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TOPICAL REVIEW

A Comprehensive Review of Centralized Current/Power Control Schemes for Parallel Inverters and AC Microgrids

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ABSTRACT The penetration of distributed energy resources is drastically increasing in the distribution systems. Inverters are employed to efficiently process the harvested energy of these energy resources. These inverters are commonly operated in parallel with some loads to form a microgrid. The control of these inverters has become a vital component to operate their microgrid. The microgrid formed by the inverters and loads can be operated into two main modes, which are the grid-connected mode and the islanded mode. Any control (operational) scheme for the microgrid should be able to operate these inverters along with their microgrid in these two modes, and it should enable the whole microgrid to have a seamless transition from one mode to another. This paper articulates different control schemes that are employed to operate parallel/several inverters within microgrids or connected to distribution systems. There are serval classifications for these control schemes used for inverters in microgrids. The main focus of this review paper is dedicated to the centralized control (with/without inter-communications) schemes that are developed to operate several parallel inverters within the microgrid to control current, voltage, and power at different operating conditions.

INDEX TERMS Microgrids, centralized control schemes, parallel inverters, current control, voltage control, power control.

I. INTRODUCTION

The microgrid has become a new trend at low-voltage and medium-voltage levels [1], [2]. The common structure of the AC microgrid contains distributed energy resources (DER), which are commonly interfaced with inverters to manipulate the harvested energy of these sources. All inverters should be operated by the control schemes to achieve some objectives. These objectives can be summarized as,

- Adjust the voltage at the point of common coupling (PCC) with the loads' variation.
- Stabilize the frequency within the acceptable range [2].
- Share the power among the working inverters (whether equal or unequal power-sharing).
- Operate the microgrid at different modes: Islanded and grid-connected.
- Coordinate the microgrid with other microgrids or with the distribution system.
- Achieve a stable steady-state performance and a fast-dynamic performance for current, voltage, or power.

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All aforementioned objectives put much more stress on the utilized control (operational) scheme. Therefore, the control scheme of any microgrid becomes a vital component for the operation of this microgrid. Several publications have been presented to classify different control schemes for microgrid operations. Some of these publications classify the control schemes from their location with respect to their inverters as centralized and de-centralized control schemes [3], [4], [5], [6], [7]. In centralized control schemes, there is one control scheme/unit that is used to govern all inverters; it's more convenient for small microgrids. If each inverter has its own control scheme in the decentralized control scheme, this scheme becomes more suitable for medium-size and large-size microgrids [3], [4], [5], [6], [7]. Other publications classify the control schemes as schemes with inter-communications among the inverters and schemes without inter-communications among the inverters [8], [9], [10]. Another classification depends on the main functionality of the inverter in the grid such as grid-forming power inverters, grid-feeding power inverters, and grid-supporting power inverters [11], [12], [13].

Some classifications focus on hierarchical control (with more emphasis on droop control) along with its derivatives such as conventional droop control, (active power-frequency droop and reactive power-voltage magnitude droop), droop control with virtual impedance, adaptive droop control, reverse droop control (active power-voltage magnitude droop and reactive power-frequency droop), [4], [7], [14], [15]. Some other publications present a classification for the control structures and their controllers within the primary control level in hierarchical control [11], [12], [16]. These controllers are mainly utilized at the primary current/voltage control level, which may include the following: Proportional-integral controller, proportional-resonant controller, dead-beat controller, sliding mode controller, repetitive voltage control, H_∞, and weighting current distribution. The basic structure of droop control is investigated in some review publications [6], [7], [17], which cover the primary, secondary, and tertiary control levels in hierarchical control. These publications ([6], [7], [17]) investigate the typical structure of hierarchical control. Different levels of hierarchical control are typically divided and classified in the following way for AC microgrids: Primary control level is devoted to the generation of voltage and frequency references and power-sharing among inverters (islanded). The secondary control level is designed for the restoration of voltage and frequency deviations to standard values. The tertiary control level is dedicated to synchronization, seamless transition, and power flow control with the external grid.

The previous paragraph sheds light on different classifications clarifying various control schemes for microgrids. This paper articulates the central/centralized control schemes with/without inter-communications among inverters. Some review publications cover some centralized control schemes/techniques. For instance, the master-slave technique is only mentioned in [4] and [6] as a centralized control scheme. Some control schemes, which necessitate inter-communications among inverters, (such as master-slave, peak-value based current-sharing, average current-sharing, circular chain control, angle droop, and consensus-based droop), are also cited in [12] to operate inverters and to control their injected power. The master-slave and current/power-sharing control techniques for parallel inverters are reported in [15]. The master-slave, instantaneous current-sharing, circular chain control, peak-value based current-sharing, distributed control, and angle droop techniques are also cited as techniques that require inter-communications among working inverters [8], [9]. Based on the authors' best knowledge and survey, there is no comprehensive survey paper dedicated to the centralized (communication-less or communication-based) control schemes only unlike what is published about droop control along with its derivatives [4], [7], [14], [15]. In most of the publications covering the central/centralized control schemes, more emphasis is directed toward the master-slave schemes even without giving in-depth details about their versions and derivatives [15], [16]. Regarding the master-slave control schemes previously published, these master-slave schemes are classified from the inverter operation perspective as current-controlled mode and voltage-controlled mode [15]. Another classification for the master-slave schemes is given as dedicated and oscillating master units [16]. In [9], the master-slave schemes are classified from their controllers' location as schemes without a centralized controller, schemes with a centralized controller, and schemes with an auto controller.

The salient shortcoming of the published review/survey publications for the centralized control schemes is that these publications are not particularly focused on these centralized schemes [9], [12], [15], [16]. The only review publication, with the title central control [17], shows the operation of central control for the microgrid at a grid-connected mode and an islanded mode. The focus of this publication, [17], is so broad since it covers AC and DC microgrids with versatile roles of their central control, which include power quality, protection, and stability. In [17], no detailed information is given for the classification of the central control schemes/controllers.

The motivation of this presented paper is to alleviate the aforementioned drawbacks documented in the previous review/survey publications. Simply, these drawbacks are the lack of in-depth information/knowledge/classification for the centralized control schemes along with their different versions and derivatives. This paper is divided into nine sections. Section II illustrates the suggested classification of centralized control schemes. The third section covers current distribution control with its subcategories, the fourth section demonstrates instantaneous current/power control, the fifth section explains current/power accumulation control with its versions, the sixth section explicates miscellaneous control, and the seventh section gives a comparative analysis among all schemes presented from the third section to the sixth section. The eighth section shows the propounded classification of the controllers/control techniques used in the schemes presented from the third section to the sixth section. The last section concludes the findings of this review paper.

II. SUGGESTED CLASSIFICATION OF CENTRALIZED/CENTRAL CONTROL SCHEMES

Few publications cover the detailed classification for the centralized/central (with and without inter-communications) control schemes for parallel inverters and AC microgrids. The main theme of this suggested classification is the current control structure and its integration with the overall operational scheme. The suggested classification is divided into four main categories: Current distribution control, instantaneous current/power control, current/power accumulation control, and miscellaneous control. The suggested structure of centralized control is already illustrated in Fig. 1, which shows different centralized control schemes from the current/power perspective with the suggested ramification of each category. Some details for each category will be documented in the forthcoming sections.

III. CURRENT DISTRIBUTION CONTROL (1ST CATEGORY)

The control schemes of this category have the main objective of sharing the load currents with supplementary objectives of the system redundancy and regulating the system voltage. Therefore, any control scheme within this category operates the inverters such that the load currents are divided among working inverters. This category includes several subcategories such as average current-sharing [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], one cycle control [33], [34], [35], [36], circular chain control [37], [38], [39], weighted current control [40], [41], [42], and current limitation control [43], [44]. All these subcategories will be clarified later in the subsequent subsections.

A. AVERAGE CURRENT-SHARING CONTROL

The basic concept of this control scheme is to measure the load current and send a reference current to the switching modulation technique of each inverter to operate the inverter and inject an average RMS current similar to its reference. This scheme requires inter-communications among the inverters (modules). The inter-communications take place in the current-sharing bus and synchronizing reference voltage as shown in Fig. 2, which depicts the typical configuration of the average current-sharing control scheme. This injected current is generated through a current loop whose current reference may be connected to another voltage loop [18], from a frequency encoded signal [19], or from switching ripples encoded signal [20]. In [21], the voltage reference is decoupled from the current reference, (unlike [18] and [20]). The current reference of [21] has its own bus in order to achieve a fast-dynamic response toward the stepping loads. The instantaneous average-RMS output current, (the output of the current loop regulated at each switching cycle), is controlled such that it gives a better performance for equal current-sharing and voltage regulation [22].

The stability and robustness of the average current-sharing are realized by separating the current loop from the voltage loop [23], which leads to fast equal current-sharing and tight voltage regulation. The inter-communications among the inverters are emphasized in [24] in terms of two common lines: The first common line for synchronizing the voltages and the other common line for current-sharing among inverters. These common lines achieve real redundancy at the end. Minimization of the circulating current among the inverters is achieved in [25] by using the optimal control, (through adjusting the feedback gain), for the current loop such that the output current of each inverter becomes similar to the other inverters' currents. The harmonic circulating current of [26] and the fundamental circulating current of [27] are existent among the inverters due to non-synchronized PWM applied on parallel inverters [26], [27]. This circulating current is mitigated using a current feed-forward compensator and a decoupled loop for active and reactive components of the fundamental current with the average current-sharing schemes [26]. The nested structure of the voltage loop with the current loop is proposed in [28] such that the current reference is obtained from the voltage loop. This structure achieves accurate equal current-sharing and minimizes the circulating currents.

The average current-sharing is presented in [22] and [29], where all inverters share the synchronizing voltage reference and current-sharing bus. The only difference in [29] is that the control loop depends on the proportional-resonant controllers. The average current scheme presented in [30] has the capability to operate the microgrid at the grid-connected and islanded modes. A corrective feedforward term associated with the deadbeat control is used to have a fast line current response for both modes. In [30], the whole control scheme is developed in the stationary α - β frame, where the output of the current loop is augmented to the corrective term to generate a voltage reference. Two control schemes are developed in [31], at which the main difference between them is the measurement of the current; the first scheme depends on the measurements of the load current while the second scheme relies on the measurements of the total inverters' currents. In both schemes of [31], an active damping loop is employed to damp the filter resonance. Average current control of the parallel inverters is implemented in [32], where all inverters are operated at a voltage-controlled mode in the rotating d - q frame using the space vector pulse width modulation, and each current component has one PI controller. Excellent current-sharing is realized in [32] with a minimum circulating current, and consequently; the current mismatch of each inverter is less than 0.2%.

