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Loss Reduction of Low Voltage Distribution Network by Considering of Load Balancing Impact

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Abstract

Every year, a large part of the energy produced by power plants is lost on the way to the consumer in the entire power system, and a significant share of these losses is related to the distribution networks. One of the most important factors affecting losses in distribution networks is the existence of load imbalance due to the random consumption of subscribers and the lack of equal distribution of subscribers among different phases of the network. The main challenge in this field is the lack of an effective method to study the effect of load balancing on the losses of a large-scale network. In this regard, this paper studies the effect of load balancing on network loss reduction by applying the concept of clustering and representative feeders. the effectiveness of the proposed method has been proved by the simulations on the low voltage distribution network of Alborz province, and the results show the high efficiency of the proposed method.

Keywords: loss reduction, load balancing, low voltage distribution network
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1. Introduction

Every year, a significant portion of the energy produced by power plants is wasted in the power grid on the way to consumers, with a considerable portion of these losses occurring in the distribution sector. By losses in distribution networks, we mean the difference between the delivered energy and the energy sold. It is predicted that by 2040, the electricity consumption will reach 2,600 billion KWh [1,2]. With the natural increase in electricity consumption, the amount of losses is also expected to increase.

Nowadays, many countries are working to reduce energy losses, and the remarkable success of some of these countries demonstrates the possibility of reducing losses. Reducing losses not only eliminates the costs associated with them but also frees up the capacity of the lines and somewhat reduces the need for networks upgrade. Compared to transmission networks, distribution networks have a lower voltage level, resulting in a higher current, which causes more losses in distribution networks. Therefore, reducing losses in electricity distribution networks is of great importance [3,4].

Losses in distribution networks occur for various reasons such as inappropriate use of transformers, unbalanced loads, high capacitance of capacitors, use of wires with low cross-sections in low voltage networks, untimely servicing of lines, transformers and other equipment. Therefore, various methods have been proposed to reduce these losses, one of the most important of which is balancing the feeder loads in weak pressure networks [5]. In balanced conditions, the current and voltage in each bus of the system have equal values in each phase, with a 120-degree phase difference. In distribution networks, due to the non-uniform distribution of single-phase loads on three phases, the random connection and disconnection of single-phase loads from the network, and the existence of unbalanced three-phase loads, the imbalance of voltage and current is inevitable. Therefore, distribution networks are usually unbalanced and a relatively large current passes through their neutral wire [6,7]. The current passing through the neutral wire increases losses in unbalanced systems compared to balanced ones.

However, in low voltage distribution networks, there are challenges due to the lack of necessary data for estimating losses caused by current imbalances, and solutions have also been proposed to address these issues. For example, [8] has used statistical and regression methods to estimate losses caused by phase current imbalances in low voltage networks. In [9], considering the advances in artificial intelligence-based methods, a combination of clustering and classification methods has been applied to estimate energy losses caused by imbalances in low voltage distribution networks facing data scarcity. So far, many studies have been conducted on load balancing in distribution networks, some of which have addressed the issue of reducing losses, while others have only presented a suitable method for balancing the system. As an example, [10] has used automatic switches to reduce the load imbalance of low voltage transformers. After collecting the load of each phase by monitoring systems, the necessary commands are given to the switching equipment to automatically move the phases and reduce the load imbalance and losses of the system. However, the use of this method requires online monitoring and surveillance infrastructure, and in addition, due to the use of switching equipment, it will be costly.

[11] has pointed out that losses in distribution transformers are small, but when faced with a large number of transformers, these losses become significant. Therefore, the impact of load imbalance on the secondary side of distribution transformers on their losses has been investigated in the following. Studies have been conducted on distribution transformers with capacities of 35, 45, and 75 KVA in the power distribution company of Brazil, which show that load imbalance increases transformer losses by 27, 19, and 10 respectively, compared to the balanced state. Reference [12] has used LABVIEW software to move consumers towards load balancing and reduce losses. The voltages, currents, and power factors are obtained based on the common meter, and then LABVIEW software measures the power and predicts the unbalanced current in the three-phase distribution network and moves a certain number of consumers to balance the load.

