Phase Swapping Load Balancing Algorithms, Comprehensive Survey

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Abstract: *The power quality nowadays of the low voltage distribution system is vital for the utility and the consumer at the same time. One disturbing issue affected the quality conditions in the radial distribution system is load balancing. This survey paper is looking most the articles that deal with the phase nodal and lateral phase swapping because it is the efficient and direct method to maintain the current and voltage in balance situation, lead to a suitable reduction in the losses and preventing the wrong tripping of the protective relays.*

***Index Terms*— Algorithm, Distribution system, feeders, Load balancing, Low voltage, Phase swapping.**

I. Introduction

From more than one decade and a half, many types of research on the balancing of three or four-wires in the low voltage (LV) distribution network that called by the (feeders) were carried. It solved the problem that coming from spreading the single-phase loads, not in an equal manner among the three distribution feeders [1]. When the loads not distributed evenly on the feeders, the investment on the power system will increase, and from another side, the operation cost can be more. The unequal current flowing in the feeders can cause also increasing in the neutral current that tripping the feeder service, the sensitive loads in the network will not operate normally, the security of the line will reduce for the labors and overloaded the equipment of the power system [2]. Besides the disadvantages mentioned earlier, it makes the power losses more in the system, drive to unbalanced in voltage [3]. The process of system balancing not guarantee just an equal current in each feeder but also improve the security, the voltage profile and ensure that the power quality will be better [4]. The careful reading to these articles that deal with the unbalancing problem lead the reader to conclude that the problem solved either by 1) feeder's reconfiguration at the system level or by 2) phase swapping at the feeder level [5] as shown in Fig. 1. The first technique did not give a solution in the optimal case in spite of they can lead to a perfect suboptimal solution.

So, this survey will represent a massive survey concern about papers deal with the various algorithms used to overcome the problem of load balancing by the phase swapping technique. The paper organized as follows: Section (1) presents an introduction to the reasons that make the researches looking to solve the balancing problem in various methods and the advantageous coming from solving this complex problem. Section (2) gives a two-basic definition for the meaning of the unbalancing in the electrical distribution networks. Section (3) dedicated to the broad search and tracking any paper used the phase swapping either by the nodal or lateral method to achieve the phase balancing among the feeders of the distribution networks. Eventually, the conclusion in section (4).

II. The Unbalancing

According to the Ref. [6] the unbalance in the LV feeders refer to " The currents are drawn from each feeder not equal in magnitude with an electric angle equal to 120°". The imbalance in feeder means that the current in each feeder not identical in magnitude or the difference between the three phases is not equal to 120°, or maybe both of them.

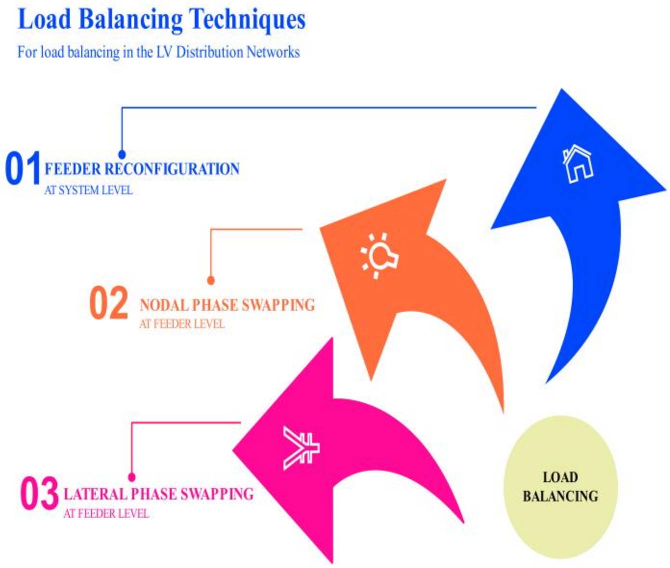

Fig. 1 Imbalance healing techniques for the distribution network

III. Phase Swapping algorithms

This method regarded a direct way and can achieve the goal of balancing with minimum cost. This technique makes the distribution feeders in the systems with an open loop or radial structure reach to the balancing situation. The balancing process achieved by changing the single-phase domestic loads connection (Home1 to Home n) from its original phases and retaping it to other phases among the three phases distribution feeder by using the switch selector. The distribution feeders define as the three-phases, four wires system in the secondary side of the distribution transformers as shown in Fig.2.

