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Decentralized secondary control for frequency regulation based on fuzzy logic control in islanded microgrid

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ABSTRACT

This paper presents a fuzzy-based decentralized secondary control for frequency restoration and active power-sharing in an islanded microgrid, this controller uses the local frequency error to generate an extra term for compensating the deviation and maintaining accurate active power-sharing. No communication infrastructures are needed, event detection, time dependent-protocols, and state estimation are not required. Its design and implementation are straightforward, also, it offers quick dynamic frequency recovery with accurate active power-sharing. To verify the validity of the proposed controller, several tests have been carried out: frequency restoration and active power-sharing during load disturbances, synchronization with plug and play (PnP) ability, as well the communication latency impact. Moreover, the effect of data drop-out and interferences were analyzed in real-time simulation using Truetime. The results have shown the high capability and the fast response of frequency restoration while maintaining the active power-sharing, no oscillations and ripples were presented in steady-state response, likewise, a smooth dynamic response during PnP test is observed. The communication latency and interferences have no impact on the proposed controller that showing a significant improvement in settling time 50% without frequency packet losses and 81%, 90% in the presence of 30% and 70% of frequency packet losses respectively.

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1. INTRODUCTION

Distributed generators (DGs) based on renewable energy sources have emerged considerably in the last decade [1], to integrate and exploit them in a good manner, a new paradigm called microgrid (MG) has appeared as an optimal solution to deal with this challenge [2], and it gained significant attention from researchers [3]. A MG is an interconnection of DG units such as PV systems, wind turbines, battery energy storage units, and loads in low/medium voltage distribution [4], [5], MG can work autonomously in islanding mode or tied to the utility grid in grid-connected mode as can be seen in Figure 1 [6], [7], and it compromises different technologies to achieve their main purpose as reliable power supply system such as power electronics, communication infrastructures, and control systems [8]. MG has the advantages of local production and local consumption which means less transmission lines and hence less losses, further, it is reliable against sudden faults where the probability of blackout occurs is decreased, and it offers a bidirectional power flow, thus the consumer is part of the grid [9].

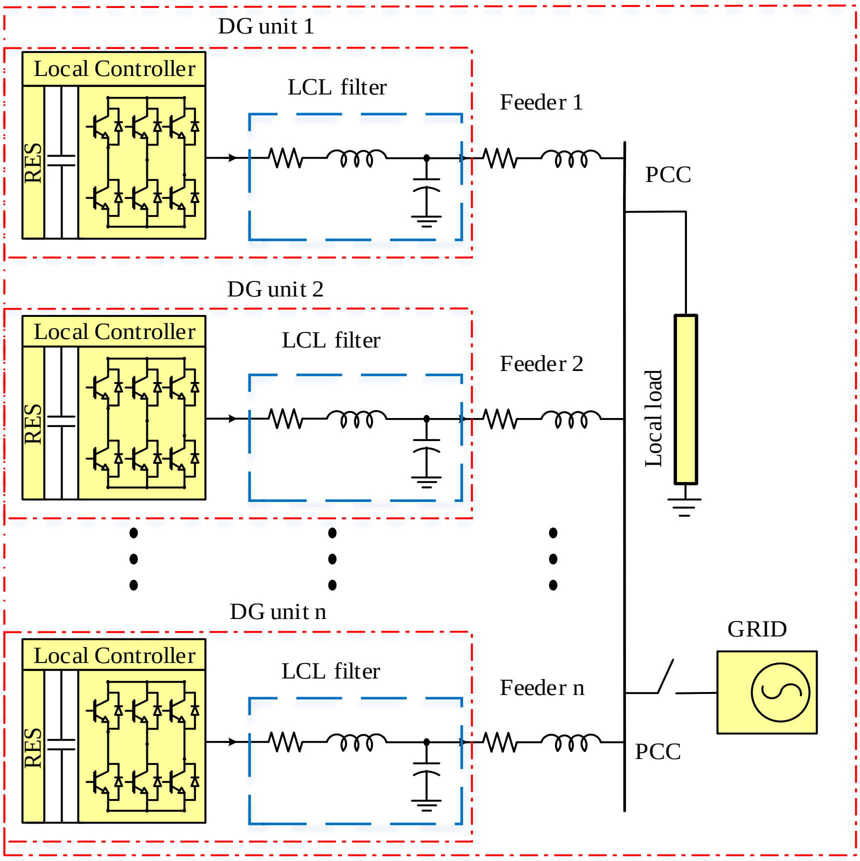


Figure 1. Fundamental structure of a microgrid

Hierarchical control topology is the most adopted approach for MG control and it attracted more and more attention due to its capability to meet MG's control challenges [10]-[12]. Hierarchical control is divided into three layers, first one is primary control which is based on droop control [13]-[15], virtual impedance [16], [17], voltage and frequency control loops [18]-[20], this layer is fully decentralized and no communication infrastructures are needed, their main task is to maintain voltage and frequency regulation, and to share active and reactive powers between voltage source inverters equally [21]. In contrast, the tertiary layer requires communication to manage the power flow among the MG and the external electrical distribution system [8], [22], the secondary control layer (SC) permits compensating the voltage and frequency deviations caused by the inherent characteristic of droop control in the primary control layer [11], [23], the SC is classified into three categories according to the implementation topology as illustrated in Figure 2, the first one which is the most recognized is the centralized topology as can be seen in Figure 2(a), the centralized SC use a microgrid central controller (MGCC) [8], [23] to send and receive information using a communication infrastructure [24], the second one is the distributed control approach Figure 2(b), where the DG units work cooperatively by communicating to each other to attain an agreement situation among all DG units [25], [26], the last one is the communication free decentralized technique as depicted in Figure 2(c), which is implemented locally like primary control [23].

