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Distributed Secondary Control for Islanded MicroGrids – A Networked Control Systems Approach

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Abstract— This paper presents a novel approach to conceive the secondary control in droop-controlled MicroGrids. The conventional approach is based on restoring the frequency and amplitude deviations produced by the local droop controllers by using a MicroGrid Central Controller. A distributed networked control system is used in order to implement a distributed secondary control thus avoiding the use of a MicroGrid Central Control. The proposed approach is not only able to restore frequency and voltage of the MicroGrid but also ensures reactive power sharing. The distributed secondary control do not relies on a central control, so that the failure of a single unit will not produce the fail down of the whole system. Experimental results are presented to show the feasibility of the distributed control. The time latency limits of the communication systems are studied as well.

I. INTRODUCTION

MicroGrids (MGs) are local grids that comprise different technologies such as power electronics converters, distributed generations (DGs), energy storage systems, and telecommunications which can operate connected to the traditional centralized grid (macrogrid) but also could operate autonomously in islanded mode.

Control strategies have an important role to provide global stability in MGs. Recently, hierarchical control for MGs has been proposed in order to standardize their operation and functionalities [1]. In such a hierarchical approach, three main control levels have been defined. The primary control is the first level which is independent, dealing with the local control loops of the DG units. This can be performed by voltage and current loops, droop functions, and virtual impedances. Conventionally, the active power–frequency droop control and the reactive power–voltage droop are adopted as the decentralized control strategies in the power electronic based MGs for the autonomous power sharing operations. Although the primary level does not require for communications, in order to achieve global controllability of the MG, secondary control is often used.

The conventional secondary control approach relays on using a MicroGrid Central Controller (MGCC), which includes slow controls loops and low bandwidth communication systems in order to measure some parameters in certain points of the MG, and to send back the control output information to each DG unit [1], [2]. On the other hand, this MGCC also can include tertiary control, which is more related to economic optimization, based on energy prices and electricity market [1]. Tertiary control exchanges information with the distribution system operator (DSO) in order to make feasible and to optimize the MG operation within the utility grid.

Secondary control is conceived to compensate frequency and voltage deviations produced inside the MG by the virtual inertias and output virtual impedances of primary control. This concept was used in large utility power systems for decades in order to control the frequency of a large area electrical network [3], and it has been applied to MGs to restore frequency and voltage deviations [1], [2], [4]-[6]. Furthermore, global objectives regarding voltage control and power quality of the MG, such as voltage unbalance and harmonic compensation have been proposed recently in additional secondary control loops [7], [8]. In all of these literatures, a central secondary control (CSC) has been used in order to manage the MG.

Moreover, primary and tertiary controls are decentralized and centralized control levels respectively, since while one is taking care of the DG units, the other concerns about the MG global optimization. However, although secondary control systems conventionally have been implemented in the MGCC, in this paper we propose to implement it in a distributed way along the local control with communication systems. In this sense, a local secondary control is determined for each DG to generate set-points of the droop control to restore of the deviations produced by the primary control.

This kind of distributed control strategies, which are also named networked control systems (NCS), have been reported recently in some literatures [9]-[11]. In [9], a pseudo-decentralized control strategy has been presented for
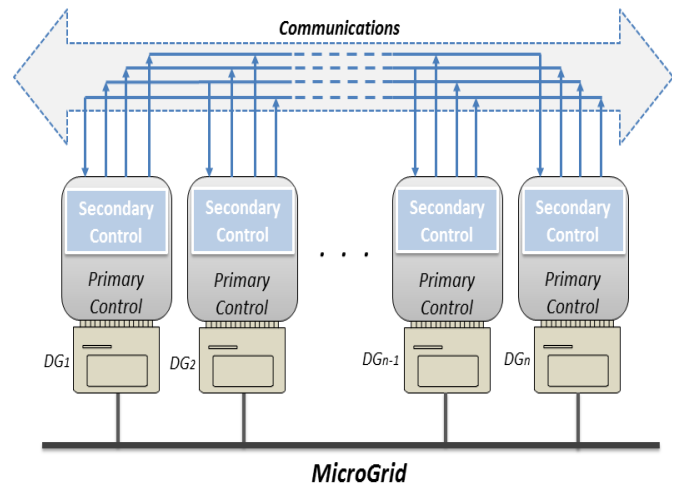

Fig. 1. Networked controlled MicroGrid system.

