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Performance Evaluation of Secondary Control Policies with Respect to Digital Communications Properties in Inverter-based Islanded Microgrids

Pau Martí, *Member, IEEE*, Manel Velasco, Enric Xavier Martín, Luis García de Vicuña, Jaume Miret, *Member, IEEE* and Miguel Castilla

Abstract—A key challenge for inverted-based microgrids working in islanded mode is to maintain their own frequency and voltage to a certain reference values while regulating the active and reactive power among distributed generators and loads. The implementation of frequency and voltage restoration control policies often requires the use of a digital communication network for real-time data exchange (tertiary control covers the coordinated operation of the microgrid and the host grid). Whenever a digital network is placed within the loop, the operation of the secondary control may be affected by the inherent properties of the communication technology. This paper analyses the effect that properties like transmission intervals and message dropouts have for four existing representative approaches to secondary control in a scalable islanded microgrid. The simulated results reveals pros and cons for each approach, and identifies threats that properly avoided or handled in advance can prevent failures that otherwise would occur. Selected experimental results on a low-scale laboratory microgrid corroborate the conclusions extracted from the simulation study.

Index Terms—Microgrids, islanded mode, secondary control, communications, power sharing, frequency restoration, transmission intervals, message dropouts, performance evaluation

I. INTRODUCTION

Microgrids (MGs) are expected to constitute a scalable power system with a high service standard by adequately combining advanced power electronics technologies, information and communication technologies, and new control and management strategies. In essence a MG consists of a combination of diverse distributed generation (DG) units, loads and storage systems managed by fast acting power electronics [1]. The MG is connected to the distribution network through a single point of common coupling (PCC), and may operate in grid-connected or islanded mode.

The MG islanded operational mode is significantly more challenging than the grid connected mode because the dynamics of the MG are no longer dominated by the main grid [2]. Out of the three control levels, namely primary, secondary and tertiary control, defined by the standard control architecture for AC and DC MGs [3], [4], the islanded operational mode of a MG only requires the first two.

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The primary control is the first level in the control hierarchy and it is used to interconnect voltage source inverters (VSI) working autonomously in parallel. A common control approach is to apply the droop method [5], [6], which is based on the principle that the frequency and the amplitude of the inverter can be used to control active and reactive power flows for load sharing in MG islanded mode operation. Although the droop method ensures power sharing and it has interesting properties such that it is implemented locally at each inverter because it only uses local measurements, it has several drawbacks such as introducing frequency and voltage deviations in steady state.

Secondary control aims at guaranteeing that the frequency and voltage deviations will be eliminated after every load or generation change inside the MG. Apart from a few autonomous control approaches (e.g. [7]), many existing solutions (see [8]–[18] to name a few) have considered the use of some sort of communication channel, almost always in the form of a digital network, between VSIs in order to meet the frequency and voltage restoration goal. Depending on the logical operation of these policies, different traffic schemes, ranging from the one-to-all to the all-to-all, may apply, posing diverse traffic demands to the underlying communication network.

Whenever a digital network is placed within the loop, then the control system is classified as a networked control system (NCS). All definitions found in literature for an NCS have one key feature in common. This defining feature is that control and thus time sensitive information (reference inputs, plant outputs, control inputs, etc.) is exchanged at discrete time instants among control system components (sensor, controller, actuator, etc.) using a shared network [19]. The analysis and design of NCS usually accounts for the set of inherent properties that these systems have such as message dropouts, time delays, transmission intervals, quantization, sampling schemes, and traffic scheduling (see e.g. [20], [21]). But this research is not fully reflected in the power systems literature.

In most of the literature relating to power systems, it is assumed that the transmission of signals to and from the central control unit or between inverters occur over an ideal, lossless and delay-free communication network. However, this tendency is starting to change, and several results do put emphasis on the networking system in terms of communications infrastructure [22]–[24], in terms of communication technologies [25]–[27], and more relevant to this paper, in

terms of the impact that communications have in distributed power applications [28]–[32]. However, none of the previous works provide a unified and complete analysis of policies and communications properties as it is performed in this paper.

Particularly, the analysis performed in this paper alerts of possible problems that may appear in the implementation of existing distributed policies for frequency restoration: whenever traffic exchange is required, communications properties should be analyzed or even incorporated in the design phase. Otherwise, performance degradation and even instability may appear.

The paper makes an effort explaining, from a qualitative point of view, the effect that communication properties have in the behavior and performance of each policy. Hence, it avoids a deeper theoretical analysis, which could be an interesting study complementing the current approach presented in this paper. Several of the referred existing results for frequency restoration provide theoretical stability analysis focusing on the presented approaches and often ideal conditions (see for example [12] or [17] for the case of consensus-based secondary control approaches). A more general stability analysis for NCS subject to diverse communication properties and constraints can be found for example in [20].

A. Paper contributions and structure

The contribution of this paper is to provide a comparative performance analysis of representative frequency restoration strategies for secondary control in islanded MGs with respect to properties of the digital communication network. To this extend, within the existing literature, a set of four prototype control policies for frequency restoration are identified in Section II. Moreover, for each policy both a) a simple but still complete mathematical description and b) the assumed data exchange that constitute the communication interaction principle among the distributed VSI is provided. Section III presents the simulation setup, with an especial emphasis on describing the key properties that are commonly considered in NCS analysis and design. The dual formalization of each of the four policies permits discovering which control and communication parameters play a key role in the simulation results presented in Section IV. The qualitative comparative analysis identifies advantages and disadvantages of the evaluated policies, which are corroborated by experimental results in Section V. The analysis provides valuable insight for future design of secondary control policies for islanded MGs, which are summarized in the paper conclusions in Section VI.

II. SELECTED POLICIES FOR SECONDARY CONTROL

A. Primary droop control

The droop method is often proposed as a standard control technique to interconnect inverters in parallel, and it mimics the behavior of a synchronous generator, which reduces the frequency when the active power increases. In fact, the conventional droop method that is locally implemented at each VSI can be expressed as

$$\omega_i = \omega_0 - m_i P_i \quad (1)$$

$$V_i = V_0 - n_i Q_i \quad (2)$$

where ω_i and V_i are the inverter output frequency and voltage, ω_0 and V_0 are the frequency and voltage references, P_i and Q_i are the output active and reactive power of the inverter, and m_i and n_i are the droop control gains.