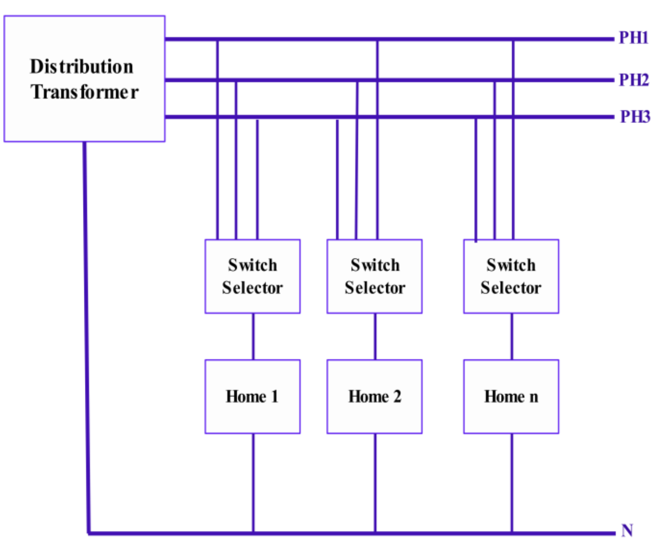

Fig. 2 Distribution feeder

The process of moving the load from one phase to another phase called by the swapping process. The appropriate swapping of specific loads among the phases can consequent to make all phases of the distribution network in the balancing case. In 1998, J. Zhu et al. published a pioneer paper and they used the Mixed-Integer Programming (MIP) to achieve the optimization with the phase swapping. They assumed for the simplification purpose that the drop voltage is not considered in the problem formulation. Besides that, all the loads have an equal power factor. The effect for that, they modelled the loads only by their current magnitude in the problem formulation. The result in the illustrative example show that the MIP could achieve the load balancing to an extraordinary extent [7]. In Ref. [8], the authors regarded that the feeder reconfiguration not useful way in load balancing due to some limitations and draw the attention to four articles as evidence for their opinion. Because of that, they are solving the NP-complete problem optimization problem by using a heuristic method called the simulated annealing (SA) algorithm. The algorithm gives an accepted solution for the phase balancing problem and in suitable computation time. The result showed that the cost and the quality would be reduced and improved by applying the SA. SA can consume more time, and there is a chance to miss the optimal solution, but it can avoid the local minimum and give better answer compared with the Greedy or the Quenching algorithms. In [9], Chen and Cherng used the genetic algorithm (GA) to executing the phase management in an optimal manner between the primary feeder and the distribution transformers in Taiwan Power Company (Taipower) distribution systems. The result of applying the GA algorithm result in considerable improvement on the tested feeder with 28 loads. The enhancement in feeder includes the unbalanced voltage, the neutral current flowing from the neutral point to the ground, also the losses in power and voltage drop. In [10], the authors are targeting the large scale system with an unbalanced state and radial configuration. The proposed algorithm rephased the single and double laterals to achieve balancing. It has the ability to elimination some laterals that are not possible to reach for by the field team. This algorithm does not care for the local minima because it gives the best phase moves until it lies in it. To ensure it worked successfully it tested on 100 laterals, the result achieved the phase balancing and reduced the losses in power significantly. In [11], Knolseisen et al. using the (GA) to achieve the load balancing in the secondary distribution system by swapping the loads among network phases. This article aims to improve the service quality by minimizing the drop-in voltage among the primary feeder that comes as a consequence of the load balancing and using the mono-objective approach. Gandomkar in [12] used the swapping technique to reach the balancing. The (GA) was used to finding the solution of balancing issue in the feeders of the LV distribution with 135 laterals that represents a large-scale combinational problem from the view of optimization. By this method, with just a few movements the losses in the circuit are improved. In [13], Khodr et al. design algorithm swaps the loads among the phases of the distribution network to achieve load balancing. The goal behind that is to make the load on the phases near the average. The MIP algorithm solved using the LINDO platform. The MIP reduced the unbalance by 5.26% compared to the system status before the balancing process. In [14], the authors used the fuzzy logic to reach the load balancing in the distribution feeders. They prefer using the swap technique on the system reconfiguration by using the tie and the sectionalizing switches. The tie switches give worse unbalance in the voltage and current. The algorithm tested on the distribution feeders by simulation in MATLAB® platform. The result showed that the algorithm could solve the unbalance problem to a large extent. Lafortune et al. in [15] used the Tabu search (TS) algorithm to solve the problem of finding the optimal swap in the single-phase loads connected to the distribution feeders to performing the load balancing. It represents a heuristic method that can deal with the non-linear problem effectively with minimum cost. It used to minimize the imbalance in the current, make the number of swaps and power losses less and finally take the KVA imbalance in consideration also. The simulation results of conducting the TS on 24 loads revealed that imbalance in current reduced to seventeen percent and the losses in power reduced to fifteen percent in a peak load day. The KVA decreased to just fourteen percent from the initial configuration. The exciting thing here all the earlier mentioned reduction happened only by four loads swapping on the feeders. In [16], the authors trying to make the LV and medium voltage (MV) distribution network operators in the optimal performance conditions. From their point of view, that may happen when the loss in the distribution network is minimum, the transformers and cables not overloaded, no imbalance in voltage neither in the current available in that network. To solve the imbalance issue in LV feeders, the authors contribute a heuristic method, and neural network implemented it in MATLAB® platform with 15 input