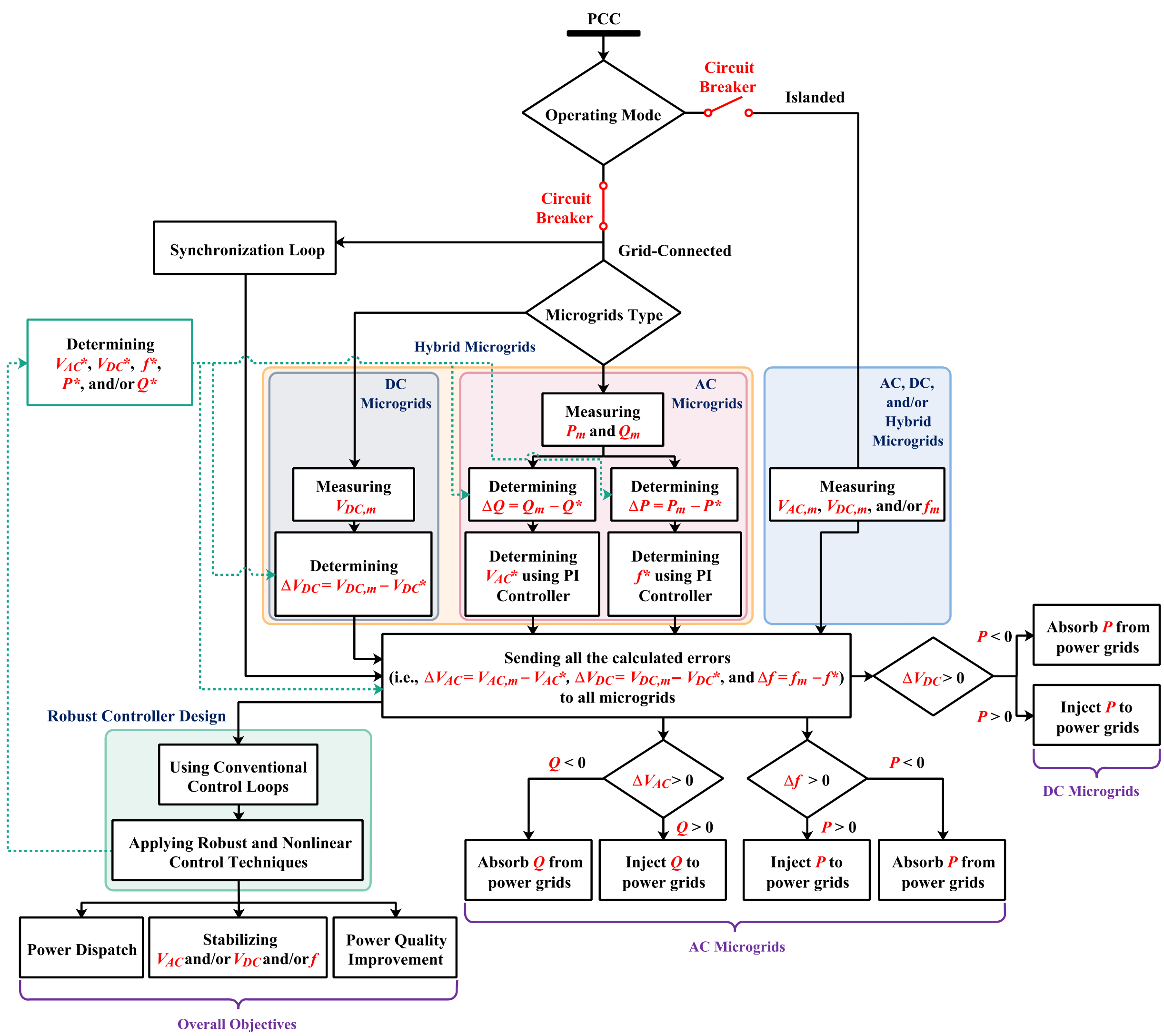

Fig. 2. Flowchart of robust control strategies for microgrids.

