On the Secondary Control Architectures of AC Microgrids: An Overview

Yousef Khayat, Qobad Shafiee, Senior Member, IEEE, Rasool Heydari, Mobin Naderi, Tomislav Dragicevic, Senior Member, IEEE, John W. Simpson-Porco, Member, IEEE, Florian Dörfler, Member, IEEE, Mohammad Fathi, Frede Blaabjerg, Fellow, IEEE, Josep M. Guerrero, Fellow, IEEE, and Hassan Bevrani, Senior Member, IEEE

Abstract—Communication infrastructure (CI) in microgrids (MGs) allows for the application of different control architectures for the secondary control (SC) layer. The use of new SC architectures involving CI is motivated by the need to increase MG resilience and handle the intermittent nature of distributed generation units (DGUs). The structure of secondary control is classified into three main categories including centralized SC (CSC) with a CI, distributed SC (DISC) generally with a low data rate CI, and decentralized SC (DESC) with communication-free infrastructure. To meet the MGs operational constraints and optimize performance, control and communication must be utilized simultaneously in different control layers. In this survey, we review and classify all types of SC policies from CI based methods to communication-free policies, including: CSC, averaging based DISC, consensus-based DISC methods, containment pinning consensus, event-triggered DISC, washout-filter based DESC, and state-estimation based DESC. Each structure is scrutinized from the viewpoint of the relevant literature. Challenges such as clock drifts, cyber-security threats, and the advantage of event-triggered approaches are presented. Fully decentralized approaches based on state-estimation and observation methods are also addressed. Although these approaches eliminate the need of any CI for the voltage and frequency restoration, during black start process or other functionalities related to the tertiary layer a CI is required. Power hardware-in-the-loop (PHIL) experimental tests are carried out to compare the merits and applicability of the different SC structures.

Index Terms—Centralized control, decentralized control, distributed control, communication-free control, event-triggered control, microgrids, secondary control.

I. INTRODUCTION

C ontrol objectives in islanded MGs are fulfilled by a hierarchical control platform to set the FaV amplitudes to desired values. PC, SC, and TC are the main control layers which are introduced achieve stability and performance requirements [1]–[4].

The first control layer in the hierarchical control platform is the decentralized PC layer, typically consisting of inner current and voltage control loops, a virtual impedance loop, and a droop mechanism controller. Stabilization of the system’s FaV amplitudes and power sharing between units are the main control objectives in the PC layer. The FaV stabilization is generally achieved by current and voltage control loops, and power sharing is achieved by the droop control mechanism. Voltage and current loops can also be embedded in a single controller, which can dramatically improve the dynamic performance of the system [5]. The virtual impedance loop as an optional loop acts in MGs with mismatched inductive/resistive feeder impedance, to enhance the power quality and power

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sharing accuracy of the MG [6]. Droop control is inspired by conventional power systems, and mimics the steady-state characteristics of a synchronous generator [7]. However, non-droop methods have also been introduced as alternatives [8]–[11].

Steady-state error and FaV amplitude deviations are the drawbacks of the droop control mechanism. Therefore, SC is introduced to eliminate the FaV deviations [12], [13]. Though SC can also be used to improve reactive power sharing accuracy, suppress circulating currents, and harmonic elimination [13], there are fundamental conflicts between accurate reactive power sharing and voltage regulation [14].

Power management and coordination of DGUs at optimal equilibrium points are responsibilities of MGCC, which also determines EC commands due to load-shedding and intentional/unintentional plug in/out of DGUs. Long-term operation concerns such as economic issues and electricity markets are controlled in the global control. Global control and MGCC are located in TC layer in some references [1].

The objective of this survey is to provide an overview of existing SC architectures and to highlight opportunities for future research in this domain. There are some papers that provide a review of the state of the art of MG modelling [15], [16], MG control [17]–[23]. MG stability and protection [24], [25], power sharing methods [7], [26], [27], and distributed secondary control [12], [28] with focus on MAS-based approaches [29]. The present survey is distinct from these surveys in that it comprehensively reviews the SC architectures along with their recent challenges. These architectures are categorized into three main classes: CSC, DISC, and DESC. Several approaches are introduced for each class and summarized in Table I.

### A. Time-scale of the Secondary Control in MGs

Unlike the conventional power systems, MGs employ power-electronic interfaces. Although these interfaces are generally fast enough to provide a rapid control response to a disturbance (such as load/generation changes or contingencies), the activated power by DGUs has several limitations [153]. Due to the low inertial feature of MGs and capacity limitations of DGUs, a change in the load has a significant impact on the system operation. For instance, the frequency response of an MG and a huge power system is shown in Fig. 1. When a disturbance is applied at time $t_0$, in the conventional power systems the main control design concern is time-scale. In MGs, both time-scale and the amount of activated power need to be considered.

### B. Description of the SC Functions

Droop control adjusts the FaV amplitudes by

$$\omega_i = \omega^* - m_i P_i, \quad P_i = G_{LPP}(s)p_i, \quad (1a)$$

$$v_i = v^* - n_i Q_i, \quad Q_i = G_{LPP}(s)q_i, \quad (1b)$$

where $G_{LPP}(s) = \omega_c(s + \omega_c)^{-1}$ is a low-pass filter with cutoff frequency $\omega_c$ for measuring power, and $p_i$ and $q_i$ are the instantaneous active and reactive powers, calculated as

$$p_i = v_{od,i}I_{od,i} + v_{dq,i}I_{dq,i}, \quad (2a)$$

$$q_i = v_{dq,i}I_{od,i} - v_{od,i}I_{dq,i}, \quad (2b)$$

where $v_{od,i}$, $v_{dq,i}$, $I_{od,i}$ and $I_{dq,i}$ are the output voltage and current of DGU$_i$ in the dq frame, respectively. In (1), $m_i$ and $n_i$ are the droop controller gains, and $\omega_i$ and $v_i$ are the FaV reference values for the inner voltage loop. Obviously, any changes in active and reactive powers will change the FaV reference values. This will lead to steady-state errors and to inaccurate active and reactive power sharing between units.