The centralized and distributed secondary control topologies are highly dependent on communication infrastructures which increase the complexity and the cost. Moreover, the needing for a communication system reduces the reliability and the resiliency of the MG due to uncertainties such as communication delays [27]-[29] and data-drop out, also communication systems expose the system to cyber-attack threats [30], as a result, many literatures proposed fully decentralized technics, an equivalent secondary control based on a washout filter is proposed in [31] it has the advantage of low complexity, however it suffers from steady state-error and slow dynamic response which need to be improved in future works. Based on state-estimation new approaches have been addressed in [32]-[34] their major superiority is in the accurate active and reactive power-sharing independently; however, these approaches related to the system model which serve as an alternative of communication infrastructures by estimating the state of the remains DG units in the MG system , thus a high computational burden is required and hence leading to increase the complexity and cost which reduce the efficiency of the system, further a decentralized secondary control approach (SC) utilizes the active power estimation is developed in [35] unlike the above-mentioned state-estimation techniques, which require a complete knowledge of the MG topology to estimate the variables, this approach uses the unique property of the frequency in islanded MGs as a global variable in steady state to estimate the active-power, the only drawback is the slow dynamic restoration up to 2s, in [36] a switched secondary frequency compensation is proposed based on switching between two configurations as the secondary control is established using a low-pass filter which exhibits design tradeoff between transient response and accuracy, this approach breaks this design tradeoff and provides fast transient response with small error in steady-state while using a time-dependent control which increases the complexity, especially the parameters design which decreases the system stability, although a decentralized optimal secondary controller is developed in [37] based on a quadratic cost function in the form of a linear quadratic regulator (LQR) solution with a straightforward and simple design procedure, a frequency self-restoration based on droop control is presented in [38], it has a fast dynamic response, but it suffers from overshoots with the presence of ripples in the steady-state response.

As can be observed from the previous paragraph, the existing decentralized technics suffer from many drawbacks such as steady-state error, slow dynamic response, time and system dependent, complexity and high computational burden. In addition, no study investigated the effect of interferences such as emergency control, plug, and play of DG units with a high-priority task. Therefore, this paper proposes a decentralized secondary control for frequency regulation and active power-sharing based on fuzzy logic control in islanded MG, the fuzzy logic can be used as an intelligent approach to deal with the imperfections of the conventional controllers aiming to cover the complex systems with their uncertainties and inaccuracies, the proposed secondary control is fully decentralized, except in the emergency conditions where the system is controlled using a MGCC and tertiary control. Based on a fuzzy logic controller and on the unique feature of frequency in islanded MGs as a global variable in steady state the objective was to elaborate a robust control for the frequency while at the same time respecting the dynamic constraint and treatment-time to achieve a fast dynamic restoration without overshoot and ripples in a steady-state regime, an enhanced dynamic behavior of a PI regulator was used for the design of the fuzzy controller, simulation results show the high performances and capabilities of the proposed technic. The main contributions and novelties of this paper can be listed as shown in:

- Unlike [36], which proposed an adaptive neuro-fuzzy inference system for a distributed microgrid topology, our model takes advantage of the unique feature of the frequency in islanded MGs as a global variable to develop a decentralized topology.
- Extending the works in [32], [39] by developing a fuzzy controller to eliminate frequency deviation of microgrids meanwhile ensuring the precise active power sharing between inverters, the proposed controller offers a quick dynamic frequency recovery and it is much faster than conventional controllers with an accurate active power tracking and its design with implementation are straightforward.
- In contrast of distributed approach, the proposed method is communication-free.
- Event detection, time dependent-protocols, and state estimation are not required.
- The settling time is improved by 50% compared to the conventional PI controller.
- Similarly in the presence of 30 % and 70 % of packet losses the settling time is improved by 81% and 90 % respectively which confirms the high performance.
- No overshoots and oscillations in frequency are presented in case of the presence of communication delays and no ripples in the steady-state response.
- It shows high flexibility and robustness during plug-and-play operation.
- Interferences such as emergency control and economic dispatch have no impact on the proposed controller.

The rest of the paper is structured as shown in: Section 2 the secondary control function in a multilayer control structure with the proposed method are described, moreover, the existing secondary control technics were listed and compared in terms of their advantages and disadvantages. Section 3 exhibits the simulation results based on multiple scenarios including the comparison, the results were discussed in the same section. Finally, the paper is concluded in section 4.

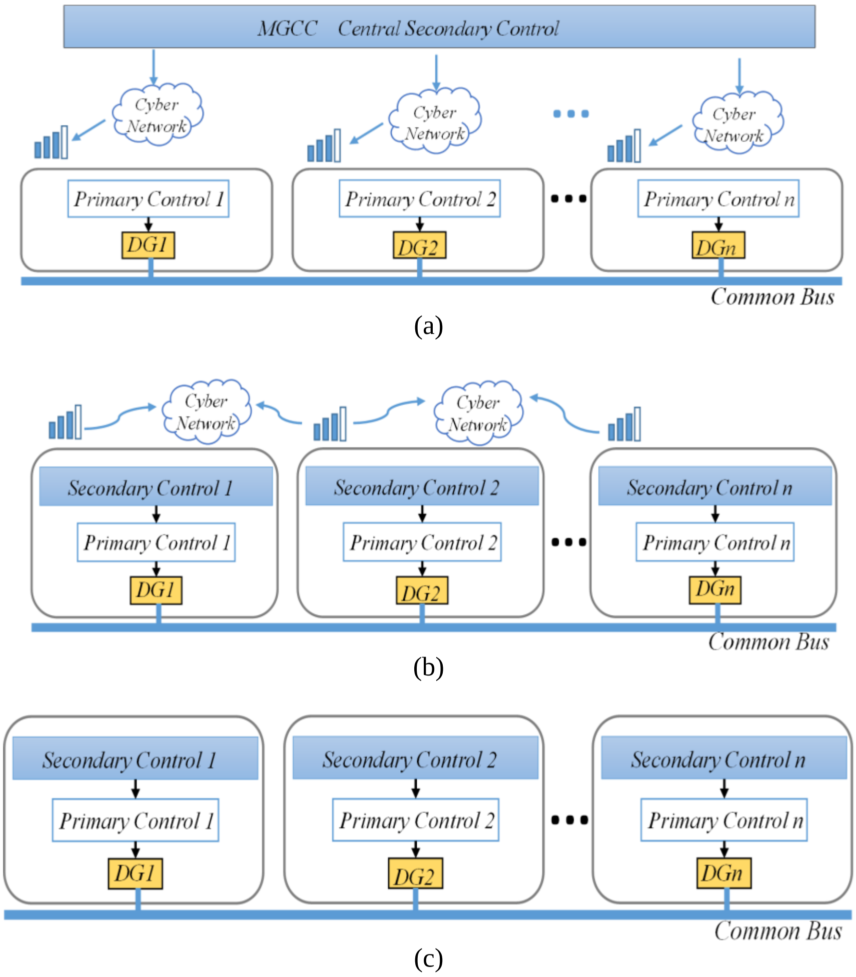


Figure 2. Secondary control topologies; (a) centralized SC, (b) distributed SC, and (c) decentralized SC