B. ONE CYCLE CONTROL

In the one cycle control scheme (OCC), the current is controlled over each switching cycle such that the injected

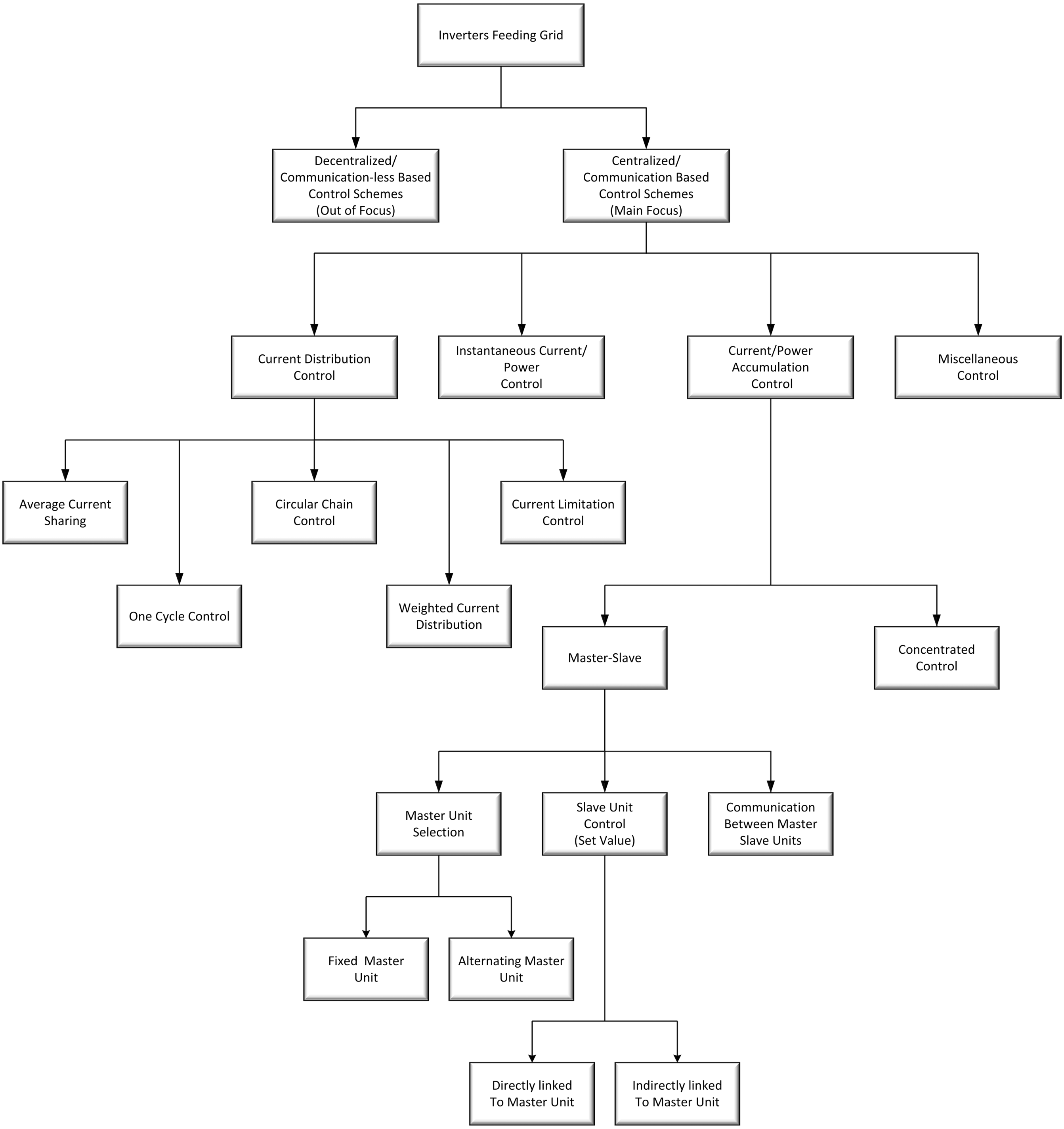

FIGURE 1. **Suggested classification for centralized control schemes.**

current is equal to its reference during steady-state and transient durations [33]. This control scheme has been applied on two inverters in [34] and [35] to equalize the current of each inverter and minimize the circulating current between inverters. In [35], the OCC scheme is combined with vector and bipolar operations, and a simple adds-on communication tool is established between inverters. In addition to the previous advantages, the low-distortion current and unity power factor are also achieved [36]. The operation of OCC presented in [34], [35], [36] is modelled in Fig. 3. The general formulation of OCC starts with defining the modulation ratios (d_{ap}, d_{bp}, d_{cp}) for the upper switches (S_{ap}, S_{bp}, S_{cp}) of the two-level inverters. So, the voltage relationship between the input modulation and the output voltage of the inverter is

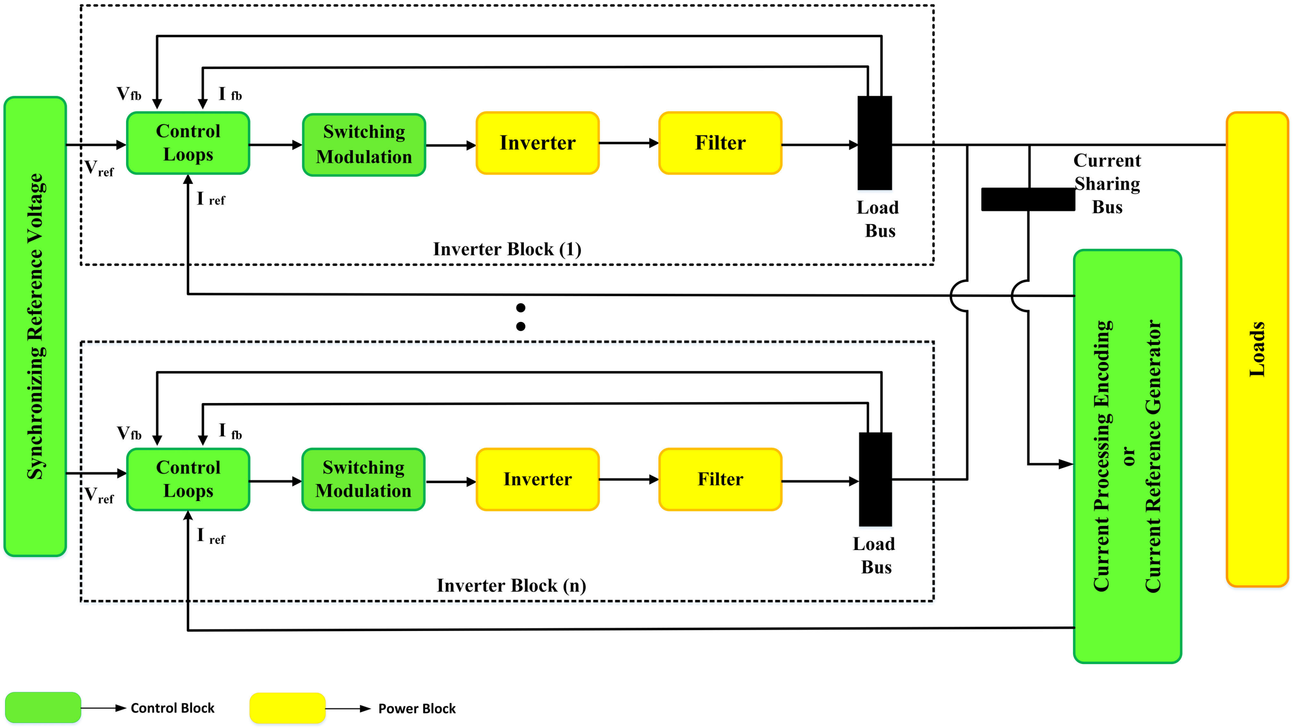

FIGURE 2. Typical configuration of average current-sharing scheme.

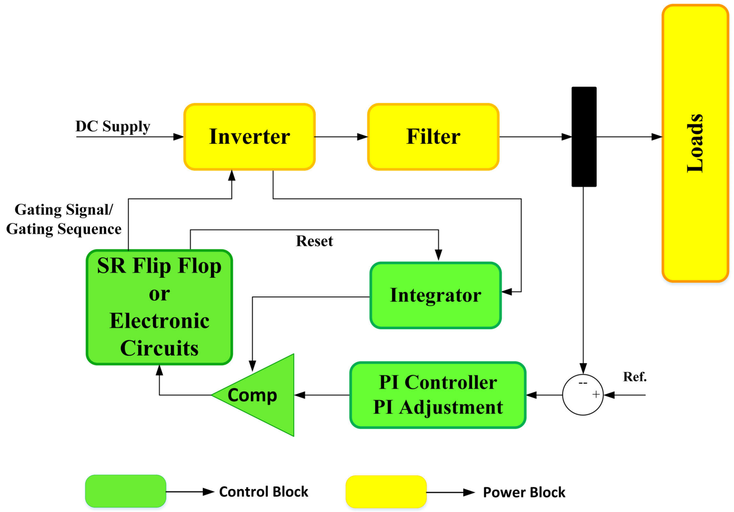

FIGURE 3. One cycle control for both vector operation and bipolar operation modes [34], [35], [36].

written as [34], [35], [36],

$$\begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} d_{ap} \\ d_{bp} \\ d_{cp} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

where E is the DC voltage and v_a, v_b, v_c are output voltages. The formula in (1) is singular, there is no unique solution. Two approaches are adopted to overcome this problem; these approaches are vector operation mode and bipolar operation mode [34], [35], [36].

C. CIRCULAR CHAIN CONTROL

The circular chain control (3C) scheme has the traditional structure of the inner current loop and the outer voltage loop. The circular chain is constructed from the connection among the inverters. The input reference current is augmented by the signal obtained from the output current of the previous inverter as shown in the typical configuration of Fig. 4 [37], [38], [39]. The output of the 3C scheme [37], [38] is compared

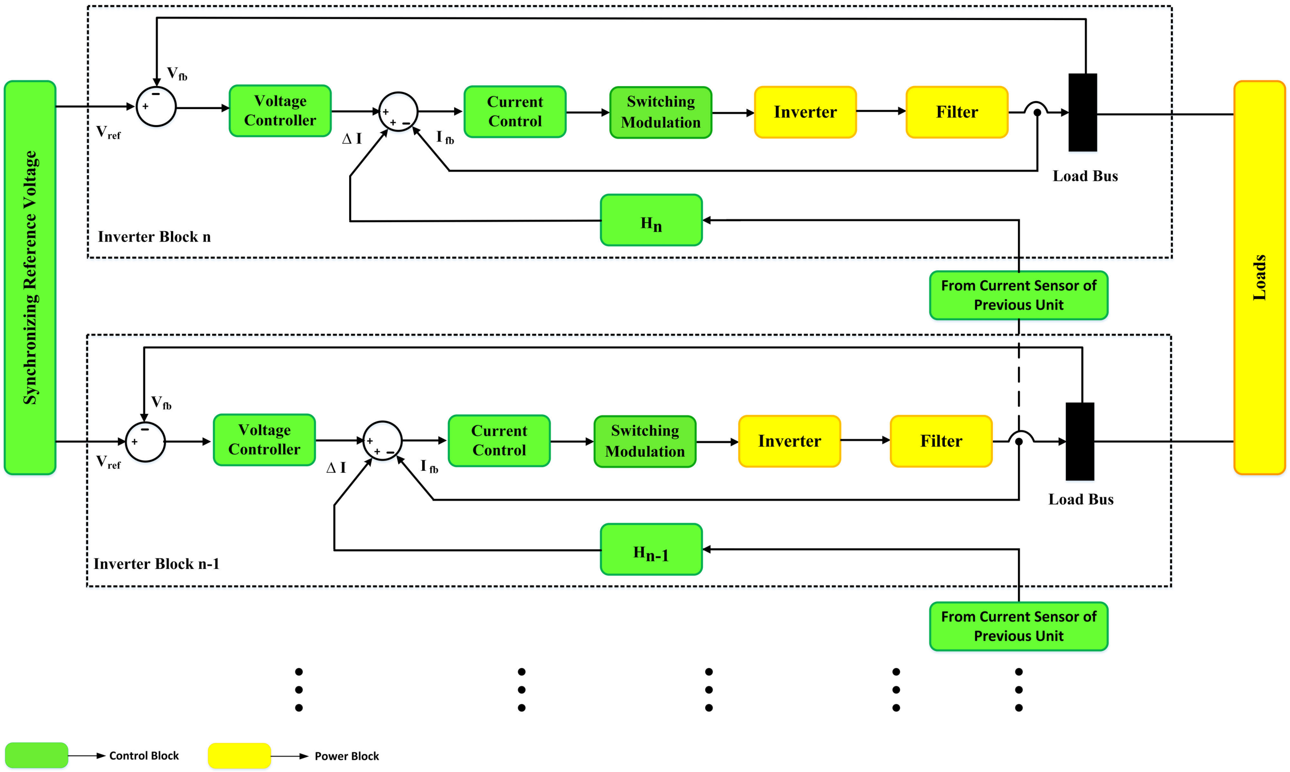

FIGURE 4. Configuration of circular chain control.

to the master-slave and current-limiting control techniques, and it is concluded that it is competitive with those techniques in terms of its transient response, but it is more robust than the current limiting control.

