On the Secondary Control Architectures of AC Microgrids: An Overview

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***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. The structure of SC 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 experimental tests are carried out to compare the merits and applicability of different SC structures.**

***Index Terms*—Centralized control, communication-free control, decentralized control, distributed control, event-triggered control (ETC), microgrids (MGs), secondary control (SC).**

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NOMENCLATURE

MG	Microgrid.
CI	Communication infrastructure.
DGU	Distributed generation unit.
CSC	Centralized secondary control.
DISC	Distributed secondary control.
DESC	Decentralized secondary control.
MGCC	Microgrid central controller.
PnP	Plug and play.
ETC	Event-triggered control.
IR	Inertial response.
PC	Primary control.
SC	Secondary control.
EC	Emergency control.
AGC	Automatic generation control.
TC	Tertiary control.
FaV	Frequency and voltage.
LPF	Low-pass filter.
MAS	Multiagent system.
BW	Bandwidth.
PCC	Point of common coupling.
LBCL	Low-bandwidth communication link.
SoC	State of charge.
PHiL	Power hardware in the loop

Variables

G_{LPF}	Transfer function of the LPF.
ω^*	Nominal frequency of the system.
v^*	Nominal voltage of the system.
ω_c	Cutoff frequency of the LPF.
s	Laplace variable.
α_{ij}	Coupling strength between adjacent DGUs.
δu_i	Correction term forwarded from SC.
K	Control gain matrix or gain.
$x_i(t)$	State variable.
N	Number of MG's DGUs.
$\mathcal{G}$	MG's communication digraph.

I. INTRODUCTION

CONTROL objectives in islanded MGs are fulfilled by a hierarchical control platform to set the FaV amplitudes to desired values. PC, SC, and TC, the main control layers,

TABLE I
SC POLICIES AND CONTROL STRUCTURES IN AC MGS

SC Policy	Control Method	References
CSC	Centralized	[30]–[47]
DISC	Averaging	[14], [48]–[56]
	Consensus	[57]–[121]
	Event-triggered	[122]–[134]
DESC	Washout-filter based	[135]–[138]
	Local measurement based	[139]–[145]
	State-estimation / observer based	[146]–[152]

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 a mismatched inductive/resistive feeder impedance, to enhance the power quality and power 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, nondroop 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 eliminate harmonics [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 the TC layer [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 modeling [15], [16], MG control [17]–[23], MG stability and protection [24], [25], power sharing methods [7], [26], [27], and DISC [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.

Compared to the existing surveys, this article provides the following features.

1) A precise SC architecture classification, based on the required CI, is presented. It covers not only MASs, but also decentralized and event-triggered-based approaches.
2) An investigation on reactive power sharing and how ETC can reduce the required communication BW, based on different event-trigger conditions, is incorporated and compared with general continuous data transmission.
3) Time-delay effect on DISC and DESC approaches is highlighted, and its malicious effect, which leads to instability in DISC approaches, is shown.
4) Experimental results are carried out to compare the control structures and verify the applicability, merits, and drawbacks of different SC architectures.

The rest of the survey begins with the function and time scale of the SC in Section II. Following, the CSC approaches, which mainly focus on harmonic elimination, are analyzed in Section III. In Section IV, the DISC architectures are classified in three main categories based on the CI data transmission, i.e., averaging, consensus, and event-triggered. Moreover, the CI time-delay and clock drift phenomena are also considered. In Section V, the DESC architectures are investigated, and their challenges are presented. Finally, in Section VIII, we summarize the conclusion remarks of the survey.

II. TIME SCALE AND FUNCTION OF THE SC

A. *Time Scale of the SC 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

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

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

where $G_{\mathrm{LPF}}(s) = \omega_c (s + \omega_c)^{-1}$ is an LPF with cutoff frequency ω_{c} for measuring power, and p_i and q_i are the instantaneous active and reactive powers, respectively, calculated as

$$p_i = v_{od,i} i_{od,i} + v_{oq,i} i_{oq,i} \tag{2a}$$

$$q_i = v_{oq,i} i_{od,i} - v_{od,i} i_{oq,i} \tag{2b}$$

where $v_{od,i}$, $v_{oq,i}$, and $i_{od,i}$, $i_{oq,i}$ are the output voltage and current of DGU$_i$ in the dq frame, respectively. In (1), m_i and n_i

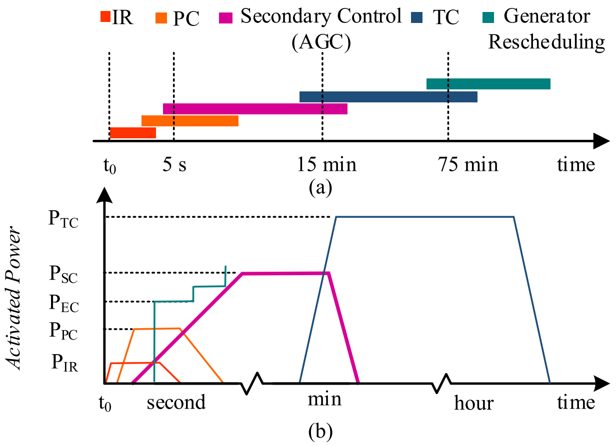


Fig. 1. (a) Typical time scale of frequency-related dynamics in conventional power systems [154]. (b) Activation of frequency control loops following a disturbance at t_0 in an MG [155].

are the droop controller gains, and ω_i and v_i are the FaV reference values for the inner voltage loop. Obviously, any change 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 ω_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 $\mathcal{N} = \{1, \ldots, N\}$, then this may be expressed as

$$\lim_{t \to t_f} \omega_i(t) = \omega^* \tag{3a}$$

$$\lim_{t \to t_f} v_i(t) \approx v^* \tag{3b}$$

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

$$\lim_{t \to \infty} (n_i Q_i(t) - n_j Q_j(t)) = 0 \tag{3d}$$

for all $i, j = 1, \ldots, N$, where (3a)–(3d) represent frequency restoration and voltage regulation in finite time t_f and power sharing in the 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 SC resources of the system. A simple version is given by

$$\underset{P_i}{\text{minimize}} \quad \sum_{i \in \mathcal{N}} \frac{1}{2} m_i P_i^2 \tag{4a}$$

$$\text{subject to} \quad \sum_{i \in \mathcal{N}} P_i = P_{\text{load}} \tag{4b}$$

where P_{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 us to specify more sophisticated (nonquadratic) 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] and [157] for analogous approaches relating voltage and reactive power control with associated optimization problems.

