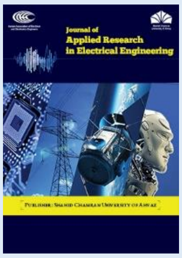
J. Appl. Res. Electr. Eng., Vol. 3, No. 2, pp. 159-167, 2024 DOI: 10.22055/jaree.2024.45398.1092

Shahid Chamran University of Ahvaz

Iranian Association of Electrical and Electronics Engineers

Journal of Applied Research in Electrical Engineering

E-ISSN: 2783-2864
P-ISSN: 2717-414X
Homepage: https://jaree.scu.ac.ir/



Research Article

Voltage Regulation in Low Voltage Distribution Networks Using Reactive Power Capability of Photovoltaic Inverters (PV) and PID Consensus Algorithm

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Abstract: The dominant measures taken in distribution networks to solve the problem of voltage instability include feeder reconfiguration techniques, allocation of capacitor banks, use of tap changer, etc. However, these traditional methods suffer from numerous problems. Many studies have been carried out to solve these problems in recent years. Compared with traditional methods, reactive power control (RPC) of photovoltaic (PV) inverters does not require additional investment, and given that PV inverters often function at a capacity below their rated value, the excess capacity can be utilized to assist in supplying reactive power to the grid. However, achieving voltage regulation in imbalanced distribution networks via RPC is a complex issue. Hence, the primary objective of this work is to utilize the reactive power capacity of photovoltaic inverters to achieve decentralized regulation of effective voltage of the network using consensus algorithm and PID controller in two stages.

Keywords: Distributed generation sources, Consensus algorithm, Unbalanced four-wire distribution network, PID voltage control.

Article history
Received 27 November 2023; Revised 26 February 2024; Accepted 11 August 2024; Published online 30 October 2024.

How to cite this article
I. A. Hassanvand, J. Ebrahimi, and M. Abasi, " Voltage Regulation in Low Voltage Distribution Networks Using Reactive Power Capability of Photovoltaic Inverters (PV) and PID Consensus Algorithm," *J. Appl. Res. Electr. Eng.*, Vol. 3, No. 2, pp. 159-167, 2024. DOI: 10.22055/jaree.2024.45398.1092

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1. INTRODUCTION

1.1. Problem statement and motivation

In the field of electricity generation and reduction of air and environment pollution, the use of distributed generation sources (DGs) has been given much attention in recent years. In this regard, the restructuring of power systems and a competitive electricity market have been established. In fact, the connection of micro-resources with a capacity of several hundred kilowatts to low-voltage networks enhances the reliability of consumers and reduces the costs of investment and expansion of transmission networks [1]. With the ever-increasing expansion of power system in the 20th century, centers of generation and consumption of electrical energy have been connected in meshed configurations. In these networks, the direction of power transfer was always from the generation centers to the consumer. The 21st century and the increasing need for energy resources at the global level provided the basis for the participation of consumers in the power system. This participation can be realized in three sectors: generation, storage, and management of electrical energy. The expansion of renewable energy sources, which both have a very low marginal cost and thus very high efficiency, leads to the reduction of air pollution. Also, the emergence of, which are mostly installed at the distribution level and on the consumer side, the discussion on stability and adaptability of the network has resulted in changes in the structure of power systems. The necessity of investment at the end of lifespan of the system and also investment to resolve the lines congestion by electricity market methods, along with the progress made in the field of telecommunication systems that have significantly changed the speed of information transmission and significant progress in the field of information technology and the possibility of applying their economic utilization in power systems are among the factors that make it necessary to change the traditional integrated power system [1,2].

1.2. Literature review

A study conducted by the World Energy Council has forecasted that the proportion of worldwide electricity production derived from renewable energy sources will rise from 23% in 2010 to approximately 34% by 2030. In an ideal power system, the voltage and frequency at every supply point remain consistent and devoid of harmonics. The three-phase voltages and currents exhibit balance, with a power factor of unity. These qualities are unaffected by the size and characteristics of the loads. Regarding the voltage stability of distribution networks, many studies and methods have been proposed so far. For example, a distributed hierarchical control technique has been proposed to utilize the probable capacity of PV inverters in developing a distributed reactive power compensation plan for regulating voltage in balanced LV 3ph 4-wire distribution systems and deal with the problems of voltage fluctuations through the real-time adjustment of the reactive power injection or the consumption of fast-response PV inverters.