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distributed generation networks which operate in distributed manner using a Global Supervisory Controller (GSC) and local controllers with some intelligence. In the other hand, a master-slave control by using networked control strategy for the parallel operation of inverters has been introduced in [15]. The method is employed to achieve the superior load-sharing accuracy compared to conventional droop scheme with low-bandwidth communication. The system robustness has been considered in the case of communication failure as well. In [11], technical aspects of providing frequency control reserves (FCRs) and the potential economic profitability of participating in FCR markets for both decentralized and centralized coordination approach based on a setup of multiple MGs are investigated.

In this paper, a distributed secondary control strategy is proposed for power electronics-based MGs, including frequency, voltage and reactive power sharing controllers. This way, every DG has its own local secondary control which can produce appropriate control signal for the primary control level by using the measurements of other DGs in each sample time. In order to investigate the impact of communication on this new control strategy, the communication latency is considered when sending/receiving information to/from other DG units and the results are compared with the conventional MGCC.

II. PROPOSED DISTRIBUTED SECONDARY CONTROL

The problem of using a MGCC is that a failure in that unit can result in a bad function of the system. In order to avoid a single centralized controller, a distributed control system approach is proposed in this paper. The initial idea is to implement primary and secondary controllers together as a local controller. Fig. 1 shows the diagram of a fully distributed control system. Primary and secondary controls are implemented in each DG unit. The secondary control is placed between the communication system and the primary control. Frequency control, voltage control, and reactive power sharing will also review by using this control approach. However, this control strategy can be used to share active power in high *R/X* MicroGrids as well. In this case, secondary control in each DG collects all the measurements (frequency, voltage amplitude, and reactive power) of other DG units by using the communication system, average them and produce appropriate control signal to send to the primary level removing the steady state errors. This concept can be seen in Fig. 2 which illustrates more details about the distributed secondary control for an individual DG (DG_k) in a MG.

A. Frequency control

Taking the idea from large electrical power systems, in order to compensate the frequency deviation produced by the local P-w droop controllers, secondary frequency controllers have been proposed. Next step where the proposal of local frequency restoration integrator in order to regulate the frequency deviation [13]. However, the approach need for communications in order to avoid that the different stories of each local inverter make the MG system unstable.

In the proposed secondary control strategy, each DG can measure the frequency error in every sample time, sent to others, averages the frequency measured by other DGs, and then restore the frequency internally as

$$\delta f_{DG_k} = k_{Pf}\left(f_{MG}^* - \bar{f}_{DG_k}\right) + k_{if}\int\left(f_{MG}^* - \bar{f}_{DG_k}\right)dt$$

$$\bar{f}_{DG_k} = \frac{\sum_{i=1}^{N} f_{DG_i}}{N} \tag{1}$$

being k_{Pf} and k_{if} the *PI* controller parameters, f_{MG}^* is the MG frequency reference, $\bar{f}_{DG_k}$ is the frequency average for all DG units and δf_{DG_k} is the control signal produced by the secondary control of DG_k in every sample time. Here, $i = 1,2,...,N$, $k = 1,2,...,n$, N is the number of packages (frequency measurements) arrived through communication system and *n* is number of DG units.

B. Voltage control

Similar approach can be used as in the distributed frequency control one, in which each inverter will measure the voltage error, and tries to compensate the voltage deviation caused by the *Q–V* droop. The advantage of this method in front of the conventional one is that the remote sensing used by the secondary control is not necessary, so that just each DG terminal voltage, which can be substantially different one from the other, is required. In this case, the voltage restoration is obtained as follows:

$$\delta E_{DG_k} = k_{PE}\left(E_{MG}^* - \bar{E}_{DG_k}\right) + k_{iE}\int\left(E_{MG}^* - \bar{E}_{DG_k}\right)dt$$

$$\bar{E}_{DG_k} = \frac{\sum_{i=1}^{N} E_{DG_i}}{N} \tag{2}$$

where δE_{DG_k} is the restoration voltage of DG_k is produced by using the *PI* control of the error between voltage reference of MG (E_{MG}^*) and voltage average of DG units ($\bar{E}_{DG_k}$) in every sample time.