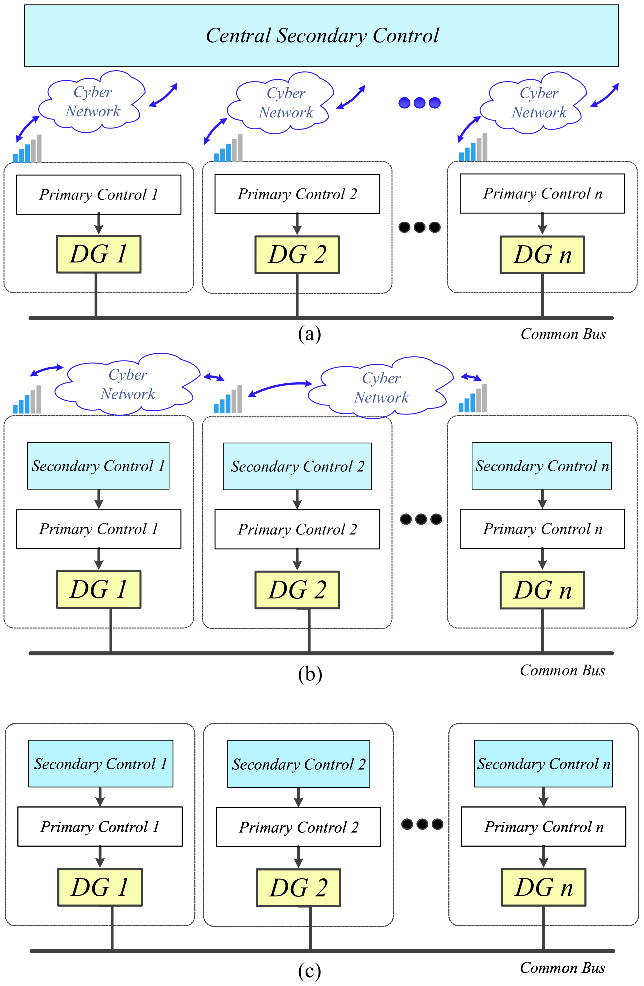


Fig. 2. Three main SC architectures: (a) CSC, (b) DISC, and (c) DESC.

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

$$\omega_i = \omega^* - m_i P_i + \delta u_{\omega,i} \tag{5a}$$

$$v_i = v^* - n_i Q_i + \delta u_{v,i} \tag{5b}$$

where $\delta u_{\omega,i}$ and $\delta u_{v,i}$ are the control signals forwarded from the SC. Sharing 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,

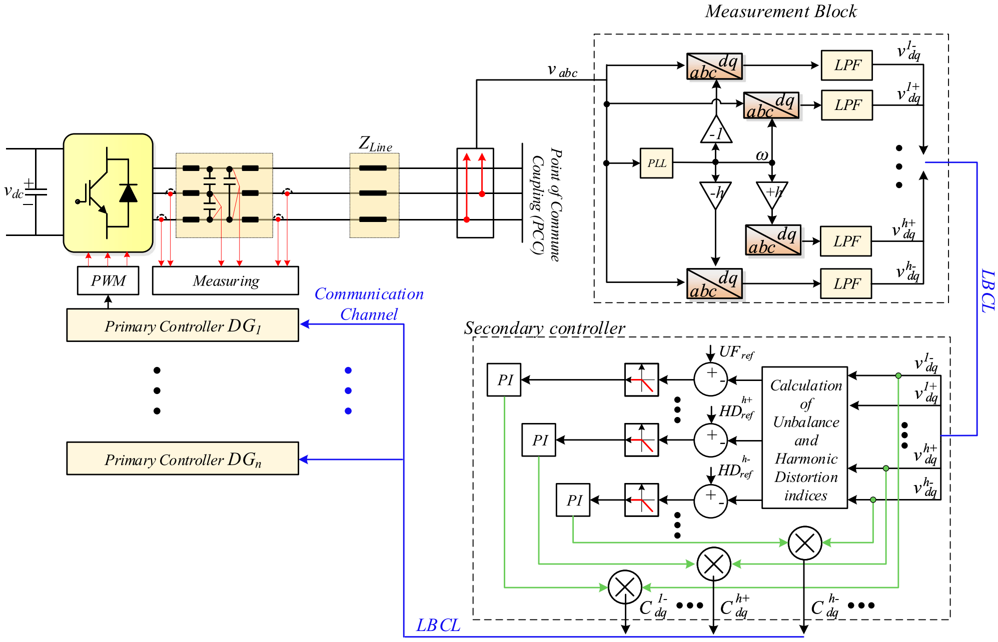


Fig. 3. CSC scheme for voltage unbalance compensation [32].

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 Table VI. Moreover, its SC is implemented as Fig. 3 for 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 PCC by sending the harmonic elimination efforts to the DGUs primary controllers through an LBCL. Fig. 4 shows the simulation results for the harmonic compensation performance of the CSC. As 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.