So far, many methods have been carried out for optimal operation of distributed generation resources and voltage control in the distribution system. In most of these studies, centralized control methods have been adopted to address the optimization problem. For instance, the authors in [1] used the method of real-time prediction of reactive power injection into the network. BESS is regarded as a fusion of storage units and voltage source converter (VSC) that enables autonomous regulation of active and reactive power injection into the grid. [2]. In [3], the issue was initially defined as a convex quadratic optimization problem with linear constraints. Subsequently, a distributed accelerated dual descent (DADD) algorithm was introduced to address the optimization problem by employing the anticipated dual decomposition and accelerated gradient methodologies.

In another study [4], the voltage regulation of distribution networks was considered by optimally regulating the reactive power of distributed energy sources (DER). The task is initially described as a convex quadratic optimization problem with linear constraints, using the linearized Dist. Flow model. Subsequently, a DADD algorithm was introduced to address the optimization problem by employing anticipated dual decomposition and accelerated gradient approaches. A method to control the voltage and ensure the security of reactive power reserve in steady-state mode was also proposed, especially since the static synchronous compensator (STATCOM) reference voltage is regulated to maintain the voltage in the sensitive buses according to the load variation. The proposed algorithm in this method includes two parts of the voltage control algorithm and the SVC reactive power reserve control algorithm. Once the reactive power reserve is terminated, the bus voltage deviation can be minimized by adjusting STATCOM reference voltage within the reactive power reserve range [4]. The proposed algorithm in [4] includes two parts: voltage control algorithm and SVC reactive power reserve control algorithm Reference [5] examined the most efficient method of compensating for active and reactive power in a power system under continuous loading conditions, utilizing a battery energy storage system (BESS). In order to achieve this objective, a voltage stability assessment model is utilized, which incorporates data regarding the flow of active and reactive power down the transmission line.

Conversely, a comprehensive technique for controlling reactive power in PV inverters was suggested [5]. This method is categorized into four control modes based on weather and load conditions: normal operation control mode, reverse power control mode, cloud control mode, and night control mode. The four control modes alternate based on particular switching rules to ensure the precise quantity of reactive power is injected or consumed by the PV inverter. The impacts of four control types were statistically significant in isolated operations. The integrated control method resulted in a reduction of approximately 2% in the PCC voltage deviation from its standard value. Hence, the suggested control technique holds significant practical significance in enhancing power quality and optimizing the utilization of PV inverters. The proposal in [6] suggests a coordinated optimization of both active and reactive power of BESS in order to minimize power losses and voltage variations in the active distribution network (AND). Next, a tailored solution for this optimal problem is introduced, utilizing the particle swarm algorithm. Reference [7] suggests implementing constant reactive power control (CRPC) as a means to mitigate the transient overvoltage of the AC system at the sending end. The proposed CRPC system can enhance the consumption of reactive power by the rectifier, diminish the interchange of reactive power between the AC and DC systems, and mitigate the occurrence of transient overvoltage.

However, in many studies conducted in the field of voltage regulation of unbalanced four-wire networks, a suitable and efficient method has not been proposed. For example, in [8,9], only centralized methods are mentioned regarding voltage correction. Increasing the cross-section of the conductors and reducing their impedance is proposed in [10]. Ref. [11,13,14] focused on investigating the Volt-Var control method by adopting a smart PV inverter. On the other hand, the use of a powerful search algorithm in finding the optimal solution has not been considered. A majority of the research focus only on balanced networks.

1.3. Research gaps

According to the conducted research, there are the following research gaps that need further investigation and research, these gaps are:

- The issue of unbalance and voltage regulation at the same time has not been considered in other sources.
- The use of particle consensus algorithm and PID controller to solve similar problems has not been considered
- Voltage angle adjustment has not been investigated in other articles.

1.4. Novelty and contributions

Therefore, to overcome the shortcomings in the research on voltage correction of unbalanced distribution network using, this paper presents a new method of voltage profile correction in two stages by DGs. The proposed method provides a suitable solution for balancing the three-phase voltage in the first stage and correcting the voltage to the optimum level by means of the centralized consensus algorithm and the PID controller using the DGs. The evaluation and comparison of the proposed model is done by implementing it on the standard IEEE 14-bus network. The main contributions of this paper include:

- Utilization of the centralized consensus algorithm for precise correction of the network voltage
- Also, the work of this article has been done in two steps. In the first step, the unbalance is fixed, and in the second step, the voltage is adjusted optimally with the PID controller.
- Implementation of the proposed method on a standard IEEE network
- In most of the articles, voltage imbalance and voltage balancing have been discussed, while in the purpose of this article, in addition to voltage imbalance resolution, voltage regulation and its improvement have also been considered.

In the continuation of the paper, Section 2 is dedicated to the formulation and outline of the problem. Section 3 describes the solution method. The analysis of the results is presented in Section 4 and finally Section 5 provides the conclusion.

