A practical approach for distribution network load balancing by optimal re-phasing of single phase customers using discrete genetic algorithm

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Abstract

Voltage and current imbalance have adverse impacts on power systems such as power loss increase, communication interference, component life time reduction etc. This paper attempts to look at unbalance impacts from Distribution System Operator's (DSO) view point in order to understand them and then mitigate the impacts. Since solving the unbalance conditions is influenced by the way the imbalance is defined, standard unbalance indexes are studied, and new indexes are proposed in this paper. Re-phasing of the customers is selected to reduce the level of unbalance in distribution feeders. Due to the huge number of customers, a wide variety of choices can be selected for re-phasing of customers which makes the solution questionable. Therefore, Discrete Genetic Algorithm (DGA) as a metaheuristic method has been utilized in order to distribute customers among the network phases optimally considering the fact that DSO has a limitation for the re-phasing practice. The aim is to reduce the unbalance indexes and power losses throughout the network. Simulations have been carried out on a real test case network which shows the importance of load balancing and its effects on the power losses, voltage profile and current flow in that network. The effectiveness of the proposed indexes has also been demonstrated for the four-wire multi-grounded distribution system. Since re-phasing of the majority of customers in distribution networks seems impractical, a re-phasing limitation is also investigated in this paper, and some practical suggestions of optimal load balancing in a real-world low voltage distribution systems have been presented here. Results show the importance of load balancing in power loss reduction and voltage unbalance improvement in the low voltage four-wire multi-grounded distribution system. They also illustrate that by changing phases of a few customers, power losses and unbalance indexes will be improved significantly.

Keywords: Load balancing, unbalance index, losses reduction, voltage unbalance, re-phasing, discrete genetic algorithm.

Nomenclature

r_a	resistance of phase *a* ($\Omega/_{km}$)
h_b, h_a	height of phase *a* and *b* (*m*)
d_{ab}	distance between phase *a* and *b* (*m*)
GMR_a	geometric mean radius of phase *a*
f	network frequency
ρ	ground resistivity
U_{ref}	reference bus voltage
$I_{in}, I_{ic}, I_{ib}, I_{ia}$	injected currents to the neutral and phases *c*, *b* and *a* of i^{th} load,

	respectively
S_{ic}, S_{ib}, S_{ia}	customers power in the phases *c, b* and *a*, respectively
$U_{ia}, U_{ib}, U_{ic}, U_{in}$	voltages with respect to the earth at node i
$J_{\ell g}, J_{cc}, J_{\ell b}, J_{\ell a}$	currents in line l
M	set of lines fed by node *j*
U_{av}	amount of average line voltage
U_{-}	negative sequence of voltage
U_{+}	positive sequence of voltage
U_0	voltage zero sequence component
I_0	current zero sequence component
I_{-}	current negative sequence component
I_{+}	current positive sequence component
N_n	number of nods
$R_{a,i}$, $R_{b,i}$ $R_{c,i}$, and $R_{n,i}$	resistance of phases *a, b, c,* and neutral wire of i^{th} branch, respectively
$I_{a,i}$, $I_{b,i}$ $I_{c,i}$, and $I_{n,i}$	current of phases *a, b, c,* and neutral wire of i^{th} branch, respectively

RPh_i	A binary variable that is equal to 1 when i^{th} customer is re-phased
RPh^{max}	maximum number of re-phasable customers
$IEC\_U_{\max}$	maximum permissible voltage unbalance
IEC_U_l	voltage unbalance at node l
P_i	possibility of parent i
WC	the worst cost between parents
C_i	cost of parent i
β	selection pressure

1. Introduction

Power quality has become a considerable issue over the past years thus a part of power systems studies has been devoted to increasing it. The power quality studies investigate the effects of voltage harmonics, flickers, voltage sag and swell, notching, unbalanced voltage, etc on the stability of a power system [1].

Load unbalance is one of the conventional problems in the distribution networks [2]. It is caused by inappropriate distribution of demands among network phases, variety of customers usages, existence of unbalanced three-phase loads and distribution networks nonsymmetrical impedances. The load unbalance causes current unbalance, and consequently voltage unbalance in the network. The voltage and current unbalance provoke network losses, voltage drop, heating of components and eventually reduction of the network efficiency. IEEE, IEC, and NEMA propose different indexes to evaluate the voltage and current unbalances.

1-1- Literature review

Many works have been carried out about load unbalance and its effects on distribution networks and their components. In [3], unbalance effects on distribution network transformers (DT) have been investigated. In [4-7], effects of unbalance on induction motors have been studied and in [8-13] the effects of unbalance on doubly fed induction generators have been investigated. References [14-22] have also analyzed different unbalance aspects in converters. Increased neutral line voltage due to unbalance loads has been studied in [23]. Authors in [24] have focused on the unbalance issue of the four-wire distribution systems. The zero sequence current has been considered in the paper. The authors have modified available definitions and attempted to display the relationship between unbalance degree and its consequent effects on the distribution system.

Many papers have been published about the load unbalance decrement domain. Generally, these studies are divided into two main categories. In the first category, active and reactive power compensation is applied to the network to mitigate the voltage and current unbalances in electrical distribution networks. In some researches of this category, capacitor placement has been conducted to mitigate the voltage and current unbalances in electrical distribution networks. Authors of [25] have presented a reactive power compensation method to diminish the negative and zero sequence loads to boost the power factor of unbalanced four-wire distribution feeders. Star and delta connected static reactive power compensators have been employed to inject a different amount of reactive power to each phase. The noticeable deficiencies of the aforementioned method in the reference [25] are as follows: 1) high initial investment cost, 2) high over haul and maintenance costs, especially for the switchable capacitors, 3) abrupt increase in the system unbalance level due to the probable fail of the installed capacitor bank in one of the phases. With regards to these deficiencies, the mentioned method cannot be a suitable choice for distribution companies to improve unbalance level in distribution systems. In some other researches in this category, distributed generators and energy storage units are utilized to mitigate the voltage and current unbalances in electrical distribution systems. In this regard, reference [26] has presented a technique to reduce the voltage and current unbalances in the system with high penetration of photovoltaic which can be seen as a controllable energy storage unit. Reference [27] has also suggested a control algorithm in an energy system to investigate the energy storage capability in order to prevent the system from voltage unbalances and network losses. In last, the method for mitigation of voltage and current unbalances, using distribution static var compensators and dynamic voltage restorers, has been discussed. Authors in [28] have used a three-phase insulated gate bipolar transistor (IGBT)-based static var compensator to reduce the voltage and current unbalances in the grid. In [29], the application of distribution static var compensators and dynamic voltage restorers have been addressed for voltage unbalance reduction within low voltage distribution networks. In this reference, unequal distribution of single-phase rooftop PVs between the three phases have been considered. The main drawbacks of the first category is the high initial investment costs and high over haul and maintenance costs. In the second category, the load balancing is mainly carried out by re-phasing of the single phase costumers. For radial distribution systems, [30] has suggested a method based on genetic algorithm (GA) to solve the problem of phase rearrangement among distribution transformer banks. In [31], a model has been proposed for simultaneous optimization of re-phasing, reconfiguration, and DG placement in order to decrease the total cost and improve the voltage profile without taking into account the imbalance indices. Similarly, a model has been suggested in [32] for phase arrangement of laterals and the distribution transformers based on bacterial foraging (BF) oriented by particle swarm optimization (PSO) algorithm (BF-PSO). In [33], the cost of re-phasing is considered using an expert system for reducing the neutral current. Reference [34] investigates the effects of the load variability and phase imbalance on low-voltage grid losses and new indices have been proposed to reduce the network loses. In [35] a model has been presented for decomposing the unbalance of load variability into the two parts of systematic unbalance and random unbalance for better demand side management. [36] and [37] have proposed methods based on Immune Algorithm (IA) and Particle Swarm Optimization (PSO) algorithm, respectively. They have proposed these methods to rearrange the distribution transformers and phases to enhance the network balance. The main drawback of the second discussed category is missing consideration of the zero sequences of voltages and currents which can be very high in the low voltage four-wire grounded distribution networks.

Two main questions we are aiming to respond in this paper as follows:

1. In reality, it is clear that re-phasing can be applied for limited number of customers. The extent that this limitation influences the balancing of low voltage distribution network is the question intended to answer in this paper.
2. Whether inclusion of voltage and current's zero sequence components in unbalance indexes improve their performance considering the fact that the value of voltage and current's zero sequence component in low voltage distribution systems is high.