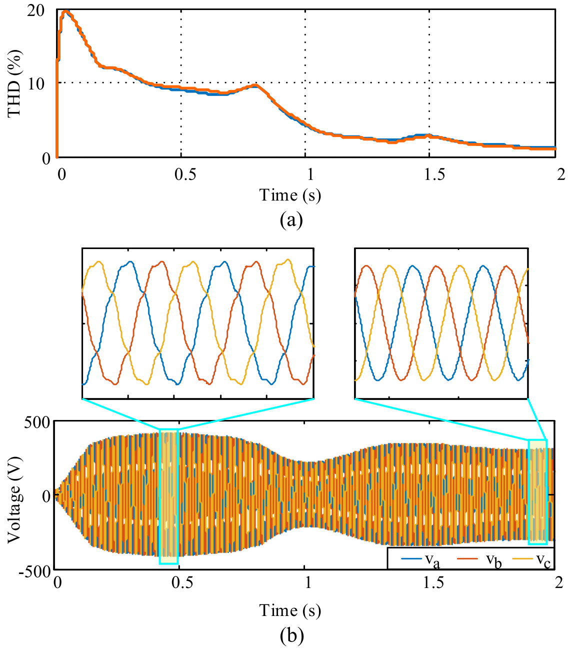


Fig. 4. Harmonic elimination by CSC. (a) Voltage THD reduction. (b) Voltage waveforms.

IV. DISTRIBUTED SECONDARY CONTROL

As units in an MG are heterogeneous and spatially distributed, distributed control or MAS network controls is a promising approach to enhance MG stability and performance while addressing reliability and enhancing scalability of MGs. In distributed

TABLE II
LITERATURE REVIEW ON CSC GOAL SATISFACTION

Ref.	Main Contribution	Complexity	Physical Insight	Necessity of Assumption	PnP Verification	Controller type
[30]–[36]	Harmonic cancellation	Low	High	Low	Yes	PI
[36], [43]	Voltage unbalance compensation	Low	Medium	Low	No	PI
[45]	Voltage unbalance compensation	Low	Medium	High	No	Cost Function
[42], [46]	Reactive power management	Medium	Medium	Low	No	Cost Function
[37], [40]	Stability enhancement	High	Medium	Low	No	Adaptive
[41]	SoC considerations in the SC	High	Medium	High	Yes	PI
[44]	Considers model of time delays	Medium	High	low	No	Gain Scheduling
[39]	Incorporates technical constraints	High	High	Low	No	Optimal-Convex

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 modeling and networks is presented, first. Cosider an MG system with N DGUs, which is 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:

$$\begin{aligned} \dot{x}_i(t) &= Ax_i(t) + Df(t, x_i(t)) + Bu_i(t) \\ y_i(t) &= Cx_i(t) \end{aligned} \tag{6}$$

where $i = 1, 2, \ldots, N$, 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,

$$\lim \|y_i(t) - y_j(t)\| = 0 \quad \forall\, i,\ j = 1, 2, \ldots, N. \tag{7}$$

The communication network of an MAS can be expressed by a directed graph (digraph) $\mathcal{G}$, which is usually modeled as $\mathcal{G} = (\mathcal{V}_\mathcal{G}, \mathcal{E}_\mathcal{G}, \mathcal{A}_\mathcal{G})$ with a nonempty finite set of $\mathcal{N}$ nodes $\mathcal{V} = \{\nu_1, \nu_2, \ldots, \nu_N\}$, a set of edges or arcs $\mathcal{E}_\mathcal{G} \subset \mathcal{V}_\mathcal{G} \times \mathcal{V}_\mathcal{G}$, and the associated adjacency matrix $\mathcal{A}_\mathcal{G} = [\alpha_{ij}]_{N\times N}$. In an 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 a nominal value x^*. By averaging the values received from other DGUs, a control signal can be built as

$$\delta u_i = K_i(s)\left(x^* - \frac{1}{N}\sum_{i\in\mathcal{N}} x_i(t)\right) \tag{8}$$

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

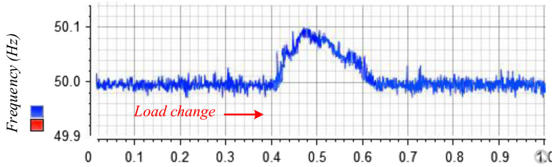


Fig. 5. Frequency restoration applying a high-BW averaging DISC structure [49].

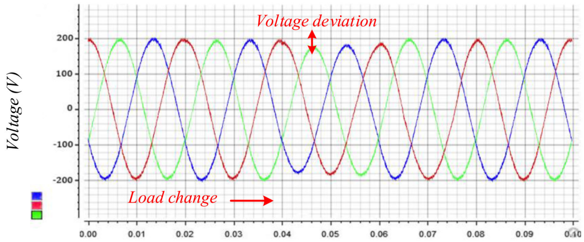


Fig. 6. Voltage recovery applying a high-BW averaging DISC structure [49].

Figs. 5 and 6 show the MG frequency restoration and voltage recovery performance of a high-BW averaging DISC proposed in [49], respectively.