The frequency droop (1) ensures an accurate active power sharing between VSIs due to the global properties of the frequency because in steady state ω is the same for all the inverters. However it has an inherent trade-off between the active power sharing and the frequency accuracy because frequency deviations may appear, which should be corrected by the so-called secondary control. On the other hand, the voltage droop (2) does not ensure an accurate reactive power sharing between VSIs due to the fact that voltage is a local output variable of each inverter. And similar to the frequency droop, the voltage droop has also an inherent trade-off between the reactive power management and the voltage accuracy, which also provokes voltage deviations to be corrected by the secondary control.

B. Policies for secondary control

The existing literature on secondary control for islanded MGs (previously cited) always sets the same goal looking at the system frequency: to restore the frequency to the nominal value ω_0 while maintaining the active power sharing achieved by the frequency droop (1). However, looking at the voltage, diverse control objectives may be considered because a standard policy specifying the MG voltage management is lacking. See [33] for a review and evaluation of different policies for secondary voltage control, where a common set of metrics was defined to assess pros and cons of the existing results that meet different goals. Hence, the comparative performance evaluation presented in this paper focuses only on frequency secondary control policies with a double control objective: active power sharing and frequency restoration.

An effective approach to remove the frequency deviation is to add a corrective term δ_i in the frequency droop (1) as

$$\omega_i = \omega_0 - m_i P_i + \delta_i \quad (3)$$

in order to allow each inverter correcting the frequency deviation error e_i computed as

$$e_i = \omega_0 - \omega_i \quad (4)$$

where ω_0 is the desired frequency and ω_i is a suitable measure of the frequency. The correction term δ_i should operate at least as an integral-like control of the frequency error e_i (4), and depending on its implementation, different strategies can be distinguished. It is important to note that it is still an open problem under which conditions distributed integral controllers can stabilize a plant in general [34]. Under the assumption that the steady state frequency in the MG should be the same at each VSI, if all m_i gains have the same value, perfect power sharing means that the corrective term δ_i for all inverters should be the same, as it can be deduced from (3).

In order to achieve this behavior, a "simple" implementation of integral control of the frequency error at each VSI (namely *distributed integral controllers*) to compute δ_i could be considered. However, this is not possible in the general case

because the connection and disconnection of VSIs and loads in the MG may cause transient dynamics in the frequency that would imply different integral histories which means that different corrective terms δ_i would be computed and applied, leading to a MG with restored frequency but failing at meeting the power sharing goal.

In the following, four policies for secondary control designed to restore the frequency (while avoiding the different history problem) implementing different approaches to achieve integral-like control are presented.

1) *Centralized control*: The simplest approach to restore the frequency is to apply a centralized integral controller such as a standard PI (proportional-integral). As indicated in [3], this is conventionally achieved by the MGCC (MG central controller), which computes the frequency error e_i (4), using a given single measure of the bus frequency ω_{pcc} at the PCC, namely e_{pcc} and applies a PI controller

$$\delta_i = K_P e_{pcc} + K_I \int e_{pcc} dt \quad (5)$$

where K_P and K_I are the control gains, being the only parameters that can be tuned to meet any given control specifications. The δ_i control action is then send to each inverter for droop control (3). In terms of communication scheme, the centralized control policy will require sending the correction term δ_i (5) periodically to all inverters. Hence, it applies a broadcast traffic pattern where an entity sends data to all the other entities in the system, following a one-to-all communication scheme.

2) *Decentralized control*: In order to provide a richer set of control parameters, the decentralized control could be applied based on local PIs at each VSI, as suggested in the overview given for example in [11]. The foreseen problem that different histories in standard integral controllers may provoke can be avoided if the frequency error (4) is common to all distributed PIs. To this end, the MGCC can be in charge of computing the frequency error e_{pcc} as in the previous policy, which would be sent to each inverter to compute δ_i using a local PI controller as

$$\delta_i = K_{P,i} e_i + K_{I,i} \int e_i dt \quad (6)$$

with $\forall i, e_i = e_{pcc}$, and where $K_{P,i}$ and $K_{I,i}$ are the control gains that are local to each inverter. In terms of communication scheme, the decentralized control policy will require sending the error term e_{pcc} periodically to all inverters, thus following the same communication one-to-all pattern as in the centralized policy.

3) *Averaging control*: In order to avoid the single point of failure that the MGCC implies for the centralized and decentralized control strategies, the so-called averaging control can be applied, see for example [16]. In this case each inverter a) measures the frequency level ω_i , b) sends it to all the others inverters, c) averages the frequency received from the others N inverters,

$$\bar{\omega}_i = \frac{1}{N} \sum_{k=1}^N \omega_k \quad (7)$$

and d) then restores the frequency using a local PI controller like the one previously given in (6) where the frequency error is computed using $\bar{\omega}_i$ as follows

$$e_i = \omega_0 - \bar{\omega}_i \quad (8)$$

together with the droop controller (3). The averaging control increments the traffic exchange compared to the previous two policies. For this case, all inverters have to send the measured frequency to the rest of inverters in the MG. Hence a broadcast scheme is also used, but for all inverters, implying an all-to-all communication scheme.

4) *Consensus control*: For frequency restoration, a consensus based approach (see for example [12]) may compute the corrective term δ_i as

$$\delta_i = \alpha_i \left(\int (\beta_i e_i + \gamma_i \varepsilon_i) dt - \omega_i \right). \quad (9)$$

which includes an integral of the sum of two errors, e_i and ε_i . The first one is the tracking frequency error computed as

$$e_i = \sum_{k \in \mathcal{N}} (\omega_i - \omega_k) + \chi_i (\omega_i - \omega_0) \quad (10)$$

that has also two terms, one that refers to the averaging of the frequency deviation between the local inverter and its neighbors, and the other one that refers to the inverter local frequency error. The second error term in (9) computed as

$$\varepsilon_i = \sum_{k \in \mathcal{N}} (\delta_k - \delta_i) \quad (11)$$

is the averaging of the error droop correction term. The consensus control scheme can be tuned using the control gains $\alpha_i, \beta_i, \gamma_i, \chi_i \in \mathbb{R}^+$, whose specific values may be adjusted to keep the system stable (as indicated in [12]) and meet given performance specifications. The operation of the consensus policy (9) requires each inverter to communicate with their neighbors the inverter output frequency ω_i and the droop correction term δ_i . In the study presented next there is no restriction on the number of neighbors that exchange data, and therefore, all inverters are considered to be neighbors between them and all they broadcast both values, which implies also an all-to-all communication scheme. This is done on purpose in order to better assess the impact of the communication properties on the evaluated policies.