The problem of phase imbalance in electric power distribution systems has become increasingly important due to the increased use of renewable energy sources such as single-phase solar panels. This problem is exacerbated by the widespread use of complex single-phase loads. Reference [13] discusses the issue of phase imbalance in connecting a large number of single-phase solar sources and loads to three-phase distribution systems. In addition, a genetic algorithm has been used to minimize the system's imbalance. It should be noted that increasing the number of solar sources leads to increased system randomness, which complicates the assessment of system imbalance. Therefore, a probabilistic data estimation method has been used in this study to estimate the required random data (solar radiation, load power) for the system under study. The test results on a 37-bus feeder show a significant reduction in system current imbalance during the study period. In addition, voltage imbalance and energy losses are reduced under optimal system performance, resulting in a minimum 11.19 reduction in losses in the case study.

Due to the intelligentization of distribution networks, dynamic load balancing using remote controllable switches has been given more attention. For example Reference [14] has used feed-forward back-propagation neural network (FFBPNN), radial basis function neural network (RBFNN), and a hybrid to create optimal load balance using automatic controllable switches, and the results show that the hybrid method has the best performance. The key challenge of distribution networks is that these networks only have the monthly reading of customers' meters which is called data-scarce distribution systems due to the lack of enough information. For this reason Reference [15] using particle swarm optimization (PSO) algorithm to reduce the average-load losses. Reference [16] using hybrid Differential Evolutionary Particle Swarm Optimization (DEEPSO) algorithm for single-phase consumer allocation on the three phase of the LV network, used for optimal phase load balancing.

All the studies mentioned above have been conducted on a single or a few feeders or transformers, and none of the references have conducted studies on a large-scale network. Therefore, this article proposes a method to examine the impact of load balancing on reducing losses in a large-scale distribution network.

2. Methodology

Unbalanced conditions can have a significant impact on distribution network losses, and therefore, the development of methods to evaluate these losses is essential. In the method presented in this article, a new approach is introduced to estimate distribution network losses considering load imbalance, using representative feeders. In this method, the effect of unbalance on distribution network losses is calculated using statistical analysis of unbalance indices. Performing load shedding and evaluating the impact of load balancing on distribution network losses for all available feeders in the low voltage distribution network is impractical, considering the vast number of possible scenarios. Therefore, based on the available information of network, first, a representative feeder is extracted, then load flow is conducted and the impact of load balancing on losses is performed on representative feeders.

In general, the workflow for studying the effect of load balancing on reducing losses in low voltage networks, as shown in Figure 1, is as follows: Based on the available feeder data, representative feeders are extracted. In the next step, an appropriate probability distribution function is extracted based on the criterion used to evaluate the level of load imbalance. Then, various load arrangements are created for a specific value of that criterion, and in each of these cases, losses are calculated. Finally, the amount of losses is averaged for that specific criterion value. This process is repeated for different values of the load imbalance criterion, and ultimately, the calculated losses for each of these cases are compared to the case where the load imbalance is equal to zero, to determine the expected reduction in losses due to load balancing.

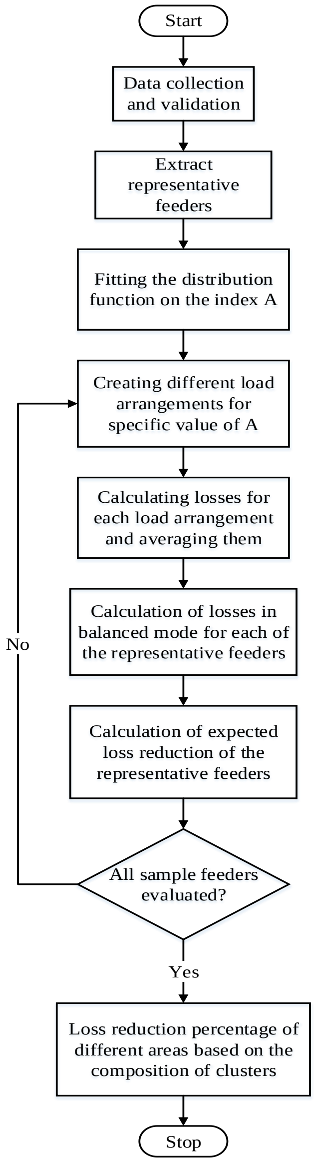

Fig. 1. Flowchart of the proposed method for studying the effect of load balancing on reducing losses..

