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Robust Secondary Controller for Islanded Microgrids with Unexpected Electrical Partitions under Fault Conditions

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Abstract: This paper proposes a sophisticated, fault-tolerant, and centralized secondary controller that is designed for inverter-based, islanded microgrids. The proposed controller enhances system resilience to unexpected network partitions, which typically occur due to the tripping of protective devices under fault conditions. In typical radially configured MGs, a line fault can cause protective devices to isolate the faulted line, thereby splitting the MG into two electrically independent sub-microgrids (SMGs), while retaining the existing communication and control framework. In contrast to traditional centralized and distributed secondary controllers, which often fail to restore the frequency to the nominal value (50 Hz) in split SMGs, the proposed controller exhibits exceptional performance. Through simulation studies on 6-bus and 13-bus islanded MG setups, the controller has not only demonstrated its ability to swiftly restore the nominal frequency in both SMGs within a few seconds (specifically 5 s), but also to ensure fair power distribution among the distributed generators (DGs) supplying the SMGs. This rapid frequency stabilization underscores the controller's effectiveness in maintaining stable frequency levels immediately following a fault. In contrast, the use of traditional centralized and consensus controllers typically results in a frequency deviation of about 3 Hz from the nominal value in one of the SMGs during the microgrid's partition.

Keywords: faults; frequency restoration; microgrid partition; secondary control; voltage restoration



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1. Introduction

Microgrids (MGs) are small-scale networks consisting of controllable components that can operate in grid-connected or islanded modes. During islanded operation, the control objectives of a MG are performed by a hierarchical control scheme consisting of three layers: primary, secondary, and tertiary [1]. The primary layer has the fastest reaction, and it is responsible for maintaining frequency stability and balance between power generation and consumption. The primary objective of the secondary layer is to eliminate the frequency and voltage deviations resulting from the primary layer. Secondary control strategies are categorized, depending on their communication infrastructure and control algorithms, into two major schemes: (a) centralized control [2,3], and (b) consensus (or distributed control) [4–6]. Last years, the traditional secondary control methods have been advanced via more sophisticated approaches that serve specific goals, as explained below. Finally, the tertiary control, with the slowest reaction time (in the order of several minutes or even hours), performs power and energy management, system optimization, economic dispatch [2], etc.

1.1. Review of Sophisticated Secondary Controllers

In the literature, there are several variations of the classical secondary control approaches mentioned above [2–6], each attempting to achieve a specific objective. These

variants have more sophisticated characteristics. Specifically, Lu et al. [7] proposed a robust distributed controller, which effectively treats the disturbances and noises in the communication links between the DGs. The information exchange among DGs occurs in a discrete form, significantly reducing the communication requirements. Ahumada et al. [8] introduced a centralized predictive model and Smith predictor secondary controller, with improved performance under communication delays between the controller and DGs. Alhasnawi et al. [9] proposed a consensus-based secondary controller to mitigate frequency deviation, power-sharing imbalances between DGs, and voltage violations in islanded MGs. These were designed for use during fault conditions and before the action of protective devices. Shahab et al. [10] introduced a cooperative adaptive sliding mode consensus controller to explicitly address frequency and voltage restoration and provide stringent real power sharing in islanded MGs in the presence of actuation/propulsion faults and disturbances. Peng et al. [11] introduced a novel hierarchical control structure designed to suppress power oscillations in DGs under unbalanced conditions.

Zhou et al. [12] proposed a secondary control scheme for networked MGs to restore the communication among interconnected MGs in case the central controller or the master controllers of the interconnected MGs fail. Du et al. [13] introduced a distributed secondary controller for network MGs, also employing smart switches, aiming to reduce the transient voltages during MGs reconfiguration. Similar approaches to achieving the seamless reconfiguration of MGs were also proposed in [14,15], using single- and three-phase mathematical formulations, respectively.

Additionally, resilient and fault-tolerant control methods have been developed to mitigate the impact of false data injection (FDI) attacks on secondary controllers, thereby enhancing systems' cyber resilience. Zhou et al. [16] analyzed the impacts of cyber-attacks on communication links, local controllers, and the master controller, as they can significantly disrupt the optimal operating conditions of MGs. In response, they propose a cyber-attack-resilient distributed control strategy that enables each participant detect and isolate corrupted links and controllers in timely and economical fashion. Their control strategy proves effective against time-varying attack signals and successive attacks, while preserving the operational merits of the MG. Researchers have also explored the consequences of denial-of-service (DoS) attacks on power systems and developed potential countermeasures. DoS attacks can severely disrupt operations by blocking data transmission among BESSs, compromising devices and jamming communication networks. Liu et al. [17] introduced a frequency control strategy for MGs that included an intrusion detector, enhancing the resilience of frequency control under DoS attacks. Ding et al. [18] addressed the challenge of implementing distributed resilient finite-time control for multiple heterogeneous battery energy storage systems within a microgrid, particularly for when they are subject to DoS attacks. To counteract these threats, they introduce a distributed secure control framework equipped with an acknowledgment (ACK)-based attack detection strategy and a communication recovery mechanism. This approach effectively mitigates the impact of DoS attacks by restoring the disrupted topology graphs to their original connected states. Wang et al. [19] developed a cyber-resilient control strategy for islanded MGs equipped with DGs and energy storage systems. This was designed to withstand hybrid cyber-attacks, including FDI and denial-of-service (DoS) attacks. This innovative approach leverages an adaptive method to mitigate the effects of bounded FDI attacks on secondary controllers while maintaining resilience to certain DoS attacks on communication links. The proposed control method effectively ensures frequency restoration, uniform power distribution, and an energy balance among DGs and ESSs, even during these complex hybrid attacks.

Despite their sophisticated contributions to several applications, none of the controllers in [7–19] handle the frequency problems occurring at the SMGs after unexpected network partitions in the event of faults. To the best of our knowledge, the consequences of unexpected MG partitions were studied for the first time by Rosero et al. in [20]. More specifically, Figure 6 of [20] clearly depicts the frequency and active power deviations in the split SMGs under unexpected electric and communication partitions of islanded

MGs. A similar finding was confirmed by Zhou et al., in Figure 11 of [21]. However, these studies did not propose any measures with which to address these issues. Later, in [22], Rosero et al. developed a secondary controller that operates without droop control but seamlessly transitions to droop mode upon detecting a partition. Despite this advancement, as highlighted in Section V.D of [22], the controller effectively addresses only the instabilities caused by communication failures and does not solve the frequency deviations resulting from electrical partitions, which remains a critical unresolved challenge. Table 1 summarizes the main contributions of all cited references, including the proposed method.

Table 1. Summary of literature advancements on secondary control.

Reference	Year	Advances in Secondary Control
[7]	2017	Treats disturbances and noises in the communication links between the DGs
[8]	2016	Improves the performance under conditions of communication delays
[9]	2021	Improves the performance during a fault in an electric network
[10]	2020	Treats actuation/propulsion faults and disturbances
[11]	2017	Minimization of active power and reactive power oscillations
[12]	2020	Treats failures of central and master controllers in interconnected microgrids
[13]	2019	Reduces the transient voltages during MG reconfiguration
[14]	2021	Reduces the transient voltages during MG reconfiguration
[15]	2023	Reduces the transient voltages during MG reconfiguration
[16]	2020	Treats FDI cyber-attacks on the communication links and controllers
[17]	2020	Treats DoS cyber-attacks on the communication links and controllers
[18]	2020	Treats DoS cyber-attacks on the communication links and controllers
[19]	2023	Treats FDI and DoS cyber-attacks on the communication links and controllers
[20]	2019	Studies the consequences of unexpected electrical and communication MG partitions
[21]	2020	Studies the consequences of unexpected electrical and communication MG partitions
[22]	2020	Improves the performance under unexpected communication MG partitions
Proposed	2024	Improves the performance under unexpected electrical MG partitions