III. SIMULATION SETUP

A. Microgrid

The energy distribution system used for the performance analysis is an scalable MG that has a tree topology that slightly varies as the MG grows. The possibility of increasing the network size permits to assess the effect that the number of cooperating DGs has with respect to the performance of the evaluated control strategy.

Table I provides the system parameters for the MG, VSIs, loads and lines. The MG may include 4, 8, 16, or 32 DG units that are electronically coupled generators working as VSI. They are responsible for fixing the voltage frequency and amplitude of the MG when operating in islanded mode.

TABLE I
MG CONFIGURATION PARAMETERS.

Grid	$\omega_0 = 50\text{Hz}$, $V_0 = 314\text{V}$
Generator/load pair	S_n (per VSI) = 500kVA $R_{load} \in \{0.21, 0.45\}\Omega$ $L_{load} \in \{0.47, 1\}\text{mH}$
Lines	$R_{line} \in \{1.3, 8.8\}\text{m}\Omega$ $L_{line} \in \{10.2, 11.3\}\mu\text{H}$

They are assumed to be always active and sized in such a way that have enough capacity to supply the loads.

Next to each generator, a local load has been placed. All the loads are assumed to be always active, posing the same constant power demand. They are modeled by a series connection of a resistance and an inductance, $R_{load}L_{load}$, whose values are randomly distributed within specific ranges to achieve different type of loads, some of them being more resistive and other more inductive, as specified in Table I. Each MG has an additional resistive load that allows performing a step load change at the middle of each simulation from 100% to 80% of full power for each VSI.

Pairs of generator/load are connected by distribution lines, whose impedances are modeled using the same pattern applied to loads. They are modeled as a series connection of a resistance and an inductance, $R_{line}L_{line}$, whose values are also randomly distributed within specific ranges to achieve different types of lines, as specified in Table I.

Figure 1 illustrates an scheme of the 32-node MG. Numbers identify pairs of generator/load connected to the same bus. The MG components have been simulated using Simulink/Matlab SimPowerSystems, that provides component libraries and analysis tools for electrical power systems.

Generators are interconnected with an Ethernet network in a bus line topology. A standard Ethernet (IEEE 802.3 [35]) network has been chosen because it is the underlying local area network of the reduced OSI (Open Systems Interconnection) stack defined by the IEC 61850 [36], which is a standard of the International Electrotechnical Commission that regulates communication within electric power systems. The Ethernet network and traffic simulation is carried out using the True-Time simulator [37], which facilitates the simulation of networked control systems. The Ethernet network is configured with a data rate of 100Mbps and a minimum message size of 512 bits, required for the collision detection mechanism.

The use of a multi-purpose shared digital communication network to connect spatially distributed elements introduces uncertainty in the closed loops due to communication imperfections and constraints [38]. The time elapsed between sampling and the decoding varies due to network access delays and transmission delays, which ends up producing varying sampling/transmission intervals. Another significant issue for digital transmissions is the possibility that data may be lost while in transit through the network. Typically, packet dropouts result from transmission errors in physical network links or from buffer overflows due to congestion.

In order to cover these communication properties, the transmission intervals T_{xI} over ethernet are specified to take values in $\{0.01, 0.1, 0.3, 0.5, 1\}$ s, which is a set of feasible

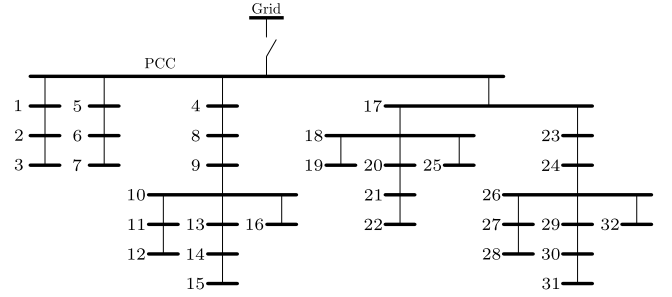


Fig. 1. Scheme for the 32-node microgrid setup

TABLE II
SCENARIOS COVERED IN THE PERFORMANCE ANALYSIS.

Strategies	Com. pattern	Parameters	Power sharing	Freq. rest.
Without control	No	nodes	No	X
Droop only	No	nodes	Yes	No
Distributed integral	No	nodes	No	Yes
N. 1: centralized	one-to-all	nodes, T_{xI} , Loss	Yes	Yes
N. 2: decentralized	one-to-all	nodes, T_{xI} , Loss	Yes	Yes
N. 3: averaging	all-to-all	nodes, T_{xI} , Loss	Yes	Yes
N. 4: consensus	all-to-all	nodes, T_{xI} , Loss	Yes	Yes

values for secondary control policies. The message dropouts are quantified as loss percentage that specifies the probability that a message is lost during transmission. It is important to stress that lost messages will consume network bandwidth, but will never arrive at all destinations. Loss percentage values are allowed to take values in $\{0\%, 10\%, 20\%, 30\%, 40\%, 50\%\}$.

B. Comparative performance evaluation structure

The comparative performance analysis covers several scenarios, which are summarized in Table II. For each strategy, the table specifies the communication pattern that the secondary control applies, the parameters that can be evaluated (number of nodes, named *nodes*, different transmission intervals, named T_{xI} , and different loss percentage values, named *Loss*), and whether the strategy pursues power sharing and frequency restoration.

