Phase Balancing using Mixed-Integer Programming

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ABSTRACT: Unbalanced feeder systems cause deteratorating power quality and increase investment and operating costs. Feeder reconfiguration and phase swapping are two popular methods to balance the systems. For an unbalanced feeder system, feeder reconfiguration is difficult to meet the phase balancing criterion due to the limited number of sectionalizing switches available. Phase swapping is another alternative and direct approach for phase balancing. Phase swapping has not received its deserved attention due to the complexity of feeder systems, the dimension of problems, and totally overlooking the impacts of phase imbalance. Phase swapping can economically and effectively balance the feeder systems to improve power quality and reduce power system total cost. Deregulation arises competition on power quality, service reliability, and electricity price. Therefore phase swapping can enhance utilities competitive capability. This paper proposes a mixed-integer programming formulation for phase swapping optimization. Single-phase loads are treated differently with three-phase loads. Nodal phase swapping and lateral phase swapping are also introduced. An example is used to illustrate the proposed method.

Key Words: Phase balancing, Feeder Reconfiguration, Phase Swapping, Mix-Integer Programming, Deregulation, Power Quality, Electricity Price, Nodal Phase Swapping, Lateral Phase Swapping.

1. Introduction

In power distribution systems, unbalanced feeder structures and unbalanced loading are common phenomena. Unbalanced feeders not only increase energy losses and the risk of overloading situations, but also affect system power quality and electricity price. For example, the unbalanced loading causes unbalanced voltages even the voltage at source is balanced. Lower, higher, or unbalanced voltage can reduce efficiency and may damage appliances. In this case, utilities either reconfigure the systems or install transformers or capacitors to keep voltages within limits. Unbalanced systems also increase the risk of overloading on a phase line or ground line. Overloading causes utility facilities overheating and even damaged. In addition, an unbalanced feeder has a large ground current, which may trip the protective devices. Furthermore, in unbalanced feeders, the improvement of the utilization factor is limited by the capacity of the ground line or one phase line. Upgrading ground lines or feeder lines require huge investment costs, which may be unnecessary if the system is well balanced. Sometimes, the unbalanced situations are acceptable if the flows are far below their capacity. If the flows are close to their capacity, even a small unbalanced flow can cause serious consequence.

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Phase balancing problem is to make a feeder system balanced in terms of phases. A balanced system has smaller worst voltage drops and energy losses. *Phase balancing improves system quality, security, and reliability. Phase balancing can improve utilization factors of existing facilities and defer feeder expansion projects.* As a result, an utility can produce power with higher quality and lower electricity price, which will attract customers to the utility and enhance the utility competitive ability in the deregulated environments.

Original feeder system design depends on the accuracy of the given load data. Many distribution load forecasting methods have been proposed to improve the accuracy of load forecast in the past several decades [1, 2]. Distribution load forecasting not only predicts the magnitude of loads but also predicts the location of loads by providing a load map. Based on the load map, a balanced feeder system is routed to deliver electric power to the customers. However, the prediction errors and unbalanced load growth will make the feeder unbalanced.

There are two options for phase balancing. One is feeder reconfiguration at the system level; the other is phase swapping at the feeder level. Since feeder reconfiguration is primarily designed for load balancing among the feeders, it cannot effectively solve phase balancing problem. Therefore, most researchers did not consider phase balancing in feeder reconfiguration. Only a few people incorporated phase balancing into feeder reconfiguration approaches based on the unbalanced feeder systems. But it is realized that feeder reconfiguration is not sufficient to make unbalanced feeder systems phase balancing [3]. Lin and Chin proposed a fuzzy logic approach to reconfigure feeders on the inter-feeder load balance and inter-phase load balance sequentially [4]. The conflict objectives may result in an unsolvable dead lock. Wang et al. proposed an efficient formula to update power flows and losses in terms of the on/off switch operations [5]. They noted that system imbalance has significant

impact on the schemes for network reconfiguration and the determination of the on / off status of sectionalizing and tie switches. The phase imbalance impact upon system performance should not be overlooked. In [6], Borozan proposed a heuristic method to determine the minimum loss configuration for the three-phase distribution systems. The approach worked well with the balanced network. But for the unbalanced network, suggested balancing the feeder system in terms of phases before the approach is applied. In general, feeder reconfiguration can not balance the unbalanced feeder systems effectively.

