

Enhancing voltage profile in islanded microgrids through hierarchical control strategies

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ABSTRACT

This paper presents a novel approach aimed at enhancing the voltage profile of an islanded microgrid (MG) through the utilization of Phasor Measurement Units (PMUs) and a hierarchical control system for Distributed Generators (DGs). Recognizing the criticality of maintaining an optimal voltage profile for essential loads within an MG, we assume that PMUs are strategically placed across the MG based on existing placement methodologies to ensure the observability of load buses. The synchrophasor measurements captured by these PMUs are leveraged within an offline-designed tertiary control layer of the hierarchical framework, which in turn sets the voltage reference for the secondary control layer of DGs across the MG. This approach effectively enhances the voltage profile of vital load buses within the MG. The proposed hierarchical strategy encompasses primary, secondary, and tertiary levels of control, responsible for stabilizing voltage and frequency, computing power references, and managing power flow, respectively. PMU measurements play a crucial role in the secondary control level by continuously monitoring deviations. By ensuring the effective placement of PMUs, the proposed framework enables efficient control, leading to notable improvements in the voltage profile and power management. To evaluate the effectiveness of our approach, five test networks were used: 14-bus, 30-bus, 39-bus, 57-bus, and 118-bus test networks. Simulation results demonstrate an impressive over 80 % enhancement in the MG's voltage profile achieved by our proposed method. Additionally, our heuristic strategy efficiently assigns the closest load bus to each DG while aggregating equidistant bus deviations. Collectively, our research underscores the significant impact of PMU measurements and a well-structured hierarchical voltage control system in substantially improving the voltage profile of MGs.

1. Introduction

MGs utilize DGs and storage to supply dependable energy to specific locations, operating either in grid-connected or islanded mode [1]. Sophisticated hierarchical control strategies are necessitated to ensure stability and reliability [2]. PMUs enhance MG monitoring and controllability by providing synchrophasor data for real-time situational awareness. This data is leveraged in numerous applications like fault and islanding detection, and system restoration [3]. Specifically, PMU voltage, frequency, and phase angle measurements enable detecting deviations from optimal voltage profiles, allowing secondary controllers

to optimize system operation [4].

A significant amount of research has been conducted on the optimal PMU placement (OPP) problem considering different aspects of the problem including but not limited to fundamental state observability analysis such as numerical and topological observability analysis [5], addressing practical constraints like N-1 contingencies [6], the extension of the OPP problem to consider various PMU applications such as fault location [7,8], and development of exact methods to solve the linear mathematical formulation of the OPP problem [9]. The optimal placement of PMUs and the observability analysis discussed in the literature have significant implications for the hierarchical control of MGs. By leveraging the real-time measurements provided by PMUs,

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Nomenclature			
k_p	Proportional control gain	ω_{MG}^*	Reference MG frequency
k_i	Integral control gain	$\Delta E(S)$	Laplace transformation of voltage compensation
V_i	Voltage phasor of bus i obtained by PMUs	\hat{V}_i	Voltage phasor at bus i
V^{rated}	Rated voltage phasor of MG	$\hat{\theta}_j$	j^{th} measurement obtained from PMUs
ΔV_i	Deviation of voltage phasor of bus i from the rated voltage phasor	H	The measurement Jacobian matrix
δV_i	Output of PI controller in islanded tertiary control	MG	Microgrid
E_i^*	Output of islanded tertiary control for bus i as the reference of secondary control	PMU	Phasor Measurement Units
E_{MG}	Actual reference MG voltage magnitude	DG	Distributed Generators
E_{MG}^*	Reference MG voltage magnitude	WAMS	Wide Area Management System
ω_{MG}	Actual MG frequency	OPP	Optimal PMU placement
		VSG	Virtual Synchronous Generators
		VSC	Voltage source converter
		PI	Proportional-integral

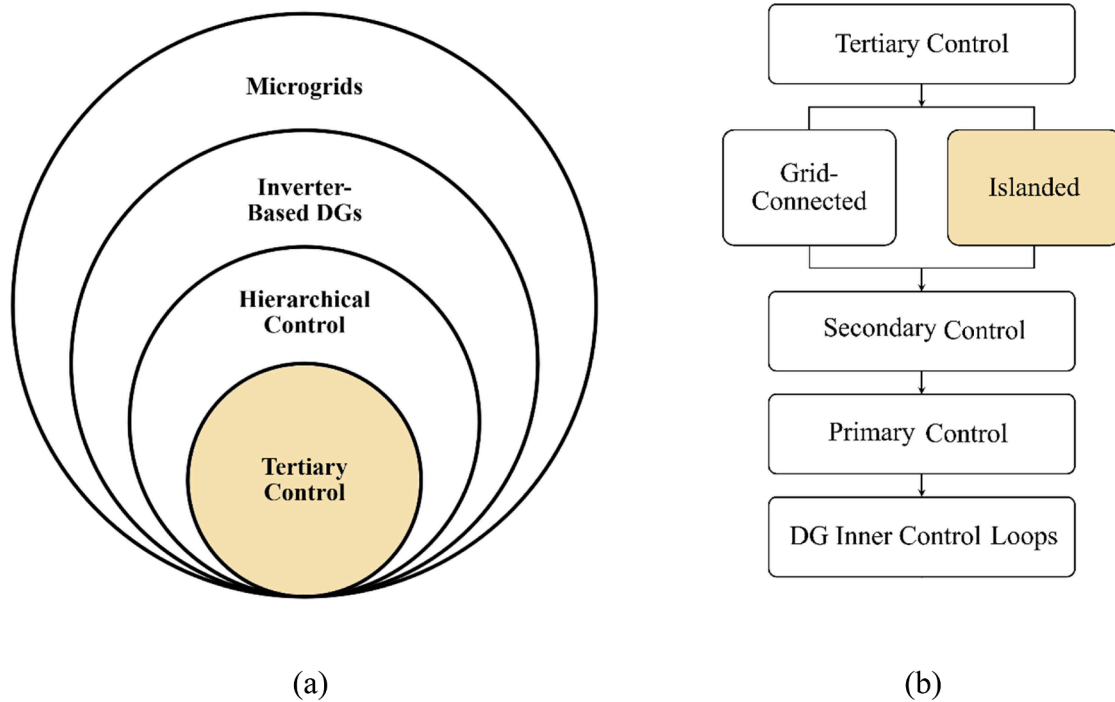


Fig. 1. General perspective of the focus area of this research.

advanced control strategies can be implemented to enhance the operation and stability of MGs.