The role of SC is to eliminate the deviations of $\omega_i$ and $v_i$ while simultaneously maintaining the stability of power sharing, voltage, and frequency of the MG. If the set of DGUs in the MG is labeled $N = \{1, \ldots, N\}$, then this may be expressed as

$$\lim_{t \to t_1} \omega_i(t) = \omega^*, \quad (3a)$$

$$\lim_{t \to t_1} v_i(t) = v^*, \quad (3b)$$

$$\lim_{t \to \infty} (m_i P_i(t) - m_j P_j(t)) = 0, \quad (3c)$$

$$\lim_{t \to \infty} (n_i Q_i(t) - n_j Q_j(t)) = 0, \quad (3d)$$
for all \(i,j = 1, \ldots, N\), where (3a), (3b), (3c), and (3d) represent frequency restoration and voltage regulation in finite time \(t_f\) and power sharing in steady-state, respectively. In order to share active and reactive power accurately, the voltage values of DGUs must not be perfectly regulated to their reference values, hence the \(\approx\) symbol in (3b) [14].

Another way to formulate the frequency and active power control objectives (3a) and (3c) is in terms of an optimization problem which allocates the secondary control resources of the system. A simple version is given by

\[
\begin{align*}
\text{minimize} & \quad \sum_{i \in N} \frac{1}{2} m_i P_i^2, \quad (4a) \\
\text{subject to} & \quad \sum_{i \in N} P_i = P_{\text{load}}, \quad (4b)
\end{align*}
\]

where \(P_{\text{load}}\) is the total load in the system. In the problem (4), the quadratic cost (4a) should be minimized subject to balance of active power in the MG, as given by (4b); note that (4b) holds if and only if the frequency objective (3a) holds. It can be shown [88] that the optimal solution of this problem leads to (3a) and (3c). However, this optimization-based perspective allows to specify more sophisticated (non-quadratic) cost functions and constraints giving rise to principled nonlinear controllers achieving the specifications (3) subject to dead-zones, saturations, and alike [120]. We refer to [156], [157] for analogous approaches relating voltage and reactive power control with associated optimization problems.

The SC addresses the above limits by considering a correction term to the droop controller (1) as

\[
\begin{align*}
\omega_i &= \omega^* - m_i P_i + \delta u_{\omega,i}, \quad (5a) \\
v_i &= v^* - n_i Q_i + \delta v_{v,i}, \quad (5b)
\end{align*}
\]

where \(\delta u_{\omega,i}\) and \(\delta v_{v,i}\) are the control signals forwarded from the SC. Shaping of data — such as FaV and active and reactive power — between DGs can be used to design the SC control signals achieve the control objectives above. In addition, power quality improvement and synchronization (when connecting the MG to the main grid) are other functions introduced under the name of SC [87], [119], [158]–[163]. Fig. 2 illustrates centralized SC, DISC, and DESC architectures for achieving this, which will be investigated in the following sections.

III. CENTRALIZED SECONDARY CONTROL

In the CSC structure, a central controller coordinates the DGs and restores the FaV amplitudes, as shown in Fig. 2(a). However, any failure whether in CI or CSC affects the overall stability and performance of the MG. Active power management, voltage control, reactive power management, frequency restoration and harmonic cancellation are the main features of the CSC. In this structure, all required data, i.e., the DGU's FaV, are generally transmitted through a high data rate CI. Therefore, any deficiency in the CI or failure degrades the MG efficiency.

The main challenges in the CSC architecture have been identified to be harmonic cancellation, unbalanced current reduction, and other power quality and management issues to enhance the system performance. The employed controllers for this architecture with its control goal are tabulated in

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**Fig. 1.** (a) A typical time-scale of frequency-related dynamics in conventional power systems [154], and (b) activation of frequency control loops following a disturbance at \(t_0\) in an MG [155].

**Fig. 2.** Three main secondary control architectures: (a) CSC, (b) DISC, and (c) DESC.
Fig. 4. Harmonic elimination by CSC. (a) Voltage THD reduction, and (b) voltage waveforms.

TABLE II. LITERATURE REVIEW ON CSC GOAL SATISFACTION.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Main Contribution</th>
<th>Complexity</th>
<th>Physical Insight</th>
<th>Necessity of Assumption</th>
<th>PnP Verification</th>
<th>Controller type</th>
</tr>
</thead>
<tbody>
<tr>
<td>[30]–[36]</td>
<td>Harmonic cancellation</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Yes</td>
<td>PI</td>
</tr>
<tr>
<td>[36], [43]</td>
<td>Voltage unbalance compensation</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Yes</td>
<td>PI</td>
</tr>
<tr>
<td>[45]</td>
<td>Voltage unbalance compensation</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>No</td>
<td>Cost Function</td>
</tr>
<tr>
<td>[42], [46]</td>
<td>Reactive power management</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>No</td>
<td>Cost Function</td>
</tr>
<tr>
<td>[37], [40]</td>
<td>Stability enhancement</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>No</td>
<td>Adaptive</td>
</tr>
<tr>
<td>[41]</td>
<td>SoC considerations in the SC</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Yes</td>
<td>PI</td>
</tr>
<tr>
<td>[39]</td>
<td>Incorporates technical constraints</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>No</td>
<td>Optimal-Convex</td>
</tr>
</tbody>
</table>

Table VI. Moreover, its SC is implemented as Fig. 3 to harmonic elimination. Fig. 3 shows the CSC structure for the harmonic compensation in the studied MG shown in Fig. 10(b). The CSC compensates for the MG harmonics at the point of common coupling (PCC) by sending the harmonic elimination efforts to the DGUs primary controllers through a low bandwidth communication link (LBCL). Fig. 4 shows the simulation results for the harmonic compensation performance of the CSC. As it can be seen, before the CSC activation, the total harmonic distortion (THD) at the PCC is around 10%, while, after CSC activation at t=0.75 s, the THD decrease by 2% which shows the performance of CSC for harmonic compensation.

The CSC architecture is applied in the literature to address harmonic cancellation, unbalanced current reduction, and other power quality and management issues to enhance the system performance. The employed controllers for this architecture with its control goal are tabulated in Table II.

IV. DISTRIBUTED SECONDARY CONTROL

As units in a MG are heterogeneous and spatially distributed, distributed control or MAS network controls are a promising approach to enhance MG stability and performance.
MG, DGUs are considered as the nodes of the communication graph $G$. The communication network of an MAS can be expressed by variables which can reach an agreement as by employing the CI such that a desired subset of the state cooperative control means to implement a distributed protocol where $\alpha_i \in \mathbb{N}_+$.

