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Forward-Backward Technique Based on Multi-Objective Optimization for Unbalanced Load Current of Multi-Carrier Networks

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Abstract
In this paper, the Forward-Backward (FB) strategy has been developed to solve the load flow (LF) problem of a large-scale multi-carrier network. The Teaching–Learning-Based Optimization (TLBO), as a powerful heuristic tool, has been used for the optimization of the proposed LF. For this purpose, a large-scale unbalanced multi-carrier energy system (MCES) including an IEEE 33-bus system, a natural gas network with 25 nodes, and a heat network with 20 nodes have been considered to ascertain the applicability of the proposed FB-based machine learning strategy. By minimizing an objective function of the MCES system under unequal constraints, the TLBO tries to solve the optimization problem of MCES. The unbalanced current and voltage performance of the MCES system has been investigated by employing the current unbalance index (CUI) and voltage unbalance index (VUI). The numerical analysis with the application of the current unbalance index and voltage unbalance index has been studied to appraise the efficiency of the proposed optimal strategy to solve the LF problem of the MCES system.

Keywords: Forward-Backward (FB), Multi-Carrier Energy System (MCES), Teaching–Learning-Based Optimization (TLBO), Current Unbalance Index (CUI).

1. INTRODUCTION

Due to the non-uniform distribution of single-phase loads, accidental connection, and the presence of unbalanced three-phase loads, voltage imbalance is inevitable in distribution systems [1-3]. This imbalance eventually leads to imbalances in currents or powers, which in a way causes instability problems and complexity in the network. Most consumers of electricity in distribution networks are single-phase consumers while the distribution of these subscribers in the three phases is not uniform (see Fig. 1) [4, 5].

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Most methodologies adopted in transmission (or sub-transmission) networks are unable to effectively handle the distributed plants due to the following reasons: a) The transmission lines in the distribution network have radial properties which sometimes have poor performance in the mesh structure. b) The transmission lines of the distribution system have a wide range of independent R and reactance X, which is greater than the transmission system from R / X to the distribution network. Therefore, the R / X ratios in the distribution network are not identical compared to the transmission network. c) Distribution networks unlike transmission networks in phases do not have the same load which is regarded as an unbalanced network [6-8].

Generally, various indicators have been adopted in the literature to estimate the imbalance in electrical distribution networks. Among them, load imbalance is considered one of the most important indicators to measure the quality of electrical energy. The load flow (LF), as one of the most powerful concepts for the analysis and design of power systems, is widely adopted in the operational and planning stages of power systems [1, 7, 9, 10]. The LF techniques are required to ameliorate the scheduling and planning of power systems and distributed networks. In fact, the load numerical analysis of LF is an effective tool to handle distributing systems with various topologies and configurations that examines parameters such as phase angle, real/imaginary power, and power losses [11]. However, despite the dramatic progress in micro-computers and automated distribution plants, finding appropriate solutions for the practical applications of such systems is a challenging task. The main goal of providing LF solutions is to develop faster computational models with less computer memory. An accurate analysis of various merits is required in the context of

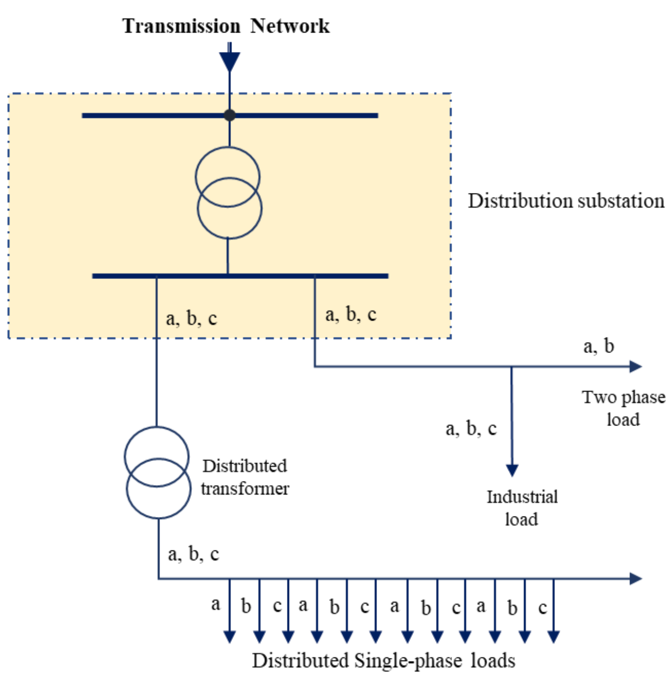


Fig. 1. Typical schematic of distribution feeder.

computation efficiency and convergence speed. Achieving advanced methodologies requires a careful analysis of the advantages and disadvantages of existing methods in relation to memory storage needs, computational speed, and convergence criteria. Up to now, various algorithm-based methodologies such as admittance matrix [12], Newton-Raphson (NR) [13-15], and decoupled and fast decoupled techniques [16, 17] have been adopted to obtain LF solutions. Among them, it has shown that the NR scheme takes longer to replicate than other versions while this approach demonstrates far faster convergence specifications.

According to the above view, the contemporary researchers in the field of the power system are aware of the changing methods of managing distribution systems, and the result of their continuous efforts can be referred to various techniques of distribution system analysis. Up to now various methodologies such as artificial intelligence [18], deep learning [19], reinforcement learning [20-22], meta-heuristic algorithms [23-25] have been developed for optimization problems. For example, Miu et al. [26] have developed a robust technique for solving three-phase radial distribution networks where the monotonic characteristics of the voltage magnitude have been adopted according to load changes. However, the method proposed in [26] suffers from high complexity which restricts its applicability in real-world plants. In [7], Ghatak and Mukherjee proposed a backward forward sweep (BFS) technique based on load impedance matrix (LMI) for unbalanced systems that offers special flexibility in terms of network topology. In this line, Kumawat et al. [27] adopted the Jaya algorithm for network optimization and solving unbalanced three-phase load current, while in [28], five new versions of the Newton power current scheme have been developed by considering load specification, transformer, and distributed generation models for the three-phase unbalanced LF problems. In [29], by employing the graph theory and injected current, a three-phase power-current strategy based on decomposed NR (DNR) has been applied to the unbalanced radial distribution systems.

The importance of studying unbalanced networks will be doubled when the sensitive position of these networks in the space of multi-port systems is studied. Electrical distribution networks are one of the most vital energy networks in the space of multi-carrier systems that are directly connected to networks such as natural gas and regional or local heating networks. The main question is what effects unbalanced behavior in these networks can have on a set of multi-carrier systems. Therefore, in this paper, the Teaching–Learning-Based Optimization (TLBO) algorithm has been implemented for solving the multi-carrier energy systems (MCESs) when the systems are subjected to unbalanced loads in the distribution networks. The main contributions are organized as:

1) The LF problem of a large-scale unbalanced distribution network including IEEE 33-bus system, a natural gas network with 25 nodes, and a heat network with 20 nodes has been solved by employing Forward-Backward scheme (FB).