load currents real data. The result of the algorithm was better in the balancing value and faster compared to the neural network techniques. Lin et al. in [17] trying to solve the problem of unbalanced three-phase distribution feeders in (Taipower) company. The proposed way to do that is by optimal rephasing of the open-wye, open-delta (OYD) distribution transformers, and the laterals by using the expert system in a simulation environment. The paper includes two phases; phase one dedicated to solving the increased in the neutral current by rephasing one lateral. The phase two aiming to reduces the losses in power by rephasing one distribution transformer. At the same time contributed in to make the neutral current also decreased furthermore by rephasing another lateral. The data collected by Supervisory Control and Data Acquisition System (SCADA) before and after applying the two phases algorithm show a meaningful decreasing in the neutral current. The ability to transfer the load between the distribution feeders in the case of faults enhanced as a result of three-phase balancing in the distribution system. Raminfard et al. in [18] introduced an updated edition from the Leap-frog method (LFOP) called by modified LFOP (MOLFOP) to make the distribution feeders in the LV distribution networks near the balancing situation. The authors according to MOLFOP redistribute the single and double loads among the three phases feeders. This step reduced the load magnitude on each phase among the phases. The results show better current balancing among the feeders when applied on two feeders of the electrical distribution company in Tabriz. In reference [19], the authors used hybrid heuristic greedy and fuzzy techniques to achieve load balancing in LV feeder. They realized the balancing case by retaping the single and two laterals that already connected to the primary trunk. The greedy role specified from which lateral among all the lateral in the network should begin to get the best and quick solution. The Fuzzy (depending on the different memberships chosen carefully) will give the suitable switching that produces the balancing. The result from applying the algorithm on IEEE 34 node show a reduction in the current deviation taking in the consideration the limits of the current and the voltages. In [20] the primary objective of the authors is minimizing the phase current deviation in the three-phase three-wire distribution system. The authors used the Self-adaptive Hybrid Differential Evolution (SaHDE) in the article. It has many merits like it is has a self-tuning mechanism to choosing the control parameters, rapid in convergence and regarded as a simple optimization procedure. It satisfied the load balancing in the feeder with consideration for the voltage and capacity constraints by determining the optimal phase transfer. The result after applying the algorithm in modified IEEE 34 and IEEE 123 nodes show that it is excellent compared with algorithms like Differential evolution (DE) algorithm and Hybrid differential evolution (HDE). Hooshmand et al. in [21] used bacterial foraging (BF) particle swarm optimization (PSO) to generate the (BF-PSO) algorithm. The weighted objective function regarded support feeder neutral current, voltage limitation, cost of rephasing and finally the satisfying the balancing for the radial and meshed networks. The simulation test for the algorithm on feeder No. 3062 in Ahwaz, Iran appears that the profile of the voltage is close to each other, the neutral current and power losses reduced to a large extent and besides all that it achieved the balancing among the three phases. In [22], the authors combined the swapping technique that can achieve the phase balancing and reducing the neutral current with the reconfiguration technique that can reduce the loss in the network. All that happens and executed when the Nelder Mead algorithm linked with a bacterial foraging algorithm (BF–NM) to solve a fuzzy multi-objective function. The result from IEEE 123 nodes simulation show that the technique is useful in balancing made and in the reduction of the system costs. In [23], Echeverri et al. in their article that published in 2012 solved the problem of the phase balancing and success in the primary goal to loss reduction. The researchers proposed a new method for phase balancing planning that in origin regarded as a nonlinear programming problem. These types of problem consider as a combinational problem, so using the modified version of the GA algorithm called Chu-Beasley Genetic Algorithm (CBGA) solved the problem successfully when the CBGA Algorithm has been tested with the IEEE 37 and 19 buses test system. In Ref. [24], the authors achieved the reached to a result state that dynamic programming is the best algorithm to perform load balancing. They Compare its performance with another five algorithms; simulated annealing, genetic algorithm, a greedy algorithm, backtracking algorithm, and an exhaustive search. The dynamic programming and the Genetic algorithm have the same performance to satisfying the load balancing. The significant merit for the first one on genetic was there needing to fewer swaps to obtaining the load balancing. In [25], the authors applied the adding decaying self-feedback continuous neural network (ADSCHNN) algorithm to reach the load balancing. In the first, the loads have been represented by the current or the power they are consumed at the connection point. ADSCHNN solved the optimal