DGUs (as agents) work together to cooperatively control the load change.

In distributed control of MASs, such as an MG, a number of DGUs (as agents) work together to cooperatively control the MG and fulfill a set of objectives.

In this case, the behavior of the MG depends on the agent (i.e., DGU) dynamics and the topology of the employed CI. In the following, DISC policies are classified into averaging, distributed consensus, and event-triggered methods.

The basic preliminary for distributed cooperative control is an appropriate knowledge about the CI and its topology. Thus, in this section a brief review on CI modelling and networks are presented, firstly. In an MG system with $N$ DGUs, which characterized by a state variable $x_i(t) \in \mathbb{R}^n$ subject to a control input $u_i(t) \in \mathbb{R}^n$ given as follows:

$$\dot{x}_i(t) = A x_i(t) + D f_i(t, x_i(t)) + B u_i(t),$$

$$y_i(t) = C x_i(t),$$

where $i = 1, 2, ..., N$, and $y_i(t)$ stands for the output variables which need to be synchronized or regulated on a desired value. Cooperative control means to implement a distributed protocol by employing the CI such that a desired subset of the state variables can reach an agreement as $t \to \infty$; that is

$$\lim_{t \to \infty} \|y_i(t) - y_j(t)\| = 0, \quad \forall i, j = 1, 2, ..., N.$$  \hspace{1cm} (7)

The communication network of an MAS can be expressed by a directed graph (digraph) $\mathcal{G}$, which it is usually modelled as $\mathcal{G} = (\mathcal{V}_G, \mathcal{E}_G, A_G)$ with a nonempty finite set of $N$ nodes $\mathcal{V} = \{v_1, v_2, ..., v_N\}$, a set of edges or arcs $\mathcal{E}_G \subset \mathcal{V}_G \times \mathcal{V}_G$, and the associated adjacency matrix $A_G = [a_{ij}]_{N \times N}$. In a MG, DGUs are considered as the nodes of the communication digraph, i.e., $\mathcal{V}$, and the edges of the corresponding digraph $\mathcal{G}$ of the communication network denote the communication links.

### A. Average-based DISC

In the averaging-based structure, each DGU measures its FaV amplitudes and communicates them to all other DGUs.

Let $x_i$ denote a variable of interest (frequency, voltage, active power, etc.), with nominal value $x^*$. By averaging the values received from other DGUs, a control signal can be built as

$$\delta u_i = K_i(s) \left( x^* - \frac{1}{N} \sum_{i \in \mathcal{N}} x_i(t) \right),$$

$$\delta u_i = K_i(s) \sum_{j \in \mathcal{N}, j \neq i} \alpha_{ij} (x_j(t) - x_i(t))$$  \hspace{1cm} (9)

to form the SC inputs in equation (5) \cite{14}, \cite{48}–\cite{51}, \cite{53}, \cite{54}, \cite{88}, \cite{120}. The controller $K_i(s)$ can be designed in different ways (e.g., PI) and tuned for dynamic performance.

Fig. 5 and Fig. 6 show the MG frequency restoration and voltage recovery performance of a high bandwidth averaging DISC proposed in \cite{49}, respectively.

### B. Consensus-based DISC

For MASs, the CI structure shows the direction and information of the agents as DGUs in a MG. Algorithms leading to agreement among all DGUs are called consensus, agreement, or distributed averaging algorithms \cite{169}. Robustness of this technique is proved in several research works even in the presence of communication delays \cite{44}, \cite{53}, \cite{116}, \cite{121}, \cite{170}. In order to restore the FaV in the MG applying the consensus-based techniques, the following distributed protocol is used \cite{14}, \cite{55}, \cite{88}, \cite{164}, \cite{168}

$$\delta u_i = K_i(s) \sum_{j \in \mathcal{N}, j \neq i} \alpha_{ij} (x_j(t) - x_i(t))$$

to produce the control signals in (5). Fundamental performance limitations of such controllers have been examined in \cite{165}–\cite{167}. If the controller $K_i(s)$ in (11) contains integral control, then in steady-state it will hold that $x_i = x_j$ for all $i, j \in \mathcal{N}$.

As a concrete example, this could correspond to active power sharing if $x_i = m_i P_i$, which would meet the control objective...
in (3c). In (11), the coefficients $\alpha_{ij}$ are nonnegative and are the elements of the so-called adjacency matrix of the graph describing the CI. DGUs $i$ receives information from DGU $j$ if $\alpha_{ij} \neq 0$; see [169] for more details. The summary of methods employing consensus protocols in the SC design procedure is illustrated in Fig. 7.

In order to control an MAS such as an MG converging to a given desired value, the distributed pinning consensus protocol is presented [177]. The term “pinning control” in distributed cooperative control means merely a fraction of nodes in the studied network, which are pinned by the designer to the objective trajectory and the rest of the nodes communicate with each other to achieve the expected networked tracking. A DISC problem is to find correction terms $\delta u_{v,i}$ and $\delta u_{s,i}$ in (5) such that satisfy (3). To this end, the cooperative objectives can be expressed in terms of the local neighborhood tracking error,

$$e_i = \sum_{j \in N} \alpha_{ij} (x_j(t) - x_i(t)) - g_i (x_i(t) - x^*)$$

and the correction term can be calculated as:

$$\delta u_i = -cK_i e_i,$$

where $i = 1, 2, ..., N$, the pinning control gain $g_i \geq 0$ and $g_i = 0$ shows there is no control over the DGU$_i$, $x^*$ is the desired value for the consensus state $i$, $c \in \mathbb{R}$ is the coupling gain and $K_i$ is the feedback control vector. This approach has been employed as pinning-consensus (or leader-following consensus) problems in secondary layer of the MGs. [86], [87], [109], [113].