D. WEIGHTED CURRENT DISTRIBUTION CONTROL

This control technique is similar to average current-sharing control, (presented in subsection A). The average load current is calculated and it goes to a weighting circuit, which gives different weights to the current based on the rating of each inverter [40], and along with its practical implementation using microcontrollers as presented in [41]. More details about the design of weighting current distribution are given in [42]. Eventually, the current reference is fed from both an outer voltage control loop and a weighted current control loop. The typical configuration of the weighting current control scheme is shown in Fig. 5. As clarified in [42], the weighted current distribution is based on an operational amplifier (op-amp) circuit, which consists of two cascaded stages. The general formula for the weighted current distribution is expressed as a voltage signal. For instance, the weighting current signal for inverter (i) in term of a voltage value is given as V_{i-avg}. The output of the 1st stage op-amp is formulated as [42],

$$\begin{aligned} V_{i-avg} &= -\frac{(\frac{R}{N_1}//\frac{R}{N_2}//\ldots.//\frac{R}{N_n})}{R} \\ &\quad \times (I_{out-1}+I_{out-2}+\ldots+I_{out-n}) \\ V_{i-avg} &= -\frac{(I_{out-1}+I_{out-2}+\ldots+I_{out-n})}{N_1+N_2+\ldots N_n} \end{aligned} \tag{2}$$

where n is the total number of inverters, R is the input resistor of the 1st stage, N_i is a factor proportional to the rating of each inverter (i), I_{out} is the measured output current of each inverter, V_{i-avg} is a voltage signal corresponding to the weighted average current. The desired output current of each inverter at the 2nd stage (in terms of a voltage command $V_{command-i}$) is calculated as,

$$V_{command-i} = V_{i-avg}{}^{*}N_i \tag{3}$$

E. CURRENT LIMITATION CONTROL

Current limitation control is introduced to overcome pitfalls of the conventional operation for parallel inverters, where this technique takes few control forms. One form is developed to minimize the circulating current among parallel inverters [43]. Minimization of the loop (circulating) current is done through coupling inductors. Another form is realized by dividing the instantaneous sinusoidal load current into several non-sinusoidal shapes [44], where each inverter is operated at a current-controlled mode to inject such a specific current shape. When all these current shapes are summed at the load bus, they form the complete sinusoidal load current.

F. COMPARATIVE ANALYSIS AMONG SCHEMES OF CURRENT DISTRIBUTION CONTROL

This section demonstrates the summary of comparative analysis for all subcategories included in the current distribution control (1st category). The summary of the main characteristics of all control techniques in the 1st category is listed

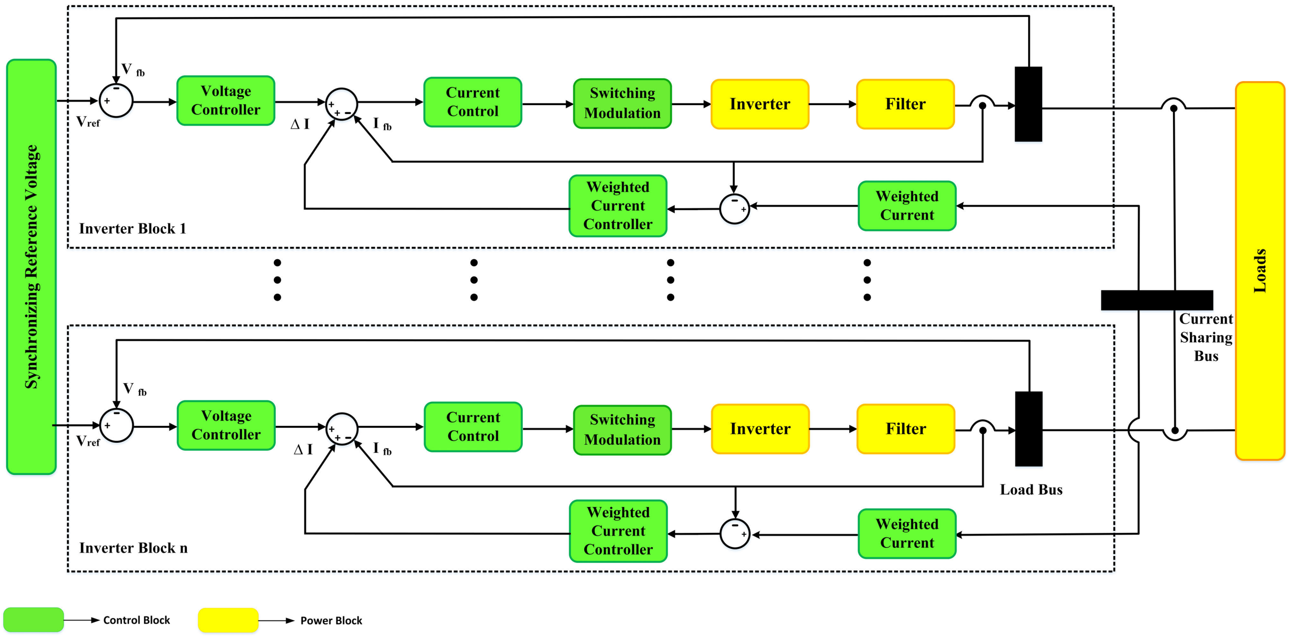

FIGURE 5. Configuration of weighted current distribution control.

in Table 1, and the advantages and disadvantages of these abovementioned control techniques are tabulated in Table 2.

IV. INSTANTANEOUS CURRENT/POWER CONTROL (2^{ND} CATEGORY)

What makes this category unique and different from the current distribution schemes, (mentioned in the third section), is that the instantaneous current (not average root mean square) is controlled through the current control loop [45], [46], [47], [48], [49], [50] to have equal current-sharing, and consequently; equal power distribution among inverters. Its reference is driven through both the voltage loop and the mismatch between the current reference and output current [45], [46].

A little deviation from the main concept (mentioned above) is introduced in [47], at which the current mismatch loop is not required, and the current is equally divided among inverters. The main contribution of [48] is to introduce a virtual impedance in the control scheme of each inverter to guarantee equal current-sharing and minimize the circulating current. Estimation techniques are integrated with the instantaneous current-sharing scheme to estimate the virtual impedance [49], and eventually; equalize the injected currents among inverters. The concept of virtual impedance is also introduced in [50] to minimize the circulating current and equalize the current-sharing among inverters.

In [50], equal current-sharing is realized through the current error, which is processed by this virtual impedance and its outcome goes to the current loop. The publications [22], [29] cover both average and instantaneous current-sharing because they apply the concept of average current, but this average is calculated over a very short (instantaneous) interval.

Therefore, instantaneous current control is also applied to the multi-inverter system [22], [29], which considers the instantaneous average root mean square currents along with the current unbalance, the inverter impedance, and lines' impedances for the stability analysis. The typical configuration of the instantaneous current-sharing scheme is displayed in Fig. 6.

V. CURRENT/POWER ACCUMULATION CONTROL (3^{RD} CATEGORY)

Current accumulation (accretion) control is firstly mentioned in [16]. In this category, the currents of some inverters or all inverters are summed up at the load side. There may be a sort of inter-communications between a central controller and other local controllers to operate all inverters. In this control scheme, all loads are mostly connected to one load bus, which is connected to all inverters. Current accumulation (accretion) control includes two main subcategories: Master-slave control schemes [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85] and concentrated/central current control schemes [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100].

A. MASTER-SLAVE SCHEME

The master-slave control scheme is the most common control scheme within the centralized (communication-based) category [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85]. The main concept of this scheme is that one

TABLE 1. Summary of main characteristics for control schemes within current distribution control.

Control Scheme	Main Features
Average Current Sharing	• Reference current is generated from the load side (current sharing bus) to operate each inverter for equal current sharing. • Inter-communications among inverters are a must. • Inverters can be operated in a current-controlled mode or a voltage-controlled mode
One Cycle Control	• Inverter's current is controller over each switching cycle to have equal current sharing among inverters. • Operation of inverter is a bit complicated depending on two techniques for switching modulation: Vector operation and bipolar operation.
Circular Chain Control	• Reference current of each inverter is determined with help of the injected current of the previous inverter. • This control scheme has mostly a cascaded structure of voltage and current loops. • Circular chain is constructed from the connection among the inverters, where inter-communications among inverters are required to form the circular chain.
Weighted Current Distribution Control	• It is similar to average current sharing, but it is used for unequal sharing for current among inverters based on their ratings. • It has similar structure to circular chain control in terms of the cascaded structure of both current and voltage loops.
Current Limitation Control	• Each inverter is operated in a current-controlled mode to inject a specific current based on its reference. • This technique has a great matching between the reference current and its injected current, which minimizes the circulating current among inverters.

TABLE 2. Summary of advantages and disadvantages of each subcategory within current distributed control.

Control Scheme	Potential Advantages	Potential Disadvantages
Average Current Sharing	• Conventional version is simple for implementation • Equal current sharing is easily achievable. • Voltage can be regulated as well. • Several advanced controllers can be employed to increase the accuracy such as optimal controller [25], proportional-resonant [29], and deadbeat controllers [30].	• It requires inter-communications to generate current references and voltage references • Circulating fundamental current exists among inverters, but it can be minimized [27]. • Circulating harmonic currents exist among inverters, but they can be minimized [26]. • It requires some sensors to measure load currents and inverters' currents, but the number of sensors can be reduced [31].
One Cycle Control	• Constant frequency operation is realized [34]-[36]. • Low current distortion [35]. • Unity power factor [36].	• Stability and robustness of this technique have not been tested. • Circulating current is not mitigated. • It injects power oscillations to the system [33].
Circular Chain Control	• Simple structure to control the output of each inverter. • It has a moderate transient performance compared to other centralized schemes [36]. • Its robustness can be improved by using optimal control [37].	• Inter-communications among inverters are required to form the circular chain [36]-[38]. • It is only operative for equal current distribution.
Weighted Current Distribution Control	• Unequal and equal current distribution based on different inverter rating is achievable [40]-[42].	• Stability and robustness are not investigated. • Circulating current is not mitigated.
Current Limitation Control	• It provides a capability for unequal distribution of current among inverters, and it minimizes the circulating current.	• It generates many harmonics [44] • Its dynamic performance is not examined carefully [43], [44]. • Stability and robustness are not investigated [43], [44].

inverter (usually with the maximum rating) is operated at a voltage-controlled mode, while the other inverters are operated at a current-controlled mode. In this paper, the master-slave scheme is further divided into several subcategories based on several factors such as the selection of the master unit, the generation of a reference signal for slave units, and the communication tools/means between the master and slave units.