2) Various unbalanced indicators have been formulated to control the unbalanced amount in the unbalanced distribution network and to examine the negative effects of this issue in all multi-carrier energy systems (MCESs).
3) By defining an appropriate objective function for the distribution network, the TLBO approach has been applied to the complex MCESs under the unbalanced power effects in each phase.
4) Another contribution is the study of the effects of unbalanced behavior in the electrical distribution network which is an inherent nature of these networks, on natural gas networks and regional heating.

The rest of this work is as: the mathematical formulation of an unbalanced distribution network is presented in Section 2. The TLBO for the optimization problem is illustrated in Section 3. Section 4 introduces various types of indicators in the distribution networks. In Section 5, the simulation outcomes of various case-studies along with the detailed analysis are presented. The obtained results are concluded in Section 6.

2. THE MATHEMATICAL MODELS OF UNBALANCED DISTRIBUTION NETWORKS

Due to the unique characteristics of distribution systems (e.g., radial structure, high R / X ratio, unbalanced loads, etc.), the conventional deterministic methodologies are not adopted in distribution networks because of their slow convergence [29, 30]. The FB strategy is one of the most common strategies in the distribution networks which is developed based on calculating the current and voltage of nodes using Kirchhoff's current and voltage laws. The load distribution process in balanced systems is such that the problem is solved for one phase and then generalized to other phases by creating a phase difference of 120º. But in unbalanced systems, due to the difference between amplitudes and phases, the problem must be directly solved for all three phases.
Although integrated multi-carrier energy systems (MCESs) and distribution networks can be modeled as both equilibrium and unbalanced, these networks are inherently unbalanced. This unbalance is mainly related

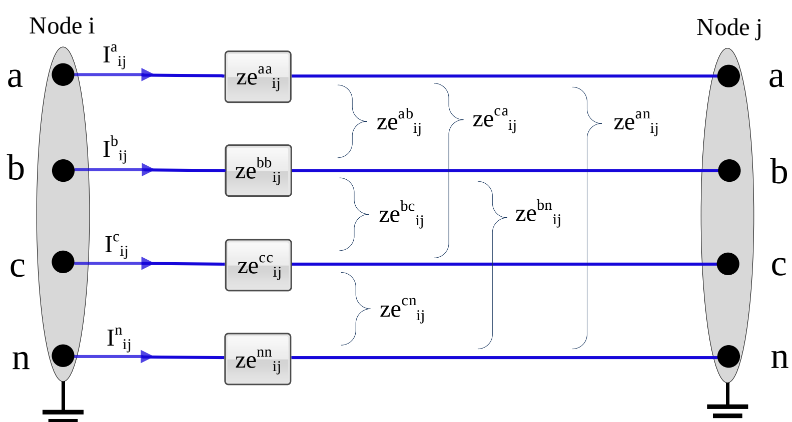


Fig. 2: Four-wire line model for an unbalanced electrical distribution network.

to the difference in the amount of electricity demand in each phase. As a first step in modeling an unbalanced distribution network, matrices related to an unbalanced line must be defined. In general, an unbalanced branch or line of the distribution network can be defined as Fig. 2.

According to Fig. 2, each phase has its impedance and due to the inductive properties of the cables, there is a reciprocal impedance between the two conductors. For the above structure, the relationship between the bus voltage and the current passing through the lines is as follows [7, 31]:

$$\begin{bmatrix} V_i^{ag} - V_j^{ag} \\ V_i^{bg} - V_j^{bg} \\ V_i^{cg} - V_j^{cg} \\ V_i^{ng} - V_j^{ng} \end{bmatrix} = \begin{bmatrix} ze_{ij}^{aa} & ze_{ij}^{ab} & ze_{ij}^{ac} & ze_{ij}^{an} \\ ze_{ij}^{ba} & ze_{ij}^{bb} & ze_{ij}^{bc} & ze_{ij}^{bn} \\ ze_{ij}^{ca} & ze_{ij}^{cb} & ze_{ij}^{cc} & ze_{ij}^{cn} \\ ze_{ij}^{na} & ze_{ij}^{nb} & ze_{ij}^{nc} & ze_{ij}^{nn} \end{bmatrix} \begin{bmatrix} I_{ij}^{a} \\ I_{ij}^{b} \\ I_{ij}^{c} \\ I_{ij}^{n} \end{bmatrix} \tag{1}$$

where $V_i^{ag} = V_i^a$, $V_i^{bg} = V_i^b$, $V_i^{cg} = V_i^c$, and $V_i^{ng} = V_i^n$ denote the voltage of a, b, c, and n at node i with considering ground, respectively; V_{ij}^{ag}, V_{ij}^{bg}, V_{ij}^{cg}, and V_{ij}^{ng} denote the voltage drop between i and j in a, b, c, and n, respectively; I_{ij}^{a}, I_{ij}^{b}, I_{ij}^{c}, and I_{ij}^{n} denote the current in phases a, b, c, and neutral between i and j respectively; ze_{ij}^{aa} ze_{ij}^{bb}, ze_{ij}^{cc}, and ze_{ij}^{nn} denote the self-impedance between i and j in phases a, b, c, and neutral, respectively; ze_{ij}^{ab}, ze_{ij}^{ac}, ze_{ij}^{an}, ze_{ij}^{ba}, ze_{ij}^{bc}, ze_{ij}^{bn}, ze_{ij}^{ca}, ze_{ij}^{cb}, ze_{ij}^{cn}, ze_{ij}^{na}, ze_{ij}^{nb}, and ze_{ij}^{bc} are the mutual impedance corresponding to phases a, b, c, and neutral between i and j.

With unbalanced line modeling, the load on each bus must also be considered with the appropriate model in the network. It is assumed that the loads are constant power and the three-phase loads are connected to the star arrangement. Therefore, the relationship between voltage V, current I, active load power P, and reactive load power Q of three phases (a, b, c) can be expressed as follows [5]:

$$I_m^k = \left[\frac{P_m^k - jQ_m^k}{V_m^k}\right]^*, m\epsilon[a, b, c] \tag{2}$$

Unbalanced loads in the distribution network led to current inequality in different phases. In general, for any electrical distribution system, the bus voltage and current injected into the system on each bus can be related using the following equation [31]:

$$I = Y_{bus} * V \tag{3}$$

In fact, current and voltage are connected to each other through the admittance matrix Y_{bus}. In such a system, the admittance matrix follows a structure similar to the following definitions [5].

