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Multi-objective Unbalanced Distribution Network Reconfiguration through Hybrid Heuristic Algorithm

G. Mahendran†, M. Sathiskumar*, S. Thiruvenkadam* and L. Lakshminarasimman**

Abstract – Electrical power distribution systems are critical links between the utility and customer. In general, power distribution systems have unbalanced feeders due to the unbalanced loading. The devices that dependent on balanced three phase supply are affected by the unbalanced feeders. This necessitates the balancing of feeders. The main objective of reconfiguration is to balance the loads among the phases subject to constraints such as load flow equations, capacity and voltage constraints and to reduce the real power loss, while subject to a radial network structure in which all loads must be energized. Therefore, the distribution system reconfiguration problem has been viewed as multi-objective problem. In this paper, the hybrid heuristic algorithm has been used for reconfiguration, which is the combination of fuzzy and greedy algorithms. The purpose of the introduction of greedy is to refrain the searching for the period of phase balancing. The incorporation of fuzzy helps to take up more objectives amid phase balancing in the searching. The effectiveness of the proposed method is demonstrated through modified IEEE 33 bus and modified IEEE 125 bus radial distribution system.

Keywords: Power distribution network, Greedy, Fuzzy, Phase balancing

1. Introduction

Distribution systems are unbalanced in nature due to unbalanced loading at the nodes. Unbalanced loading increases energy loss and risk of capacity constraint violation and also deteriorates power quality and rise in electricity cost. The imbalanced feeder system can be balanced by implementing the phase swapping technique. Phase balancing not only concentrates on phase currents but also improves voltage, security and reliability. This result in a power service with higher quality and lower cost, and will improve the utility's competitive edge in the deregulated markets.

The authors [1-4] addressed phase balancing problem by handling phase balancing into feeder reconfiguration approaches. The solution techniques were not suitable under all the conditions of the distribution system. The method to identify phase swapping schemes to balance a radial feeder system based on the loads at each load point had been described in [5]. Simulated annealing [6] procedure had been adopted for phase balancing for large-scale system. This technique is realized as time-consuming compared to the other heuristic techniques and does not guarantee to bring the global optimum solution.

† Corresponding Author: Department of Electrical and Electronics Engineering, P. A. College of Engineering and Technology, Tamilnadu, India (dhanush_gm@yahoo.co.in)
* Department of Electrical and Electronics Engineering, P. A. College of Engineering and Technology, Tamilnadu, India (sathis_m02@yahoo.co.in, thirutamil_s@yahoo.com)
** Department of Electrical Engineering, Annamalai University, Chidambaram, Tamilnadu, India (llnarasimman@gmail.com)
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A heuristic rule-based algorithm with backtracking search [7] had been proposed to solve the phase balancing problem. The connection types of laterals in each service zone were identified and a three-phase load flow program with rigorous feeder model was executed to calculate phase current loading of each branch. The authors of [8] had explained a method to state locations wherever the imbalances do not get worse during the course of phase balancing with limited phase moves. An algorithm [9] based on immune algorithm was introduced to obtain the re-phasing strategy by considering the unbalance of the phasing currents, customer service interruption costs and labor cost to perform optimal re-phasing strategy. In previous proposed methods, the authors concentrated on finding solution for phase balancing and anxious on other constraints.

This paper proposed a hybrid fuzzy-greedy algorithm which provides solution for phase balancing as well as addresses the constraints such as load flow equations, capacity and voltage constraints, while subject to a radial network structure in which all loads must be energized. The search over the distribution network has been improved with the introduction of greedy algorithm. Through the integration of heuristic fuzzy, constraints are taken care with phase balancing.