1) SELECTION OF MASTER UNIT

The master unit is considered as a brain of the whole system. In some publications, this master unit is fixed, and it cannot be changed to other units [51], [52], [53], [54], [55], [56], [57], [61], [62], [65], [66], [67], [70], [71], [72], [74], [76], or it can be changed to another unit to enhance the reliability/redundancy of the whole system [51], [55], [58], [59], [60].

a: FIXED MASTER UNIT

In this subcategory, the master unit is always fixed, and it is not changed at any system condition or within the control scheme [52], [53], [54], [55], [56], [57], [61], [62], [65], [66], [67], [70], [71], [72], [74], [76]. In all publications where the master unit is fixed, the master unit is responsible for adjusting the voltage's magnitude and frequency, and the slave units are accountable for injecting active and reactive

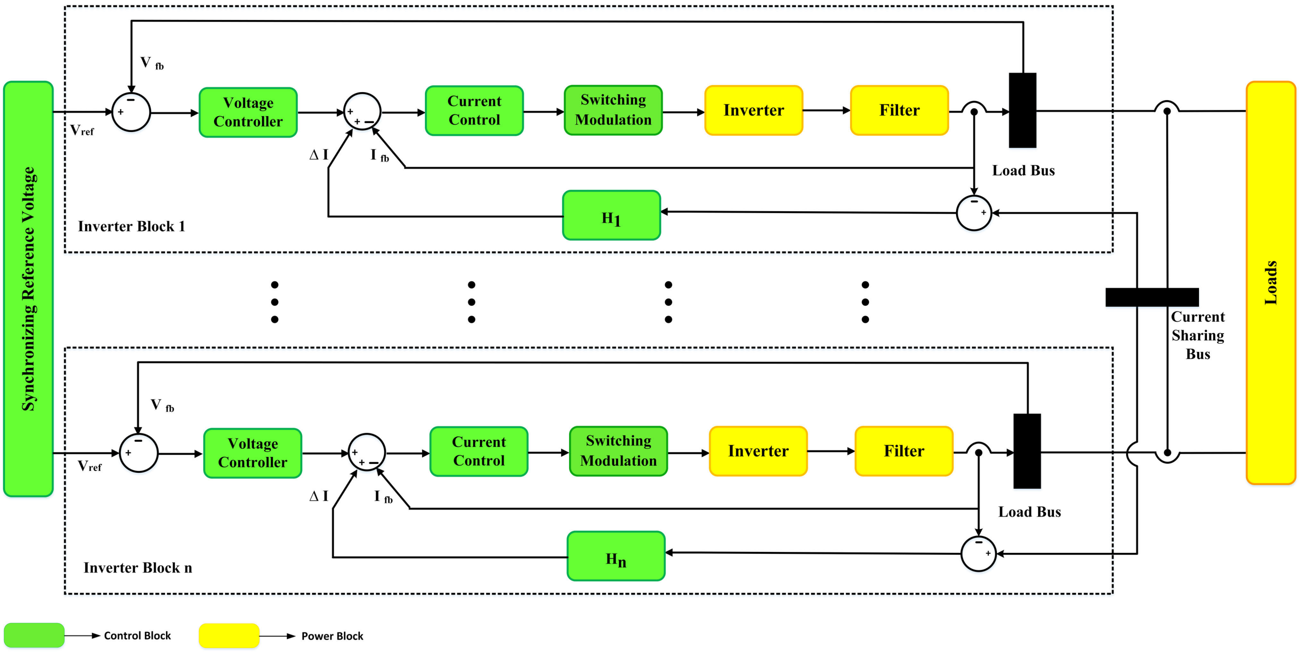

FIGURE 6. Configuration of typical instantaneous current-sharing scheme.

power. In old publications [52], [53], [54], [55], [56], [57], this fixed master unit is considered for the UPS systems and redundant parallel-inverters. In [61], the master unit is operated at a voltage-controlled mode when the microgrid is intentionally islanded and the same unit is operated at a current-controlled mode when the microgrid is connected to the main grid. The same concept of operation for the master unit is reported in [62], [65], [66] for a seamless transition between a grid-connected mode and an islanded mode. The fixed master and slave units are interfaced with a medium-voltage system through a transformer with a single secondary winding so that all inverters share the AC and DC sides [67]. The master unit is utilized to control the power flow between the DC and AC sides of a hybrid microgrid in different modes of operation [70]. The master unit is always operated at a voltage-controlled mode [71], and it shares the slave unit for the load current when they all are operated at a current-controlled mode. The main objective of the presented schemes in [71], [72], [76] is to improve the power quality at the load bus beside the power-sharing. In [74], the master unit is a synchronous generator, and the master and slave units are cooperated to supply the required power. This means that the slave units are controlled to inject specific power, and the master unit keeps the balance between the generated power and load power [74].

b: ALTERNATING MASTER UNIT

In this subcategory, the master unit is not always fixed, and another unit (slave unit) can be operated as a master unit [51], [55], [58], [59], [60]. This alternative master unit is adopted in the microgrid because if the master unit is fixed and it fails its operation due to any reason, the whole system collapses. In [55], the frequency value and phase synchronization are given to all units. A random selection is given to any unit based on a rotating priority window, which leads to a true redundancy. The master unit is automatically chosen based on a single common status line [55], the chosen master unit gives the reference currents to other slave units in addition to it stabilizes the voltage of the system.

The parallel operation of inverters with different ratings is introduced in [58], and the master unit is selected to be the inverter with the largest rating [58]. If this chosen master fails, another inverter with the second-largest rating becomes a new master unit. The roles of the master unit and slave units are swapped in [59] since the master unit drives the power bus and the slave units adjust the reference frequency and voltage according to the power bus. In [60], all system information (voltage reference, required active power, and required reactive power) is shared over a controller area network (CAN) bus to all identical inverters. In each cycle, all inverters act as master units, which achieves a good level of redundancy.

2) SLAVE UNIT CONTROL

In this subcategory, the link between the master unit and the slave units is investigated such that the reference signal of all slave units is generated by the master unit, or it emanates from another control block/unit inside the whole control scheme. This subcategory is divided into two further subcategories: Directly linked to the master unit [55], [56], [57], [59], [60], [70], [77], [79], [85], and indirectly linked to the master unit

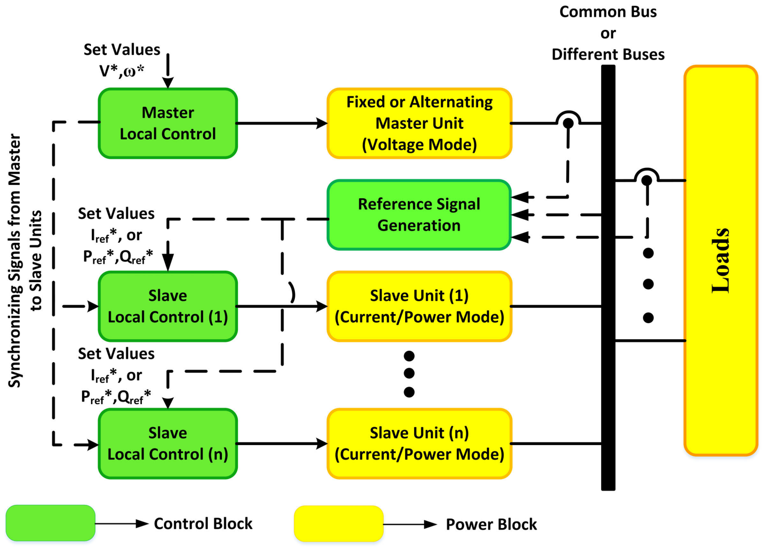

FIGURE 7. Typical configuration for master unit directly linked to slave unit.

[57], [58], [61], [64], [65], [67], [68], [69], [71], [73], [74], [75], [76], [78], [80], [81], [82], [83], [84].

a: DIRECTLY LINKED TO THE MASTER UNIT

In this subcategory, the reference signals of each slave unit are directly generated by the master unit. Technically speaking, the master unit directly generates a current reference and drives the slave units at a current-controlled mode using hysteresis current control (HCC) [55], [56], [57], [70], [77], [79]. In [59], the master unit generates a certain power (P_{bus}) and its associated power deviation ($\Delta P = P_{bus} - P_{i-inverter}$) is used to drive the slave units, which are employed to compensate for the frequency deviation as well. Similarly, the same procedure is repeated for reactive power [59]. Another scheme is presented in [60], in which the inverters are identical, and they share the same reference signals through a CAN bus to drive all inverters, which are operated at a current-controlled mode. In [85], all units are operated in a constant P-Q operation at a grid-connected mode, and they are operated in a constant V/f operation at an islanded mode [85]. The voltage and frequency references of [85] are generated by a frequency deviation of the master unit. Similarly, the same procedure is applied to slave units to have constant P-Q operation. The typical control scheme for this subcategory is shown in Fig. 7.

b: INDIRECTLY LINKED TO MASTER UNIT

In this subcategory, the reference signal of the slave unit is not directly related or linked to the outputs of the master unit, or both master and slave units are receiving their references from another central sub-system (central control unit). The instantaneous current reference is generated from the current-sharing bus (linked to the load side), where the current reference is equal to the load current divided by the number of slave units or shared with different weights among inverters [58], [64]. In [57], both techniques (directly and indirectly linked to the master unit) are covered. The current reference of the slave unit can be obtained from the master unit, and it can be also received from the load current only. A central synchronization method (called dual second-order generalized integrator-frequency-locked loop) is proposed in [61] to drive the master unit at a grid-connected mode in order to control its injected power, and it generates the voltage reference oscillator for the slave units at an islanded mode. Another centralized power calculator is developed in [65] to calculate the current references for all units (master and slave) at the islanded mode.

A main central control unit (MCCU) is presented in [67], which is responsible for the MPPT of PV panels, and it generates a reference signal for all units. All units are connected to the same DC source, and they are connected to the same secondary side of a step-up transformer through a three-phase three-limbs transformer. A multilevel central control scheme is presented in [68], where it has two main layers: The upper layer is for the multi-agent system of power balance and economic dispatch; meanwhile the lower layer is designated for voltage and current control of the master and slave units. The hierarchical structure of droop control is employed in [69] for the master-slave scheme. The primary control level governs the inverters to be operated at a current-controlled mode such that the injected active and reactive currents are adjusted to their references. At the same time, the secondary control level takes care of voltage stabilization, power-loss reduction, and power-sharing. The same concept presented in [69] is applied in [71] and [76] under the name of supervisory control, which is associated with a conservative power theory to improve the voltage quality. The master-slave control scheme introduced in [73] aims at improving the V/f of the master unit, while the slave units are operated at the P-Q mode, and there are no communications between the control block of the master unit and the control block of the slave unit.

In [74], the master unit is a synchronous generator operated at a constant-voltage and constant-frequency operation; meanwhile, the slave units (inverters) are independently operated at a constant *P-Q* mode to share the load power. In [75], the master-slave scheme is integrated with peer-to-peer control, where all distributed energy sources are controlled using droop control and the MPPT for both the PV and the wind turbine. Finally, all these local controllers presented in [75] are connected to the microgrid control center. Sliding mode control (SMC) for the master and slave units is proposed in [78], where the output of sliding mode control for the master unit dispatches the voltage reference with its frequency; meanwhile, the output of sliding mode control of slave units generates the reference signals of active and reactive currents, and both sliding mode controllers work independently.

Different quasi-droop based master-slave schemes are proposed in [80], [81], [84], where the master unit is controlled by droop control to operate the inverter at a voltage-controlled mode and finally adjust its voltage and frequency. Similarly, the slave unit is controlled by another droop control to operate the inverter at a current-controlled mode and consequently inject the required load power (active and reactive). In [82], the master and slave units have a cascaded connection. The master unit is operated based on its power factor-frequency (pf-ω) droop to ensure the power balance at the constant output voltage. At the same time, the slave unit has its control (not related to master control), which adopts the cascaded structure of voltage and current loops to apply the MPPT on non-dispatchable energy resources connected to the slave units [82]. SMC presented in [78] is also utilized in [83] for the master unit and slave unit. Each unit has its own SMC, which is used to govern the injected voltage of the master unit and control the injected current of the slave units. The typical control scheme for this subcategory is illustrated in Fig. 8.