1.2. Contribution of the Paper

This paper presents a robust centralized secondary controller designed to fill the gaps in existing research into secondary controllers, with respect to the frequency deviations caused in split SMGs after unexpected electrical MG partitions. In contrast to the existing literature, which presents frequency deviations in the range of several Hz, the proposed controller ensures rapid frequency restoration (in less than 5 s) and uniform power sharing among the DGs across all split SMGs. To clarify, with reference to the network depicted in Figure 1, after an electrical partition occurs, the proposed controller prompts DG 1 to restore the frequency of SMG 1 to 50 Hz, while doing the same for SMG 2 via the control of DG 2 and DG 3. Moreover, DG 2 and DG 3 maintain uniform power sharing throughout the electrical partition. Conversely, it is shown through simulation results that the traditional centralized and consensus-based secondary controllers present considerable frequency deviations from the nominal level in one of the two split SMGs. These features make the proposed controller an excellent tool for MGs experiencing frequent unexpected partitions, ensuring continuous and high-quality supply to all consumers. Beyond its primary benefit of maintaining the nominal frequency of all SMGs during unexpected electrical partitions, the proposed controller offers additional advantages, including:

- ✓ Easy implementation to real microgrids. The controller is designed using straightforward digital equations, as detailed in Section 3, making it compatible with widely used commercial digital signal processors (DSPs). This compatibility ensures that the

proposed control algorithm can be easily adapted and utilized within microgrid central controllers (MGCCs) in centralized infrastructure. Moreover, the simplicity of its design facilitates quick deployment and integration, minimizing potential disruptions and the need for extensive training or system modifications.

- ✓ Low communication requirements. The proposed controller does not require any communication with the protective devices of the MG, thus reducing the complexity of the overall installation. The only communication infrastructure required is between the MGCC and the DGs of the microgrid.
- ✓ Topology-independent implementation. The controller is designed to deliver consistent performance without the need for recalibration following network reconfigurations or load changes. It is initially set up based on the number of DGs and maintains its calibration permanently. This one-time setup ensures that the controller can seamlessly adapt to varying operational conditions without additional intervention, simplifying the management of the system.

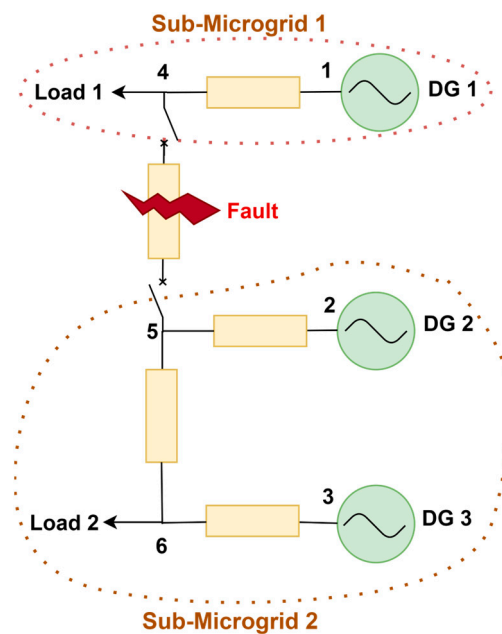


Figure 1. Example 6—bus islanded MG with 3 DGs and 2 loads.

The rest of the paper is structured as follows: Section 2 reviews the traditional secondary controllers. Section 3 describes the proposed controller. Section 4 presents the simulation results, while Section 5 concludes the paper.

2. Review of Traditional Secondary Controllers

Practically, the scope of secondary control is to optimally calculate the terms $u_{p(i)}$ and $u_{q(i)}$ of the droop equations of the primary layer, given in (1)–(2), in order to restore the frequency and voltage of an MG.

$$\omega_i = \omega_{ref(i)} - K_{P(i)} \cdot P_{G(i)} + u_{p(i)} \quad (1)$$

$$V_i = V_{ref(i)} - K_{Q(i)} \cdot Q_{G(i)} + u_{q(i)} \quad (2)$$

Note that, in the equations above, ω_i , $\omega_{ref(i)}$, $K_{P(i)}$, $P_{G(i)}$, V_i , $V_{ref(i)}$, $K_{Q(i)}$ and $Q_{G(i)}$ are the angular frequency measured by DG i , reference angular frequency of DG i , frequency droop gain, positive sequence active power output, positive sequence voltage magnitude, reference voltage, voltage droop gain, and positive sequence reactive power output of DG i , respectively.

Each secondary control scheme employs a different methodology to compute $u_{p(i)}$ and $u_{q(i)}$, as explained below. To facilitate explanation, let us first assume utilization of the

islanded MG of Figure 1. The communication structure of the two major schemes is shown in Figure 2.

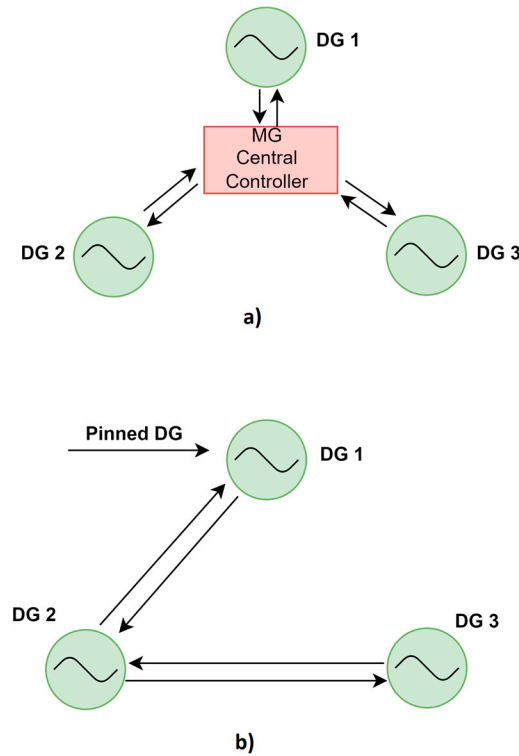


Figure 2. Communication graphs of the 6-bus MG. From top to bottom (a): centralized control; (b): consensus (distributed) control.

The communication structure of a centralized controller, shown in Figure 2a [2,3], is based on a kind of one-to-all communication, where a microgrid central controller (MGCC) measures the voltage and frequency at a specific point of the network and restores them using simple PI controllers. The terms $u_{p(i)}$ and $u_{q(i)}$, shown in (1) and (2), are calculated from the MGCC as follows $\forall i \in \{1, 2, 3\}$:

$$u_{p(i)} = K_{p,pro}^{gain} \cdot (\omega_{set} - \omega_{MGCC}) + K_{p,int}^{gain} \cdot \int (\omega_{set} - \omega_{MGCC}) \quad (3)$$

$$u_{q(i)} = K_{q,pro}^{gain} \cdot (V_{set} - V_{MGCC}) + K_{q,int}^{gain} \cdot \int (V_{set} - V_{MGCC}) \quad (4)$$

where $K_{p,pro}^{gain}$, $K_{p,int}^{gain}$, $K_{q,pro}^{gain}$, and $K_{q,int}^{gain}$ are the proportional and integral gains of the PI controllers, ω_{MGCC} and V_{MGCC} are the angular frequency and voltage measured by the MGCC, and ω_{set} and V_{set} are the desirable frequency and voltage values. It is shown in (3)–(4) that all DGs receive the same $u_{p(i)}$, $u_{q(i)}$ values from the MGCC, and thus they shift their droop equations equally, thus preserving the desired power sharing.