2. PROBLEM FORMULATION

This section presents a novel approach for regulating the reactive power of both single-phase and three-phase PV inverters, which can be linked to any combination of the three phases of a LVDN. The control algorithm enables PV inverters to transfer reactive power with LVDN in order to rectify voltage imbalance and enhance voltage profiles. Collaborative inverters can effectively achieve desired outcomes while relying solely on local measurements and restricted communication lines. The control strategy is comprised of two distinct parts. Voltage imbalance compensation is achieved in the initial stage by employing distributed single-phase compensators. During the second phase, the reactive power of the PV inverters is modified in order to enhance the voltage profile along the feeder. This adjustment is achieved by utilizing three-phase inverters.

2.1. Voltage imbalance compensation (Step1)

The definition of voltage imbalance in international communities has different complexity and practical limitations. But the National Electric Manufacturers Association (NEMA) definition of line voltage unbalance rate (LVUR) is as Eq (1) and Eq (2).

$$LVUR\% = \frac{max\{\Delta\left|V_i^{AB}\right|,\Delta\left|V_i^{BC}\right|,\Delta\left|V_i^{CA}\right|\}}{\left|V_i^{ave}\right|} \tag{1}$$

$$\left|V_i^{ave}\right| = \frac{\left|V_i^{AB}+V_i^{BC}+V_i^{CA}\right|}{3} \tag{2}$$

where $\Delta\left|V_i^{AB}\right|, \Delta\left|V_i^{BC}\right|, \Delta\left|V_i^{CA}\right|$ are the phase-to-phase voltage deviation from $\left|V_i^{ave}\right|$ (the average voltage of PP) at the *i*th bus. According to Eq. (2), the lower value of LVUR means that the network suffers from low imbalance. We have adopted the definition of the LVUR for the purpose of evaluation and compensation of voltage imbalance as it is effective and leads to straightforward computing. To make sure the electrical appliances work safely, the European EN50160 standard specifies allowable range for LVDNs as the rate of voltage unbalance of less than 2% for 10 minutes.

This approach relies solely on measuring the PP voltage, eliminating the need for intricate calculations. The suggested method employs a distributed delta compensator that delivers varying levels of reactive power in each phase. The primary objective is to minimize the voltage disparity between the PP points at the measurement location in order to enhance the voltage imbalance ratio as specified in Eq. (3).

$$UR_{PV,i}^{PP}(t) = \begin{cases} k_v^{ind/cap}\ (V_i^{PP}(t) - V_i^{ave}) + UR_{PV,i}^{PP}(t-\Delta t) V_i^{PP}(t) \neq V_i^{ave} \\ 0 V_i^{PP}(t) = V_i^{ave} \end{cases} \tag{3}$$

In general, $V_i^{PP}(t)$ is the voltage across the PP inverter, V_i^{ave} represents the average voltage across the PP compensator. k_v^{cap} and k_v^{ind} are two constant parameters for setting and regulating the speed and accuracy of the controller design, and Δt represents the sampling time. $UR_{PV,i}^{PP}(t)$ controls the active power exchanged by PP inverters by taking into account the voltage difference and $UR_{PV,i}^{PP}$ of the previous step. When the voltage across the PV inverter, i.e., $V_i^{PP}(t)$, is greater than average V_i^{ave}, then $UR_{PV,i}^{PP}(t)$ is positive. This means that the PV requires absorbing reactive (inductive) power to reduce the voltage of the connection point. Nonetheless, negative $UR_{PV,i}^{PP}$ enforces the PV inverter to feed reactive (capacitive) power to increase the voltage. Eventually, the reactive power exchange by PP inverters can be given as Eq (4).

$$Q_{PV,i}^{ref,PP} = UR_{PV,i}^{PP}(t) \times Q_{PV,i}^{max} \tag{4}$$

$$Q_{PV,i}^{max} = \pm\sqrt{(S_{PV,i}^{max})^2 - (P_{PV,i})^2}$$

where $Q_{PV,i}^{ref,PP}$ is reactive power that should be exchanged by the inverter, and $Q_{PV,i}^{max}$ is the maximum reactive power of the PV inverter [22].