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & ze_{ij}^{bc} \\ ze_{ij}^{ca} & ze_{ij}^{cb} & ze_{ij}^{cc} & Y_{22} \\ Y_{22} & Y_{22} & Y_{22} & Y_{22} \end{bmatrix} \begin{bmatrix} I_{ij}^{a} \\ I_{ij}^{b} \\ I_{ij}^{c} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} \tag{5}$$

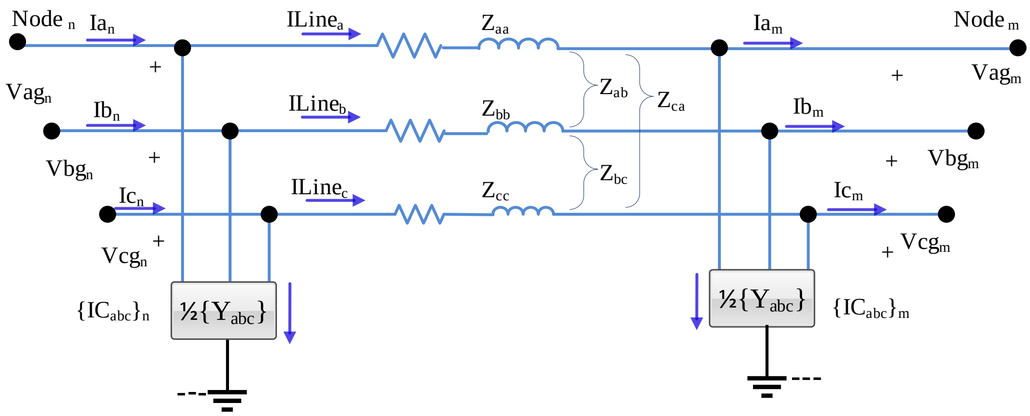


Fig. 3. The unbalanced three-phase line to consider line capacitors.

where $Y_{dd}(1 \leq d \leq n)$ denotes the sum of all the admittances related to node d; $Y_{dm}(1 \leq d, m \leq n)$ denotes the negative of all admittances related between nodes d and m. Considering the interactions between the phases, the equivalent representation of an unbalanced line in the electrical network, and if capacitive effects are also modeled, can be illustrated in Fig. 3.

The unbalanced load's distribution networks are modeled as:

$$S_{total} = P_{total} + jQ_{total} = (P_{e0} + P_{e1}.|V| + P_{e2}.|V|^2) + j(Q_{e0} + Q_{e1}.|V| + Q_{e2}.|V|^2) \tag{6}$$

Here $P_{e0} + jQ_{e0}$ denotes the complex power element under constant power; $P_{e1} + jQ_{e1}$ denotes the complex power element under constant current; $P_{e2} + jQ_{e2}$ denotes the complex power element under constant admittance, V denotes the complex voltage of the node. The active and reactive power injected into a particular bus can be written as follows:

$$S_i = P_i + jQ_i = \tag{7}$$

$$V_i . I_i^* = \sum_{j=1}^{n} |V_i Y_{ij} V_j| \measuredangle (\delta_i - \theta_{ij} - \delta_j)$$

where $V_i = |V_i| \measuredangle \delta_i$ and $V_j = |V_j| \measuredangle \delta_j$ denote the voltage levels corresponding to the nodes i and j; $Y_{ij} = |Y_{ij}| \measuredangle \theta_{ij}$ denotes the component on the i^{th} row and the j^{th} column of the admittance matrix. With the necessary mathematical rewrites in this relation, a separate negative expression can be provided for each of the active and reactive powers, given as:

$$P_{i,calc} = \sum_{j=1}^{n} |V_i . Y_{ij} . V_j| \cos(\delta_i - \theta_{ij} - \delta_j) \tag{8}$$

$$Q_{i,calc} = \sum_{j=1}^{n} |V_i . Y_{ij} . V_j| \sin(\delta_i - \theta_{ij} - \delta_j) \tag{9}$$

Since the injection of network power in each bus must be equal to zero, this calculated mixed power must be equal to the planned power, which consists of the predicted load consumption and the production of the expected power in each bus.

Remark 1: The proposed load distribution equations can finally be implemented using the FB method and the output results. In this work, the FB method is used to solve the load distribution problem and the TLBO algorithm has been adopted to solve the optimization problem.

In summary, this section provides a mathematical model of the unbalanced electrical distribution network. In this regard, as a first step in modeling an unbalanced distribution network, an unbalanced four-wire-line model of the distribution network is defined in Fig. 2. From the mathematical point of view, related matrices to the above-mentioned line must be defined which are reported in Eqs. (1)-(8). This procedure is proposed in most literature such as [5, 31-33].

For more description, Eq. (1) takes into account the self and mutual coupling effects of the unbalanced line section. Equations (2) and (3) represent the equivalent current-injection model and the relationship between bus voltages and line currents in general form, respectively. The unbalanced load demands are modeled as Eq. (6), and Eqs. (7)-(9) illustrate the overall power flow formulations. These formulas are used to implement the unbalanced power flow problem.

3. TLBO ALGORITHM FRAMEWORK

The native TLBO algorithm approach, which was influenced by conventional teaching methods, is separated into two components. TLBO, like most stochastic algorithms, searches for the best answer through the procedure of population evolution. The students in a class are referred to as the population, while the various topics are compared to the choice parameters in an optimization problem. The population's best student is chosen as the instructor. The fitness value of a person in the population is comparable to a learner's academic achievement. The process of the TLBO algorithm is divided into two stages: teacher and learner. Learners (students) are treated as the population in the teacher process where various topics are chosen the diverse the coefficients of the optimization problem, and the mean value of the topic is regarded as the fitness value. The best learner among the students is selected as the teacher and it improves the mean of class according to its level. In the learner stage, the knowledge of learners is enhanced by interacting with themselves. This is accomplished by random learning with other learners in the class. When a student has a higher level of knowledge than other students, then the knowledge can be transferred to improve their level. In the basic algorithm, the duplicate elimination step is also included [34, 35].

3.1. Teacher Phase

In the teacher process, the performance of students (cost function) can be improved by interacting with the teacher in the classroom environment. Many attempts have been conducted by the teacher in the regard to improving the average knowledge of the student. An individual candidate (X_i) within the population denotes a single possible candidate solution for a specific optimization problem. At each generation i, assume that there are D topics (i.e., number of problem variables), and N be the number of students (i.e., population size $k = 1, 2, \ldots, N$) in a classroom. The best student with the high-cost function, who is thought to be the most informed, is designated as the teacher $\left(T^k\right)$. During the teacher mechanism, the basic algorithm tries to ameliorate the position of individual candidates (X_i) by moving towards the location of the T^k by considering the mean value of the individuals $\left(M^k\right)$. The learner's improvement is affected by the difference between the position of individual learners and the quality of the teacher, which is described by [36, 37]:

$$X_{diff}^{k} = rand \times (T^k - t_f M^k) \tag{10}$$

$$t_f = round[1 + rand(0,1)] \tag{11}$$

where $rand$ is a random factor within [0 1].

The movement specifications of TLBO are simulated by:

$$X_{new}^{k+1} = X_{old}^{k} + X_{Diff}^{k} \tag{12}$$

where X_{old}^{k} is the previous value of the student, and X_{new}^{k+1} denotes the current position.

3.2. Learner Phase

During the execution of the learner procedure, the learner (X_i) improves its position by using the knowledge of learning an arbitrary learner (X_j), where $i \neq j$. The new student is

$$X_{new} = \begin{cases} X_i + rand \times \left(X_i - X_j\right) & \text{if } f(X_i) < f\left(X_j\right) \\ X_i + rand \times \left(X_j - X_i\right) & \text{if } f(X_i) > f\left(X_j\right) \end{cases} \tag{13}$$

where $X_j = \left[x_{j,1}\ x_{j,2} \ldots . x_{j,D}\right]$, and $f\left(X_j\right)$ is the j[th] cost function.

The overall flowchart of the proposed technique is depicted in Fig. 4, while Table I demonstrates the algorithmic steps of TLBO for the optimization of the multi-carrier energy system.