In the consensus control, DGs only communicate with some neighboring DGs [4,5], yielding a type of neighbor-to-neighbor communication. In consensus algorithms, the frequency controller performs, simultaneously, frequency restoration and active power sharing between the DGs, while the voltage controller executes voltage restoration or reactive power sharing. The mathematical expression of the frequency controller is quoted in (5) $\forall i \in \{1, 2, 3\}$, where g_i determines the access of DG i to the desired frequency (ω_{set})

and β_{ij} depends on the connectivity between DG i and j . If DG i communicates directly with DG j , then $\beta_{ij} \neq 0$; otherwise, it is zero.

$$u_{p(i)} = K_{p,int(i)}^{gain} \cdot \int \left(g_i \cdot (\omega_{set} - \omega_i) + \sum_{j=1}^{N_{dg}} \beta_{ij} \cdot (u_{p(j)} - u_{p(i)}) \right) \quad (5)$$

The mathematical formulation of the voltage controller is expressed by (6) $\forall i \in \{1,2,3\}$, where the parameters h_i and r_{ij} vary depending on whether the controller performs voltage regulation ($h_i \neq 0, r_{ij} = 0$) or optimal reactive power sharing ($h_i = 0, r_{ij} \neq 0$). For more details, please refer to ([5], Section IV.C).

$$u_{q(i)} = K_{q,int(i)}^{gain} \cdot \int \left(h_i \cdot (V_{set(i)} - V_i) + \sum_{j=1}^{N_{dg}} r_{ij} \cdot (K_{Q(j)} \cdot Q_{G(j)} - K_{Q(i)} \cdot Q_{G(i)}) \right) \quad (6)$$

Despite the benefits that each of the aforementioned controllers possesses, they all have an important drawback: they lose their ability to restore the frequency in split SMGs under unexpected electrical partitioning. For example, let us assume that a fault happens in line 4–5 of the MG of Figure 1. The protective devices of the line are likely to switch the line off, thus unexpectedly forming two sub-microgrids (SMGs). The first consists of DG 1 and load 1, while the second includes DG 2, DG 3, and load 2. Since the controllers of either scheme cannot see the tripping of the line 4–5, they will continue to apply the same $u_{p(i)}$ to all DGs, as dictated by (3), (5), even though the partitioning of the MG results in the newly formed SMGs supporting different load levels. This discrepancy leads to frequency deviations in one of the two SMGs.

3. Proposed Centralized Secondary Controller

For the sake of clarity, the proposed controller will be explained using the simple network in Figure 1; however, it is scalable and can be extended to larger MGs as well. Its communication graph is quoted in Figure 3, depicting all transmitting signals for the frequency restoration from and to the MGCC. Each DG $i \in \{1, 2, 3\}$ operates in droop control (primary layer), represented by (1)–(2). The MGCC receives the frequency signals (ω_i) from DGs and updates the droop equations via output signals $u_{p(i)}$.

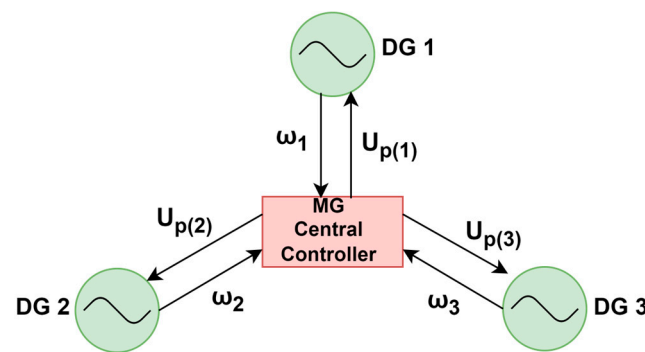
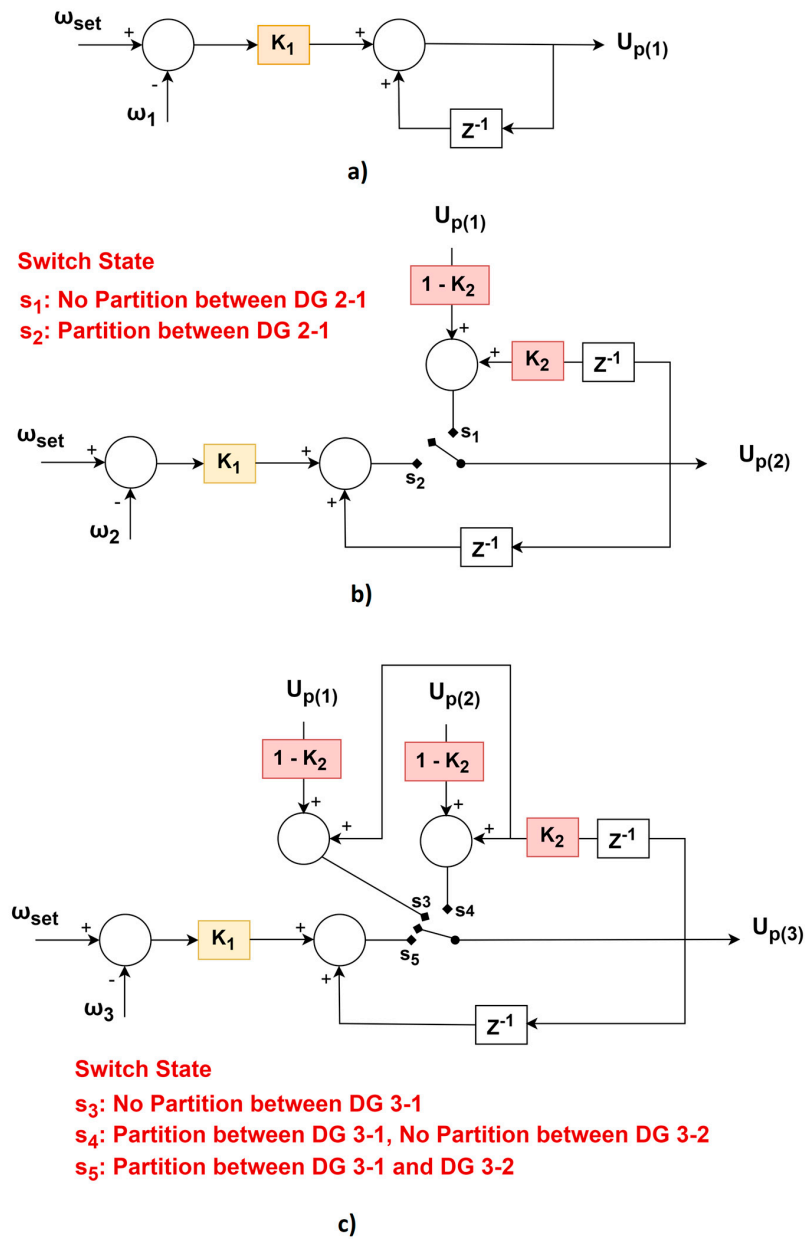


Figure 3. Communication graph of the proposed centralized secondary controller.

The block diagram of the proposed controller (given in Z domain) is depicted in Figure 4. The controller is installed within the MGCC and has a centralized structure. The $u_{p(1)}$ (namely, the secondary signal of DG 1) is computed in a similar manner to that employed the conventional centralized control, as shown in (7):

$$u_{p(1)}^t = u_{p(1)}^{t-1} + K_1 \cdot (\omega_{set} - \omega_1^t) \quad (7)$$

where $u_{p(1)}^t$ denotes the $u_{p(1)}$ at the present time instant t , $u_{p(1)}^{t-1}$ at the previous time instant $t - 1$, ω_{set} is the desirable value of angular frequency (e.g., $2 \cdot \pi \cdot 50$ rads/s), and K_1 is the gain. Equation (7) represents a typical digital PI controller.



Conditions of Switch States	
s_1	$H(0.001 - \omega_1^t - \omega_2^t) = 1$
s_2	$H(\omega_1^t - \omega_2^t - 0.001) = 1$
s_3	$H(0.001 - \omega_1^t - \omega_3^t) = 1$
s_4	$H(\omega_1^t - \omega_3^t - 0.001) H(0.001 - \omega_2^t - \omega_3^t) = 1$
s_5	$H(\omega_1^t - \omega_3^t - 0.001) H(\omega_2^t - \omega_3^t - 0.001) = 1$

Figure 4. Block diagram of proposed secondary controller. From top to bottom: calculation of (a) $u_{p(1)}$, (b) $u_{p(2)}$, and (c) $u_{p(3)}$. State of switches (s_1 – s_5) is determined based on frequencies of DGs, according to conditions of table.

