Ternary genetic algorithm for load dynamic balancing in low voltage three-phase 400 V networks

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Article Info

ABSTRACT

In three-phase low voltage networks, the random behavior of single-phase loads and also their placement in different parts of single-phase feeders, leads to load imbalance in these networks. Unbalanced load causes losses and voltage drop in three-phase feeders. In this paper, using a different proposed approach based on genetic algorithm, N loads are spread over the grid phases so that the minimum current difference between the phases is formed and the ground current approaches zero. The proposed method is compared with the random load distribution method and the results are analyzed. Among the most important results obtained, we can point out the difference in the calculation time of the two methods by reaching an optimal value, and the calculation speed of the proposed method is significantly better. The proposed method can be an effective tool for dividing the load on different phases of the network in order to prevent imbalance.

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1. INTRODUCTION

Along the transmission and distribution lines, the electric power is delivered to the consumers. Due to a decrease in voltage magnitude and rising distribution losses, distribution lines perform less efficiently. The biggest source of electricity losses is the distribution system. The network reconfiguration use the conventional switching indices. The switching problem has been solved using a novel strategy in the current work [1]. It is suggested that a distributed intelligent home load transfer strategy be used to dynamically reduce voltage imbalance (VU) along low voltage distribution feeders [2]. To reduce VU along the feeder, this plan moves residential loads from one phase to others. The distribution transformer's central controller, which is located there, monitors how much energy is used in each home to identify which ones should be switched from one initially connected phase to another. Each residence is supplied by a three-phase output connection on a static transfer switch that aids in the transfer. For distribution network operators (DNOs) to assess the overall cost of phase imbalance and the possible benefit of phase balancing, it is crucial to understand imbalance-induced energy losses [3], [4].

The low voltage [5] home feeders are typically three-phase, four-wire systems in many regions of the world, provided by Dyne three-phase transformers [2]. Other nations' distribution networks are likewise prone to imbalance-induced energy losses [6], [7]. Using Carson's equations to describe the lines, Kersting [8] determines the energy loss on the neutral wire of overhead wires in the distribution network.

Based on the difference between the corresponding neutral line resistance and the line resistance of a transposed three-phase line, Pajic and Emanuel [9] determines neutral energy losses. The neutral energy loss brought on by non-linear three-phase loads is calculated in [10]. The neutral energy loss in medium voltage distribution networks caused by load imbalance is calculated in [11]. The energy losses in distribution networks, including those on the phases and neutral wire, are calculated in references [12], [13].

Today, the utilities manually change the connection phase of some of the customers to equalize the distribution of the loads among the phases in order to decrease the unbalance problem in low-voltage (LV) feeders. For the purpose of reducing imbalance in LV feeders, various solutions are suggested. Some traditional approaches for enhancement include increasing the cross-section of the feeder or installing capacitors. At their connecting terminals, distribution static compensator (DSTATCOM) can also be utilized to balance voltage. To reduce volume units (VU) and power loss, network reconfiguration can be done by simply switching the phase connections of the three phases on the primary side of the distribution transformer. However, this procedure is static and is only performed once. It is demonstrated that a static transfer switch (STS) can supply a sensitive load from two distinct feeders by swiftly switching the load from one three-phase feeder to another, protecting the load from voltage sag/swell. To decrease VU in the network, an analogous network reconfiguration and load transfer technique, derived from [14], [15], can be implemented in LV feeders. In this study, a dynamic residential low tension (LT) system that is intelligent is provided.

Hirth and Ziegenhagen [16] discusses three ways that variable renewable energy (VRE) and balancing systems communicate with one another: the effect of VRE forecast mistakes on balancing reserve requirements; the provision of balancing services by VRE generators; and the incentives offered by imbalance charges to enhance forecasting. We then suggest the energy-efficient minimum criticality routing algorithm, which combines energy efficiency routing and load balancing, to reduce the network's bit energy consumption parameter [5]. This research suggests the energy-efficient multi-constraint rerouting (E2MR2) technique to further increase network energy efficiency. E2MR2 takes advantage of rerouting approach to ensure network quality of service (QoS) and maximum delay limitations and uses energy consumption model to establish link weight for optimal energy efficiency. The load balancing and congestion issue with an IPv6 routing protocol for low-power and lossy networks (RPL) is examined in [17]. In particular, we demonstrate that the majority of packet losses during periods of high traffic are caused by congestion and that RPL suffers from a significant load balancing issue with regard to routing parent selection. This article suggests a straightforward but efficient queue utilization-based RPL (QU-RPL) that provides load balancing and greatly outperforms the regular RPL in terms of end-to-end packet delivery performance in order to solve this issue.