B. Consensus-Based DISC

For MASs, the CI structure shows the direction and information of the agents as DGUs in an MG. Algorithms leading to agreement among all DGUs are called consensus, agreement, or distributed averaging algorithms [164]. Robustness of this technique is proved in several research works even in the presence of communication delays [44], [53], [116], [121], [165]. In order to restore the FaV in the MG applying the consensus-based techniques, the following distributed protocol is used [14], [55], [88], [166], [167]:

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

to produce the control signals in (5). Fundamental performance limitations of such controllers have been examined in [168]–[170]. If the controller $K_i(s)$ in (11) contains integral control, then in the 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 α_{ij} are nonnegative and are the elements of the so-called adjacency matrix of the graph

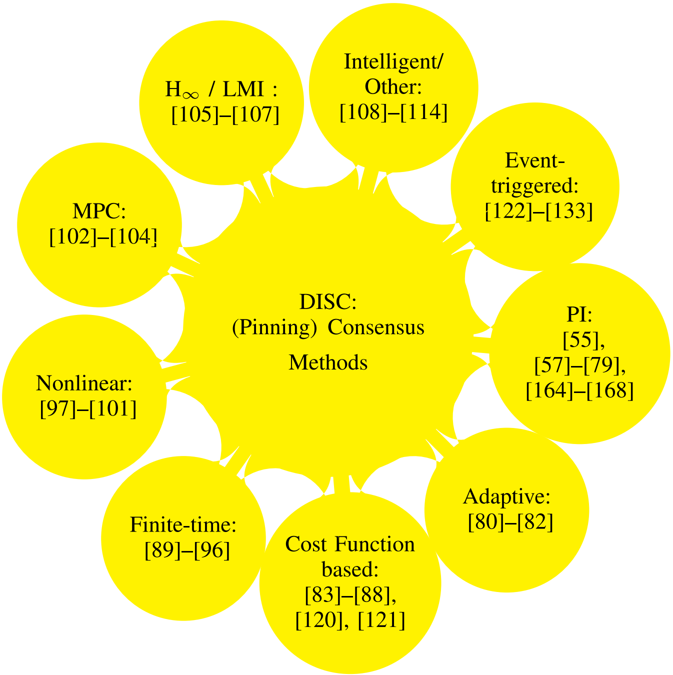


Fig. 7. Distributed consensus SC methods.

describing the CI. DGUs i receive information from DGU j if $\alpha_{ij} \neq 0$; see [164] 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 $\delta u_{\omega,i}$ in (5) so as to satisfy (3). To this end, the cooperative objectives can be expressed in terms of the local neighborhood tracking error as

$$\boldsymbol{e_i} = \sum_{j\in\mathcal{N}} \alpha_{ij}(x_j(t) - x_i(t)) - g_i(x_i(t) - x^*) \tag{10}$$

and the correction term can be calculated as

$$\delta u_i = -cK_i\boldsymbol{e_i} \tag{11}$$

where $i = 1, 2, ..., N$, the pinning control gain $g_i \geq 0$, and $g_i = 0$ show that 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, the 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 control of N nonlinear agents in (6) with the dynamic of the ith agent can be expressed as follows:

$$\dot{x}_i(t) = Ax_i(t) + Df(t, x_i(t)) + Bu_i(t), \quad i \in \mathscr{V}_{\mathscr{F}} \tag{12}$$

$$\dot{x}_i(t) = Ax_i(t) + Df(t, x_i(t)), \quad i \in \mathscr{V}_{\mathscr{L}} \tag{13}$$

where $\mathscr{V}_{\mathscr{F}} \triangleq \{1, \ldots, M\}$ and $\mathscr{V}_{\mathscr{L}} \triangleq \{M+1, \ldots, N\}$ stand for the followers' and the leaders' sets, respectively. Similar to (11), the containment protocol for the followers in (12) can be calculated as

$$\delta u_i = \sum_{j=1}^{N} (x_j(t) - x_i(t)), \quad i \in \mathscr{V}_{\mathscr{F}}. \tag{14}$$

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

C. *Event-Triggered DISC*

Over the past few 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 criterion is satisfied or an event is triggered. Then, a sampled-data control method is performed, and data are 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 the 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.

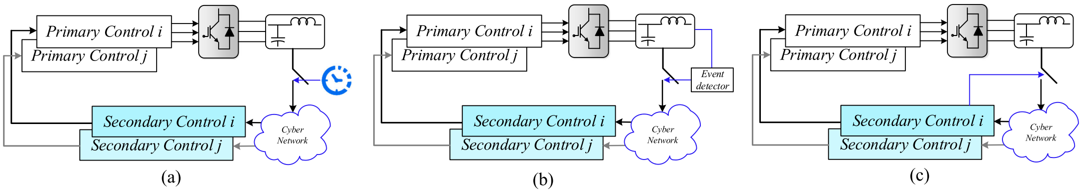


Fig. 8. Event-triggered based DISC structures. (a) Time-triggered DISC. (b) Event-triggered DISC. (c) Self-triggered DISC.

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 an 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 the 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, the 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 interevent 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/ω droop (5a), the power sharing performance of Q/v droop (5b) is generally unsatisfactory. This is due to the fact that voltage is a local variable and is 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 toward 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 μ is the relative drift of the crystal oscillator of processor clock [195].

Several papers investigate clock drifts influence on the SC policies. The clock drift phenomenon in the MG was modeled and investigated first in [178]. Then, in [63] and [196], a comprehensive analysis of the performance of SC policies with respect to clock drifts is 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]:

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

$$v = v^* - n\left(\frac{s}{s+k_q}\right)\left(\frac{\omega_c}{s+\omega_c}\right)q. \tag{15b}$$

If the MG is stable, then by applying the final value theorem to (15), one can show that ω_i and v_i converge to their reference