Shan et al. [10] designed a fuzzy controller for improving the voltage quality of distributed generators in islanded mode, outperforming conventional methods in simulations. Moutevelis et al. [11] simulated a secondary controller for distributed generators to regulate voltage in distribution networks, which periodically updates virtual admittance gains through optimization to prevent voltage fluctuations. Abouassy, Ahmed M., et al. [12] discussed the power-sharing problem in islanded MGs and presented various droop-based control techniques to address this issue. Hui et al. [13] presented a coordination control method for isolated urban MGs with highly distributed generator penetration. The method taps flexibility from both supply and demand sides to improve stability and resilience. Meng et al. [14] modeled a two-layer frequency control strategy for MGs, with lower-layer control integrating primary and secondary control and lower-layer optimizing power sharing to optimize economic operation at a short timescale. Mi et al. [15] simulated a droop control for parallel distributed generators in islanded DC

MGs, ensuring accurate load sharing without requiring changes for added/removed DGs or loads. España et al. [16] discussed a distributed optimization technique for optimal active and reactive power flow in islanded MGs. Alghamdi et al. [17] presented a decentralized secondary control strategy to mitigate voltage harmonics in isolated MGs using a modified droop controller and harmonic droop controller. Hou et al. [18] used a decentralized control approach for an isolated MG using consensus algorithms. Hernández et al. [19] designed a vehicle-to-grid model to simultaneously provide primary frequency control and dynamic grid support at the plug-in terminal, without disturbing scheduled charging. Bueno et al. [20] assessed the stability of transmission systems with large utility-scale PV plants during various disturbances using quantitative stability indices. Askarzadeh et al. [21] analyzed voltage behavior in distribution systems considering uncertainties from PV and electric vehicle charging loads using a probabilistic approach. Feng et al. [22] discussed an enhanced MG power flow approach that incorporates hierarchical control effects for accurate power sharing and voltage regulation. Golsorkhi et al. [23] used a decentralized control approach

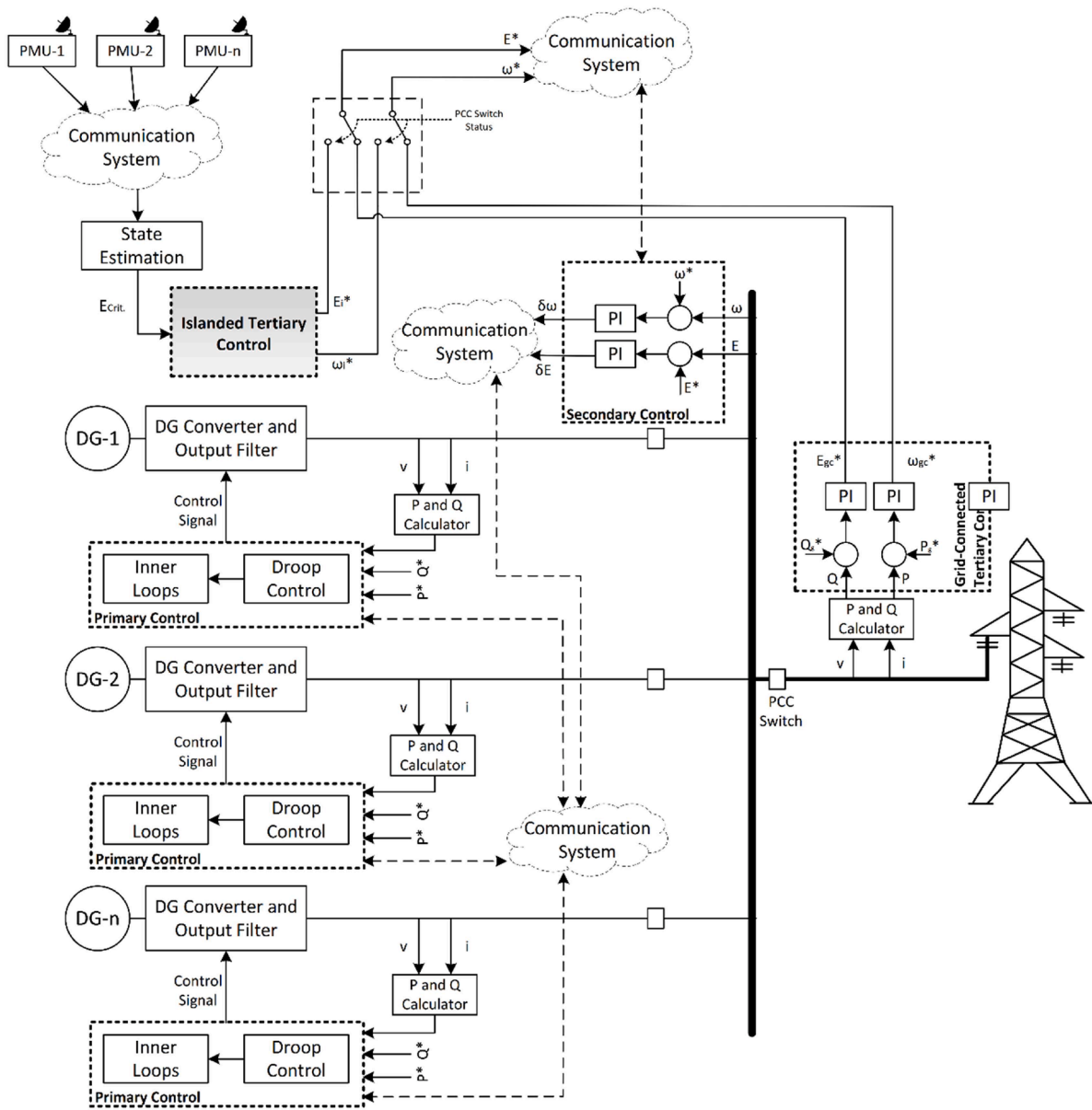


Fig. 2. Correlation of three levels of hierarchical control strategy for an MG.

for an isolated MG using consensus algorithms. Droop control is used at the DER level for load sharing, and a correction voltage is added to eliminate the effect of line impedances on current sharing accuracy. Su et al. [24] utilized a control strategy using synchronized measurements and an adaptive delay compensator to enhance secondary frequency control in islanded MGs, validated through numerical simulations. As recent studies have [25,26] control schemes allow emulating the behavior of synchronous generators through power electronic converters. This facilitates provision of grid support functionality and inertia emulation to enhance frequency regulation. In the context of hierarchical microgrid control, VSG algorithms could be integrated at the primary level to enable grid-forming capabilities and inertial response. The secondary level could potentially override VSG setpoints based on optimization and tertiary objectives. While the focus of the current work is the coordination of secondary and tertiary control, analyzing the integration of VSG-based primary control merits exploration in future work. VSG schemes represent a promising approach to facilitate stable operation and grid support within islanded microgrids, and their application warrants consideration within the hierarchical coordination framework proposed here.