loads' reconnection among the phases by choosing the best location for each load and this regarded as a combinational optimization problem. The result of applying the algorithm on a real data shows a reasonable reduction in the power losses compared with that obtained from heuristic algorithm and those from a fuzzy logic expert system. In [26], the balancing in the three-wires distribution feeders has been achieved by rephrasing the laterals according to a heuristic logarithm. It applied to two actual underground feeders (GV52) in Taichung District of Taipower with a length of 2.2 Km for the simulation purpose to ensure the algorithm effectiveness. The result of applying a heuristic algorithm that has a backtracking search mode confirmed the unbalance index, and the neutral current will reduce. In Ref. [27], Zdraveski et al. used the client-server addressing concepts with a hierarchical model for solving the load balancing problem. The primary objective here is to minimize the losses in power in the power distribution network (PDN) by using the nodes strategy. The availability of the smart meters that can communicate and work as actuator enables the authors regarded the primary node in the PDN as a parent (central power meter) and the others as children (can view as ad hoc network). They are adding a microcontroller that can controls a rotary cam switch in each node. The approach has been applied on IEEE 34-Bus, 37-Bus and 123-Bus networks and proved itself by achieving load balancing and reduce the losses in power. In [28], the authors for limitation aim proposed a model, built based on the Linear Integer-Mixed Programming. After that, they design a hybrid multi-objective optimization model named by Evolutionary Particle Swarm Optimization (FEPSO), it including the concepts of the particle swarm, evaluation and the fuzzy at the same time. The simulation results from implementing FEPSO and FSA on the existing LV feeder system in the city of Bariloche, Argentina show an excellent load balancing. Mendia et al. in [29] trying to solve the balance problem in the low voltage distribution system that coming as a consequent for the new houses connected to the network. The sharp load growing in the network represent a stubborn and challenging problem, and the suitable solution was by the modified of Harmony Search (HS) algorithm. The algorithm takes in its consideration the single and bi-phase loads that connected to the distribution network. The phase swapping by HS of those loads depending on real load data recorded in each hour achieved a good improvement in the quality besides the HS consumes less computational time compared with the genetic algorithm (GA) as an example. In [30], the authors propose an algorithm to targeted the end of the distribution system that is in public 3 phase 4 wire system to solve the load unbalancing issue depending on the master unit near the transformers and the slave units near the consumers. The algorithm has advantages like it is less in the computational time, it is simple, not expensive for implementing it in the distribution system and reduce the inrush current during the TRAIC switching process. In Ref. [31], the authors solved the unbalancing dilemma that ordinarily available in the low voltage distribution networks. The nodal phase swapping procedure had been used and performed by design a residential load swapping mechanism that consists of three parts: user controller unit, signal processing unit and the calculation unit. The balancing issue solved by a multi-objective algorithm called “improved multi-population genetic algorithm (IMPGA)”. The experimental and simulation outcomes prove that there is a decreasing in the unbalance rate. In Ref. [32], K. Ma et al. suppose a statistical approach for correcting phase swapping in the low voltage networks (415V) that suffering from a lack in the data by a method called guidance of phase swapping. The scarcity of data forms a problem in case there is a necessity for load balancing. The guidance method not requested data collected from the network or the customer meters and instead of that, the annual data of phase currents collected from the substation, the load profile typical curves and the weights on each of the three phases can be enough for the swapping process. The proposed guidance strategy can reduce the imbalance problem in a 99% LV networks by around 35%. The method reaches to 14.3% phase imbalance degree less than that achieved in the case of rich-data low voltage networks. In [33], the authors applied the robust optimization technique to lessen the unbalancing in the feeders with a minimum number of swapping for the low voltage networks with uncertain data. The uncertainty is coming from the penetration of PVs and the electric vehicle in the distribution networks that regarded a variable load with high inconstant data. The performance measured by three metrics: between phase imbalance, single-phase imbalance and the percentage of the single-phase difference. The applying of robust Phase Balancing can decrease the imbalance of single and between phase about 11% if it compared with the deterministic Phase Balancing. The using of the look-ahead technique gives a significant enhancement for the distribution network by reducing the imbalance for the single-phase and between phases by 30% if there a three swapping per day. The techniques used for make the feeders in balancing situation that mentioned in the survey so shown in Fig.3.