The contribution of our paper lies in the novel approach to the calculation of $u_{p(2)}$ and $u_{p(3)}$ (namely, the secondary signal of DG 2 and 3). Specifically, $u_{p(2)}$ and $u_{p(3)}$ are obtained in the manner shown in (8) and (9), respectively.

$$u_{p(2)}^t = H(0.001 - |\omega_1^t - \omega_2^t|) \cdot (K_2 \cdot u_{p(2)}^{t-1} + (1 - K_2) \cdot u_{p(1)}^t) + H(|\omega_1^t - \omega_2^t| - 0.001) \cdot (u_{p(2)}^{t-1} + K_1 \cdot (\omega_{set} - \omega_2^t)) \quad (8)$$

$$u_{p(3)}^t = H(0.001 - |\omega_1^t - \omega_3^t|) \cdot (K_2 \cdot u_{p(3)}^{t-1} + (1 - K_2) \cdot u_{p(1)}^t) + H(|\omega_1^t - \omega_3^t| - 0.001) \cdot H(0.001 - |\omega_2^t - \omega_3^t|) \cdot (K_2 \cdot u_{p(3)}^{t-1} + (1 - K_2) \cdot u_{p(2)}^t) + H(|\omega_1^t - \omega_3^t| - 0.001) \cdot H(|\omega_2^t - \omega_3^t| - 0.001) \cdot (u_{p(3)}^{t-1} + K_1 \cdot (\omega_{set} - \omega_3^t)) \quad (9)$$

It is noted that in (8)–(9) the function H denotes the Heaviside function, as follows,

$$H(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases} \quad (10)$$

while K_1 and K_2 are algorithm gains. The term $H(|\omega_i - \omega_j| - 0.001)$, as applied in Equations (8)–(9), signifies a criterion for identifying a potential electrical partition between DG i and j . Specifically, the condition $|\omega_i - \omega_j| > 0.001$ holds if DG i and j are electrically isolated. The threshold value of 0.001 is chosen arbitrarily. Practically, the detection of unexpected electrical partitions is realized by comparing the frequencies of DGs within the Heaviside functions H of Equations (8) and (9). If the difference between the frequencies of DG i and j surpasses a certain threshold (arbitrarily set to be equal to 0.001 in this paper), it means that the respective DGs are electrically split, potentially due to a fault. This occurs as the frequencies of the split MGs inherently deviate from each other due to their different load conditions. Subsequently, the proposed algorithm modifies the $u_{p(i)} = u_{p(j)}$ signals accordingly to restore the frequency of all sub-microgrids, while maintaining equal power sharing between the DGs within each sub-microgrid.

For example, with reference to Figure 1, due to the MG partition, $H(|\omega_1^t - \omega_2^t| - 0.001) = 1$, indicating the presence of an electrical partition between DG 2 and 1, since $\omega_1^t \neq \omega_3^t$. Consequently, the control strategy for DG 2 transitions to $u_{p(2)}^t = (u_{p(2)}^{t-1} + K_1 \cdot (\omega_{set} - \omega_2^t))$, yielding a decentralized (local) integral controller for this DG. At the same time, $H(|\omega_1^t - \omega_3^t| - 0.001) = 1$ and $H(0.001 - |\omega_2^t - \omega_3^t|) = 1$ indicate that there is an electric partition between DG 3 and 1 and no partition between DG 3 and 2, respectively. As a result, according to Equation (9), $u_{p(3)}^t = K_2 \cdot u_{p(3)}^{t-1} + (1 - K_2) \cdot u_{p(2)}^t$, resulting in DG 3 following the secondary signal of DG 2.

The block diagram illustrating the secondary control signals $u_{p(i)} \forall i \in \{1, 2, 3\}$ is quoted in Figure 4. The positions of these switches ($s_1, \dots, s_5$) are determined by the frequencies of the DGs, as outlined in the conditions listed in the table at the bottom of Figure 4. Mathematically, these conditions are represented using Heaviside functions and are comprehensively integrated into Equations (8) and (9), as explained above. An interpretation of Figure 4 is quoted in Figure 5 in the form of a flowchart.

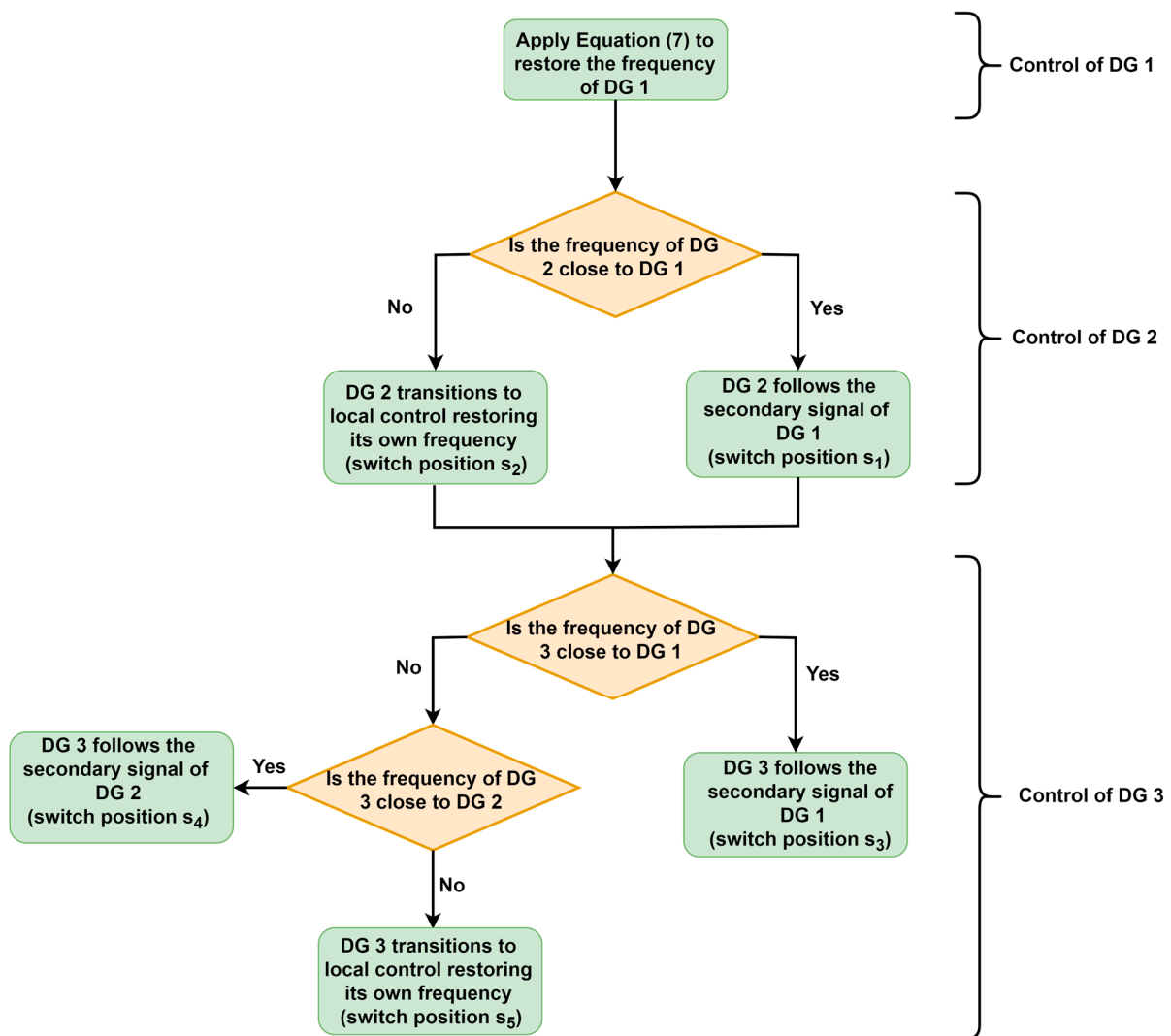


Figure 5. Flowchart of the proposed secondary controller for the reference network.