To provide a visual overview of the key contributions, Fig. 1 illustrates the focus areas of this research. Fig. 1. (a) shows the general landscape, positioning microgrids and inverter-based distributed generators as the technologies of interest and the situation of hierarchical control structure in this specific research area. Zooming in, Fig. 1. (b) depicts the hierarchical control framework, which provides a high-level layout of the techniques developed in this paper and their implementation within microgrid hierarchical control.

Moreover, Fig. 2 presents a comprehensive overview of the hierarchical control strategy in microgrids, highlighting the integration of our proposed tertiary control strategy within the framework. The details of the tertiary control strategy and its impact on voltage regulation are elaborated in the subsequent sections.

To propel the investigation in this specific research domain, this paper presents a novel hierarchical control approach to enhance the voltage profile of an islanded MG utilizing PMU measurements. Strategically placed PMUs provide observability of load buses. A tertiary control layer is introduced that integrates these measurements to calculate voltage deviations, providing reference signals to the underlying secondary control of DGs to minimize deviations. Therefore, the

key contributions of this study are as follows:

- 1) We propose a novel tertiary control strategy that leverages PMU data to improve the voltage profile of islanded microgrids within the hierarchical control framework. This integrated approach allows the tertiary level to optimize voltage regulation using real-time phasor measurements.
- 2) We develop an efficient offline design methodology for the tertiary control layer based on network topology and location of DGs. This provides a computationally simple way to determine voltage set-points for secondary control without complex real-time optimization.
- 3) By leveraging PMU infrastructure to coordinate hierarchical control, our findings demonstrate the immense potential to effectively tackle the key challenge of voltage management in islanded microgrids. The analysis provides valuable insights into the design trade-offs between different tertiary control architectures using practical case studies. Our findings highlight the immense potential of leveraging PMU infrastructure to tackle a key challenge of voltage control in islanded microgrids through hierarchical coordination resulting in a substantial improvement in the voltage profile of islanded microgrids.

2. Hierarchical control of MGs

The MG's control strategy involves primary, secondary, and tertiary control levels addressing varying timeframes necessitating a hierarchical control structure that caters to each requirement at separate control hierarchies. The primary control in MGs stabilizes voltage and frequency, distributes generation power among DGs, and mitigates circulating current to prevent equipment damage. However, the primary control has the potential to induce frequency and voltage variation even during stable conditions. The secondary control corrects voltage and frequency issues in the MG caused by the primary control and operates slower than the primary control to maintain separate control loops. This decoupling enables separate design considerations for each control loop and facilitates their individual optimization. The tertiary control assumes responsibility for managing power flow between the MG and the main grid, with a primary focus on achieving optimal economic operation. This control level operates at a slower pace compared to the preceding levels and takes economic considerations into account when determining the most efficient functioning of the MG. When connected to the main grid, DGs can regulate the power flow between the MG and the main grid by adjusting the voltage magnitude and frequency. However, in an islanded MG that has no energy transaction with the grid, stabilizing the voltage profile of the MG is highly important that can be handled by a new tertiary control structure proposed in this paper.

In the proposed methodology, synchrophasor measurements play a crucial role in capturing the dynamic behavior of the MG. Fig. 2 shows the hierarchical control strategy for an MG in which the three-level control mechanisms communicate with each other through communication systems. It should be noted that in the islanded mode, the purpose of implementing a tertiary control is to provide voltage magnitude and frequency references for secondary control of DGs to improve the voltage profile of the system. Since the focus of this paper is studying the MG operation in islanded mode, a novel tertiary control mechanism is proposed, shown as islanded tertiary control in the figure, to enhance the voltage of buses supplying critical loads. The details of each level of MG hierarchical control strategy are explained as follows [3].

2.1. Primary control

The primary control sets the reference values for voltage and current control loops of DGs, which can operate in either PQ or voltage control mode. In PQ mode, the DGs' active and reactive power delivery is

regulated based on predetermined reference values. This control strategy is executed using a voltage source converter (VSC) with current control. In voltage control mode, the DG functions as a VSC, and the primary control sets the reference voltage. Typically, this reference voltage is determined using traditional droop characteristics [27].

2.2. Secondary control

The secondary control serves the objective of mitigating the voltage and frequency deviations within the MG, and is responsible for computing the active and reactive power references, which are then transmitted to each power converter. These values allow for the adjustment of the droop control slope in the primary control. The extent of frequency deviation is contingent on the active power delivered to the connected load. Hence, the balance between the connected load and generated active power can serve as a basis for determining control parameters aimed at offsetting this frequency variation [28]. A proportional-integral (PI) controller can be employed for frequency control and compensation as Eq. (1).

$$\Delta\omega(S) = \left(k_P + \frac{k_I}{S}\right)(\omega_{MG}^* - \omega_{MG}) + (\Delta\omega_{ss}) \quad (1)$$

Where k_P and k_I are the control gains. Also, ω_{MG} and ω_{MG}^* are the actual and reference MG frequency. The error between ω_{MG} and ω_{MG}^* is mitigated through the utilization of a PI controller in conjunction with $\Delta\omega_{ss}$ which is the frequency derived from the synchronization loop of the utility grid and will be omitted in the islanded mode. The frequency control parameter can be incorporated into the droop control of the power converter to address frequency errors.