1-2- Paper contribution

Due to the asymmetrical impedances of the low voltage distribution networks, a small amount of voltage unbalance is inevitable. Unequal distribution of the single-phase loads along the three phases is the main reason for the current and voltage unbalance in the distribution networks [38]. Therefore, in this paper, an effort has been accomplished to focus on single phase customers' re-phasing in order to improve the voltage, and current unbalance indexes and power losses. It should be noted that the percentage of zero sequence of voltages and currents in the low voltage distribution systems are relatively high in comparison to the medium voltage distribution systems. Since the zero sequences of voltage and current have been ignored in the NEMA, IEC and IEEE standards, in this paper, a new index is proposed to evaluate the unbalance of voltage and current, especially for the low voltage distribution networks. The newly proposed indexes will be able to remove the deficiency of NEMA, IEC and IEEE indexes. A DGA is used to get the optimum customers re-phasing considering the defined index. Because of the practical and financial constraints of DSOs, only a limited number of customers might get re-phased in a distribution network. Therefore a limitation for the number of re-phased customers is also investigated in this paper.

In summary, the main contributions of this paper are highlighted as follows:

- Proposing a simple and efficient index to evaluate the voltage and current unbalance of four-wire grounded distribution networks.
- Investigating the limitation for the number of re-phased customers which this limitation stems from practical difficulties associated with re-phasing of each customer by DSO.
- Establishing the importance of load balancing in the four-wire distribution networks.
- Presenting a comparative study between application of the IEEE, IEC, and NEMA indexes in four-wire grounded distribution networks.
- Using appropriate discrete genetic operators which are specially designed for the load balancing problem.

1-3- Paper Organization

This paper is organized as follows: Four-wire network modeling and load flow method are proposed in section 2. Next, the NEMA, IEC and IEEE indexes and a new index are described in section 3. Following that, load balancing problem in distribution networks including objective function and constraints are proposed in section 4. The discrete genetic algorithm is explained in section 5. Afterward section 6 has been devoted to numerical results and finally, conclusion is proposed in section 7.

2. Modeling

2.1. Network model

In order to conduct accurate study of a real three-phase distribution network, apart from self impedances of phases, mutual impedances between

- Neutral wire and phases
- Neutral wire and ground
- Phases and ground

should be regarded. Fig.1 demonstrates the model of a four-wire multi-grounded distribution line [39].

Fig. 1 *Model of a three-phase four-wire multi-grounded distribution line (reproduced according to [39])*

The impedance matrix can be represented as follows [39]:

$$[Z_L]=\begin{bmatrix} \bar{Z}_{aa} & \bar{Z}_{ab} & \bar{Z}_{ac} & \bar{Z}_{an} & \bar{Z}_{ag} \\ \bar{Z}_{ba} & \bar{Z}_{bb} & \bar{Z}_{bc} & \bar{Z}_{bn} & \bar{Z}_{bg} \\ \bar{Z}_{ca} & \bar{Z}_{cb} & \bar{Z}_{cc} & \bar{Z}_{cn} & \bar{Z}_{cg} \\ \bar{Z}_{an} & \bar{Z}_{bn} & \bar{Z}_{cn} & \bar{Z}_{nn} & \bar{Z}_{gn} \\ \bar{Z}_{ga} & \bar{Z}_{gb} & \bar{Z}_{gc} & \bar{Z}_{gn} & \bar{Z}_{gg} \end{bmatrix} \tag{1}$$

The self impedances and mutual impedances between phases are calculated using the well-known Carson's equations considering the fact that the ground acts as a perfect conductor [40]:

$$\bar{Z}_{aa} = r_a + j4\pi\times10^{-4} f.Ln\left(\frac{2h_a}{GMR_a}\right) \Omega/km \tag{2}$$

$$\bar{Z}_{ab} = j4\pi\times10^{-4} f.Ln\left(\frac{\sqrt{d_{ab}{}^2+(h_a+h_b)^2}}{\sqrt{d_{ab}{}^2+(h_a-h_b)^2}}\right) \Omega/km \tag{3}$$

where:

r_a	resistance of phase *a* (Ω/km)
h_b, h_a	height of phase *a* and *b* (*m*)
d_{ab}	distance between phase *a* and *b* (*m*)
GMR_a	geometric mean radius of phase *a*
f	network frequency
$Ln(z)$	gives the natural logarithm of z (logarithm to the base e which e is the exponential constant with the numerical value $\cong 2.71828$)

The ground self-impedance ($\bar{Z}_{gg}$) and the mutual impedance ($\bar{Z}_{ag}$) are obtained by equations (4) and (5) as follows [39-40]:

$$\bar{Z}_{gg} = \pi^2\times10^{-4} f - j0.0386\times8\pi\times10^{-4}.f + j4\pi\times10^{-4}.f\times Ln\frac{2}{5.6198\times10^{-3}} \tag{4}$$

$$\bar{Z}_{ag} = j2\pi f \times 10^{-4} Ln \frac{h_a}{\sqrt{\rho / f}} \tag{5}$$

where ρ is ground resistivity. It is determined based on ground return condition which is 100 ohm-meter for average damp earth [41].

2.2. Transformers' model

Two different aspects can be regarded when a transformer performs under unbalance situations including:

- Unbalance propagation from LV network to MV network

  Since transformers determine how the low voltage unbalance penetrates into the upstream voltage level (medium voltage), consideration of transformer when the under-study distribution system includes different voltage level such as 400 V and 20 kV, is very important. Unbalance propagation from low voltage to medium voltage distribution system requires simulation of magnetic fluxes and wiring of the transformer.

- power losses

  Power losses of transformers are increased in the presence of unbalance loads. Power loss rise due to series impedance of transformer was readily calculated by power flow studies whereas impact of unbalance on core losses of transformer needs finite element simulation of the transformer core.

Since the understudy distribution system just has one voltage level in addition of the fact that increment of core transformer losses due to unbalance loads is negligible comparing to distribution feeders losses, a simple model of transformer has been used in this study.

2.3. Unbalance load flow

The proposed power flow is a modified method based on reference [39] to analyze unbalanced radial networks. This method is capable of considering ground effects and neutral voltage calculation. The backward-forward sweeping power flow has been used in the proposed method. The backward sweep is used to calculate current plus voltage drop of branches and forward sweep is performed to update voltages according to voltage drops.

The unbalance load flow has three steps as follows:

Step 1) calculating the buses' current

$$\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \\ I_{in} \\ I_{ig} \end{bmatrix}^{(k)} = \begin{bmatrix} \left(\dfrac{S_{ia}}{U_{ia}-U_{in}}\right)^{(k-1)^*} \left|\dfrac{U_{ia}-U_{in}}{U_{ref}}\right|^{m} \\ \left(\dfrac{S_{ib}}{U_{ib}-U_{in}}\right)^{(k-1\ )^*} \left|\dfrac{U_{ib}-U_{in}}{U_{ref}}\right|^{m} \\ \left(\dfrac{S_{ic}}{U_{ic}-U_{in}}\right)^{(k-1)^*} \left|\dfrac{U_{ic}-U_{in}}{U_{ref}}\right|^{m} \\ \dfrac{-Z_{gi}}{Z_{nni}+Z_{gi}}\left(I_{ia}^{(k)}+I_{ib}^{(k)}+I_{ic}^{(k)}\right) \\ \dfrac{-Z_{nni}}{Z_{nni}+Z_{gi}}\left(I_{ia}^{(k)}+I_{ib}^{(k)}+I_{ic}^{(k)}\right) \end{bmatrix} \qquad (6)$$

where U_{ref} is the reference bus voltage, $I_{in}, I_{ic}, I_{ib}, I_{ia}$ are the injected currents to the neutral and phases *c, b* and *a* of i^{th} load, respectively. S_{ic}, S_{ib}, S_{ia} are customers power in the phases *c, b* and *a* respectively, and $U_{ia}, U_{ib}, U_{ic}, U_{in}$ are respectively the voltages of phases a, b, c, and neutral wire to the earth at node i. m equals to zero for constant power loads and equals to 1 for constant current loads. Furthermore, it equals to 2 for constant impedance loads [42]. Z_{gri} is earth impedance in node *i*:

$$Z_{gi} = Z_{gri} + Z_{ggi} \tag{7}$$

Step 2) calculating branches current (backward sweeping)

In this step, current of branches is calculated from the end of the line (line section in the last layer) to the reference bus. The current in the line section *l* is given by:

$$\begin{bmatrix} J_{\ell a} \\ J_{\ell b} \\ J_{\ell c} \\ J_{\ell n} \\ J_{\ell g} \end{bmatrix}^{(k)} = \begin{bmatrix} I_{ja} \\ I_{jb} \\ I_{jc} \\ I_{jn} \\ I_{jg} \end{bmatrix}^{(k)} + \sum_{m \in M} \begin{bmatrix} J_{ma} \\ J_{mb} \\ J_{mc} \\ J_{mn} \\ J_{mg} \end{bmatrix} \tag{8}$$

where $J_{\ell g}, J_{cc}, J_{\ell b}, J_{\ell a}$ are currents in line *l* and *M* is set of lines fed by node *j*.