2. METHOD

The first layer of the hierarchical control is represented by the droop control which adjusts the frequency and voltage according to the measured active and reactive power based on the droop coefficient m_i and n_i calculated according to the small-signal analysis presented in [14], it can be expressed as:

$$\omega_i = \omega^* - m_i P_i \tag{1a}$$

$$V_i = V^* - n_i Q_i \tag{1b}$$

Being, ω_i and $\omega^*$are refer to the angular frequency and its reference respectively, P_i is the active power output, V_i and V^*refer to the voltage amplitude output and its reference, Q_i the reactive output. As shown in (1), ω_i and V_i are used to synthesize the three-phase reference voltage to be provided for the inner current and voltage control loops. It is clear from the above-mentioned equation that a change in both active and reactive powers leads to frequency and voltage change respectively, especially when adding loads this leads to the frequency and voltage droops, which result in steady-state errors that need to be compensated.

The secondary control eliminates these deviations by providing an extra term to the primary layer and it can be expressed mathematically by:

$$\lim_{t \to t_f} \omega_i(t) = \omega^* \tag{2a}$$

$$\lim_{t \to t_f} V_i(t) \approx V^* \tag{2b}$$

practically, it is impossible to achieve perfect voltage regulation and reactive power sharing using only the droop method in (1b) since the voltage is a local output variable of the MG. In this sense, this paper focused only on the MG frequency compensation and supposed that the Q−V droop control loop adjusts the V_i for the DG units. Thus, to attain an accurate active power-sharing and impose the reference frequency without steady-state errors, the SC level provides an extra term to (1a) as shown in:

$$\omega_i = \omega^* - m_p \cdot P_i + \delta\omega_i \quad (3)$$

The additional control term $\delta\omega_i$ provided by the SC to the primary layer and ω_i is the corrected frequency of ith DG unit which leads to maintaining the frequency at its nominal value as can be seen in Figure 3. Noticing that another extra term is required for the synchronization and to ensure a seamless transition between operation modes, either for synchronizing the DG units between each other in case of plug-and-play operation or to synchronize the MG with the classical grid in case of grid-connected mode generally the synchronization loop considered as part of SC; moreover, an islanding detection approach also can be included in this level.

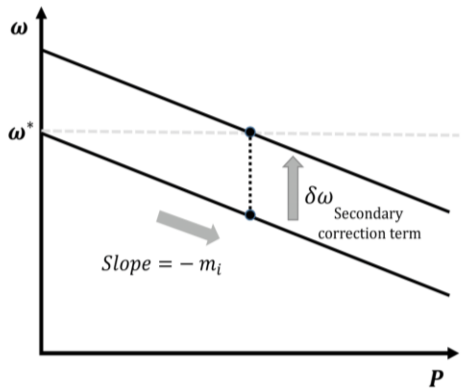


Figure 3. Primary and secondary control actions

Table 1 summarizes the advantages and disadvantages of different secondary control technics including the proposed one. As mentioned before for the centralized topology the need for communication and remote measurement threat the system stability by time delays and data drop, which degrade the power quality as well as communication failure can interrupt the electricity supply. Similarly, the distributed approach proposes communication between microgrids units for enhanced reliability, but, in case of a single failure of communication, it will affect the entire stability. Hence new communication less technics have emerged, to enhance the resilience of MGs and drop out of the communication network.

The proposed secondary control is fully decentralized, except in emergency conditions where the system is driven using the upper layer which is the tertiary control. Based on a fuzzy logic controller the objective was to design a robust control for the frequency meanwhile respect the dynamic constraint and treatment time, the structure of the controller is depicted in Figure 4. The use of fuzzy logic controllers in the last decade has been widely increased for power systems and power electronics applications [43], [44] the conventional secondary controller based on PI regulators suffers from many drawbacks due to their design which is tuned on a predefined operating point, any change in the operating conditions outside the operating point leads to the loss of system stability due to the incapability of the PI controller for providing suitable performances, moreover, it has a slow dynamic response which can affect the sensitive loads such as data centers. The fuzzy logic can be used as an intelligent approach to deal with the imperfections of the conventional controller aiming to cover the complex systems with their uncertainties and inaccuracies. A fuzzy-PI structure is used to perform the fuzzy controller based on a PI behavior profile, the gains are adapted in function of the frequency error and the derivative of the error.

The input error e_ω and their derivative de_ω values are normalized as shown in:

$$e_\omega = K_{e_\omega}(\omega^*(k) - \omega_i(k)) \quad (4a)$$

$$de_\omega = K_{de_\omega}(e_\omega(k) - e_\omega(k-1))/T_z \quad (4b)$$

where T_z is the sampling time and K_{e_ω}, K_{de_ω} are the normalization gains or the scaling factors. The output generates the variation of the corrective term which is after the integration and normalization gives the external signal ω_i. The scaling factors are very important in the design of the controller to adjust the sensibility of the fuzzy controller and the stability of the system, it allows the normalization of the inputs and the outputs in the required gap of the universe of discourse, these parameters are obtained after trial and error method. Fuzzification is the process of transforming a crisp input value into a fuzzy value that is achieved by the use of the information in the knowledge base. Although various types of curves can be used. Triangular, gaussian, and trapezoidal membership functions which are the most popular in the fuzzification process. The implementation of these types of membership functions can be easily achieved using embedded controllers.