TABLE III
TYPICAL ETC MECHANISMS FOR MASs

	Threshold Mechanism	Ref.	Complexity	BW Reduction (%)
Fixed threshold	$\|e_i(t)\| \geq \delta_i$	[171]	Low	more than 50
Time-dependent threshold	$\|e_i(t)\| \geq c_0 + c_1 e^{-\mu_i(t)t}$	[172]	Medium	more than 70
Continuous state dependent	$\|e_i(t)\| \geq \sigma_i \|X_i(t)\|$	[173]	Medium	more than 70
Sampled state-dependent	$\|e_i(t)\| \geq \sigma_i \left\|X_i(s_k^i)\right\|$	[174]	Medium	more than 70
Sampled state-dependent and a positive offset	$\|e_i(t)\| \geq \sigma_i \left\|X_i(s_k^i)\right\| + \delta_i$	[175]	High	more than 80
Sampled state-dependent and a time-dependent positive offset	$\|e_i(t)\| \geq \sigma_i \left\|X_i(s_k^i)\right\| + c(t)$	[176]	High	≈ 90

TABLE IV
CLOCK DRIFT PHENOMENON LITERATURE

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

values. A simplified generalized bandpass washout filter SC is introduced in [136] as

$$\omega = \omega^* - \frac{m}{k_{p\omega}+1} \cdot \underbrace{\underbrace{\frac{\omega_{\mathrm{c}}}{s+\omega_{\mathrm{c}}}}_{\text{low-pass}} \cdot \underbrace{\frac{s}{s+\dfrac{k_{i\omega}}{k_{p\omega}+1}}}_{\text{high-pass}}}_{\text{bandpass filter}} \cdot p \tag{16a}$$

$$v = v^* - \frac{n}{k_{pv}+1} \cdot \underbrace{\underbrace{\frac{\omega_{\mathrm{c}}}{s+\omega_{\mathrm{c}}}}_{\text{low-pass}} \cdot \underbrace{\frac{s}{s+\dfrac{k_{iv}}{k_{pv}+1}}}_{\text{high-pass}}}_{\text{band-pass filter}} \cdot q\,. \tag{16b}$$

By adopting appropriate values for the high-pass filter as $k_{p\omega} = k_{pv} = 0$, $k_{i\omega} = k_p$, and $k_{iv} = k_q$, the washout filter based SC (15) can be implemented as well. The generalized bandpass washout filter for the SC is realized by cascading an LPF 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 the Q/ω and P/v droop control strategy as follows:

$$\omega = \omega^* + n_q \frac{s}{A_\omega s^2 + B_\omega s + C_\omega}\left(\frac{\omega_c}{s+\omega_c} \cdot q\right) \tag{17a}$$

$$v = v^* - m_p \frac{s}{A_v s^2 + B_v s + C_v}\left(\frac{\omega_c}{s+\omega_c} \cdot p\right). \tag{17b}$$

Similar to [145], the effect of a fully decentralized second-order washout filter can be investigated for the future research studies 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], the authors used local signals to design an 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], and [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 the 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 modeling 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, the authors of [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.

TABLE V
LITERATURE REVIEW ON DESC GOAL SATISFACTION

Ref.	DESC type	Controller type	Complexity	Stability Analysis	PnP Verification
[135], [136]	Washout filter-based	(15)	Low	Yes	Yes
[138]	Washout filter-based	(16)	Low	Yes	No
[139]	Local Variable	Time-dependent switched PI	High	Yes	Yes
[143], [144]	Local Variable	Linear quadratic regulator	Low	Yes	Yes
[141]	Local Variable	Integrator based	Medium	No	No
[146]	Nonlinear observer	PI	High	Yes	No
[147]	Observer-based	MPC	High	Yes	No
[149]	Sliding-mode estimator	Averaging integrator	High	Yes	No