Unlike the leader-following consensus control, where there exists only one leader in the MG as a MAS, containment control protocol is presented in the presence of multiple leaders and followers in an MAS such as MG [66]. For MGs with many DGUs, conventional consensus is often not sufficient, as the CI topology may be very dynamic. There are many open research challenges in this direction, such as choosing the (optimal) pinned DGUs, convergence rate based on the MG scale, the optimal number of follower DGUs, and switched-CI challenges for networked MGs. The role of containment control can be highlighted in the presence of multiple leaders and multiple followers in an MAS, where the control objective is to bring all the followers into a convex hull spanned by the leaders. The containment protocol of $N$ nonlinear agents in (6) with the dynamic of $i^{th}$ agent can be expressed as follows:

$$\dot{x}_i(t) = A x_i(t) + D f(t, x_i(t)) + B u_i(t), \quad i \in \mathcal{V}_F$$

$$\dot{x}_i(t) = A x_i(t) + D f(t, x_i(t)), \quad i \in \mathcal{V}_F$$

where $\mathcal{V}_F \triangleq \{1, ..., M\}$ and $\mathcal{V}_F \triangleq \{M + 1, ..., N\}$ stand for the followers’ and the leaders’ sets, respectively. Similar to (11), the containment protocol for the followers in (IV-B) can be calculated as

$$\delta u_i = \sum_{j=1}^{N} (x_j(t) - x_i(t)), \quad i \in \mathcal{V}_F.$$ 

Finally, there is a large independent literature developing distributed consensus-based secondary control strategies deriving from distributed algorithms to solve the optimization problem (4), see [28, Section IV.C] for a review.

C. Event-triggered DISC

Over the past years, the ETC has been increasingly employed at the SC level of MG control, as it reduces information exchange among DGUs while retaining stability [122]-[133]. Practically, instead of continuous data exchange among DGUs, the required data can be shared when a criteria is satisfied or an event is triggered. Then, a sampled-data control method is performed, and data is exchanged by a designed mechanism on ETC [171], [184]. As illustrated in Fig. 8, time-triggered, event-triggered, and self-triggered sampling methods are three presented approaches to realize ETC methods.

In time-triggered SC, the control is driven by a clock [185]. This periodic paradigm can be seen as an open-loop sampling (see Fig. 8(a)). In the event-triggered SC, a signal is sent to the SC if an event has occurred, rather than a continuous signal transmission. This can be considered as an introducing feedback in the sampling process (see Fig. 8(b)). It requires the permanent monitoring of the state(s) to determine current performance. Finally, in the self-triggered control, the current state is employed not only to compute the control signal (the input to the system), but it should be calculated the next time for recomputation of control law. Though this mechanism is still closed-loop based on the current performance, permanent monitoring of the state(s) is no longer required (see Fig. 8(c)). A common structure of the ETC can be computed based on the errors between the current instant and the last event of the state variable. The errors are based on the observed and measured value of the state variable [186].

In the ETC designs, the following practical issues should be considered:

1) Event Mechanism: Design of a mechanism for event detection is a key challenge for computing event time instants, which directly depends on reducing the recomputation of control law and communication of neighbors. Basically, the structure of the event mechanism should be physically explainable and easy to implement from a practical perspective. As an open research problem, in the MG applications, estimation and observation approaches can be utilized to reduce the employed CI by designing a event mechanism for the SC [187], [188].

2) Consensus ETC: If ETC is combined with consensus, the measurements of neighboring DGUs are available only at event time instants. Therefore, an important concern for consensus-ETC designs is how to efficiently employ such information to recompute control law under the designed ETCs. Besides, it is a great challenge to design both the controller in (11) and a threshold-based mechanism for event detection in a unified framework, while the stability of the system must be maintained without occurring Zeno phenomenon.

3) Zeno Phenomenon: When the ETC generates an infinite number of sampling instants (events) during a finite time, Zeno phenomenon occurs [189] and makes the solution inapplicable for the real-world systems. This concern should be considered...
in the control design procedure. To achieve this goal, switching approaches are addressed which by finding a waiting time guarantees a lower bound for the inter-event times in the event mechanism [190].

In what summarized in Table III, a number of typical ETC mechanisms developed for consensus protocols of MASs in the existing literature are classified. Nonetheless, we may concentrate on various definitions of the sampling error, e.g., see the tracking error in (10), and threshold without further investigation on their Zeno behavior features because most of them can rule out this phenomenon.

### D. Problem Based DISC

In this subsection, the works mainly focused on the challenges associated with the SC are presented. These challenges are investigated in the following items.

1) **Voltage stability and reactive power sharing**: Unlike the $P/\omega$ droop (5a), the power sharing performance of $Q/\omega$ droop (5b) is generally unsatisfactory. This is due to the fact that voltage is a local variable, and in a direct conflict with reactive power. Due to the circulating reactive power and inaccurate reactive power sharing, this issue should be considered in a conservative manner. This challenge, as another SC function, is addressed in [10], [14], [92], [115]–[117], [119] and [125].

2) **Clock drifts**: A key challenge towards a DGU synchronization, connecting an MG to grid, simultaneous FaV regulation, and accurate power sharing in an MG is the implementation of the designed controller through appropriate hardware. Since each converter in the converter-based MGs operates based on the clock of its processor, a prevalent phenomenon in digital control implementation is clock drift [191]–[193], which may degrade the performance of the system (for example see [194] for recognition of clock synchronization challenges). Because of the popularity of crystal oscillator-based clock processors, with nominal frequency $f_c$, a small uncertainty in clock drift makes the clock cycle of the processor as $\Delta t_c = 1/f_c(1+\mu)$, where $\mu$ is the relative drift of the crystal-oscillator of processor clock [195].