C. Line impedance independent power equalization

Power equalization is also possible by using distributed average power sharing. The averaging power process is done in each DG, so that finally, as the information is common, all of them will have the same reference. Therefore, the reactive power sharing by the secondary control can be expressed as

$$\delta Q_{DG_k} = k_{PQ}\left(Q_{DG_k} - \bar{Q}_{DG_k}\right) + k_{iQ}\int\left(Q_{DG_k} - \bar{Q}_{DG_k}\right)dt$$

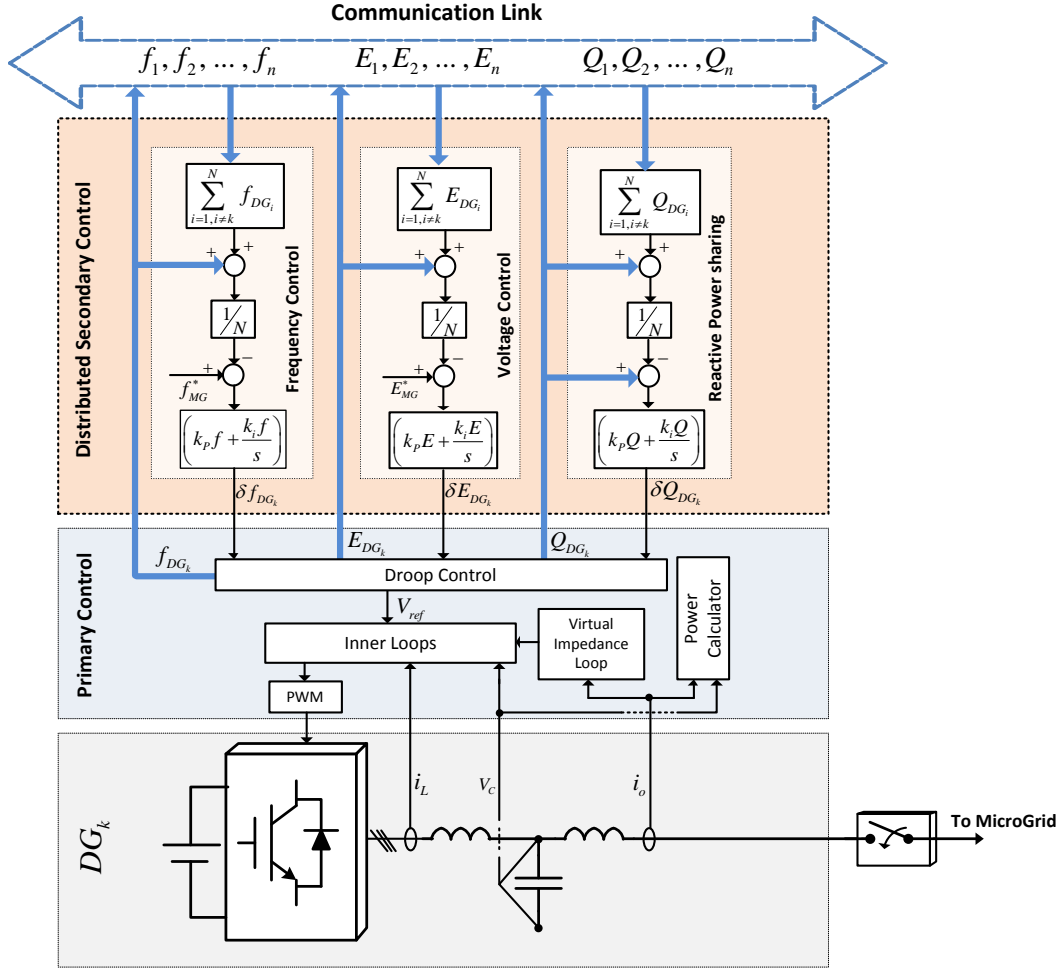$$\bar{Q}_{DG_k} = \frac{\sum_{i=1}^{N} Q_{DG_i}}{N} \tag{3}$$

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Fig. 2 Scheme of the proposed distributed secondary control for a DG in a MG

being k_{PQ} as the proportional term, k_{iQ} is the integral term, Q_{DG_k} is reactive power of DG_k, $\bar{Q}_{DG_k}$ is average of reactive power for all DG units, and δQ_{DG_k} is the control signal produced by the secondary control in every sample time, to share the reactive power between the DG units. This way, reactive power sharing can be obtained independently from voltage sensing mismatches or line impedances in the MG.