2. Problem Formulation

In this paper, the objective is to minimize the phase current deviation and real power loss subject to capacity and voltage constraints and, while subject to a radial

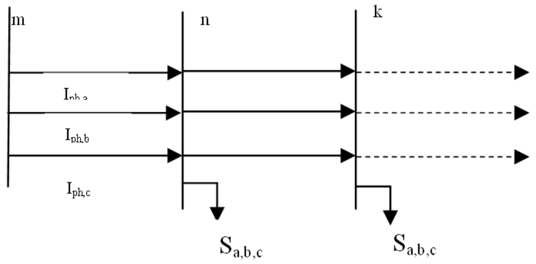

Fig. 1. Three phase three wire sample radial distribution system

network structure in which all loads must be energized.

A 3 phase-3 wire distribution system is shown in Fig. 1. The system has got three buses m, n and k, two branches between buses m-n and n-k, loads connected at the buses n and k and served from single feeder. The objective function for the system shown in Fig. 1 is given by,

$$C = \min(D\, I_m) \tag{1}$$

Subject to,

$$|V_{min}| < |V_{nb}| \leq |V_{max}|$$

$$|I_{max}| > |I_k|$$

where,

$$DI_j = \max(|Dev_a^j|, |Dev_b^j|, |Dev_c^j|) \tag{2}$$

$$Dev_i^j = \frac{I_{ph,i}^j}{I_{ave}^j} - 1 \tag{3}$$

$$I_{ave} = \frac{I_{ph,a} + I_{ph,b} + I_{ph,c}}{n_p} \tag{4}$$

subject to,

1) minimization of the deviations of node voltages
2) minimization of the branch current constraint violation
3) minimization of power loss and
4) retain radial structure & all the loads should be served

Where,

Dev_a, Dev_b and Dev_c are the phase current deviations of the phases a, b and c respectively;

DI_j refers maximum deviation index of the jth node;

Iph,a, Iph,b and Iph,c are the phase currents of the phases a, b and c respectively;

i= phases a, b and c;
j= nodes m,n,k…….nb
k= 1,2,3,4…..nl
n_p = Number of phases present
nb = total number of buses present in the system;
nl = total number of lines present in the system;
V_{max}= maximum bus voltages limit, 1.0 pu assumed;
V_{min} = minimum bus voltages limit, 0.9 pu assumed;

The equation is (3) used to measure how much phase current is above or below the average phase current at the nodes. If the resultant value of (3) is -0.5, then it indicates that the phase current is running 50% below the average. Similarly, a resultant value of 0.5 would indicate 50% above the average. If only single phase current present in any node then its deviation will be 200% above the average. From the above statements it is obvious that the perfect balance occurs when currents in all phases are equal and deviation is zero. Perfect imbalance occurs if there is only one phase that carries current while the other two phases have no current.

3. Proposed Algorithm

As per the proposed algorithm, the main objective is phase balancing at the feeder level. Phase balancing has been achieved through phase swapping. It can be classified as nodal phase swapping and lateral phase swapping. Nodal phase swapping is the load swapping at a node while lateral phase swapping is to retap the laterals to the primary trunk. If lateral phase swapping is applied, all the nodes on this lateral will not be allowed for nodal phase swapping. Therefore, the lateral can be treated as a fictitious node on the primary trunk. Lateral phase swapping is the same as nodal phase swapping from the point of view of mathematical formulation.

It is understood that distribution network has numerous nodes and obvious that it may have more laterals on it. Once we consider laterals are the control variable, the searching for the best configuration becomes tiresome. It should address from which lateral the solution process should begin for the best and speedy search. The greedy algorithm addresses the problem of identifying the node sequence for searching. The search over the distribution network has been improved with the introduction of greedy algorithm.

3.1 Greedy algorithm (GA)

A greedy algorithm is any algorithm that follows the problem solving metaheuristics of making the locally optimal choice at each stage with the hope of finding the global optimum. Most of the greedy algorithms should have two important properties:

i. Greedy choice property

We can make whatever choice seems best at the moment and then solve the sub problems that arise later. The choice made by a greedy algorithm may depend on choices made so far but not on future choices or all the solutions to the sub problem. It iteratively makes one greedy choice after another, reducing each given problem into a smaller one.

ii. Optimal substructure

A problem exhibits optimal substructure if an optimal solution to the problem contains optimal solutions to the sub-problems. In other words, a problem has optimal substructure if the best next move always leads to the optimal solution.