Several papers investigate clock drifts influence on the SC policies. Clock drift phenomenon in the MG was modeled and investigated firstly in [178]. Then, in [63] and [196] a

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**Fig. 8. Event-triggered based distributed secondary control structures: (a) time-triggered DISC, (b) event-triggered DISC, and (c) self-triggered DISC.**

### TABLE III. TYPICAL ETC MECHANISMS FOR MASs.

<table>
<thead>
<tr>
<th>Threshold Mechanism</th>
<th>Ref.</th>
<th>Complexity</th>
<th>BW Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed threshold</td>
<td>$|e_i(t)| \geq \delta_i$</td>
<td>[171]</td>
<td>Low</td>
</tr>
<tr>
<td>Time-dependent threshold</td>
<td>$|e_i(t)| \geq \sigma_0 + c_1 e^{-\mu_1(t)}$</td>
<td>[172]</td>
<td>Medium</td>
</tr>
<tr>
<td>Continuous state dependent</td>
<td>$|e_i(t)| \geq \sigma_1 |X_i(t)|$</td>
<td>[173]</td>
<td>Medium</td>
</tr>
<tr>
<td>Sampled state-dependent and a positive offset</td>
<td>$|e_i(t)| \geq \sigma_1 |X_i(s_k)| + \delta_i$</td>
<td>[174]</td>
<td>Medium</td>
</tr>
<tr>
<td>Sampled state-dependent and a time-dependent positive offset</td>
<td>$|e_i(t)| \geq \sigma_1 |X_i(s_k)| + c(t)$</td>
<td>[176]</td>
<td>High</td>
</tr>
</tbody>
</table>

### TABLE IV. CLOCK DRIFT PHENOMENON LITERATURE.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>SC Policy</th>
<th>Main Achievements</th>
<th>drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>[178]</td>
<td>Without SC</td>
<td>Robust against clock drift</td>
<td>- Huge computations</td>
</tr>
<tr>
<td>[179]</td>
<td>Droop free</td>
<td>+ Experimental verification</td>
<td>- Not considered PnP challenges</td>
</tr>
<tr>
<td>[180]–[182]</td>
<td>DISC</td>
<td>+ Derive tuning criteria for zero steady-state frequency deviations</td>
<td>- Not considered sufficient criteria</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Low inertia system is considered</td>
<td></td>
</tr>
<tr>
<td>[183]</td>
<td>DESC</td>
<td>+ PI based DESC investigation</td>
<td>- Not considered PnP challenges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Slow transient response</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE V. LITERATURE REVIEW ON DESC GOAL SATISFACTION.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>DESC type</th>
<th>Controller type</th>
<th>Complexity</th>
<th>Stability Analysis</th>
<th>PnP Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>[135], [136]</td>
<td>Washout filter-based</td>
<td>(15)</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>[138]</td>
<td>Washout filter-based</td>
<td>(16)</td>
<td>Low</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[139]</td>
<td>Local Variable</td>
<td>Time-dependent switched PI</td>
<td>High</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>[143], [144]</td>
<td>Local Variable</td>
<td>Linear quadratic regulator</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>[141]</td>
<td>Local Variable</td>
<td>Integrator based</td>
<td>Medium</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[146]</td>
<td>Nonlinear observer</td>
<td>PI</td>
<td>High</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[147]</td>
<td>Observer-based</td>
<td>MPC</td>
<td>High</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>[149]</td>
<td>Sliding-mode estimator</td>
<td>Averaging integrator</td>
<td>High</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
A comprehensive analysis of the performance of SC policies with respect to clock drifts are presented. However, all the reviewed models are based on the PI controller in Table IV, where the main achievements and drawbacks of clock drift studies are listed. Considering this phenomenon in different secondary controllers and different conditions such as PnP is an open area for research.

V. DECENTRALIZED SECONDARY CONTROL

In DESC approaches, CIs are not used for FaV restoration; Each DGU restores its FaV amplitudes to nominal values separately. Although the CI is not applied in the SC operation, the CI is required for transferring data from the TC and MGCC layers [197]. For instance a global CI is required for coordination of the DGUs during black start and PnP processes, real-time monitoring or functionalities of the MGCC, and TC higher control loops. Design procedures employed in this structure are divided into the three main categories, as follows.

A. Washout Filter-Based DESC

This approach is implemented on the droop control layer, as follows [137]:

\[
\omega = \omega^* - m \left( \frac{s}{s + k_p} \right) \left( \frac{\omega_c}{s + \omega_c} \right) p \quad (15a)
\]

\[
v = v^* - n \left( \frac{s}{s + k_q} \right) \left( \frac{\omega_c}{s + \omega_c} \right) q \quad (15b)
\]

If the MG is stable, then by applying the final value theorem to the equations (15), one can show that \(\omega_j\) and \(v_j\) converge to their reference values. A simplified generalized band-pass washout filter SC is introduced in [136] as
\[
\begin{align}
\omega &= \omega^* - \frac{m}{k_{pw} + 1} \cdot \frac{\omega_c}{s + \omega_c} \cdot \frac{s}{k_{iw} + \frac{k_{pw} + 1}{s + \omega_c}} \cdot p \tag{16a}
\end{align}
\]
\[
\begin{align}
v &= v^* - \frac{n}{k_{pv} + 1} \cdot \frac{\omega_c}{s + \omega_c} \cdot \frac{s}{k_{iv} + \frac{k_{pv} + 1}{s + \omega_c}} \cdot q \tag{16b}
\end{align}
\]

By adopting appropriate values for the high pass filter as \( k_{pw} = k_{pv} = 0 \), \( k_{iw} = k_p \), and \( k_{iv} = k_q \), the washout filter based SC (15) can be implemented as well. The generalized band-pass washout filter for the SC is realized by cascading a low-pass filter and a high-pass filter. Its frequency characteristics affect the SC transient response. An analogy between angle droop and frequency droop with new perspectives on virtual impedance regarding the washout filter has been done in [136]. In addition, in [145] the effect of fully decentralized integral control through leaky integral control is studied and the authors provided a comprehensive performance and robustness analysis as well as optimal tuning recommendations for local PI based SC.

A second-order washout filter based power sharing approach for UPS with stability analysis is introduced in [138] for \( Q/\omega \) and \( P/\omega \) droop control strategy as follows:

\[
\begin{align}
\omega &= \omega^* + n_q \frac{s}{A_c s^2 + B_c s + C_c} \left( \frac{\omega_c}{s + \omega_c} \cdot q \right) \tag{17a}
\end{align}
\]
\[
\begin{align}
v &= v^* - m_p \frac{1}{A_c s^2 + B_c s + C_c} \left( \frac{\omega_c}{s + \omega_c} \cdot p \right) \tag{17b}
\end{align}
\]

Similar to [145] the effect of fully decentralized second-order washout filter based can be investigated for the future researches by providing a comprehensive performance and robustness analysis as well as optimal tuning of the coefficients of the filter.

B. Local Variable-Based DESC

In [140] authors used local signals to design a SC without any CI according to a time-dependent protocol. An optimal linear quadratic regulator based DESC for frequency restoration is also presented in [143], [144], [198].