III. EXPERIMENTAL RESULTS AND DISCUSSION

An experimental MG setup as shown in Fig. 3 was used to test the performance of the proposed approach, consisted on two DG inverters forming as an islanded MG, including an experimental setup with the two Danfoss 2.2 kW inverters, the dSpace1103 control board, LCL filters, and measurement LEM sensors. A diode rectifier is used as nonlinear load, loaded by a capacitor, and a 200 ohms linear load, as well as an RL load with a 15mH inductance connected to the common point. The switching frequency was 10 kHz. The electrical setup and control system parameters are listed in Table I. All the parameters are the same for both DG units.

Two different sections have been considered for obtaining the experimental results. In the first section, the performance of the new secondary control strategy in order to restore frequency and voltage variations as well as active and reactive power sharing is depicted.

In the second part, effects of DSC on frequency and reactive power control, for a certain amount of communication latency delay has been displayed and the results have been compared with the conventional centralized secondary control. Four scenarios were considered for both sections:

- *Scenario 1* ($0 < t < 5s$): DG units operate without load and secondary control is not enabled.
- *Scenario 2* ($5 < t < 10$s): A linear load 400 Ω is added to the common point.
- *Scenario 3* ($10 < t < 20s$): The linear load is changed to 200 Ω.
- *Scenario 4* ($20 < t < 40s$): Distributed secondary control finally is activated.

A. Frequency/Voltage Restoration and Q Sharing

The performance of DSC applied to a MG has been depicted in Fig. 3. Fig 4(a) and Fig 4(b) showing how the new secondary control strategy restores frequency and voltage deviation of the DGs. Frequency and voltage deviations are seen at t=5s and t=10s when loads suddenly are

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connected to the MG. At t=20s, the restoration process starts to act by activating the DSC for both DGs at the same time. It can be seen that frequency and voltage values are slowly and successfully regulated inside the islanded MG, removing the static deviations produced by the droop control.

Fig 4(c) shows active power changes in the DGs for each scenario. This figure shows that active power can be shared sufficiently between DGs even before activating the DSC by means of droop control. These results illustrates that the P-ω droop control is sufficient to share the active power accurately since the frequency is a global variable in a MG. Notice that there is a small increase in active power to restore the frequency deviation when secondary control is activated.