On the other hand, phase swapping is a direct and effective way to balance a feeder in terms of phases. At the time being, distribution engineers already use phase swapping to balance phase loading based on their experiences and trial and error method. The procedure, which is a labor intensive and time-consuming, is show in Figure 1. Furthermore, the result usually is far from optimal.

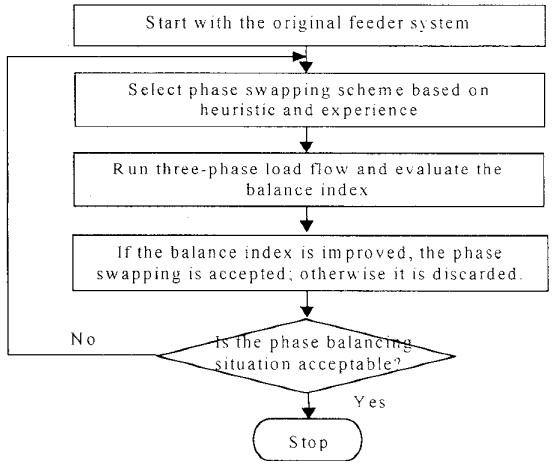

Figure 1. Trial and error to balance a feeder

This paper develops a methodology to identify phase swapping schemes to balance a radial feeder system based on the loads at each load point and the original load tapping scheme. Section 2 will introduce phase balancing problem. Section 3 will propose the phase swapping optimization formulation for single-phase loads and three-phase loads. Section 4 will demonstrate the proposed formulation by a six-node system. Section 5 is the conclusion of this paper.

2. Phase Swapping Problem

The voltage drop is not considered in our proposed phase balancing formulation to simplify the problem. Also we assume that all the loads have the same power factor. Thus all the loads can be modeled by their current magnitudes. Phase swapping balances the system by re-tapping loads or laterals to the phase lines. It requires each single-phase load connecting to a phase line and each phase line has at most one load at a node. Since unbalancing is usually not emergent condition as long as it does not causes device overloading or extensive voltage drops or ground relay tripped, phase swapping is carried out during maintenance or restoration periods.

Single-phase loads are treated differently from three-phase loads in the phase swapping formulation. There are six options to tap the loads to feeder for three single-phase loads tapping on a three-phase feeder. There are three options for a three-phase load (e.g. three-phase induction motor) so as to keep the same phase sequence. Phase swapping 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 re-tap 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.

Phase balancing has several significant benefits, such as improving power quality and utilization factor of existing facilities, and reducing energy losses and price. However, each phase swapping operation is associated with certain costs on lineman expenses, maintenance expenses, and planned outage duration, we could not afford to swap phases for all nodes at all the time. The number of phase swapping need to be compromised between benefits and costs.

Phase swapping can be treated as load assignment to lines, which is modeled as an integer-programming problem. For example, a single phase load can only be assigned to either phase a, phase b, or phase c. Therefore, the decision variables for phase swapping are of the load either connected or not connected to a phase line, which can be represented as 1 or 0. Each node is associated with a set of decision variables to represent its tapping scheme. Since voltage drops and energy losses are ignored, Kirchoff's Current Law (KCL) are linear constraints. Once the objective is a linear function, then phase swapping problem can be modeled as a mixed-integer-programming.

Each branch of the feeder is associated with a balance index, for example, unbalanced flow, which is defined as the maximum difference of flows at this branch. The lower the unbalanced flow is, the more balanced the branch is. Balancing a feeder is not just for source flows but for the whole feeder. Not all branches are worthwhile to be monitored. Only those branches, which have important facilities (e.g. transformer or regulator) or critical impacts to power quality, are monitored. The phase balancing on multiple branches in a feeder can be formulated as a multi-objective optimization problem, which is solved by weighting factor method. The objective function is to minimize the weighted sum of the unbalanced flows, where different weights are assigned to each branch based

on its importance (e.g. proportional to flow or capacity), balance requirement, and utilization factor.