C. Estimation-Based DESC

Recently, several papers have presented fully DESC schemes utilizing the state estimation methods in autonomous MGs [149]–[152]. To deal with the associated challenges of the global cooperative control in DESC structure, state variable estimation approaches have been recommended [199]–[201]. Recently, a decentralized state estimation method has been introduced for the hybrid AC/DC MGs [150]. Generally, estimation methods deserve significant attention because of their communication-free feature. However, in the MG applications, estimation/observation methods depend on the modelling of the system. They serve as alternatives to CIs to inform the dynamics of the rest of MG to the local SC units. In addition, [146] and [149] have addressed a nonlinear and Luenberger-like observers for DESC approaches by replacing the measurements in (11) with estimates as:

\[
\delta u_i = K_i(s) \sum_{j \in \mathcal{N}} \alpha_{ij} (\hat{x}_j - x_i) \tag{18}
\]

where \( \hat{x}_j(t) \) is the estimated value of variable \( x_j(t) \) to design the DESC. Specifications of the reviewed DESC approaches are introduced in Table V. In addition, a simple overview of the SC implementation for master-slave, averaging, consensus and estimation based control architectures is demonstrated in Fig. 9. Based on the presented SC architectures, the controller \( K_i(s) \) can be designed considering stability and performance issues.

VI. RESULT COMPARISON

In order to scrutinize the performance of the defined control structures, an autonomous four-units test MG is implemented. The case study MG comprises four VSCs connected to the common bus through dedicated LC filters shown in Fig. 10. The rated frequency and voltage are 50 Hz and 325 V, respectively. The control parameters and more details of the MG are shown in Table VI.

Fig. 11(a) and (b) shows the reactive power sharing performance of the consensus based DISC and ETC based DISC (inspired from [125]), respectively. At \( t=12 \) s the secondary controller is activated and the reactive power is shared properly among DGUs. In both cases, i.e., consensus based DISC and ETC based DISC, the reactive power sharing is carried on...
properly. However in ETC based DISC the transmitted data rate is lower than the consensus based DISC. It is worth to note that the reactive power error and its thresholds is illustrated in Fig. 12(b).

Fig. 12 shows evaluation of measurement errors of DGU₁ under four different ETC mechanisms. In order to a fair comparison, all the four mechanisms have been normalized. It is shown how varies the number of events in different ETC structures with a fixed or adaptive thresholds. In Fig. 12(a) a constant threshold is applied, hence, if the error exceed the predefined threshold, an event signal is transferred. In Fig. 12(b) the ETC presented by authors in [125] with its adaptive threshold is applied. As it can be seen, in this ETS structure, the number of transmitted signals and events in lower than constant threshold. Fig. 12(c) and (d) show the self-triggered mechanisms proposed in [134] to decrease the number of transmitted data. In Fig. 13 a comprehensive comparison, in terms of the transmitted data rate and required communication link among CSC and different DISC architectures i.e. Averaging, consensus, event triggered and self triggered is demonstrated. In this case, two signals i.e., reactive power and voltage, are transmitted through different architectures.
obviously CSC structures relay on the transmitted data through no effect on the performance of DESC, while DISC and infrastructure, time delay or communication disturbances have time delays. As the DESC don’t need the communication delay’s effect in DISC approaches.

Fig. 14 shows a comparison between DESC and DISC structure considering communication link time delay. A frequent load change is applied at t=15 s and t=17 s. Fig. 14(a) demonstrates the performance of the DESC structure and Fig. 14(b)-(d) shows the DISC structure performance with different time delays. As the DESC don’t need the communication infrastructure, time delay or communication disturbances have no effect on the performance of DESC, while DISC and obviously CSC structures relay on the transmitted data through communication infrastructure. As can be seen from Fig. 14(b)-(d), by increasing the time delay, the control performance of DISC degrades.

![Fig. 14. Performance comparison of decentralized control scheme [144] versus distributed secondary control introduced at [50] by considering communication delay’s effect in DISC approaches.](image)

**TABLE VI. PARAMETERS OF THE TEST SYSTEM**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage of rectifier</td>
<td>$V_{DC}$</td>
<td>650 V</td>
</tr>
<tr>
<td>Nominal voltage magnitude</td>
<td>$V_1$</td>
<td>325 V</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>$f$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>$f_s$</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Capacitance of LCL filter</td>
<td>$C_f$</td>
<td>25 µF</td>
</tr>
<tr>
<td>Inductances of LCL filter</td>
<td>$L_1 / L_o$</td>
<td>1.8 mH</td>
</tr>
<tr>
<td>Load 1</td>
<td>$Z_1$</td>
<td>43.1 , 0.3 H</td>
</tr>
<tr>
<td>Load 2</td>
<td>$Z_2$</td>
<td>124.1 , 0.1 H</td>
</tr>
<tr>
<td>Line 1</td>
<td>$Z_{12}$</td>
<td>0.411 , 3.6 mH</td>
</tr>
<tr>
<td>Line 2</td>
<td>$Z_{23}$</td>
<td>0.812 , 1.8 mH</td>
</tr>
<tr>
<td>Line 3</td>
<td>$Z_{34}$</td>
<td>0.412 , 1.2 mH</td>
</tr>
</tbody>
</table>

As can be seen, lower rate of data transmission is required for the event and self triggered DISC, while for the CSC the higher rate of transmitted data is needed.

![Fig. 14(a) DESC, (b) DISC (Without delay), (c) DISC (Delay=200 ms), (d) DISC (Delay=600 ms)](image)

**VII. OPEN ISSUE CONCERNS**

So far, challenges on event-triggered and pinning consensus methods have been reviewed. More challenges can still be noted in the following.

The effects of malicious cyber-attacks on CI such as denial-of-service [108], [202]–[204], and false-data injection attacks, as well as detection and localization of the attacked nodes and links, and designing appropriate strategies beside the controller should be further considered. In [205] a review of cyber attacks for the power system is presented, which can be also applied on the MG. The promise of observer/estimator based controllers, in order to achieve stability margins and reliability of the system under diverse uncertainty, will introduce new SC architectures for the MG.