in the literature have the same structure as shown in Fig. 2. In this figure, P_m, P^*, Q_m, and Q^* represent the measured active power, reference active power, measured reactive power, and reference reactive power, respectively, and V_{AC}^*, V_{DC}^*, and f^* are the reference AC voltage, reference DC voltage, and reference frequency, respectively. The measured values of AC voltage, DC voltage, and frequency are indicated by $V_{AC,m}$, $V_{DC,m}$, and f_m, respectively. In addition, ΔV_{AC}, ΔV_{DC}, and Δf are the calculated error of the AC voltage, DC voltage, and frequency, respectively. According to Fig. 2, when the microgrid operates in grid-connected mode, the active and reactive power can be controlled by adjusting the frequency, i.e., phase changes in the steady-state, and the AC voltage magnitude inside the microgrid, respectively. When the microgrid comprises both AC and DC sources, the DC voltage magnitude should be also adjusted. To prevent voltage and frequency instability and improve the power quality, a centralized controller, which uses internal control loop controllers principles, at the tertiary level that sends the reference signals should be disconnected during islanding. The synchronization loops are being used to maintain the microgrid synchronized with the grid. Robust controllers are designed when the calculated errors, i.e., ΔV_{AC}, ΔV_{DC}, and Δf, which are sent to all microgrids, become available and are fed into the control loops. Adopting and implementing an appropriate robust control method leads to proper active and reactive power dispatch, stabilizing the AC voltage and/or DC voltage and/or frequency and mitigating their changes, improving the power quality, etc. It should be noted that depending on the characteristics of the designed controller and availability of the measuring devices, the calculated errors may vary. Active and reactive power control in microgrids is a function of frequency and voltage deviations control. Since the frequency is zero in DC microgrids, the DC voltage plays an important role in active power flow control. If the DC voltage deviations in DC microgrids are greater than zero, using Kirchhoff's current law, the active power can be calculated, where $P > 0$ shows there is excess active power that should be injected into power grids and $P < 0$ indicates that there is active power deficiency and microgrids should absorb power from power grids (or any other sources from neighbors). On the other side, since the frequency and AC voltage are, respectively, the determining factors of active and reactive power flow control in AC microgrids, by calculating/measuring their

TABLE I
THE SUMMARY OF THE EXISTING ROBUST CONTROL METHODS FOR THE OPERATION OF MICROGRIDS IN POWER SYSTEMS

Reference	Type of Microgrids	Structure	Operating Mode	Main Control Objective(s)	Proposed Method
[8]	AC Microgrids	Decentralized	Grid-Connected	AC Voltage and Frequency	State Feedback Control
[9]	AC Microgrids	Centralized	Islanded	AC Voltage and Frequency	Master-Slave Synchronization Control
[32]	AC Microgrids	Decentralized	Islanded	AC Voltage	PID Control Based on Cohen-Coon Algorithm
[33]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	ESO-Based Distributed Control
[34]	AC Microgrids	Centralized	Islanded	Frequency	Dynamic Event-Triggered Control
[35]	AC Microgrids	Decentralized	Grid-Connected	Frequency	MAAC Control
[36]	AC Microgrids	Centralized	Islanded	Frequency	Virtual Inertia Control
[37]	Hybrid Microgrids	Decentralized	Islanded	Frequency	PI Control Based on KT
[38]	AC Microgrids	Decentralized	Islanded	Frequency	Direct Droop Control
[39]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Multi-Agent Consensus-Based Control
[40]	AC Microgrids	Centralized	Grid-Connected	Frequency	Distributed Averaging Integral Control
[41]	DC Microgrids	Centralized	Islanded	DC Voltage	LMI Control
[42]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Stochastic Consensus-Based Control
[43]	AC Microgrids	Decentralized	Islanded	AC Voltage	ADRC-Based Distributed Control
[44]	DC Microgrids	Decentralized	Grid-Connected	DC Voltage and Frequency	ISS Lyapunov-Based Control
[45]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Lipchitz-Continuous Secondary Control
[46]	DC Microgrids	Decentralized	Islanded	DC Voltage and Power Dispatch	Adaptive Partial Feedback Linearizing Control
[47]	Hybrid Microgrids	Decentralized	Islanded	Battery Current	NRFOC Control
[48]	AC Microgrids	Centralized	Grid-Connected	Power Dispatch	Two-Layer Hierarchical Control
[49]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Distributed Discrete Two-Level Control
[50]	AC Microgrids	Decentralized	Islanded	Frequency and Power Dispatch	Improved Hierarchical Distributed Control
[51]	AC Microgrids	Decentralized	Islanded	Power Dispatch	Two-Layer Self-Consistent Control
[53]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	H_∞ Control
[54]	DC Microgrids	Decentralized	Islanded	DC Voltage	Non-Fragile H_∞ Control
[55]	AC Microgrids	Decentralized	Grid-Connected	Power Quality	H_∞ Three Degrees of Freedom Control
[56]	AC Microgrids	Decentralized	Grid-Connected	AC Voltage and Frequency	Multi-Stage H_∞ Control Based on HSA
[57]	AC Microgrids	Decentralized	Islanded	Frequency	H_∞ Multi-Variable Control
[59]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Two Degrees of Freedom Droop Control
[60]	AC Microgrids	Decentralized	Grid-Connected	Power Dispatch and Power Quality	Distributed Finite-Time Droop-Based Control
[61]	DC Microgrids	Decentralized	Islanded	Power Dispatch	Droop-Based Control
[62]	AC Microgrids	Decentralized	Grid-Connected	Power Dispatch and Power Quality	*DQ*-Voltage Droop-Based Control
[63]	AC Microgrids	Decentralized	Grid-Connected and Islanded	AC Voltage and Power Dispatch	Improved Hierarchical SMC-Based Control
[64]	DC Microgrids	Decentralized	Islanded	DC Voltage	Decentralized Second-Order SMC-Based Control
[65]	AC Microgrids	Decentralized	Grid-Connected	DC Voltage and Power Dispatch	PFCE-SMC-Based Control
[66]	AC Microgrids	Decentralized	Grid-Connected	AC Voltage and Frequency	Nonlinear SMC-Based and Distributed Control
[67]	AC Microgrids	Decentralized	Islanded	Frequency	Multiobjective SCAWM Control
[68]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Second-Order SMC-Based Control
[69]	DC Microgrids	Decentralized	Islanded	DC Voltage	Nonlinear Integral Backstepping-Based Control
[70]	AC Microgrids	Decentralized	Islanded	AC Voltage	Augmented Backstepping Control
[71]	DC Microgrids	Decentralized	Islanded	DC Voltage	Fully Decentralized Backstepping Control
[72]	DC Microgrids	Centralized	Islanded	DC Current	CKF Control
[73]	DC Microgrids	Decentralized	Islanded	DC Current	Non-Fragile Fuzzy Control
[74]	DC Microgrids	Decentralized	Islanded	DC Voltage	LP Based on Chebyshev Theorem
[75]	Hybrid Microgrids	Decentralized	Grid-Connected and Islanded	Power Dispatch	Bi-Level Two-Stage Optimal Scheduling Control
[76]	Hybrid Microgrids	Decentralized	Grid-Connected	AC Voltage and DC Voltage	Nonlinear Fixed-Structure Control
[77]	Hybrid Microgrids	Decentralized	Grid-Connected	Power Dispatch	Nonlinear State Feedback Control
[78]	AC Microgrids	Decentralized	Grid-Connected	Optimal Power Dispatch	Optimal Control
[79]	AC Microgrids	Decentralized	Grid-Connected	Power Dispatch	Optimized Two-Stage Energy Sharing Control
[80]	AC Microgrids	Decentralized	Grid-Connected	Optimal Power Dispatch	IGDT-Augmented LR-Based Control
[81]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	SDP-Based Control
[82]	AC Microgrids	Decentralized	Islanded	AC Voltage and Power Dispatch	TS Fuzzy Control
[83]	AC Microgrids	Decentralized	Islanded	Frequency	Active Damping Control
[84]	DC Microgrids	Decentralized	Islanded	DC Voltage and Power Dispatch	Optimal Control
[85]	Hybrid Microgrids	Centralized	Grid-Connected	Power Dispatch	Frequency Superimposed Coordinated Control
[86]	AC Microgrids	Decentralized	Islanded	AC Voltage and Frequency	Bialternate Sum Matrix Control
[87]	AC Microgrids	Decentralized	Grid-Connected and Islanded	AC Voltage and Frequency	Nonlinear Ecological Systems-Based Control
[88]	AC Microgrids	Decentralized	Islanded	Power Dispatch and Power Quality	3IMPLL Control
[90]	AC Microgrids	Decentralized	Grid-Connected	Power Quality	Affinely Adjustable ADMM Control