Step 3) calculating buses voltage (forward sweeping)

Calculating the voltages starts from the reference bus toward the end. The voltage at node *j* is given by:

$$\begin{bmatrix} U_{ja} \\ U_{jb} \\ U_{jc} \\ U_{jn} \\ U_{jg} \end{bmatrix}^{(k)} = \begin{bmatrix} U_{ia} \\ U_{ib} \\ U_{ic} \\ U_{in} \\ U_{ig} \end{bmatrix}^{(k)} - \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} & Z_{ag} \\ Z_{ab} & Z_{bb} & Z_{bc} & Z_{bn} & Z_{bg} \\ Z_{ac} & Z_{bc} & Z_{cc} & Z_{cn} & Z_{cg} \\ Z_{an} & Z_{bn} & Z_{cn} & Z_{nn} & Z_{ng} \\ Z_{ag} & Z_{bg} & Z_{cg} & Z_{ng} & Z_{gg} \end{bmatrix} \begin{bmatrix} J_{\ell a} \\ J_{\ell b} \\ J_{\ell c} \\ J_{\ell n} \\ J_{\ell g} \end{bmatrix} \tag{9}$$

Steps 1 to 3 are repeated until conditions (10) are met.

$$\begin{cases} U_{ia}^{(k)} & -U_{ia}^{(k-1)} & \prec \varepsilon \\ U_{ib}^{(k)} & -U_{ib}^{(k-1)} & \prec \varepsilon \\ U_{ic}^{(k)} & -U_{ic}^{(k-1)} & \prec \varepsilon \\ U_{in}^{(k)} & -U_{in}^{(k-1)} & \prec \varepsilon \\ U_{ig}^{(k)} & -U_{ig}^{(k-1)} & \prec \varepsilon \end{cases} \tag{10}$$

The initial voltage is considered equal to the reference bus voltage in all buses [39].

$$\begin{bmatrix} U_{ia} \\ U_{ib} \\ U_{ic} \\ U_{in} \\ U_{ig} \end{bmatrix}^{(\circ)} = \begin{bmatrix} U_{ref} \\ a^2.U_{ref} \\ a.U_{ref} \\ \circ \\ \circ \end{bmatrix} \quad , \quad a = e^{j\frac{2\pi}{3}} \tag{11}$$

3. Unbalance indexes

3.1. Existing Standards in balancing

Up to now, various standards have been proposed as the unbalance indexes measuring the voltage and current unbalances. Some well-known indexes will be presented in the following.

3.1.1. NEMA Standard

According to the NEMA Standard, the general definition of unbalance voltage coefficient is as follows:

$$MDV = \frac{\Delta U_{\max}}{U_{av}} \times 100 \tag{12}$$

where $\Delta U_{\max}$ is the maximum voltage difference from average line voltage. U_{av} is the amount of average line voltage [24, 43]. Unbalance in voltages angles (with equal magnitude) can not be observed by using the equation (12), however, the voltage unbalance exists. The current unbalance index MDI that is represented in equation (13) is computed by replacing current instead of voltage which similarly carries the discussed deficiency:

$$MDI = \frac{\Delta I_{\max}}{I_{av}} \times 100 \tag{13}$$

3.1.2. IEC Standard

International electronic committee (IEC) defines voltage unbalance coefficient as follows:

$$VUF = \frac{|U_-|}{|U_+|} \times 100\% \tag{14}$$

where U_- is the negative sequence of voltage and U_+ is the positive sequence of voltage [5, 44]. Also, the current unbalance index is defined in the same way as follows:

$$IUF = \frac{|I_-|}{|I_+|} \times 100\% \tag{15}$$

3.1.3. IEEE Standard

In 1996, IEEE defined a definition of voltages unbalance relation as follows [45]:

$$TDV = \frac{U_-}{U_+} \times 100 \tag{16}$$

For declaration of the current unbalance index, *TDI* is defined like voltage unbalance index [24]:

$$TDI = \frac{I-}{I+} \times 100 \tag{17}$$

A deficiency that appears in the IEC and IEEE unbalances indexes is the renunciation of the current and voltage’s zero sequence components. Also, there are some states of voltage and current unbalances that negative current sequence becomes zero while there is a current unbalance (see figure 2 as an instance). The negative current sequence for this figure is calculated (18).

$$I- = \frac{1}{3}\left[(i_a) + \left(a^2 i_b\right) + \left(a i_c\right)\right] = \tag{18}$$

$$\frac{1}{3}\left[3 + (1 < 240)\left(\sqrt{3} < -90\right) + (1 < 120\ )\left(\sqrt{3} < 90\right)\right] =$$

$$\frac{1}{3}\left[3 + \left(\sqrt{3} < 150\right) + \left(\sqrt{3} < 210\right)\right] = 0$$

Fig. 2 *A sample of current unbalance*

3.2. Proposed balancing indexes

Equation (19) is an extensive relation for the unbalance condition of current in four-wire distribution systems. Since all of the existing sequence components has been considered in this equation, it can measure any probable unbalances in a distribution system.

$$NFI = \frac{|I_0| + |I_-|}{|I_+|} \tag{19}$$

where *NFI* is the current unbalance index, I_0 is the current zero sequence component, I_- is the current negative sequence component and I_+ is the current positive sequence component. In the same way, voltage unbalance index presented as follows:

$$NFV = \frac{|U_0| + |U_-|}{|U_+|} \tag{20}$$

where *NFV* is the voltage unbalance index and U_0, U_- and U_+ are zero, negative and positive sequence components of voltage respectively.

3.3. Extension of Unbalance indexes in Distribution Networks

All above voltage indexes demonstrate the amount of unbalance in a 3-phases voltage vector, however, in distribution networks the amount of voltage unbalance in each bus can be different from nearby buses (the same trend happens for current). Therefore the proposed index should be extended in such a way that the unbalance measurement in a network can be carried out. The proposed index equation (20) has been extended as follows:

$$X = \frac{1}{n}\sum_{j=1}^{n} K_j \tag{21}$$

where n is the number of distribution network buses without the reference bus. K is one of the indexes of IEEE, NEMA, IEC or the proposed indexes.

4. Load balancing by re-phasing of single phase customers

4.1. Explanation of considered case

One of the common ways of keeping the load balance in low voltage distribution networks is re-phasing the single phase customers. It can lead to more reduction of unbalance indexes by increasing the number of re-phased costumers, but seemingly impractical. It is because of practical difficulties for DSOs to re-phase many customers. The problem can be taken into account as an optimization model with objective functions and constraints as below:

4.2. Objective functions

Minimizing the voltage and current unbalance indexes and the network losses are considered as objective function. Feeding phase of each customer is a decision variable. However, multi objective optimization may be a better approach to balance the voltages and currents, it is focused on comparing the NEMA, IEC and IEEE indexes and proposing new indexes in this paper. Equations (22) to (30) are presented as objective functions:

$$OF_1 = \sum_{i=1}^{N_b}\left(R_{a,i}\left|I_{a,i}\right|^2 + R_{b,i}\left|I_{b,i}\right|^2 + R_{ci}\left|I_{c,i}\right|^2 + R_{n,i}\left|I_{n,i}\right|^2 \right) \tag{22}$$

$$OF_2 = \frac{1}{N_n}\sum_{i=1}^{N_n} MDV_i \tag{23}$$

$$OF_3 = \frac{1}{N_b}\sum_{i=1}^{N_b} MDI_i \tag{24}$$

$$OF_4 = \frac{1}{N_n}\sum_{i=1}^{N_n} VUF_i \tag{25}$$

$$OF_5 = \frac{1}{N_b}\sum_{i=1}^{N_b} IUF_i \tag{26}$$

$$OF_6 = \frac{1}{N_n}\sum_{i=1}^{N_n} TDV_i \tag{27}$$

$$OF_7 = \frac{1}{N_b}\sum_{i=1}^{N_b} TDI_i \tag{28}$$

$$OF_8 = \frac{1}{N_n}\sum_{i=1}^{N_n} NFV_i \tag{29}$$

$$OF_9 = \frac{1}{N_b}\sum_{i=1}^{N_b} NFI_i \tag{30}$$

where N_n is the number of nodes. N_b is the number of branches. $R_{a,i}$, $R_{b,i}$, $R_{c,i}$ and $R_{n,i}$,, are resistances of phases *a*, *b*, *c*, and the neutral wire of the *i*th branch, respectively. $I_{a,i}$, $I_{b,i}$, $I_{c,i}$, and $I_{n,i}$ are currents of phases *a*, *b*, *c*, and the neutral wire of the *i*th branch, respectively.

