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Optimal Phase Balancing Planning for Loss Reduction in Distribution Systems using a Specialized Genetic Algorithm

Planeamiento Óptimo de Balance de Fases para Reducción de Pérdidas en Sistemas de Distribución usando un Algoritmo Genético Especializado

Planejamento Ótimo de Balanço de Fases para Redução de Perdas em Sistemas de Distribuição Usando um Algoritmo Genético Especializado

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Se aceptan comentarios y/o discusiones al artículo

Abstract

Unbalanced operation of distribution systems deteriorates power quality and increases investment and operation costs. Feeder reconfiguration and phase swapping are the two main approaches for load balancing, being the former more difficult to execute due to the reduced number of sectionalizing switches available in most distribution systems. On the other hand, phase swapping constitutes a direct, effective and low cost alternative for load balancing. The

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main contribution of this paper is the proposal of an optimization model and a solution technique for phase balancing planning in distribution systems. As regards the optimization model, a mixed integer nonlinear programming formulation is proposed. On the other hand, the proposed solution technique consists on a specialized genetic algorithm. To show the effectiveness of the proposed approach, several tests are carried out with two distribution systems of 37 and 19 buses, this last one with different load models. Results showed that in addition to the achievement of the primary objective of loss reduction, phase balancing allows obtaining other technical benefits such as improvement of voltage profile and alleviation of congested lines.

Key words: Distribution systems, phase balancing, energy loss reduction.

Resumen

La operación desbalanceada de los sistemas de distribución deteriora la calidad de la potencia y aumenta los costos de inversión y operación. La reconfiguración de alimentadores y el intercambio de fases son los dos principales enfoques para balance de fases, siendo el primero más difícil de llevar a cabo debido al número reducido de seccionalizadores disponibles en la mayoría de los sistemas de distribución. Por otro lado, el intercambio de fases constituye una alternativa directa, efectiva y de bajo costo para el balance de fases. La contribución principal de este artículo es la propuesta de un modelo de optimización y una técnica de solución para el planeamiento de balance de fases en sistemas de distribución. En cuanto al modelo de optimización, se propone una formulación no lineal entera mixta. Por otro lado, la técnica de solución propuesta consiste en un algoritmo genético especializado. Para mostrar la eficacia de la metodología propuesta varios ensayos son realizados con dos sistemas de distribución de 37 y 19 barras, este último con diferentes modelos de carga. Los resultados muestran que además de conseguir el objetivo principal de reducción de pérdidas, el balance de fases permite obtener otros beneficios técnicos como el mejoramiento del perfil de tensiones y reducción de la congestión en las líneas del sistema.

Palabras claves: Sistemas de distribución, balance de fases, reducción de pérdidas de energía.

Resumo

A operação desbalanceada dos sistemas de distribuição deteriora a qualidade da potência e aumenta os custos de investimento e operação. A reconfiguração de alimentadores e o intercambio de fases são as principais abordagens para o balanço de fases, sendo o primeiro o mais difícil de realizar devido ao reduzido número de chaves de manobra disponíveis na maioria dos sistemas de distribuição. Por outro lado, o intercambio de fases constitui uma alternativa direta, efetiva e de baixo custo para o balanço de fases. Neste artigo propõe-se um modelo de otimização e uma técnica de solução para o planejamento de balanço de fases em sistemas de distribuição. Quanto ao modelo de otimização, propõe-se uma formulação não-linear inteira mista. Por outro lado, a técnica de solução proposta consiste em um algoritmo genético especializado. Para mostrar a eficácia da metodologia proposta, vários testes foram realizados com dois sistemas de distribuição de 37 e 19 barras, este último com diferentes modelos de demanda. Os resultados mostram que além de atingir o objetivo principal de redução de perdas, o balanço de fases permite obter outros benefícios técnicos como o melhoramento do perfil de tensões e redução do congestionamento nas linhas do sistema.

Palavras chaves: Sistemas de distribuição, balanço de fases, redução de perdas de energia.