deviations, an overall estimation of the net energy excess and/or deficiency can be done. Considering that both the frequency and AC voltage deviations are greater than zero, active power is a function of frequency, and its positive/negative value shows that the power should be injected into/absorbed from power grids. In addition, the AC voltage can directly affect the reactive power control, where the positive/negative value of reactive power shows that the power should be injected into/absorbed from power grids.

Table I shows the summary of the existing robust control methods for the operation of microgrids in power systems. The research studies in the literature are categorized based on the type of microgrids (AC microgrids, DC microgrids, or hybrid microgrids), the controller structure (centralized or decentralized), the operating mode (grid-connected, islanded, or both), and the main control objectives (controlling AC voltage and/or DC voltage and/or frequency, power quality, and power-sharing). Considering the microgrid capacity, droop control strategies are appropriate for small-capacity microgrids at the primary level. Taking the structure of microgrids into account, at the secondary level of control, the centralized and decentralized structures are suitable for small-scale and large-scale microgrids, respectively. Finally, unlike islanded mode, grid connection requires the tertiary control.

VI. Recommendations for Future Research

For proper operation of microgrids, reliable communication infrastructure, as well as applicable control algorithms, is essential. To enhance the reliability of power systems and optimize energy dispatch, hybrid microgrids are required. To achieve these, robust control schemes should be considered for microgrids under the scenario of increasing penetration of DGs into power systems. The design complexity and cost of implementing control schemes for microgrids and their robustness against external disturbances, system modes of operation, and unpredictability of RESs are the dominant considerations to design robust controllers for microgrids. Taking the mentioned explanations into account, there are some fundamental discussions on robust control strategies for microgrids, as follows.