The first scenario illustrates the state of the distribution network when primary and secondary controls at each inverter are disconnected, named *Without control*, implying that no power sharing occurs (frequency restoration does not apply since no frequency deviations occur). Note that for this case (and for all the analyzed scenarios) the internal current and voltage loops are active, which for this particular scenario leads to a situation where the frequency is kept at the desired value while power sharing is no achieved. The second scenario corresponds to the case where only primary droop control is applied, referred as *Droop only*, which leads to accurate power sharing but introducing frequency deviation. The third scenario corresponds to the the case where local integral controllers using local measurements is applied, referred as *Distributed integral* controllers, that suffers the previously described problem of different integral histories. In these three scenarios no communication exchange takes place. But they are covered for the sake of completeness because the com-

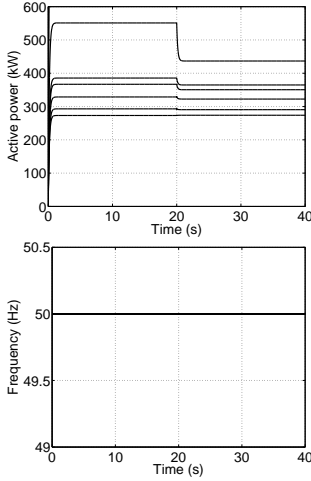


Fig. 2. Without control

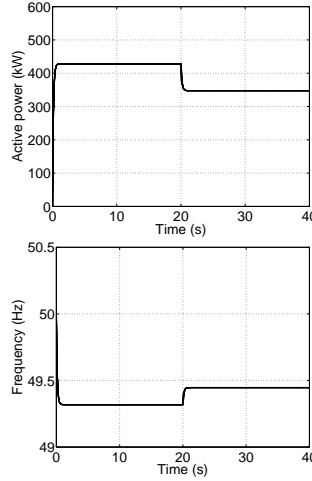


Fig. 3. Droop only control

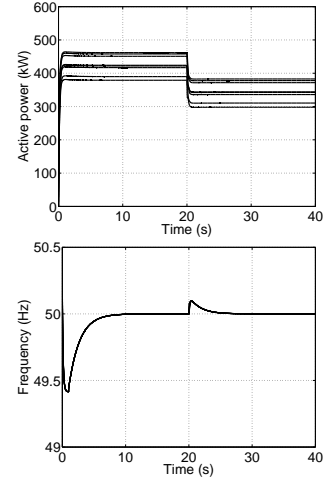


Fig. 4. Distributed integral

parative performance evaluation has only sense for scenarios where secondary control applies and makes use of digital communications to exchange control data.

The next four scenarios in Table II correspond to the cases where droop control is applied together with one of the secondary policies for frequency restoration discussed previously, policies that are named *N. 1: centralized*, *N. 2: decentralized*, *N. 3: averaging*, and *N. 4: consensus*. For these policies, apart from the number of inverters being considered, each policy is executed with the five different transmission intervals T_{xI} in the Ethernet that has six different loss probability percentage $Loss$. Hence, four secondary policies with this different parameters expand over $4(\text{policies}) \times 4(\text{MG-size}) \times 5(T_{xI}) \times 6(Loss) = 480$ simulation cases. A common feature for these four policies is that they are designed to achieve power sharing and frequency restoration. The communication scheme for these policies vary. The *centralized* and *decentralized* use the one-to-all paradigm while the *averaging* and *consensus* use the all-to-all paradigm.

All the simulation runs follow the same simple pattern over 40s. At time $t = 0s$, all pairs of generator/load become active, and at time $t = 20s$ the additional resistive load produces the step change. Whenever a control policy is applied, it is active during the whole simulation time.

IV. SIMULATION RESULTS

Next, the most relevant results are summarized. For the sake of clarity, many figures have been omitted because they do not add relevant information with respect to the figures that have been selected.

The control parameters used for all simulated policies are summarized in Table III. The droop control gain for all inverters is the same, $m_i = 10 \cdot 10^{-6}$. The control gains for all frequency restoration policies have the same values except for the last strategy. The first three policies are based on PI controllers and the proportional and integral gains have been selected to restore the frequency in less than 10s. In addition, their selection has considered that they must meet the specified performance in all the MG setups while showing a robust

TABLE III
CONTROL PARAMETERS.

Strategies	Equations	Control Parameters
Droop param.	(1),(2)	$m_i = 10 \cdot 10^{-6}$, $n_i = 100^{-6}$
N. 1: centralized	(4),(5)	$K_P = 0.05$, $K_I = 0.6$
N. 2: decentralized	(4),(6)	$\forall i$, $K_{P,i} = 0.05$, $K_{I,i} = 0.6$
N. 3: averaging	(6)-(8)	$\forall i$, $K_{P,i} = 0.05$, $K_{I,i} = 0.6$
N. 4: consensus	(9)-(11)	$\alpha_i = 2$, $\beta_i = 0.01$, $\gamma_i = 0.1$ and $\chi_i = 200$

behavior in front of small variations in the communication parameters with respect to the ideal case. The last policy is characterized by four control parameters (α_i , β_i , γ_i and χ_i), that have been tuned to achieve similar transient dynamics and similar sensitivity to small variations in the communication parameters than the previous three policies while fulfilling the required stability conditions. In particular, the control parameters summarized in Table III fulfill the control specifications in a neighborhood of the ideal case, that is, in the 4-node MG setup for a) any of the analyzed transmission intervals when no losses occur and b) for any of the loss percentage values for the shortest transmission interval.

Figures 2, 3, and 4 show the active power (top subfigure) and the frequency (bottom subfigure) of each inverter output in the case of 8-nodes MG setup (the same type of results are also observed in the other MG setups). And they correspond the first three scenarios summarized in Table II, *without control*, *droop only*, and *distributed integral*. When no hierarchical control is applied, Figure 2, all generators inject a different active power, whose magnitude depends on the seen line impedance while having a constant frequency, 50 Hz. Figure 3 illustrates that droop control achieves an accurate power sharing at the cost of introducing deviations in the frequency. Figure 4 shows the case where *distributed integral* is applied by means of local PIs that having different integral histories are able to restore the frequency at the cost of failing at power sharing.