1 Introduction

Energy losses in electric distribution systems refer to the difference between the amount of energy purchased by the distribution company and the amount of energy billed to consumers. Losses are classified as technical and non-technical. While non-technical losses are not associated to the physical characteristics of the electrical network, technical losses are inherent to any electrical system. These losses are caused by the energy dissipation in lines, electrical connections, transformer cores and other equipment. Also, energy losses might increase due to wrong sizing of conductors, inadequate connections and high impedance faults. The magnitude of energy losses depends mainly on the loading pattern of distribution lines as well as load types. In electric distribution systems the load on the three phases of primary feeders and secondary lines is usually unbalanced. Load imbalance might lead to undesirable situations, which include: i) the increase of current in the most loaded phase, ii) the presence of current in the neutral conductor, iii) over-voltage problems in the least loaded phase, and iv) feeder tripping due to over neutral current. Power losses in distribution networks can vary significantly depending on load imbalance. For example, for a pure-resistive line section with and phase currents of 50A\100A\150A, power losses, without considering the neutral line, are 35kW; balancing the currents to 100A\100A\100A power losses reduce to 30kW. Consequently, if the loads on each phase are properly balanced, technical losses can be reduced. The goal of phase balancing (PB) is to reduce active power losses and consequently:

- Increase the capacity of distribution lines, which can be used to meet future load growth without changing conductors.
- Improve voltage profile due to the homogenization of voltage drops in each phase of the distribution line.

There are several methodologies reported in the specialized literature to approach the PB problem. In [1] the PB problem is formulated as a mixed integer programming problem with linear constraints. The mathematical model only considers constraints regarding current limits. Voltage constraints are not considered due to their intrinsic nonlinearity. The objective function is based on the imbalance of the system, which is measured through the phasing currents. In [2] a rephrasing strategy of distribution systems based on an expert system is proposed. The rephrasing strategy aims to reduce the neutral current and consequently, prevent the tripping of the over-current relay of the neutral conductor. In [3] the PB problem is approached by means of a backtracking search algorithm. In this case, a phase unbalance index is calculated based on the phasing current magnitudes of each line segment and branch. The phase balancing is enhanced using a heuristic rule-based search that aims to minimize the phase unbalance index. In [4] an immune algorithm is proposed for the phase balancing problem. In this case, the objective function considers the imbalance of phasing currents and the customer service interruption cost. In [5] the PB problem is solved using the Simulated Annealing metaheuristic. The objective function penalizes the unbalance degree of the system in terms of the percentage of power flow in each phase, and also considers the number of phase changes performed in the network. The nonlinearity of the problem is implicitly considered through a three-phase power flow calculation. Similar approaches combining phase balancing and feeder reconfiguration are presented in [6] and [7], this last one using the Tabu Search metaheuristic. In [8] the phase balancing is performed by introducing new winding connections in ordinary two winding transformers. In [9] the phase balancing is performed by a particle swarm optimization technique. In this case the objective function considers four components: the neural current, rephrasing cost, voltage drop and line losses. These components are fuzzified and then integrated as a multi-objective function. A particle swarm optimization is also proposed in [10] to approach the phase balancing problem, restricted to radial distribution systems. In references [1] to [7] the strategy of

PB consists in reconnecting loads individually. Although this strategy might lead to a high reduction of power losses, its implementation in real systems requires high investment and detailed information regarding all loads.
In references [11], [12], [13], and [14] the PB problem is approached form the point of view of feeder reconfiguration. In this case, the load is distributed among primary feeders, and the reconfiguration is performed through sectionalizing switches. The practical applicability of such technique is questionable, since most actual distribution systems lack enough sectionalizing switches for performing such reconfiguration. On the other hand, considering an automatic operation of the distribution system as proposed in [1] - [5] or and a single point of the load curve and as proposed in [6] and [7] is not practical; first, because the connections of the customers are not automatically switchable between different phases; and second, because to properly model energy losses, a load duration curve, instead of a single operation point, must be considered. This creates a new perspective of the problem named as phase balancing planning. The idea is to plan the PB over a given time horizon, so that the results ensure the effectiveness of the corrective actions implemented throughout this period. This paper proposes a new approach for PB planning using a specialized Genetic Algorithm (GA) which considers a discretized load duration curve. In contrast with traditional PB approaches, the proposed model does not include an imbalance index of the system; instead, the system balance is a consequence of the loss reduction obtained by the reconnection of loads in different phases.

2 Mathematical Model

The mathematical model of the PB planning problem must represent the different load configurations (connection schemes) in the distribution system. For this, an integer variable H_i, with 6 possible values, representing how load is connected to bus i is defined. The possible connection schemes are presented in Table 1. In order to prevent damage for reverse rotation, the phase sequence (either positive or negative) is not changed in branches with rotating three-phase loads. For example, a Y-open Delta-open transformer with its primary connected to phases A and B (A, B, *) can only be reconnected to phases B and C (*, A, B), or C and A (B, *, A) in order to assure the same phase sequence of the rotating loads connected to the secondary of the transformer.