In general, greedy algorithms have five pillars to format the problem and solution:

i. A candidate set, from which a solution is created.
ii. A selection function, which chooses the best candidate to be added to the solution
iii. A feasibility function that is used to determine if a candidate can be used to contribute to a solution
iv. An objective function, which assigns a value to a solution, or a partial solution, and
v. A solution function, which will indicate when we have discovered a complete solution

For the phase balancing problem, the formation of problem and solution has been made as,

i. Candidate set, set of move points in unbalanced RDS;
ii. Selection function, sequencing move points in increasing order of branch phase deviation (Devi; where i=1,2,…nl; nl is total number of branches present in the network) at the initial configuration/ after the arrival of every new configuration;
iii. Feasibility function, function which checks existence of move points in network and existence of laterals in each move point;
iv. Objective function, traverse all the move points of network one by one in sequence;
v. Solution function, terminate process after iteration or condition.

Though the introduction of greedy algorithm speeds-up the searching process of phase balancing, it requires addressing the constraints with objective. This can be achieved through the incorporation of heuristic fuzzy with greedy.

3.2. Fuzzy operations for phase balancing problem

In fuzzy domain, each objective is associated with a membership function. The membership function indicates the degree of satisfaction of the objective. In the crisp domain, either the objective is satisfied or it is violated, implying membership values of unity and zero, respectively. When there are multiple objectives to be satisfied simultaneously, a compromise has to be made to get the best solution. The three objectives described in the preceding text (minimization of phases imbalance, minimization of buses voltage deviation and minimization of branches current deviation) are first fuzzified and then, dealt with by integrating them into a min-max imperative of fuzzy satisfaction objective function.

In the proposed method for network reconfiguration, the terms μPi, μVi, μIi and μFi indicates the membership function for phase current deviation, node voltage deviation, branch current deviation and power loss deviation respectively. The higher membership value implies a greater satisfaction with the solution. The membership function consists of a lower and upper bound value together with a strictly monotonically decreasing and continuous function for different objectives are described below.

3.2.1 Fuzzy-set model of the bus voltage deviations

The intention of this membership function is that the deviation of nodes voltage should be less. The Eq. (5) gives the maximum deviation amongst the buses of phases a, b and c voltages. The maximum deviation amongst phases is derived from Eq. (6).

$$\left.\begin{aligned} Ya &= \max \mid Vs,a - Vi,a\mid \\ Yb &= \max \mid Vs,b - Vi,b\mid \\ Yc &= \max \mid Vs,c - Vi,c\mid \end{aligned}\right\} \tag{5}$$

Where
$V_{s,a}$,$V_{s,b}$ and Vs,c are the substation voltages at phases a,b and c respectively
Vi,a Vi,b and Vi,c are the voltages at phases a,b and c of the bus 'i' respectively
i= 1,2,…..nb;
nb=number of buses present in the system
And,

$$Y_j = \max(Y_a, Y_b, Y_c) \tag{6}$$

where, 'j' refers influence of j^{th} later phase swapping

If maximum value of nodes phase voltage deviation is less, then a higher membership value is assigned and if deviation is more, then a lower membership value is assigned. The membership function for maximum bus voltage deviation index is written

$$\mu_{V,j} = \begin{cases} \dfrac{y_{max} - y_j}{y_{max} - y_{min}} & \text{for } y_{min} < y_j < y_{max} \\ 1 & \text{for } y_j \le y_{min} \\ 0.0 & \text{for } y_j \ge y_{max} \end{cases} \tag{7}$$

In the present work, y_{min}=0.9 and y_{max}=1.2 have been considered.