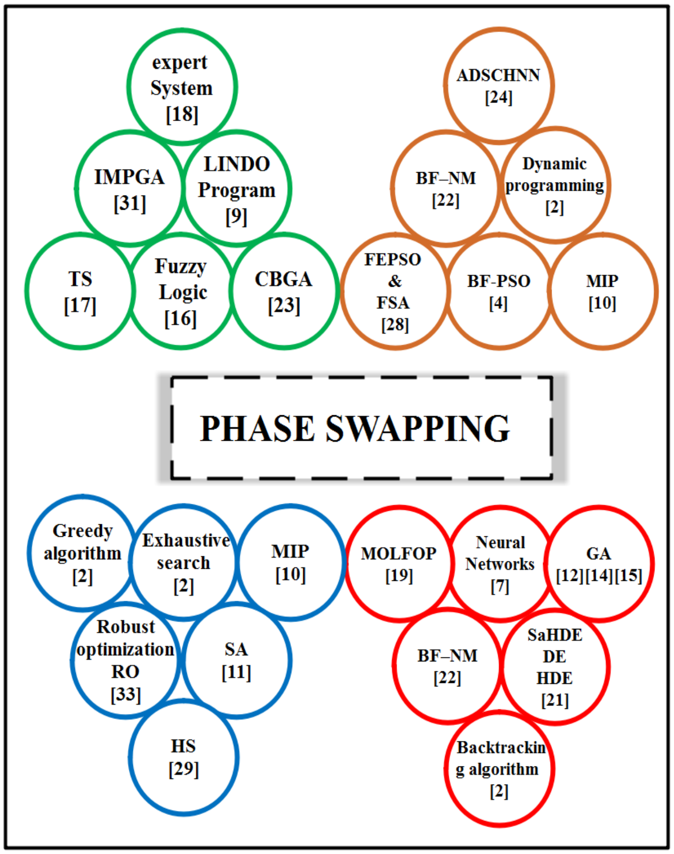

Fig. 3 The techniques mentioned in the survey to achieve load balancing

The Table 1 proposed to enable the readers with timeless to see the papers result that investigated in this survey beside briefly other details set for comparison purpose and that regarded as a silent feature because the researcher can go directly to the paper that related to his work without wasting any time in searching.