In this case, every load i has an associated number , ranging from 1 to 6, representing the possible phase changes as shown in Table 2. Configuration 1 (H=1) indicates that there is not phase swapping. The other five configurations imply phase swapping either with or without sequence change. For example, configuration 6 (H=6) establishes that a connection ABC (default connection) must be changed to a CBA connection.

Table 1: Different connection schemes

Original connection		New valid connection
2ϕ	(A,B,C)	(C,A,B)(B,C,A)
3ϕ	(A,B,*)	(B,*,A)(*,A,B)
	(*,B,C)	(C,*,B)(*,B,C)
	(C,A,*)	(A,*,C)(*,C,A)
1ϕ	(A,*,*)	(*,A,*)(*,*,A)
	(B,*,*)	(*,B,*)(*,*,B)
	(C,*,*)	(*,C,*)(*,*,C)

Table 2: Possible load configurations

Number (H)	Connection	Sequence
1	ABC	No sequence change
2	BCA	
3	CAB	
4	ACB	Sequence change
5	BAC	
6	CBA	

The mathematical model of the PB problem can be considered either for a specific point of a load curve, or for a medium-term horizon planning. In the later case, a discretized load duration curve is used. The mathematical model is given by (1)-(5).

$$\min \sum_{t=1}^{Nt} T_t \sum_{i=1}^{N-1} R_i \frac{P_{it}^2 + Q_{it}^2}{V_{it}^2} \tag{1}$$

$s.t.$

$$P_{kt}^{Spe} - P^{Calc}(V_{kt}, \theta_{kt}, \beta, H) = 0 \tag{2}$$

$$Q_{kt}^{Spe} - Q^{Calc}(V_{kt}, \theta_{kt}, \beta, H) = 0 \tag{3}$$

$$V_k^{\min} < V_k < V_k^{\max} \tag{4}$$

$$P^{\min} < P_{it} < P^{\max} \tag{5}$$

Where P_{it} and Q_{it} are the active and reactive power flow in line i for the load level t, respectively. R_i is the resistance of line i. P_{kt}^{Spe} and Q_{kt}^{Spe} are the specified values of the active and reactive power injections in node k for load level t, respectively. V_{kt} and θ_{kt} represent the voltage magnitude and angle in node k for load level t, respectively. N_t is the number of load levels considered in the load duration curve, $N-1$ is the number of lines of the system, T_t is the length, in hours, of load level t, β represents additional parameters of the power flow such as line impedances, shunt reactances, etc. H is an integer variable $H_i \in \{1, \ldots, 6\}$ representing the possible phase changes as shown in Table 2. Note that objective function (1) is the minimization of energy losses. To account for a change in such losses, these must be computed with the expression shown in (1) and compared with those obtained for the base case (without phase swapping).

Constraints (2) and (3) represent the power balance equations which are enforced by solving a three-phase power flow. The power balance equations (in their active and reactive form) state that the specified power (generation minus demand) must be equal (within certain tolerance) to the calculated power. This last one depends on voltages, angles, the parameters of the network, and phase changes.

Constraint (4) represents the voltage limits in every node of the network and constraint (5) represents the active power flow limits throughout the planning horizon considered. Due to the characteristics of the PB problem, a three-phase modeling of all electrical devices is performed. To enforce constraints (2) and (3) a three-phase power flow as described in [15] was implemented. In this case, all neutral lines are supposed to be solidly grounded. This last consideration allows the series impedance matrix to have a fixed size of 3 × 3, independently of the number of conductors per phase and neutral lines. Whenever the size of the matrix is exceeded, a Kron reduction is applied element by element.

3 Solution Technique

As the PB planning is represented as a mixed integer nonlinear programming problem, which features combinatorial explosion, a suitable solution technique would be to use the so called Genetic Algorithms. In this paper, a modified version of the basic GA, known as the Chu-Beasley Genetic Algorithm (CBGA) [16] is implemented. The main characteristic of the CBGA consists in keeping the size of the population constant throughout the iteration process. Furthermore, the CBGA guarantees the diversity of all individuals (chromosomes), through the implementation of a substitution process, in which only a single chromosome is substituted in each generational cycle under pre-established conditions of feasibility and optimality. Just like the basic GAs, the CBGA uses the operators of selection, recombination and mutation. In the CBGA presented in this paper, slight variations are performed on these operators, most notably, the inclusion a function that returns the degree of unfeasibility of a configuration (chromosome) which is incorporated in the objective function.