Henceforth, the focus will be on the *centralized*, *decentralized*, *averaging*, and *consensus* policies. Figure 5 shows for the 4-node MG setup the active power (top subfigures)

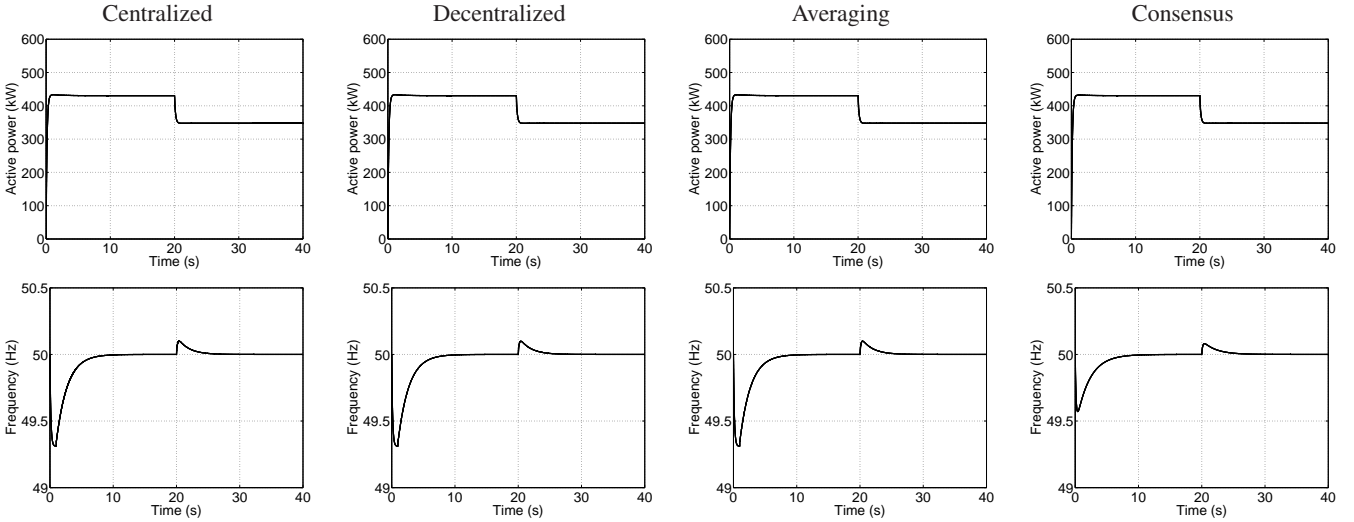


Fig. 5. Strategies in the ideal case: Active power and frequency for the 4-nodes MG with no losses and the shortest transmission interval (0.01s).

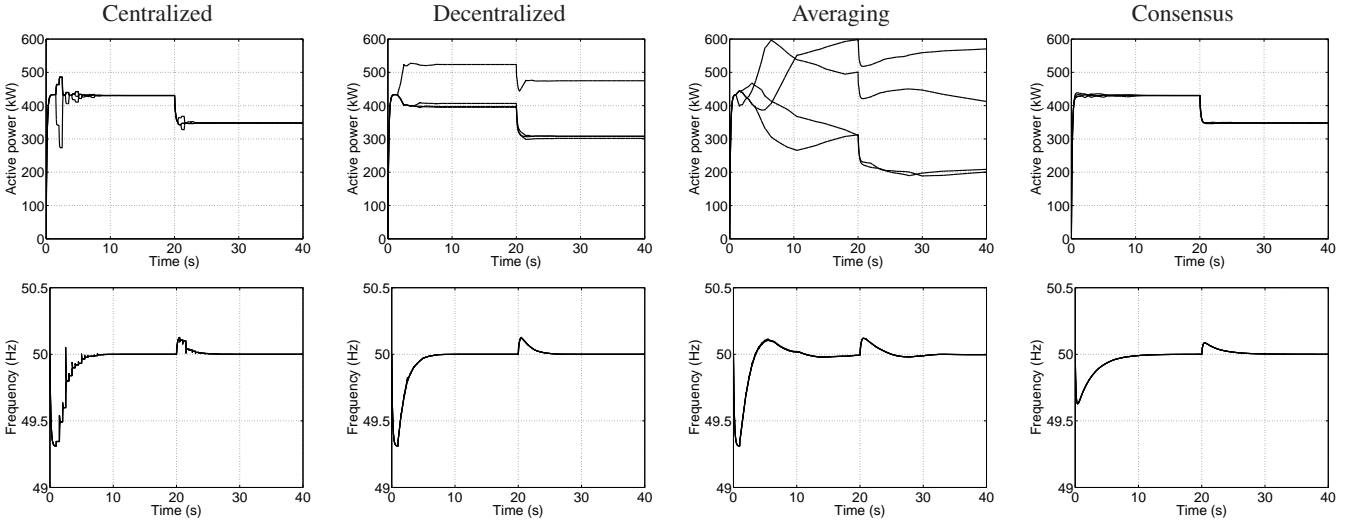


Fig. 6. Strategies performance: Active power and frequency for 4-nodes MG with 30% of losses and a transmission interval of 0.5s

and the frequency (bottom subfigures) of each inverter output in the ideal case in terms of communication properties. That is, the sampling interval for all policies is the shortest one, $T_{xI} = 0.01s$, and no message losses occurs. Active power and frequency for the four strategies exhibit similar dynamics as expected, achieving the same goal: accurate power sharing and accurate frequency restoration (the same type of results can be observed in the 8, 16 and 32-nodes MG). Although the dynamics are similar, Fig. 5 is included on purpose to show that the starting point (ideal scenario) for all the policies is the same to ensure a fair analysis.

Figure 6 provides an overview of the diverse system performance that can be achieved depending on the applied policy for a particular scenario. For each of the policies, the loss percentage is $Loss = 30\%$ and the transmission interval is $T_{xI} = 0.5s$. It can be observed that two policies, *centralized* and *consensus* achieve a perfect power sharing after the transient while the *decentralized* and *averaging* are not able to achieve the same active power at each inverter. It is interesting to observe that for this particular scenario,

the active power dynamics of each inverter for the *averaging* policy suffer larger deviations than the *decentralized* one. And looking at the *centralized* or *consensus* policies, both achieve perfect power sharing while exhibiting different transient dynamics. However, even observing the big disparity of behaviors in active power profiles (top subfigures), all the policies are capable of restoring the frequency to the nominal value (bottom subfigures).