Taking the same argument into account, voltage magnitude compensation can also be achieved in the secondary control using a PI controller. PI control parameters are calculated for each converter connection point. The voltage controller in the secondary control uses the voltage profile of each converter to determine deviations and compensates for them through voltage adjustments in the primary control. This ensures that every converter can simultaneously engage in voltage compensation. The voltage magnitude compensation signal can be calculated as Eq. (2).

$$\Delta E(S) = \left(k_P + \frac{k_I}{S}\right)(E_{MG}^* - E_{MG}) \quad (2)$$

Where k_P and k_I are the control gains. Also, E_{MG} and E_{MG}^* are the actual and reference MG voltage magnitude, and $\Delta E(S)$ is the Laplace transformation of voltage compensation parameter which is transmitted to the primary control of the converter.

2.3. Tertiary control

The main objective of tertiary control in grid-connected mode is to determine the operational level of active power for each DG, enabling power flow control between MG and the grid. By adjusting the frequency and magnitude of DGs voltages, the power flow can be regulated effectively. However, in the islanded mode, the tertiary control should ensure that MG operates within its rated limits. Hence, it should provide the frequency and voltage magnitude references for DGs to ensure that MG can satisfy the frequency requirements and also compensates for the voltage deviation of the critical loads. In this regard, the details of the control mechanism for tertiary control of islanded MG are proposed in section 3.

3. Proposed control strategy

In this section, a novel framework is proposed to use the capability of synchrophasors provided by PMUs to improve the voltage profile of the MG based on the hierarchical structure of the control framework of DGs.

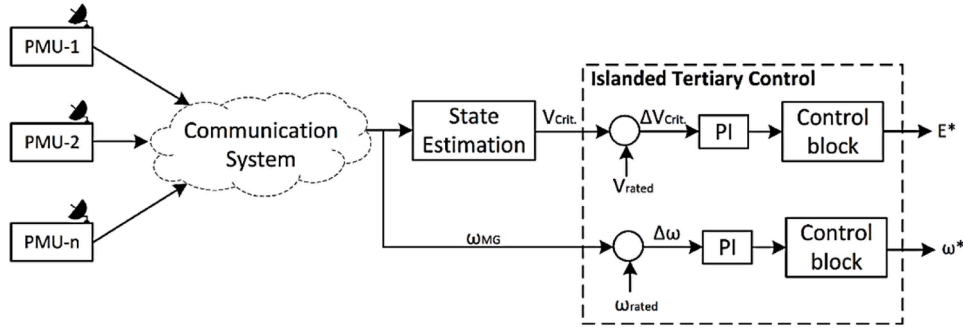


Fig. 3. The proposed closed-loop control structure for tertiary control in islanded mode.

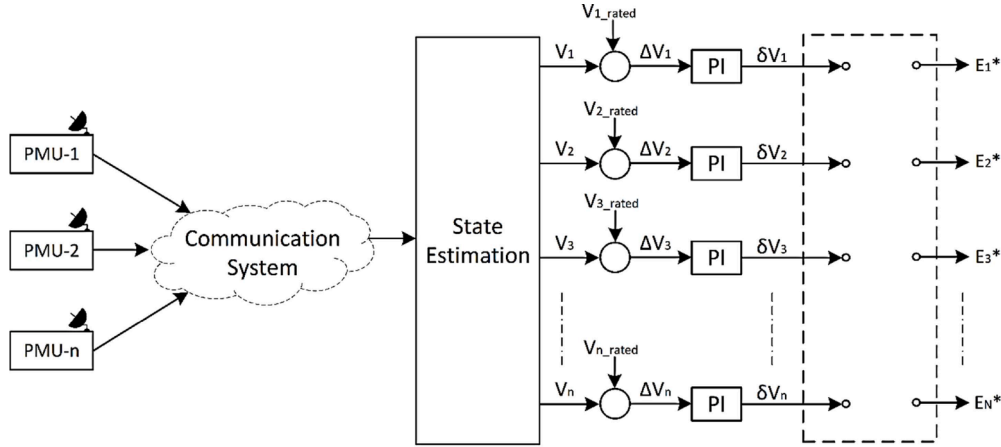


Fig. 4. Schematic of the control block for voltage reference in islanded tertiary control.

As explained in Section 2, the secondary control is responsible for mitigating the frequency and voltage deviations. This is achievable through appropriate settings of voltage and frequency reference in the droop control framework of the secondary control level. Choosing a proper reference can help MG to improve the voltage profile of critical loads. Since we assumed that PMUs are strategically placed within the MG ensuring observability of important buses, voltage phasor measurements of all load buses can be captured. These voltage phasor measurements, obtained through the synchrophasors provided by PMUs, serve as valuable real-time data for monitoring voltage deviations and formulating appropriate control actions. It is essential to highlight that our proposed framework, while not directly focused on PMU placement, acknowledges and accommodates uncertainties within the microgrid system. The strategic placement of PMUs, as assumed in our model, takes into account potential contingencies such as load forecasting errors and component outages. We recognize that uncertainties in PMU placement strategy and state estimation can arise from various factors, including loss of communication infrastructure, outage contingencies of lines, DGs, PMUs, and current measurement channels of PMUs. Our approach not only assumes complete state observability but also accounts for uncertainties in PMU placement, allowing the system to adapt to unforeseen variations. The robustness of our design is further emphasized by the offline design methodology based on network topology, providing inherent resilience without requiring precise operating point estimates. The hierarchical control strategies, incorporating adaptive mechanisms and real-time feedback, dynamically respond to changes in load conditions, effectively mitigating the impact of uncertainties in load forecasting and outages. By leveraging the availability of voltage phasors at load buses, our control strategy utilizes these measurements in the tertiary control layer of the hierarchical framework to improve the voltage profile of the MG. Therefore, a closed-loop

control structure is proposed based on the available voltage phasors of load buses and the secondary control of DGs to improve the voltage profile of MG. The proposed closed-loop control structure is shown in Fig. 3.