Brinkel et al. [18] suggests a system for reducing photovoltaic (PV) output fluctuations by changing how electric vehicles (EVs) charge, and we evaluate the efficacy of the suggested system. The findings show that changes in PV output have little effect on voltage levels in 2030, yet in 2050, variations in PV output result in significant voltage variations. The grid location, installed PV capacity, and grid configuration all have an impact on how much the voltage fluctuates. In the year 2050, these voltage changes may result in unsightly light flicker for a major portion of the day. On-load tap changers (OLTCs) at transformer stations can be used to manage voltage in the LV grid, but they have a limited impact at the ends of feeder lines and are unable to slow down abrupt voltage changes [19], [20]. For the purpose of reducing PV variation, dump loads [21] and diesel generators in conjunction with battery systems [22] should be avoided because they both have detrimental environmental effects. Reactive power regulation in PV inverters can also be used to reduce swings in PV power production, however this has the potential to reduce inverter lifetime [23], [24]. Additionally, in the event that a PV system is partially shaded, the voltage drop can be minimized by using advanced maximum power point tracking (MPPT) algorithms in conjunction with DC-DC converters in PV inverters [25], [26]. Several research have suggested using energy storage devices to reduce fluctuations, such as battery systems [27]–[29] and capacitors. However, battery systems have very significant upfront costs, whereas capacitors have a limited capacity.

EVs' ability to reduce variations in PV output is discussed in a variety of research. References [30]–[38] suggest solutions in which the PV inverter is positioned behind an EV parking lot or an EV charging station to capture variations in PV generation. These devices can only steady the output of a single PV inverter; they cannot offer a system-wide solution. Wang et al. [31] suggest a system in which EVs modify their charging power to make up for the lower PV power injected during a cloud transient. The minimizing of voltage fluctuations is one of the goals of the multi-objective EV charging algorithms proposed by Javadian et al. [32] and Alam et al. [33]. Jayalakshmi and Gaonkar [34] suggest a system that combines an EV and a stationary battery system to reduce fluctuation issues. Based on thorough solar forecasts and adjustments to the OLTC tap sites, Suzuki et al. [35] suggests a comprehensive mitigation technique for EV-based rapid voltage swings. Last but not least, Chukwu and Mahajan [36] use a charging

algorithm that minimizes EV charging costs while reducing rapid PV production variations by EVs to calculate the rise in charging prices for EV owners in a modest 4-bus system.

As shown in Figure 1, it is important to divide the load on different phases of the network in order to balance the load. Using a smart method, this paper divides the number of loads placed on each phase by considering the best state in terms of the current balance of each phase so that the ground current flows to its minimum value [37]. The innovation of this paper is the use of 3 modes for each chromosome length, while in most smart methods, only two modes 0 and 1 are used. The advantage of the proposed method is its speed of calculation compared to random load division. According to the Figure 1, the network loads are divided by the proposed method by disconnecting and connecting the switches in such a way that the lowest ground current (i_{NL}) is generated. The general circuit for calculating the current of each line is shown in Figure 2. The whole paper is divided into five sections. The formulation of the basic method and the proposed method are presented in sections 2 and 3. The results and discussion of the proposed method are presented in section 4. Finally, the conclusion of the proposed method is determined in section 5.
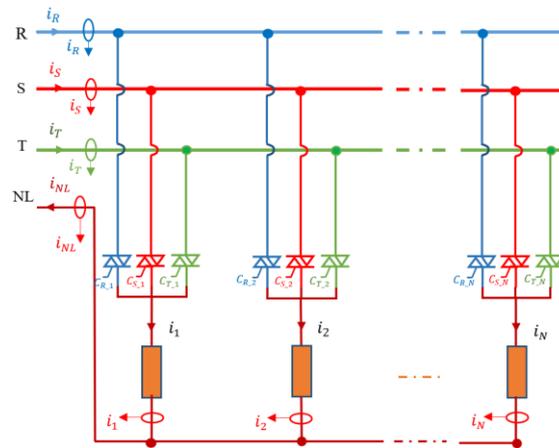