3.1 Codification

The codification shows how a candidate solution is represented; it constitutes a key aspect of any GA since it can facilitate or complicate the implementation of the different operators. In this case, the codification adopted for an alternative of solution X, corresponds to the chromosome shown in figure 1. Every gene of the chromosome has a value ranging from 1 to 6, associated to the different possible connections shown Table 2. A neighbor solution of X, defined as X’, is generated by randomly changing any position of X within a range of 1 to 6. Figure 2 shows an example of a neighbor solution.

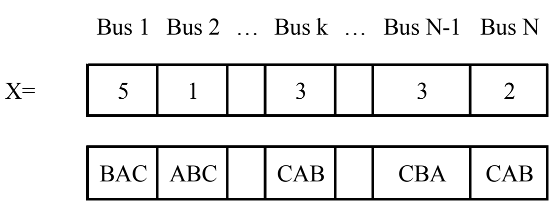


Figure 1: Proposed codification

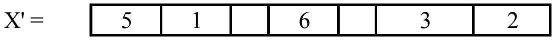


Figure 2: Neighbor solution

3.2 Chu-Beasley Genetic Algorithm (CBGA)

The CBGA is defined by the following steps:

- Generate an initial population: In this work the initial population is randomly generated, guaranteeing that there are not repeated chromosomes. However, the initial population can also be obtained using heuristic strategies.
- Selection: Two parents are chosen using selection by tournament. Every configuration is evaluated considering two aspects: i) the value of the objective function and ii) the grade of unfeasibility. This last consist in a function that returns positive values, proportional to the violation of the constraints, and zero when the configuration is feasible.
- Recombination: The two parents selected in the previous step interchange their information, creating two offspring. In conventional GAs the two offspring can be part of the individuals in the next generation; however, in the CBGA one offspring is randomly selected as candidate to substitute an individual of the current population.
- Mutation: In this case, a position of the chromosome is randomly selected with a given probability and mutated. The mutation is implemented by creating a neighbor solution.
- Population substitution: In the CBGA only a single individual of the current population can be substituted by the configuration obtained in the previous steps. In the substitution process no repeated solutions are allowed. This philosophy guarantees high diversity and avoids premature convergence to local optima. Furthermore, at the end of the optimization process, all individuals of the population will be of high quality. In consequence, the CBGA has the potential of providing multiple near-optimal solutions. The population substitution is performed considering the following steps:

- If the offspring is unfeasible, but with a lower unfeasibility degree than at least one of the individuals of the current population, then, the individual with the greatest unfeasibility degree is substituted by the offspring.
- If the offspring is feasible, and there is at least one unfeasible individual in the current population, then, the unfeasible solution with the greatest unfeasibility degree is substituted by the offspring.
- If the offspring is feasible, and all individuals in the current population are also feasible, then, the offspring only replaces the worst individual of the current population if it is better and also different from this one.

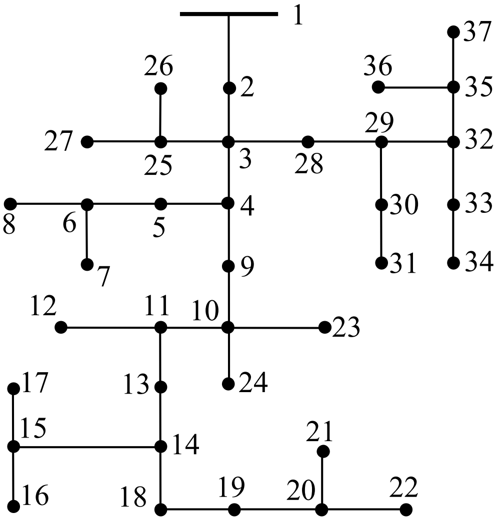
The process stops if the incumbent (the best solution found in the process) does not change after a predefined number of generations, or when the maximum number of generations has been reached.