In the proposed framework, the voltage profile is calculated from phasor measurements obtained through PMUs using state estimation techniques. The general state estimation process can be mathematically described as Eq. (3):

$$\hat{V}_i = f(\hat{\theta}) \cong \sum_j H_{ij} \times \hat{\theta}_j \quad (3)$$

Where \hat{V}_i represents the estimated voltage phasor at bus i , $\hat{\theta}_j$ is the j^{th} measurement obtained from PMUs, and H is the measurement Jacobian matrix. Moreover, in the context of microgrids, achieving an accurate voltage profile through state estimation involves considerations distinct from conventional power systems. Unlike conventional power systems, microgrids exhibit unique operational characteristics, necessitating a tailored approach to state estimation. Notable differences arise from the inclusion of frequency as a state variable, the implementation of droop control in primary regulation, and the existence of secondary and tertiary regulation mechanisms. In microgrids, the frequency, in addition to voltage, plays a pivotal role in system dynamics, requiring specialized algorithms to account for its influence as a state variable. Furthermore, the incorporation of droop control, inherent in primary regulation, introduces nonlinearities that demand specific treatment in the state estimation process. The coexistence of secondary and tertiary regulation layers in microgrids further distinguishes the state estimation framework, as these layers contribute to the overall hierarchical control strategies. While conventional state estimation techniques form the basis, adapting and extending them to accommodate these microgrid-specific elements is crucial for accurately capturing the system's state

Table 1
General parameters of the modified standard test networks.

Parameter		Rated value/Description
V^{rated}		220 ^V
f^{rated}		50 ^{Hz}
S^{rated}		100 ^{VA}
Z_{base}		48.4 ^{Ω}
DGs		3-phase PWM-based inverters
DGs inner loop control	K_V	0.005 ^{p.u.}
	K_f	0.02 ^{p.u.}

and ensuring effective control [29].

Therefore, phasor measurements provided by PMUs are gone through the phasor state estimator and the voltage phasors of all critical buses are estimated. It is important to note that the detailed formulation of the state estimation process and its associated matrices are derived from the methodology presented [29,30] addresses static state estimation in electric power systems. Our work builds upon this established methodology, assuming its application for obtaining accurate voltage profiles in the microgrid context. [30]. Then, based on the difference between the desired voltage magnitude and the real-time voltage magnitude of all critical buses, appropriate reference points for the secondary control loop of all DGs across the MG are provided. The same approach is chosen for the frequency control. The voltage deviations are gone through a PI controller to minimize the error in the closed-loop feedback control. The control block uses the output of the PI controllers as the input signals to provide better set-points for the voltage reference of the secondary control level of DGs across the MG. The general schematic of the control block is shown in Fig. 4.

As can be seen, the proposed control block gathers voltage deviation data across the MG to provide improved secondary control setpoints for DGs. A controller should find an appropriate relationship between the inputs and the outputs of the control block that can be designed in two ways: (1) Real-time optimization-based design, and (2) Offline design.

Real-time optimization utilizes PMU measurement to minimize voltage deviations via an optimization-based simulation to obtain optimal references for the secondary control loops to minimize the total voltage deviation across the network. However, due to the nonlinear and simulation-based nature of the real-time optimization problem, it can be computationally extensive. In contrast, the offline design uses some heuristic methods to obtain a proper combination of voltage deviations for each of the DGs. Although the offline design cannot guarantee the minimum voltage deviation across the network, it is definitely less time-consuming and computationally less extensive. Therefore, in this paper, based on a comprehensive analysis of different combinations of voltage deviations discussed in section 4, a heuristic approach to obtain the best offline design for the control block is proposed to improve the voltage profile of the MG in an islanded mode. As this control strategy is based

Table 2
Voltage deviations of load buses with respect to the single-feedback scenario.

Bus Number	Voltage Deviation (V)
1	-12.01
2	-9.674
3	-5.614
4	-6.427
5	-7.317
6	-5.279
9	2.746
10	3.071
11	-0.1858
12	-1.529
13	-0.06243
14	5.528

Table 3
Voltage deviations of load buses with respect to the five independent feedbacks scenario.

Bus Number	Voltage Deviation (V)
1	-0.543
2	-0.9408
3	-10.82
4	-3.618
5	-2.837
6	-4.818
9	0.8887
10	1.64
11	-0.6801
12	-1.241
13	0.07759
14	4.563

Table 4
Voltage deviations of load buses with respect to the combinatorial feedbacks scenario.

Bus Number	Voltage Deviation (V)
1	-1.103
2	0.2284
3	4.305
4	-0.527
5	-0.7151
6	-4.384
9	-2.62
10	-1.149
11	-1.878
12	-1.093
13	-0.034
14	2.577

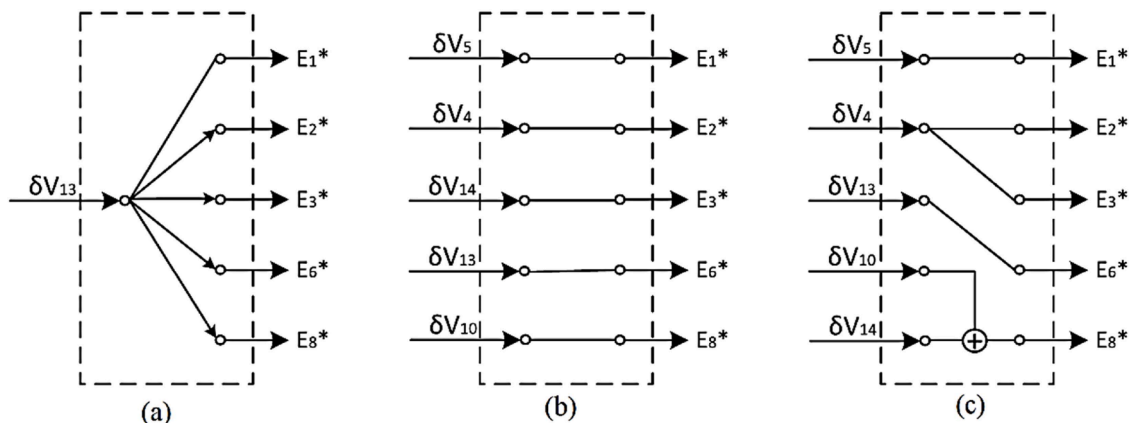


Fig. 5. Three proposed control structures for the IEEE 14-bus network. a) Single-feedback, b) five independent feedbacks, and c) combinatorial feedbacks.