References [206] and [207] provide an approach towards observability and controllability analysis of the networked linear systems subject to data losses. However, the time-varying delays introduce negative effect on $PnP$ scenarios. This issue requires further research. Another generally open issue is the performance and robustness of secondary MG controllers, when the system is driven by measurement noise and disturbances.

Multi-MG structures are also introduced as a more resilience solution, which can have a static or dynamic topology and interconnect on a same distribution feeder. The main difference between the static and dynamic multi-MG is that the dynamic multi-MGs have a changing point of interconnection. This can be realized by smart static switches. Fig. 15(a) shows a static multi-MG in which they can be networked with each other by a static switch located in the common bus. Figs. 15(b) and 15(c) show two possible topology of a dynamic multi-MG. As it can be seen, the multi-MG’s topology can change based on the static switch situation. Another classification of Multi-
MG systems can be done based on the interlink devices and how MGs are connected with each other. However, multi-MGs can be networked by controllable circuit breakers (CBs), e.g., smart switches (SSWs) with cost-efficient reasons, back-to-back converters (BTBCs) are another solution which can be employed for implementing extra functionalities by cooperative control approaches. Networked multi-MGs through power electronic interfaces can be constructed in various structures. AC-DC Multi-MGs, AC-DC interlinking lines, interlinking devices, distributed and decentralized control, as well as communication methods, lead to different Multi-MG structures. Apart from the stability analysis/requirements within a multi-MG cluster, the distributed cooperation among multiple-MG clusters is also essential to increase the reliability of the whole multi MG-cluster system. In this way each MG will be able to absorb power from its neighbors in an emergency situation. To this end, several works have been done, which employed decentralized/distributed secondary control approaches [208]. Self-healing capability of the distribution system after extreme faults by designing a control framework for multi-MG systems, robust distributed control for more resilient energizing, and power exchange strategies based on the instantaneous static switch are some examples of control methods that can be performed in secondary layer to improve the power exchange among multi-MG systems. Nevertheless, the important role of secondary control either in distributed or decentralized manners for more resilience and improve the power exchange is not addressed properly. Reducing the communication infrastructure by self-triggered, event-triggered, or even decentralized approaches leads to a more secure-resilience multi-MG system, which needs to employing efficient cyber-control study as open issues to shed light.

VIII. Conclusion
This paper presented an overview of the secondary control structures in the hierarchical control of autonomous MG. In order to improve the reliability, energy management of the MG, centralized SC is established. CSC is reviewed in detail and merits and drawbacks of this structure, such as communication deficiencies, have also been summarized. Due to the single point of failure of the centralized structure, distributed structure is presented. DISC strategies are categorized based on different communication structures and transmitted data into the three main topologies: averaging based, consensus-based, and event triggered based approaches. However, in consensus structure, with increasing the number of DGUs, new concerns are revealed and stated as open issues. Furthermore, event based DESC structures, configurations and formulations are scrutinized. Finally, DESC structures which are entirely communication-free are presented. Design procedures employed in this structure are divided into the three main categories, i.e., washout filter based, local variable based and estimation based approaches. Although DESC structure have no communication challenges, i.e., CI delay and data dropout, in order to achieve a comprehensive control, an accurate estimation of neighbour DGUs variable is required. Voltage stability, reactive power sharing, and clock drift challenges of SC for experimental implementations are also summarized. Finally, a comprehensive comparison, as well as control design challenges, formulations and open issue concerns have been presented.

IX. APPENDIX
The communication links of the studied MG for the consensus DISC and ETC-DISC is given as follows:

$$A_G = [\alpha_\alpha]_{4 \times 4} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}.$$  

By a simplified $Q_v$ dynamics for DGU, given as:

$$\dot{V}_i = u_i$$

$$Q_i = |B_{ii}|V_i^2 - \sum_{m \in N} |B_{im}|V_mV_j$$

where $V_i$ is the output voltage amplitude of DGU; $u_i$ is the control effort; $B_{ii}$ is the shunt susceptance of DGU. In
[125] an ETC-DISC for proportional reactive power sharing is formulated by

\[ u_i(t) = -\frac{\kappa}{X_i} V_i(t) \sum_{j \in N} \alpha_{ij} \left( Q_i(t_k^j+i) - Q_j(t_k^j+i) \right) \]  

(20)

where \( k_i(t) = \arg \max_k \{ t_k^i \leq t \} \), \( X_i \) and \( X_j \) stand for the \( Q_{ac} \) droop coefficients of DGU

\( i \) and DGU

\( j \). The ETC, which determines the event times \( t_k^i \) of DGU

\( i \), was designed as

\[ |e_i(t)| = |Q_i(t_k^i+i) - Q_i(t_k^i+i) - Q_j(t_k^j+i) - Q_j(t_k^j+i)| \]  

(21)

where \( e_i(t) = Q_i(t_k^i+i) - Q_i(t_k^i+i) \), \( Q_i(t_k^i+i) \) stands for the transmitted measurement of \( Q_i(t) \) at the event time instant \( t_k^i \), \( k \in N \), and \( \eta \) is a positive constant and its maximum value can be chosen lower than the maximum eigenvalues of Laplacian matrix \( A_c \).

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Qobad Shafiee (S’13 - M’15 - SM’17) received PhD degree in electrical engineering from the Department of Energy Technology, Aalborg University (Denmark) in 2014. He is currently an Assistant Professor, Director of International Relations, and Program Co-Leader of the Smart/Micro Grids Research Center at the University of Kurdistan, Sanandaj, Iran, where he was a lecturer from 2007 to 2011. In 2014, he was a Visiting Scholar with the Electrical Engineering Department, the University of Texas at Arlington, Arlington, TX, USA. He was a Post-Doctoral Fellow with the Department of Energy Technology, Aalborg University in 2015. His current research interests include modeling, energy management, control of power electronics-based systems and microgrids, and model predictive and optimal control of modern power systems.

Rasool Heydari (S’16-M’19) received the Ph.D. degree in electrical engineering from the Department of Energy Technology, Aalborg University, Denmark, in 2019. He was also a visiting researcher with ABB Corporate Research, Västerås, Sweden, in 2019. He is currently a Post-Doctoral Fellow with the Department of Electrical Engineering, the Mads Clausen Institute, University of Southern Denmark, Odense, Denmark. His principal field of interest include control, stability and dynamic analysis of power electronic systems, mainly distributed and grid-connected converters and microgrid.