4.3.Constraints

1) The customer feeding connection should be constant.

2) The number of re-phasing customers should follow Eqn. (31).

$$\sum_{i=1}^{N_c} RPh_i \leq RPh^{max} \tag{31}$$

where N_c is the number of customers. RPh_i is equal to 1, when the i^{th} customer is re-phased. RPh^{max} is the maximum number of re-phasable customers specified by DSO.

3) Current limitation in branches

$$\begin{gathered} |I_i| \leq I_{i,\max} \\ i = \{a_1, b_1, c_1, n_1\}, \{a_2, b_2, c_2, n_2\}, \ldots, \{a_{N_b}, b_{N_b}, c_{N_b}, n_{N_b}\} \end{gathered} \tag{32}$$

where a_1 is phase a in branch 1, b_2 is phase b in branch 2, c_2 is phase c in branch 2, n_{N_b} is neutral wire in branch N_b and N_b is the total number of branches.

4) Limitation in the amount of voltage unbalance on each node.

$$\begin{gathered} IEC\_U_l \leq IEC\_U_{\max} \\ l = 1, 2, \ldots, m \end{gathered} \tag{33}$$

In this equation, $IEC\_U_{\max}$ is the maximum permissible voltage unbalance and IEC_U_l is the voltage unbalance in node l.

4.4. Fitness Function

The constraints and the objective function have been handled in equation (34)

$$\begin{aligned} & Fitness\ Function = Objective\ Function + \\ & PF \times \left(max\left(\left(\sum_{i=1}^{N_c} RPh_i \right) - RPh^{max}, 0 \right) + \sum_{i=1}^{N_n} \left(max(IEC\_U_i - IEC\_U_{max}, 0) \right) \right. \\ & \left. + \sum_{i=1}^{N_b} max\left(|I_i| - I_{i,max}, 0 \right) \right) \end{aligned} \tag{34}$$

To satisfy constraints while optimizing an objective function, it is known to impose a penalty factor (PF) to solutions violating the constraints. Therefore, the final solution of the Genetic Algorithm will fully obey all the constraints since the penalty factor weight is considerable.

5. Optimizing based on genetic algorithm

Genetic algorithms (GA), like many other artificial intelligence methods, are based on natural phenomena. GA has three main parts including crossover, mutation and selection [46]. Due to the efficiency and flexibility of GA, it has been extensively used in numerous fields in recent years. There are many successful GA applications in the power systems, such as optimal power flow [47-48], unit commitment [49], economic dispatch [50-51], capacitor placement [52-53], distributed generations planning [54-56], distribution networks reconfiguration [57], energy management [58], supply restoration [59-60], volt/var/total harmonic distortion control [61], maintenance strategy [62], placement of power quality monitors [63] and voltage regulator placement [64].

After multiple comparisons of the performances, the GA has proved itself as an acceptable algorithm to solve the load balancing problem [30]. Different parts of DGA, related to the load balancing problem, is described in the following. At this regard, phases *a*, *b* and *c* are shown with digits 1, 2 and 3, respectively. Each digit shows a feeding phase of each customer.

5.1. Parent selection

Parent selection is carried out by roulette wheel operator. The possibility of every parent selection is measured by (36):

$$\rho_i = e^{\frac{-\beta \times c_i}{wc}} \qquad (35)$$

$$P_i = \frac{\rho_i}{\sum_{j=1}^{n} \rho_j} \tag{36}$$

where cost the is C_i ,parents betweenworst cost the is WC , i parentpossibility of the is P_i of the parent i and β is the selection pressure.

5.2. Crossover operator

New chromosomes are generated by performing crossover. Commonly-used crossover operators are as follows:

5.2.1. Single point crossover

Single point crossover is the most prevalent crossover which generates two offsprings from two parents. A point is selected from $N_{\mathrm{var}}-1$ possible points. This point is selected by uniform probability distribution function. Each parent is divided into two parts as fraction and remaining, after determining crossover point. Crossover is formed by combination of the rest part of a parent with the fraction part of another parent. As a result, two solutions are generated.

5.2.2. Double point crossover

Double point crossover is same as single point crossover, but two points are selected from $N_{\mathrm{var}}-1$ points, randomly.

5.2.3. Uniform crossover

A binary vector is generated with the size of gene numbers. Each binary digit is generated randomly by uniform probability distribution function. For instance, assume a vector as follows:

$$B = [0 \quad 1 \quad 1 \quad 0 \quad 1 \quad \ldots \quad 0 \quad 1]_{1\times N_{\mathrm{var}}} \tag{37}$$

Two offsprings' chromosomes of two parents are generated as follows:

$$Y_1 = BX_1 + (1-B)X_2 \tag{38}$$

$$Y_2 = BX_2 + (1-B)X_1 \tag{39}$$

Here, three mentioned crossover methods are applied to use good properties of the methods. In this regard, the roulette wheel selection method is used to select the type of crossover. The probability of using single point crossover, double point crossover, and uniform crossover are 0.1, 0.2 and 0.7, respectively. Fig. 3 shows parents and children utilizing mentioned crossovers.

Fig. 3 *Crossover operator in DGA: a) Parent chromosomes; b) children chromosome by using single point crossover; c)children chromosome by using double point crossover; d) children chromosome by using uniform crossover*

5.3. The mutation operator

The mutation operator is applied by changing few genes of parent's chromosomes. The mutation increases the variety of new solutions. This variety is very important to reach the optimum solution. Implementing the mutation increases the probability of obtaining global solutions. If a gene is selected randomly, then, the new mutated value of the gene will be selected from the rest of the states for the gene. For instance, if the gene is 2 (phase b) then mutated gene will be selected from $\{1,3\}$. One of the essential parameters in the mutation operator is mutation ratio. In this paper, mutation ratio is considered to be 0.03. The mutation operator in DGA is explained in Fig. 4.

Fig. 4 *Mutation operator in the discrete genetic algorithm; a) Parent chromosomes; b) children chromosome by one mutated gene; c) children chromosome by two mutated genes.*

Thus, if *n* consumers were located on *m* utility poles, coding would be presented for it as Fig. 5. In this type of coding, for every customer, such as c_1 to c_n, numbers of 1,2,3 are considered so that number 1 is considered as phase *a* and number 2 is considered as phase *b*, and number 3 is considered as phase *c*.

Fig. 5 *Chromosome structure*

6. Simulation results

Simulations are carried out in three scenarios on a modified version of a real 32-bus four-wire distribution system in Iran (Bandar Abbas City) in order to demonstrate the efficiency of the proposed method to balance the voltages and the currents. Single-line diagram of the case is provided in Fig. 6.

In the first scenario, the importance of the voltage and current balance in distribution networks has been demonstrated. The proposed indexes are compared with the conventional indexes in the second scenario, and re-phasing limitation is also investigated in the third scenario.

Fig. 6 *Test system (real system in Bandar-Abass City distribution system)*

6.1. First scenario

Minimizing losses is the main purpose of this scenario (equation (22) is the objective function). Fig.7a highlights voltage of buses before and after load balancing in the network. The condition of the voltage profile for buses close to the feeder end is critical. For example, the voltage of phase *a* at bus 32 is 0.954 p.u., 0.9334 p.u. in phase *b* and 0.8715 p.u. in phase *c*. The voltage magnitudes of different phases get closer after optimal load balancing. The voltage values of 0.9216, 0.9281 and 0.9314 p.u. are obtained after load balancing in bus 32 in phases a, b and c, respectively. As the number of customers has been increased in phase *a* in comparison with phase *c*, the voltage of phase a decreased after optimal load balancing.

Neutral wire voltage is depicted in Fig. 7b. It can be observed that the neutral wire voltage is high especially for the buses close to tail part of the feeder. After load balancing, the neutral wire voltage declines.

The neutral wire current is available in Fig. 7c. The current value is high and inacceptable in primary buses while it has been decreased after load balancing.