A) representative feeders Calculation

Representative feeders are indicative of the behaviour and losses of feeders in a cluster. The method of calculating these feeders in conditions of information weakness is as follows: First, the required information is collected from each cluster and divided into two categories of constant and variable information. Variable information refers to the information that changes in representative feeders, while constant information refers to the information that is constant in the representative feeders of each cluster. The constant information of the representative feeders includes the main branch resistance, sub-branch resistance, span length, cluster load factor, peak load of cluster subscribers, and subscribers' power factor. Variable information includes the length of the main branch, the number of sub-branches, the total number of sub-branches, and the number of representative feeder subscribers. The constant and variable information of representative feeders can be calculated based on the information collected for each cluster. By calculating the constant and variable information, a spectrum of feeders can be obtained representing the behaviour of cluster feeders.

Due to the extent of the low voltage network, it is very difficult and expensive to collect and check the information of the entire network. In this regard, in order to reduce the costs imposed on the distribution company to study the low voltage network, top-down and bottom-up methods were introduced along with the integrated method. In these methods, a part of the network whose information is available or it is easier to collect information is selected as a sample and the necessary checks are carried out on it, then the results of the checks are generalized to the entire network. is the sample space.

The power losses in low voltage distribution lines are directly proportional to the loading on those lines. The loading on a substation, which steps down voltage from higher levels and feeds low voltage lines, indicates the overall loading on the low voltage feeders it supplies. Therefore, the loading level of a distribution substation can serve as a reasonably good proxy for the loading on the low voltage feeders it feeds. The load measurement of distribution substation is done annually or twice a year. While the substation load measurement is done once a year. Also, the peak load of summer is measured and recorded in databases. In the loadings of distribution substations, the amount of flow of phases, the percentage of substation loading and unbalanced indicators are measured.

At this stage, in order to choose the homogenous feeders of the sample space, you can use the information of the substation loadings. In this case, according to the percentage of substation loading, a number of substations are selected as samples. Using this approach, more than 200 substations are selected as a sample and its information is taken from the databases of the distribution company.

After selecting 200 substations as a sample, information on descriptive variables of losses is extracted using ARCGIS. the information, which have a high impact on the amount of network losses, are:

- Main feeder length in terms of span
- Number of sub-branches (branches)
- The total number of spans of sub-branches (branches)
- The number of consumers on the main branch
- The number of consumers on sub-branches
- Total number of consumers of the feeder

Obtaining representative feeders is based on the analysis of common features. Due to the fact that the load of consumers has a high influence on the way of designing distribution networks; Therefore, the clustering of loads can have a significant effect on the accuracy of the proposed method. There are different methods for clustering consumer loads. The most traditional and easiest method of load clustering in terms of implementing load clustering is based on the tariffs assigned to consumers. Due to the fact that the tariffs allocated to the subscribers are registered by the distribution companies, this type of load clustering can be easily implemented. Other parameters that can be used in load clustering are:

- Load type
- Annual energy consumption
- Type of weather conditions
- Urban or rural
- Economic status of consumers at the household level

Due to the fact that most of the load in low voltage networks is domestic, in terms of load clustering, loads can be divided into four clusters: commercial, well-off household, medium household, poor household. According to the fact that the amount of consumption of household subscribers has a direct relationship with their level of well-being, it is possible to determine the amount of household loads with low, medium and high consumption from the level of well-being of consumers. In this regard, the percentage of each of the consumers in each of the studied areas is determined with the help of experts who are proficient in those areas.