4 Test and Results

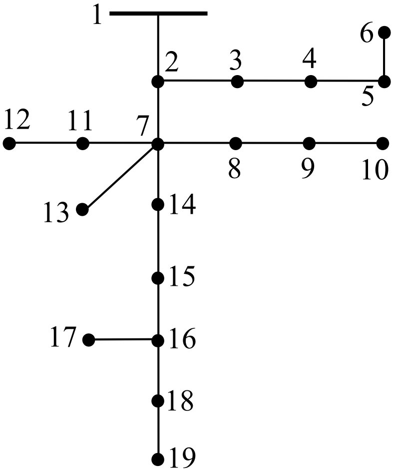
To show the effectiveness of the proposed approach, two distribution systems were used, namely, the IEEE 37 bus test system, and a system of 19 buses. This last one with different load models. In both cases, the CBGA was set with a population of 10 chromosomes and a mutation rate of 10%. The numeration of lines is given by the number of the ending bus minus one. For example, the line connecting nodes 3-28 is numbered as line 27. The results are presented below.

4.1 Test with the IEEE 37 bus test system

Figure 3a depicts the IEEE 37 bus distribution test system. In this case the nodes of the system have been renumbered. The original numeration as well as line configurations and load data can be consulted in [17]. This system corresponds to a real distribution system located in California and is constituted entirely by underground lines. It has a transformer in unbalanced operation and a voltage regulator at the substation. Both devices are not taken into account in the present analysis. The transformer, located between nodes 10-24 was removed (along with node 24); and the voltage regulator located between nodes 1-2 was substituted by a distribution line with length of 1850 feet and configuration type 721 [17].



(a) IEEE 37 bus test system



(b) 19-bus distribution system

Figure 3: Distribution test systems

The high imbalance of all loads allows applying the PB planning algorithm proposed in this paper. For this, it is assumed that all loads can be reconfigured. This assumption leads to the worst possible scenario from the standpoint of the proposed methodology (the one with the highest combinatorial explosion). A one-year horizon planning is considered. The load duration curve is discretized in three load levels (high, medium and low) as shown in Table 3.

Table 3: Load duration curve

Duration (h)	1000	3000	4760
Load (%)	100	60	30

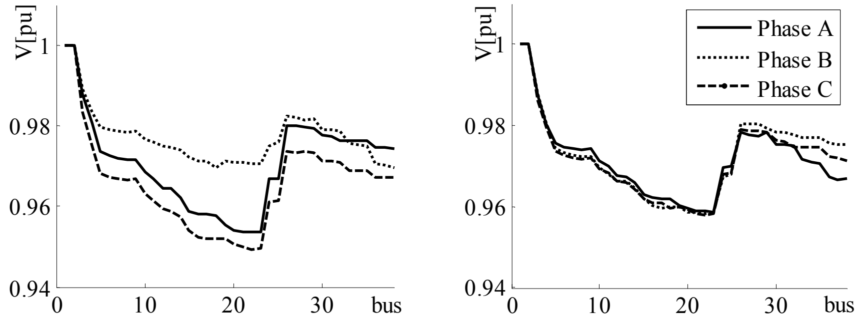
After running a power flow with the base configuration (without PB) it was found that the annual energy losses are 155258 kW.h/year. Nevertheless, such losses can be reduced in up to 9.35% through PB. Table 4 shows the 10 balancing plans obtained with the CBGA at the end of the optimization process. In this case the bus and its corresponding new configuration is indicated. A dashed line indicates that there is no change in load configuration. It can be observed that all PB plans contribute to an important reduction of energy losses ranging from 7.95% for plan 10 to 9.35% for plan 1. The best alternative corresponds to plan 1.

Table 4: Load balancing plans for a one-year horizon planning

Bus	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6	Plan 7	Plan 8	Plan 9	Plan 10
2	BCA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA
26	CAB	BCA	BCA	BCA	BCA	BCA	BCA	BCA	BCA	BCA
28	CBA	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB
30	CAB	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA
31	BAC	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB
32	ACB	–	–	–	–	–	–	–	–	–
36	BCA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA
37	CAB	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC
34	CAB	BAC	BAC	BAC	ACB	ACB	ACB	ACB	ACB	ACB
5	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB
7	CBA	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB
8	CAB	–	BAC	BAC	BAC	BAC	CBA	BAC	–	BAC
9	CBA	BCA	BCA	BCA	BCA	CBA	BCA	CBA	CBA	CBA
23	ACB	ACB	ACB	ACB	ACB	BCA	ACB	BCA	BCA	BCA
12	CBA	CAB	CAB	CAB	CAB	–	CAB	CAB	CAB	CAB
13	BAC	–	–	–	–	–	–	–	–	–
14	BAC	CAB	CAB	CBA	CAB	ACB	CBA	ACB	ACB	ACB
16	CAB	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB	ACB
17	ACB	BCA	BCA	BCA	BCA	BCA	BCA	BCA	BCA	BCA
18	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB
19	–	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA
21	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC
22	BCA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	CBA	–
27	CBA	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC	BAC
6	BCA	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB	CAB
Losses (kW.h/year)	140740	141540	141650	141650	141760	141810	141890	142110	142430	142920
Reduction (%)	9.35	8.84	8.76	8.76	8.69	8.66	8.61	8.47	8.26	7.95