4. Simulation Results

To validate the proposed controller, simulations were performed in MATLAB/Simulink 2019, using a 6-bus and 13-bus network. Moreover, a comparison against the state-of-the-art secondary controllers [2–6] is carried out through further simulations to highlight the superior characteristics of the proposed controller in restoring the frequency of all split SMGs under partitions.

4.1. Low-Voltage 6-Bus Network

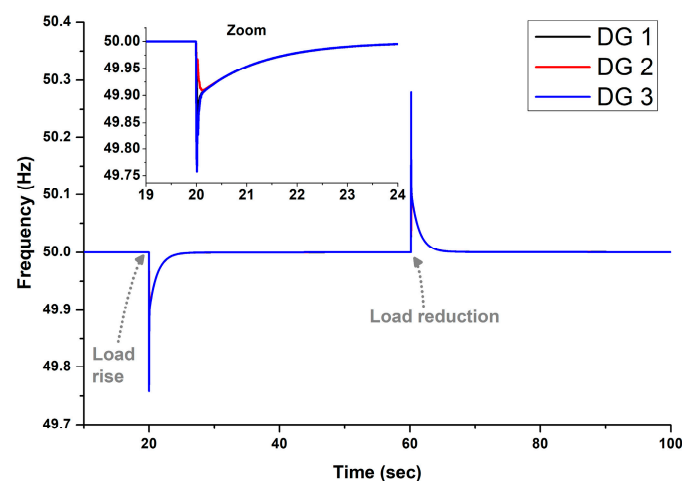
The structure of the 6-bus network is illustrated in Figure 1, with the network parameters listed in Table 2. The following two Simulink test cases were studied:

- Test 1: Load 2 is doubled at $t = 20$ s and returned to its initial value at $t = 60$ s, with no microgrid (MG) partition occurring.
- Test 2: A fault is introduced at $t = 20$ s in the line between buses 4 and 5. The protective devices respond to clear the fault, resulting in the temporary formation of two sub-microgrids [23], as depicted in Figure 1. The fault is resolved at the $t = 40$ s, and the line is reconnected.

Table 2. Parameters of the 6-bus network.

Resistance of the lines	0.25 Ω /km
Self-reactance of the lines	0.6 mH/km [2]
Mutual-reactance of the lines	0.1 mH/km [2]
Line lengths	0.1 km [2]
Lines' thermal limits	Neglected [2]
Loads (modeled as constant impedances)	Load 1: $R//L = 0.1 \Omega//0.001 \text{ H}$ Load 2: $R//L = 0.2 \Omega//0.002 \text{ H}$
$K_{P(i)} \ (i = 1, 3)$	$1 \times 10^{-6} \text{ (Hz/W)}$
$K_{P(i)} \ (i = 2)$	$0.5 \times 10^{-6} \text{ (Hz/W)}$
$K_{Q(i)} \ (i = 1, 2, 3)$	$2 \times 10^{-4} \text{ (V/VAR)}$
Primary droop $V_{ref(i)} \ (i = 1, 2, 3)$	270 V
Primary droop $f_{ref(i)} \ (i = 1, 2, 3)$	50 Hz
Ground resistances	25 Ω [2]

The results of Test 1 are presented in Figures 6–8. Specifically, Figure 6 displays the frequencies of the DGs using the proposed controller, demonstrating its capability to quickly restore frequency after each load change. Figure 7 illustrates the output signals of the controller, as calculated by Equations (7)–(9), which dynamically adapt to aid in frequency restoration. All DGs have the same secondary control signals. Finally, Figure 8 shows the output powers of the DGs. According to Table 2, the droop gain $K_{P(2)} = 0.5 \cdot K_{P(i)}$ for $i = \{1, 3\}$; thus, DG 2 contributes twice the power compared to DG 1 and DG 3.

**Figure 6.** DG frequencies for Test 1, determined using the proposed controller.

The results of Test 2 are quoted in Figures 9–11. As shown in Figure 9, despite the partition of the MG into two sub-microgrids at $t = 20 \text{ s}$, the frequency is restored in both SMGs in around 5 s. After the re-unification, the frequency is again restored to 50 Hz. The output signals of the controller for the second test are quoted in Figure 10. Due to the partition of the MG, the secondary control signal of DG 1 differs from those of DG 2 and 3. The reason for this is that, during the partition, DG 1 solely undertakes Load 1, forcing its frequency to be reduced. Consequently, a stronger secondary signal is required to restore the frequency in SMG 1. Lastly, Figure 11 displays the output powers of the DGs during the second test. Notably, DG 1 outputs the highest power during the partition as it solely supplies the entire Load 1. Following reunification, DG 2 exhibits the highest power output due to its lower droop gain $K_{P(2)}$.

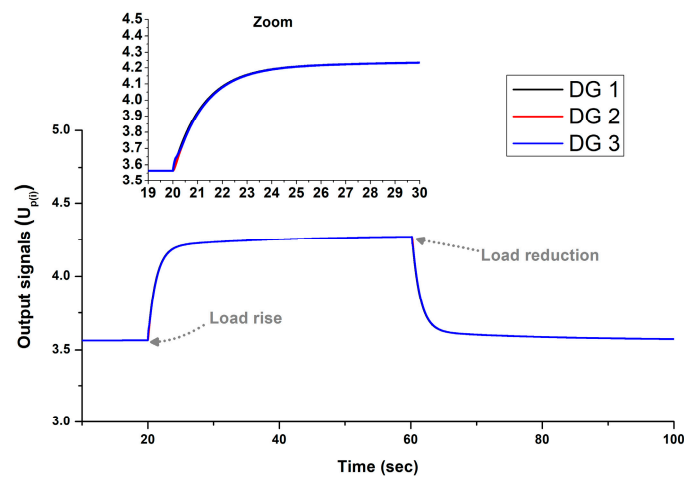


Figure 7. Output signals of the proposed controller for Test 1.

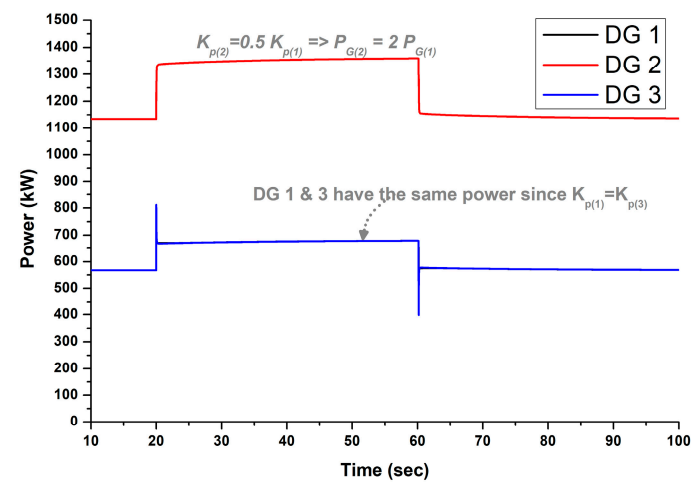


Figure 8. Power of DGs for Test 1 using the proposed controller.

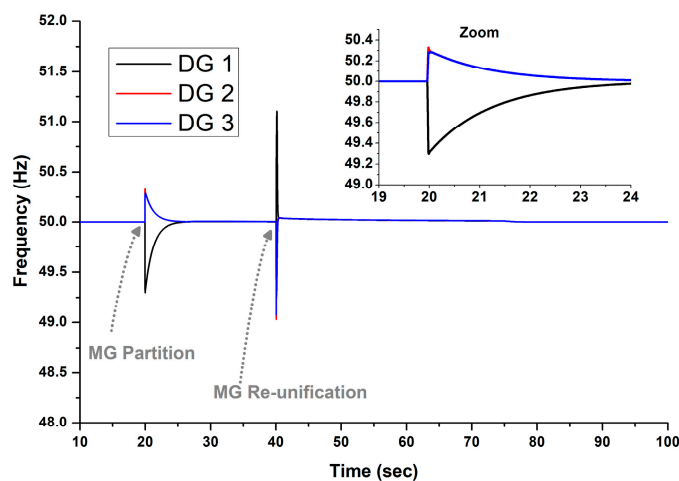


Figure 9. DG frequencies for Test 2, determined using the proposed controller.