As mentioned, the information of the representative feeders are divided into two categories, variable and fixed, and the method of calculating each of these categories are mentioned below.

peak load of consumers:The amount of peak load of consumers is a direct function of the type of load group that has been studied. The amount of peak load of consumers who have the same load group is almost in the same range. To calculate the amount of peak load of consumers of representative feeders, it is necessary to calculate the average peak load of consumers of the sample space.

Load factor and simultaneity factor of consumers: The load factor and simultaneity factor are fixed information of representative feeders and are a function of the type of load group of consumers. To estimate these coefficients, it is necessary to examine the loads in the sample space.

Characteristics and resistance of conductors used in representative feeders: The resistance of different parts of representative feeders plays a significant role in calculating its losses. In the design of low voltage distribution networks, due to the high current in the main branches, the cross-section of the conductors used in the main branches is generally higher than the cross-section of the conductors used in the sub-branches. For this reason, it is better to consider two types of conductors with different cross-sections for representative feeders. In the parts of the two circuits of the feeder, the resistance must be halved. The resistance of representative feeders is calculated using the information available in the sample space based on (1).

$$R = \frac{\sum R_i L_i}{\sum L_i} \quad (1)$$

Let R_i denote the resistance of section i of the representative feeder, and let L_i denote the length of section i of that feeder.

Span length: *S*pan of the distance between electric poles is called the span of the length of the branches. The length of each span depends on the geography and design of the distribution network of the low voltage section. In the calculations of this study, the length of each of the spans of the representative feeders will be fixed and equal to the average length of the spans of the sample space feeders.

Variable information:The variable information of the representative feeders of the sample space is extracted from the statistical analysis of the information in the sample space.

B) The index for assessing the degree of load imbalance

So far, various indices have been introduced for evaluating the degree of load imbalance. In this article, for assessing the degree of current imbalance, two indices A and B, which have been published by Tavanir Company, are used. This criterion is used in the mentioned guideline to calculate the degree of current imbalance. In this approximation, there is no need to measure the phase angles of the currents. It should be noted that due to the independence of this criterion from the phase angle of the current, it has a special simplicity and its application has an advantage of higher operational ease compared to other computational methods. This guideline recommends using it. Before defining A index, a parameter called D, which represents the degree of deviation from the equilibrium state, is defined as follows:

$$D = \sqrt{-2 + \frac{6(I_R^2 + I_S^2 + I_T^2)}{(I_R + I_S + I_T)^2}} \quad (2)$$

In this parameter, the degree of deviation will vary from 0 to 2. A value of zero indicates an amplitude equal to the three-phase current range, and a value of two indicates zero current for two phases and only one phase having a current. Since the above formula is per-unit, the degree of deviation D can be the same in different current ranges. Therefore, if we multiply the measured deviation D by the neutral current, the resulting product will more appropriately represent the three-phase imbalance. Now, based on the above explanations, index A can be defined as follows:

$$A = \sqrt{-2 + \frac{6(I_R^2 + I_S^2 + I_T^2)}{(I_R + I_S + I_T)^2}} \times (I_N)_{meter} \quad (3)$$

Actually, index A indicates the value of the neutral current and the amount of three-phase imbalance. If it is high, one of the following situations exists:

- The value of the neutral current is high.
- The degree of three-phase current imbalance is high.
- Both of the above conditions have occurred together.

The exact allowable amount of deviation from the balanced state depends heavily on technical and economic studies, such as the cost of power and energy losses, the cost of balancing and displacement operations, etc. If these studies have not been carried out, a rough value of 10 is suggested as the maximum allowable criterion for post imbalance.

C) Fitting the probability density function of the unbalance indices

At this stage, based on the measurement data obtained during peak hours from LV feeders, the probability density function of the unbalanced index for each cluster needs to be calculated. The purpose of calculating the probability density function of the unbalanced index in each cluster is to evaluate the probability of different indices occurring in the feeders of a cluster. The calculation of the probability density function of unbalanced indices is performed using the frequency of the measurement data. It should be noted that the peak load measurement of distribution feeders and the unbalanced indices are carried out by distribution companies during hours close to peak time each year, and access to this information is easy through the distribution company. In order to fit the best probability density function for the measured data of the unbalanced index cluster, the function fitting flowchart for the measured data of the unbalanced index in Figure 2 has been used.