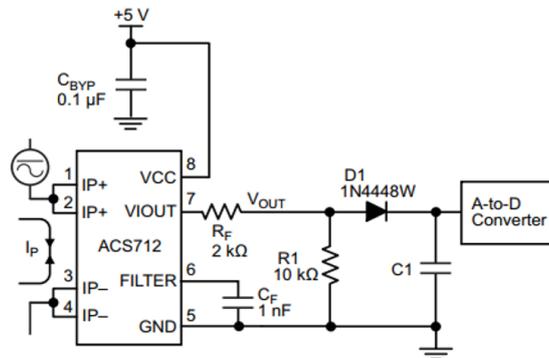Figure 1. The general structure of load division on different phases of a three-phase system

Figure 2. Current measurement circuit of each line

2. PROBLEM FORMULATION

The sinusoidal voltage for three phases is defined as follows:

$$v_R(t) = V_{max} sin(\omega t) \tag{1a}$$

$$v_S(t) = V_{max} sin(\omega t + \frac{2\pi}{3}) \tag{1b}$$

$$v_T(t) = V_{max} sin(\omega t + \frac{4\pi}{3}) \tag{1c}$$

therefore, by defining a general formula for voltage, depending on the value of alpha, the voltage can be applied to any of the phases [38], [39].

$$v_k(t) = V_{max}sin\left(\omega\,t + \alpha_k\frac{2\pi}{3}\right)\begin{cases} v_k(t) = v_R(t) & \alpha_k = 0 \\ v_k(t) = v_S(t) & \alpha_k = 1 \\ v_k(t) = v_T(t) & \alpha_k = 2 \end{cases} \tag{2}$$

Similarly, with the phase difference φ_k, the current relationship depending on α_k is defined as:

$$i_k(t) = i_{k\text{-}max}sin(\omega\,t + \alpha_k\frac{2\pi}{3} - \varphi_k)\quad k=1,2,...,N \tag{3}$$

when the load is in balance:

$$i_{NL}(t) = \sum_{k=1}^{N} i_k(t) = 0 \tag{4}$$

The (4) is defined in phasor form in the steady and permanent sinusoidal state as follows:

$$\overline{i_{NL}} = \sum_{k=1}^{N} \overline{i_k} = 0 \tag{5}$$

where the $\overline{i_{NL}}$ and $\overline{i_k}$ are respectively phasor of $i_{NL}(t)$ and $i_k(t)$. So we can write:

$$\overline{i_{NL}} = 0 \Rightarrow |\overline{i_{NL}}| = 0 \Rightarrow \left|\sum_{k=1}^{N} \overline{i_k}\right| = \left|\sum_{k=1}^{N} i_{k-max}\left(cos\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right) + j\,sin\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right| = 0 \tag{6a}$$

$$\Rightarrow \left|\sum_{k=1}^{N} i_{k-max}\left(cos\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right| + \left|\sum_{k=1}^{N} i_{k-max}\left(sin\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right| = 0 \tag{6b}$$

$$\Rightarrow \left(\sum_{k=1}^{N} i_{k-max}\left(cos\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right)^2 + \left(\sum_{k=1}^{N} i_{k-max}\left(sin\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right)^2 \tag{6c}$$

Figure 3 shows the currents of different phases in a phasor form on the voltage phasor screen, so that the goal is to minimize the size of the ground current, so that practically the current in the phases reaches its most optimal state of balance. Therefore, the objective function of the problem (minimization i_{NL}) is defined as (7) [40], [41].

$$Min\,i_{NL} = Min\,\left(\sum_{k=1}^{N} i_{k-max}\left(cos\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right)^2 + \left(\sum_{k=1}^{N} i_{k-max}\left(sin\left(\alpha_k\frac{2\pi}{3} - \varphi_k\right)\right)\right)^2 \tag{7}$$