Table 1. Summarize of different secondary control technics

Control	Concept	Advantages	Disadvantages
Centralized Secondary Control	- Central Controller [11], [23]	- Active and reactive power management - Harmonic cancellation - Real-time monitoring of the system - Unbalanced current reduction	- any failure in Communication infrastructure or CSC affects the overall MG system - Communication delays and data drop
Distributed Secondary Control	- Average-based DISC [25]	-Robust to single-point-failures - Easy to implement (An embedded controller is enough) - flexibility and redundancy - less expensive control hardware	- Communication complexity - Clock drifts - Voltage stability and reactive power-sharing - Communication infrastructure
	- Consensus-based DISC [40], [41]	- Higher control accuracy under disturbances and communication delays -Simple control algorithm, easy to implement -Plug-and-play operation -Robust to single-point-failures	- Reducing the recomputation and communication - Voltage stability and reactive power-sharing - Communication infrastructure
	- Event-triggered DISC [23], [42]	- Reducing the recomputation and communication - support the plug-and-play function - Easy to implement -Robust to single-point-failures	- Clock drifts - Voltage stability and reactive power-sharing - Zeno phenomenon - Communication infrastructure
Decentralized Secondary Control	- Washout Filter-Based DESC [31]	- Fully decentralized and easy to implement - Low complexity	- Steady-state error - Slow dynamic response
	- Local Variable-Based DESC [36], [37]	- Fast active power responses - Communication-free	- Increase complexity - Time-dependent - Slow dynamic response
	- Estimation-Based DESC [32], [33]	- Communication-free - Precise active and Reactive power-sharing independently	- Depend on the modeling of the system - High computational burden
	- Proposed DESC based fuzzy logic controller	- Communication-free - Quick dynamic frequency recovery - No overshoots and oscillations in frequency - Accurate active power-sharing - Easy to design and implement -No steady-state error -No impact of interferences - Less computational burden	- Fuzzy controller scaling factors are selected based on trial and error method.

The membership functions are defined mathematically with many parameters. To enhance the performances of the fuzzy logic controller these parameters can be adapted to obtain the desired outputs. The distribution and the number of the membership functions in the universe discourse are very crucial, and the calculation time of the algorithm should be considered especially for the practical implementation a good design mean less computational burden and hence less cost. The design steps are illustrated in Figure 5. A triangular and trapezoidal membership functions have been selected for the input and output variables distributed in five symmetric and equidistant subsets are selected as can be seen in Figure 5(a). The universe of discourse gap is determined between [-1.5 1.5], this choice makes the fuzzification easier because it decreases the computation time in the real-time implementation.

The different groups are defined using the following linguistic variables:

- NL: Negative Large
- NS: Negative Small
- ZE: Zero
- PS: Positive Small
- PL: Positive Large

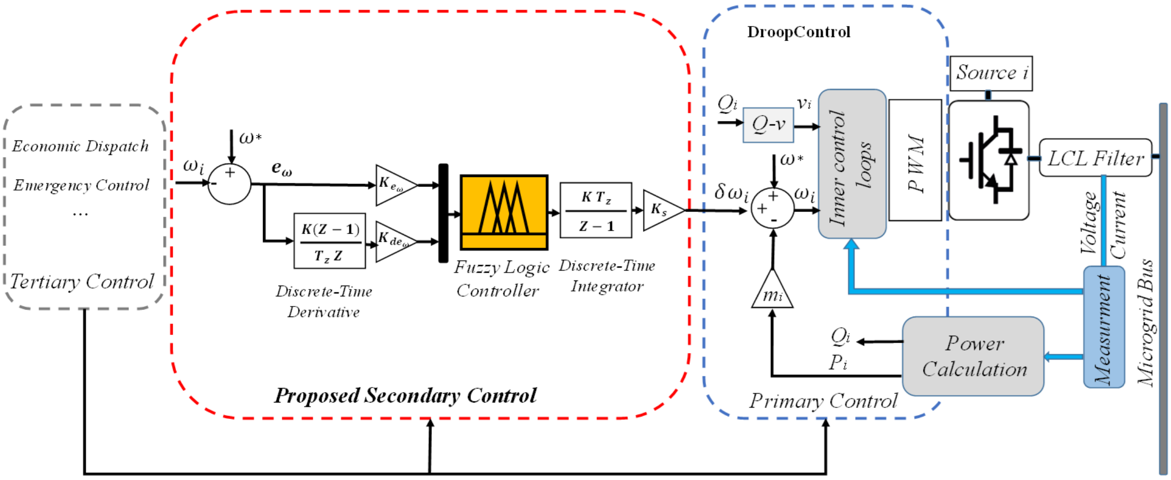


Figure 4. Proposed decentralized secondary control for microgrids

The rules base plays an important role in the behavior of the fuzzy controller, hence a good design of the table of rules leads to better performances, generally the construction of the interference table is based on qualitative analysis of the process. From the previous study [11] of the closed-loop system behavior using a PI controller and based on the expertise, fuzzy rules are established to tie the inputs and output. The general form of the step response and the derivative of the error are shown in Figure 5(b). Depending on the amplitude of $e_\omega$and the sign of de_ω, the response is divided into four intervals (from (1a) to (4a)) such that:

$$\begin{cases} a_1: e_\omega > 0 \text{ et } de_\omega < 0 \\ a_2: e_\omega < 0 \text{ et } de_\omega < 0 \\ a_3: e_\omega < 0 \text{ et } de_\omega > 0 \\ a_4: e_\omega > 0 \text{ et } de_\omega > 0 \end{cases}$$

For instance, at the start of the compensation (point 1) the response is strongly inferior to the reference, and hence the error is PL and their derivative value is ZE, thus the output control signal should be PL. When the error is near zero (point 2) and their derivative value is NL the output signal changes to ZE to avoid a big overshoot value, after the overshoot (point 3), the error is NL and their derivative also, thus the output signal should be strongly reversed to NL, in case of the overshoot still exist and the error is NS with the response is near to the reference (point 4), thus the error derivative value changes their sign to PS, in this case, the output signal should be ZE to minimize the undershoot.

Since there are five fuzzy sets, this implies twenty-five possible combinations of these inputs, and therefore twenty-five rules. The rules are like this:

1- If (e_ω is NL) and (de_ω is NL) then ($\Delta\delta\omega_i$ is NL)

25- If (e_ω is PL) and (de_ω is PL) then ($\Delta\delta\omega_i$i is PL).

Hence the inference matrix deduced according to the reasoning of "McVicar-Whelan" is as shown in Table 2, The Mamdani method is used for the interference method.