1) Scalability: Most of the case studies are small-scale microgrids. One of the research gaps is to make a better understanding of the applicability of the proposed approaches to larger systems when the computational burden can be a realistic concern.

2) Robustness Assessment: Robustness is a quantifiable concept. However, in many research studies, the robustness of the proposed controller is not clearly assessed. It is clear that there is not a perfect universal robust controller that would fit all needs in microgrids. Hence, the limitations of the proposed controllers should be discussed along with the conditions to which the controller is shown to be robust.

3) Evaluation Approach: Theoretical microgrids are commonly proposed as case studies to evaluate the effectiveness of control algorithms. Real-world power grids are not as clean as theoretical systems, and they contain some features that are not usually considered in generic models. For instance, in many research studies, the uncertainties of RESs are considered that are not close to uncertainties in a real-world system.

Future developments of the control systems for microgrids should be focused on the following topics.

4) Optimal Operation of Microgrids: New optimization approaches and algorithms with a view to reducing the operational costs of microgrids should be developed.

5) Real-Time Monitoring and Control of the Load Demand: Novel methods for real-time monitoring and control of the load demand should be explored. This can improve the power quality situations of future microgrids.

6) Generation Capacity Expansion: With a view to meeting customers growing demand in the future and due to the fact that control methods and their implementations considering communication infrastructure can directly affect the cost function of expansion planning, the generation capacity of microgrids should be increased using appropriate design means and considerations.

7) Microgrids Interoperability: Future microgrids should have proper interconnection and interaction capabilities toward realizing smarter power grids.

8) Model-Free Control Methods: With the growing use of microgrids, model-free control methods, such as data-driven and machine learning-based approaches, can play a key role in the control and management of microgrids in the near future. However, machine learning-based control approaches for microgrids are currently limited. Therefore, consideration of such control approaches without the need for exact models of future microgrids is highly recommended.

9) New Business Models Facilitating Transactive Energy: Future microgrids should be designed considering new business models facilitating transactive energy that can allow customers, either as individuals or in aggregate, to actively engage in energy markets by negotiating and responding to "value signals" based on demand, price, time of day, and other considerations.

10) Intelligent Energy Management System: New methods based on intelligent techniques, such as fuzzy logic and artificial neural networks, considering both technical and financial aspects should be investigated for the future energy management systems of microgrids.

11) Bulk Power Injection From Microgrids Into Power Grids Considering Power Systems Protection and Power Quality Standards: New protection methods and power quality standards, including specific indices, are required to be developed to allow for bulk power injection from microgrids into power distribution grids.

12) Bidirectional Real-Time Electricity Trade Among Prosumer-Based Microgrids and Utilities: New methods employing bidirectional capabilities should be explored for real-time electricity trade among prosumer-based microgrids and utilities' control centers.

13) Using Fast Communication Infrastructure to Reduce the Delay in Communication With Secondary and Tertiary Control Levels: In order to reduce the impact of time delays that arise inherently from communication systems, faster communication mediums, such as 5G-based technology, should be considered in future microgrids.

VII. Conclusion

This article presents an exhaustive overview of robust control schemes for AC, DC, and hybrid microgrids with different topologies and different forms of connection to power grids. For all control approaches discussed in this article, the main control target(s) and the proposed method of control are comparatively discussed. In addition, several research gaps are identified regarding case studies and evaluation approaches. New research lines are recommended to improve the performance of robust AC, DC, and hybrid microgrids controllers.

REFERENCES

[1] F. Mohammadi *et al.*, "Emerging issues and challenges with the integration of solar power plants into power systems," *Sol. Energy Convers. Commun. Springer Proc. Energy*. Cham, Switzerland, Springer, Sep. 2020.

[2] A. Abdollahi *et al.*, "Optimal power flow incorporating FACTS devices and stochastic wind power generation using krill herd algorithm," *Electronics*, vol. 9, no. 6, Jun. 2020.

[3] T. T. Nguyen *et al.*, "Optimal scheduling of large-scale wind-hydro-thermal systems with fixed-head short-term model," *Appl. Sci.*, vol. 10, no. 8, Apr. 2020.

[4] A. H. Shojaei *et al.*, "Multi-objective optimal reactive power planning under load demand and wind power generation uncertainties using ε-constraint method," *Appl. Sci.*, vol. 10, no. 8, Apr. 2020.

[5] M. Neagoe *et al.*, "A comparative analysis of the solar energy receiving share using four tracking system types at mid-latitude regions," *Sol. Energy Convers. Commun. Springer Proc. Energy*. Cham, Switzerland: Springer, Sep. 2020.

[6] C. Mehdipour *et al.*, "Design and analysis of a stand-alone photovoltaic system for footbridge lighting," *J. Sol. Energy Res.*, vol. 4, no. 2, Jun. 2019.