3. Result and discussion

According to the information of the low voltage distribution network of Alborz province, representative feeders have been obtained for each cluster of feeders, and studies will be carried out to evaluate the effect of load balancing on reducing their losses. In other words, all existing feeders are placed in clusters with the names of commercial feeders, well-off households, average households, poor households, and for each cluster, representative feeders are selected based on the mentioned criteria, and then balancing studies are carried out on these sample feeders.

According to the energy sales information and by dividing the total energy of each load cluster by the total energy sales, the participation percentage of subscribers in each feeder can be obtained, Which is 0.248 for commercial household, 0.236 for well-off household, 0.23 for average household, and 0.286 for poor household, respectively.

Now, in order to apply the load imbalance in the mentioned network, according to the data related to the Alborz network, first the statistical distribution of the imbalance index A was obtained (Figure 3), and then according to this statistical distribution, the imbalance was implemented in different states of the sample feeders and the losses in We calculate each state.

Considering the average value of unbalance index, A equal to 10%, then using the placement of single-phase loads on sample feeders for each cluster, a number of arrangements that lead to 10% unbalance according to index A, with the help of unbalanced load distribution obtained and then in each of the obtained situations, the system losses are obtained and finally, by averaging the loss values, the amount of system losses is obtained in the case where the imbalance index A is equal to 10%. In the same way, by considering different values for index A and repeating the mentioned steps, losses are calculated in different situations. It should be noted that we do this for all sample feeders belonging to each cluster of feeders. The results are presented in table 1, 2, 3, 4. After carrying out load distribution and calculating losses in different situations for different values of index A for representative feeders of each cluster, with the help of the cumulative distribution function of index A which can be seen in Figure 4, the expected values of losses, the reduction of losses and neutral current for each commercial, prosperous household, poor household and average household feeders can be calculated. The results can be seen in Table 5.

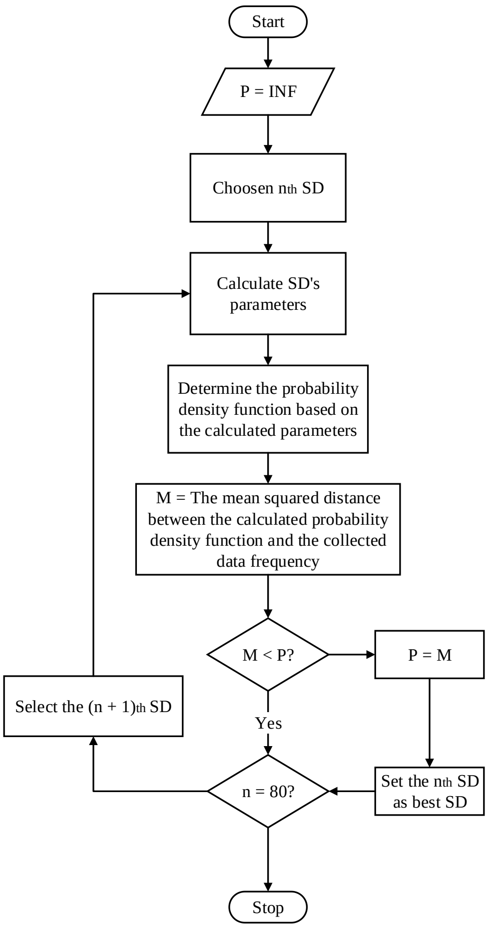

Fig. 2. Algorithm for fitting a suitable distribution function.

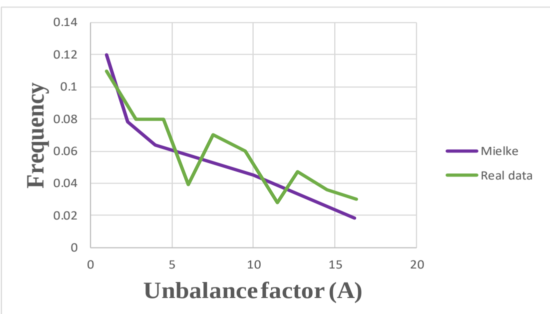

Fig. 3. Statistical distribution of imbalance index A

Table.1.
Results of studies related to average household representative feeders.