2.2. Distributed consensus algorithm and local PID controllers (Step2)

After implementing the suggested technique to balance the network, the voltage regulation algorithm can be applied separately to each phase of the LVDN to ensure that the bus voltages remain within the acceptable range. The approach suggested relies on distributed consensus control to coordinate PV inverters without requiring a central controller. Implementing RPC for PV inverters has the potential to enhance voltage profiles along the feeder. In this section, we design a consensus control mechanism and a PID controller to proportionally distribute the reactive power needed for voltage regulation. The voltage limit should be equal to the value represented by EQ. (5).

$$V_{thr}^{cap} < V_i^{PN}(t) < V_{thr}^{ind} \tag{5}$$

The V_i^{PN} is the phase-to-ground voltage in bus *i*, V_{thr}^{cap} is the lower voltage boundary for voltage exchange and V_{thr}^{ind} is the upper power boundary for voltage exchange. Finally, the information is shared between the PID controllers of different inverters, then the local PIDs exchange reactive power with the network by using this information to regulate the voltage within the permissible limit. The PID controller is commonly employed in applications related to engineering because of its operational and architectural flexibility [22,24]. The design of this controller does not necessitate advanced expertise. It decreases the steady state inaccuracy and enhances the transient and steady state responses [25]. The process of choosing PID controller parameters is crucial as the controller's effectiveness relies on the precise selection of these parameters. The Ziegler-Nichols method, Youla parametric method, Lambda tuning method, Cohen-Kuhn method, and Wang-Jung-Chan method are considered the most effective approaches for building PID controllers. These techniques enable the creation of PID controllers with increased flexibility and extra functionalities, while maintaining a straightforward layout complexity. Implementing advanced PID controller design techniques increase the level of intricacy and necessitates a deeper understanding of mathematics [21,26].

The PID controller integrates the proportional, integral, and derivative structures into a unified package. The PID controller's basic transfer function can be expressed as Eq. (6):

$$C(s) = k_p + \frac{k_i}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s} \tag{6}$$

where, k_p, k_i, and k_d are proportional, integral, and derivative gains. The inclusion of the proportional term in the controller enhances the system's transient response. The integral term is the key component of the controller and is employed to minimize the steady-state error, while the derivative term is adopted for over-reduction of the system. The structure of a PID controller and problem flowchart are given in Fig. 1. Voltage control based on the distributed consensus algorithm and PI controller

To set voltage on a desirable value in this study, which is 1 p.u., the following control dynamics is used as eq (7):

$$V_{ni} = (V_i^{mg} - V_i^{con})(P_i^T + \frac{P_i^I}{s}) \tag{7}$$

In general, V_{ni} is the control voltage, reference voltage of the desirable voltage, V_i^{con}denotes the output voltage of the consensus algorithm for each agent (bus), P_i^T is the proportional coefficient of the PI controller, and P_i^I is the integral coefficient of the controller [23].

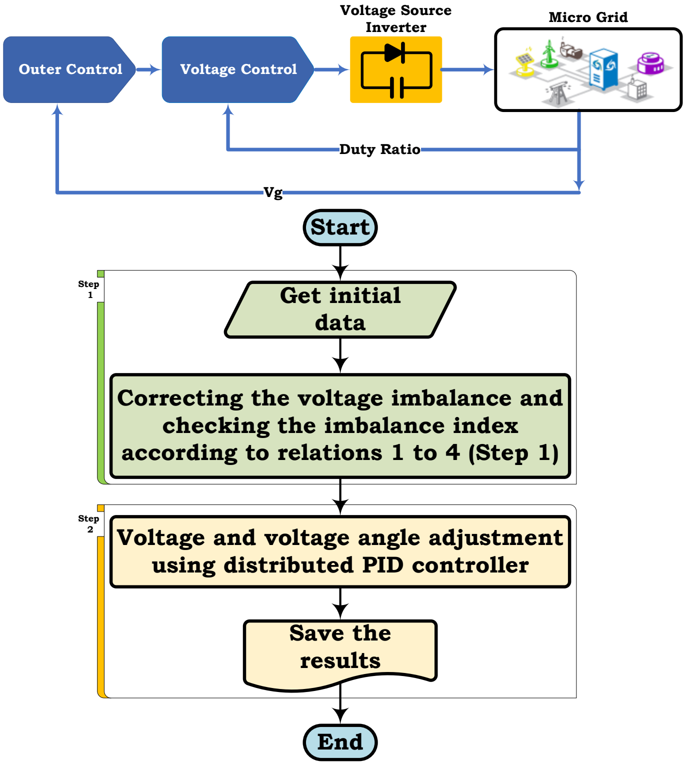

Fig. 1. Structure of a PID controller and process flowchart

2.3. Problem constraints

There are constraints in the power output of DGs, which are of great importance and all of them must be observed to reach the correct solution. The constraints of the proposed optimization problem are described below:

2.3.1. *Power balance constraint*

The presence of DG in the network should be such that all control variables and system variables satisfy the power flow equations of the network. In the following equations, active and reactive power is shown according to power flow equations Eq (8).