3) COMMUNICATIONS AMONG MASTER AND SLAVE UNITS

This subcategory focuses on the communications tools/means and techniques for data transfer among the master and slave units rather than the structure and functionality of the master-slave control scheme itself. The early publication of the master-slave scheme [57] stipulates that the communications between the master unit and its associated slave units require a high bandwidth.

Some communication tools/means such as a CAN-bus and an Ethernet-bus have been introduced to the master-slave scheme to investigate the impact of the fast communication on the master-slave performance in terms of the precision of synchronization and accuracy for current-sharing [60], the energy management system [63], and the voltage stability and power quality [69]. The malfunction of the communication system among the slave units and central microgrid control is also investigated in [75] for the grid-connected and islanded modes. Delay in the communication system between the master and slave units is investigated versus the system stability [77], [79].

B. CONCENTRATED CONTROL

The major difference between this subcategory (concentrated control) and current distribution control (1^{st} category in the third section) is that the latter category is applied to current control only, and it requires a sort of inter-communications among its inverters. In this subcategory [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], the concentrated control/controller is giving control/reference signals to all/some units (inverters) in the microgrid; these reference signals may be current or power that should be injected by each inverter in the microgrid. Furthermore, this concentrated control can be applied to power/voltage/current (not limited to current), and it may or may not require inter-communications among its inverters. A concentrated control generates its output to several parallel inverters simultaneously [86] such that each inverter is operated at a voltage-controlled mode to stabilize the voltage at the loads' bus. In [87], the central controller dispatches the power references to all distribution generators such that the operation of the microgrid is optimized, where this central controller is also connected to the distribution management system. A similar concept of central power control is applied to inverters in a hybrid (DC-AC) microgrid to mitigate the power flow mismatch [88]. The central control scheme of [89] is employed to stabilize the voltage at the PCC, restore the frequency to its nominal value, and finally minimize the circulating current by equalizing the injected power of each inverter. The central control scheme presented in [89] is mainly based on PI controllers for the voltage and frequency loops.

The concentrated control schemes presented in [90], [99], and [100] operate all inverters concurrently at a voltage-controlled mode when the microgrid is operated at an islanded mode, and the same inverters are operated at a current-controlled mode when the microgrid is operated at a grid-connected mode. The central control schemes of [91] and [96] are a repetition of what is published in [87] with extra supervisory control on active power curtailment and the state of charging for the distributed energy storage system. The research work in [92] differs from other publications such that the synchronized measurements are conducted using the phasor measurement units (PMUs), and this proposed central controller is based on the linear quadratic Gaussian (LQG). The research work of [93] is similar to that of [87], where the global management controller (GMC) is connected to both the central control unit and the distribution system operator (DSO). The idea of central control in [94] is similar to [99] and [100], but the main difference among these publications is the reference signals, which are given in terms of power (active and reactive) in [94] and in terms of current/voltage in [99] and [100]. The power mismatch in [94] is adjusted by the change in the angle and magnitude of the injected voltage of each inverter. In [95], the adaptive centralized controller is mainly used to have a fast frequency adjustment for intentional and unintentional islanding. A clear distinction between centralized control and decentralized control for smart grids is depicted in [97], where it clarifies different connections between the controllers and their inverters. The research work presented in [98] is similar to that of [87], [91], and [96] with a proposed centralized scheme that aims to control the injected reactive power in the whole grid. The injected reactive power of [98] is calculated in a few iterations using the extended load flow, in which the buses are classified as *PV* and *PQ* buses. The typical configuration of central control of this subcategory is displayed in Fig. 9.

VI. MISCELLANEOUS CONTROL (4TH CATEGORY)

This category includes some publications [101], [102], [103], [104], [105], [106], [107], [108], [109], which do not follow the typical structures/objectives for the control schemes documented starting from the third section to the fifth section. Meaning that the publications of this 4th category tackle problems in microgrids, which are not pertaining to the traditional control objectives. The publications of [101], [102], [103], [104], [105], [106], [107], [108], [109] have titles containing traditional control names (like master-slave, etc...), but the core contribution of these publications within this category is concentrated on extra research topics/ideas, which are not the traditional objectives of control schemes.

For instance, power quality is the main concern of [101] in the islanded and grid-connected modes. At the grid-connected mode of [101], the power reference is converted into a current reference, and the inverter is operated at a current-controlled mode, where all harmonics are converted into a current reference added to the other references of the current loop. In the islanded mode of [101], the voltage loop and current harmonics generate the required current references for the current loop. It is worth mentioning that both power quality and control schemes share the core contribution of some other publications. For instance, the traditional control objectives and improvement of power quality are realized in [72] and [76]. Communications between microgrid central control (MGCC) and local control of the generation units (synchronous generator) are the main focus in [102]. The objective of this MGCC is to monitor the injected power into the main grid at a grid-connected mode and to stabilize the voltage at a stand-alone mode. The communication means are done through a data acquisition card in MGCC and an Ethernet card in local control using LabView [102].

The focus of [103] is given to the short-circuit calculations for the islanded microgrid. During the fault in the microgrid, the inverter model changes due to the fast response of its control. Thus, the energy source in the microgrid is not permanently constant, which requires new models to calculate the balanced and unbalanced faults currents. The microgrid of [104] is connected to the medium-voltage distribution system, and the problem of reverse power from the low-voltage microgrid to the medium-voltage distribution system is investigated whenever the generated energy of the distributed energy resources is greater than that taken by the loads. This reverse power of [104] is associated with an increase in the DC voltage side and voltage frequency of the master unit. This voltage frequency of the master unit is always monitored using the second-order generalized integrator PLL (SOGI-PLL). When its frequency is increased, it triggers inverters, (connected to the medium-voltage grid), to reduce their injected power.

The key contribution of [105] is the structure of the microgrid (three-phase four-wire grid) and its interaction with inverters whose topology is single-phase. In this publication [105], the control scheme is presented to show the power quality improvement, the voltage profile, and the reduction of power-loss in the grid. In [106], the microgrid reconfiguration (changing its topology) with the associated adaptation of its control scheme is tackled. In the same publication [106], the resilient microgrid formation (load restoration) consists of several islands, in which each island has only one master unit that is responsible for voltage and its frequency in each island. The reconfiguration problem of the microgrid in [106] is solved using the mixed-integer second-order cone programming relaxation (MISOCP).

In [107], the solid-state transformers (SST) are converted into inverters (master SST and slave SSTs) when the microgrid is disconnected from the main grid. The voltage and system stability are the focal themes of this publication, and it is conducted using the μ-synthesis method. The contribution of [108] is the optimal allocation of the master unit and slave units such that the energy loss is minimized. This optimization problem of [108] is solved by mixed-integer non-linear programming along with the optimal load flow. The optimization is also intermingled with the control scheme in [87], where the emphasis is split between the central control scheme and the optimized operation of distributed generation units. Synchronization of the master unit with the main grid is the contribution in [109], where the objective of its control is to establish synchronization between both grids.

VII. COMPARATIVE ANALYSIS AMONG AFOREMENTIONED CONTROL SCHEMES

This section manifests a systematic comparative analysis among the control schemes mentioned in the four main categories of Fig. 1 starting from the third section (1st category) to the sixth section (4th category). The main characteristics of each category are depicted in Table 3. The comparative analysis (in terms of advantages and disadvantages) is summarized in Table 4.

VIII. CONTROLLERS CLASSIFICATION WITHIN CENTRALIZED CONTROL SCHEMES

As mentioned before in the introduction section, the classification in Fig. 1 is dedicated to the central/centralized (with and without inter-communications among inverters) control schemes. The essential component in these presented schemes to realize the control objectives is the controller(s) used/developed/formulated in the current/

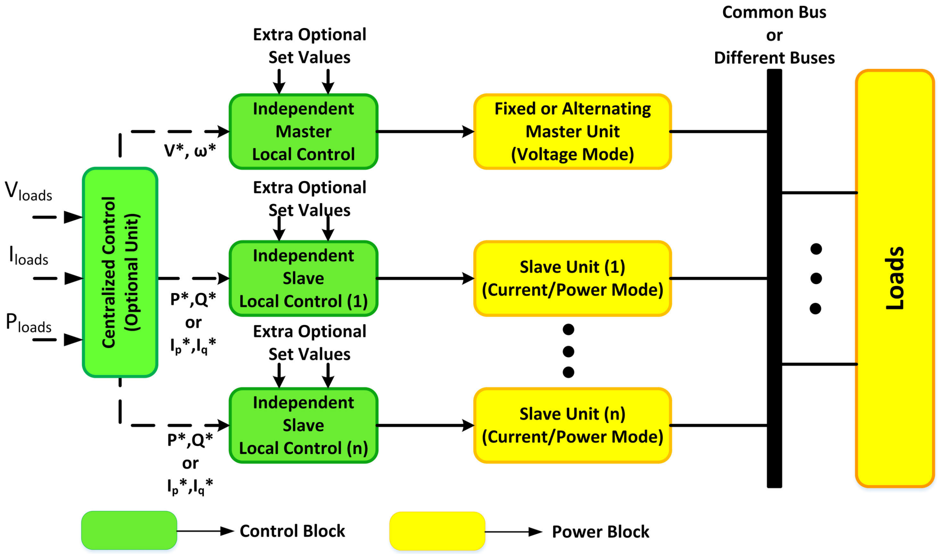

FIGURE 8. Typical configuration for master unit indirectly linked to slave unit.

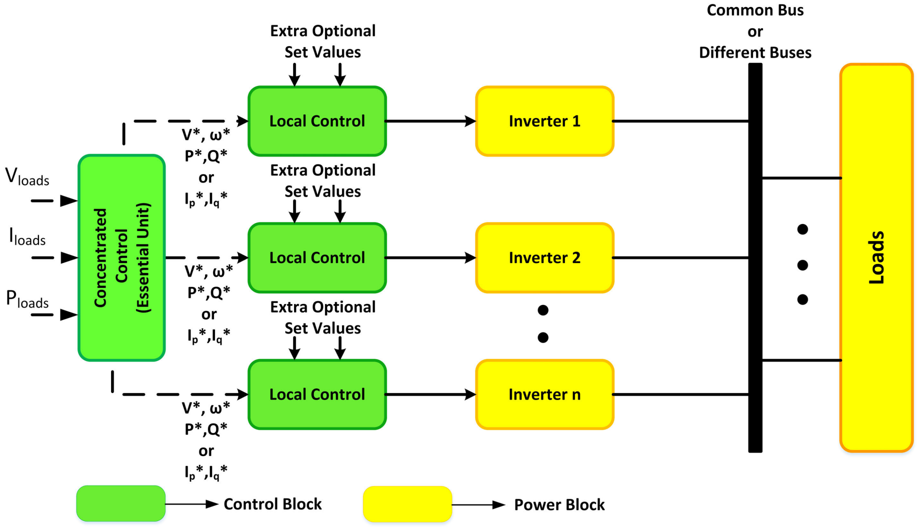

FIGURE 9. Typical configuration for concentrated control.

voltage/power loops. Several review publications shed light on different controllers used in different control schemes.

This paragraph tackles some publications that have different classifications for controllers used in the control schemes for microgrids. A controllers' classification for the primary control level of control schemes is given in [11]. This classification covers many controllers such as the proportional-integral-derivative (*PID*), proportional-resonant (*PR*), current predictive control (*PC*), dead-beat control (*DB*), hysteresis current control (*HCC*), linear quadratic regulator/gaussian (*LQR/LQG*), sliding mode control (*SMC*), H-infinity control ($H\infty$), repetitive control (*RC*), and neural network and fuzzy logic-based control schemes. These controllers have been reviewed without detailed information and without an illustrated classification. A more specific classification is developed in [16] for one category of the centralized current control, (instantaneous current control). This publication ([16]) covers a few controllers such as *PR* controllers, *SMC* controllers, dead-beat controllers, and $H\infty$ controllers.