Fig. 7 *Balancing importance in the distribution network; a) Voltage profile before and after load balancing; b) Neutral wire voltage before and after load balancing; c) Neutral wire current before and after load balancing.*

6.2. Second scenario

In this scenario, the load balancing is conducted in order to minimize the losses (equation (22)) and minimize the traditional and proposed indexes (equations (23) to (30)). Results are summarized in Table 1. Vertical parameters are the indexes considered for load balancing as the objective function. Results demonstrate that considering the voltage unbalance, current unbalance or losses as an objective function of load balancing leads to different results. It is clear that with consideration of new indexes as the objective function, better results are achieved compared to the traditional indexes. In other words, minimization of NFV (equation

(29)) as the objective function results in minor losses in comparison with minimization of NEMA-V index (equation (23)) and IEC-V index (equation (25)). Minimum losses are also obtained by minimization of NFI (equation (30)) index compare with minimization of NEMA-I index (equation (24)) and IEC-I index (equation (26)). The main question is that, instead of load balancing based on the voltage or current indexes, why the loss itself is not minimized directly? Main goals of load balancing in a network are decreasing the losses and increasing the power quality. As shown in Table 1, if the load balancing is done based on NFI index, the losses value will be the closest to minimum achievable losses. As an added advantage, the value of the negative sequence of voltage (it is detrimental for induction motors and increases power losses) and negative and zero sequence of current (it increases transformer losses and decreases the available capacity of transformers) will be decreased. Considering all the circumstances above, with considering NFI index, not only the losses can be minimized efficiently, but also some detrimental sequences will be declined remarkably. As an answer to the mentioned question, it should be noted that consideration of current or voltage indexes as objective function (equation (30)) have more advantageous compare to regarding the equation (22) as the objective function. Therefore, according to the results, load balancing based on NFI has been proposed.

Table 1 *Results of load balancing based on different indexes*

6.3. The third scenario

In the distribution level, customer phase changing can be done considering some limitations. For instance, the number of re-phased customers has a maximum boundary for

DSOs due to practical difficulties. In this scenario, determination of the maximum number of customers for phase changing has been investigated. First, changing of customer's phases are conducted to decrease losses (equation (22) is the objective function) with considering that limitation. The proposed test case has 131 customers. Therefore, the maximum allowable change starts from 10 to 60 with pitch 10. Results are shown in Fig. 8a graphically. In this state, losses are equal to the noticeable value of 11.464 KW by changing the phases of mere 10 customers. It means 45% reduction in the power losses is achievable by re-phasing of just 10 customers. It is evident that the falling trend of the power losses decreases when the number of changes becomes more than 20 which can be called as saturation of the power loss reduction. With respect to loss reduction benefits, in this case, the most beneficial condition happens with 20 customers for phase change.

In addition, re-phasing of customers is done to decrease voltage, and current unbalance in this scenario. Proposed indexes are considered as the objective function for this purpose. The maximum allowable customers for re-phasing is considered the same as the previous section. Results are shown in Fig. 8b and Fig. 8c. The simulations show that acceptable results are concluded for voltage and current indexes with 20 re-phased customers. Therefore, if the objective function is minimization of the voltage and current indexes, a rational number of changes are 20 because more re-phrasing attempts do not lead to a noticeable difference.

Fig. 8 *Re-phasing customers phase; a) to minimize losses by considering changes limitation; b) to minimize NFI by considering changes limitation; c) to minimize NFV by considering changes limitation*

7. Conclusion

In this paper, a new definition of unbalance indexes was proposed. Rearrangements of customers' phases are also suggested using discrete genetic algorithm (DGA) which resulted in both loss reduction and balance improvement. Therefore, it is feasible to rearrange the phase of customers periodically to achieve those goals. Simulations were conducted in three scenarios. The first scenario showed the condition of voltage and current after load balancing. In other words, the voltage and current of natural wire and variance of different phases' voltage will be decreased by optimal load balancing in distribution networks. In addition, optimal load balancing increases the minimum value of the network voltage. The second scenario demonstrates better results when the new indexes are used in comparison with other standard indexes such as IEC and NEMA. The load balancing is conducted for minimizing current unbalance index as the proposed approach. This index leads to better power quality. The negative sequences of current and voltage with NFI objective are lower than the mentioned sequences when losses is considered as the objective function. Furthermore, the obtained losses value with the proposed current index is very close to the obtained losses value when the objective is only the loss minimization. Applying a limitation for number of customer to experience phase changing is also explained in the third scenario. By changing phases of a few customers, power quality and network losses have been improved in this scenario.

References:

[1] Garciaa DC, Filho ALF, Oliveira MAG, et al. Voltage unbalance numerical evaluation and minimization. Electric Power Systems Research 2009; 79: 1441–1445.

[2] Sun Y, Xie X, Li P. Unbalanced source identification at the point of evaluation in the distribution power systems. Int Trans Electr Energ Syst. 2017; e2460. https://doi.org/10.1002/etep.2460.

[3] Faiz J, Ebrahimi BM, Ghofrani M. Mixed Derating of Distribution Transformers Under Unbalanced Supply Voltage and Nonlinear Load Conditions Using TSFEM. IEEE Transactions on Power Delivery 2010; 25 (2): 780-789.

[4] Ansari AA, Deshpande DM. Investigation of performance of 3-phase asynchronous machine under voltage unbalance. Journal of Theoretical and Applied Information Technology 2006; 6 (1): 21-26.

[5] Abu-Elhaija W, Muetze A. A voltage unbalance factor coding technique for three-phase induction motors. Int Trans Electr Energ Syst. 2018;e2554. https://doi.org/10.1002/etep.2554.

[6] Donolo P, Bossio G, De Angelo C. Analysis of voltage unbalance effects on induction motors with open and closed slots. Energy Conversion and Management 2011; 52: 2024–2030.

[7] Anwari M, Hiendro A. New Unbalance Factor for Estimating Performance of a Three-Phase Induction Motor With Under- and Overvoltage Unbalance. IEEE Transactions on Energy Conversion 2010; 25 (3): pp. 619-625.

[8] Moghadam FK, Ebrahimi S, Oraee A, Velni JM. Vector control optimization of DFIGs under unbalanced conditions. Int Trans Electr Energ Syst. 2018; e2583. https://doi.org/10.1002/etep.2583.

[9] Martinez MI, Tapia G, Susperregui A, *et al*. DFIG Power Generation Capability and Feasibility Regions Under Unbalanced Grid Voltage Conditions. IEEE Transactions on Energy Conversion 2011; 26 (4): 1051-1062.

[10] Xu H, Hu J, He Y. Integrated Modeling and Enhanced Control of DFIG Under Unbalanced and Distorted Grid Voltage Conditions. IEEE Transactions on Energy Conversion 2012; 27 (3): 725-736.

[11] Javan E, Darabi A, Ghafoori Gharib HR, Emami A. Improved control of DFIG using stator-voltage oriented frame under unbalanced grid voltage conditions. Int. Trans. Electr. Energ. Syst. 2013; 23 (6):767–783.

Kiani M, Lee WJ. Effects of Voltage Unbalance and System Harmonics on the Performance of Doubly Fed Induction Wind Generators. IEEE Transactions on Industry Applications 2010; 46 (2); 562-568.

[12] Abad G, Rodr´ıguez MA, Iwani G, *et al*. Direct Power Control of Doubly-Fed-Induction Generator-Based Wind Turbines Under Unbalanced Grid Voltage, IEEE Transactions on Power Electronics, 2010; 25 (2): 442-452.

[13] Yao J, HuiLi, Chen Z, *et al*. Enhanced Control of a DFIG-Based Wind-Power Generation System with Series Grid-Side Converter under Unbalanced Grid Voltage Conditions. IEEE Transactions on Power Electronics 2012; 28 (7): 3167–3181.

[14] Ojo O, Bhat I. Influence of Input Supply Voltage Unbalances on the Performance of AC/DC Buck Rectifiers. Proc. 25th Annual IEEE Power Electronics Specialists Conference 1994; Taipei: 777-784.

[15] Zhou N, Ye L, Lou X, Wang Q. Novel optimal control strategy for powerfluctuation and current harmonic suppression of a three-phase photovoltaic inverter under unbalanced grid faults. Int. Trans. Electr. Energ. Syst.2016;26:1049–1065.

[16] Wang YJ, Pierrat L, Feuillet R. An Analytical Method for predicting Current Harmonics Produced by anAC/DC Converter under Unbalanced Supply Voltage. Int. Trans. Electr. Energ. Syst. 1992;2 (1): 237–244.

[17] Meersman B, Renders B, Degroote L, *et al*. Three-phase inverter-connected DG-units and voltage unbalance. Electric Power Systems Research 2011; 81: 899–906.

[18] Maswood AI, Ooi HP, Gabriel, *et al*. Comparative study of multilevel inverters under unbalanced voltage in a single DC link. IET Power Electron. 2013; 6 (8): 1530–1543.

