Phase Balancing of Distribution Systems Using a Heuristic Search Approach

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Abstract
In this paper, a heuristic backtracking search algorithm is proposed to adjust the phasing arrangement of primary feeders and laterals for phase balancing of distribution systems. The phase unbalance index of distribution feeders is calculated based on the phasing current magnitude of each line segment and branch, which has been solved by a 3-phase load flow program. The database of an outage management system (OMS) is used to retrieve the component attributes and the topology process is executed to determine the electrical network configuration and the customers served by each distribution transformer. By using the monthly energy consumption of customers in customer information system (CIS) and the typical daily load patterns of customer classes, the hourly loading profiles of distribution transformers and service zones can be derived to solve the individual phase loadings of each primary feeder and lateral. The phase balancing of distribution systems is enhanced by heuristic rule-based searching process to minimize the phase unbalance index. To demonstrate the effectiveness of proposed methodology, a practical distribution feeder with 2754 customers is selected for computer simulation to enhance three-phase balancing of distribution systems. It is concluded that three-phase balancing of distribution systems can be obtained by considering customer load characteristics.

Keywords
Automated mapping/facility management (AM/FM), Topology process, Node reduction, Customer information system (CIS)

1. INTRODUCTION
For distribution systems in Taiwan Power Company (Taipower), the transformer banks with open-wye, open-delta connectivity are widely used to serve both 1-Φ and 3-Φ loads. The 100 kVA 1-Φ transformer serves both 1-Φ and 3-Φ loads while the smaller 50 kVA 1-Φ transformer serves only 3-Φ loads. Even with 3-Φ balance loading at the secondary side, the two phases at the primary side becomes unbalanced because of different load allocation due to 30° phase shift of primary and secondary windings [1]. Besides, only 2 out of 3 phases at the primary side are used to serve the transformer bank, it is very difficult to maintain three-phase balance with the variation of customer load demand. The current unbalance will lead to extra system losses, communication interference, equipment overloading and malfunction of protective relays. With the dramatically load growth for the past decade in Taiwan, more and more air conditioners are used in the commercial and residential areas of Taipower system. Three phase unbalance of distribution feeders becomes worse with load growth, which results in feeder tripping due to over neutral current, especially when load transfer between two feeders is performed. Distribution engineers have to practice phase swapping to improve phase loading balance based on system operation experience with trial-and-error methods. It is very labor intensive and time-consuming because phase balancing of distribution systems will be varied with the change of load characteristics of customers served by each distribution transformer. Besides, the magnitude of neutral current of distribution feeders is very stochastic and may cause random tripping of feeders due to neutral current constraint. In order to prevent unintentional service interruption by LCO protective relays due to over neutral current, the heuristic rules have been applied in this study to re-phase primary feeders and laterals within each service zone by considering the daily load patterns of customers served.

To improve three-phase balance of distribution systems, two approaches have been presented [2], [3]. One is to reconfigure distribution systems by proper switching operation, which is primarily designed to solve the overload problem of main transformers/feeders [4]-[6]. On the other hand, phase arrangement is a direct and effective way to achieve phase balance of distribution feeders in terms of phase loading. Since the phase current loading of laterals and whole feeder will be time variant because of the stochastic load characteristics of customers over study time period, the optimization of phase arrangement becomes very complicated and tedious to be solved with conventional trial-and-error method.

In this paper, a heuristic rule-based algorithm with backtracking search is proposed to solve the phase balancing problem. The connection types of distribution transformers/laterals in each service zone are identified and a three-phase load flow program with rigorous feeder model is executed to calculate phase current loading of each branch. The input bus data and branch data for three-phase load analysis can be obtained by retrieving the attributes of system components such as line segments, transformers, etc. in the database of automatic mapping and facility management system [7]. The hourly loading of each transformer is then derived by using the typical daily load patterns of customer classes and the monthly power consumption of customers served. The topology of distribution network is identified by executing the connectivity trace of system component. By this way, the data information required by load flow analysis is therefore generated automatically to enhance the efficiency and accuracy of computer simulation to solve phase currents.
of primary feeders and laterals.