The inner-loop controllers (primary control level) are surveyed in [12], which encompasses *PI* controllers, *PR* controllers, dead-beat controllers, model predictive controllers, hysteresis current controllers, H-infinity controllers, repetitive controllers, neural network, fuzzy logic-based controllers, sliding mode controllers, and the linear quadratic regulator and linear-quadratic integrator. Another comparison showing the merits and demerits of each controller is listed in [12]. In this section, Fig. 10 displays

TABLE 3. Characteristics of each main category in Fig. 1.

Control scheme	Main Features
Current distribution control	Including subcategories • Reference current is generated from the loads' side, it is an arbitrary value, or it is determined by the injected current of the previous inverter. Inverters can be operated in a current-controlled mode or a voltage-controlled mode. • The common structure of this control technique is a cascaded structure of both current and voltage loops. • Equal or unequal current sharing can be achieved through different control techniques within this category.
Instantaneous current /power control	• References current is generated from the voltage loop and the mismatch between the injected current and its set value. • Instantaneous current (not the average root mean square) of the inverter is controlled through a current controlled loop for equal current sharing. • It may be integrated with a virtual impedance to guarantee equal current sharing and minimize the circulating current.
Current/Power accumulation control	Master-slave including subcategories • Reference current is generated from the loads' bus, where all loads are connected to the same bus (typical structure of small microgrids). Therefore, inverters' currents are augmented to supply the loads' current. • Inter-communications among inverters may be required between the master unit and slave units (it depends on the type of master-slave control). • Inverters are operated in a current-controlled mode (for current control) and a voltage-controlled mode (for power control). • It can be used for equal or unequal current/power-sharing.
	Concentrated control • Reference current is generated from the loads' bus where all loads are connected to the same bus (typical structure of small microgrids). Therefore, inverters' currents are augmented to supply the loads' current. • Inter-communications among inverters are not required. • Inverters are operated in a current-controlled mode (for current control) and a voltage-controlled mode (for power control). • It is mainly used for equal current/power-sharing.
Miscellaneous control	• This category does not focus on current/power control, but it rather focuses on other issues such as power quality, communication means, short-circuit calculations, forward and reverse power flow, structure and reconfiguration of microgrids, solid-state transformer, and optimal locations of generation units. • There is no typical characteristics nor the typical structure of the control schemes in this category. The control scheme is designed based on its objective.

a suggested classification for the common controllers used in the centralized control schemes of Fig. 1. This proposed classification is divided into two main categories: Controllers formulated/operated in the time-domain and controllers formulated/operated in the frequency-domain.

A. TIME-DOMAIN FORMULATION/OPERATION

This subcategory includes all controllers that require the time domain for the controllers' development, formulation and/or operation. Some controllers essentially necessitate the state-space formulation for the system understudy and others do not essentially require any state-space formulation.

1) CONTROLLERS WITHOUT STATE-SPACE FORMULATION

This subcategory includes all controllers, which do not entail any state-space formulation for their development and/or operation.

a: PROPORTIONAL CONTROLLER (P)

The proportional controller is just a gain, which is used to process the error. This *P* controller does not guarantee the steady-state, transient, and dynamic stability performance of the overall system for all different operating conditions. Its transfer function is simply defined as,

$$H(s) = K_p e \tag{4}$$

where K_p and e are the proportional gain and the error, respectively. For instance, this controller is utilized in the hysteresis current control [43]. It is commonly used to adapt the modulation index of parallel inverters [53], and it is also designated for the current control loop in the master-slave [55]. This controller is used to convert any change in active power into a corresponding change in the output frequency [59], [96] and any change in the reactive power into a corresponding change in the voltage magnitude [85], [96] with the objective of seamless transfer between the grid-connected to islanded modes. The proportional controller is employed in the current loop for the power-sharing in [90], and it is adopted in the power loop to generate the current references [110].

b: PROPORTIONAL-INTEGRAL CONTROLLER (PI)

The *PI* controller is the basic classical controller that is widely used in the time domain. It is used to adjust overshoot, transient time, and steady-state errors. Tuning its parameters works very well for an operating condition to adjust the steady-state and transient performance, but there is no

TABLE 4. Summary of advantages and disadvantages of each main category in Fig. 1.

Control scheme	Potential advantages	Potential disadvantages
Current distribution control	Including subcategories	
	• It provides equal and unequal current distribution [18]-[44]. • It has a fast dynamic performance toward load stepping [36].	• Inter-communications are always required [37]-[42]. • Most control schemes suffer complexity because of the nested structure of voltage and current loops. • Circulating current (fundamental and harmonics) is a major problem [33]-[36]. • Stability and robustness are not well checked with few exceptions as presented in [37].
Instantaneous current /power control	• It mainly provides equal sharing [45]-[48], [50], [22], [30]. It also may provide unequal current sharing based on inverter capacity [49]. • Stability is analyzed in [22], [29]. • Circulating current is solved in [29], [48], [49].	• Transient performance toward load stepping is not well examined. • Control loops depend mostly on linear controllers such as proportional-integral [46] and proportional-resonant [29] controllers.
Current/Power accumulation control	Master-slave including subcategories	
	• Circulating current is minimal compared to the instantaneous current control and current distribution control [15], [16]. • Variation of the frequency with loading conditions does not exist because only one master unit takes care of the system frequency, (unlink droop control scheme [15], [16]). • Common drawbacks of droop control [14] (such as low X/R, different feeder impedances, cold start, etc…), are not applicable in master-slave schemes because all slave units are mostly operated as current sources. • Improved master-slave schemes do not need inter-communications among units [64], [74], [75], [78], [80], [82]-[84].	• For the conventional master-slave schemes, communication of signals cannot be transferred over a long distance, [52]-[57], [61], [62], [65]-[67], [70]-[72], [74]. • Transient performance includes a large overshoot in current. • The inter-communications require a high bandwidth for instantaneous voltage/current control [57]. • For the fixed master unit, the failure of this unit leads to the collapse of the whole control scheme [52]-[57],[61],[62],[65]-[67],[70]-[72],[74]. • Communications delay between the master unit and slave units may lead to system instability [77], [79].
	Concentrated control	
	• It can provide equal power sharing [88]-[100], or unequal power sharing [94]. • In the islanded mode, the frequency is well adjusted with a fast-dynamic performance [89], [95]. • Seamless transition from islanded mode to grid-connected mode is also investigated [100].	• It may require communications between the central control unit and the inverter or its local control [87]-[98]. • It is applicable in case the inverters are closely spaced, otherwise more sophisticated communication systems are required [91], [96].
Miscellaneous control	• Some uncommon control issues have been given consideration in this category such as power quality [101], communications issues [102], short-circuit calculations [103], reverse power flow [104], structure of microgrid and power quality [105], reconfiguration of microgrid [106], solid-state transformers [107], optimal location for generation units [108], and synchronization with the grid [109].	• The main focus for this category is given to some issues that are not directly related to the control scheme itself [101]-[109]. The structure and performance of this control scheme are not considered the main contribution in these publications [101]-[109].

guarantee this *PI* controller with its fixed parameters will give its best performance at different operations.

The integral part gives infinite gain at zero frequency, which forces the steady-state error to be zero, while the proportional part adjusts the overshoot and/or fastness of the system to reach the steady-state performance. Its transfer function is defined as,

$$H(s) = (K_p + \frac{K_i}{s})e \tag{5}$$

where K_p, K_i are proportional and integral gains, while e is the error. This *PI* controller is commonly used in the current loops in [22], [24], [32], [46], [101] for current-sharing among parallel inverters/UPS. It is also employed in the master control loop for voltage adjustment and in the slave control loop to adjust the output current [56], [58], [60], [67], [77], [79]. The *PI* controller is engaged in the *V-f* and *P-Q* loops [62], [63], [66], [103]. In [75] and [80], the *PI* controller is devoted to adjusting the relationship *P-f* in the master-slave and peer-to-peer control schemes.

Droop control is integrated with the master-slave scheme to modify power control [81], and the *PI* controller is utilized in its power loop to adjust the injected active and reactive power through active and reactive currents. A similar control concept is conducted in [84], where the in-phase and quadrature voltages are controlled through active and reactive currents. The active and reactive power references are converted into current references through *PI* controllers [88]. The *PI* controller is used in the central control scheme presented in [89] to alleviate the voltage and frequency deviation from their normal values. At the grid-connected mode of [90] and [96], the *PI* controller is included in the current loop, and it is also employed in the power loop at an islanded mode. The *PI* controller is also employed to smoothen the transition from the grid-connected mode to the islanded mode for parallel inverters [111]. The *PI* controller in [111] is included in the voltage loop to generate the current reference of the subsequent current loop.

c: PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROLLER (PID)

The *PID* controller gives an extra degree of freedom over the *PI* controller. Therefore, the derivative gain is mainly used to adjust the transient performance like the overshoot and settling time. On other hand, it is not widely used compared to the *PI* controller because the derivative term magnifies the noise and harmonics in microgrids. Its transfer function is given as,

$$H(s) = (K_p + \frac{K_i}{s} + K_d s)\ e \tag{6}$$

where K_d is the derivative gain. The current is controlled in the circular chain control (3C) using a *PID* controller [37]. In [55], the *PID* controller is used in the voltage loop to stabilize the voltage in the master-slave control scheme.

d: PROPORTIONAL-RESONANT CONTROLLER (PR)

The *PR* controller fits the operation of the microgrid in any stationary frame ($\alpha - \beta$ frame or $a - b - c$ natural frame), where the voltage and current are expressed as sinusoids in this stationary frame. The ideal *PR* comes because of transforming the *PI* controller into a stationary frame with the infinite gain ω_0 to force the error value to zero while keeping no phase shift and no gain at other frequencies. This controller transfer function is defined as,

$$H(s) = (K_p + \frac{2K_i s}{s^2 + \omega_0^2})\ e \tag{7}$$

where ω_0 is a resonant frequency. From the practical perspective, an ideal *PR* cannot be implemented because its quality factor is infinite, which cannot be practically implemented by any circuit. Therefore, the approximate (non-ideal) *PR* controller is defined as,

$$H(s) = (K_p + \frac{2K_i s\omega_{cut}}{s^2 + 2s\omega_{cut} + \omega_0^2})e \tag{8}$$

where ω_{cut} is the cut-off frequency. This *PR* is utilized in some central control schemes due to its advantageous performance for improving the steady-state error. For example, the *PR* controller is included in the scheme of instantaneous average current-sharing [26]. In [68], the *PR* is also used in the nested structure of voltage and current loops to operate the slave unit. The *PR* controller is employed in the single current loop at a grid-connected mode and dual voltage-current loops at an islanded mode [112], and it is also used for seamless transfer between both modes. In [113], both *PR* and *PI* are compared for the same inverter connected to the grid, this comparison indicates that the *PI* controller gives slightly better transient current performance than the *PR* controller for the same inverter at a current-controlled mode.

e: HYSTERESIS CURRENT CONTROLLER (HCC)