[19] Roiu D, Bojoi RI, Limongi LR, *et al.* New Stationary Frame Control Scheme for Three-Phase PWM Rectifiers Under Unbalanced Voltage Dips Conditions. IEEE Transactions on Industry Applications 2010; 46 (1): 268-277.

[20] Eid A, Abdel-Akher M. Voltage control of unbalanced three-phase networks using reactive power capability of distributed single-phase PV generators.Int Trans Electr Energ Syst. 2017:e2394. https://doi.org/10.1002/etep.2394.

[21] Li Z, Li Y, Wang P, *et al.* Control of Three-Phase Boost-Type PWM Rectifier in Stationary Frame Under Unbalanced Input Voltage. IEEE Transactions on Power Electronics 2010; 25 (10): 2521- 2530.

[22] Castilla M, Miret J, Camacho A, *et al*. Modeling and Design of Voltage Support Control Schemes for Three-phase Inverters Operating under Unbalanced Grid Conditions. IEEE Transactions on Power Electronics 2014; 29 (11): 6139 – 6150.

[23] Ahmadi G, Shahrtash SM. Neutral to Earth Voltage Reduction Methods in Three-Phase Four Wire Distribution Systems. Proc. International Conference on Electrical and Electronics Engineering 2008; Bursa: 134-138.

[24] Tavakoli Bina M, Kashefi A. Three-phase unbalance of distribution systems: Complementary analysis and experimental case study. Electrical Power and Energy Systems 2011; 33: 817–826.

[25] Lee SY, Wu CJ. On-line reactive power compensation schemes for unbalanced three phase four wire distribution feeders. IEEE Transactions on Power Delivery 1993; 8 (4): 1958-1965.

[26] Chua KH, Wong J, Lim YS, *et al.* Mitigation of Voltage Unbalance in Low Voltage Distribution Network with High Level of Photovoltaic System. Energy Procedia 2011; 12: 495 – 501.

[27] Chua KH, Lim YS, Taylor P, *et al.* Energy Storage System for Mitigating Voltage Unbalance on Low-Voltage Networks With Photovoltaic Systems. IEEE Transactions on Power Delivery 2012; 27 (4): 1783-1790.

[28] Xu Y, Tolbert LM, Kueck JD, *et al.* Voltage and current unbalance compensation using a static var compensator. IET Power Electron. 2010; 3 (6): 977–988.

[29] Shahnia F, Ghosh A, Ledwich G, *et al.* Voltage unbalance improvement in low voltage residential feeders with rooftop PVs using custom power devices. Electrical Power and Energy Systems 2014; 55: 362–377.

[30] Chen TH, Cherng JT. Optimal Phase Arrangement of Distribution Transformers Connected to a Primary Feeder for System Unbalance Improvement and Loss Reduction Using a Genetic Algorithm. IEEE Transactions on Power Systems 2000; 15 (3): 994-1000.

[31] Kaveh MR, Hooshmand R-A, Madani SM. Simultaneous optimization of re-phasing, reconfiguration and DG placement in distribution networks using BF-SD algorithm. Applied Soft Computing. 2018; 62:1044-55.

[32] Hooshmand RA, Soltani S. Fuzzy Optimal Phase Balancing of Radial and Meshed Distribution Networks Using BF-PSO Algorithm. IEEE Transactions on Power Systems. 2012;27(1):47-57.

[33] Lin C, Chen C, Chuang H, Huang M, Huang C. An Expert System for Three-Phase Balancing of Distribution Feeders. IEEE Transactions on Power Systems. 2008;23(3):1488-96.

[34] Carvalho PMS, Ferreira LM, Santana JJ, Dias AMF, Machado JAC. Combined Effects of Load Variability and Phase Imbalance onto Simulated LV Losses. IEEE Transactions on Power Systems. 2018:1-.

[35] Kong W, Ma K, Wu Q. Three-Phase Power Imbalance Decomposition Into Systematic Imbalance and Random Imbalance. IEEE Transactions on Power Systems. 2018;33(3):3001-12.

[36] Huang MY, Chen CS, Lin CH, *et al.* Three-phase balancing of distribution feeders using immune algorithm. IET Gener. Transm. Distrib. 2008; 2 (3): 383 –392.

[37] Tuppadung Y, Kurutach W. The Modified Particle Swarm Optimization for Phase Balancing. Proc. IEEE Region 10 Conference 2006; Hong Kong: 1-4.

[38] Santos Valois PV, Vieira Tahan CM, Kagan N, *et al.* Voltage unbalance in low voltage distribution networks. Proc. 16th International Conference and Exhibition Electricity Distribution (CIRED) 2001; Amsterdam.

[39] Ciric RM, Feltrin AP, Ochoa LF. Power Flow in Four-Wire Distribution Networks—General Approach. IEEE Transactions on Power Systems 2003; 18 (4): 1283-1290.

[40] Ciric RM, Ochoa LF, Padilha A. Power flow in distribution networks with earth return. Electrical Power and Energy Systems 2004; 26: 373-380.

[41] Anderson PM. Analysis of faulted power systems; IEEE Press Power Systems Engineering Series, 1995.

[42] Subrahmanyam JBV. Load flow solution of unbalanced radial distribution systems', Journal of Theoretical and Applied Information Technology 2005; 6 (1): 1040 –1051.

[43] Pillay P, Manyage M. Definitions of Voltage Unbalance. IEEE Power Engineering Review 2001; 21 (5): 50-51.

[44] Gosbell VJ, Herath HMSC, Perera S, *et al.* Sources of error in unbalance measurements. 2002.

[45] Singh AK, Singh GK, Mitra R. Some Observations on Definitions of Voltage Unbalance. Proc. 39th North American Power Symposium 2007; Las Cruces: 473 – 479.

[46] Goldberg DE. Genetic Algorithms in Search, Optimization and Machine Learning; 1st edn, Addison-Wesley Longman Publishing Co. 1989.

[47] Devaraj D, Yegnanarayana B. Genetic-algorithm-based optimal power flow for security enhancement. IEE Proc.-Gener. Transm. Distrib. 2005; 152 (6): 899- 905.

[48] Bakirtzis AG, Biskas PN, Christoforos E. Optimal Power Flow by Enhanced Genetic Algorithm. IEEE Transactions on Power Systems 2002; 17 (2): 229-236.

[49] Maifeld TT, Sheble GB. Genetic-based unit commitment algorithm. IEEE Transactions on Power Systems 1996; 11 (3): 1359-1370.

[50] Orero SO, lrving MR. Economic dispatch of generators with prohibited operating zones: a genetic algorithm approach. IEE Proe.-Gener. Transm. Distrib. 1996; 143 (6): 529-534.

[51] Song YH, Chou CSV. Advanced engineered-conditioning genetic approach to power economic dispatch. IEE Proc.-Gener. Transm. Distrib. 1997; 144 (3): 285-292.

[52] Masoum MAS, Ladjevardi M, Jafarian A, *et al.* Optimal Placement, Replacement and Sizing of Capacitor Banks in Distorted Distribution Networks by Genetic Algorithms. IEEE Transactions on Power Delivery 2004; 19 (4): 1794-1801.

[53] Moradian S, Jadid S, Homaee O. Optimal allocation of capacitors with stand-alone VAr control systems in radial distribution networks. International Transactions on Electrical Energy Systems 2014; 25 (7): 1333-1348.

[54] Foster JD, Berry AM, Boland N, *et al*. Comparison of Mixed-Integer Programming and Genetic Algorithm Methods for Distributed Generation Planning. IEEE Transactions on Power Systems 2013; 29 (2): 833–843.

[55] Hong YY, Lian RC. Optimal Sizing of Hybrid Wind/PV/Diesel Generation in a Stand-Alone Power System Using Markov-Based Genetic Algorithm. IEEE Transactions on Power Delivery 2012; 27 (2): 640-647.

[56] Evangelopoulos VA, Georgilakis PS. Optimal distributed generation placement under uncertainties based on point estimate method embedded genetic algorithm. IET Gener. Transm. Distrib. 2014; 8 (3): 389–400.

[57] Braz HDDM, Souza BAD. Distribution Network Reconfiguration Using Genetic Algorithms With Sequential Encoding: Subtractive and Additive Approaches. IEEE Transactions on Power Systems 2011; 26 (2): 582- 593.

[58] Arabali A, Ghofrani M, Etezadi-Amoli M, *et al.* Genetic-Algorithm-Based Optimization Approach for Energy Management. IEEE Transactions on Power Delivery 2013; 28 (1): 162-170.

[59] Jiang Y, Jiang J, Zhang Y. A Novel Fuzzy Multiobjective Model Using Adaptive Genetic Algorithm Based on Cloud Theory for Service Restoration of Shipboard Power Systems. IEEE Transactions on Power Systems 2012; 27 (2): 612- 620.