3.2.2 Fuzzy-set model of the branch current loading

The intention of this membership function is that to minimize the branch current constraint violation. The main purpose of this membership function is to determine the branch current loading during each new configuration. Initially, all the branches current capacity are defined as Ii ;where, i=1,2,3….nl; nl is the total number of branches in the RDS. During each new configuration the new value of branches phase currents are received through Radial Load Flow (RLF) and defined as Ii,a, Ii,b and Ii,c for the phases a,b and c respectively. Then, the branch current loading index is calculated for the branch ‘i' as

$$\text{Branch current loading index(BCLIi)} = \frac{\max(Ii,a,Ii,b,Ii,c)}{Ii} \tag{8}$$

where, $I_{i,a}$, $I_{i,b}$ and $I_{i,c}$ are the i^{th} branch loading of the phases a, b and c respectively after phase swapping

I_i is the i^{th} branch current capacity
i=1,2…..nl; nl refers total number of branches

The maximum branch loading index during j^{th} phase swapping is defined as

$$Z_i = \max\left(BCLI_i\right) \tag{9}$$

When maximum value of branch current loading index exceeds unity, membership value will be lower and as long as it is less than or equal to unity, membership value will be maximum, i.e. unity. The membership function for maximum branch current loading index is written as

$$\mu I, j = \begin{cases} \dfrac{Z\max - Zj}{Z\max - Z\min} & \text{for } Z\min < Zj < Z\max \\ 1 & \text{for } Zj \le Z\min \\ 0.0 & \text{for } Zj \ge Z\max \end{cases} \tag{10}$$

In this work, z_{min}=0.1 and z_{max}=2.5 have been considered

3.2.3 Fuzzy-set model of the phase current deviation

Phase balancing is one of the major objectives of network reconfiguration. An effective strategy to increase the loading margin of heavily loaded phases is to transfer part of their loads to lightly loaded phases. Phase load balancing index has been calculated for the phases a,b and c as per the Eq. (2) during jth phase swapping. Let us define, m

$$x_j = \max\left(Dev_a, Dev_b, Dev_c\right) \tag{11}$$

Eq. (11) indicates that a better load balancing can be achieved if the value of xi is low. Therefore, for lower xi, higher membership grade is assigned and for higher xi lower membership grade is assigned. The membership function at jth configuration can be expressed as follows,

$$\mu P, j = \begin{cases} \dfrac{X\max - Xj}{X\max - X\min} & \text{for } X\min < Xj < X\max \\ 1 & \text{for } Xj \le X\min \\ 0.0 & \text{for } Xj \ge X\max \end{cases} \tag{12}$$

In the present work, xmin=1.0 and xmax=1.15 have been considered.

3.2.4 Fuzzy-set Model for Power Loss Minimization

The deviation of power loss (Pnloss) of the new configuration to the previous configuration loss (Ptloss) is to be identified with the objective of minimizing the system power loss. The power loss of the system has been obtained from radial load flow for each new configuration. Moreover, the amount of the Pnloss resulting from any branch exchange can be estimated as ‘very close, ‘close' or ‘not close' to the Ptloss. Therefore, the linguistic terms can be formulated as a membership function by the fuzzy notation. The membership function μFj has been depicted using Eq. (13). A small difference between Pnloss and Ptloss possesses a larger membership value. The membership function at jth configuration can be expressed as follows,

$$\mu Fj = \begin{cases} \dfrac{X\max - Xj}{X\max - X\min} & \text{for } X\min < Xj < X\max \\ 1.0 & \text{for } Xj \le X\min \\ 0.0 & \text{for } Xj \ge X\max \end{cases} \tag{13}$$

where, $X_j = P_{nloss}/P_{tloss}$

In the present work, X_{min}=0.5 and X_{max}=1.0 have been considered.

The purpose of the feeder reconfiguration can be achieved by the decision fuzzy set D, which is derived from the intersection of the three membership functions μ_{Vi}, μ_{Ii} and $\mu_{Pi,}$ μ_{Fi}. However, the optimal decision is the highest membership value of μ_D. Thus, an optimal decision fuzzy set D can be designated as follows,

$$\mu_D = \max\left\{\min\left[\mu_{vi}, \mu_{Ii}, \mu_{Pi}, \mu_{Fi}\right]\right\} \tag{14}$$

Where,
i=1,2,….n_p ; n_p = total number of phase swapping combinations on a lateral.