3. Mixed-Integer-Programming Formulation

Given a radial feeder configuration and the loads $(d_{i,1}, d_{i,2}, d_{i,3})$ at node i, the objective of Mixed-Integer Programming (MIP) is to find the optimal loads assignment on the phase (a,b,c) of the feeder so that the unbalanced flows at the monitored branches are minimized. The unbalanced flow at branch j, U_j, is defined as the maximum difference of phase flow currents at branch j. For example, the unbalanced flow U_j of branch j shown in Figure 2 (j is for branch number, i is for node number) is:

$$U_j = \max\left\{\left|I_{j,a} - I_{j,c}\right|, \left|I_{j,b} - I_{j,c}\right|, \left|I_{j,a} - I_{j,b}\right|\right\} \quad (1)$$

where: $I_{j,\phi}$ is the current of phase ϕ at branch j

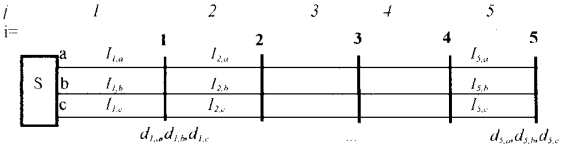

Figure 2: A small feeder system

For the feeder system shown in Figure 2, each load is tapped to a phase line at a node. The KCL is represented as:

$$I_{j,\phi} = I_{j+1,\phi} + d_{j,\phi} \qquad j = 1, .., 4 \qquad (2)$$

$$I_{5,\phi} = d_{5,\phi} \qquad \phi = a, b, c \qquad (3)$$

From the end of feeder to the source, the branch flows are updated for every branch and phase. For any phase swapping at node i, all the upper stream flows (i.e. $j \le i$) are changed while its down stream flows (i.e. $j > i$) are not changed. For example, phase swapping at node 3 will affect its upper stream flows, $\psi_3 = \{1,2,3\}$. However, it will not affect its down stream flows, $\eta_3 = \{4,5\}$.

A typical feeder system is not as simple as the feeder shown in Figure 2. A typical node at phase ϕ is shown in Figure 3, where *k1*, *k2*, and *k3* are the down stream branches of node i, and j is the upper steam branch of node i. The KCL at node i is described as:

$$I_{j,\phi} = d_{i,\phi} + I_{k1,\phi} + I_{k2,\phi} + I_{k3,\phi} \qquad (4)$$

for node i and phase ϕ.

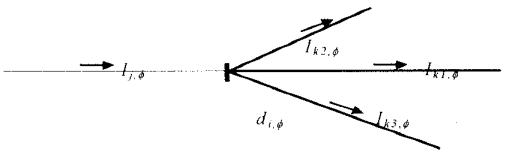

Figure 3. KCL at node i and phase ϕ

The integer decision variable $\pi^i_{\phi,\omega} \in \{0,1\}$ indicates that the ωth load at a node i is connected to phase ϕ or not. The integer variables must satisfy several constraints to ensure that one and only one load is assigned to a phase line. This assignment problem can be formulated into the following mixed-integer-programming model (for single-phase loads):

Minimize U_j

Subject to:

$$\max\left\{\left|I_{j,a} - I_{j,c}\right|, \left|I_{j,b} - I_{j,c}\right|, \left|I_{j,a} - I_{j,b}\right|\right\} = U_j \qquad (5)$$

$$I_{j,\phi} = \sum_k I_{k,\phi} + \pi^i_{\phi,1} \cdot d_{i,1} + \pi^i_{\phi,2} \cdot d_{i,2} + \pi^i_{\phi,3} \cdot d_{i,3} \qquad (6)$$

$$\pi^i_{\phi,1} + \pi^i_{\phi,2} + \pi^i_{\phi,3} = 1 \qquad \text{for all } \phi = a, b, c \qquad (7)$$

$$\pi^i_{a,\omega} + \pi^i_{b,\omega} + \pi^i_{c,\omega} = 1 \qquad \text{for all } \omega = 1,2,3 \qquad (8)$$

$$I_{j,\phi} \le C_j \qquad (9)$$

$$\pi^i_{\phi,\omega} \in \{0,1\} \qquad \text{for all } i \qquad (10)$$

where

j is any monitored branch,

U_j is the unbalanced flow on branch j,

$I_{j,\phi}$ is the ϕ phase flow on branch j,

$\pi^i_{\phi,w}$ is the decision variable for ωth load tapping to phase ϕ at node i,

C_j is the phase line capacity of branch j.