[7] B. M. Eid, N. A. Rahim, J. Selvaraj, and A. H. El Khateb, "Control methods and objectives for electronically coupled distributed energy resources in microgrids: A review," *IEEE Syst. J.*, vol. 10, no. 2, pp. 446–458, Jun. 2016.

[8] F. Mohammadi *et al.*, "A bidirectional power charging control strategy for plug-in hybrid electric vehicles," *Sustainability*, vol. 11, no. 16, Aug. 2019.

[9] Y. Xu, "Robust finite-time control for autonomous operation of an inverter-based microgrid," *IEEE Trans. Ind. Inform.*, vol. 13, no. 5, pp. 2717–2725, Oct. 2017.

[10] M. H. Aslinezhad *et al.*, "Over current relays protective coordination in distribution systems in presence of distributed generation," *Int. J. Tech. Phys. Probl. Eng.*, vol. 3, no. 2, Jun. 2011.

[11] H. Zayandehroodi *et al.*, "Impact of distributed generations on power system protection performance," *Int. J. Phys. Sci.*, vol. 6, no. 16, Aug. 2011.

[12] D. E. Olivares *et al.*, "Trends in microgrid control," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014.

[13] N. Soni, S. Doolla, and M. C. Chandorkar, "Improvement of transient response in microgrids using virtual inertia," *IEEE Trans. Power Deliv.*, vol. 28, no. 3, pp. 1830–1838, Jul. 2013.

[14] K. A. Alobeidli, M. H. Syed, M. S. El Moursi, and H. H. Zeineldin, "Novel coordinated voltage control for hybrid micro-grid with islanding capability," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1116–1127, May 2015.

[15] P.-H. Huang, P. Liu, W. Xiao, and M. S. El Moursi, "A novel droop-based average voltage sharing control strategy for DC microgrids," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1096–1106, May 2015.

[16] X. Tang, X. Hu, N. Li, W. Deng, and G. Zhang, "A novel frequency and voltage control method for islanded microgrid based on multienergy storages,," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 410–419, Jan. 2016.

[17] S. Riverso, F. Sarzo, and G. Ferrari-Trecate, "Plug-and-play voltage and frequency control of islanded microgrids with meshed topology," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1176–1184, May 2015 .

[18] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of power sharing control strategies for islanding operation of AC microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[19] J. G. Ndirangu, J. N. Nderu, A. M. Muhia, and C. M. Maina, "Power quality challenges and mitigation measures in grid integration of wind energy conversion systems," in *Proc. 2018 IEEE Int. Energy Conf.*, Jun. 2018, doi: 10.1109/ENERGYCON.2018.8398823.

[20] G. M. S. Islam, A. Al-Durra, S. M. Muyeen, and J. Tamura, "Low voltage ride through capability enhancement of grid connected large scale photovoltaic system," in *Proc. 37th Annu. Conf. IEEE Industr. Electron. Soc.*, Nov. 2011, pp. 884–889, doi: 10.1109/IECON.2011.6119427.

[21] J. W. Simpson-Porco *et al.*, "Synchronization and power sharing for droop-controlled inverters in islanded microgrids," *Automatica*, vol. 49, no. 9, Sep. 2013.

[22] J. Schiffer *et al.*, "*Conditions stability of droop-controlled inverter-based microgrids*," *Automatica*, vol. 50, no. 10, Oct. 2014.

[23] J. W. Simpson-Porco, F. Dörfler, and F. Bullo, "Voltage stabilization in microgrids via quadratic droop control," *IEEE Trans. Automat. Control*, vol. 62, no. 3, pp. 1239–1253, Mar. 2017.

[24] T. Morstyn, B. Hredzak, R. P. Aguilera, and V. G. Agelidis, "Model predictive control for distributed microgrid battery energy storage systems," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 3, pp. 1107–1114, May 2018.

[25] C. Kammer and A. Karimi, "Decentralized and distributed transient control for microgrids," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 1, pp. 311–322, Jan. 2019.

[26] M. Cucuzzella, S. Trip, C. De Persis, X. Cheng, A. Ferrara, and A. van der Schaft, "A robust consensus algorithm for current sharing and voltage regulation in DC microgrids," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 4, pp. 1583–1595, Jul. 2019.

[27] S. S. Madani, C. Kammer, and A. Karimi, "Data-driven distributed combined primary and secondary control in microgrids," *IEEE Trans. Control Syst. Technol.*, vol. 29, no. 3, pp. 1340–1347, May 2021.

[28] S. Sen *et al.*, "Microgrid control: A comprehensive survey," *Annu. Rev. Control*, vol. 45, Jan. 2018.

[29] M. S. Mahmoud *et al.*, "Adaptive intelligent techniques for microgrid control systems: A. survey," *Int. J. Electr. Power Energy Syst.*, vol. 90, Sep. 2017.