3.2 Three phase system connection types

Usually, phase balancing has been done at the laterals. The character of the lateral may be either three-phase, double-phase or single-phase. For re-phasing, three-phase laterals are left out for consideration. As the changing of phase sequence on the three-phase motor could cause harm to the motor. A single-phase or double-phase lateral that is ‘moveable’ and connected to a three-phase lateral which is called as move point. A lateral that is considered for moving is made up of a move point and all downstream lateral from that move point.

Re-phasing a lateral means consistently changing the phase(s) of the move point and all downstream belonging to that lateral. Thus, when a move point is re-phased, all subsequent laterals in the lateral are re-phased consistent with the changes made at the move point. The possible connection schemes of the single phase laterals and two-phase are listed out in the Table 1 and Table 2 respectively. From the tables, it is understood that a single-phase lateral has two re-phasing alternatives, and a two-phase lateral has five re-phasing alternatives

Table 1. Different combinations of single phase laterals

Possible Combination sets in single phase laterals	A	B	C
A	x		
B		x	
C			x

Table 2. Different combinations of two phase laterals

Possible Combination sets in Two phase laterals	AB	AC	BC	BA	CB	CA
AB	x					
AC		x				
BC			x			
BA				x		
CB					x	
CA						x

3.3 Computational flowchart

The phase balancing process starts with identifying the move points in the system. After executing the three phase radial load flow, the move points are arranged as per the deviations (Greedy approach). Then, re-phasing begins from the most phase current deviated move point. Then, the three fuzzy set models are defined such as μV, μI , μP and μF for finding the closeness in buses voltage deviations, branches current deviations, phase current deviations and power loss deviation respectively. The membership values of the fuzzy sets pertain to respective configuration has been retrieved through three phase radial load flow. After introducing min-max imperative to the membership values, the healthier configuration was identified amongst various possible combinations of laterals. The complete optimization procedure based on hybrid Greedy-heuristic fuzzy has been illustrated in flowchart shown in Fig. 2.