Defuzzification is the process of converting the fuzzy output sets produced by the inference mechanism. To generate the most certain low-level controller action. Many methods exist in literature to perform the defuzzification, the most popular is the center of gravity method which is used in this case due to its reputation in the control field to obtain the variation of the external term, where the $\Delta\delta\omega_i$ is determined from the geometric center of the variable fuzzy output, their discrete equation is as shown in:

$$\Delta\delta\omega = \frac{\sum_{i=1}^{n} \delta\omega(x_i)\mu_{\delta\omega}(x_i)}{\sum_{i=1}^{n} \mu_{\delta\omega}(x_i)} \quad (5)$$

Notice that as mentioned before the fuzzy controller gain values play a crucial role in obtaining the suitable dynamic response, previous tests of the controlled system are helpful in the selection of the initial values of the fuzzy logic controller gains. If there is a lack of information about the controlled system, the suitable parameters can be calculated by trial and error method or using optimization algorithms such as particle swarm optimization as presented in [45]. The PSO approach is an excellent optimization methodology and a promising method for solving the optimization problem of the fuzzy logic controller and defining the suitable parameters, further, a quasi-oppositional harmony search (QOHS) algorithm is adopted in [46] which is a new variant of derivative-free metaheuristic algorithm that mimics natural and systematic phenomena. Figure 5(c) depicts the output surface for the fuzzy controller, it gives the first output variable according to the first two input variables.

Table 2. Table of rules

e_ω / de_ω	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

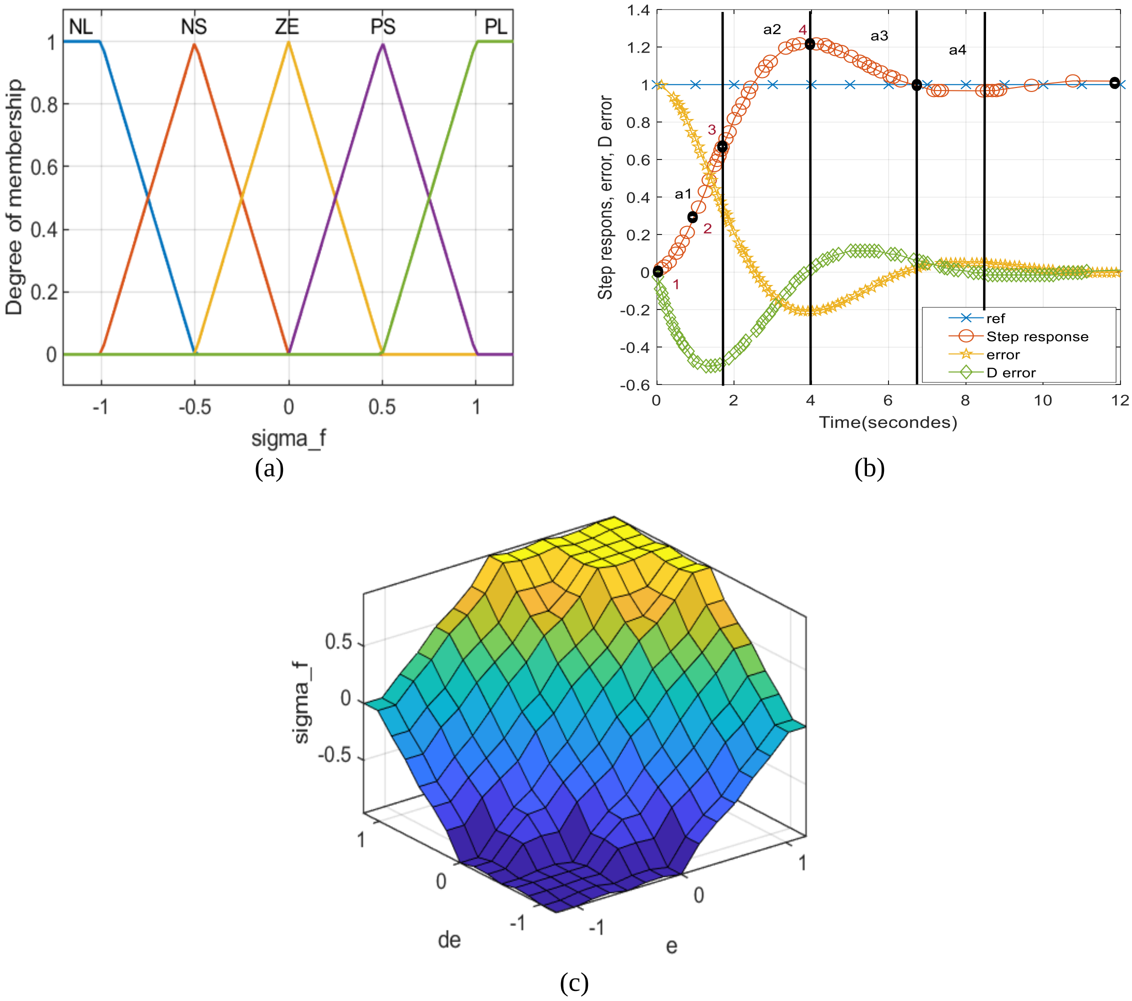


Figure 5. Fuzzy logic controller design steps membership functions (a) the deduction of the rules from a temporal analysis (b), and (c) output surface plot of the fuzzy controller

3. RESULTS AND DISCUSSION

To evaluate the effectiveness and the performance of the proposed technic, a MG simulation model is set up on MATLAB software as shown in Figure 6. It consists of two DG inverters with the same rating powers forming an islanded MG and LCL filters are used, a low pass filter is integrated into the output of the power measurement units in the primary level to suppress harmonics. The electrical and control parameters are listed in Table 3, all parameters have been adjusted based on the developed model, the proposed controller is studied and analyzed in the following parts.