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0$$
$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N} V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{8}$$

2.3.2. *Voltage limits*

The presence of DG in the network should not make bus voltages exceed the defined limits. So Eq (9),

$$\mathrm{V_i^{min}}<\mathrm{V_i}<\mathrm{V_i^{max}},\ \mathrm{i} = 1 \dots, \mathrm{N_i} \tag{9}$$

2.3.3. *Line capacity limits*

The limitation on the power flowing through the lines is given by:

$$|\mathrm{S_i}|\leq|\mathrm{S_i^{max}}| \qquad \mathrm{i}=1,\dots,\mathrm{N_b} \tag{10}$$

2.3.4. *Limits on generators power output*

$$\mathrm{P_{gi}^{min}}<\mathrm{P_{gi}}<\mathrm{P_{gi}^{max}} \tag{11}$$

3. SOLUTION METHOD

This section introduces a novel approach for regulating the reactive power of PV inverters that are linked in an arbitrary manner to the three phases of a power system. The control algorithm enables PV inverters to interchange reactive power in order to rectify voltage disparities and enhance voltage profiles. Inverters can work together to achieve desired results only through local measurements and limited communication links. The control strategy is divided into two stages. In the first stage, voltage imbalance compensation is done using distributed single-phase compensators. The second stage takes the reactive power of the PV inverters to enhance the voltage profile on the feeder with the help of the existing PP inverters that are connected to the grid in three phases.

Compared with centralized and decentralized control strategies, distributed control systems offer superior control performance but require communication links as a trade-off. The benefits of this technique include the capacity to easily adjust the system's size, strength against failures, decreased computing demands, great adaptability, absence of a single point of weakness, and the distribution of tasks among local controllers [15-17].

3.1. Problem solution using the consensus algorithm

The communication network of a multi-agent cooperative system can be modeled with a directed graph (digraph). A digraph is usually a set $G_r = (V_G, E_G, A_G)$ with a non-empty finite set with N groups$V_G = \{v_1, v_2, \dots, v_N\}$and a set of arcs $E_G \subset V_G \times V_G$ and an adjacency matrix $A_G = [a_{ij}] \in R^{N\times N}$. In a microgrid, DGs perform the role of communication digraph nodes. The arcs of the communication network diagram represent the communication links. In the current study, the digraph is assumed time invariant, that is, A_G is constant, and an arc from node j to node i is specified by (v_j, v_i), which means that node i receives information from node j. $a_{ij}$is the weight of the arc (v_j, v_i), and $a_{ij} > o$ if $(v_j, v_i) \in E_G$; otherwise, $a_{ij} = 0$. Node i is a neighbor of node j if $(v_j, v_i) \in E_G$. The set of neighbors for node j is denoted by $N_j = \{i \left| \left((v_j, v_i) \in E_G \right) \right.\}$. In a digraph, if i is a neighbor of j, then node j can receive information from node i, but the opposite is not necessarily true [18,19]. In a microgrid, DGs are considered as communication digraph nodes. The arcs of the communication network diagram represent the communication links. Due to the fact that in this article, distributed solar generation sources are used for voltage balancing and regulation, therefore, ten selected points were selected by a simple genetic algorithm location with the aim of improving voltage stability and voltage division. The genetic algorithm with the initial population of 50 and the number of iterations of 600 has been implemented on a 14-base network. 10 candidate buses for DG installation are selected in such a way that the grid voltage stability is improved.

In this study, we have considered a graph with 10 nodes (agents) on buses 4, 5, 7, 8, 9, 10, 11, 12, 13, and 14 for the distributed consensus algorithm. To better understand, the communication graph between the agents on the buses is shown in Fig. 2.

Also, the Laplacian matrix and its eigenvalues are given as Eq (12):

$$L = \begin{bmatrix} 3 & -1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 \\ -1 & 4 & -1 & 0 & 0 & -1 & 0 & -1 & 0 & 0 \\ 0 & -1 & 4 & -1 & 0 & 0 & -1 & 0 & -1 & 0 \\ 0 & 0 & -1 & 4 & -1 & 0 & 0 & -1 & 0 & -1 \\ 0 & 0 & 0 & -1 & 3 & 0 & 0 & 0 & -1 & -1 \\ -1 & -1 & 0 & 0 & 0 & 3 & -1 & 0 & 0 & 0 \\ -1 & 0 & -1 & 0 & 0 & -1 & 4 & -1 & 0 & 0 \\ 0 & -1 & 0 & -1 & 0 & 0 & -1 & 4 & -1 & 0 \\ 0 & 0 & -1 & 0 & -1 & 0 & 0 & -1 & 4 & -1 \\ 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & -1 & 3 \end{bmatrix} \quad (12)$$

with eigenvalues of

$$\begin{gathered} \lambda_{g1} = 0.7639, \lambda_{g2} = 2.7639 \\ \lambda_{g3} = 0, \lambda_{g4} = 4 \\ \lambda_{g5} = 4, \lambda_{g6} = 4 \\ \lambda_{g7} = 4, \lambda_{g8} = 4 \\ \lambda_{g9} = 5.2361, \lambda_{g10} = 7.2361 \end{gathered} \quad (13)$$