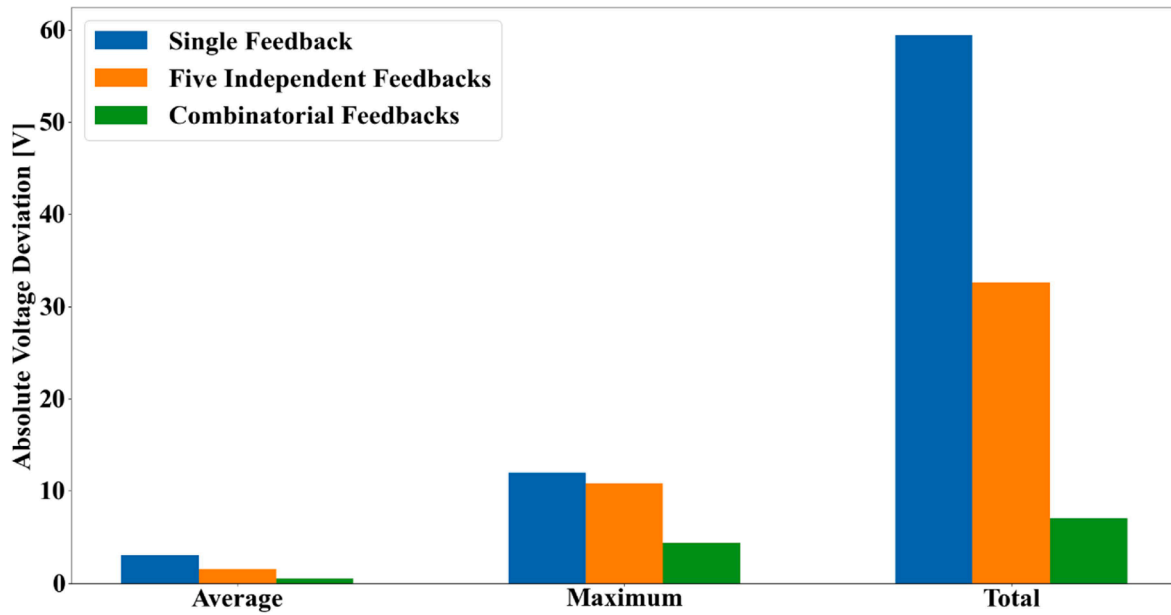


Fig. 6. Comparing three control strategies.

on the network topology, it is impossible to propose a general structure for the architecture of the control block. However, some rules to improve the design of the control block are proposed.

- 1- The voltage deviation of all observable load buses should be included in the design.
- 2- For each of the DGs, assign the closest load bus for the closed-loop feedback.
- 3- If a load bus has almost the same topological position to more than one DG, assign the voltage deviation of this bus to all the DGs with almost the same distance.
- 4- The remaining DGs receive feedback from the remaining buses with the least distance.
- 5- If more than one load buses have almost the same topological distance from a DG, assign the aggregated voltage deviations of those load buses to that DG.

The above rules are the main principles of designing an appropriate control strategy for the control block shown in Figs. 3 and 4.

4. Numerical results

To assess the efficiency of our proposed islanded tertiary MG control, our methods are applied to five different test networks: IEEE 14-Bus [31], IEEE 30-Bus [32], New-England 39-Bus [33], IEEE 57-Bus [34], and IEEE 118-Bus [35] standard test networks. In the proposed hierarchical control methodology, the values of k_p and k_l are control gains that should be determined through appropriate design or tuning methods. In our simulation, the parameters are considered as: $k_p = 1$, $k_l = 2$ for Eq. (1) and $k_p = 1$, $k_l = 4$ for Eq. (2).

Simulink environment of MATLAB is used for simulating the MG and the proposed hierarchical control framework. The computational time for simulating the hierarchical control of MG in Simulink was from 65 s for IEEE 14-Bus test network to 15 min for IEEE 118-Bus test network on a core i-9, 2.5 GHz processor computer.

To adapt the standard IEEE test networks as representative islanded microgrid models for evaluating our proposed control strategy, we made the following modifications:

- The network voltage levels were reduced to a distribution level of 220 V to be representative of typical microgrid voltage standards.

- Existing generators were modeled as distributed inverter sources to emulate the power electronics-interfaced sources prevalent in microgrid systems.
- Network impedances were proportionally scaled down to accurately reflect the lower 220 V distribution voltages according to $Z^\Omega = Z^{p.u.} \times Z_{base}$, where $Z^{p.u.}$ is the per-unit impedance of the standard test networks. Moreover, the demands are proportionally scaled down to the rated power of 100^{VA}.

The general parameters of the modified test networks are described in Table 1.

The test networks were transitioned to islanded operating mode and integrated with the hierarchical control framework needed to evaluate our tertiary control approach for standalone microgrids. Through these adjustments to translate the original test cases into representative microgrid models, we aimed to provide standardized, validated benchmarks to assess the performance of the proposed voltage control methodology. The scaled voltage levels, distributed generation sources, reduced impedances, and implementation of islanded hierarchical control provide appropriate simulation environments to demonstrate the improvements enabled by our tertiary control contribution.

4.1. Offline tertiary control design for IEEE 14-Bus network

In this section, some control designs for the control block shown in Figs. 3 and 4 are proposed to analyze the performance of the system and the voltage profile of critical loads. We designed three scenarios to explain and evaluate the effectiveness of our proposed control strategy. To simulate the scenarios, the IEEE 14-Bus network with the necessary modifications to enable hierarchical control is considered.

4.1.1. Single feedback scenario

To enable a comparative analysis, we implemented a single-feedback control strategy as a representative approach of existing techniques that use a single voltage reference for distributed generators across the microgrid. Due to the lack of prior studies directly comparable to our proposed tertiary control design and specific focus on voltage profile enhancement, this single-feedback scenario provides a baseline for comparison to demonstrate the relative improvements enabled by our approach.