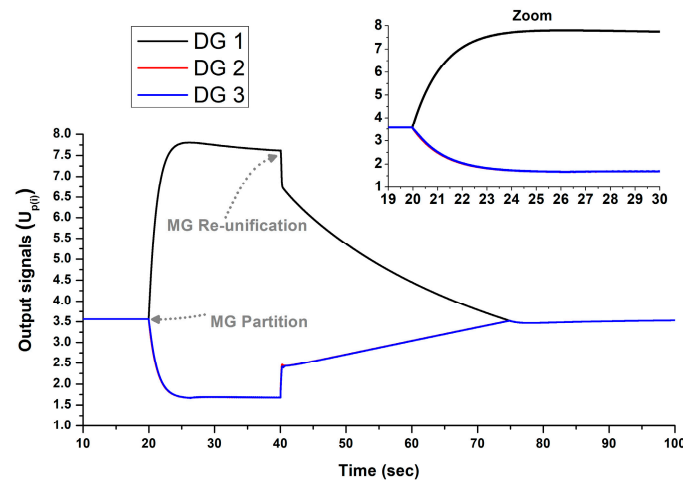


Figure 10. Output signals of the proposed controller for Test 2.

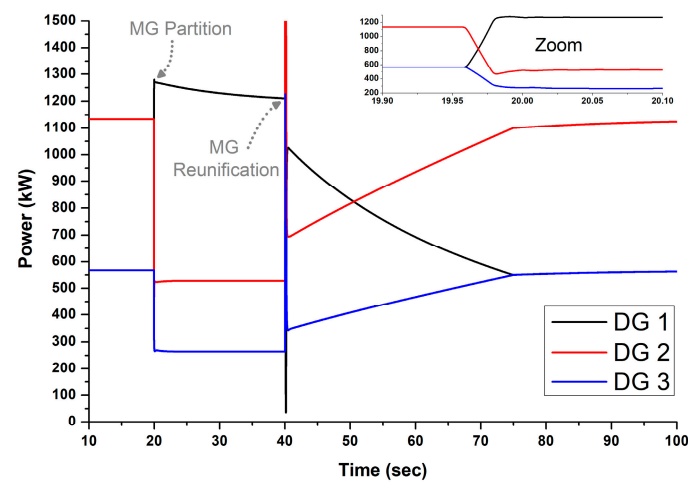


Figure 11. Power of DGs for Test 2, determined using the proposed controller.

4.2. Medium-Voltage 13-bus Network

Test 3 employs the 12-bus medium-voltage MG shown in Figure 12, employing the network parameters detailed in Table 3. All DGs are assumed to be of the same size, having equal $K_{P(i)}$ gains. A fault is presumed to occur between buses 4 and 9 at $t = 20$ s, leading to the activation of protective devices and splitting the MG into two sub-microgrids (SMGs): DGs 1, 2, and 3 and DGs 4 and 5, respectively. The fault is cleared at $t = 40$ s, resulting in the reunification of the MG. In this test, the performance of the proposed secondary controller is evaluated against the typical centralized controller [2,3], as described in Equations (3) and (4), and the consensus controller [4,5], specified in Equations (5) and (6).

The results of the proposed controller are presented in Figures 13–15, in comparison to those of the typical centralized controller [2,3], shown in Figures 16–18, and the consensus controller [4–6], shown in Figures 19–21. Specifically, Figure 13 shows the frequency restoration of all DGs during the partition and after the reunification of the MG. Despite the partition, the frequency is successfully restored to 50 Hz during both phases, showcasing the proposed controller's ability to detect the split and assign distinct secondary control signals to each DG. Figure 14 displays the output signals, highlighting the differential secondary control signals received by DGs 1–3 compared to DGs 4–5, reflecting their different load challenges. After reunification, all DGs receive the same secondary signals to equally distribute the overall load of the MG. Figure 15 illustrates the active power outputs of the DGs, showing that during the partition, DGs 1–3 maintain an equal loading that is lower than that of DGs 4–5.

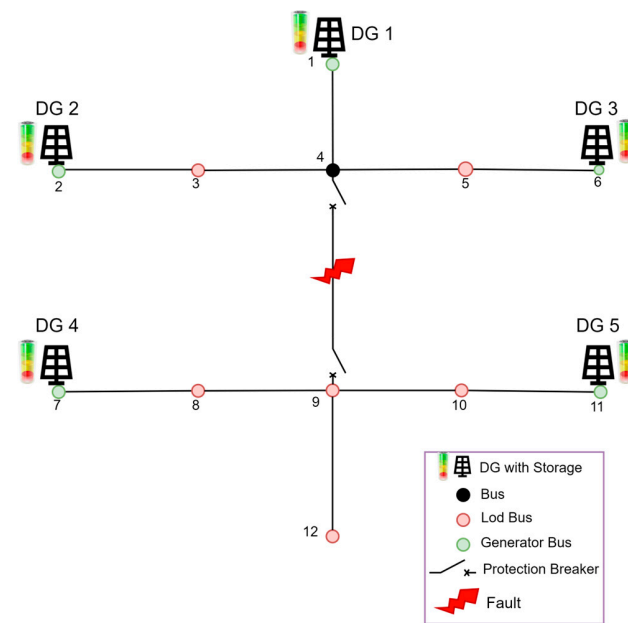


Figure 12. Examined 12-bus medium-voltage islanded microgrid, consisting of 5 droop-controlled DGs.

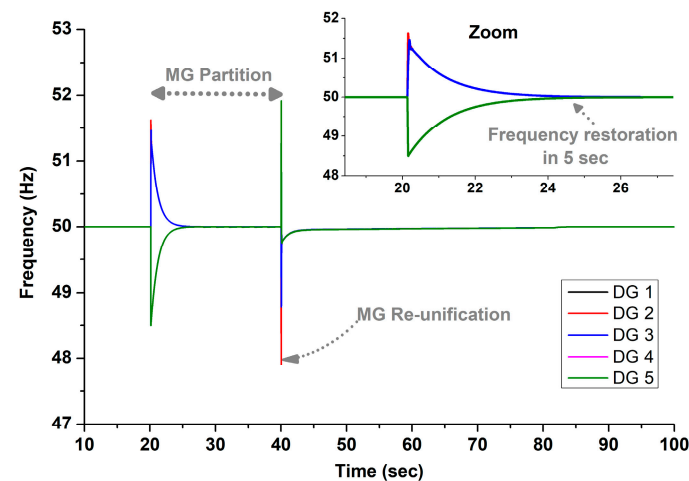


Figure 13. DG frequencies for Test 3, determined using the proposed controller.

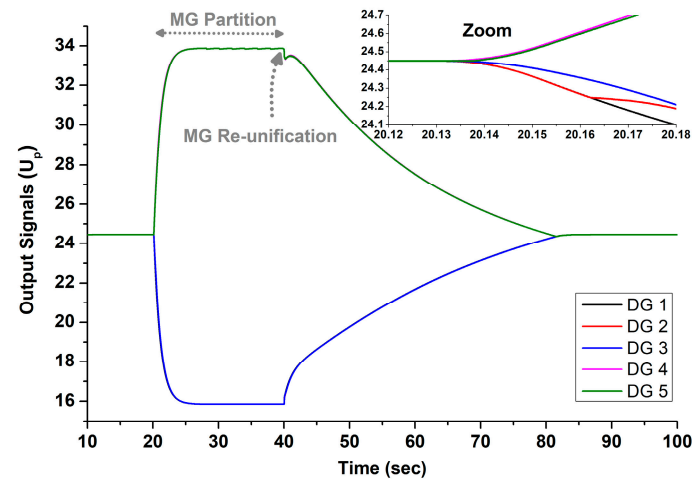


Figure 14. Output signals of the proposed controller for Test 3.