In the next section, the results obtained from two basic methods and GA algorithm are examined and a comparison is made between them for the efficiency of the GA method.
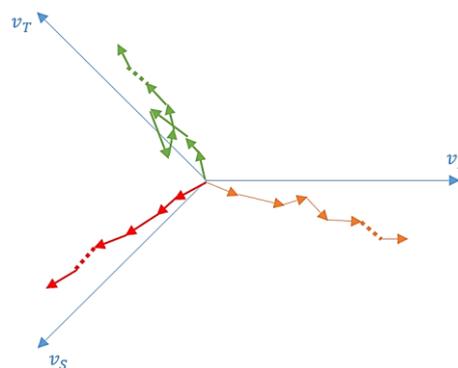

Figure 3. Voltage and current of different phases in equilibrium

3. THE PROPOSED GENETIC ALGORITHM

A genetic algorithm is a method of random search based on natural selection and genetic mechanisms. Goldberg was the first to introduce the standard form of a genetic algorithm [42], [43]. The genetic algorithm begins with a set of random solutions known as (population). The term "chromosome" refers to each component of the population and serves as a solution to the issue. Chromosomes change during

successful iterations referred to as (generation). Chromosomes are assessed by computing the fit function for each generation. One of the two operators of gene transfer and mutation produces additional chromosomes, known as (children), to produce the following generation. The next generation is also created through selection of others to maintain population stability or selection based on the importance of the fitness function of parents and offspring. The method is directed to the best chromosome after a number of generations, which in the best scenario offers a roughly optimal solution to the problem. Usually, the initial selection is done randomly. In random sampling, the actual number of chromosomes to be multiplied is determined based on the probability of survival of that chromosome. The most well-known of these methods are (relative Dutch selection) or (selection based on the roulette wheel) where the survival probability for each chromosome is determined based on the value of its fitness function. For chromosome k with the fitting function f_k, the probability of selecting P_k is calculated as (8).

$$P_k = \frac{f_k}{\Sigma f_i} \tag{8}$$

Crossover is the most important genetic operator, which is done to combine two chromosomes from parents and create new children. One-point cutting, two-point cutting, multi-point cutting and uniform crossover methods are common types of crossovers [44]. In this operator, the crossover rate (P_c) is defined as a ratio of the number of children produced from each generation to the value of the current generation. Gene mutation is another operator that can cause changes in one or more genes of a chromosome [44]. In the genetic algorithm, gene mutation plays a sensitive role in one of two ways: replacing the lost genes of the generation during the selection process in the form of a new chromosome or inserting genes that are not present in the current generation into the new generation. The mutation rate (P_m) is expressed as a percentage of the set of genes of each generation. The flowchart of the proposed algorithm is shown in Figure 4.
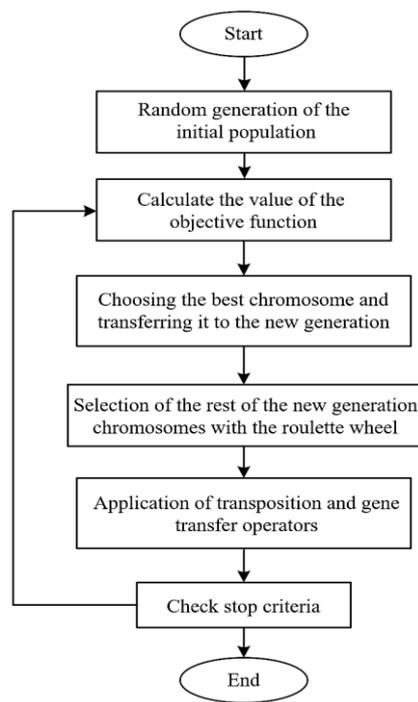

Figure 4. Flowchart of the proposed algorithm

4. RESULTS AND DISCUSSION

In this section, by using two modes (random and smart GA algorithm), the calculation of the lowest transient current from the neutral wire is discussed. In general, there is 3^N possible state that if the time required for each state is t, then the time required to check all states according to the random state is equal to $3^N.t$. The time obtained to calculate each state is equal to 11.833 ms (t=11.833 ms). Therefore, the time required to calculate 1000 loads (N=1000) is shown in Figure 5. The specifications of the desired system to calculate this time are CPU core i7, 8Gbyt Ram and 2Gbayt Graphic Ram. As shown in Figure 5, the calculation time is depending on the number of loads of degree three.
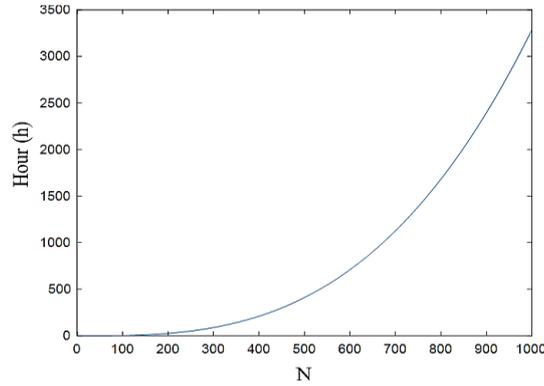
Figure 5. Total time required to calculate all states for 1000 loads