In the first scenario, the control block only uses the voltage phasor of

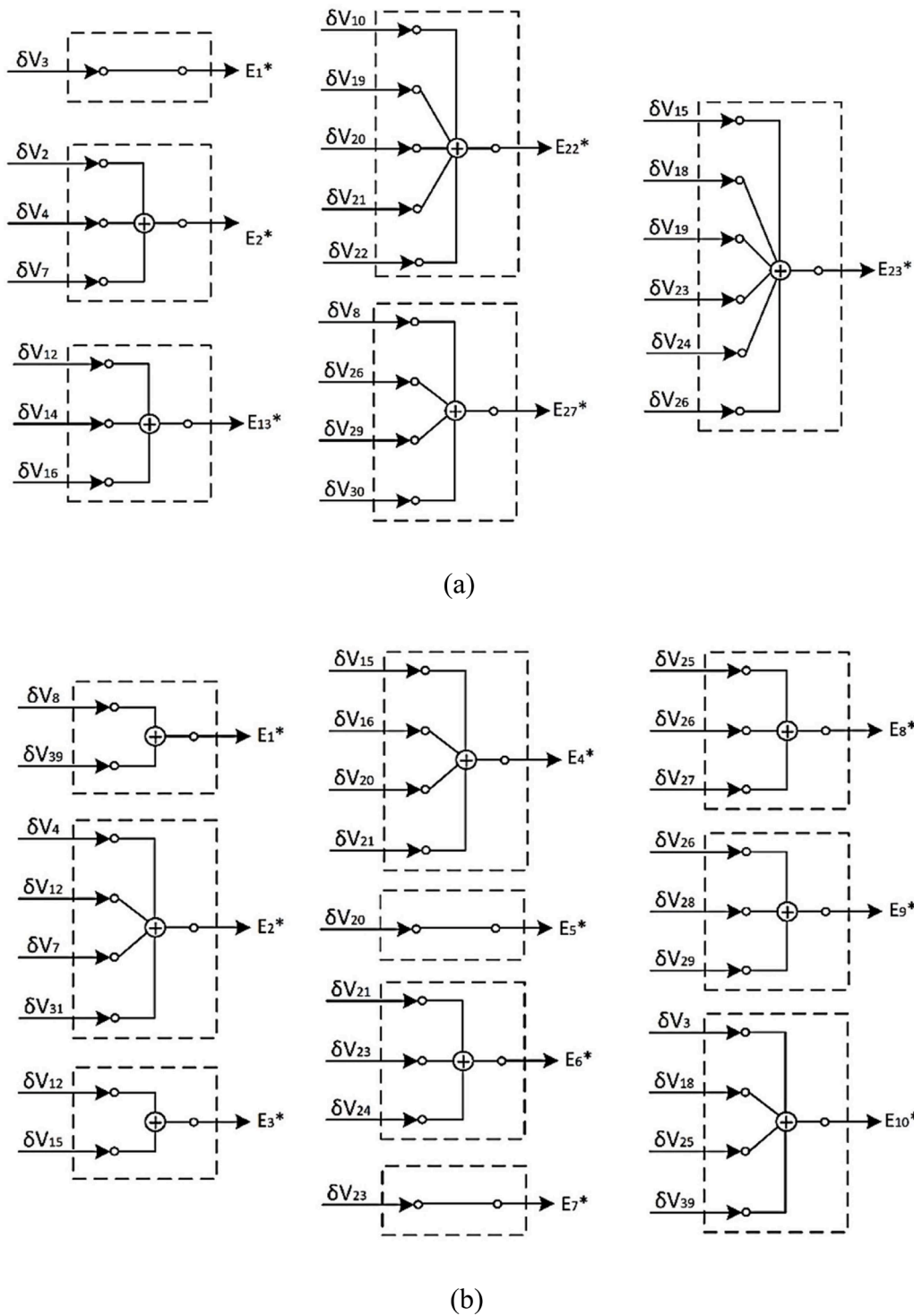


Fig. 7. The schematic of control block for tertiary control level of a) 30-bus network, and b) 39-bus test network.

bus 13 to produce reference settings for the secondary control of all DGs. The control strategy in this scenario is shown in Fig. 5. a.

Table 2 displays the voltage deviations of load buses for this particular control strategy.

As can be seen from Table 2, the minimum and the maximum voltage deviations are for buses 13, and 1, respectively. Due to having the single feedback from the voltage phasor of bus 13, it was definitely expected that the entire secondary systems are working together to minimize the voltage deviation of bus 13 and it should have the minimum voltage deviation across the MG. On the other hand, bus 1 is the furthest bus

from bus 13 from the topological point of view. Therefore, to minimize the voltage deviation of bus 13 which is a load bus that has a voltage lower than the rated voltage, bus 1 needs to increase its voltage more than other DGs. The total absolute voltage deviation of all load buses in this scenario is 59.45^v which is 0.27^{pu} at the 220^v voltage level of the system. In other words, the total absolute voltage deviation in the single-feedback scenario is 27 %.

4.1.2. Five independent feedbacks scenario

In this scenario, the control block uses the voltage phasors of five

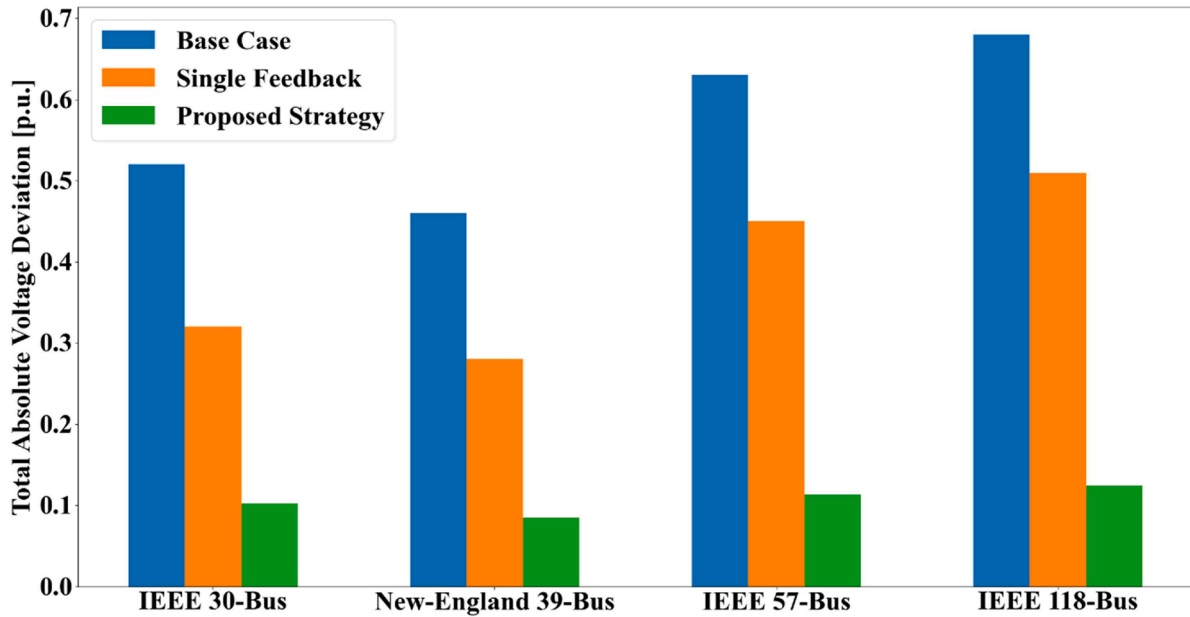


Fig. 8. Comparing total absolute voltage deviation for test networks with three control strategies.