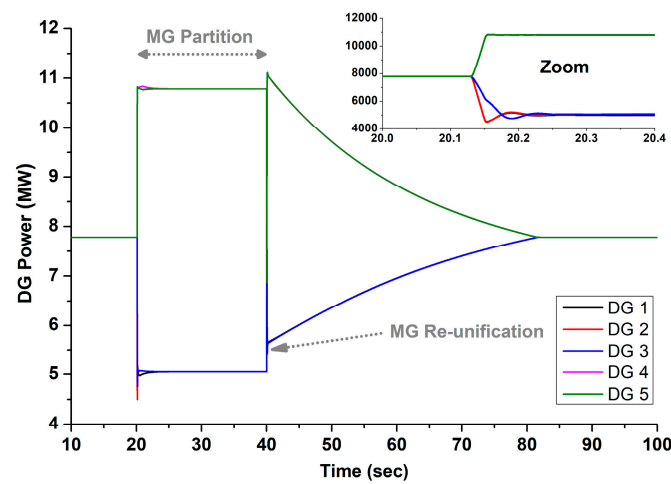


Figure 15. Power of DGs for Test 3, determined using the proposed controller.

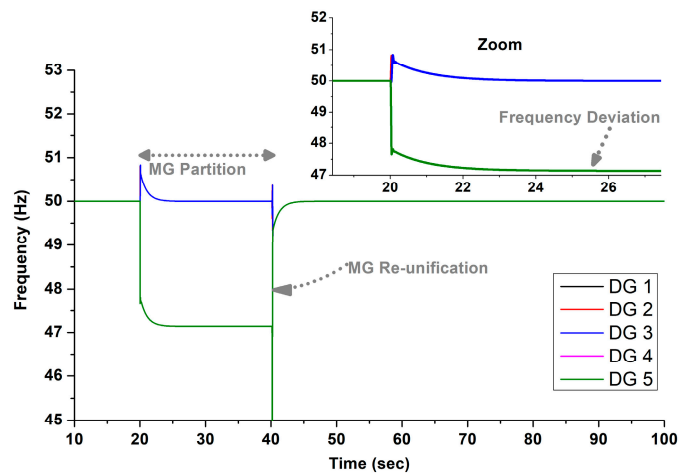


Figure 16. DG frequencies for Test 3, determined using the typical centralized controller [2,3].

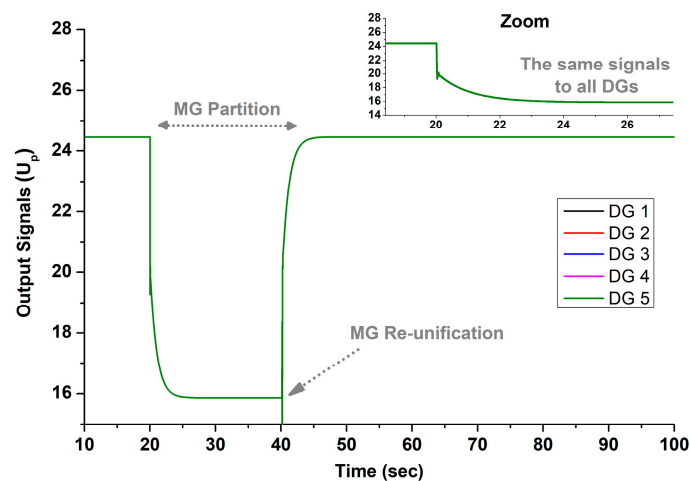


Figure 17. Output signals of the typical centralized controller for Test 3 [2,3].

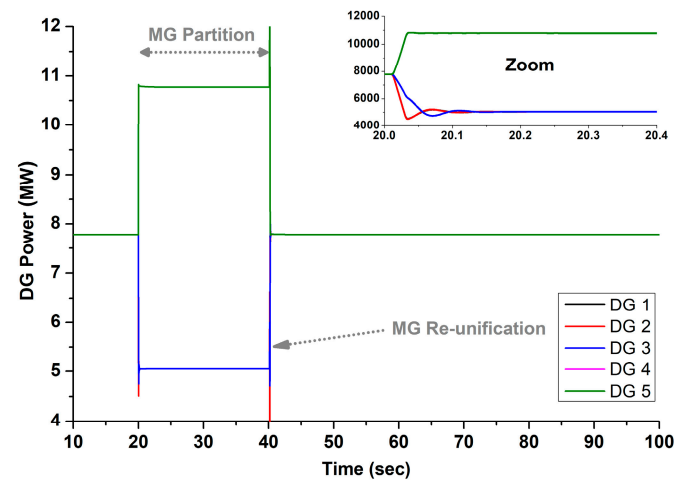


Figure 18. Power of DGs for Test 3, determined using the typical centralized controller [2,3].

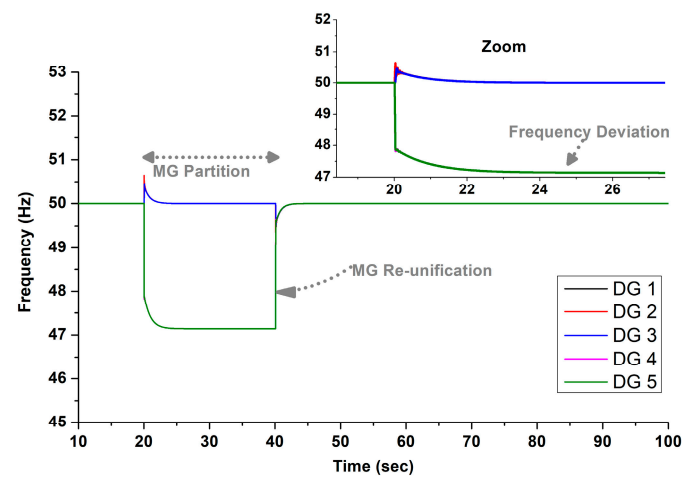


Figure 19. DG frequencies for Test 3, determined using the typical consensus controller [4–6].

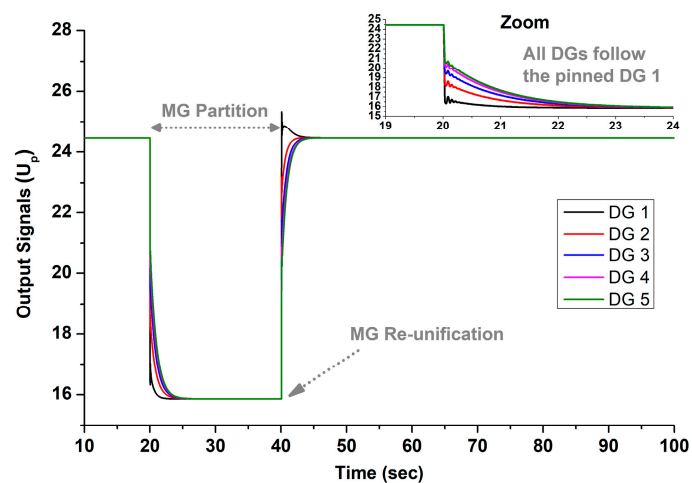


Figure 20. Output signals of the typical consensus controller for Test 3 [4–6].

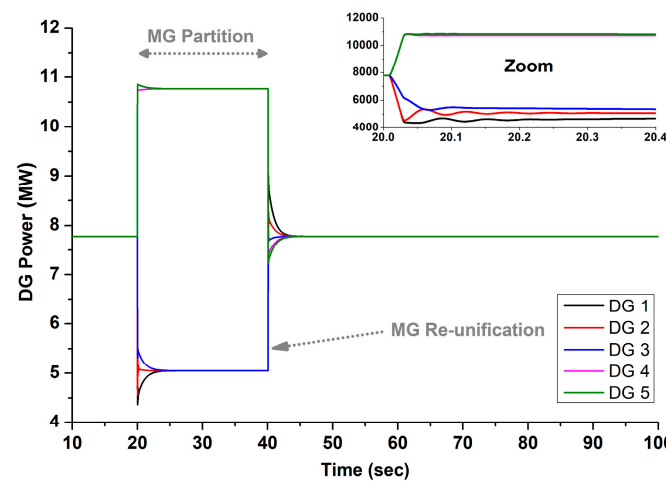


Figure 21. Power of DGs for Test 3, determined using the typical consensus controller [4–6].