The TLBO algorithm is used in this paper as a solution method for solving the optimal energy flow problem. The full description of TLBO methodology and its related flowchart can be found in [38]. However, in this section, a brief review of this algorithm has been summarized in Table (1). In addition, the overall flowchart of the utilized procedure for solving the energy scheduling of the proposed multi-carrier energy system (MCES) has been investigated in Fig. (4).

4. EFFECTS OF UNBALANCED ELECTRICAL DISTRIBUTION NETWORKS ON MULTI-CARRIER NETWORKS

Suppose a gas-generating unit injects power into the electrical distribution network. This unit can inject different powers in different phases. Now consider that the power injection of this unit into phases a, b, and c is equal to P_a, P_b, and P_c, respectively, so the total power is as:

$$P_{tot} = P_a + P_b + P_c \tag{14}$$

If the amount of fuel consumed by this production unit is considered, this amount of fuel can be calculated with the help of heat rate curves. Therefore, by dividing the amount of production capacity by the amount of efficiency in each phase, the amount of gas consumed was obtained, given as:

Table 1. ***The procedure of TLBO algorithm with teacher and learner phase.***

Pseudo-code of implemented TLBO algorithm.	
1.	Set Population Size (n)
2.	Set the maximum number of iterations
3.	Organize the initial population members
4.	Calculate the objective function for each population member
5.	Identify the best solution
6.	While $\text{iter} < \text{iter}_{\text{max}}$
7.	$t_f = \text{round}[1 + \text{rand}(0,1)]$
8.	Calculate the mean of control variables
9.	for $k = 1{:}\,n$
10.	Modify existing k^{th} solution
11.	Check the feasibility of new solution using constraints
12.	If a new solution is better than the existing solution
13.	$X_i = X_{new}^i$
14.	end if
15.	Select any two solutions randomly X_i and X_j so that $i \neq j$
16.	Calculate $f(X_i)$ and $f\left(X_j\right)$
17.	Update solutions based on the learner phase
18.	Check the feasibility of new solutions using constraints
19.	If a new solution is better than the existing solution
20.	$X_i = X_{new}^i$
21.	end if
22.	Update teacher value
23.	$\text{iter} = \text{iter} + 1$
24.	end for
25.	end while

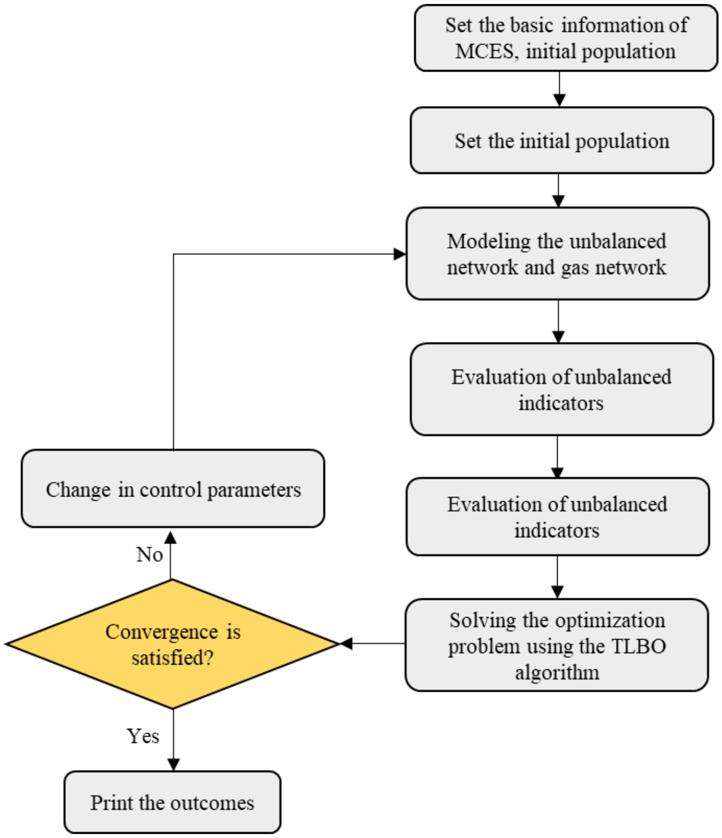


Fig. 4. Overall flowchart of the proposed technique.

$$f_a = \frac{P_a}{\eta_a}, \quad f_b = \frac{P_b}{\eta_b}, \quad f_c = \frac{P_c}{\eta_c} \tag{15}$$

$$f_{tot} = f_a + f_b + f_c \tag{16}$$

4.1. Indicators to Check the Unbalanced Amount of Electrical Distribution Networks

4.1.1. Current Unbalance Index

Checking the unbalanced current performance can be considered both over the network and across the entire feeders. The advantage of checking this indicator along all feeders is that it allows the balance of all lines if it is considered only above the feeder, it only observes the power received from the transmission network. To provide a relationship in this regard, one can define [6]:

$$I_{un}\% = \max\left(\frac{|I_a - I_{av}|}{I_{av}}, \frac{|I_b - I_{av}|}{I_{av}}, \frac{|I_c - I_{av}|}{I_{av}}\right) * 100 \tag{17}$$

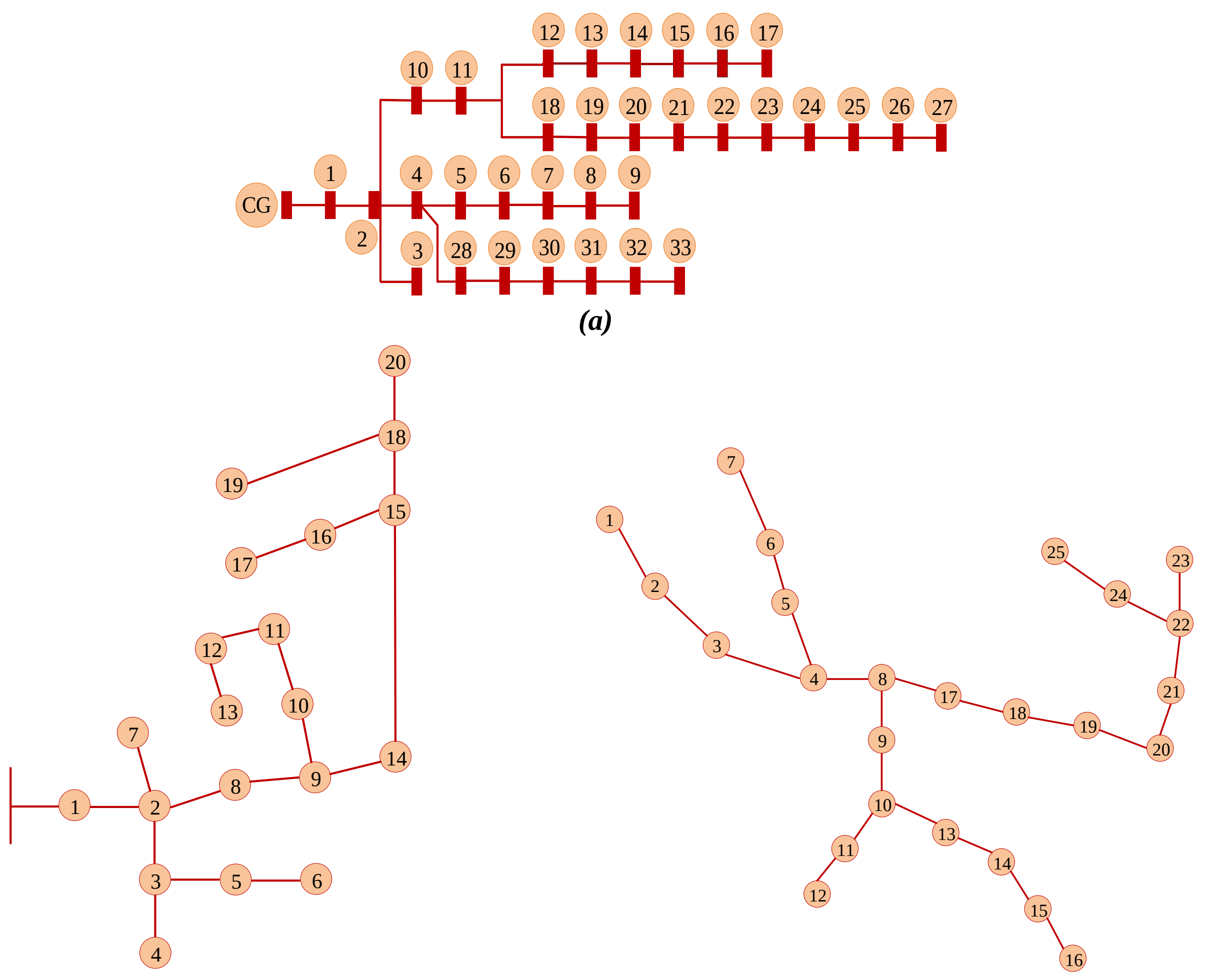
Alternatively, it should be noted that in unbalanced systems, all three components of positive, negative, and zero sequences can exist simultaneously. Obviously, the lower the amount and percentage of negative and zero components in the network, the more balanced the network can be claimed. Therefore, in this paper, we first extract the current components of positive, negative, and zero sequences, then measure the ratio of negative and zero components to the positive component and try to reduce these ratios. In this case, the following relationship can be suggested:

$$I_{un}\% = \frac{I_0}{I_1} * 100 \quad \text{or} \quad = \frac{I_2}{I_1} * 1 \qquad (18)$$

4.1.2. Voltage Unbalance Index

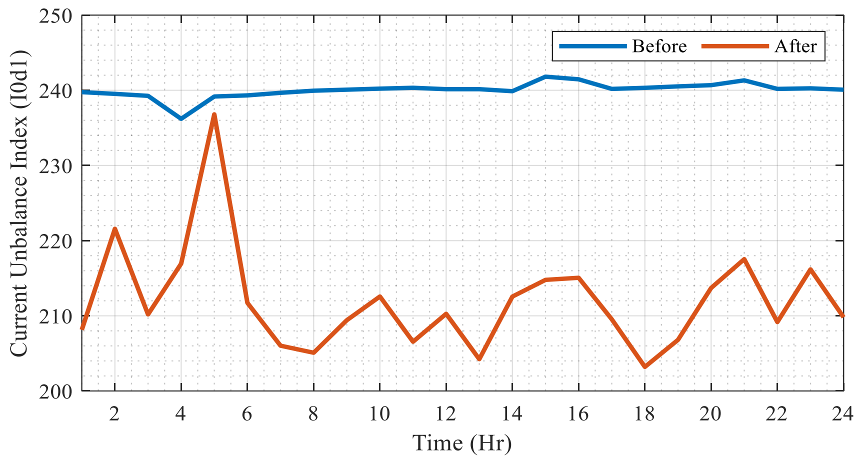
This index is mathematically the same as the previous index in that the maximum voltage deviation of three phases is obtained by dividing the value of the average voltage in a line by the same average value. This indicator can be controlled by installing a capacitor in the distribution network. This indicator can even control losses in an unbalanced distribution network. The relation related to the unbalanced voltage index can be expressed as follows [6].

$$V_{un}\% = \max\left(\frac{|V_a - V_{av}|}{V_{av}}, \frac{|V_b - V_{av}|}{V_{av}}, \frac{|V_c - V_{av}|}{V_{av}}\right) * 100 \qquad (19)$$

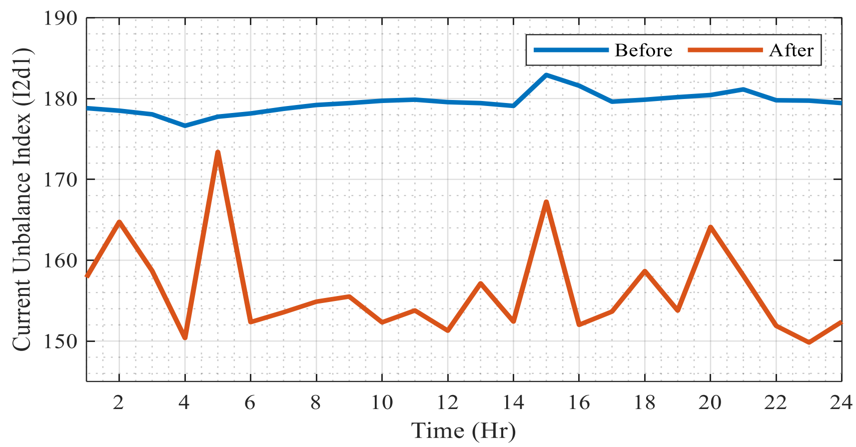


(a) ***(b)*** ***(c)***

Fig. 5. The schematic of case studies, a) 33 electric buses, b) a network of 25 nodes of natural gas, c) a network of 20 nodes.



(a)



(b)

Fig. 6. Total unbalanced current in 24 hours a day before and after unbalanced control by distributed generation units under a) zero to positive sequence ratio, b) negative to positive sequence ratio.

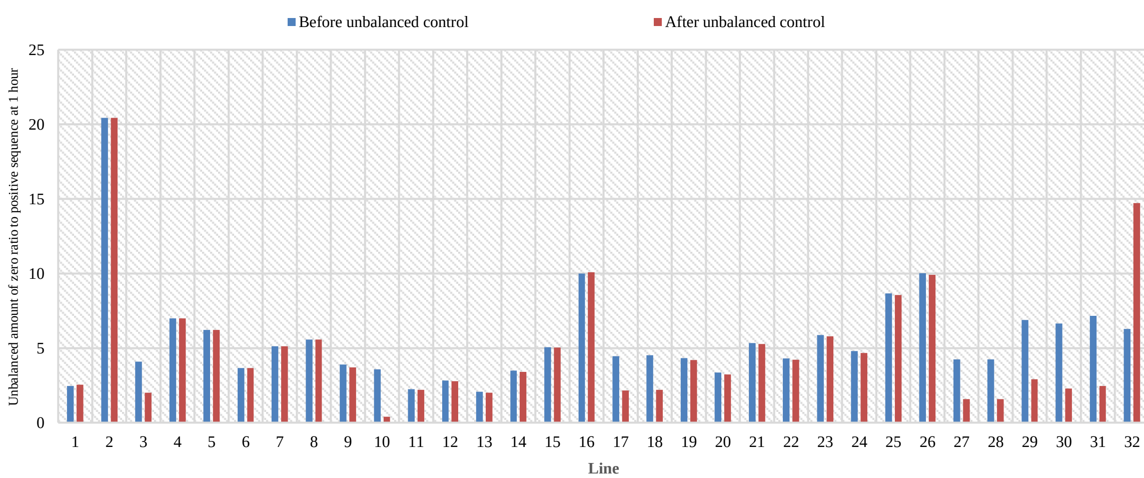


Fig. 7. Unbalanced amount of zero sequence ratio to positive sequence at 1 hour by transmission lines.