[30] F. R. Badal *et al.*, "A survey on control issues in renewable energy integration and microgrid," *Protection Control Modern Power Syst.*, vol. 4 no. 1, Apr. 2019.

[31] A. M. Bouzid *et al.*, "A survey on control of electric power distributed generation systems for microgrid applications," *Renewable Sustain. Energ. Rev.*, vol. 44, Apr. 2015.

[32] S. K. Sarkar *et al.*, "A comparative study of high performance robust PID controller for grid voltage control of islanded microgrid," *Int. J. Dyn. Control.*, vol. 6, Nov. 2017.

[33] P. Ge *et al.*, "Extended-state observer-based distributed robust secondary voltage and frequency control for an autonomous microgrid," *IEEE Trans. Sustain. Energy*, vol. 11, no. 1, pp. 195–205, Jan. 2020.

[34] C. Yang *et al.*, "Dynamic event-triggered robust secondary frequency control for islanded AC microgrid," *Appl. Energy*, vol. 242, May 2019.

[35] A. Khorshidi *et al.*, "Robust multi-agent asynchronously compensated decentralized frequency synchronization control scheme for microgrids," *J. Electr. Eng. Technol.*, vol. 15, Apr. 2019.

[36] T. Kerdphol, F. S. Rahman, M. Watanabe, and Y. Mitani, "Robust virtual inertia control of a low inertia microgrid considering frequency measurement effects," *IEEE Access*, vol. 7, pp. 57550–57560, 2019.

[37] A. J. S. J. Veronica *et al.*, "Robust PI controller design for frequency stabilisation in a hybrid microgrid system considering parameter uncertainties and communication time delay," *IET Gener. Transm. Distrib.*, vol. 13, no. 14, Jul. 2019.

[38] S. Roozbehani *et al.*, "Frequency control of islanded wind-powered microgrid based on coordinated robust dynamic droop power sharing," *IET Gener. Transm. Distrib.*, vol. 13 no. 21, Nov. 2019.

[39] J. Hu *et al.*, "A consensus-based robust secondary voltage and frequency control scheme for islanded microgrids," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020.

[40] A. Krishna *et al.*, "Distributed secondary frequency control in microgrids: Robustness and steady-state performance in the presence of clock drifts," *Eur. J. Control*, vol. 51, Jan. 2020.

[41] M. Mehdi *et al.*, "Robust control of a DC microgrid under parametric uncertainty and disturbances," *Electr. Power Syst. Res.*, vol. 179, Feb. 2020.

[42] N. Mahdian Dehkordi *et al.*, "Robust distributed stochastic secondary control of microgrids with system and communication noises," *IET Gener. Transm. Distrib.*, vol. 14 no. 6, Mar. 2020.

[43] M. Zhang *et al.*, "A robust distributed secondary voltage control method for islanded microgrids," *Int. J. Electr. Power Energy Syst.*, vol. 121, Oct. 2020.

[44] A. Iovine *et al.*, "Nonlinear control for DC microgrids enabling efficient renewable power integration and ancillary services for AC grids," *IEEE Trans. Power Syst.*, vol. 34, no. 6, Nov. 2019.

[45] X. Meng *et al.*, "A nonlinear, bounded and Lipchitz continuous distributed active power sharing control method for islanded AC microgrids," *IEEE Access*, vol. 7, 2019.

[46] M. A. Mahmud, T. K. Roy, S. Saha, M. E. Haque, and H. R. Pota, "Robust nonlinear adaptive feedback linearizing decentralized controller design for islanded DC microgrids," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 5343–5352, Sep.–Oct. 2019.

[47] B. Yang *et al.*, "Design and implementation of battery/SMES hybrid energy storage systems used in electric vehicles: A nonlinear robust fractional-order control approach," *Energy*, vol. 191, Jan. 2020.

[48] H. Cai and G. Hu, "Distributed robust hierarchical power sharing control of grid-connected spatially concentrated AC microgrid," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 3, pp. 1012–1022, May 2019.

[49] Y. Xu, Q. Guo, H. Sun, and Z. Fei, "Distributed discrete robust secondary cooperative control for islanded microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3620–3629, Jul. 2019.

[50] A. Naderipour *et al.*, "Hierarchical control strategy for a three-phase 4-wire microgrid under unbalanced and nonlinear load conditions," *ISA Trans.*, Vvol. 94, Nov. 2019.

[51] J. Lai *et al.*, "Robust self-consistent control of PV-battery-based microgrids without continuous communication," *Int. J. Electr. Power Energy Syst.*, vol. 119, Jul. 2020.

[52] F. Mohammadi *et al.*, "An improved mixed AC/DC power flow algorithm in hybrid AC/DC grids with MT-HVDC systems," *Appl. Sci.*, vol. 10, no. 1, Jan. 2020.