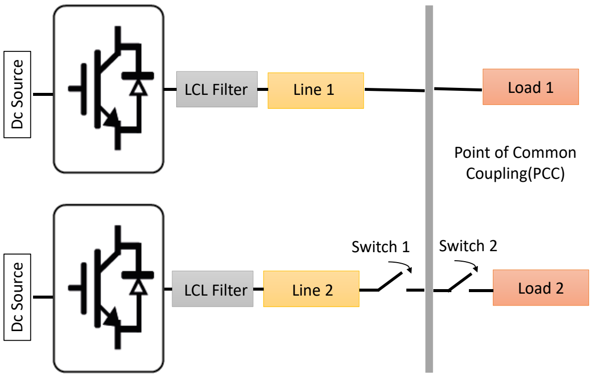


Figure 6. Microgrids Configuration of the studied MG

Table 3. Simulation Parameters

Parameter	Symbol	Value
Powerstage		
Nominal Voltage	V	311 V
Nominal Frequency	f	50 Hz
Input / Output Inductance of LCL filter	L/L_o	800 /250 uH
Filter Capacitance	C	60 uF
Line 1	$R1/L1$	0.5/1 mΩ/uH
Line 2	$R2/L2$	2/3 mΩ/uH
Load 1	–	500 W
Load 2	–	500 W
DC Voltage	V_{dc}	400 V
Primary&Voltage/Current P Control for DG1/DG2		
Voltage proportional gain/integral term		0.2/100
Current proportional gain /integral term		5/400
Proportional frequency droop	m	0.0003 W/rd
Proportional amplitude droop	n	0.001 Var/V
Decentralized Secondary control		
Scale factor proportional term for error	Ke_{ω}	1
Scale factor proportional term for error derivative	$Ke_{d\omega}$	0.1
Integral term	K_s	1000

3.1. Frequency restoration and active power-sharing during load disturbances

This test is performed to evaluate the frequency compensation and the accuracy of sharing active power, the obtained curves are exhibited in Figure 7. It consists of comparing the conventional P-ω droop control method with the proposed decentralized secondary control. First at t=0s until t=3 s the MG system is running under the conventional droop control and the two load are connected as can be seen in Figure 7(a) and 7(b) from t=0 s to t=3s the droop mechanism is adjusting the frequency magnitude according to the measured active power and a considerable frequency deviation from its nominal value is presented, while the active power-sharing is well maintained by the droop mechanism until t=3 s the communication free proposed control is activated thus the deviation is compensated while maintaining an accurate active power-sharing (see Figure 7(a)). A load change is applied to the MG system to confirm the high performance of the proposed control, as shown in Figure 7(a) at t=6s load 2 is turned off the active power is decreased and the frequency is perturbed by presenting an overshoot for a certain time, however, this perturbation is removed due to the fast response of the proposed controller and the frequency is restored to their nominal value within an acceptable range. The current is decreased smoothly without presenting disturbances Figure 7(c), the load 2 is turned on another time at t=9s similarly, the proposed SC compensate the error quickly and fixed the frequency to their reference value, the current is increased to supply the loads Figure 7(d). The reactive power-sharing is not equal as shown in Figure 7(d) due to the inherent limitation of the droop control method [47], [48].

3.2. Synchronization and plug-and-play capability

Black start and synchronization process of the two DGs units is performed in this test. The connection and disconnection of the second DG unit to the MG system is realized as can be observed in Figure 7(e) from the interval t ϵ [0,1s] the black start occurred where the two sources are synchronized to each other and they immediately start feeding the load meanwhile sharing the active power equally. At t=1s the second DG unit is intentionally disconnected, and the rated power of the first DG unit is increased immediately to ensure supply continuity. At t=2s DG unit two is reconnected and the active power signals are matched after 0.5s which confirms the capability of maintaining the active power sharing during these circumstances. The frequency drop in Figure 7(f) during the black start and load disturbance refers to the droop mechanism, similarly for the frequency overshoot at the load disconnection, the action of the proposed DSC compensates this deviation quickly and restores it to its rated value with a better dynamic response. Noticing that every reconnection to the MG system necessitates a synchronization procedure often using a PLL to match the frequency and the phase angle with the MG to minimize circulating currents among DG units besides eliminating fluctuations and disturbances.

3.3. Impact of communication latency

Communication infrastructures for data exchange are a crucial part of MGs, especially in the secondary control layer. To show the communication less feature of the developed controller this latter is compared with a centralized SC as presented in Figure 8. The centralized SC suffers from major drawbacks represented by time delay and data drop-out. Firstly a communication time delay is simulated using the same electrical parameters for both MG models to achieve an accurate comparison using centralized and decentralized SC under an amount of communication latency equal to 200 ms. As observed in Figure 8(a) the frequency response of the centralized topology presents damped oscillation with a big settling time equal to 1.7s, the increment of the time delay leads to the loss the system stability, however, the decentralized SC f Figure 8(b) isn't impacted by the communication because it implemented locally, with a reduced settling time estimated by 0.2 s.

3.4. Comparative study of dynamic response

To verify and confirm the superiority of this method, the fuzzy logic controller is compared with the conventional PI controller used in [11]. The comparison investigates the dynamic response of the system and the compensation time, as can be seen in Figure 8(c). The compensation for the fuzzy logic controller starts after 0.06s from the drop of frequency, however in the case of the PI regulator the compensation starts after 0.15s; moreover, the fuzzy controller reaches the nominal value in 0.5s on the other hand 1.3s for the PI controller which confirms the flexibility and the rapidity of the proposed control, the same way in case of adding or removing loads the dynamic response of proposed controller is quick than the PI controller with a neglected overshoot. The above-mentioned tests show the flexibility of the proposed technic under different disturbances constraints and their behaviors against this test are very satisfactory.

3.5. Effect of data drop-out

Data drop-out or packet loss is one of the major drawbacks of communication systems. It can directly affect and degrade the performances of the system outputs. The performance of the proposed SC in the presence of packet losses has been tested and compared to the PI controller in real-time simulation considering the different amounts of data drop-out, 30%, and 70%. As shown in Figure 9 it can be observed that both controllers have acceptable performance in eliminating the frequency deviation for 30% data drop-out when data drop-out is up to 70%, the proposed SC can recover the system in 0.5 s; however, the PI controller is unable to recover the frequency quickly, it takes about 3 s to restore the system into their nominal frequency, comparing to the PI controller the proposed SC has a fast and flexible dynamic response which guarantee the stability of the system.

3.6. Effect of interferences

In real systems, there may exist interferences. In the case of a MG system interferences can be represented in emergency control, plug and play of DG units with a high priority task. In this test the simulation involves an interfering node sending disturbing traffic and disturbing high-priority tasks executing in the controller node, it can be seen in Figure 10 that the interferences with high-priority tasks have no impact on the proposed SC and the recovering time and the dynamic response are not affected which confirm the high performance of the proposed controller.