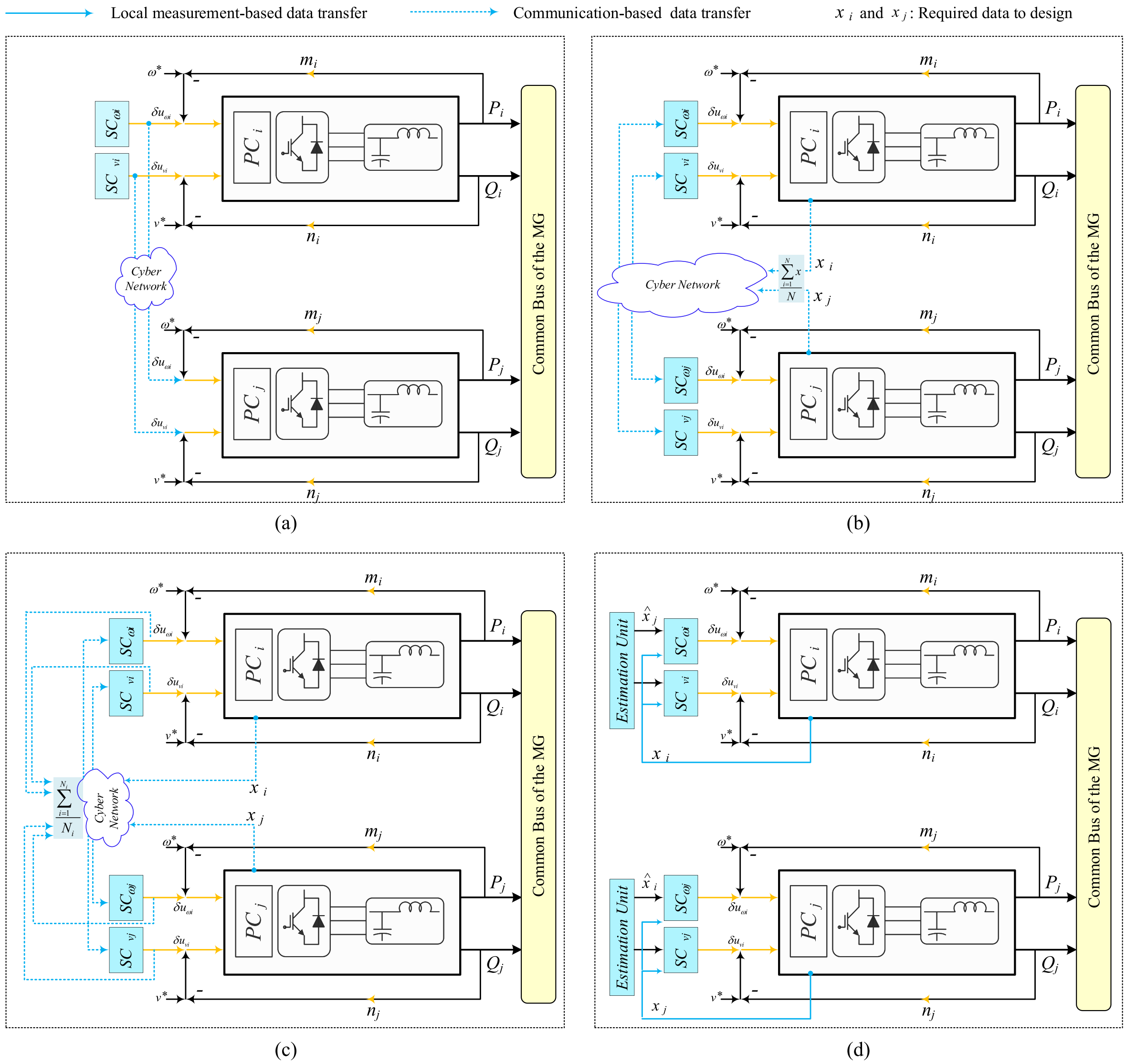


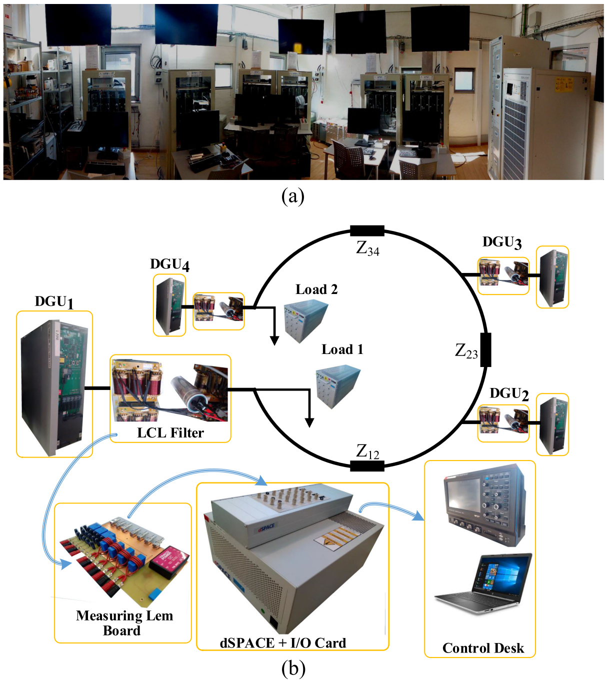
Fig. 9. SC structures. (a) Centralized master–slave SC. (b) Distributed averaging SC. (c) Distributed consensus SC. (d) Decentralized estimation-based SC.

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-unit 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


(a)

(b)

Fig. 10. Laboratory environment and setup circuit diagram. (a) Center for Research on Microgrids, Aalborg University. (b) Circuit schematic for the experimental tests.

TABLE VI
PARAMETERS OF THE TEST SYSTEM

Electrical Parameters		
Parameters	Symbol	Value
Output voltage of rectifier	V_{DC}	650 V
Nominal voltage magnitude	V_i	325 V
Nominal Frequency	f	50 Hz
Switching Frequency	f_s	10 kHz
Capacitance of LCL filter	C_f	25 μ F
Inductances of LCL filter	L_i / L_o	1.8 mH
Load 1	Z_1	43 Ω , 0.3 H
Load 2	Z_2	124 Ω , 0.1 H
Line 1	Z_{12}	0.4 Ω , 3.6 mH
Line 2	Z_{23}	0.8 Ω , 1.8 mH
Line 3	Z_{34}	0.4 Ω , 1.2 mH
Inner loop coefficients and other control Parameters		
Control Parameters	DGU: 2 and 4	DGU: 1 and 3
$P-\omega$ droop coefficient	0.001 rad/W.s	0.002 rad/W.s
$Q-v$ droop coefficient	0.005 V/VAr	0.01 V/VAr
Current integral / proportional terms	1000 / 0.5	1000 / 0.5
Voltage integral / proportional terms	120 / 0.05	120 / 0.05
Control design gain c	200	200

(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 are illustrated in Fig. 12(b).

Fig. 12 shows evaluation of measurement errors of DGU$_1$ under four different ETC mechanisms. For a fair comparison, all the four mechanisms have been normalized. It is shown how the number of events varies 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 the authors in [125] with its adaptive threshold is applied. As can be seen, in this ETS structure, the number of transmitted signals and events is lower than constant threshold. Fig. 12(c) and (d) shows the self-triggered mechanisms proposed in [134] to decrease the amount 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. As can be seen, a 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 shows a comparison between DESC and DISC structures 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 does not need the CI, 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 CI. As can be seen from Fig. 14(b)–(d), by increasing the time delay, the control performance of DISC degrades.

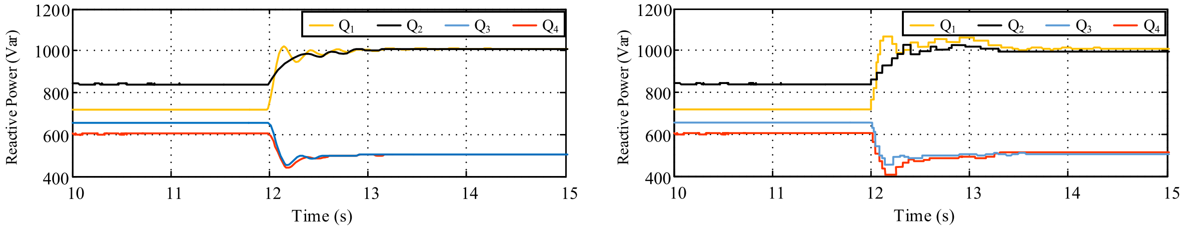
VII. OPEN ISSUE CONCERNS

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 also be 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.