This controller is under the umbrella of the on-off control theory. It is mainly used to control the injected current of the voltage source converter, (current-controlled mode). It has the advantages of simplicity, but it has the demerits of a variable switching frequency and high current ripples. In [64] and [65], both master and slave units are operated using *HCC*, in which these units are operated in a current-controlled operation at a grid-connected mode (for all units) and at an islanded mode (for slave units). In [113], *HCC* is compared to both *PI* and *PR* controllers for the current performance of an inverter connected to a grid. The outcome of this comparison pinpoints the demerit of *HCC*, which is the uncontrollable current ripples. It is known that any inverter is mostly operated at a constant-power mode when this inverter is connected to a microgrid [114]. At this constant-power mode, the power references are converted into current references to operate the inverters using *HCC*.

f: H-INFINITY CONTROL (H_∞)

H_∞ belongs to the optimal control theory, where the control requirements are seen as an optimization problem with some constraints. H_∞ can be used with/without state-space formulation. Its basic formulation based on Fig. 11 is summarized in [115] as,

$$\begin{bmatrix} z \\ y \end{bmatrix} = P \begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} P_{11}w + P_{12}u \\ P_{21}w + P_{22}u \end{bmatrix} \tag{9}$$

where P is the plant model with a level of uncertainty, w is the reference mixed with disturbances, u is the manipulated variables, y is the measured variables, z is the error, and K is the feedback gain. The input-output relationship is expressed as,

$$u = Ky \tag{10}$$

$$y = (I - P_{22}K)^{-1}P_{21}w \tag{11}$$

$$u = K(I - P_{22}K)^{-1}P_{21}\omega \tag{12}$$

$$z = (P_{11} + P_{12}K(I - P_{22}K)^{-1}P_{21})\ w \tag{13}$$

$$z =: F_l(P, K)\, w =: T_{z\leftarrow w}w \tag{14}$$

where $F_l(P, K)$ is the lower linear fractional transformation (LFT). The expected output of H_∞ is to find the matrix K that leads to minimize the error and minimize $\|F_l(P, K)\|_\infty$. H-infinity control has been applied to microgrids and parallel inverters to overcome the uncertainty in the system parameters and to guarantee system stability. In the scheme of average current-sharing [23], *HCC* generates current ripples, which inflict the voltage regulation in the microgrid. Therefore, H_∞ is included in the voltage loop to reduce the voltage distortion. In [37] and [38], H_∞ is devoted to the voltage loop of circular chain control to reduce the interactive effect among parallel inverters. The presented H_∞ of [115] is employed to design a stabilizing compensator in the current loop of

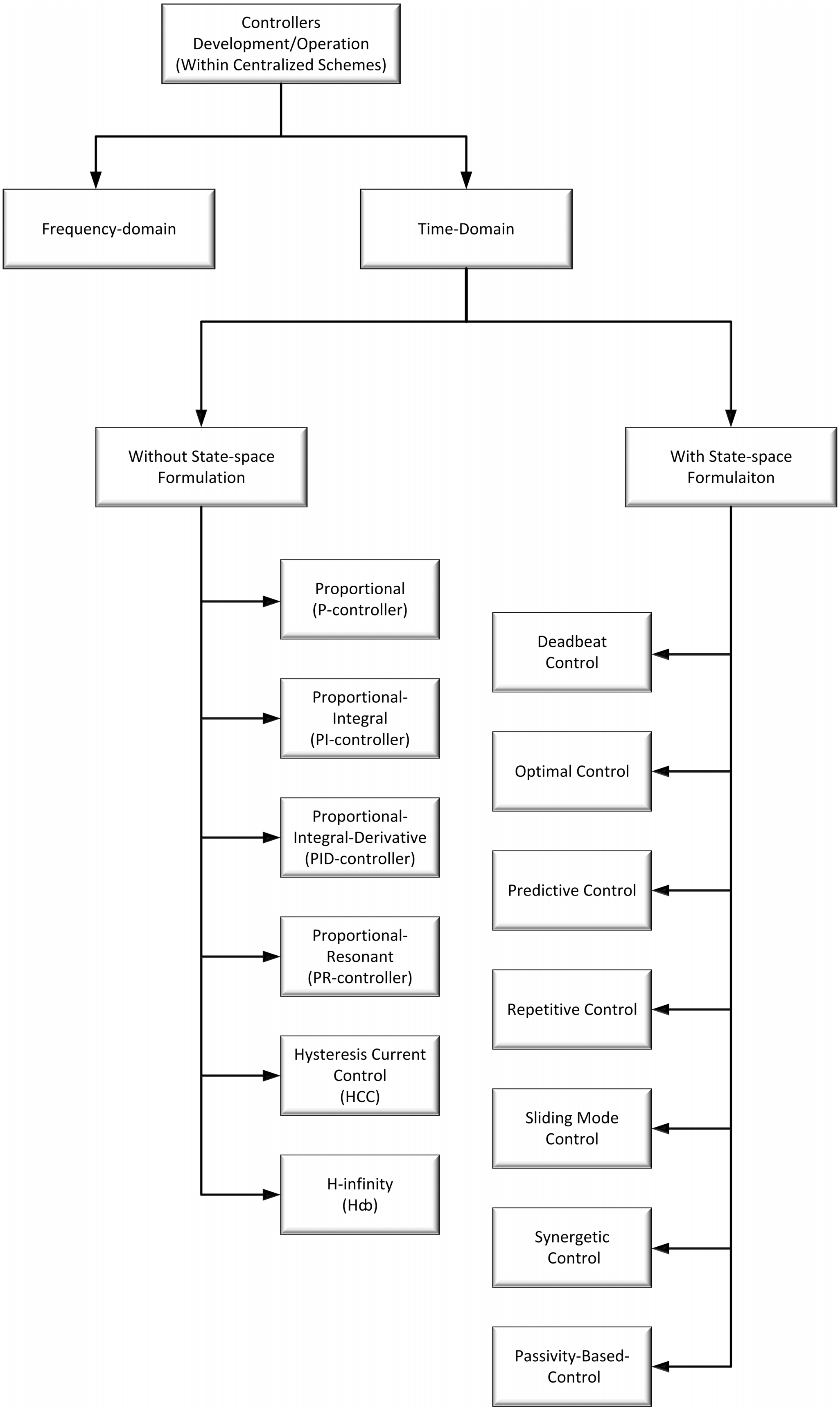

FIGURE 10. Classification of controllers within centralized control schemes.

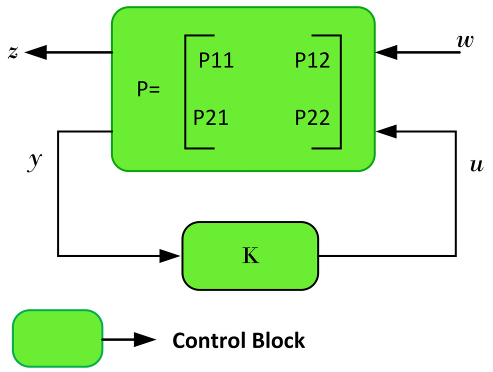

FIGURE 11. Basic control block of H∞.

parallel inverters in their microgrid. The objective of this stabilizing compensator, [115], is to eliminate the impact of harmonics and improve the current tracking performance. In the same paper, [115], H_∞ depends on a state-space formulation for its development, but H_∞ is placed in the category of the controller without any state-space formulation because the majority of its publications cited in this review publication, ([23], [37], [38]), do not require a clear state-space form.

2) CONTROLLERS WITH STATE-SPACE FORMULATION

The subsequent controllers necessitate a state-space form for its development and problem formulation. This category includes some controllers as will be demonstrated in the subsequent sections.

a: DEADBEAT CONTROLLER

The concept of deadbeat control is applied to a fully controllable system in a discrete-time domain and a continuous-time domain, where all poles are placed at the origin (part of state feedback control). Its idea is to force state variables of the system to converge toward steady-state values in the smallest number of "n" steps, where n is the order of the system (depending on its initial condition). The deadbeat can achieve zero error, shortest rise time, and shortest settling time with minimum overshoot/undershoot. The basic formulation for the feedforward deadbeat controller depends on its simplified transfer function that is expressed as [116],

$$T(z) = z^{-k}, \quad k > 1 \tag{15}$$

where k is the system delay, and it is equal to multiple integers of the sampling interval. The transfer function of the closed-loop system is defined as,

$$T(z) = \frac{y(z)}{w(z)} = \frac{D(z)HG(z)}{1 + D(z)HG(z)} \tag{16}$$

where, H is the z-transform of zero-order-hold, $G(z)$ is the plant model, $y(z)$ is the output, $w(z)$ is the input, $D(z)$ is the transfer function of the controller, which can be rewritten as,

$$D(z) = \frac{1}{HG(z)} * \frac{T(z)}{1 - T(z)} = \frac{1}{HG(z)} * \frac{z^{-k}}{1 - z^{-k}} \tag{17}$$

If the deadbeat controller is placed in the feedback path [33], [116], [117] then its basic formulation starts with,

$$x(k+1) = Ax(k) + Bu(k) \tag{18}$$

$$u(k) = -Kx(k) \rightarrow x(k+1) = (A - BK)x(k) \tag{19}$$

where K is the feedback gain. The characteristics equation is written as,

$$|zI - A + BK| = (z - \beta_1)(z - \beta_2)\ldots(z - \beta_n) \tag{20}$$

The feedback gain can be obtained using alternative ways. In case $\beta_1,\ \beta_2,\ \ldots,\beta_n$ are distinctive poles, the desired state feedback gain K is written as,

$$K = [1\ 1\ \ldots\ 1][\xi_1 : \xi_2 :\ \ldots : \xi_n]^{-1} \tag{21}$$

These $\xi_{i \rightarrow 1\ to\ n}$ are eigen vectors of matrix (A-BK) where ξ_1, ξ_2,…,ξ_n, are obtained as,

$$\xi_i = (A - \beta_i * I)^{-i}B,\ i = 1, 2, \ldots n \tag{22}$$

For deadbeat control, $\beta_1 = \beta_2 = \ldots\ldots = \beta_n = 0$, then K is expressed as,

$$K = [1\ 0\ \ldots\ 0][\xi_1 : \xi_2 :\ \ldots : \xi_n]^{-1} \tag{23}$$

where $\xi_1 = A^{-1}B, \xi_2 = A^{-2}B, \ldots\ \xi_n = A^{-n}B$. Alternatively, K of (23) can be also obtained from Ackermann's formula [116].

Due to good characteristics of the deadbeat controller, it has been integrated in different control schemes for microgrid applications. For the presented scheme of weighted average current control [30], the quasi-deadbeat controller is designed in the current loop to have a fast line current response, (equivalent to minimization of the line current error), and to damp the filter resonance. Modified deadbeat control is utilized in [117] for parallel inverters so that the steady-state and dynamic performance for the inverter current is accurate; in addition, its controller is insensitive to the parametric variations.

b: OPTIMAL CONTROL

Optimal control adjusts the system performance over a period of time such that a certain objective function is satisfied within this period. In [25], the performance index is optimized, where it contains errors in the output voltage and current of each inverter. This performance index gives an optimal feedback gain matrix, which is used to minimize the error in the voltage and current loops. Optimal control is also utilized in [118] such that the power flow between the microgrid and distribution system is optimized to economize the operation of microgrids.

c: PREDICTIVE CONTROL

The term model predictive control (MPC) is not referred to a specific control strategy, but it rather contains a wide range of control strategies that makes explicit use of a process model to predict the behavior of the system and generate the optimal control signals by minimizing an objective function [119]. Predictive control is realized through two sequential steps: Modelling the system under study to predict its output (1^{st} step) and optimizing this model to generate an optimal action that drives its predicted output to follow its reference (2^{nd} step). Mathematically, the state variable x can be predicated at the next iteration $k+1$ as $\hat{x}(k+1)$, which can be obtained from the system model as,

$$\hat{x}(k+1) = f(x(k), u(k)) \tag{24}$$

where $f(x(k), u(k))$ represents a state-space model of the system at iteration k. The cost function expressed as Euclidean distance between the predicted state $\hat{x}(k+1)$ and its reference x^* is given as,

$$cost = \sum_{minimum} \left(w \left|x^* - \hat{x}(k+1)\right|\right) \tag{25}$$

The output of this cost function is used to generate the switching sequences S for the inverters. The operation of model predictive control is exemplified in Fig. 12. [120]. Centralized model predictive control has been applied in different microgrids [93] to arrange the power flow between these microgrids and the main grid (distribution system operator). The main objective of presented predictive control, [93], is to maximize the use of renewable energies in each microgrid and control the power exchange among different microgrids by minimizing this exchanged power with the distribution system. Model predictive control is also utilized in [121] to operate the microgrid that is based on a battery storage system. Its predictive central control operates the microgrid with an objective of minimizing the operational costs for the PV-based microgrid through real-time measurements.