2. INFORMATION SYSTEM INTEGRATION

To solve the hourly phase current loading of service zones and line segments by considering load characteristics of customers served, the electrical network topology of distribution systems has to be represented according to component attributes which are retrieved from the AM/FM database. The daily load patterns of customer classes derived by load survey study [8] and the energy consumption of customers in CIS database are applied to find the hourly power demand of each customer. With the customer-to-transformer mapping, the hourly loading of each distribution transformer is solved by integrating the power profiles of all customers served. The parallel distributed process is used to solve the phasing balance of laterals for different primary line segments simultaneously to accelerate the simulation process. Fig. 1 shows the overall structure of phase balancing with information system integration.

2.1 AM/FM database

For more effective phase balancing study, the AM/FM database is used to support input data requirement by creating distribution circuit models and performing customer-to-transformer mapping process. The Oracle database of AM/FM system in Taipower provides the capability to integrate the graphic representation of components with spatial relationship and information management. The database scheme is defined with several levels to represent real objects with data type of attributes according to data requirement of application functions to be supported.

![AM/FM database diagram](image)

Table 1 shows the attributes of connectivity table for Taipower circuit model. The fields “facility types”, “facility ID”, “node 1”, “node 2”, “supplying feeder1”, “supplying feeder2”, and “power direction” are used to perform the connectivity trace of schematic circuit diagram.

![Table 1](image)

**Fig. 2. The identification of customer-to-transformer mapping.**

2.2 Topology processing (TP) and node reduction

Topology processing is to identify the network configuration of distribution feeders based on the attributes of network connectivity model and the dynamic switch statuses in AM/FM database. By tracing the FROM and TO fields of connectivity table, which points to the upstream and downstream device of each component, the system network configuration is determined and updated according to the operation of switching devices.

A distribution system component can be categorized as either branch or node. Each branch is an arc connected to two nodes...
while each node is a connecting point of branches attached to it. A branch can be any device with two terminals such as line sections, switches, transformers, etc., and a node is an electricity point that connects different branch devices together. The topology tracing can be executed by starting from a given node or a branch and continues by taking the other terminal (node) of a branch as the new node and all branches connected to the new node are represented as the new branches. The topology processing is completed when an open tie switch is reached or all devices have been completely traced.

After topology processing, the node reduction is applied to remove those facilities such as power fuses, poles, high voltage mold joints, etc., which are redundant for phase balancing study. The radial network configuration of distribution feeders is verified by data validation and the impedances of line segments are calculated according to the corresponding conductor types and branch lengths.

2.3 Individual phase load evaluation by considering customer load pattern

The evaluation of hourly loading of individual phase will affect the accuracy of phase balancing study. With the variation of customer load characteristics and load composition, it becomes very difficult to estimate phase loading of each service zone. This paper presents a systematic method to solve the hourly phase loading by using customer load patterns and monthly energy billing data of customers served at each load point.

Typical daily load patterns of various customer classes are derived in this paper to determine the load variation of distribution transformers, primary feeders and laterals [9-11]. The load composition of each service transformer is divided into commercial, industrial, and residential loads. The load survey study has been executed in previous works [8] to derive the normalized typical load patterns of test customers which have been selected by stratification method.

The customer billing data are retrieved from CIS database to find total monthly energy consumption by each customer. The hourly power consumption profiles of each customer class for both the weekday and weekend during various seasons are therefore determined by allocating the total power consumption to each hourly lot according to the typical load patterns. Based on the connectivity of customers and service transformers, the power demand of each distribution transformer is then determined. By executing three-phase load flow analysis with the phasing and hourly loadings of distribution transformers, the phase currents of service zones, laterals and primary feeders for each study hour can therefore be solved.

3. THE PROPOSED ALGORITHM

3.1 Problem formulation

Before applying the heuristic search algorithm for phasing arrangement of laterals to achieve three-phase balance of distribution feeders, the “phasing unbalance index” (PUI) is defined as follows [12]:

\[
PUI = \frac{\text{Max}(|I_a - I_{avg}|, |I_b - I_{avg}|, |I_c - I_{avg}|)}{I_{avg}} \times 100\%
\]

where

- \(I_a, I_b, I_c\): current loadings of phase a, b, and c at node \(j\),
- \(I_{avg}\): average phase current.