In this MIP formulation, equality (5) is the unbalanced flow at the monitored branch j; equation (6) represents the KCL constraints at node i; equation (7) ensure that each phase has a load assigned; equation (8) ensure that each load is only assigned to a phase; inequality (9) is the line capacity constraints. The objective of the MIP model is to minimize the unbalanced flow at the monitored branch j.

The above formulation is a typical mixed-integer linear programming problem, which can be solved by branch-and-bound method and cutting plane algorithm [7]. A node on a three-phase feeder has a single-phase load, thus only *three* 0-1 integer variables and *one* constraint, denoted as 3/1, are needed. A node on three-phase feeder has two single-phase loads, then *six 0-1* integer variables and *five* constraints, denoted as 6/5, are required. For three unbalanced single-phase loads, *nine* 0-1-integer variables

and *six* constraints are required. The summary is listed in Table 1.

Table 1: Number of integer variables / constraints

# Phases / # loads	Single Phase Line	Two Phase Line	Three Phase Line
1	0 / 0	2 / 1	3 / 1
2	N/A	4 / 4	6 / 5
3	N/A	N/A	9 / 6

Three-phase loads are considered differently from single-phase loads. A three-phase load (motoring loads) only has three options for phase swapping to maintain the phase sequence. It just needs *three* 0-1 integer variables and *one* constraint to guarantee the phase sequence and constraints. An integer variable $\pi_s^i \in \{0,1\}$ represents a load tapping scheme, which is rotated from the current one at node *i*. Three-phase load swapping can be formulated as:

$$I_{j,a} = \sum_k I_{k,a} + \pi_1^i \cdot d_{i,1} + \pi_2^i \cdot d_{i,2} + \pi_3^i \cdot d_{i,3} \qquad (11)$$

$$I_{j,b} = \sum_k I_{k,b} + \pi_1^i \cdot d_{i,2} + \pi_2^i \cdot d_{i,3} + \pi_3^i \cdot d_{i,1} \qquad (12)$$

$$I_{j,c} = \sum_k I_{k,c} + \pi_1^i \cdot d_{i,3} + \pi_2^i \cdot d_{i,1} + \pi_3^i \cdot d_{i,2} \qquad (13)$$

$$\pi_1^i + \pi_2^i + \pi_3^i = 1 \qquad (14)$$

$$\pi_s^i \in \{0, 1\} \qquad \text{for s = 1, 2, 3} \qquad (15)$$

where equations (11-13) are KCL constraints at node *i* for different phase; equation (11) ensures that only one load tapping is selected.

Current flows are continuous values while the tapping scheme is discrete by nature. A feeder may have more than hundreds nodes. Therefore, the phase swapping problem can be formulated as *a large-scale mixed-integer-programming problem*. The proposed MIP model is easily set up for any radial feeder systems based on the formulation from equation (1) to (12). LINDO / LINGO optimization software package can be used to solve this model by branch-and-bound method [8]. Due to the capability of integer programming software, the MIP model is suitable to solve a small-sized feeder system. For example, LINDO can solve problems with at most 4003 integer variables, 4003 columns and 2003 rows. Therefore it is able to solve phase swapping problem for a feeder system with less than 200 nodes.

4. Illustrative Example

This section use a six-node system shown in Figure 4 to perform lateral phase swapping to balance the primary trunk to illustrate the proposed MIP phase swapping methodology. The corresponding load data is listed in Table 2. The primary trunk is branches 1 and 2. The branch 3, 4, and 5-6 are the laterals, whose phase swapping is used to balance the primary trunk.

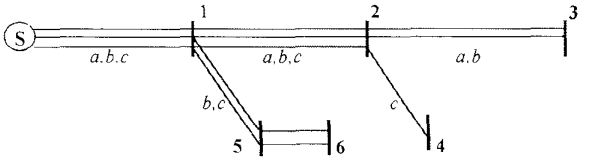

Figure 4. Six-node system

The flows on the primary trunk,

$\{I_{1,a}, I_{1,b}, I_{1,c}\} = \{55,130,110\}$ and

$\{I_{2,a}, I_{2,b}, I_{2,c}\} = \{35,65,55\}$, are extremely unbalanced. This phase balancing problem is a multi-objective optimization problem because two branches are monitored. This example will illustrate the use of weighting factor method to solve the multi-objective MIP problems.