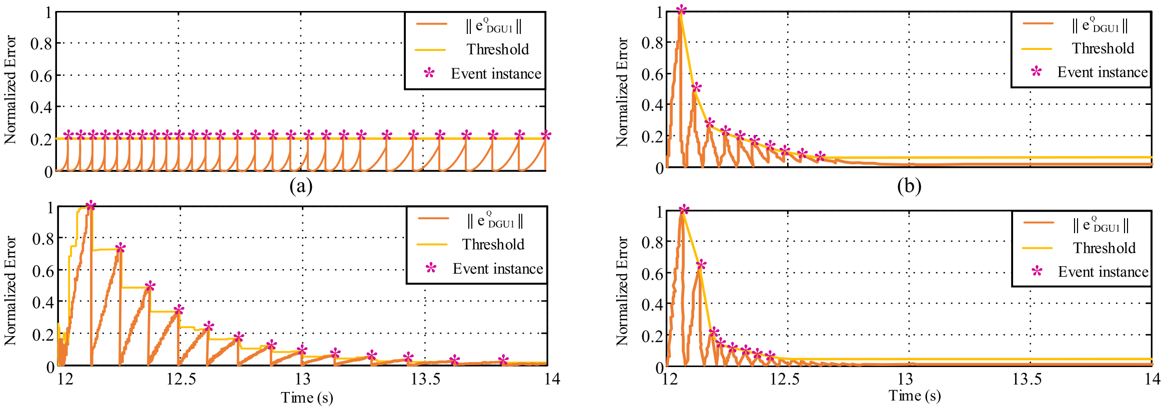
The authors of [206] and [207] provide an approach toward observability and controllability analysis of the networked linear systems subject to data losses. However, the time-varying delays introduce a negative effect on DGU synchronization after PnP scenarios. This issue requires further research. Another 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-MGs is that the dynamic



(a) (b)

Fig. 11. Reactive power sharing realization. (a) Through a consensus DISC approach presented in [10]. (b) Through an event-triggered approach presented in [125].



(c) (d)

Fig. 12. Evolution of measurement errors of DGU_1 under various ETC's mechanisms: (a) ETC with a fixed threshold, (b) distributed ETC presented in [125] (c) distributed ETC presented in [134], and (d) self-triggered control presented in [134].

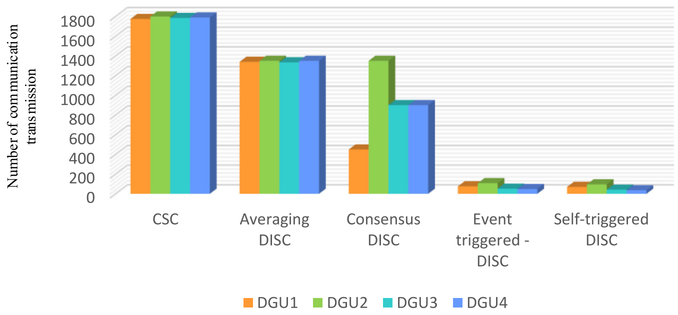


Fig. 13. Communication transmission of the studied MG under the periodic communication scheme with 150-Hz BW for CSC, DISC, event-, and self-triggered communication schemes during time interval $t \in [11 \quad 15]$ s.

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. Fig. 15(b) and (c) shows two possible topologies of a dynamic multi-MG. As can be seen, the multi-MG 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, e.g., smart switches (SSWs) with cost-efficient reasons, back-to-back converters 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 DESC/DISC approaches [208]. Self-healing capability of the distribution system after extreme faults by designing a control framework for multi-MG systems, robust distributed control