Mobin Naderi (S’16) was born in Paveh, Iran. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Tabriz University, Tabriz, Iran, in 2012 and Iran University of Science and Technology, Tehran, Iran, in 2014. He was a Visiting PhD student with Department of Energy Technology, Aalborg University, Aalborg, Denmark. He is now working toward the Ph.D. degree in the control of power systems at the University of Kurdistan, Iran. His research interests focus on robust control methods, and modeling, stability and control of autonomous and interconnected AC microgrids.

Tomislav Dragičević (S’09 - M’13 - SM’17) received the M.Sc. and the industrial Ph.D. degrees in Electrical Engineering from the Faculty of Electrical Engineering, Zagreb, Croatia, in 2009 and 2013, respectively. From 2013 until 2016 he has been a Postdoctoral research associate at Aalborg University, Denmark. From March 2016 he is an Associate Professor at Aalborg University, Denmark where he leads an Advanced Control Lab.

He made a guest professor stay at Nottingham University, UK during spring/summer of 2018. His principal field of interest is design and control of microgrids, and application of advanced modeling and control concepts to power electronic systems. He has authored and co-authored more than 180 technical papers (more than 80 of them are published in international journals, mostly IEEE Transactions) in his domain of interest, 8 book chapters and a book in the field. He serves as Associate Editor in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, in IEEE Emerging and Selected Topics in Power Electronics and in IEEE Industrial Electronics Magazine. Dr. Dragičević is a recipient of the Končar prize for the best industrial PhD thesis in Croatia, and a Robert Mayer Energy Conservation award.

John W. Simpson-Porco (S’11–M’18) received the B.Sc. degree in engineering physics from Queen’s University, Kingston, ON, Canada in 2010, and the Ph.D. degree in mechanical engineering from the University of California at Santa Barbara, Santa Barbara, CA, USA in 2015. He is currently an Assistant Professor of Electrical and Computer Engineering at the University of Waterloo, Waterloo, ON, Canada. He was previously a visiting scientist with the Automatic Control Laboratory at ETH Zürich, Zürich, Switzerland. His research focuses on feedback control theory and applications of control in modernized power grids.

Prof. Simpson-Porco is a recipient of the 2012–2014 IFAC Automatica Prize and the Center for Control, Dynamical Systems and Computation Best Thesis Award and Outstanding Scholar Fellowship.

Florian Dörfler is an Associate Professor at the Automatic Control Laboratory at ETH Zürich. He received his Ph.D. degree in Mechanical Engineering from the University of California at Santa Barbara in 2013, and a Diplom degree in Engineering Cybernetics from the University of Stuttgart in 2008. From 2013 to 2014 he was an Assistant Professor at the University of California Los Angeles. His primary research interests are centered around control, optimization, and system theory with applications in energy and power systems. His students were winners or finalists for Best Student Paper awards at the European Control Conference (2013, 2019), the American Control Conference (2016), and the PES PowerTech Conference (2017). His articles received the 2010 ACC Student Best Paper Award, the 2011 O. Hugo Schuck Best Paper Award, the 2012-2014 Automatica Best Paper Award, and the 2016 IEEE Circuits and Systems Guillemin-Cauer Best Paper Award. He is a recipient of the 2009 Regents Special International Fellowship, the 2011 Peter J. Frenkel Foundation Fellowship, and the 2015 UCSB ME Best PhD award.

Mohammad Fathi received the M.Sc. and the Ph.D. degrees in electrical engineering from Amirkabir University of Technology, Tehran, Iran in 2003 and 2010, respectively. From 2003 to 2006, he was a Lecturer with the Department of Electrical Engineering, University of Kurdistan, Sanandaj, Iran, where he is currently working as an Associate Professor. He conducted a part of his Ph.D. research work in the Communications and Networking Theory Laboratory, Royal Institute of Technology, Stockholm, Sweden from February 2010 to November 2010. His current research interests include smart grid communications and control, wireless network resource allocation, and optimization.
Frede Blaabjerg (S’89 - M’88 - SM’97 - F’03) was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. From 1988 to 1992, he got the PhD degree in Electrical Engineering at Aalborg University in 1995. He became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. From 2017 he became a Villum Investigator. He is honoris causa at University Politehnica Timisoara (UPT), Romania and Tallinn Technical University (TTU) in Estonia.

His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics and adjustable speed drives. He has published more than 600 journal papers in the fields of power electronics and its applications. He is the co-author of four monographs and editor of ten books in power electronics and its applications.

He has received 31 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, the Villum Kann Rasmussen Research Award 2014 and the Global Energy Prize in 2019. He was the Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2006 to 2012. He has been Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011 as well as 2017 to 2018. In 2019-2020 he serves a President of IEEE Power Electronics Society. He is Vice-President of the Danish Academy of Technical Sciences too. He is nominated in 2014-2018 by Thomson Reuters to be between the most 250 cited researchers in Engineering in the world.

Josep M. Guerrero (S’01 - M’04 - SM’08 - F’15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalina, Barcelona, in 1997, 2000, and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. From 2014, he was a Chair Professor with Shandong University; from 2015, he was a Distinguished Guest Professor with Hunan University; and from 2016, he was a Visiting Professor Fellow with Aston University, U.K., and also a Guest Professor with the Nanjing University of Posts and Telecommunications. Since 2019, he has also been a Villum Investigator with The Villum Foundation, which supports the Centre for Research on Microgrids (CROM), Aalborg University, where he has also been the Founder and the Director.

His research interests include different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, smart metering, and the Internet of Things for AC/DC microgrid clusters and islanded minigrids, especially focused on maritime microgrids and renewable energy systems, which are cited more than 40,000 times. He received the Best Paper Award of the IEEE Transactions on Energy Conversion, from 2014 to 2015, the Best Paper Prize of IEEE-PES, in 2015, and the Best Paper Award of the Journal of Power Electronics, in 2016. During five consecutive years, from 2014 to 2018, he was awarded by Clarivate Analytics (former Thomson Reuters) as Highly Cited Researcher. In 2015, he was elevated as the IEEE Fellow for his contributions on distributed power systems and microgrids.