After defining the communication graph of PV inverters, the distributed consensus algorithm receives the data shared for each PV with other PVs using the defined graph, and sends an estimated average of the PV values of the neighboring systems to each local controller based on the distributed consensus equations.

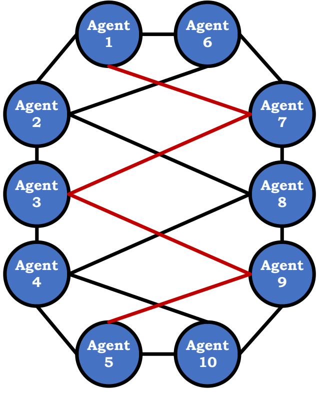

Fig. 2. A communication diagram for protocol of the average distributed consensus algorithm

Here, according to the communication graph on the target buses which has the Laplacian matrix L, the output of the consensus algorithm, which is the estimated average of the voltage values of the neighboring PVs, is shown in Fig. 1. Distributed PV inverters are connected to each other through the network communication graph $\ell(v, \varepsilon)$, where $v = \{1, \ldots, N\}$ is the points and ε shows the communication arcs between the points. Each point represents a PV inverter and each arc represents a communication link between them. If the points are connected, the data is shared through that. A set of points linked to point i is called the neighborhood of point i and is denoted byN_i. Node degree is equal to the number of neighbours' of that node, which is displayed as $d_i = |N_i|$.

Degree matrix D of a graph is defined by the d_i and also an adjacency matrix A, the elements of matrix A are $a_{ij} = 1$ if $(i, j) \in \varepsilon$; otherwise, $a_{ij} = 0$.

$L = D - A$ is the Laplacian matrix of the graph. In an undirected matrix, the Laplacian matrix has zero eigenvalues and the rest of values have an eigenvalue greater than zero. The ith PV controller receives the estimated mean state from its neighbors. The controller estimator then adopts the following average consensus protocol, Eq. (14):

$$\bar{x}_i(t) = x_i(t) + \int \sum_{j \in N_t} a_{ij} (\bar{x}_j - \bar{x}_i) \quad (14)$$

So that x_i shows a local state variable, and $\bar{x}_i$ represents the estimated average of PV values of neighboring systems.

The vector form of a distributed average consensus protocol is given as Eq. (15):

$$\dot{\bar{x}} = \dot{x} - L\bar{x} \quad (15)$$

where, $x = [x_1, x_2, \ldots, x_N]$ and $\bar{x} = [\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_N]$. Using the Laplace transform from Eq. (21), the transfer matrix of the distributed consensus algorithm is as eq (16):

$$H^{avg} = \frac{\bar{X}}{X} = s(sI_N + L)^{-1} \quad (16)$$

In this equation, X and $\bar{X}$ represents the Laplace transfer matrix of x and $\bar{x}$, respectively [20].

4. SIMULATION RESULTS

4.1. Standard IEEE 14-bus system

The system used for simulations is the standard 14-bus network, whose data can be found in [12] and it's shown in fig 3.

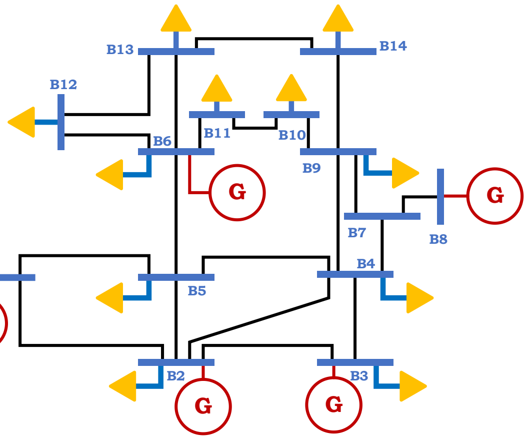

Fig. 3. IEEE 14-bus network

4.2. Results of applying the control strategy of Step 1 (Voltage imbalance compensation)

The proposed method for controlling Step 1 described in the previous sections is presented here. Its results were implemented on a standard IEEE 14-bus network and the following results were obtained. The voltage of different buses before applying the control method was as follows. As can be seen, the system is imbalanced in all buses, which is well shown in Table 1.