Henceforth, only figures showing active power curves will be given, ignoring the figures showing the frequency. This is done on purpose because for any of the transmission intervals and for any of the message percentage losses, the four secondary control policies correct the frequency deviation and restore its value to the nominal one ω_0 , for any of the MG setups. The reason for such robustness on the frequency restoration indicates that the integrator-like control that they implement achieves the control goal independently of the actual amount of control data that is effectively exchanged over Ethernet.

The design of the simulation setup permits evaluating the

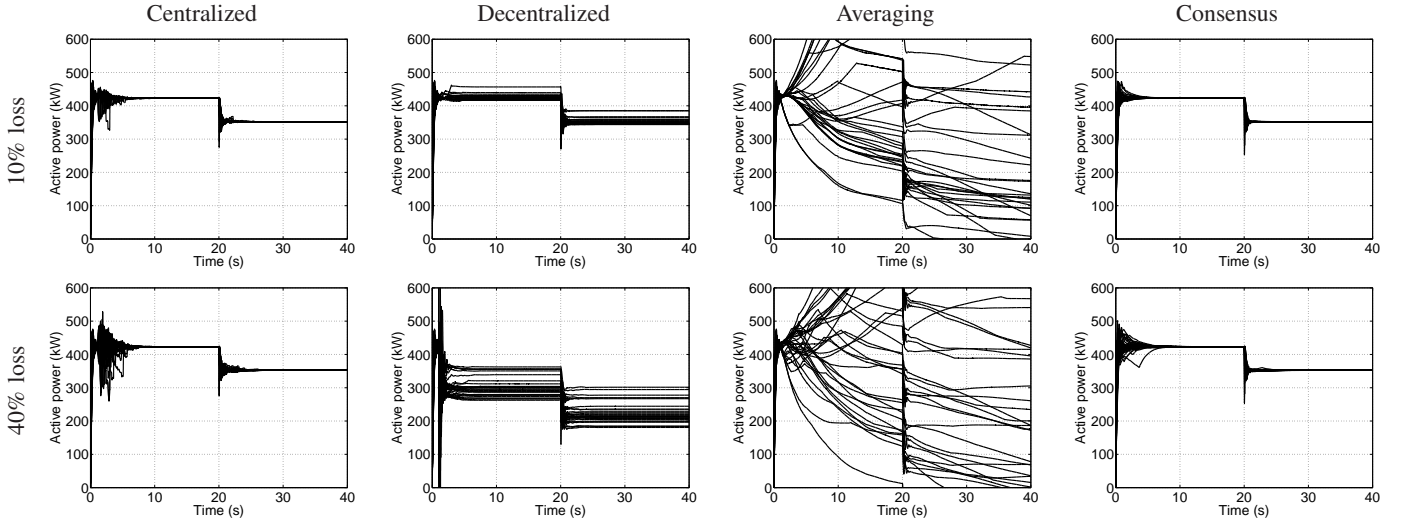


Fig. 7. Losses and transmission interval: active power in 32-nodes microgrid with 10% and 40% of losses and a transmission interval of 0.3s

TABLE IV
4-NODES MG PERFORMANCE EVALUATION SUMMARY

Loss	TxI				
	0.01	0.1	0.3	0.5	1
0	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.1	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.2	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.3	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.5	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4

TABLE V
32-NODES MG PERFORMANCE EVALUATION SUMMARY

Loss	TxI				
	0.01	0.1	0.3	0.5	1
0	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.1	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.2	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.3	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
0.5	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4

four strategies for secondary control considering the transmission interval. The first result that can be identified is that for different transmission intervals the active power profile keeps the same dynamics for the four policies under ideal conditions, i.e. negligible loss percentage, regardless of the MG size, thus providing a similar performance to the one shown in Figure 5. Therefore, they are robust with respect to different transmission interval. It has to be noted that the *consensus* policy shows a slightly longer transient dynamics as the transmission interval increases. However, the steady state dynamics are still satisfactory because perfect power sharing is achieved.

The simulation results considering the impact of the size of the MG in the four policies indicate that increasing the number of nodes imply a small degradation in the active power transient dynamics. Small degradation refers to longer settling times and bigger overshoots. Independently of these degrading effects, the steady state dynamics still meet the control goal, i.e., accurate power sharing.

The analysis of the simulation runs for the case of traffic losses permits identifying a difference among the evaluated policies, already visible in the case shown in Figure 6. The *centralized* and *consensus* policies are robust with respect to losses, always achieving perfect power sharing, while the *decentralized* and *averaging* policies are very sensitive to losses. The reason for such a difference is the following. In

the *decentralized* and *averaging*, the presence of losses imply that not all the inverters receive the same information, which produce different integral histories that ends up on different δ_i computation at all the inverters. And if frequencies are the same, having different δ_i in (6) means that the delivered active power profiles are different. On the contrary, the integrator different history problem does not appear in the *centralized* or *consensus* policies. For the *centralized*, a message loss implies that the corrective term δ_i may not arrive to a subset of inverters, which implies different transient dynamics in their active power output due to the droop equation (3). But since the frequency error will be corrected in the long term, the δ_i value will not change, and at the end, all inverters will receive it, producing a perfect power sharing. The *consensus* policy may initially produce different integral outputs for δ_i due to different frequency error histories computed in (10). However, the additional term ε_i in the consensus integral removes the deviations of the computed local corrective term δ_i with respect to the ones computed by the other inverters (11), which ensures perfect power sharing in the long term.