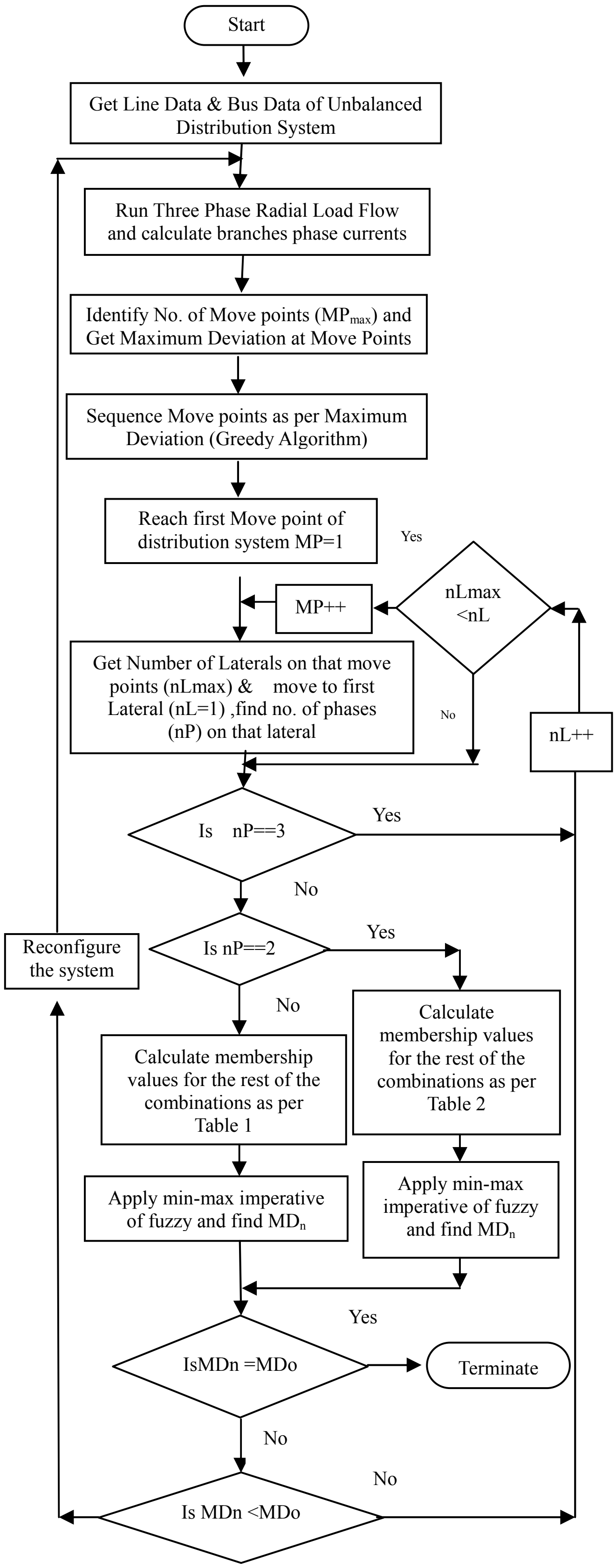

Fig. 2. Flowchart for the Proposed method

4. Simulation Results

Proposed method was implemented using J2EE (Java 2 Enterprise Edition) programming and run on Pentium-IV, 266 MHz computer. The effectiveness of the proposed algorithm has been tested with modified IEEE 34 bus distribution system and modified IEEE 125 bus distribution system.

4.1 Modified IEEE 34 bus system

The modified IEEE 34 node system [10] is an unbalanced distribution system with base kV of 24.9 kV and base MVA of 2.5 MVA. It is characterized by a very long and lightly loaded line, two voltage regulators for maintaining good voltage profile, shunt capacitors and a transformer reducing the voltage to 4.16 kV for shorter section of feeder. After executing the three phase radial load flow, the initial loading at the phases a, b and c are 25.67A, 23.54A and 33.43A respectively. The initial maximum deviation amongst phases is 21.34%. As per the Greedy algorithm, the move points are arranged in decreasing order according to the phase current deviation of the injecting lines to the move points. The line injecting to the move point 824 is having maximum deviation of 2.

The membership values of the switching operations significant to the above operations are listed in Table 3.Applying MinMax imperatives of fuzzy to the acquired data, the laterals BC, AC,B,B,BC,B are changed to CB, BA, C, C, CA, C respectively.

The corresponding phase deviation in this configuration is 2.14% which shows that the phase deviation has been reduced from the initial phase deviation of 21.24%. The final feeder phase currents A, B and C are 26.95, 27.97, 27.69 A respectively. The real power loss has been reduced to 87.56 kW from initial real power loss of 89.04 kW. The final re-phasing of the laterals is shown in Table 4. Also the final configuration branch currents and bus voltages are maintained within the limit.

Table 3. Membership values for μ_V, μ_P, μ_I and μ_F

μ_V	μ_P	μ_I	μ_F	Initial configuration/ Final configuration
0.98243	0.48392	0.73587	0.64825	BC/CB
0.94832	0.50979	0.01035	0.72146	AC/BA
0.93689	0.90435	0.49071	0.58953	B/C
0.97836	0.92525	0.95566	0.84156	B/C
0.98362	0.34964	0.88564	0.75894	BC/CA
0.98746	0.12551	0.68048	0.94562	B/C

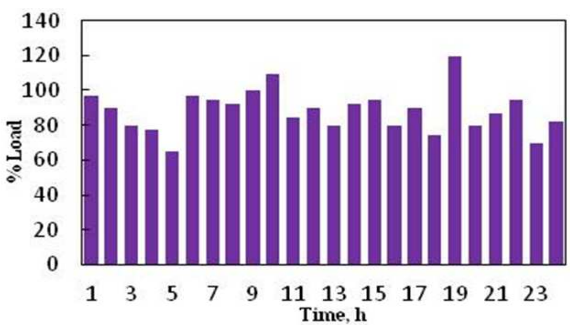

Fig. 3. Load pattern for a day

For test system, dynamic load pattern shown in Fig. 3 has been applied. The initial phase currents and final phase currents after re-phasing are shown in Fig 4. and Fig. 4. respectively. Fig. 4 clearly shows that, after applying the proposed algorithm phase current deviation has been reduced significantly.