Table 2. The load data and original tapping scheme

Node / Phase	a	b	c
1	20 A	30 A	20 A
2	25 A	35 A	40 A
3	10 A	30 A	N/A
4	N/A	N/A	15 A
5	N/A	25 A	20 A
6	N/A	10 A	15 A

Since lateral rather than nodal phase swapping is considered, the laterals can be treated as the fictitious nodes on the primary trunk as shown in Figure 5. The fictitious node is associated with the lump sum loads on this lateral by phase. In the reduced model, the primary trunk flows are identical to the original feeder system. Therefore the reduced model can be used to balance the primary trunk flows. For example, since the loads at node 5 is $\{d_{5,1}, d_{5,2}\} = \{25,20\}$ and the loads at node 6 is $\{d_{6,1}, d_{6,2}\} = \{10,15\}$, the lump loads of lateral 5-6 is $\{d_{5-6,1}, d_{5-6,2}\} = \{d_{5,1}, d_{5,2}\} + \{d_{6,1}, d_{6,2}\} = \{35,35\}$. The loads for lateral 3 or 4 are equivalent to the loads at node 3 or 4 respectively.

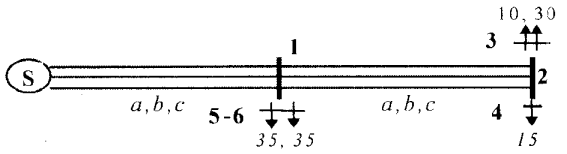

Figure 5. The reduced model for 6-node system

Each phase of a lateral may tap to one of three-phase primary trunk, represented by three 0-1 integer variables. For this feeder system, there are total fifteen 0-1 integer variables. The objective is to minimize the unbalanced flows on branches 1 and 2. The weighted sum of the unbalanced flows at the primary trunk is treated as the single objective function. The weighting factors $\{w_1, w_2\}$ are assigned based on the branch importance, for example, $\{w_1, w_2\} = \{0.6, 0.4\}$. The problem formulation becomes:

$$\text{Minimize} \quad \sum_j w_j \cdot U_j \tag{16}$$

Subject to:

$$\max\left\{\left|I_{1,a} - I_{1,c}\right|, \left|I_{1,b} - I_{1,c}\right|, \left|I_{1,a} - I_{1,b}\right|\right\} = y \tag{17}$$

$$\max\left\{\left|I_{2,a} - I_{2,c}\right|, \left|I_{2,b} - I_{2,c}\right|, \left|I_{2,a} - I_{2,b}\right|\right\} = z \tag{18}$$

$$I_{1,\phi} = I_{2,\phi} + \pi_{\phi,1}^{5-6} \cdot d_{5-6,1} + \pi_{\phi,2}^{5-6} \cdot d_{5-6,2} \tag{19}$$

$$I_{2,\phi} = \pi_{\phi,1}^{4} \cdot d_{4,1} + \pi_{\phi,1}^{3} \cdot d_{3,1} + \pi_{\phi,2}^{3} \cdot d_{3,2} \tag{20}$$

$$\pi_{a,\omega}^{\varphi} + \pi_{b,\omega}^{\varphi} + \pi_{c,\omega}^{\varphi} = 1 \qquad \text{for all lateral } \varphi \tag{21}$$

$$\pi_{\phi,1}^{\varphi} + \pi_{\phi,2}^{\varphi} \le 1 \qquad \text{for lateral } \varphi=3, 5\text{-}6 \tag{22}$$

$$I_{j,\phi} \le C_j \qquad \text{for } \phi = a, b, c\,;\ j = 2, 1 \tag{23}$$

$$\pi_{\phi,\omega}^{\varphi} \in \{0,1\} \qquad \text{for lateral } \varphi=3, 4, 5\text{-}6 \tag{24}$$

In this formula, y is the unbalanced flow for branch 1, and z is the unbalanced flow for branch 2. This MIP model can be solved by LINDO program listed in Table 3.

The results of MIP can be read from Table 4. The phase swapping scheme is: *XC51=1* and *XA52=1* means that lateral 5-6 is assigned to phase *c* and *a*; *XA41=1* means that lateral 4 is assigned to phase *a*; *XC31*=1 and *XB32=1* means that load 10 is assigned to phase *c* and load 30 is assigned to phase *b*.