In Fig. 4(d), reactive power sharing has been illustrated. This figure demonstrates the effectiveness of the proposed secondary control method when reactive power is shared. As seen, while there is a big difference between reactive power of DGs as a result of the droop control, the DSC is able to share properly the reactive power between the DGs.
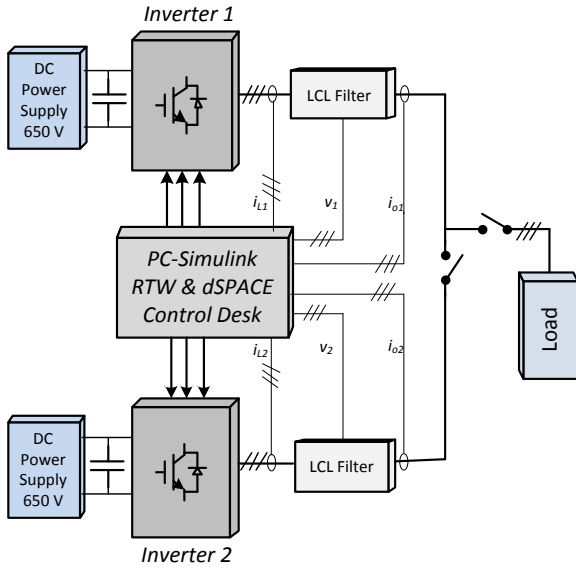
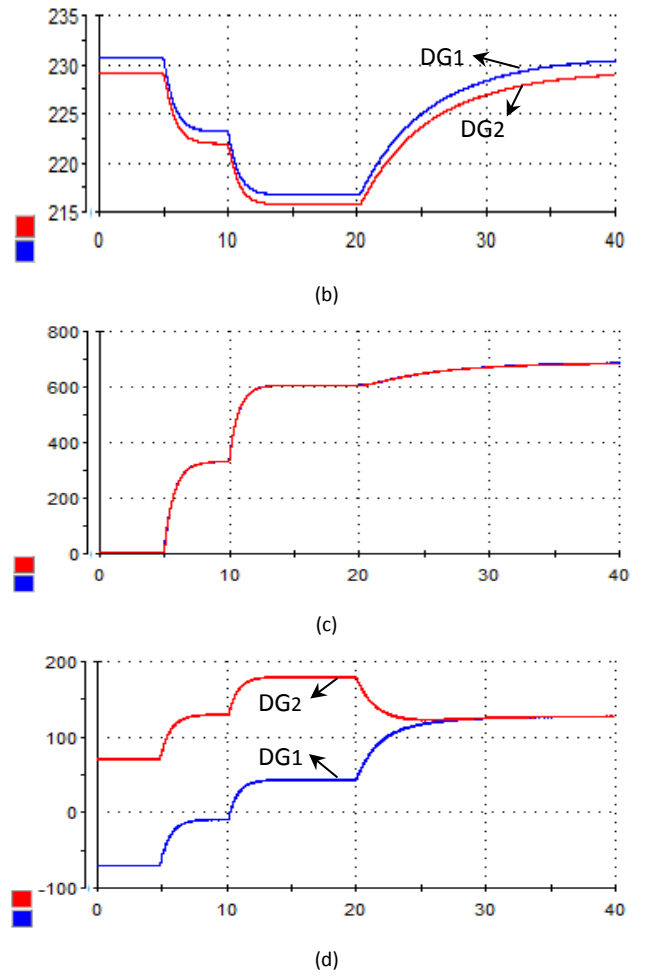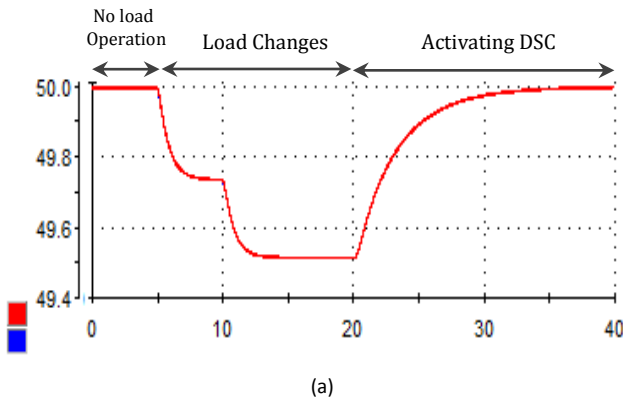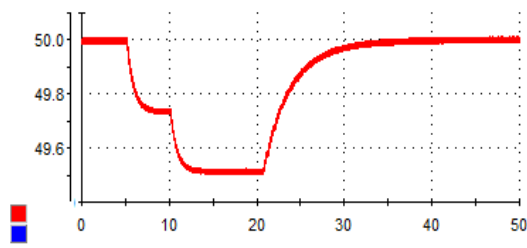Fig. 3 Schematic of Experimental setup

(a)

(b)

(c)