4.2 Modified IEEE 125 bus system

The IEEE 125 node system [10] is an unbalanced distribution system with base kV of 4.16 kV and base MVA of 100 MVA. It is characterized by overhead and underground line segments, four step-type voltage regulator, and shunt capacitors and switching to provide alternate paths of power flow.

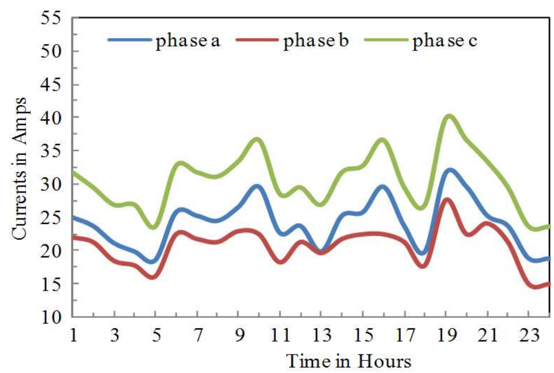

Fig. 4. Initial phase currents at the feeder for 24 hour loading

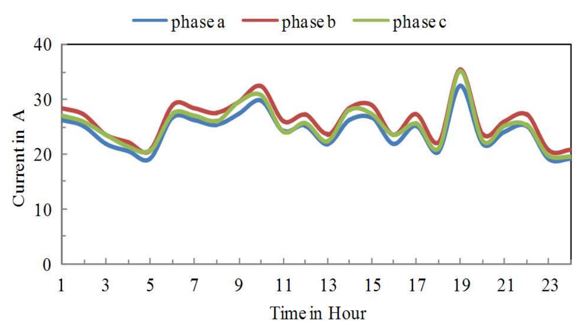

Fig. 5 Final phase currents at the feeder for 24 hour loading

Table 4. Laterals re-phasing after applying the proposed algorithm

Laterals	L4	L9	L13	L17	L23	L33
Before rephrasing	BC	AC	B	B	BC	B
After rephrasing	CB	BC	C	C	CA	C

The initial loading at the phases a, b and c are 331.28A, 207.86A and 313.53A respectively. The initial maximum deviation amongst phases is 26.86%. This system has thirteen single phase laterals, and hence all the thirteen laterals will have a maximum phase current deviation of 200%. After successfully applying the proposed algorithm to the test system, the deviation at the feeder has been reduced to 2.45% from its initial deviation. The real power loss has been reduced to 86.45 kW from initial real power loss of 87.56 kW. The final re-phasing of the laterals is shown in Table 5. The final configuration branch currents and bus voltages are maintained within the limit.

Table 5. Laterals Re-phasing of Test System II

Laterals	Before rephrasing	After rephrasing
3	B	C
4	C	A
16	C	A
21	A	B
24	B	A
26	C	C
75	A	A
79	C	C
82	B	C
95	B	B
98	A	B
113	C	B
117	A	C