After lateral phase swapping, the flows of primary trunk are $\{I_{1,a}^*, I_{1,b}^*, I_{1,c}^*\} = \{95,95,105\}$ and $\{I_{2,a}^*, I_{2,b}^*, I_{2,c}^*\} = \{40,65,50\}$. And the unbalanced flow of branch 1 is $U_1^* = 10\ A$ and that of branch 2 is $U_2^* = 25\ A$, in comparing with the original unbalanced situation, where unbalanced flows $U_1 = 75\ A$ and $U_2 = 30\ A$. Thus the weighted sum of unbalanced flow is $\sum_j w_j \cdot U^*_j = 16\ A$ (the optimal phase balancing solution for branch 1 and 2).

Table 3. LINDO program for the reduced feeder system

```
MIN   0.6 U1 + 0.4 U2
SUBJECT TO
 XA51 + XB51 + XC51 =  1
 XA52 + XB52 + XC52 =  1
 XA41 + XB41 + XC41 =  1
 XA31 + XB31 + XC31 =  1
 XA32 + XB32 + XC32 =  1
 XA51 + XA52 <=  1
 XB51 + XB52 <=  1
 XC51 + XC52 <=  1
 XA31 + XA32 <=  1
 XB31 + XB32 <=  1
 XC31 + XC32 <=  1
 - U1 + IA1 - IB1 <=  0
 - U1 - IA1 + IB1 <=  0
 - U1 - IB1 + IC1 <=  0
 - U1 + IB1 - IC1 <=  0
 - U1 + IA1 - IC1 <=  0
 - U1 - IA1 + IC1 <=  0
 - U2 + IA2 - IB2 <=  0
 - U2 - IA2 + IB2 <=  0
 - U2 - IB2 + IC2 <=  0
 - U2 + IB2 - IC2 <=  0
 - U2 + IA2 - IC2 <=  0
 - U2- IA2 + IC2 <=  0
 - 35 XA51 - 35 XA52 + IA1 - IA2 =  20
 - 35 XB51 - 35 XB52 + IB1 - IB2 =  30
 - 35 XC51 - 35 XC52 + IC1 - IC2 =  20
 - 15 XA41 - 10 XA31 - 30 XA32 + IA2 =  25
 - 15 XB41 - 10 XB31 - 30 XB32 + IB2 =  35
 - 15 XC41 - 10 XC31 - 30 XC32 + IC2 =  40
END
INTE   XA51
INTE   XB51
INTE   XC51
INTE   XA52
INTE   XB52
INTE   XC52
INTE   XA41
INTE   XB41
INTE   XC41
INTE   XA31
INTE   XB31
INTE   XC31
INTE   XA32
INTE   XB32
INTE   XC32
```

Table 4. Results of LINDO program

1) 16.000000		
Variable	Value	Reduce cost
XA51	0.000000	0.000000
XB51	0.000000	0.000000
XC51	1.000000	31.500000
XA52	1.000000	-31.500000
XB52	0.000000	-31.500000
XC52	0.000000	0.000000
XA41	1.000000	-12.000001
XB41	0.000000	0.000000
XC41	0.000000	7.500000
XA31	0.000000	-13.000000
XB31	0.000000	0.000000
XC31	1.000000	0.000000
XA32	0.000000	-29.000002
XB32	1.000000	0.000000
XC32	0.000000	10.000000
U1	10.000000	0.000000
U2	25.000000	0.000000
IA1	95.000000	0.000000
IB1	95.000000	0.000000
IC1	105.000000	0.000000
IA2	40.000000	0.000000
IB2	65.000000	0.000000
IC2	50.000000	0.000000

5. Conclusion

Phase balancing problems is becoming more and more important in the deregulated environments because it can improve power quality and reduce electricity price with the minimum costs. The paper proposes a MIP formulation to find the optimal phase swapping scheme to balance a feeder system. An illustrative example is used to demonstrate the proposed formulation for phase balancing. Phase swapping optimization can provide a better solution than the trial and error method. It can maximize the benefits for each phase swapping. The testing results show that MIP formulation for phase swapping is an effective tool to provide a phase balancing solution.

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