Table 5

Results of applying the proposed islanded tertiary control for test networks.

Test Network	Run-time (Seconds)	Voltage Profile Improvement
IEEE 30-Bus	173.2	80 %
New-England 39-Bus	210.3	81 %
IEEE 57-Bus	493.6	82 %
IEEE 118-Bus	886.5	81 %

different load buses independently for each of the DGs. In other words, the reference of the secondary control loop of each of the DGs will be set by the feedback from the voltage deviation of one of the load buses across the MG. The control strategy for this scenario is shown in Fig. 5. b. Moreover, Table 3 presents the voltage deviations in the second control scenario.

Table 2 shows a clear improvement in the voltage profile of the MG. The maximum voltage deviation was reduced from 12^V for bus 1 in the first scenario to less than 11^V for bus 3 in this scenario. Moreover, the total absolute voltage deviation of all the load buses was reduced to 32.66^V which is 0.15^{pu} . This change in the control strategy resulted in a 0.12^{pu} reduction in the total voltage deviation of all the load buses. Therefore, it can be concluded that this control strategy resulted in a 45 % improvement in the voltage profile of the MG.

4.1.3. Combinatorial feedbacks scenario

In the third scenario, the control signals are from the same load buses as in the second scenario. However, the control strategy comes with a small difference based on the proposed rules in section 3. In this scenario, the voltage deviation of some of the buses can be fed to the secondary control loops of different DGs, and also a reference of a DG can be a mixture of the voltage deviation of more than one of the load buses across the MG. The control strategy in this scenario based on the network topology is shown in Fig. 5. c.

In IEEE 14-Bus network, buses 14 and 10 have almost the same topological distance from the perspective of bus 8 and therefore, it seems that these buses can have almost equal impact on the reference of the secondary control loop of the DG installed on bus 8. Moreover, from the perspective of the load bus 4, both DGs installed on buses 2 and 3 have almost the same topological position and therefore, the voltage deviation in bus 4 can take almost the same impact from the voltage

references of DGs in buses 2 and 3. The voltage deviations for this scenario are shown in Table 4.

Fig. 6 compares the three scenarios studied in this section regarding the average, maximum, and total absolute value of the voltage deviation. The maximum deviation for the combinatorial feedbacks scenario is still for bus 3. However, it is reduced from 10.8^V to almost 4.3^V which is a 60 % reduction. The total absolute voltage deviation of all the load buses was also reduced to 20.61^V which is almost 0.094^{pu} . The proposed combinatorial control strategy in this scenario improved the voltage profile of the MG by almost 37 % compared to the second scenario and by 65 % compared to the first scenario.

Therefore, it can be seen that using the available PMU data and the proposed tertiary islanded control strategy, the overall voltage profile of the MG is improved and the total absolute voltage deviation of all the load buses reduced from 0.27^{pu} to 0.094^{pu} . This improvement was achieved without the complexities of real-time optimization and was solely based on the network topology and the position of DGs across the MG.

4.2. Larger test networks results

The architecture of the control blocks for 30-Bus and 39-Bus test networks based on the proposed heuristic control strategy in section 3, are shown in Fig. 7. The schematic of control block for other two networks cannot be shown due to the large scale of the network and the number of buses.

Based on the control strategy designed for these test networks, the results of the voltage profile of the networks assumed as isolated MGs are shown in Fig. 8 and Table 5. The base voltage for calculating the per-unit value of total absolute voltage deviations is 220^V .

The base case scenario in this experiment is to have the rated voltage as the reference of the secondary control loop of each of the DGs. Table 5 shows the effectiveness of our proposed heuristic control design based on some simple rules related to the topology of the MG and the placement of DGs. Our proposed control design resulted in over 80 % improvement in the voltage profile of the MG compared to the base case scenario.

It can be seen that although the proposed heuristic design for the control block cannot guarantee the minimum voltage deviation across the MG, it provided a significant improvement in the voltage profile without dealing with the computational complexity of the optimization

problems.

5. Conclusion

This paper proposed a novel approach to improve the voltage profile of islanded MGs using PMU devices and hierarchical control of distributed generators. We assumed PMUs are strategically placed across the microgrid based on existing methodologies to ensure observability of load buses. A three-level hierarchical control strategy was proposed utilizing PMU measurements at the tertiary control level to minimize voltage and frequency deviations. An "islanded tertiary control" structure was introduced to provide setpoints to the secondary control loops of DGs to enhance the voltage profile of critical loads in islanded mode. Two design approaches including optimization-based and heuristic offline design were explained for the tertiary control and to reduce the computational complexity, a novel heuristic offline design was proposed. Simulations on 30-bus, 39-bus, 57-bus, and 118-bus test networks showed that the proposed hierarchical control strategy with "islanded tertiary control" could improve the voltage profile of the islanded MGs by over 80 %. The heuristic offline design approach for the tertiary control, based on simple rules considering network topology and DG locations, was able to achieve a significant improvement in voltage profile leveraging available PMU measurements without complex optimization and proved to be effective in significantly enhancing the voltage profile of islanded MGs. The proposed approaches demonstrate the immense potential of PMU-based control techniques to tackle key operational challenges in future MG systems. It is worth mentioning that delays should be considered when applying the proposed hierarchical structure, particularly with PMU-based signaling. Large signal delays could hamper fast inner control loops of converters. While the analysis here focuses on foundational coordination, future work should incorporate communication and PMU delays into the models and control design to ensure robustness. The presented studies represent an initial analysis without delays, providing a basis for extensions accounting for real-world delays and latencies as future direction of this research.

CRedit authorship contribution statement

Sayed Hamid Hosseini Dolatabadi: Writing – original draft, Visualization, Methodology, Conceptualization. **Alireza Soleimani:** Writing – original draft, Methodology, Investigation, Conceptualization. **Afshin Ebtia:** Writing – review & editing, Visualization, Validation, Methodology. **Miadreza Shafie-khah:** Writing – review & editing, Validation, Funding acquisition, Formal analysis. **Tanveer Hossain Bhuiyan:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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