Figure 16 depicts the frequency behavior of the typical centralized controller, highlighting significant deviations in the second SMG during the partition. Specifically, the frequency drops as low as 47 Hz and fails to recover. Such a low frequency may trigger protective load shedding in the MG [24] or even cascading outages among the DGs, posing a risk to the overall network stability. This underfrequency event occurs because the standard secondary controller does not recognize MG partitions and continues to send uniform secondary control signals to all DGs, as shown in Figure 17, regardless of their individual loads. As a result, the group of DGs 4–5, which bear a higher load during the partition, experiences underfrequency issues.

Table 3. Parameters of the 13-bus network [25].

Resistance of the lines	0.25 Ω /km
Self-reactance of the lines	1 mH/km
Mutual-reactance of the lines	0.1 mH/km
Line lengths	10 km
Lines' thermal limits	Neglected
Loads (modeled as constant impedances)	R/ /L = 20 Ω / /0.25 H
$K_{P(i)}$ ($i = 1, 2, 3, 4, 5$)	5×10^{-7} (Hz/W)
$K_{Q(i)}$ ($i = 1, 2, 3, 4, 5$)	2×10^{-5} (V/VAR)
Primary droop $V_{ref(i)}$ ($i = 1, 2, 3, 4, 5$)	7600 V
Primary droop $f_{ref(i)}$ ($i = 1, 2, 3, 4, 5$)	50 Hz
Ground resistances	25 Ω

Finally, Figures 19–21 present the outcomes from the consensus controller. It is important to note that only DG 1 has access to the reference frequency value, acting as the pinned DG (e.g., $g_1 \neq 0$) [2]. As depicted in Figure 19, the group of DGs 4–5 experiences underfrequency conditions during the partition, similar to what is observed with the typical centralized controller. This occurs because, as specified in Equation (5), all DGs aim to align their secondary control signals with that of the pinned DG ($u_{p(1)}$), as clearly illustrated in Figure 20. As a result, during the partition, both groups of DGs display identical secondary control signals, even though DGs 4–5 are under higher loads, as evidenced in Figure 21. Consequently, the frequency drops as low as 47 Hz, jeopardizing overall MG stability.

Finally, Figure 22 illustrates the performance of the proposed controller after a topology change, specifically after the outage of DG 2. As shown, the proposed controller has the capability to restore the frequency in both split sub-microgrids, without any modification

of the controller, even after the topology changes. This robust capability highlights a key advantage of the proposed system, which is designed to deliver consistent performances and does not require recalibration after network reconfigurations. This one-time initial setup guarantees that the controller can smoothly adjust to diverse operational conditions autonomously, thereby simplifying the management of the system.

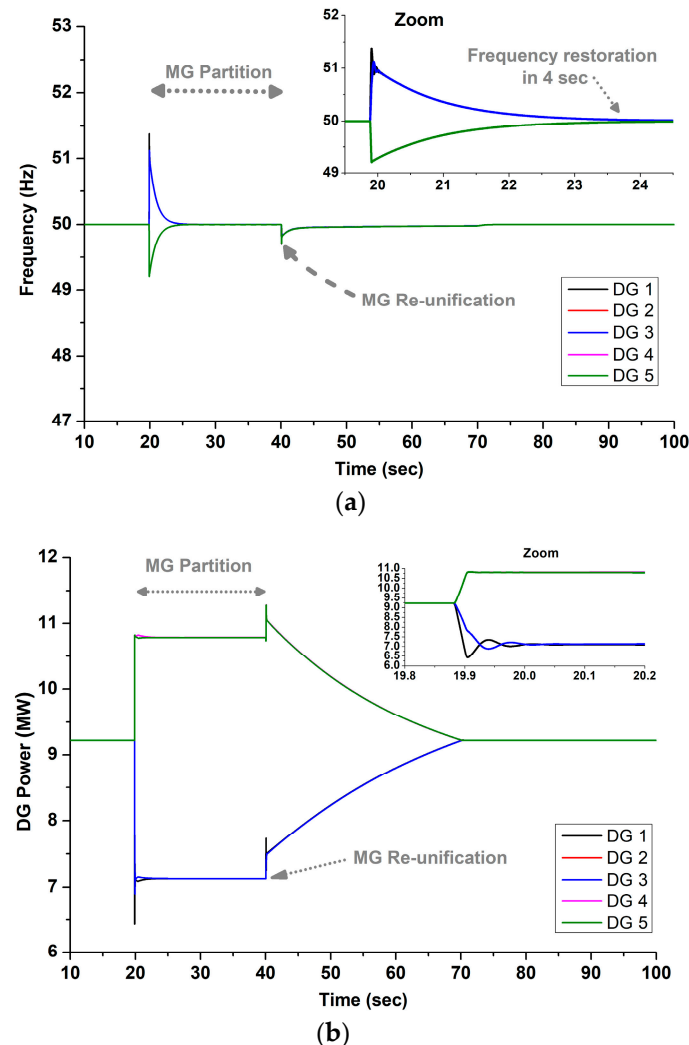


Figure 22. Repetition of Test 3 for the proposed controller, assuming that DG 2 is out of service: (a) DG frequencies, (b) active power of DGs.

5. Conclusions

This paper introduces a fault-tolerant centralized secondary controller designed for inverter-based, islanded microgrids. This controller enhances system resilience to unexpected network partitions, which typically occur due to the tripping of protective devices under fault conditions. Typically, MGs have a radial configuration where a fault in any line prompts protective devices to isolate the affected line, consequently dividing the MG into two electrically independent sub-microgrids (SMGs) while preserving the existing communication and control framework. Unlike traditional secondary controllers, whether centralized or distributed, which fail to normalize frequency in one of the two SMGs following a sudden network split, the proposed controller demonstrates remarkable capabilities. Simulation studies conducted on 6-bus and 13-bus islanded MG setups reveal that, in contrast to conventional controllers, the controller not only swiftly re-establishes the nominal frequency in both SMGs within 5 s but also ensures uniform power distribution among the

distributed generators (DGs) serving the SMGs. This quick frequency restoration validates the controller's efficiency in maintaining stable frequency levels immediately after a fault.

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Nomenclature

ω_i	Angular frequency of DG i
$\omega_{ref(i)}$	Reference frequency of DG i
$K_{P(i)}$	Frequency droop gain of DG i
$P_{G(i)}$	Active power of DG i
$u_{p(i)}$	Secondary control signal of the frequency control for DG i
V_i	Positive-sequence voltage of DG i
$V_{ref(i)}$	Reference voltage of DG i
$K_{Q(i)}$	Voltage droop gain of DG i
$Q_{G(i)}$	Reactive power of DG i
$u_{q(i)}$	Secondary control signal of the voltage control for DG i
$K_{p,pro}^{gain}$	Proportional gain of secondary frequency controller
$K_{p,int}^{gain}$	Integral gain of secondary frequency controller
$K_{q,pro}^{gain}$	Proportional gain of secondary voltage controller
$K_{q,int}^{gain}$	Integral gain of secondary voltage controller
ω_{MGCC}	Angular frequency measured by the microgrid central controller (MGCC)
V_{MGCC}	Voltage measured by the MGCC
ω_{set}	Desirable angular frequency, i.e., $2\pi \cdot 50$ rads/sec
V_{set}	Desirable voltage, i.e., 230 V
$u_{p(i)}^t$	Secondary control signal of the proposed method, for DG i , at time instant t
ω_i^t	Angular frequency of DG i at time instant t

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