Figures 4a and 4b depict the system voltage profile before and after applying the best PB plan (plan 1), respectively. It can be observed that before the application of the proposed PB plan, differences in nodal voltage magnitude of each phase are noticeable throughout the entire system, especially in nodes 17 and 23 and between phases A and B. This last one is the least loaded phase, and consequently, presents the lowest variations in voltage profile. On the other hand, the most loaded phase (phase C), presents high voltage drops, reaching the minimum voltage magnitude of 0.95 p.u in bus 23. In the proposed PB plan some loads are transferred from phase B to C, so that the voltage profile of phase C is improved (reaching 0.96 p.u in bus 23), and the voltage profile on phase B is lowered, but kept between the allowed limits. In this case, voltage magnitudes in all phases meet the voltage constraints given by: $0.95 \leq V_n \leq 1.05$.

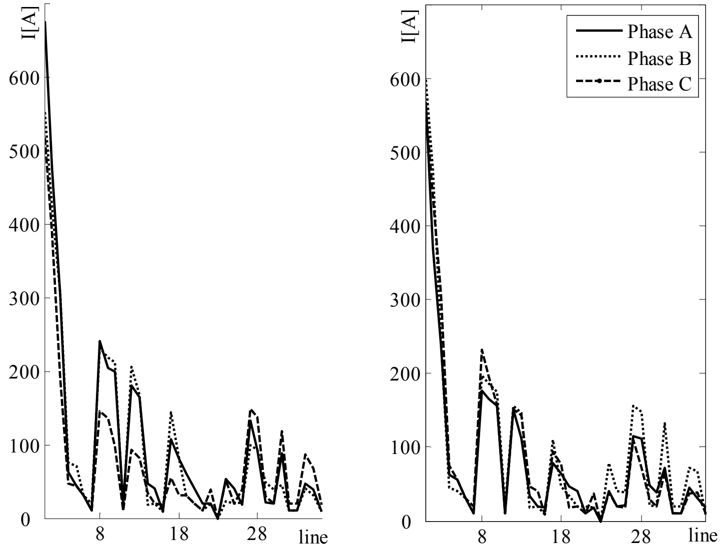
Figure 5a depicts the line currents for the base case. It can be observed that currents at the beginning of the feeder are quite unbalanced, being the highest current the one in phase A, which exceeds the maximum line capacity of 600 A. It can be observe that the current imbalance is kept throughout the system. However, after applying the proposed PB plan, the magnitudes of the currents at the beginning of the feeder are similar and are within the capacity limits of the lines as shown in Figure 5b.



(a) Base case.

(b) After applying the best PB plan (plan 1).

Figure 4: Voltage profile of the IEEE 37 bus test system.



(a) Base case.

(b) After applying the best PB plan (plan 1).

Figure 5: Current profile of the IEEE 37 bus test system.

4.2 Test with a radial 19 bus system considering different load models

In this case a radial branch of a secondary distribution system with 19 nodes and 18 lines is considered (see Figure 3b). The nominal voltage of this branch is 208V. Different types of loads have been considered by phase and node. All buses have a different percentage of load modeled as constant impedance (Z), constant current (I) or constant power (PQ). It is assumed that all loads of the system can be reconfigured and the load duration curve shown in Table 3 is used. The load and line data are presented in Table 5 and Table 6, respectively. For example, in Table 5 it can be seen that node 2 has 0.44 kW modeled as constant power in its phase A, and 0.23 KVAr modeled as constant current in its phase B. The impedance matrix of the lines is given by (6) in (Ω/km). All conductors have a current capacity of 140A.

$$Z = \begin{bmatrix} 0.6810 + j0.6980 & 0.0600 + 0.0780 & 0.0600 + j0.0500 \\ 0.0600 + j0.0780 & 0.6810 + j0.6980 & 0.0600 + j0.0360 \\ 0.0600 + j0.0500 & 0.0600 + j0.0360 & 0.6810 + j0.6980 \end{bmatrix} \quad (6)$$