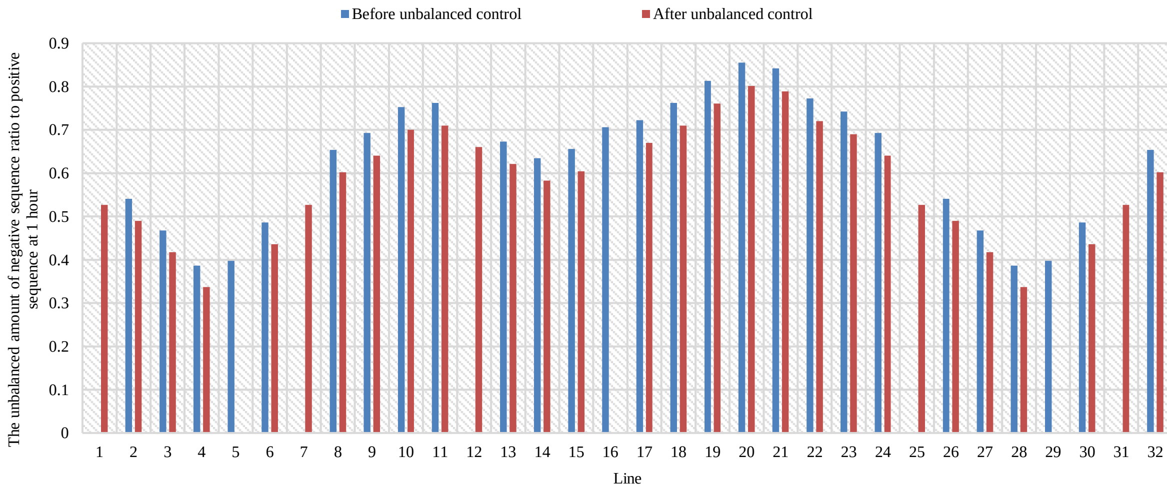


Fig. 8. The unbalanced amount of negative sequence ratio to positive sequence at 1 hour by transmission lines.

5. TEST SYSTEMS UNDER STUDY TO EVALUATE THE SECURITY OF MULTI-CARRIER SYSTEMS

In this part, a case-study network of 33 electric buses (Fig. 5 (a)), a network of 25 nodes of natural gas (Fig. 5 (b)), and a network of 20 nodes of heat (Fig. 5 (c)) are adopted to justify the proposed scheme. The networks are first operated without applying any control over the imbalances and the voltage, pressure, and temperature are calculated. Then, by applying control over the introduced indicators, the amount of unbalance index is reduced to investigate the effect of this issue on the above components.
5.1. Analysis of the current unbalance index in the network by the TLBO.

First, the network is examined normally and without any control over the amount of positive, negative, and zero sequence components of the current passing through the transmission lines. In the next case, distributed productions with the possibility of unbalanced production capacity in each phase enter the network separately, in this test system, the maximum production in each phase is 3 kW. The outcomes obtained for 24 hours a day before and after controlling the unbalanced rate are depicted in Fig. 6 (a). As illustrated in Fig. 6 (a), after the presence of distributed production, the unbalanced current amount in the distribution network has been reduced. In addition, the same outcomes can be expressed for the negative sequence mode, which is depicted in Fig. 6 (b).

The results of subfigures of Fig. 6 indicate that the presence of distributed productions strongly affects the unbalanced current rate. For example, suppose the results are examined for the first hour separately on transmission lines. These results will be in the form of Fig. 7. Comparing the outcomes of the separation of transmission lines, it can be evident that although in some cases the amount of unbalanced index has increased, in general, it has a decreasing effect on all network feeders, which is the most important result of control by distributed generation. The same argument arises for Fig. 8 for negative sequences.

It has already been said that controlling the unbalanced amount of the electrical distribution network can affect the entire MCESs. One of the most important parameters in any network is the profile of the bus or node in that network. For example, in the thermal network, temperature changes are important in a way that all other components are affected by this issue. For this purpose, we examine the temperature of the regional network before and after controlling the unbalanced amount in the electrical network. The outcomes of temperature behavior of thermal network are illustrated in Fig. 9.

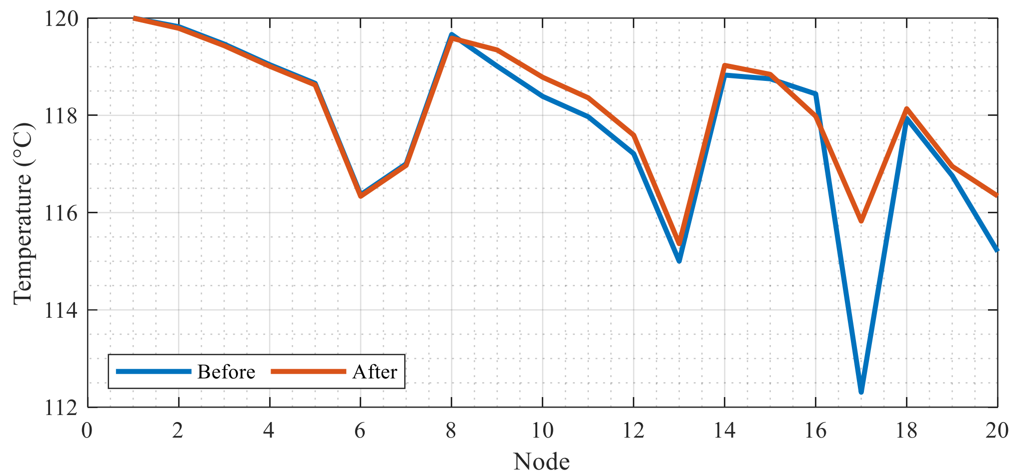


Fig. 9. Temperature behavior of thermal network nodes before and after unbalanced current control in the electrical distribution network.