As shown in Table 1, before network control, the network is unbalanced, but after that the network is balanced. The amount of imbalance should be less than 2%. All the values in these buses are in p.u. form and the values in the table are reported as percentages. Fig. 4 shows the voltage of Bus 10 before balancing. Using equation (1), the voltage imbalance rate is equal to 5.6%. According to the standard, the imbalance rate should not exceed 2%, so the voltage of this bus needs balancing.

Table 1: the LVUR values before and after applying the control method of Step 1

Bus	Before control method	After control method
1	2.6	0.1
2	3.3	0.5
3	3	0.3
4	3.8	0.4
5	3.8	0.3
6	7.3	0.3
7	3.6	0.2
8	2.6	1.1
9	4.3	0.8
10	5.6	0.8
11	8.3	1.1
12	7.7	1.2
13	8.5	1.4
14	7.8	1.3

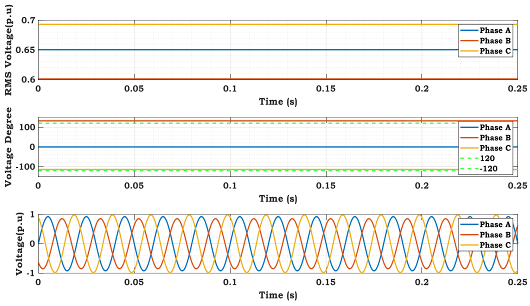

Fig. 4. Three-phase AC RMS voltage in Bus 10 before balancing the network

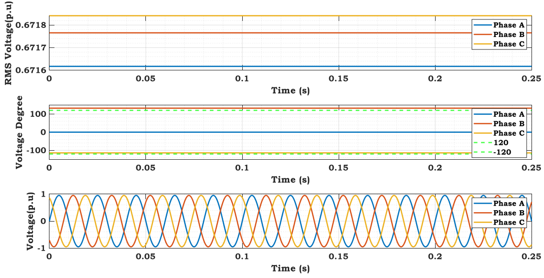

Fig. 5. Three-phase AC RMS voltage in Bus 10 after balancing the network in step 1

Fig. 5 shows the voltage of Bus 10 after applying the control method of Step 1. After it was found that there is more voltage drop in phase *A* compared to the other two phases, 0.01984 p.u reactive power is injected to this phase by using equation (1), resulting in an unbalance of 0.8%, which is less than 2%, so the voltage on this bus is balanced.

4.3. Results of applying the control strategy of Step 2 (Voltage amplitude and degree compensation)

In this research, as previously said, 10 PVs have been used to control Step 2. These 10 PVs are connected with their neighbors according to the communication graph that is defined for them. There is a PI controller in each PV that sends a control signal to the PI controller based on the voltage received from the consensus algorithm and comparing it with the desired voltage. Next, the PI controller sends the control information to the inverter power controller. The results for voltage control are in the following form for Bus 10 of the network.

Fig. 6 depicts the rms instantaneous voltage of Bus 10 after applying the control method of Step 2. In this study, the voltage level of interest is 1 p.u. or 0.71 rms. The network error value is calculated using $e = \frac{v_{ref}-v_b}{v_{ref}} \times 100$, where v_{ref} is the reference voltage (1 p.u.) and v_b is instantaneous voltage of the considered bus. Before applying the control method, the value of this error in the bus is 5.7%, and after using the control method it becomes 1.2%.

4.4. Sensitivity analysis of the results of changing the number of candidate bases

In this article, in order to investigate the sensitivity of the voltage regulation error to the number of solar sources, it has been tried to investigate the error changes in three scenarios with the number of digraph points 10, 5 and 3.

Table 2 shows the error value of each bus before and after the application of the control strategy. AS per Table 2, the control strategy was able to control the network voltage in all the network buses well and with high accuracy. In our proposed strategy, by using the consensus algorithm, we were able to increase the reliability of the network, eliminate the imbalance error, reduce the possibility of cyberattacks, and the decision for each bus is made according to the information of other neighboring buses, which is very effective in performance and improving the voltage profile. The results of Table 2 show that: by reducing the amount of candidate buses in the control network, the consensus of the particles in the network is reduced, and this raises in the voltage error and drops the voltage stability in the network.