Table 5: Load data of the 19 bus distribution system

Bus	P_A (kW) (PQ/I/Z)	Q_A (kVAr) (PQ/I/Z)	P_B (kW) (PQ/I/Z)	Q_B (kVAr) (PQ/I/Z)	P_C (kW) (PQ/I/Z)	Q_C (kVAr) (PQ/I/Z)
1	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
2	0.44/0/0	0.21/0/0	0/0.47/0	0/0.23/0	0/0/0.51	0/0/0.25
3	0/0/0	0/0/0	0/0/0	0/0/0	1.31/1.42/1.52	0.63/0.69/0.74
4	0/0/0	0/0/0	0/0/0	0/0/0	2.18/2.36/2.54	1.05/1.14/1.23
5	2.61/0/0	1.27/0/0	0/2.83/0	0/1.37/0	0/0/3.05	0/0/1.48
6	1.74/0/0	0.84/0/0	0/1.89/0	0/0.91/0	0/0/2.03	0/0/0.98
7	0/0/0	0/0/0	0/0/0	0/0/0	1.31/1.42/1.52	0.63/0.69/0.74
8	0/0/0	0/0/0	0/0/0	0/0/0	1.74/1.89/2.03	0.84/0.91/0.98
9	1.31/1.42/1.52	0.63/0.69/0.74	0/0/0	0/0/0	0/0/0	0/0/0
10	1.31/0/0	0.63/0/0	0/1.42/0	0/0.69/0	0/0/1.52	0/0/0.74
11	1.31/0/0	0.63/0/0	0/1.42/0	0/0.69/0	0/0/1.52	0/0/0.74
12	2.61/0/0	1.27/0/0	0/2.83/0	0/1.37/0	0/0/3.05	0/0/1.48
13	1.31/0/0	0.63/0/0	0/1.42/0	0/0.69/0	0/0/1.52	0/0/0.74
14	1.31/0/0	0.63/0/0	0/1.42/0	0/0.69/0	0/0/1.52	0/0/0.74
15	1.74/0/0	0.84/0/0	0/1.89/0	0/0.91/0	0/0/2.03	0/0/0.98
16	0.87/0/0	0.42/0/0	0/0.94/0	0/0.46/0	0/0/1.02	0/0/0.49
17	1.74/1.89/2.03	0.84/0.91/0.98	0/0/0	0/0/0	0/0/0	0/0/0
18	0.44/0/0	0.21/0/0	0/0.47/0	0/0.23/0	0/0/0.51	0/0/0.25
19	1.74/0/0	0.84/0/0	0/1.89/0	0/0.91/0	0/0/2.03	0/0/0.98

Table 6: Line data of the 19 bus distribution system

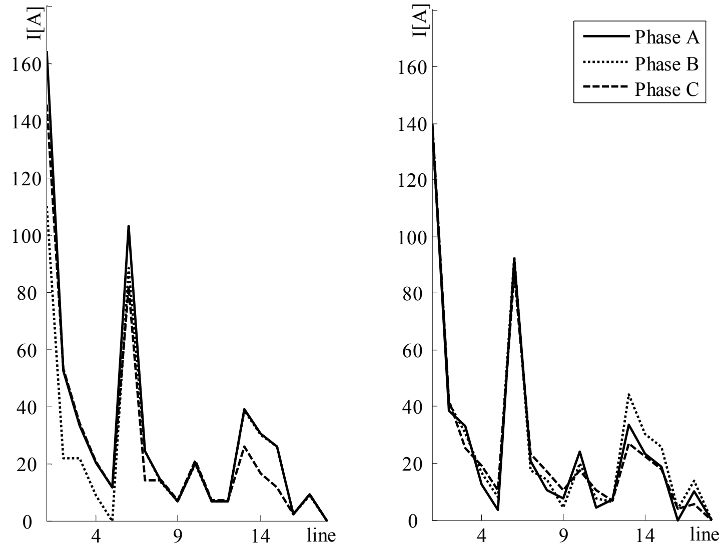
From node	To node	Length (m)	From node	To node	Length (m)
1	2	8	15	16	22
2	7	9	16	17	24
7	13	17	16	18	30
2	3	8	18	19	18
3	4	18	7	8	23
4	5	26	8	9	23
5	6	16	9	10	15
7	14	9	7	11	26
14	15	17	11	12	26

The energy losses of this system, for the base case, are 6352.7 kW.h/year. The best four BP plans obtained with the CBGA are presented in Table 7. It can be observed that all BP reduce energy losses over 11%.