4.1. Solving load balancing problem by TBGA (Trinary based GA)

We define chromosomes (α_1, α_2, ..., α_N) for the GA program as follows:

$$\alpha_1 \qquad \dots \qquad \alpha_K \qquad \dots \qquad \alpha_N$$

where α_K are chromosome genes (α_K is 0, 1, or 2). Then the total calculation time for N loads (1, 2, ..., 1000 will be shown as Figure 6. It can be seen that the problem-solving time in the second method (trinary based genetic algorithm) is much less than the direct method (finding the answer by checking all the cases). The amount of power received from each phase due to the presence of 1000 loads in the basic state and the presence of the smart algorithm is compared in Figure 7. It can be clearly seen that the difference in the power consumption from each phase in the basic state is more different than the smart algorithm. So that our goal is to minimize the power difference consumption from each phase to the other phase so that the condition of load balance is established. In addition, the ground current in the random state and the state of using the smart algorithm are shown in Figure 8. Since load balancing is maximally established using the proposed smart algorithm, the ground current in this case is 0.94 and in the base case it is equal to 362.18, which is about 385.29 times improvement in the ground current.

Also, the amount of current of each phase is presented in Cartesian form in the basic state where the ground current is high in Figure 9. It can be clearly seen that the flow of each phase is unbalanced compared to the other phase. In other words, the three-phase currents are not located on the circumference of the circle. With the presence of the smart algorithm, the flow of each phase is shown in Figure 10. Each phase is almost placed on the circumference of the circle and has reached equilibrium. Finally, the currents of each phase in the base state and the second state are marked with blue and turquoise colors respectively in Figure 11. You can clearly see the effect of the smart algorithm in balancing the flow of each phase. In addition, the ground current in the basic state is marked with red color, which is a very significant number compared to the ground current in the second state. The ground current in the second state is marked with black color, which is the result of the effect of the proposed smart algorithm.
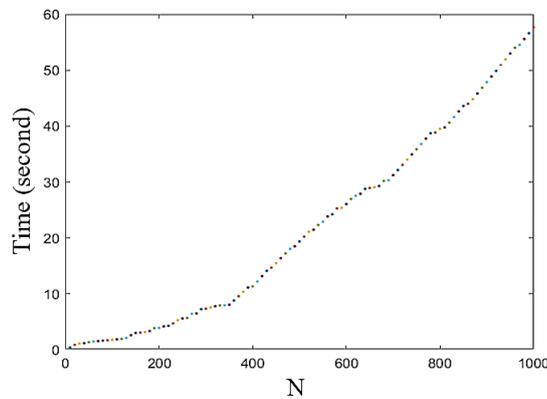

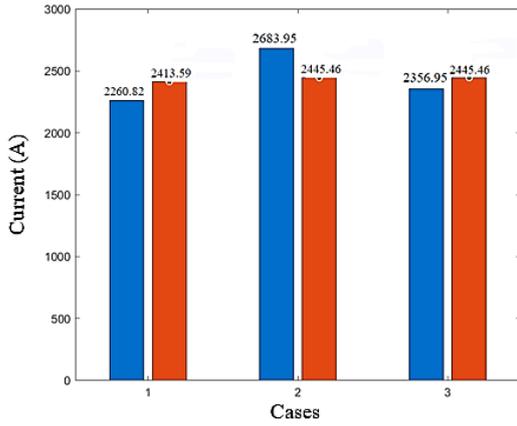Figure 6. Total calculation time for 1000 loads in proposed method