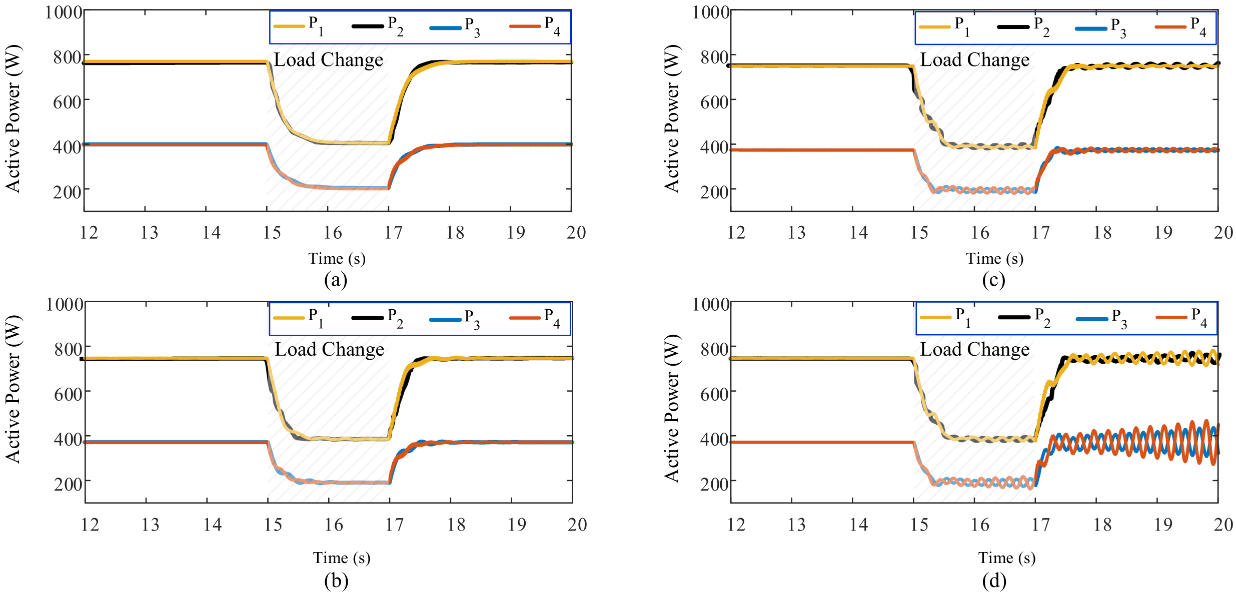


Fig. 14. Performance comparison of decentralized control scheme [144] versus DISC introduced in [50] by considering communication delay's effect in DISC approaches. (a) DESC. (b) DISC (Without delay). (c) DISC (Delay = 200 ms). (d) DISC (Delay = 600 ms).

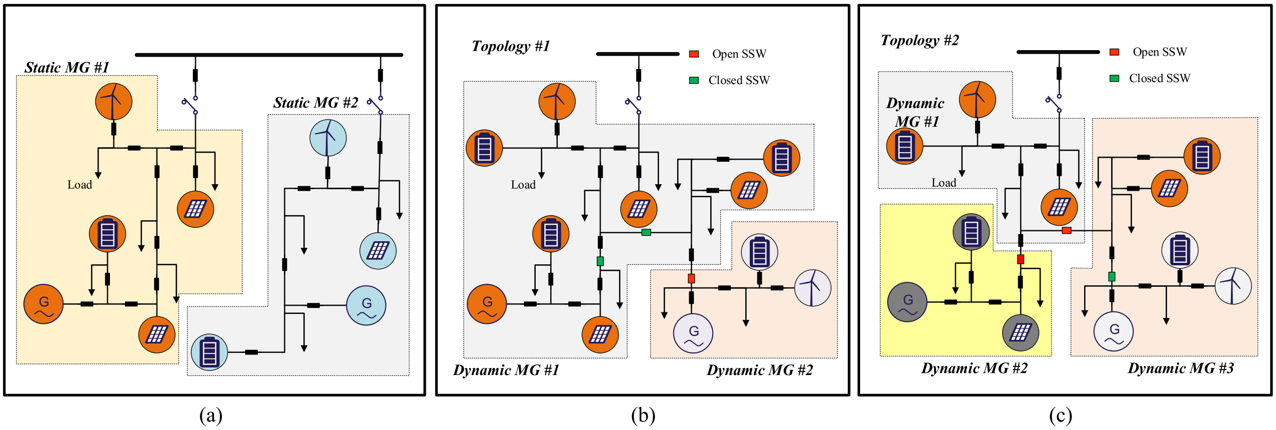


Fig. 15. Static and dynamic architectures of multi-MG systems. (a) Static multi-MG system. (b) Topology 1 of a dynamic multi-MG system employing smart SSWs. (c) Topology 2 of a dynamic multi-MG system employing smart static switches.

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 a secondary layer to improve the power exchange among multi-MG systems. Nevertheless, the important role of SC either in distributed or decentralized manners for more resilience and improvement in the power exchange is not addressed properly. Reducing the CI 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 article presented an overview of the SC structures in the hierarchical control of autonomous MG. In order to improve the reliability and 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, a 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 the 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 that 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 the DESC structure has no communication challenges, i.e., CI delay and data dropout, in order to achieve a comprehensive control, an accurate estimation of neighbor DGU variable is required. Voltage stability, reactive power sharing, and clock drift challenges of SC for experimental implementations are also summarized. Finally, a comprehensive comparison and control design challenges, formulations, and open issue concerns have been presented.

APPENDIX

The communication links of the studied MG for the consensus DISC and ETC-DISC are given as follows:

$$\mathcal{A}_{\mathcal{G}} = [\alpha_{ij}]_{4\times 4} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}.$$

By a simplified $Q - v$ dynamics for DGU_i, we have

$$\begin{aligned} \dot{V}_i &= u_i \\ Q_i &= |B_{ii}|V_i^2 - \sum_{m\in\mathcal{N}} |B_{im}|V_i V_j \end{aligned} \tag{19}$$

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

$$u_i(t) = -\tfrac{\kappa}{\chi_i} V_i(t) \sum_{j\in\mathcal{N}} \alpha_{ij} \left(\frac{Q_i(t^i_{k_i(t)})}{\chi_i} - \frac{Q_j(t^i_{k_j(t)})}{\chi_j} \right) \tag{20}$$

where $k_i(t) \triangleq \arg\max_k \{t^i_k | t^i_k \leq t\}$; χ_i and χ_j stand for the $Q - v$ droop coefficients of DGU_i and DGU_j, respectively. The ETC, which determines the event times t^i_k of DGU_i, was designed as

$$|e_i(t)| \leq \eta\chi_i \left| \sum_{j\in\mathcal{N}} \alpha_{ij} \left(\frac{Q_i(t^i_{k_i(t)})}{\chi_i} - \frac{Q_j(t^i_{k_j(t)})}{\chi_j} \right) \right| \tag{21}$$

where $e_i(t) = Q_i(t^i_k) - Q_i(t)$, $Q_i(t^i_k)$ stands for the transmitted measurement of $Q_i(t)$ at the event time instant t^i_k, $k \in N$, and η is a positive constant, and its maximum value can be chosen lower than the maximum eigenvalues of Laplacian matrix $\mathcal{A}_{\mathcal{G}}$.

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