Index A (%)	Average network loss (MW)	Average neutral current (PU)	Loss reduction (%)
0	0.0051	0	0
4	0.0054	0.1044	5.5882
6	0.0055	0.1371	7.2745
8	0.0057	0.1515	10.6471
10	0.0058	0.1611	14.0588
12	0.0061	0.1891	19.2157

Table.2.
Results of studies related to commercial representative feeders.

Index A (%)	Average network loss (MW)	Average neutral current (PU)	Loss reduction (%)
0	0.0111	0	0
4	0.0116	0.1102	4.7748
6	0.0119	0.1465	7.5676
8	0.0121	0.1603	10.4325
10	0.0129	0.1761	15.8559
12	0.0141	0.1965	26.5766

Table.3.
Results of studies related to well-off household representative feeders.

index A (%)	Average network loss (MW)	Average neutral current (PU)	Loss reduction (%)
0	0.0131	0	0
4	0.0148	0.1133	3.9816
6	0.0150	0.1432	14.9311
8	0.0152	0.1653	22.0521
10	0.0159	0.1691	26.7994
12	0.0167	0.1960	35.5054

Table.4.
Results of poor household representative feeders.

Index A (%)	Average network loss (MW)	Average neutral current (PU)	Loss reduction (%)
0	0.0121	0	0
4	0.0136	0.0966	12.3967
6	0.0139	0.1221	14.876
8	0.0147	0.1442	21.4876
10	0.0153	0.1672	26.4463
12	0.0169	0.1927	31.6694

Table.5.
Comparing leakage current in different electrical conductivity for two contact angles of water droplets

feeder	Expected network loss (MW)	Expected neutral current (PU)	Expected Loss reduction (%)
average household	0.002582	0.05875	7.06
well-off household	0.004429	0.07334	7.68
poor household	00.4091	0.06261	7.1
commercial	0.007201	0.12031	10.87

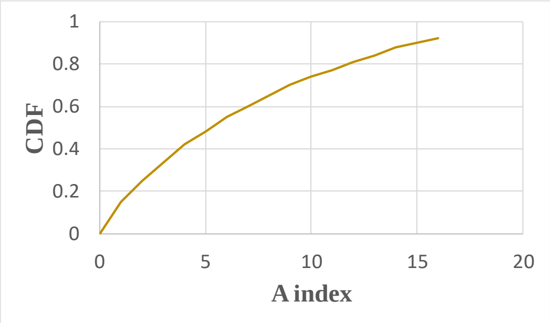

Fig. 4. Cumulative distribution function of index A

Considering that there is a combination of domestic and commercial feeders in each region of the distribution network of Alborz province, it is necessary to calculate the amount of loss improvement for different regions of Alborz province according to the results listed in table 5, the results of which are in table 6 is visible.

Table.6.
The amount of improvement in peak losses and energy in different areas of Alborz province electricity distribution company as a result of phase balancing.

Area	The rate of improvement of peak losses (%)	The rate of energy loss improvement (%)
Garmdareh	9.58	9.46
Mehrshahr	8.28	8.2
Mahdasht	8.68	8.63
Eshtehard	8.68	8.56
nazarabad	8.26	8.1
Hashtgerd	7.84	7.66
Chendar	8.7	8.48
Kamalshahr	8.38	8.31

4. Conclusion

As mentioned, various solutions have been proposed to reduce losses in distribution networks, load balancing is one of these solutions, therefore, in this article, the effect of load balancing in reducing distribution network losses using representative feeders was studied. According to Table 5, it is possible to prioritize different feeders to balance the load. As expected, among the feeders of the distribution network, load balancing of household feeders of medium and poor subscribers had the least effect on loss reduction, and commercial and household feeders with wealthy subscribers had the greatest effect on loss reduction. It should be noted that among the prosperous commercial and domestic feeders that have the greatest impact on system losses, priority is given to feeders whose A index is equal to 10 or more. Therefore, this prioritization can be used for proper planning to reduce distribution system losses.