Table1 the overall indexing of the survey

Ref.	Authors	Approach	Applied on	year	Outcomes
[7]	J. Zhu et al.	**M**ixed-**I**nteger **P**rogramming (MIP)	Six-nodes (primary trunk and laterals)	1998	• Achieve effective phase balancing • Maximize the benefits for each phase swapping

[8]	J. Zhu et al.	**S**imulated **A**nnealing (AS)	5-Nodes feeder system	1999	• SA consume time to reach balancing more than the Quenching and Greedy algorithm but it can avoid the local minima. • SA give better balancing solution than Quenching and Greedy algorithm specially for large-scale networks. • Minimize the voltage drops and the energy losses in the system
[9]	T.H. Chen et al.	**G**enetic **A**lgorithm (GA)	Radial-type primary feeder with five distribution transformers	2000	• Achieve the optimal phase arrangement • Enhance the unbalanced voltage • Reduce the voltage drop • Reducing the neutral current • Minimizing the power losses
[10]	M. Dilek et al.	Proposed Algorithm	Radial distribution system 100 laterals	2001	• Achieving the load balancing with time-varying load patterns in reasonable time. • Reducing the cost of lateral swapping. • Reduce the power losses.
[11]	A. Knolseisen et al.	GA	Secondary distribution network in the south of Santa Catarina	2003	• Improve the balancing in the secondary networks • Enhance the quality of utility services • Minimizing the voltage drops.
[12]	M. Gandomkar	GA	LV distribution network with 135 laterals	2004	• Finding the balancing of LV feeder with minimum cost. • Reducing the power losses in the system by 18% in 4 phase movement.
[13]	H. M. Khodr et al.	MIP	Radial feeder with six nodes	2006	• Reducing the unbalancing by 5.26%. • Less energy losses.
[14]	M. W. Siti et al.	Fuzzy Logic	Three-phase four-wire unbalanced feeders (South African).	2007	• Reducing the feeder unbalance.
[15]	M. Lafortune et al.	**T**abu **S**earch (TS)	Distribution feeder with 24 single-phase loads	2007	By 4 swaps from the initial phase configuration there was a: • Reduce the imbalance of the current by 17%. • Reduce the power losses by 15%. • Reduce the KVA imbalance by 14%.
[16]	M. W. Siti et al.	Proposed heuristic algorithm	MV & LV distribution feeder with real data in South Africa	2007	• Reducing losses • Better network performance. • Reducing the difference between the phase's currents.
[17]	C. H. Lin et al.	Expert system	Distribution feeder in Taipower company	2008	• Enhance the three-phase balance of distribution feeders. • Decreasing the neutral current of the feeder.
[18]	A. Raminfard et al.	**M**odified **L**eap-**F**rog (MOLFOP)	Two LV feeders of Tabriz Electric Distribution Company	2010	• Better balancing between the currents in three phases rather than some of published methods • Decreasing the neutral current • Power losses reduced to large amount.