(d)
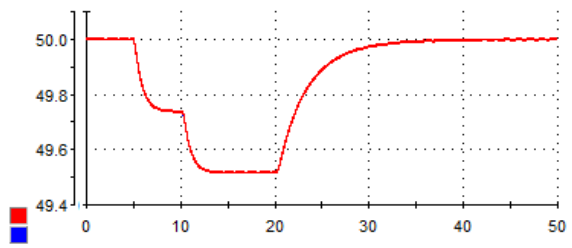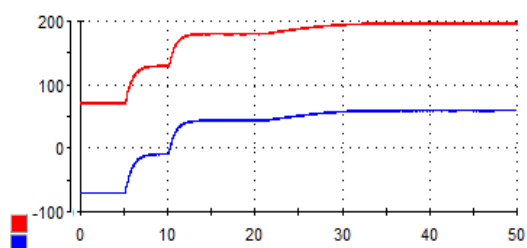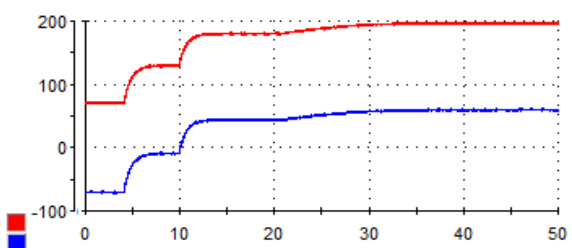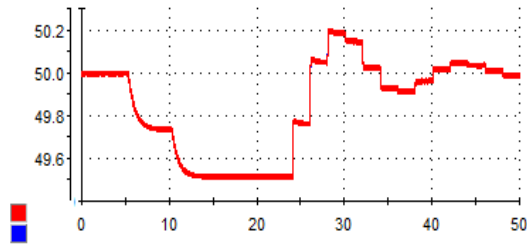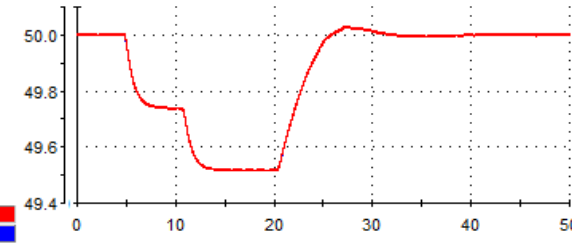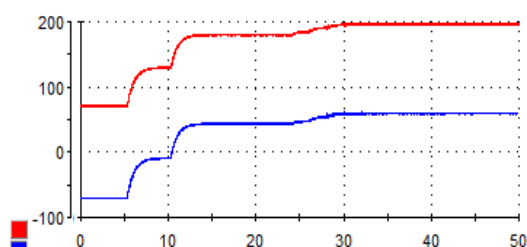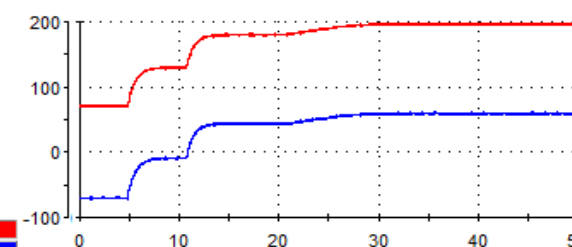
Fig. 4. Performance of DSC in a) frequency restoration b) voltage amplitude restoration c) active power sharing d) reactive power sharing