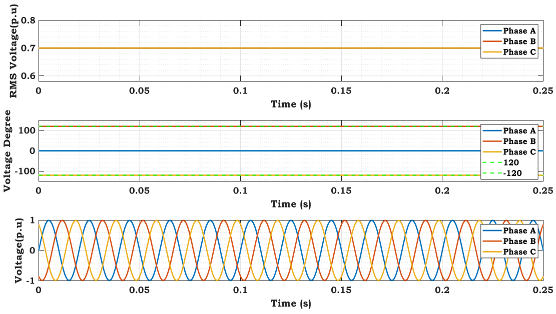

Fig. 6. Voltage of Bus 10 after applying the control strategy step 2

Table 2: Error values of each bus before and after applying the control strategy of Step 2

Bus	Before control method	After control method (10 bus)	After control method (5 bus)	After control method (3 bus)
1	8%	1.40%	2.36%	4.93%
2	11%	2.70%	3.70%	6.15%
3	9%	1.40%	2.25%	5.27%
4	12%	1.50%	1.90%	3.23%
5	9.80%	1.48%	2.96%	6.21%
6	5.50%	1.42%	3.25%	4.27%
7	6.70%	2.80%	4.74%	5.28%
8	12%	1.54%	3.36%	6.12%
9	8.60%	1.38%	2.90%	5.46%
10	5.70%	1.20%	3.60%	4.37%
11	8.90%	1.40%	2.82%	5.24%
12	7.70%	2.80%	4.69%	5.21%
13	8.50%	2.90%	5.23%	7.14%
14	7.80%	2%	4.36%	6.21%

Also, in order to compare the results and check their validity, it has been tried to compare them in terms of the percentage difference of reactive power passing through the lines in reference [1], the results of which are checked in Table 3. As it can be seen, the particle consensus algorithm used in this article has been able to qualitatively improve the imbalance of the reactive power passing through the lines better compared to reference [1]. This issue is one of the advantages of this article compared to its reference sample.

5. CONCLUSION

Various types of microgrid control strategies include centralized, decentralized, and distributed. In this study, considering the advantages of distributed control strategy compared to other control strategies, it is used. Autonomous agents in distributed control strategy utilize their individual local information and engage in communication with neighboring agents over a distributed communication graph network in order to accomplish shared objectives. The distributed control technique enhances system efficiency when compared to both centralized and decentralized control strategies. This technique has several benefits, including resilience, scalability, great adaptability, decreased computing complexity, absence of a single point of failure, and task distribution among local controllers in the microgrid. Hence, the use of a distributed control technique via a distributed communication graph network enhances the resilience of the microgrid.

sSince there is an imbalance between the three-phase voltages in most power systems, it means that the voltage value of each phase may be different from the other phase, which causes damage to consumers. According to the European standard EN50160, the acceptable range of the voltage imbalance rate is less than 2% for 10 minutes. According to Table 1, the network under study in this research has an imbalance rate higher than the standard limit under normal conditions before applying the control method, so with an absolute control method, the imbalance has been returned to the standard level, whose results are shown in Fig. 5 and Table 1. Then, the network voltage has reached the desirable value.

Table 3: Error values of reactive power in different cases

Cases	ΔQ AB (%)	ΔQ AC (%)	ΔQ BC (%)
[1] Case 2	38.9	58.12	31.41
[1] Case 3	1.94	11.54	9.7
This article	1.23	3.24	4.69

To regulate the voltage to the desired level, which is 1 p.u. in this study, the voltage of the neighbors is shared with a communication graph between the neighbors using a consensus algorithm, so that the entire network reaches a general consensus. After that, the output information of the consensus algorithm is sent to each local controller of each inverter so that these controllers can make decisions based on the local information and the information received from the consensus algorithm for accurate voltage regulation. The results obtained are shown in Fig. 6 and Table 2. As is observed, the proposed method is very accurate. The important results of this article in summary are:

- Reducing line voltage unbalance and improving voltage regulation by particle consensus algorithm compared to similar works
- Improved network voltage regulation
- Balancing grid voltage angle adjustment
- Balancing the reactive power passing through the lines

5.1. Remaining challenges and future works

In this article, it was tried to use the particle consensus algorithm to improve the voltage imbalance, voltage profile and voltage stability, but there are certainly still a number of issues in this field that can be addressed as a continuation of the work. Some of these are:

- Considering the uncertainty of solar sources and its effect on voltage stability
- Using sliding mode controller instead of PID for network control
- Considering other voltage unbalance standards and its effect on the results

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Iman Ali Hassanvand: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration. **Javad Ebrahimi**: Methodology, Resources, Software, Supervision, Validation. **Mahyar Abasi**: Visualization, Roles/Writing - original draft, Writing - review & editing.

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. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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