The purpose of this paper was to elaborate a decentralized secondary control that is achieved using a fuzzy controller and based on the unique property of the frequency in islanded MGs as a global variable. The performed tests and scenarios show the main features of the developed SC, represented in a reduced settling time compared to the conventional PI controller about 50% improvement, high flexibility against the plug-and-play operation with a smooth transition at every connection and disconnection of DG units no current fluctuations were observed, the packet losses almost has no impact on the SC and the system, in contrast of the conventional control which tends to have a slow dynamic response, interferences such as emergency control were simulated using the real-time toolbox to analyze the performance of the controller in real condition and results have shown high robustness against interferences. The performance of the proposed controller are evaluated through time domain specifications in Table 4.

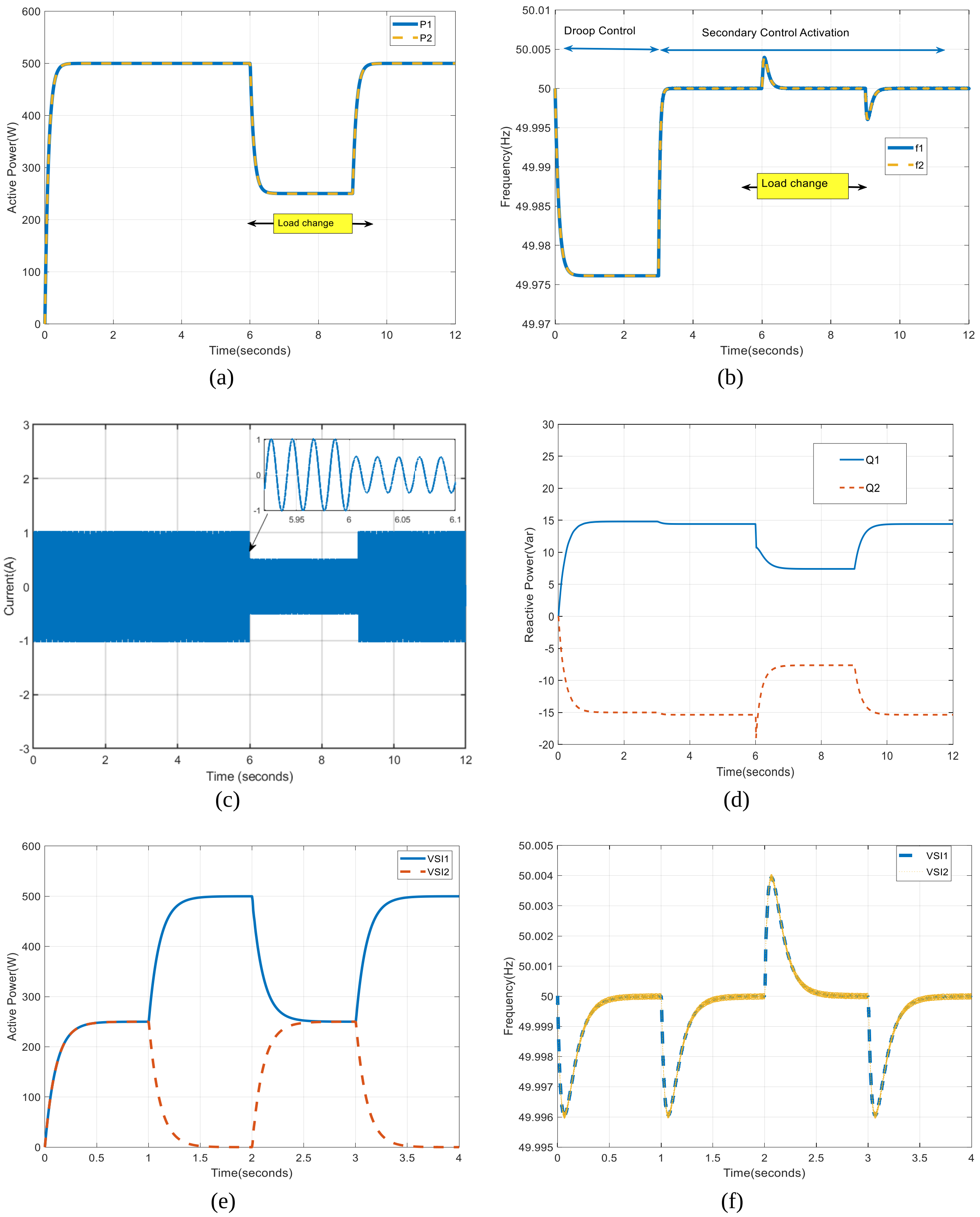
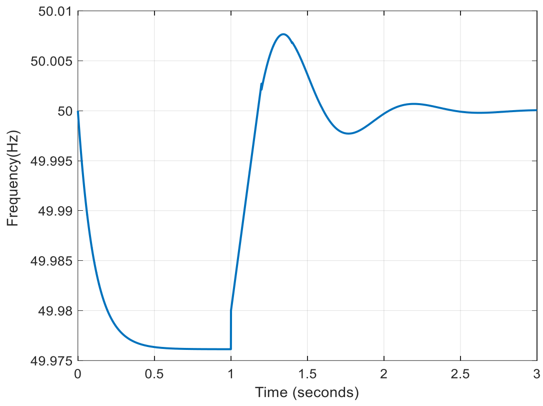
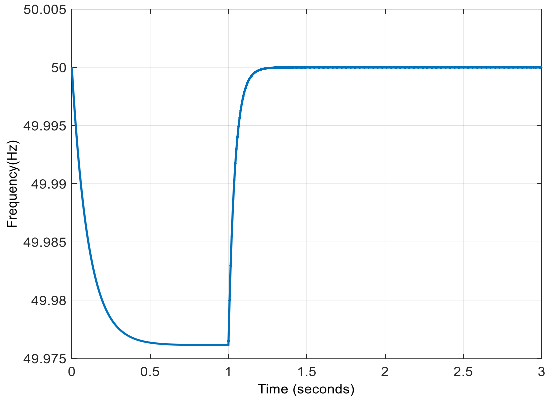