[19]	M. Sathiskumar et al.	Hybrid Greedy-Fuzzy Algorithm	Radial LV feeder in distribution system	2011	• Phase current deviation from the average has been reduced significantly. The current deviation for the initial configuration is 21.24% and 2.14% after applying the algorithm.
[20]	M. Sathiskumar et al.	**S**elf-**A**daptive **H**ybrid **D**ifferential **E**volution (SaHDE)	Radial LV feeder in distribution system	2012	• Phase current deviation from the average has been reduced significantly. The current deviation for the initial configuration is 21.24% and 1.54% after applying the algorithm.
[21]	Hooshmand et al.	**B**acterial **F**oraging **P**article **S**warm **O**ptimization (BF-PSO)	Radial and mesh networks Ahwaz, Iran	2012	• Phase balancing in radial and mesh distribution networks • Maintain the three-phase voltage • Reduce the power losses • Reduce the neutral current
[22]	Hooshmand et al.	**N**elder **M**ead with **B**acterial **F**oraging (BF–NM)	Feeder No. 3062 in Ahwaz, Iran	2012	• Very close together three-phase voltage profiles • Increasing the balance • Reduces power losses
[23]	M. Echeverri et al.	**C**hu-**B**easley **G**enetic **A**lgorithm (CBGA)	Radial IEEE 37,19 buses test system	2012	• Achieve the load balancing • Reduce the energy losses by 9.35%.
[24]	K. Wang et al.	Dynamic programming	100 Random generated loads	2013	• Achieve very good load balancing and give competitive results with the GA. • Swapping number less than GA for load balancing.
[25]	C. G. Fei et al.	**A**dding **D**ecaying **S**elf-**F**eedback **C**ontinuous **N**eural **N**etwork (ADSCHNN)	Distribution feeder with real data	2014	• Satisfying load balancing. • Reducing the total power losses. • Showed better performance than [16] and fuzzy logic expert system.
[26]	C. Lin	Proposed heuristic search algorithm	Two actual underground feeders in Taichung District of Taipower	2014	• Achieve load balancing (the daily phase unbalance index PUI decrease from 45.6% to 2.9%). • Reducing the neutral current (from 35.2A to 4.3A).
[27]	V. Zdraveski et al.	Client-server addressing concepts with a hierarchical model	IEEE 34-Bus, 37-Bus and 123-Bus networks	2015	• Achieved load balancing. • Reduce the power losses (see table1 and table2).
[28]	G. Schweickardt et al.	**F**uzzy **E**volutionary **P**article **S**warm **O**ptimization (FEPSO)	LV feeder system in Argentina	2016	• Achieved excellent load balancing compared with the SA, FSA, PSO.
[29]	I. Mendia et al.	Modified Version of the **H**armony **S**earch (Hs) Algorithm	Real data of a distribution feeder with 82 residential and 15 commercial loads collected by smart meters.	2017	• The HS algorithm achieve better balancing compared with GA (see Fig.1 and Fig.2). • Improvement the quality. • HS consumed less time compared with the GA to achieve the balancing.

[30]	M. Osama et al.	Proposed Algorithm	Low tension side of 3 phase 4 wire distribution transformer	2017	• Achieve phase balancing in low computational time. • Reducing the inrush current for the inductive loads.
[31]	G. Bao et al.	**I**mproved **M**ulti-**P**opulation **G**enetic **A**lgorithm (IMPGA)	Experimental circuit built in lab.	2019	• Reduce the three-phase unbalance rate.
[32]	L. Fang et al.	Statistical Approach	Low voltage distribution networks (415V)	2019	• Reduce the imbalance in most of LV distribution networks by 35%. • With the lack in network data, the proposed approach can give balance less by 14.3% compared with the approaches with rich-data.
[33]	X. Geng et al.	Robust optimization and look ahead techniques	Load profiles are from dataset "R1-12.47-4" [34]	2019	• The robust technique can reduce the unbalance by 11%. • The look-ahead technique can reduce the unbalance by 30% with three swaps per day. •

IV. Conclusions

Load balancing in recent years regarded one of the critical factors that should study for all who are looking for the reliability and continuous service in LV power distribution networks without any interruptions. There are two techniques to achieve the load balancing, the feeder configuration in the system level and the phase swapping in the feeder level. Phase swapping considered a direct and effective way to achieve feeder balancing. This paper search in-depth about most articles that concerned with the phase swapping in nodal or laterals way to accomplish the phase balancing because of the high importance of this topic in reduction the system losses, the operation cost, reducing the neutral currents in the distribution networks and that preventing the unnecessary tripping of the protection devices and prolonging the life of distribution equipment like the transformers.

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