To complete the effect of traffic losses in the performance of the four policies, an additional figure is presented for the 32-nodes MG size. Figure 7 illustrates the combined effect of losses and transmission rate for 10% and 40% of losses for a given transmission interval of 0.3s. The figure shows that the *centralized* and *consensus* policies maintain their perfect

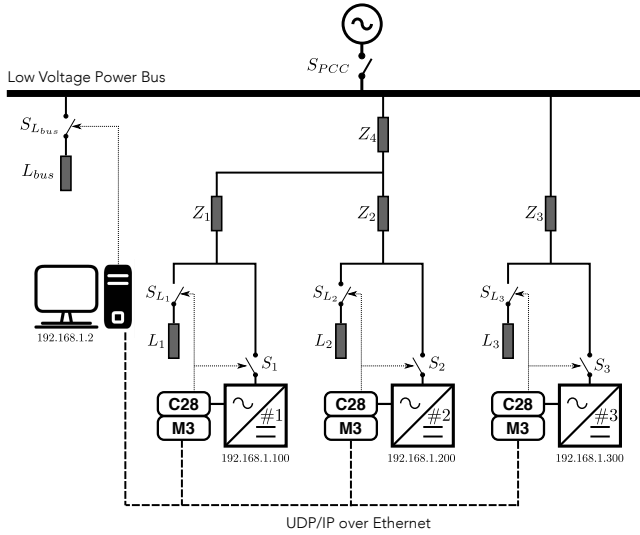


Fig. 8. Scheme for the laboratory microgrid.

power sharing, while the *decentralized* and *averaging* policies fail at the power sharing control goal.

From the analysis, it can be concluded that the four policies a) are robust with respect to different transmission intervals, b) exhibit a small degradation when increasing the MG size and c) behave very different in the presence of message losses.

Tables IV and V provide a complete overview of the performance evaluation where it can be observed the conclusions listed before. Each table refers to a MG size, and Table IV covers the 4-node MG and Table V covers the 32-node MG (the two missing tables covering the 8 and 16-node MG do not add different information than the given by the 32-node MG table). Each table evaluates two metrics: five transmission intervals TxI in columns with six loss percentage $Loss$ in rows. And each of the 30 cells contains the four policies, identified by numbers ($N. 1$: *centralized*, $N. 2$: *decentralized*, $N. 3$: *averaging*, and $N. 4$: *consensus*) that may appear canceled, as in \mathcal{X} . Whenever a policy is canceled means that it fails at meeting the power sharing control goal even knowing that the frequency has been correctly restored. And failing at the power sharing means that the difference on the injected power among all VSI exceeds a given threshold.

Looking at both tables, the first observation is that in ideal conditions, that is, with no message losses ($Loss = 0\%$) and the shortest transmission interval ($TxI = 0.01s$), all policies perform correctly (first cell). Moreover, in the event of no message losses (first row), different transmission intervals do not alter the performance and power sharing is achieved. However, when message losses start to appear (second to sixth row), policy 2 - *decentralized* and 3 - *averaging* fail at the power sharing goal (they are shown cancelled) in the general case, which indicates their lack of robustness. Only when the transmission interval is the shortest one ($TxI = 0.01s$, the first column in each table) and for all percentage loss cases, the behavior of the 2 - *decentralized* and 3 - *averaging* policies changes due to the MG size. In summary, the main conclusion is that in realistic communication channels, only

TABLE VI
LABORATORY 3-NODES MG COMPONENTS.

Load L_1	Load L_2	Load L_3	Load L_{bus}
500 W, 0 VAr	500 W, 0 VAr	500 W, 0 VAr	1500 W, 0 VAr
Line impedance Z_1	Line impedance Z_2	Line impedance Z_3	Line impedance Z_4
0.5Ω , 3 mH	0.5Ω , 1 mH	1.13Ω , 0.6 mH	0Ω , 1.0 mH

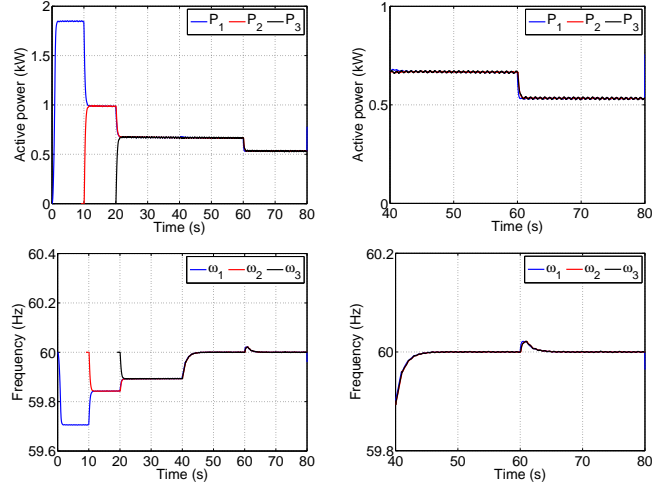


Fig. 9. Active power and frequency for the 3-nodes laboratory MG with no losses and transmission interval of 0.5s: (left) full sequence, (right) last 40s.

the 1 - *centralized* and 4 - *consensus* policies can guarantee the desired control performance.

Looking at simulation the results of the *centralized* and *consensus* policies, it is not possible to establish a decision criteria to help choosing the one to use. However, there are known facts that can be considered related to fault tolerance or communication bandwidth. In terms of fault tolerance, it is known that for master-slave configurations, as in the *centralized* case, the MGCC represents a single point of failure and replicas are required. In terms of communication bandwidth, the *consensus* requires a more intense data exchange. In this case it is also known that reducing the number of considered neighbors implies less communication demands at the cost of probably longer transients.

It is worth mentioning that for all the analyzed scenarios the system remains stable in the sense that frequency is always restored even knowing that power sharing may not be achieved, as for the case of policy 2 - *decentralized* and 3 - *averaging*. When power sharing is not accomplished, the system settles at equilibrium points that are different than the desired ones. However, for a broader set of scenarios, the system may become unstable. But this analysis is out of the scope of this paper.

V. EXPERIMENTAL RESULTS

This section presents experimental results from a low-scale laboratory microgrid that corroborate the main results obtained in the performance evaluation section.