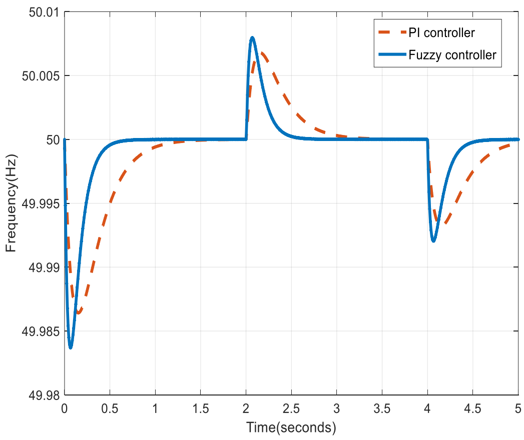
Figure 7. Performance of proposed controller under load disturbances with black start and plug and play test, (a) active power-sharing, (b) frequency restoration, (c) current, (d) reactive power, (e) black start and PNP-active power-sharing, and (f) Pnp frequency restoration



(a)



(b)



(c)

Figure 8. Performance of proposed controller, (a) frequency restoration under delay time 200 ms-centralized topology, (b) frequency restoration under delay time 200 ms-decentralized topology, and (c) comparison between fuzzy and PI controllers

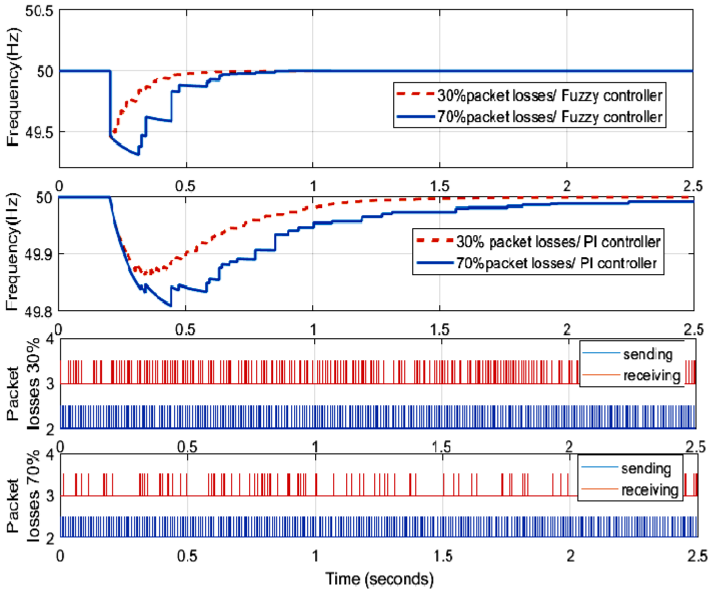


Figure 9. Performance of proposed secondary control considering data drop-out, when compared with PI controller

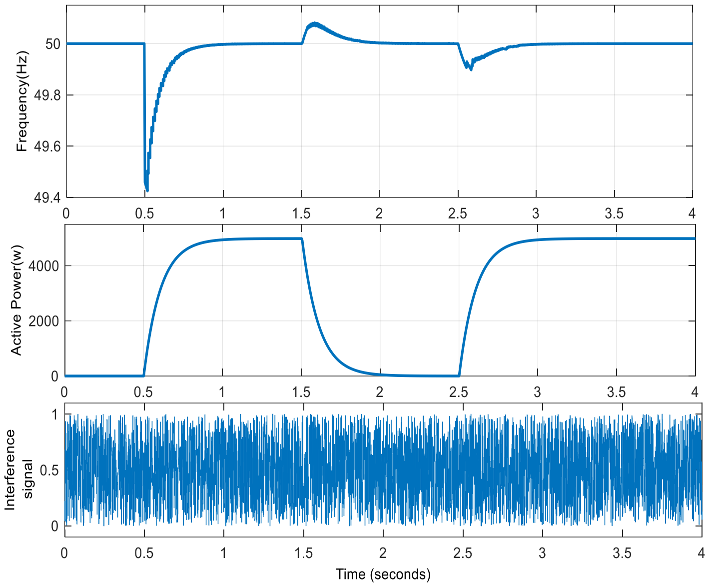


Figure 10. Performance of proposed controller under interferences

Table 4. Performance evaluation of proposed scheme through time domain specifications.

Test scenario	Type of response	Type of Controller	Max. overshoot	Min. undershoot	Peak time (s)	Settling time (s)
1 Frequency restoration	frequency deviation Figure 7(b)	Fuzzy controller	5e-3	5e-3	0.066s	0,461s
2 Plug and play test	frequency deviation Figure 7(f)	Fuzzy controller	5e-3	5e-3	0.07s	0,537s
3 Frequency restoration under delay	frequency deviation Figure 8(a) and (b)	Fuzzy controller PI controller	0 1e-1	0 3e-3	0.2s 0.3s	0.2s 1.7s
4 Comparison test	frequency deviation Figure 8(c)	Fuzzy controller PI controller	7e-3 5e-3	1e-3 7e-4	0.66s 0.2s	0.48s 1.21s
5 Under packet losses 30% - 70%	frequency deviation Figure (9)	Fuzzy controller PI controller	0 0	0 0	0 0	0.6s – 0.65s 1.6s - >2.5s
6 Under interferences	frequency deviation Figure 10	Fuzzy controller	8e-2	5.6e-1	0.073s	0.5s

4. CONCLUSION

In this paper, a decentralized secondary control for frequency regulation and active power-sharing in autonomous microgrids is introduced. The proposed communication-free SC was achieved using a fuzzy logic controller based on the local frequency error to generate an extra term to compensate the deviation and maintain accurate active power-sharing. The main contribution of this paper compared to the previous SC topologies was its decentralized control topology. Moreover, it offers a quick dynamic frequency recovery and it is much faster than conventional controllers with accurate active power tracking, its design and implementation are straightforward, no overshoots and oscillations in frequency are presented and no ripples in the steady-state response, it shows high flexibility and robustness during plug and play operation, further it is not impacted by the interferences. These performances are verified by simulation results and the comparison with the conventional PI regulator confirms that the proposed fuzzy controller is very effective in improving the transient stability of the overall system during load changes, data drop-out, and interferences especially in settling time where the improvement is estimated by 50%.

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