Table 7: Line data of the 19 bus distribution system

Bus	Plan 1 (PQ/I/Z)	Plan 2 (PQ/I/Z)	Plan 3 (PQ/I/Z)	Plan 4 (PQ/I/Z)
1	– / – / –	– / – / –	– / – / –	– / – / –
2	BCA/ BAC/ ACB	BCA/ BAC/ ACB	BCA/ BAC/ ACB	BCA/ BAC/ ACB
3	– / – / CBA	– / – / CBA	– / – / CBA	BAC/ – / CBA
4	ACB/ BAC/ BCA	ACB/ BAC/ BCA	ACB/ BAC/ BCA	ACB/ BAC/ BCA
5	ACB / – / –	ACB / – / –	ACB / – / –	ACB / – / –
6	– / CBA / –	– / CBA / –	– / CBA / –	– / CBA / –
7	– /CAB/ BCA	– /CAB/ BCA	– /CAB/ BCA	– /CAB/ BCA
8	CBA/ CBA/ BAC	CBA/ CBA/ BAC	CBA/ CBA/ BAC	CBA/ CBA/ BAC
9	BAC/ BCA/ CAB	BAC/ BCA/ CAB	BAC/ BCA/ CAB	BAC/ BCA/ CAB
10	BCA/ CAB/ ACB	BCA/ CAB/ ACB	BCA/ CAB/ ACB	BCA/ CAB/ ACB
11	BAC/ BAC/ CAB	BAC/ BAC/ CAB	BAC/ BAC/ CAB	BAC/ BAC/ CAB
12	–/ CAB/ BCA	–/ CAB/ BCA	–/ CAB/ BCA	–/ CAB/ BCA
13	ACB/ ACB/ ACB	ACB/ ACB/ ACB	ACB/ ACB/ ACB	ACB/ ACB/ ACB
14	BCA/ BAC/ CBA	BCA/ BAC/ CBA	BCA/ BAC/ CBA	BCA/ BAC/ CBA
15	ACB/ ACB/–	ACB/ ACB/–	ACB/ CBA/–	ACB/ CBA/–
16	BAC/ BAC/–	BAC/ BAC/–	BAC/ BAC/–	BAC/ BAC/–
17	–/ CBA/ BAC	–/ CBA/ BAC	–/ CBA/ BAC	–/ CBA/ BAC
18	CAB/ BAC/ BAC	CAB/ BAC/ BAC	CAB/ BAC/ BAC	CAB/ BAC/ BAC
19	CBA/ CBA/ CBA	CBA/ CBA/ CBA	CBA/ CBA/ CBA	CBA/ CBA/ CBA
Losses (kW.h/year)	5640.9	5640.9	5652.1	5652.1
Reduction (%)	11.2	11.2	11.03	11.03

The current profile of the lines before the PB is shown in 6a. It can be observed that the currents at the beginning of the feeder are quite unbalanced, being the highest current, the one in phase A, which is above its limit of 140A. Such unbalance is kept all the way through the feeder. After applying the best PB plan the magnitude of the currents throughout the system are quite similar, as shown in Figure 6b. Furthermore, the current of phase A has been set to its limit.



(a) Base case.

(b) After applying the best PB plan (plan 1).

Figure 6: Current profile of the 19 bus test system.

5 Conclusions

This paper proposes an optimization model and a solution technique for phase balancing planning in distribution systems. Both, the proposed model and solution technique have shown to be adequate and effective to approach the problem of reducing technical energy losses through phase swapping. The quality of the phase balancing plans obtained with the CBGA depends on the accuracy of the input data. Consequently, the success of the proposed methodology relies not only on a rigorous modeling of the electrical devices, but also on detailed information of the loads. On the other hand, the main advantage of using a CBGA is that, at the end of the optimization process, a set of high-quality solutions are obtained, instead of one. This gives more flexibility to the planner when analyzing investment costs.

With the implementation of the proposed methodology, in addition to the achievement of the primary objective (energy loss reduction), other benefits were also obtained. Such benefits include balanced operation, improvement of voltage profile and alleviation of congested lines. This last aspect has a direct impact on investments costs, since it might defer or avoid network upgrades, especially in those systems with high load imbalance. Consequently, the proposed model implicitly considers other aspects related to the adequate operation of the distribution system, such as balancing of currents in lines, minimization of currents in the neutral conductor and ground, voltage balance and minimization of operational costs.

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