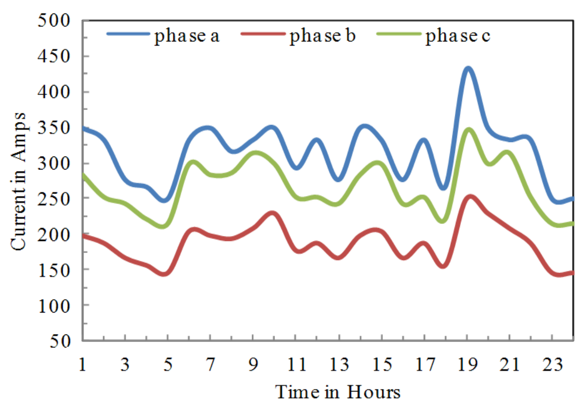

Fig. 6. Initial phase currents at the feeder for test system II

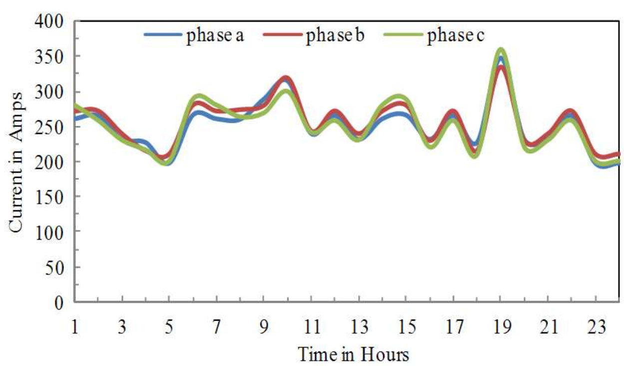

Fig. 7. Final phase currents at the feeder after re-phasing for test system II.

For test system II, the same load pattern shown in Fig. 4 has been applied. The phase currents at the feeder before and after re-phasing are shown in Fig 6 and Fig. 7 respectively. The figures describes that the deviation amongst the phases at the feeder is reduced significantly through the proposed algorithm

5. Conclusion

Phase balancing problem is becoming more important in the deregulated environments, because it improves power quality and reduces electricity price. This paper proposes a hybrid heuristic method to find the optimal phase movement to balance a LV feeder. The proposed algorithm has been tested successfully on LV distribution feeders with modified IEEE 34 node system and IEEE 125 bus distribution system. Hence with the effective introduction of the proposed reconfiguration algorithm, reduction in phase deviation, bus voltage limit, power loss and branch current limit.

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G. Mahendran, corresponding author of the paper, was born in India. He received the B.E degree in Electrical and Electronics Engineering from Bharathiar University in 1999, the M.E degree in Power Electronics and drives from Anna University of Technology, Coimbatore, India in 2011. Currently he is working as Assistant Professor in the department of Electrical and Electronics Engineering at P.A.College of Engineering and Technology, Tamilnadu, India His research interests are distribution system optimization.

M. Sathiskumar, was born in India. He received the B.E. degree in Electrical and Electronics Engineering from Bharathiar University in 1999, the M.E. degree in Power Systems from Annamalai University in 2000 and doing his Ph.D. in Power Distribution System reconfiguration at Anna University, Chennai, India. Currently, he is working as Associate Professor in the Department of Electrical and Electronics Engineering at P. A. College of Engineering and Technology, Tamilnadu, India. He is a member of IEEE and Life Member of ISTE. His research interests power distribution systems optimization, digital control techniques for power electronic circuits and artificial intelligence.

Dr. **S. Thiruvenkadam**, was born in India. He received the B.E. degree in Electrical and Electronics Engineering from Bharathiar University in 1999, the M.E. degree in Power Systems from Annamalai University in 2004 and Ph.D. in Power Distribution System reconfiguration at Anna University, Coimbatore, India. Currently, he is working as an Professor in the Department of Information Technology at P. A. College of Engineering and Technology, Tamilnadu, India. He is a member of IEEE and Life Member of ISTE. His research interests include software framework, power distribution systems, digital control techniques for power electronic circuits and power distribution systems.

Dr. **L. Lakshminarasimman**, received his B.E. in Electrical and Electronics Engineering, M.E. in Power System and PhD in Eelctrical Engineering, from Annamalai University, India in 1993, 1999 and 2008 respectively. He is currently as Professor in Dr. Mahalingam College of Engineering and Technology, Pollachi. He is on EOL from the department of Electrical Engineering, Annamali Unviersity, Annamalai Nagar. His research interests include power system analysis, power system economics and application of computational intelligence techniques to power system optimization problems. He is a member of IEEE and a life member of Indian Society for Technical Education.