3.2 Connection types

In this paper, the notation (X, Y, Z) is used to represent the phasing arrangement of each lateral. The letters X, Y, and Z are phases of the lateral to be connected to location Pos1, Pos2, and Pos3 of the primary feeder as shown in Fig. 3. In this figure, the notations of phasing assignment for lateral 1 and 2 are (A, C, B) and (B, A, C), respectively.

![Fig. 3. Sample feeder with two connecting branches.](image)

The possible connection schemes for various types of phasing arrangement are listed in Table 2 for single-phase, two-phase, and three-phase laterals. For instance, a two-phase lateral which originally has phase A in position 1 and phase B in position 2 can have any of the following rephasing schemes: (A, *, B), (*, A, B), (B, A, *), (B, *, A), (*, B, A) where connection scheme (A, B, *) represents no phase adjustment.

3.3 Heuristic backtracking search algorithm

In this paper, a backtracking search algorithm with heuristic information is proposed to solve the phasing readjustment of distribution systems from the start nodes in the child process to the goal node in the parent process. The major objective is to optimize the phasing balance of three-phase currents for all service zones, laterals and primary feeders.
The typical load patterns and energy consumption of customers served are used to solve the hourly current loading of a distribution transformer. The three-phase load flow analysis is executed for each study hour by using the current loading of each transformer to find the phase currents of each service zone and each lateral. The phase currents of each lateral are considered as input for the heuristic search algorithm by taking 24-hour loads into account.

Heuristic information is used to find the proper phase connection type for each node to enhance three-phase balance in each service zone. The following heuristic rules adopted by experienced engineers in conducting phase adjustment are illustrated as follows.

Step 1. Execute backtracking search algorithm from the nodes of the deepest level in the child process to perform phase adjustment procedures.

Step 2. Given a node labeled in the $k^{th}$ level (label $k$ level represents the topology sequence) and execute the rephasing algorithm. The phase position of the lateral which connects to this node with the smallest $PUI$ is referred as the based construction location. This lateral is called based branch (BR) before rephasing. The phase positions in other branches which have the maximum, medium and minimum currents are rephased according to the phase positions in BR with the minimum, medium, and maximum phase currents, respectively. The 3-phase currents of the upstream branches are updated according to above rephasing of the lateral.

For the previous sample feeder in Fig. 3, the phase currents of two laterals are listed in Table 3. It is found that lateral 1 with the smallest $PUI$ is referred as BR. Positions 1, 2, and 3 of lateral 1 are associated with phase A, C, and B. According to Step 2, the rephasing movement of lateral 2 for the phase associated with positions recommends that phase A, B, and C should be moved to position 1, 2, and 3 (A, B, C). The upstream branch currents $I_1$, $I_2$, and $I_3$ are then updated to be 90 A, 100 A, and 100 A.

Table 3 Phase currents of two laterals in Fig. 3.

<table>
<thead>
<tr>
<th>Lateral currents</th>
<th>Lateral 1</th>
<th>Lateral 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PUI$ (A)</td>
<td>65</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>37.5</td>
</tr>
</tbody>
</table>

In this paper, the following operation constraints are taken into consideration for rephasing.

1. No main transformers, feeders and line switches are overloaded after rephasing.
2. Radial network configuration must be maintained for distribution feeders.
3. All service zones are connected and served by the feeder.

4. NUMERICAL RESULTS

To demonstrate the effectiveness of the proposed methodology to enhance three-phase balance of service zones, laterals and distribution feeders, a practical distribution feeder GV52, in Taichung District of Taipower, is selected for computer simulation. The total length of the feeder is 2.2 km and it serves 2754 customers with 73 single-phase transformers. Fig. 4 shows the one-line diagram of the test feeder, which has been derived by node reduction and topology process.

