Electrical Power and Energy Systems 82 (2016) 420–428

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Multi-objective optimization of the balancing of phases in primary distribution circuits

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ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form 23 March 2016
Accepted 29 March 2016
Available online 13 April 2016

Keywords:
Distribution systems
NSGA-II
Phase balancing

ABSTRACT

The primary distribution systems are among the more unbalanced three-phase networks. The unbalance of the phase currents causes two fundamental problems in the circuits: the increase of energy losses in the primary feeders and the presence of a high neutral current in normal operating status that makes it difficult the detection of ground faults by corresponding protections. These circuits are always protected at the substation. Nevertheless, other protections can also be located downstream in some sections or laterals of the circuit. Additionally, a circuit or some section of it can be supplied from another adjacent circuit in emergency conditions. In all the points where a ground fault protection is used, the maximum current of imbalance must be reduced to a minimum considering the several operating conditions that can change the circuit topology. This paper formulates the problem of phase balancing as a multi-objective optimization problem that minimizes: the neutral current at the desired points of the circuit, the energy losses in the primary feeders and the number of reconnected elements to achieve these objectives. The Non-dominated Sorting Genetic Algorithm (NSGA-II) has been used to develop the optimization application, which has shown a very successful performance in the solution of the phase balancing problem. A test example with all the needed data is solved to show the advantages of the presented approach.

Introduction

Two related strategies that are applied to minimize power losses in distribution circuits are: (1) the reconfiguration; and (2) phase balancing. The reconfiguration consists of changing the system topology by the opening and closing the switches, while phase balancing refers to the redistribution of the loads into the circuit phases to improve the balance conditions.

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It should be kept in mind that the imbalance of the currents is not manifested of equal form in all the extension of a circuit. A distribution circuit can have a perfect balance at his source end and at the same time be highly unbalanced in other sections or laterals of the circuit. In this way, the losses caused by the imbalance can be high in an apparently balanced circuit.

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Normally the reconnection of a reduced number of laterals or of distribution transformers can greatly improve the phase balancing and reduce the energy losses in the primary circuit conductors.

Several programming techniques as: artificial neural networks [1,2], fuzzy logic [3], differential evolution [4], ant colony search [5], etc. have been applied for the reconfiguration of the distribution circuits by means of switching operations.

Also, the phase-balancing has been solved by different methods as: mixed-integer programming [6], simulated annealing (SA) [7,8], genetic algorithm (GA) [9], heuristic algorithms [10,11], immune algorithm (IA) [12,13], etc.

The GA approach in Ref. [9] searches the phase balancing and loss reduction by the optimization of the phase connections of the distribution transformers. However, the number of needed reconnections was too high to be practical.

The Ref. [10] presents a heuristic algorithm for the reconnection of single-phase and two-phase laterals in order to reduce losses and also improving the imbalance at various locations. Besides, another heuristic backtracking search algorithm is proposed in

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http://dx.doi.org/10.1016/j.ijepes.2016.03.047
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[11] to adjust the phase connections of primary feeders and laterals, but only the minimization of the phase unbalance index of each line segment is taken into account.

In Refs. [12,13] is proposed an immune algorithm (IA) to reconnects the laterals and the distribution transformers. The multi-objective function is formulated by considering the unbalance of currents, the customer service interruption cost and the labor costs to perform the optimal solution.

An expert system to obtain a phase balancing strategy is proposed in [14]. This tool aims to reduce the neutral current and consequently avoid the tripping of the over-current relay of the neutral conductor.

The Refs. [15–18] propose a combinatorial optimization tool based in fuzzy logic, neural networks and a fast heuristic method to balance the phase currents.

In Ref. [19] is used a GA to minimize the energy losses of the primary conductors while the neutral current at substation is confined to an accepted level.

The proposed approach in [20] executes phase balancing by introducing new winding connections in the two-winding transformers.

The phase balancing is performed in [21,22] by: particle swarm optimization, bacterial foraging and fuzzy techniques. The multi-objective function considers: the neutral current, the reconnection cost, the voltage drop and the line losses.

In Ref. [23] is investigated the use of chaotic simulated annealing, while a self-adaptive hybrid differential evolution technique and a hybrid heuristic algorithm are employed in [24,25].

Six algorithms for the phase balancing are studied in [26], which suggests a dynamic programming approach as the best suited for this problem.

In Ref. [27], the use of a balancer transformer is proposed to reduce phase unbalance and mitigate the neutral current harmonics in the secondary distribution systems.

As was presented, several methods have been applied to solving the phase balancing. However, not all approaches consider all the pertinent conditions nor use efficient multi-objective optimization techniques that allow the obtaining of the frontier of Pareto of the problem.