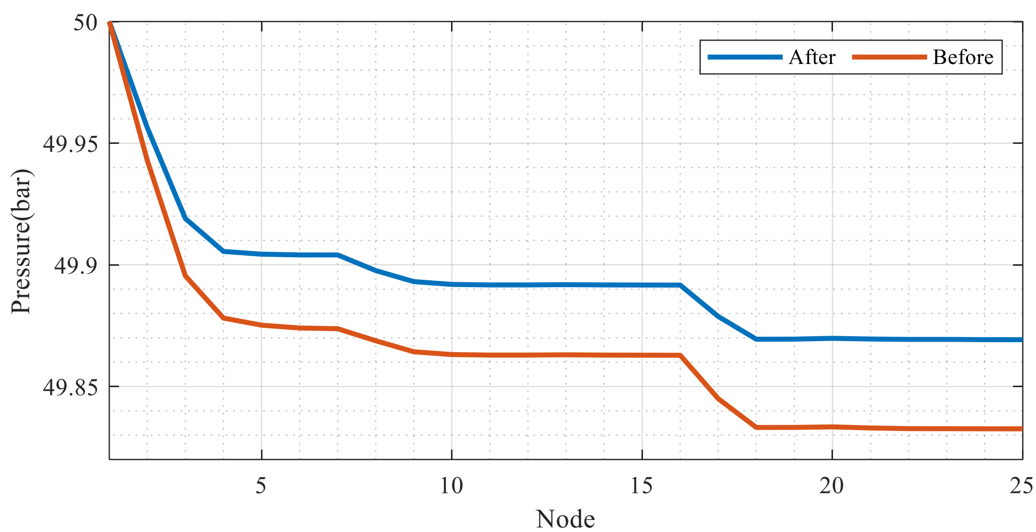


Fig. 10. Pressure behavior of natural gas network nodes before and after unbalanced current control in the electrical distribution network.

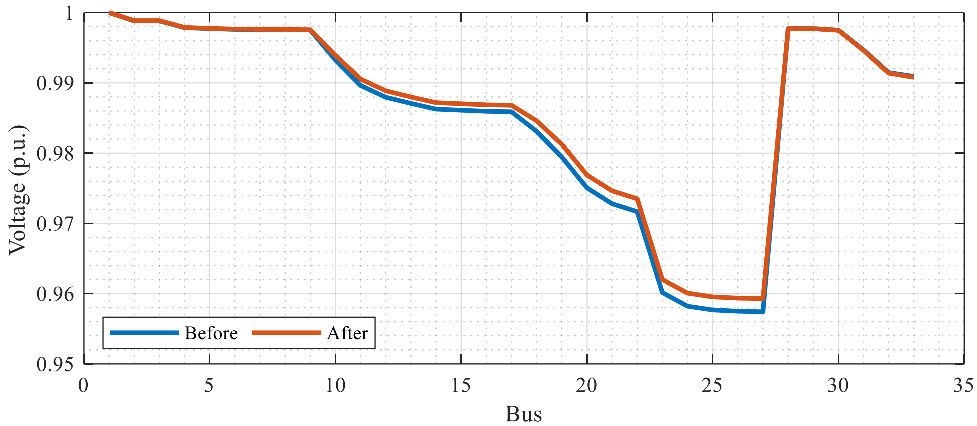


Fig. 11. Voltage behavior of electrical network buses before and after unbalanced current control in the electrical distribution network.

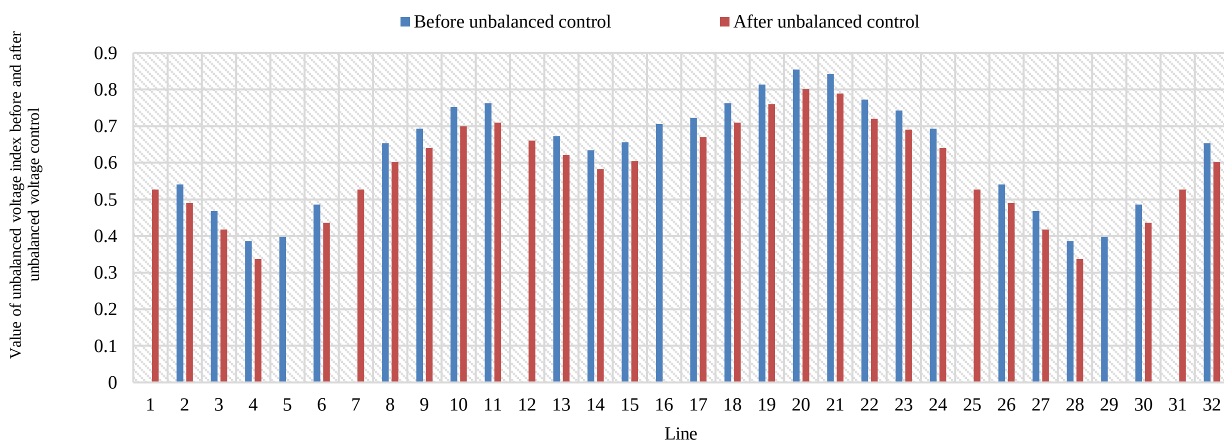


Fig. 12. Value of unbalanced voltage index before and after unbalanced voltage control in electrical distribution network by hours.

According to Fig. 9, it is obviously evident that by performing the process in unbalanced distribution networks and controlling the unbalanced amount in these networks, it is possible to control other parameters in multi-carrier networks. It is observed that after the presence of distributed productions in the electrical network to control the unbalanced amount, the temperature profile in the regional heating network has improved on average, which will have a positive effect on the entire multi-carrier network.

From the perspective of the natural gas network, this issue can be expressed in the amount of gas pressure anywhere in the network. For example, the amount of natural gas pressure at any point in the network before and after the unbalanced control is illustrated in Fig. 10.

From the outcomes of Fig. 10, it is found that by controlling the unbalanced amount in the unbalanced distribution network, the natural gas network pressure is affected and this is the same interaction of the unbalanced distribution network on other multi-carrier networks. The reason for the reduction in pressure is the consumption of natural gas by distributed generation units to control the unbalanced amount.

In addition, the voltage profile of the unbalanced distribution network in the phase a is depicted in Fig. 11, which is drawn only for the first hour. The outcomes before/after the control of the unbalanced amount in Fig. 11 demonstrate that the amount of voltage profile has been improved in these conditions, which is also true as a result of other phases.

The outcomes of Fig. 9 reveal that in general, the voltage index has improved in most hours according to the network conditions and its load. Also, it should be noted that choosing the right position for the installation of capacitors is very important at this stage, which is in the form of planning and will not be a problem in the subset. For this reason, it is not addressed in this treatise.

Another positive side of unbalanced current control in the electrical distribution network is related to the total losses, which has also improved the amount of losses in the distribution network. The numerical results to testify this saying are given in Table 2.

Remark 2: In a general perspective, it can be said that controlling the unbalanced current in the unbalanced electrical distribution network has its own advantages and disadvantages. In other words, in some cases, it can express itself positively and in some cases negatively, which according to the goals of the operator a balance between these issues can be established. Obviously, all the characteristics of a network depend on the bass profile or its nodes. Therefore, a positive or negative change in the characteristics of the buses or nodes will also affect the network parameters, which have been avoided to avoid talking too much in this section.

5.1. Analysis of Voltage Unbalance Index by Training the TLBO in the Multi-Carrier Network

In examining the voltage unbalance index, we first consider capacitors with a maximum capacity of 3 KW in each phase that can also inject power unbalanced. By injecting this amount of power into the network, the unbalanced index will be examined and its effects on the multi-carrier network will also be evaluated. The sum of the unbalanced voltage index in general before and after applying the control on the unbalanced amount is given in Table III. The outcomes denote that in general, the unbalanced voltage in the network has improved due to the presence of capacitors. If the purpose is to compare these results hour by hour, it can be carried out based on Fig. 12.