Within each service zone (node), the equivalent loads are estimated by customer-to-service transformer (phase) mapping process from AM/FM database and customer billing data in CIS. Fig. 5 shows the power profile and load composition of service zone N57 during the summer season. It is found that both residential and commercial customers contribute most of the power consumption while industrial customers consume the least power. The peak load demand of N57 is 86.9 kW at 8 PM with the power demands of commercial and residential customers as 47.8 kW and 35.4 kW respectively.
The circuit model of GV52 is retrieved from the AM/FM system with information such as conductor types and lengths, connectivity, transformer capacity and impedance. According to the hourly load estimation at each node, a power flow program with rigorous feeder model is executed to solve the phase currents at each node and the phase unbalance index of each node for heuristic search algorithm is then obtained.

By executing the proposed algorithm to solve the rephasing problem of laterals for Feeder GV52, three stages of phasing adjustment are recommended as shown in Table 4. The first stage is to rephase lateral 35 and 36 by swapping A phase and B phase. For the second stage, the original phase (A,B,C) is changed to phase (B,C,A) for lateral 37 and 38. For the third stage, the original phase (A,B,C) is changed to new phase (A,C,B) for lateral 13, and the original phase (*,B,C) is changed to (*,C,B) for the two-phase laterals 14, 15, and 16.

Fig. 6 illustrates the resultant phasing unbalance index ($PUI$) and the neutral currents of Feeder GV52 before and after rephasing. It is found that the worst three-phase unbalance occurs at 8 PM. After executing the proposed heuristic backtracking search algorithm to find the proper lateral rephasing at this time slot, the $PUI$ has been reduced from 50.71% to 2.97% with the neutral current being reduced from 52.2 A to 6.5 A at 8 PM. Besides, the daily average $PUI$ has been reduced from 45.6% to 2.9% and the mean value of the neutral current has been reduced from 35.2 A to 4.3 A.

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Table 4: Lateral rephasing of Feeder GV52

<table>
<thead>
<tr>
<th>Stages</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral</td>
<td>35-36(2Φ)</td>
<td>37-38(3Φ)</td>
<td>13-15-16 (2Φ)</td>
</tr>
<tr>
<td>Rephasing</td>
<td>(A,B,*).</td>
<td>(A,B,C)</td>
<td>(A,C,B)</td>
</tr>
<tr>
<td></td>
<td>(B,A,*).</td>
<td>(B,C,A)</td>
<td>(*,C,B)</td>
</tr>
</tbody>
</table>

Fig. 6. Phase unbalance index and neutral currents of test feeder GV52 before and after rephasing.

Fig. 7 illustrates the mean values of phase unbalance index, $PUI$s, for the selected service zones N57, N51, N37, N32, N4, and N3 over 24-hour period before and after lateral rephasing. It is found that the maximum $PUI$ is reduced from 57.9% to 6.8% for service zone N3 and three-phase balance has been improved dramatically for all service zones. Besides, more $PUI$ reduction at upstream service zones has been obtained than that at downstream service zones due to the accumulation of phasing balance of downstream service zones.

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Fig. 7. The average $PUI$s before and after lateral rephasing.
5. CONCLUSIONS
The three-phase balance of distribution feeders has been enhanced by lateral rephasing with heuristic rules. The AM/FM system is used to generate distribution network models and input data files automatically to support load flow analysis of distribution systems to find three-phase current loadings of service zones, laterals and primary feeders. By executing customer-to-transformer mapping, the customers served by each distribution transformer are identified. The hourly loading of each distribution transformer is then derived by integrating the customer power demands, which has been solved by considering the typical load patterns and energy consumption of customers served. By this manner, the phase current loading obtained will be more accurate as compared to the conventional load allocation using the transformer capacity.

To achieve better phasing balance of distribution feeders, the heuristic rules have been developed by considering operation regulation of distribution systems. A backtracking search algorithm is used to derive the proper phasings of service zones, laterals and primary feeders. To demonstrate the effectiveness of the proposed heuristic methodology to improve three-phase balance of distribution networks, a practical Taipower underground distribution system with two feeders has been selected for computer simulation. By the heuristic backtracking search algorithm to solve lateral rephasing, the neutral current and phase unbalance index of distribution feeders have been reduced. It is found that the proposed heuristic algorithm can solve the rephasing problem of distribution systems to enhance three-phase loading balance effectively by considering customer load patterns. Furthermore, the neutral current of distribution feeders can be reduced significantly to prevent feeder tripping due to over neutral current.

References