TABLE I
ELECTRICAL SETUP AND CONTROL SYSTEM PARAMETERS

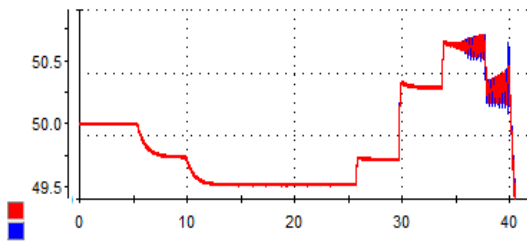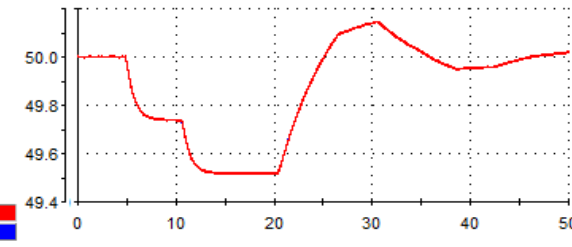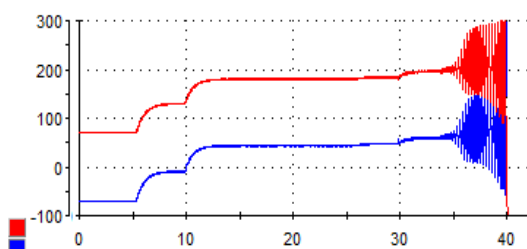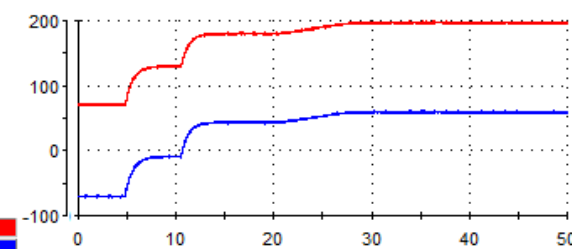| Type	Parameters		Value
	Symbol	Quantity	
Electrical setup	V_{dc}	DC Voltage	650 V
	V_{MG}	MG Voltage	311 V
	F	MG Frequency	50 Hz
	C	Filter Capacitance	25 μF
	L	Filter Inductance	1.8 mH
	L_o	Output Impedance	1.8 mH
	R_L	Resistance Load	200 Ω /400Ω
	L_L	Inductance Load	15 mH
Inner Loops	k_{pI}	Current Integral term	0.7
	k_{iI}	Current Integral term	100
	k_{pV}	Voltage Integral term	0.35
	k_{iV}	Voltage Integral term	400
Droop Control	k_{pP}	Active power droop coefficient	0.00001Ws/rd
	k_{iP}	Frequency Integral term	0.0008 Ws/rd
	k_{pQ}	Reactive power droop coefficient	0.16 VAr/V
	R_v	Virtual Resistance	1 Ω
	L_v	Virtual Inductance	4 mH
Secondary Control	k_{pF}	Frequency proportional term	1
	k_{iF}	Frequency Integral term	2 s^{-1}
	k_{pE}	Amplitude proportional term	1
	k_{iE}	Amplitude Integral term	2 s^{-1}
	k_{pQ}	Reactive power proportional term	0.0001 VAr/V
	k_{iQ}	Reactive power integral term	0.2 VAr/Vs

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Time Delay		Central Secondary Control	Distributed Secondary Control
200ms	Frequency Restoration		
	Reative Power		
2sec.	Frequency Restoration		
	Reative Power		
4sec.	Frequency Restoration		
	Reative Power		

B. Impact of the communication latency, Comparison with central secondary control

Communication has a predominant role in providing the infrastructure that enables data to be exchange among the different elements of the MG. This importance increases when distributed control approach is used for the secondary level of the MGs hierarchical control.

In this section, the impact of communication latency on the proposed control approach is presented, and then compared with those in the conventional centralized approach. Performance of the distributed secondary control has been compared with the central one for three amounts of fixed communication latency, 200ms, 2sec. and 4sec. Only frequency and voltage restoration has been considered for both secondary control strategies. All the parameters are the same for both controllers. For sake of simplicity, only frequency and reactive power responses are depicted.

Table II illustrates the effects of the communication delay on both control strategies performance, when they control reactive power of the DGs and remove frequency deviations. As can be seen, both control approaches have good performance for the latency delay of 200ms. However, the central controller is not able to restore the well frequency in the MG when communication delay increases. For a communication delay of 4 s, as presented in Table II, the central controller cannot make the system stable, becoming unstable after 35 second. While, the proposed control strategy is still stable with a delay of 6 s.

IV. CONCLUSION

This paper has introduced a distributed control strategy for droop controlled MGs. In this method, a decentralized secondary control encompasses every DG unit local controller and the communication system. Thus producing an appropriate control signal to be locally send to the local primary controller. In this sense, the failure of a DG unit will fail down only that individual unit and other DGs can work independent. Thus, adding more DG units is easy, making the system expandable.

The concept is evaluated based on the system performance in a laboratory case study with the goal of regulating voltage and frequency, and at the same time properly sharing reactive power between DG units. Furthermore, the impact of communication system delay over the MG has been compared between the proposed decentralized secondary control system and the conventional centralized one.

The results experimental showed that the proposed control strategy has a good performance in removing frequency and voltage steady state errors and can share reactive power between DG units perfectly. Even thought the secondary control proposed needs more information interchange capability, however, it shown higher robustness in front large communication latency delays.

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