[53] S. Gholami *et al.*, "Robust multiobjective control method for power sharing among distributed energy resources in islanded microgrids with unbalanced and nonlinear loads," *Int. J. Electr. Power Energy Syst.*, vol. 94, Jan. 2018.

[54] H. Hua *et al.*, "Voltage control for uncertain stochastic nonlinear system with application to energy Internet: Non-fragile robust $H\infty$ approach," *J. Math. Anal. Appl.*, vol. 463, no. 1, Jul. 2018.

[55] A. El Moubarek Bouzid *et al.*, "Robust three degrees of freedom based on $H\infty$ controller of voltage/current loops for DG unit in micro grids," *IET Power Electron.*, vol. 12, no. 6, May 2019.

[56] B. E. Sedhom *et al.*, "Robust control technique in an autonomous microgrid: A multi-stage $H\infty$ controller based on harmony search algorithm," *Iran. J. Sci. Technol., Trans. Electr. Eng.*, vol. 44, Jun. 2019.

[57] Q. L. Lam *et al.*, "Primary frequency $H\infty$ control in stand-alone microgrids with storage units: A robustness analysis confirmed by real-time experiments," *Int. J. Electr. Power Energy Syst.*, vol. 115, Feb. 2020.

[58] F. Mohammadi *et al.*, "An improved droop-based control strategy for MT-HVDC systems," *Electron.*, vol. 9, no. 1, Jan. 2020.

[59] N. Mahdian Dehkordi *et al.*, "Robust tuning of transient droop gains based on Kharitonov's stability theorem in droop-controlled microgrids," *IET Gener. Transm. Distrib.*, vol. 12, no. 14, Aug. 2018.

[60] J. Hu and A. Lanzon, "Distributed finite-time consensus control for heterogeneous battery energy storage systems in droop-controlled microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 5, pp. 4751–4761, Sep. 2019.

[61] Q. Xu, Y. Xu, C. Zhang, and P. Wang, "A robust droop-based autonomous controller for decentralized power sharing in DC microgrid considering large-signal stability," *IEEE Trans. Ind. Inform.*, vol. 16, no. 3, pp. 1483–1494, Mar. 2020.

[62] R. M. Imran, S. Wang, and F. M. F. Flaih, "DQ-voltage droop control and robust secondary restoration with eligibility to operate during communication failure in autonomous microgrid," *IEEE Access*, vol. 7, 2018.

[63] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, "Decentralized sliding mode control of WG/PV/FC microgrids under unbalanced and nonlinear load conditions for on- and off-grid modes," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3108–3119, Dec. 2018.

[64] M. Cucuzzella *et al.*, "Sliding mode voltage control of boost converters in DC microgrids," *Control Eng. Pract.*, vol. 73, Apr. 2018.

[65] A. Safa *et al.*, "A robust control algorithm for a multifunctional grid tied inverter to enhance the power quality of a microgrid under unbalanced conditions," *Int. J. Electr. Power Energy Syst.*, vol. 100, Sep. 2018.

[66] R. Zhang and B. Hredzak, "Nonlinear sliding mode and distributed control of battery energy storage and photovoltaic systems in AC microgrids with communication delays," *IEEE Trans. Ind. Inform.*, vol. 15, no. 9, pp. 5149–5160, Sep. 2019.

[67] M.-H. Khooban *et al.*, "Robust frequency regulation in mobile microgrids: HIL implementation," *IEEE Syst. J.*, vol. 13, no. 4, pp. 4281–4291, Dec. 2019.

[68] M. Cucuzzella, G. P. Incremona, and A. Ferrara, "Decentralized sliding mode control of islanded AC microgrids with arbitrary topology," *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6706–6713, Aug. 2017.

[69] H. Armghan, M. Yang, M. Q. Wang, N. Ali, and A. Armghan, "Nonlinear integral backstepping based control of a DC microgrid with renewable generation and energy storage systems," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105613.

[70] N. Mahdian Dehkordi *et al.*, "Robust reliable fault tolerant control of islanded microgrids using augmented backstepping control," *IET Gener. Transm. Distrib.*, vol. 14, no. 3, Feb. 2020.

[71] H. Amiri *et al.*, "Fully decentralized robust backstepping voltage control of photovoltaic systems for DC islanded microgrids based on disturbance observer method," *ISA Trans.*, vol. 101, Jun. 2020.

[72] M. A. Kardan *et al.*, "Improved stabilization of nonlinear DC microgrids: Cubature Kalman filter approach," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5104–5112, Sep.–Oct. 2018.

[73] N. Vafamand, M. H. Khooban, T. Dragič ević, F. Blaabjerg, and J. Boudjadar, "Robust non-fragile fuzzy control of uncertain DC microgrids feeding constant power loads," *IEEE Trans. Power Electron.*, vol. 34, no. 11, pp. 11300–11308, Nov. 2019.