This author developed an application of the NSGA-II multi-objective optimization algorithm to the phase balancing [28] that now is extended to minimize the imbalance of the phase currents in multiple points and for all the possible operating conditions.

This paper formulates the problem of phase balancing by the minimization of: (1) the imbalance current at the desired points of the circuit; (2) the energy losses in the primary feeders; and (3) the number of elements that are reconnected to achieve these objectives.

The presented work has employed the Non-dominated Sorting Genetic Algorithm (NSGA-II) to develop the optimization application, which has shown of very successful performance in the solution of the phase balancing problem. A test example with all the needed data is solved to show the advantages of the presented approach.

Problem formulation

In order to formulate the optimization problem, the independent variables and the objective functions must be defined.

Independent variables

The independent variables of this problem represent the connections to the phases of the primary circuit of: the laterals of two-phase and of a single-phase, the three-phase banks of three or two single-phase transformers and of the distribution transformers.

The floating Wye–Delta connection (Fig. 1) is used to the three-transformer banks.

The 120/240 V single-phase load ($S_{1\varphi}$) is supplied by the lighting-leg transformer while two equal power-leg transformers complete the bank for supplying the 240 V three-phase load ($S_{3\varphi}$).

If only one power-leg transformer is used and the neutral of the primary-winding is grounded, is obtained the two-transformer bank.

When there is only single-phase load, is used only a single-phase distribution transformer.

From Fig. 1, the line-line voltages at the secondary are in phase with the phase voltages in the primary circuit V_{1n}, V_{2n} and V_{3n}. Then, applying the superposition principle, the currents I_1, I_2, I_3 in the primary circuit are obtained by the expressions of Table 1.

The three-phase distribution circuit contains N_{lat} laterals of two-phase and of single-phase as well as N_{trf} three-phase transformer banks and single-phase distribution transformers that can be connected in various ways to the circuit.

Table 2 presents the possible connections of the primary terminals 1, 2, 3 of these elements according the available phases in the primary circuit.

Care must be taken to maintain the phase sequence in the secondary winding when a two-transformer bank is reconnected. Besides, if a single-phase distribution transformer is connected to a single-phase section of the circuit, there is no need to consider its reconnection.

In order to represent the selected connection for the circuit's elements (laterals and distribution transformers), the x_{con} vector of size $N_{lat} + N_{trf}$ is defined. The elements of x_{con} are integers that represent the possible connections shown in Table 2.

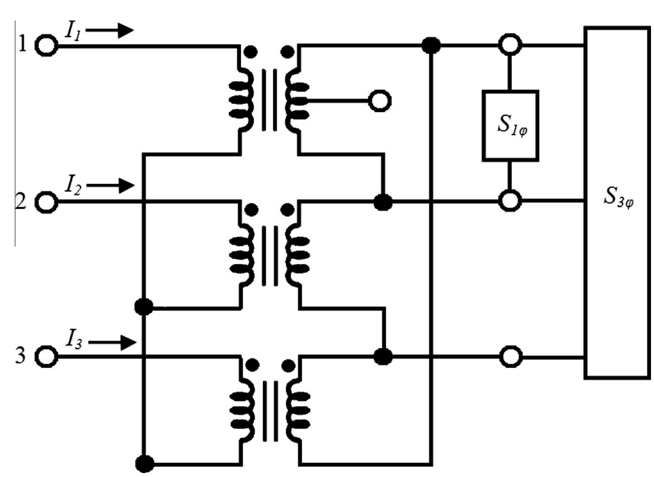

Fig. 1. Floating Wye–Delta three-transformer bank.

Table 1
Primary currents of three-phase transformer banks and distribution transformers.

Currents	Three-transformer bank	Two-transformer bank	Distribution transformer
I_1	$+\frac{2}{3}\left(\frac{S_{1\phi}}{V_{1n}}\right)^* + \frac{1}{3}\left(\frac{S_{3\phi}}{V_{1n}}\right)^*$	$\frac{1}{3}\left(\frac{S_{3\phi}}{V_{1n}} - \frac{S_{3\phi}}{V_{3n}}\right)^* + \left(\frac{S_{1\phi}}{V_{1n}}\right)^*$	$\left(\frac{S_{1\phi}}{V_{1n}}\right)^*$
I_2	$-\frac{1}{3}\left(\frac{S_{1\phi}}{V_{1n}}\right)^* + \frac{1}{3}\left(\frac{S_{3\phi}}{V_{2n}}\right)^*$	$\frac{1}{3}\left(\frac{S_{3\phi}}{V_{2n}} - \frac{S_{3\phi}}{V_{3n}}\right)^{**}$	0
I_3	$-\frac{1}{3}\left(\frac{S_{1\phi}}{V_{1n}}\right)^* + \frac{1}{3}\left(\frac{S_{3\phi}}{V_{3n}}\right)^*$	0	0