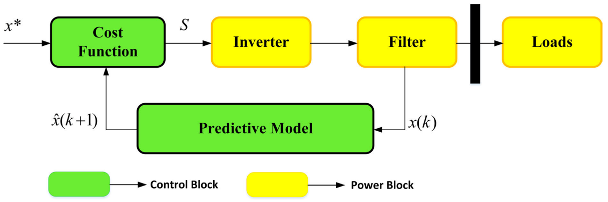

FIGURE 12. Basic operation of predictive control.

d: REPETITIVE CONTROL

Repetitive control is considered as a simple learning control technique. In the microgrid, the current of inverters is controlled in [115] by repetitive control with help of the inverter internal model in association with a feedback stabilizing compensator. This stabilizing compensator is designed by H_∞ so that the tracking error between the injected current and a periodic current reference goes to a small steady-state error [115]. Repetitive control that is included in a centralized master-slave control scheme of an AC microgrid is being employed at an islanded mode [122], in which repetitive control is applied to the synchronous reference frame to immunize the output voltage against voltage unbalance and distortion. Repetitive control is also utilized in [123] to mitigate this circulating current, where two parallel controllers (*PI* controller and odd-harmonics repetitive control) are integrated to minimize the circulating current.

e: SLIDING MODE CONTROL (SMC)

Sliding mode control is robust control against uncertainties of the system under study. Its objective is to generate a control law that forces the system states to follow a certain sliding trajectory (also named as sliding surface or sliding manifold). The basic formulation of the 1^{st} order SMC begins with defining a control law as presented in [78], [99], [100].

$$u = u_{discrete} + u_{continuous} \tag{26}$$

The $u_{discrete}$ takes the system states from a particular sliding trajectory to another trajectory, while $u_{continuous}$ keeps the system states on a designated sliding trajectory. The siding trajectory in (27) is defined as a direct/differential/integral form of a state variable error, which may be voltage/current/power error.

$$\begin{aligned} S &= \lambda_1 e, \ \ or \\ S &= (\lambda_1 + \lambda_2 \frac{d}{dt}) e, \ \ or \\ S &= (\lambda_1 + \lambda_2 \int \ dt) e \end{aligned} \tag{27}$$

where λ_1 and λ_2 are constants, e represents the error in a state variable x defined as $e = x_{desired} - x_{actual}$. The $u_{discrete}$ takes several forms to shorten the reaching mode and reduce the chattering. The $u_{continuous}$ may be obtained from the system model and the positive definite Lyapunov stability function, which is commonly defined as,

$$V = \frac{1}{2} S^T(x) S(x) \tag{28}$$

where S is defined by any formula given in (27), and x is defined as a state variable/vector defined in (27). The derivative of the function in (28) along with mathematical simplification yields,

$$\begin{aligned} \dot{V}(x) &= S^T(x)\dot{S}(x) = S^T(x)\frac{\partial S}{\partial x} x^{\cdot} \\ &= S^T(x)\frac{\partial S}{\partial x}\left[Ax + Bu_{continous}\right] \end{aligned} \tag{29}$$

The discrete input of (26), $u_{discrete}$, should be large enough to make $\dot{V}(x)$ negative and transfer the system states to a designated sliding manifold. For tracking control (state variables track set values), the condition ($S = \dot{S} = 0$ for $t > t_0$) should be applied to calculate the terms of the required control law presented in (26).

In the master-slave control scheme, sliding mode control is integrated with the control scheme in [78] to efficiently regulate the voltage and its frequency. While in the islanded mode, it is developed to convert power references into voltage references using the system model. In [83], the master unit has a sliding differential surface for the voltage error (V_{ref}-V_0), while the sliding surface of each slave unit is expressed in terms of the difference between the master injected current i_{L1} and each slave injected current

TABLE 5. Summary for potential advantages and disadvantages of controllers of Fig. 10.

Controller	Potential advantage(s)	Potential disadvantage(s)
P	It is a common controller, it does not require any complicated formulation, and it has very low computational burden.	It has limited capability in transient and steady-state performance.
PI	It is a very common controller because it has good impact at steady-state error and transient performance, and low computational burden.	Its performance is not guaranteed at different operating conditions.
PID	It gives more precise control over a steady-state and transient performance, and low computational burden.	It is rarely used because of its differential part, which magnifies the noise and distortion.
PR	It fits the stationary $\alpha-\beta$ frame and natural $a-b-c$ frame, it can eliminate a steady-state error, and it has low computational burden.	It requires accurate tuning and sensitive to the frequency variation. It has a lower gain towards harmonics rather than the fundamental, then it will not be able to mitigate the harmonics efficiently.
HCC	It is very easy to implement, it has accurate control on injected current, it can be implemented on any topology of inverter (regulator inverters and multilevel inverters).	It implicates variable switching frequency (conventional version), which generates much current ripples/harmonics.
H_∞	It is robust against the system uncertainties and disturbances, and it guarantees the stability of the system.	It requires prefect system modeling, it may become unstable in case some parameters take some values beyond common scope, it has relatively a low dynamic performance.
Deadbeat Control	It has a fast-dynamic performance.	It is sensitive to the sampling time; it requires accurate modeling for the system under study. All states should be controllable.
Optimal Control	It has a fast-dynamic performance, and both steady-state and dynamic performances are optimized simultaneously.	It requires accurate state-space modeling. Sometimes, the integration of the objective function with the system modeling becomes complex.
Predictive Control	It has a robust performance for tracking problems; in addition to its capability for the rejection of periodic disturbances.	It requires accurate state-space modeling. Optimization algorithm does not consider power quality of the output current/voltage unless a special switching modulation is included in this optimization algorithm.
Repetitive Control	It gives zero steady-state error at the fundamental frequency, it can efficiently mitigate the harmonics.	It requires accurate state-space modeling.
SMC	It is robust against system disturbances and parameters' uncertainties. It has a fast dynamic and stable steady-state performance.	It requires accurate state-space modeling, and the discrete term of its control law generates chattering.
Synergetic Control	It has a fast dynamic and steady-state performance. It has a smaller number of controllers' parameters compared to the similar version of the sliding mode control.	It is sensitive to the system parameters uncertainties/variation, which means that it is not as robust as sliding mode control.
Passivity-Based-Control	It is mainly used to guarantee the stability of the system against the system dynamics and disturbances.	It does not give a fast response toward a step change; in addition, its formulation becomes complex when it is required to control several inverter's outputs like voltage, current, and power

$i_{Ln\rightarrow n=2\ to\ N}$. Two different versions of the 1st order sliding mode controller are developed in [99] and [100] for the concentrated current control of parallel inverters. The adaptive sliding mode controller is developed in [99], while the advanced exponential sliding mode controller is formulated in [100] with an integral form of the sliding surface for the current error. The outcome of sliding mode control in [99] and [100] is the injected voltage that is applied on the microgrid to stabilize the load voltage at an islanded mode and inject specific power at a grid-connected mode.

f: SYNERGETIC CONTROL (SC)

Synergetic control is similar to SMC from the operation perspective. Synergetic control has been recently applied to the current loop for the inverter connected to a microgrid, [124], [125]. In [124], synergetic control is developed to regulate the current/power exchange between the PV system and this microgrid. The conventional synergetic defines a manifold function $\psi(x)$ as,

$$\begin{aligned}\psi(x) &= \lambda_1' e(x),\ \ or\\ \psi(x) &= \lambda_1' e(x) + \lambda_2' \dot{e}(x)\end{aligned} \tag{30}$$

where λ_1', λ_2' are positive constants and $\boldsymbol{e}$ is the error of the state variable of interest like the currents/voltages. The system states are forced to follow the above manifold function by an evolution function, which is defined as,

$$T\dot{\psi} + \varphi(\psi) = 0,\ \ \dot{\psi} = \frac{d\psi}{dx}\dot{x} \tag{31}$$

where T is a positive definite value that determines the convergence rate of the macro-variable to a specific manifold $\psi(x)$. The formulas given in (30-31) are integrated with the state-space model of the system to derive a specific control law.

g: PASSIVITY-BASED CONTROL (PBC)

Passivity-based control is a technique, which governs a system by making the closed loop system passive. Passivity-based control is a popular technique for stabilizing controllers. The advantages of this control technique can be summarized as,

- Passive systems can be easily stabilized through a feedback input.
- The passivity theorem ensures that any feedback interconnection of passive systems is again passive, which

provides a degree of robustness against the system dynamics [126].

PBC is recently developed and employed in DC microgrids and is also integrated with droop control in AC microgrids. Yet, it is rarely used in the centralized control schemes for AC microgrids. Few publications adopt *PBC* in AC microgrids and distributed energy systems. For instance, the *PI* controller is integrated with *PBC* to form a nonlinear controller that guarantees asymptotic stability in the sense of Lyapunov for adjusting the output power of the single-phase converter connected to a supercapacitor [127]. In [128], *PBC* is utilized for inverter forming-grid to regulate output voltage and inject power. Voltages and currents of the inverter are represented as state variables and their state-space formulation is integrated with *PBC* to develop control laws for each subsystem within the system under study.

B. FREQUENCY-DOMAIN FORMULATION/OPERATION

This category includes the controllers, which depend directly or indirectly on the frequency domain for their development and/or operation. This category encompasses very few controllers because the instantaneous operation of inverters matches the time domain rather than the frequency domain. The frequency domain is utilized for encoding the current-sharing information of each inverter, so each inverter generates a sinusoid signal with a specific frequency related to its average injected current [19]. In [104], the stability of the system is examined through the reverse power between the microgrid and the distribution system, which is continuously checked in the frequency domain using the second-order generalized integrator PLL (SOGI-PLL) of the master unit.

C. COMPARATIVE ANALYSIS AMONG DIFFERENT CONTROLLERS

This section shows a summary of the merits and demerits of each controller mentioned above in a concise manner as shown in Table 5.

IX. CONCLUSION

This paper introduces a new detailed classification for the centralized control schemes developed to operate parallel inverters and AC microgrids. The contribution of this presented classification is exemplified in a comprehensive review for all centralized control schemes, which may or may not require inter-communications among their inverters. This classification includes four main categories, which are current distribution control, instantaneous current/power control, current/power accumulation control, and miscellaneous control. Some categories have a further classification such as current distribution control and current accumulation control. In addition to the aforementioned classification, this review paper also presents another classification, which shows many controllers and control techniques utilized in the centralized control schemes mentioned in the main classification. In the suggested controllers' classification, the controllers are newly classified based on the domain, at which these controllers and control techniques are developed and formulated. This review paper introduces several comparisons and comparative analyses for the different categories mentioned in Fig. 1. The potential advantages and disadvantages are also listed for four categories of the main classification. In addition, all presented controllers are compared to each other to pinpoint the pros and cons for each controller/control technique utilized for the parallel inverters and AC microgrid operation.

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