[60] Luan WP, Irving MR, Daniel JS. Genetic algorithm for supply restoration and optimal load shedding in power system distribution networks. IEE Pror:-Gener. Tmnsm. Distrib. 2002; 149 (2): 145-151.

[61] Ulinuha A, Masoum MAS, Islam S. Hybrid genetic-fuzzy algorithm for volt/var/total harmonic distortion control of distribution systems with high penetration of non-linear loads. IET Gener. Transm. Distrib. 2011; 5 (4): 425–439.

[62] Heo JH, Kim MK, Park GP, *et al*. A Reliability-Centered Approach to an Optimal Maintenance Strategy in Transmission Systems Using a Genetic Algorithm. IEEE Transactions on Power Delivery 2011; 26 (4): 2171-2179.

[63] Hong YY, Chen YY. Placement of power quality monitors using enhanced genetic algorithm and wavelet transform. IET Gener. Transm. Distrib. 2011; 5 (4): 461–466.

[64] Mehdi Attar, Omid Homaee, Hamid Falaghi, Pierluigi Siano. A novel strategy for optimal placement of locally controlled voltage regulators in traditional distribution systems. Electrical Power and Energy Systems. 2018; 96: 11–22.

Figures

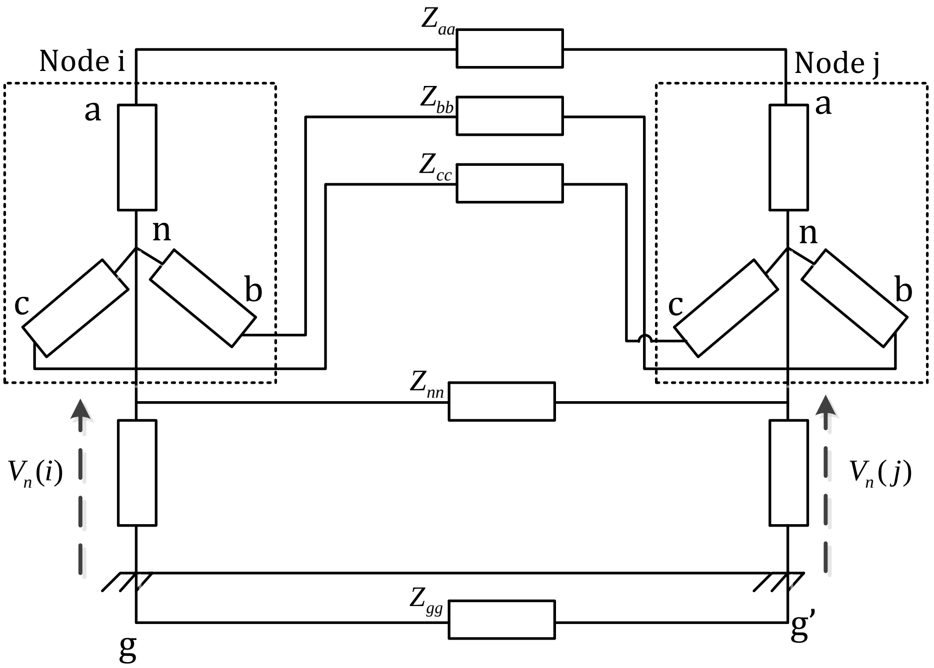


Fig. 1 *Model of a three-phase four-wire multi-grounded distribution line (reproduced according to [34])*

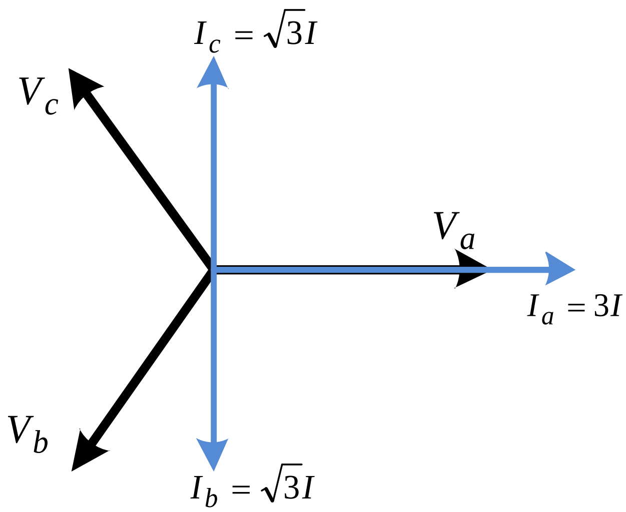


Fig. 2 *A sample of current unbalance*

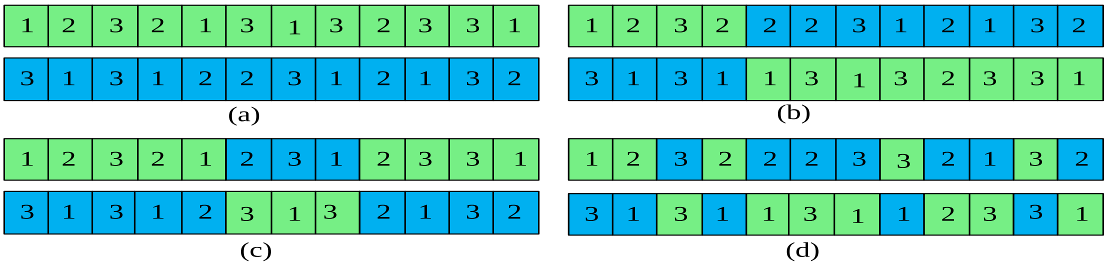


Fig. 3 *Crossover operator in DGA: a) Parent chromosomes; b) children chromosome by using single point crossover; c)children chromosome by using double point crossover; d) children chromosome by using uniform crossover*

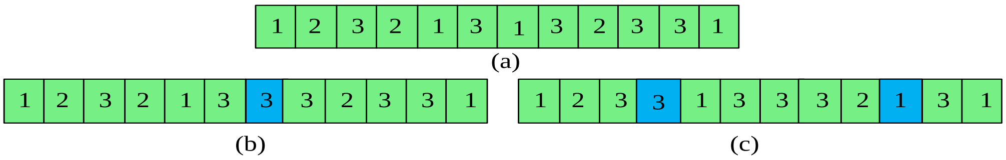


Fig. 4 *Mutation operator in discrete genetic algorithm; a) Parent chromosomes; b) children chromosome by one mutated gene; c) children chromosome by two mutated genes.*

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	•••	C_{n-7}	C_{n-6}	C_{n-5}	C_{n-4}	C_{n-3}	C_{n-2}	C_{n-1}	C_n
Utility pole No.1					Utility pole No.2								Utility pole No.m							