Table 2. ***Electrical Network Losses Before and After Unbalanced CURRENT CONTROL in the Electrical Distribution Network.***

Before unbalanced control	After unbalanced control
238.5472	210.4322

Table 3. ***Total Unbalanced Voltage Index Before and After Unbalanced Voltage Control in Electrical Distribution Network.***

Before unbalanced control	After unbalanced control
14.0130	13.6366

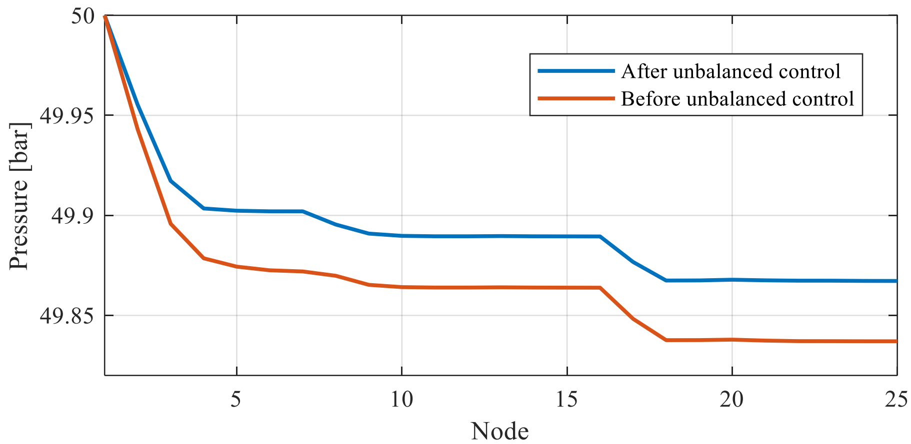


Fig. 13. Pressure behavior of natural gas network nodes before and after unbalanced voltage control in the electrical distribution network.

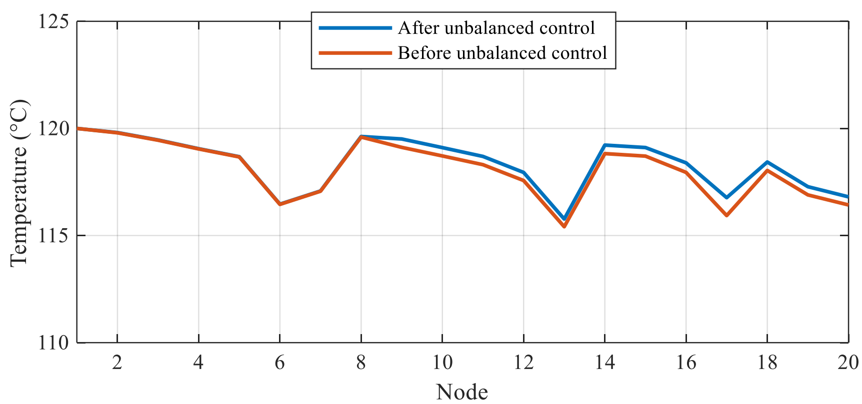


Fig. 14. Temperature behavior of thermal network nodes before and after unbalanced voltage control in the electrical distribution network.

A noteworthy point about the unbalanced voltage index is that due to the fact that this index is in direct contact with reactive power and indirectly affects the amount of active power, its changes affect the amount of mains pressure profile. Natural gas and heating network temperature are not very noticeable. The results related to natural gas network pressure are given in Fig. 13, which is an example of the effects of the voltage unbalance index on multi-carrier networks. Obviously, this index, similar to the previous stage, will have different effects on the whole set of multiple carriers, which have been omitted in this section due to the repetitive form of expressing the results.

The behavior of the thermal network after installing the capacitors is shown in Fig. 14, which shows the improvement of the thermal profile. This is one of the positive effects of unbalanced voltage control in the electrical distribution network.

The main advantage of the proposed TLBO algorithm over the other algorithms is that it is a parameter-free technique and the effectiveness of the method is not affected by the algorithm parameters. On the other hand, it should be mentioned that most of the heuristic algorithms are evaluated using their convergence curve. the convergence curves play a decisive role in the heuristic algorithms' merit-seeking ability and convergence speed, and it has been shown in many algorithms that the performance of the algorithm can be evaluated by introducing these curves. Hence, in this paper, by introducing the convergence curves the obtained results and the proposed method can be evaluated. For example, the convergence curve related to the voltage unbalanced index reduction at hour 1 is shown in Figure (15).

It should be noted that, since the TLBO algorithm does not require any parameters to be tuned, this fact makes the implementation of TLBO more accurate. In addition, this algorithm uses the mean value of the population to update the solution. Moreover, the TLBO algorithm has updated the objective function in two phases. These issues have many positive effects on the accuracy and efficiency of the proposed method.

From the results point of view, it can be seen that the voltage of electric buses, the pressure of gas nodes, and also the temperature at heat nodes are in the allowable and reasonable range. Since these variables determine the rest of the network parameters, the correct values of these variables guaranteed the results of the entire system.

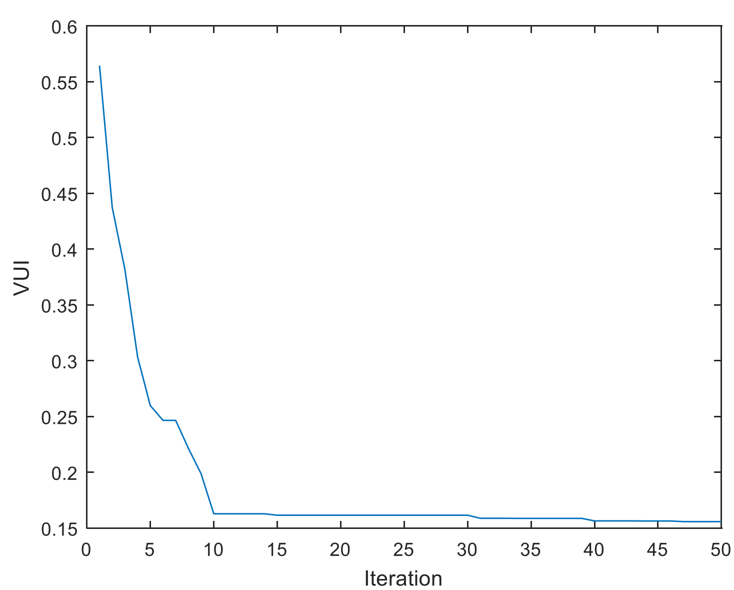


Fig. 15. Convergence curve related to the voltage unbalanced index re-duction at hour 1.

6. CONCLUTION

In this work, the LF problem of a distributed network has been solved by the Forward-Backward scheme while the potential training of TLBO algorithm is adopted to examine the effects of unbalanced in an integrated power system. A network with various case studies including IEEE 33-bus system, a natural gas network with 25 nodes and a heat network with 20 nodes have been studied for the analysis purposes. Various unbalanced indicators have been formulated to control the unbalanced amount in the unbalanced distribution network, and to examine the negative effects of this issue in all multi-carrier energy systems (MCESs). In this application, the TLBO algorithm has been constructed according to the required characteristics of the studied network. By adopting an objective function, the procedure of TLBO is executed in such a way that optimizes the LF problem of the multi-carrier system. The comprehensive numerical outcomes revealed that the heuristic algorithm-based scheme is effective for the optimal solution of the LF problem with the unbalanced to enhance the resilience of power grids under multiple line failures.

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