[74] K. E. Lucas-Marcillo *et al.*, "Novel robust methodology for controller design aiming to ensure DC microgrid stability under CPL power variation," *IEEE Access*, vol. 7, 2019.

[75] H. Qiu, B. Zhao, W. Gu, and R. Bo, "Bi-level two-stage robust optimal scheduling for AC/DC hybrid multi-microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 5455–5466, Sep. 2018.

[76] Y. Gu *et al.*, "Transfverter: Imbuing transformer-like properties in an interlink converter for robust control of a hybrid AC–DC microgrid," *IEEE Trans. Power Electron.*, vol. 34, no. 11, pp. 11332–11341, Nov. 2019.

[77] M. Zolfaghari, M. Abedi, and G. B. Gharehpetian, "Robust nonlinear state feedback control of bidirectional interlink power converters in grid-connected hybrid microgrids," *IEEE Syst. J.*, vol. 14, no. 1, pp. 1117–1124, Mar. 2020.

[78] J. Choi, Y. Shin, M. Choi, W. Park, and I. Lee, "Robust control of a microgrid energy storage system using various approaches," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2702–2712, May 2019

[79] S. Cui, Y. Wang, J. Xiao, and N. Liu, "A two-stage robust energy sharing management for prosumer microgrid," *IEEE Trans. Ind. Inform.*, vol. 15, no. 5, pp. 2741–2752, May 2019.

[80] R. Aboli *et al.*, "A hybrid robust distributed model for short-term operation of multi-microgrid distribution networks," *Electr. Power Syst. Res.*, vol. 177, Dec. 2019.

[81] M. Babazadeh and A. Nobakhti, "Robust decomposition and structured control of an islanded multi-DG microgrid," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2463–2474, May 2019.

[82] T. Hosseinalizadeh *et al.*, "Decentralised robust T-S fuzzy controller for a parallel islanded AC microgrid," *IET Gener. Transm. Distrib.*, vol. 13, no. 9, May 2019.

[83] A. Saim, A. Houari, J. M. Guerrero, A. Djerioui, M. Machmoum, and M. A. Ahmed, "Stability analysis and robust damping of multiresonances in distributed-generation-based islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 66, no. 11, pp. 8958–8970, Nov. 2019.

[84] M. Baranwal, A. Askarian, S. Salapaka, and M. Salapaka, "A distributed architecture for robust and optimal control of DC microgrids," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 3082–3092, Apr. 2019.

[85] P. Bhowmik *et al.*, "Frequency superimposed robust coordinated control in a hybrid microgrid," *Sustain. Cities Soc.*, vol. 51, Nov. 2019.

[86] M. C. Pulcherio, M. S. Illindala, and R. K. Yedavalli, "Robust stability region of a microgrid under parametric uncertainty using bialternate sum matrix approach," *IEEE Trans. Power Syst.*, vol. 33, no. 5, pp. 5553–5562, Sep. 2018.

[87] M. Pulcherio, M. S. Illindala, J. Choi, and R. K. Yedavalli, "Robust microgrid clustering in a distribution system with inverter-based DERs," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5152–5162, Sep.–Oct. 2018.

[88] R. Sharma, S. Kewat, and B. Singh, "Robust 3IMPL control algorithm for power management of SyRG/PV/BES-based distributed islanded microgrid," *IEEE Trans. Ind. Electron.*, vol. 66, no. 10, pp. 7765–7777, Oct. 2019.

[89] Q. Qu *et al.*, "Robust control design for multi-player nonlinear systems with input disturbances via adaptive dynamic programming," *Neurocomputing*, vol. 334, Mar. 2019.

[90] A. Attarha, P. Scott, and S. Thiébaux, "Affinely adjustable robust ADMM for residential DER coordination in distribution networks," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1620–1629, Mar. 2020.

[91] M. M. Ghanbarian *et al.*, "Model predictive control of distributed generation micro-grids in island and grid connected operation under balanced and unbalanced conditions," *J. Renew. Sustain. Energy*, Vvol. 9, no. 4, Aug. 2017.

[92] Y. Du, J. Wu, S. Li, C. Long, and I. Ch. Paschalidis, "Distributed MPC for coordinated energy efficiency utilization in microgrid systems," *IEEE Trans. Smart Grid*, vol. 10, no. 2, Mar. 2019.

[93] T. Dragičević, "Model predictive control of power converters for robust and fast operation of AC microgrids," *IEEE Trans. Smart Grid*, vol. 33, no. 7, Jul. 2018.

[94] L. G. Marín *et al.*, "Hierarchical energy management system for microgrid operation based on robust model predictive control," *Energies*, vol. 12, no. 23, Nov. 2019.