Fig. 5 *Chromosome structure*

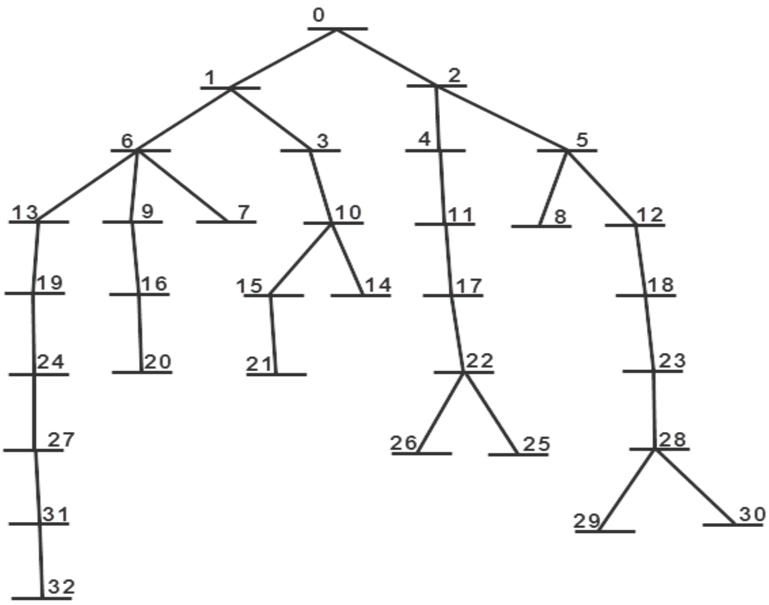
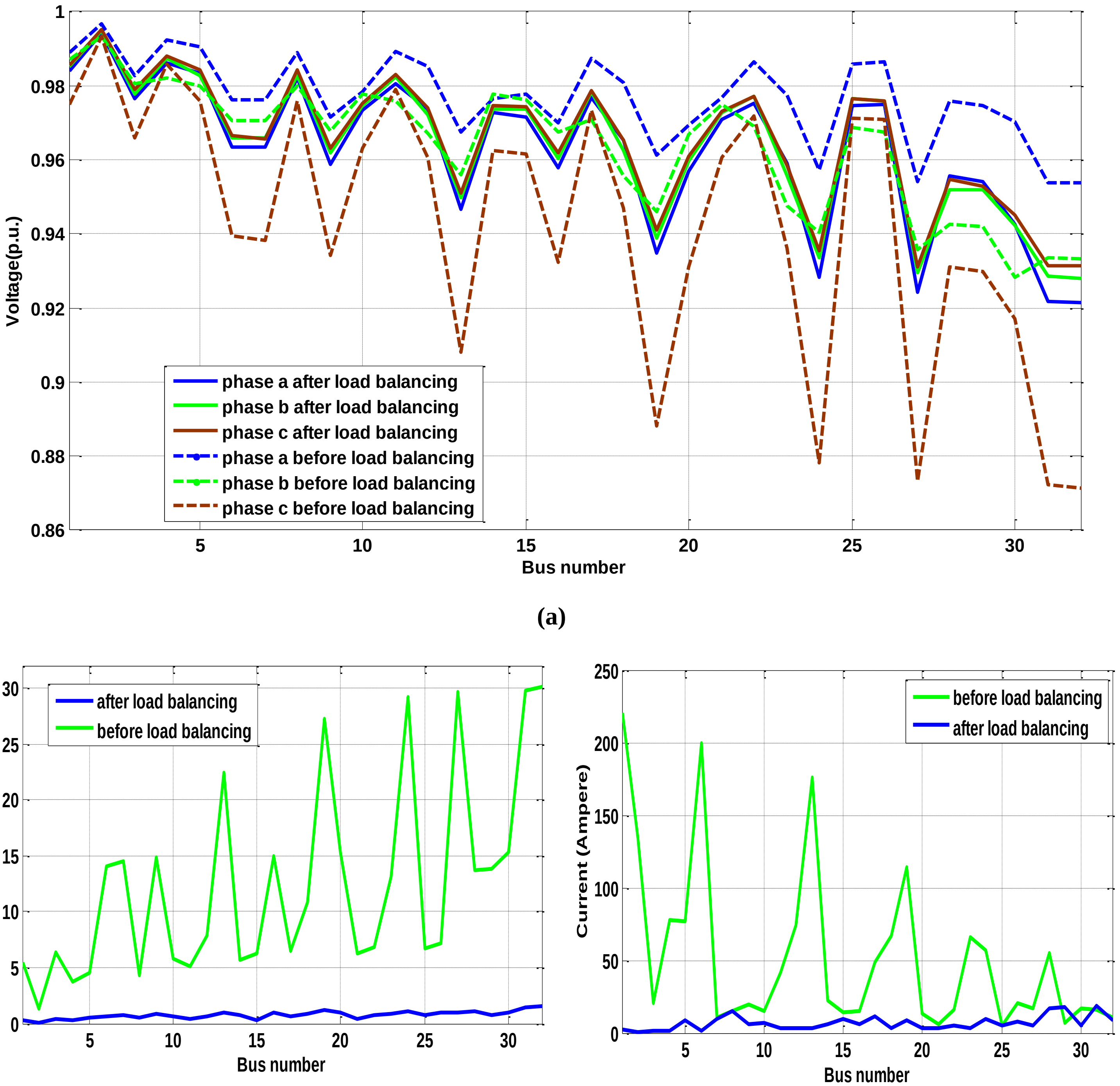


Fig. 6 *Test system (real system in Bandar-Abass city distribution system)*



(a)

(b)

(c)

Fig. 7 *Balancing importance in the distribution network; a) Voltage profile before and after load balancing; b) Neutral wire voltage before and after load balancing; c) Neutral wire current before and after load balancing.*

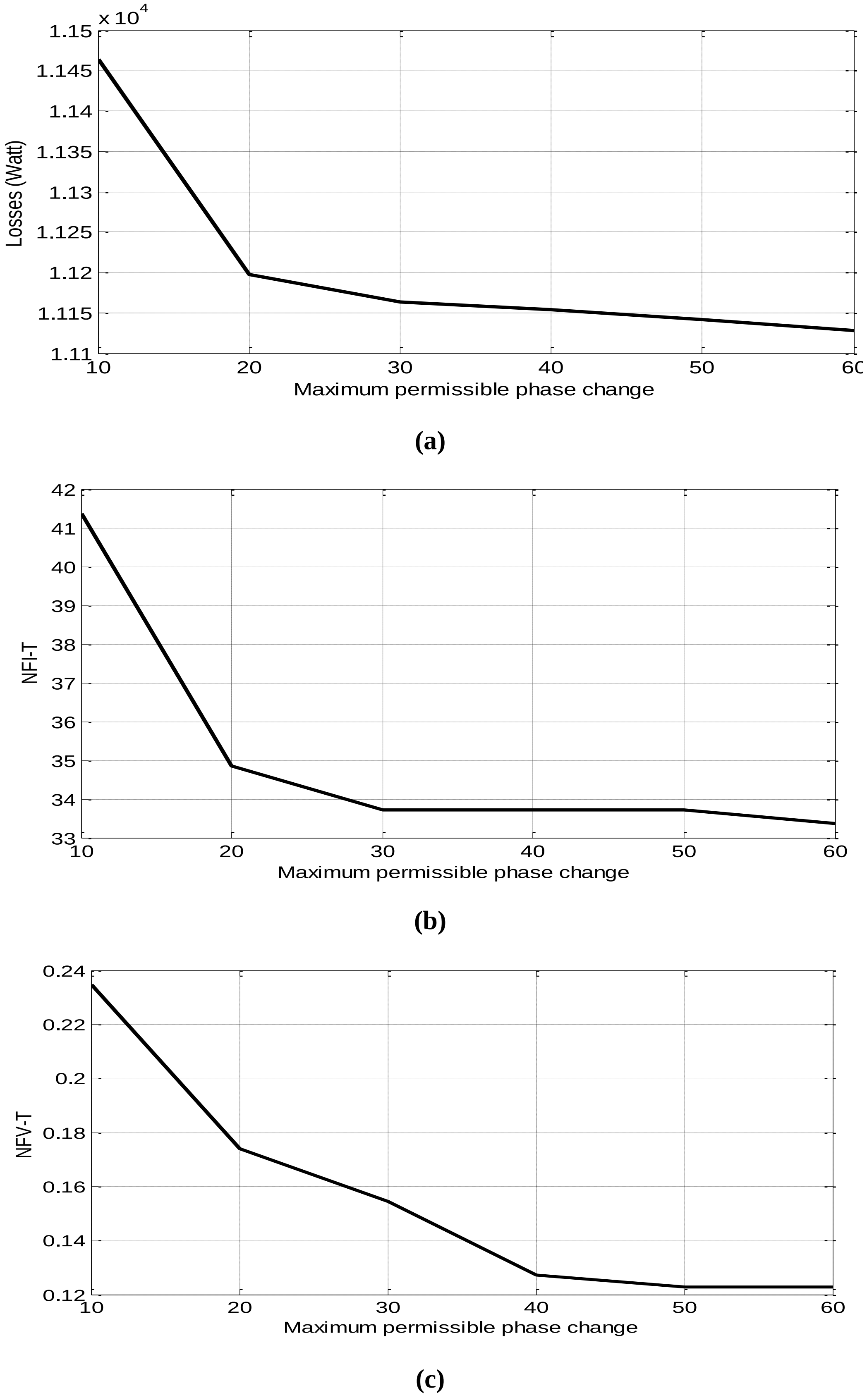


Fig. 8 *Re-phasing customers phase; a) to minimize losses by considering changes limitation; b)to minimize NFI by considering changes limitation; c) to minimize NFV by considering changes limitation*

Table

Table 1 *Results of load balancing based on different indexes*

Objective function	Results of load balancing based on different indexes				
	Loss (kW)	%U_-	%U_0	%I_-	%I_0
Loss	11.128	0.1703	0.1163	18.4018	18.0761
NEMA-I	11.490	0.0575	0.1603	24.8985	25.4289
NEMA-V	11.374	0.0214	0.1606	21.922	21.5319
IEC-I	11.250	0.1778	0.1315	15.9443	18.4524
IEC-V	11.374	0.0214	0.1606	21.922	21.5319
NF-I	11.151	0.1675	0.1171	16.0989	17.2603
NF-V	11.344	0.0624	0.0602	24.621	24.6019
Initial condition	20.842	1.1269	1.151	37.6475	34.1249