Figure 8 shows the diagram of the laboratory microgrid, which is explained in detail in [39] (chapter 14). The MG has three nodes, each one consisting of a grid-forming power

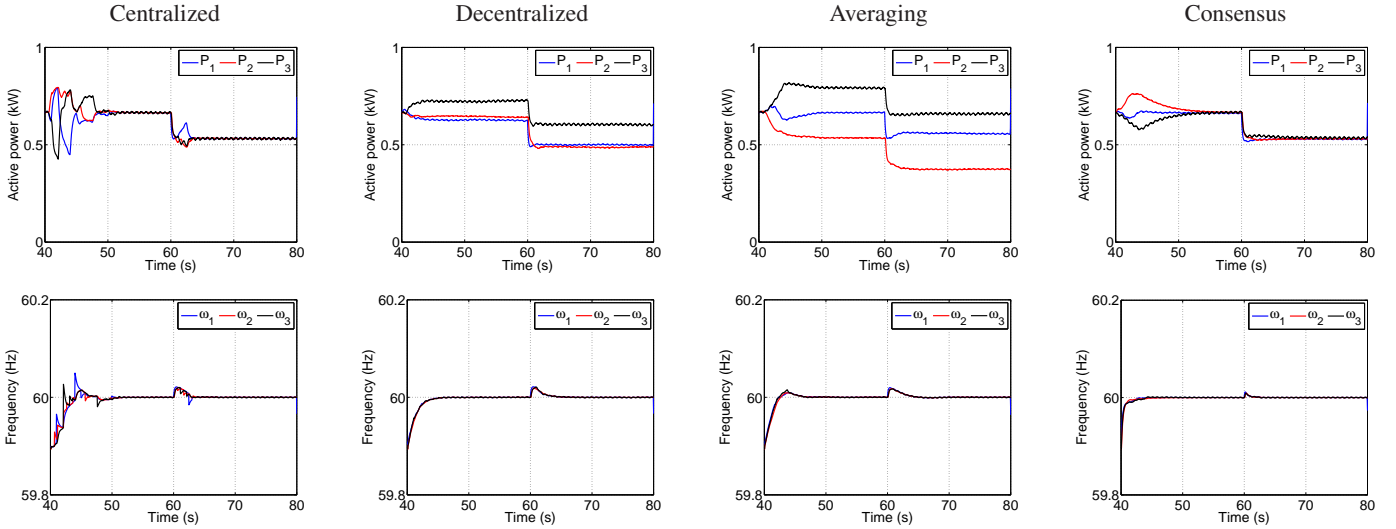


Fig. 10. Experimental result: Active power and frequency for each policy in the 3-node lab MG with 30% of losses and a transmission interval of 0.5s.

converter interfacing an energy source in parallel with a local load, plus an additional load. Each converter includes a dual-core Digital Signal Processor (DSP) to program different control strategies. The microgrid uses both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP)/Internet protocol (IP) protocols over an Ethernet link to allow communication among DSPs and with the supervisory Personal Computer, where microgrid data is gathered for monitoring purposes. Line impedances model the parasitic elements of the power cable. The nominal values of the microgrid components are listed in Table VI, where the nominal grid voltage is 155V at 60Hz.

The values for the control parameters of the four secondary control policies implemented in each DSP are equal to the ones used in the simulation analysis, previously specified in Table III. However, the droop control gain for all inverters, $m_i = 10^{-3}$, is slightly different from the one used in the simulations, $m_i = 10^{-6}$. The difference is required due to the low nominal power of the laboratory microgrid compared to the simulated microgrid, which required updating the gain values m_i in order to achieve similar dynamics between the simulations and the experiments.

Figure 9 shows the laboratory experiment corresponding to the ideal case. The left subfigures show the active power P_i and frequency ω_i for the three VSI during an experiment of 80s. The right subfigures show the same information than the left subfigures but only for the last 40s, which are comparable with the figures used throughout the simulation analysis. The experiment over 80s has the following pattern. Looking at generators and loads, at time $t = 0$ s the first pair of generator/load is activated, at time $t = 10$ s the second pair of generator/load becomes active, at time $t = 20$ s the third pair of generator/load becomes active and at time $t = 60$ s the L_{bus} load is disconnected. Looking at the control strategy, up to time $t = 40$ s, only primary droop control applies, and from $t = 40$ s to the end, droop plus secondary control applies. This can be observed at the left-bottom subfigure, where frequency restoration starts at $t = 40$ s. For this particular set of figures,

the secondary control that applies is the centralized one. The other policies give the same frequency curves.

Figure 10 shows the impact of the communication parameters for each policy for a given scenario in terms of power sharing (top subfigures) and frequency restoration (bottom subfigures). In particular, the scenario is characterized by a transmission interval of 0.5s and a loss percentage of 30%. The first observation is that frequency restoration is accomplished by all policies. The second observation is that power sharing is only achieved by the *centralized* and the *consensus* policies while the *decentralized* and *averaging* achieve a different equilibrium point.

It is important to stress that the experimental results shown in Figure 10 correspond to a feasible scenario different than the ideal one: worse scenarios can not be reproduced because security protections automatically disconnect overloaded VSIs while better scenarios give results that provide closer curves to the ones shown in Figure 9. Hence, the experimental results corroborate the simulation analysis performed in a similar scenario (see the example the 4-nodes MG with 30% of losses and a transmission interval of 0.5s illustrated in 6).

VI. CONCLUSION

This paper has presented a comparative performance evaluation of four representative frequency restoration policies for secondary control in islanded microgrids with respect to communication properties. The first result that has been identified is that the four policies, named *centralized*, *decentralized*, *averaging* and *consensus*, have been shown to restore the frequency regardless of quality of the digital communications. The second result is that focusing on power sharing, all the policies have been shown to perform appropriately when increasing the transmission interval and/or when increasing the number of inverters in the MG. And the third result, still focusing on power sharing, is that when considering different traffic loss percentages, the policies exhibited dramatic differences. Two policies, the *decentralized* and the *averaging* could never achieve power sharing while the *centralized* and *consensus*

policies always provided perfect power sharing, showing a strong and robust behavior even in the presence of losses.

Future research will approach several open issues. First, and still in terms of performance evaluation, the robustness of the consensus policy in front of communications constraints will be further evaluated when the traffic exchange involves only a limited set of neighbors. Second, the qualitative assessment presented in this paper calls for a deeper theoretical analysis where control properties such as stability and transient dynamics should be related to communication constraints. Third, the improvement of the analyzed policies, in particular those failing at meeting the control demands, will be considered in future work. And last but not least, the development of novel secondary control policies for frequency restoration will be carried out incorporating communications constraints in the design phase.

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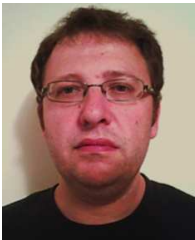
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