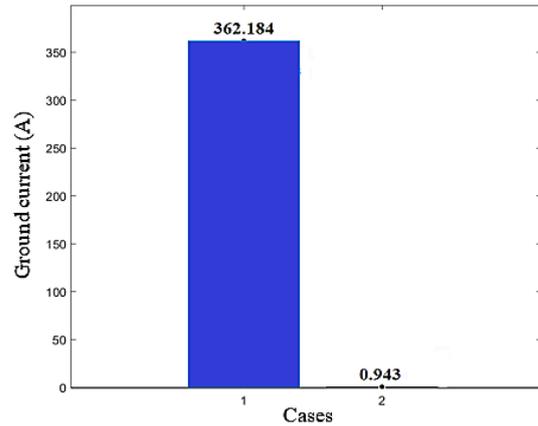Figure 7. Current of each phase in two cases

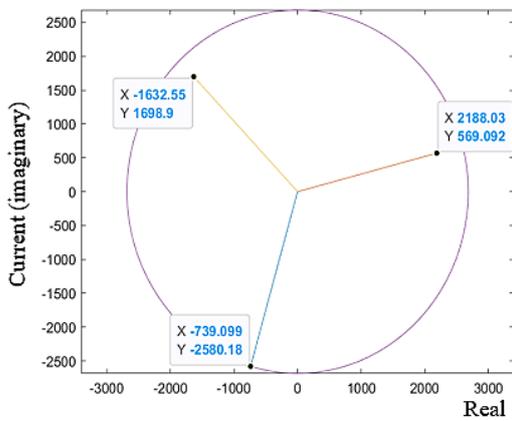Figure 8. Ground current in two cases

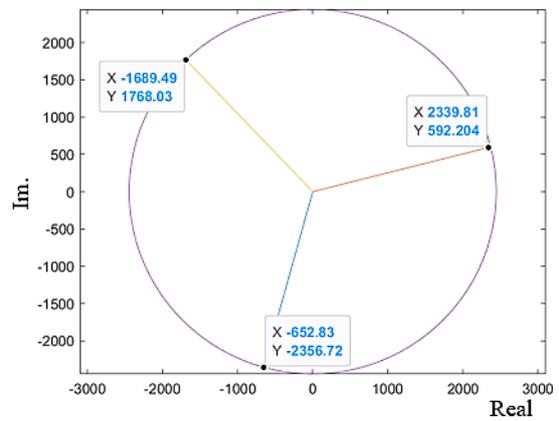Figure 9. Current of each phase in random state

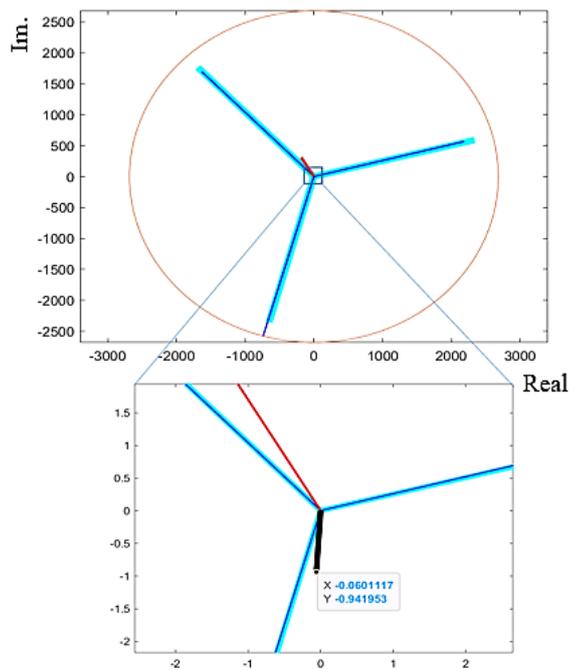Figure 10. Current of each phase in proposed method

Figure 11. Comparison of the current of each phase and ground current in two cases

5. CONCLUSION

This paper proposes a method based on smart genetic algorithm to optimize the ground current in the shortest possible time per N loads. Also, the proposed method is compared with the method of randomly assigning load to each phase. The difference between the two methods in terms of time is obvious. Among the most important results, the following can be mentioned: i) Significant reduction of ground current by 99.38% in the proposed method compared to the random mode; ii) The significant difference in the calculation time of the proposed method compared to the random method to reach the optimal solution: the time required for the proposed method is about 58 seconds, while the time required for the random method is about 3250 hours; and iii) Phase current balance in the proposed method compared to the random method. The proposed method can be used to optimize the ground current to balance the load current in the shortest possible time.

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