References

[1] None, N., 2016. *Annual Energy Outlook 2016 With Projections to 2040* (No. DOE/EIA-0383 (2016)). USDOE Energy Information Administration (EI), Washington, DC (United States). Office of Energy Analysis.

[2] Martins, A.S.C., de Araujo, L.R. and Penido, D.R.R., 2022. Sensibility Analysis with Genetic Algorithm to Allocate Distributed Generation and Capacitor Banks in Unbalanced Distribution Systems. Electric Power Systems Research, 209, p.107962.

[3] Kalambe, S. and Agnihotri, G., 2014. Loss minimization techniques used in distribution network: bibliographical survey. renewable and sustainable energy reviews, 29, pp.184-200.

[4] Cikan, M. and Cikan, N.N., 2023. Optimum allocation of multiple type and number of DG units based on IEEE 123-bus unbalanced multi-phase power distribution system. *International Journal of Electrical Power & Energy Systems*, *144*, p.108564.

[5] Al-Kharsan, I.H., Marhoon, A.F. and Mahmood, J.R., 2020. A New Strategy for Phase Swapping Load Balancing Relying on a Meta-Heuristic MOGWO Algorithm. *J. Mech. Contin. Math. Sci*, *15*(2), pp.84-102.

[6] Raminfard, A. and Shahrtash, S.M., 2010. A practical method for load balancing in the LV distribution networks case study: Tabriz electrical network. *World Academy of Science, Engineering and Technology*, *42*, pp.1193-1198.

[7] El Hassan, M., Najjar, M. and Tohme, R., 2022. A Practical Way to Balance Single Phase Loads in a Three Phase System at Distribution and Unit Level. Renew. Energy Power Qual. J, 20, pp.173-177.

[8] Fang, L. and Ma, K., 2020. Assessment of additional phase energy losses caused by phase imbalance for data-scarce LV networks. IET Generation, Transmission & Distribution, 14(4), pp.675-681.

[9] Fang, L., Ma, K., Li, R., Wang, Z. and Shi, H., 2019. A statistical approach to estimate imbalance-induced energy losses for data-scarce low voltage networks. IEEE Transactions on Power Systems, 34(4), pp.2825-2835.

[10] Ali, B. and Siddique, I., 2017, November. Distribution system loss reduction by automatic transformer load balancing. In 2017 International Multi-topic Conference (INMIC) (pp. 1-5). IEEE.

[11] Salustiano, R., Neto, E. and Martinez, M., 2013, June. The unbalanced load cost on transformer losses at a distribution system. In 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013) (pp. 1-3). IET.

[12] Sureshkumar, R. and Maithili, P., 2017. Three Phase Load Balancing And Energy Loss Reduction In Distribution Network Using Labiew. International Journal of Pure and Applied Mathematics, 116(11), pp.181-189.

[13] Mostafa, H.A., El-Shatshat, R. and Salama, M.M.A., 2014, April. Phase balancing of a 3-phase distribution system with a considerable penetration of single phase solar generators. In 2014 IEEE PES T&D Conference and Exposition

[13][14] Alhmoud, L., Nawafleh, Q. and Merrji, W., 2021. Three-phase feeder load balancing based optimized neural network using smart meters. *Symmetry*, *13*(11), p.2195.

[14][15] Homaee, O., Mirzaei, M.J., Najafi, A., Leonowicz, Z. and Jasinski, M., 2022. A practical probabilistic approach for load balancing in data-scarce LV distribution systems using discrete PSO and 2 m+ 1 PEM. *International Journal of Electrical Power & Energy Systems*, *135*, p.107530.

[15][16] Ivanov, O., Neagu, B.C., Nițu, A.I. and Gavrilaș, M., 2021, June. An Improved Metaheuristic Algorithm for Load Balancing in LV Distribution Networks. In *2021 9th International Conference on Modern Power Systems (MPS)* (pp. 1-5). IEEE.