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Metaheuristics approaches to solve combinatorial optimization problems in distribution power systems. An application to Phase Balancing in low voltage three-phase networks

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ABSTRACT

Metaheuristics algorithms are widely recognized as one of most practical approaches for combinatorial optimization problems. One the most interesting areas of application are the power systems. In particular, Distribution Systems planning and operation. This paper presents some metaheuristics approaches to solve a typical combinatorial optimization problem: the Phase Balancing in Low Voltage Electric Distribution Systems. A model supported in Linear Integer-Mixed Programming is presented, to observe and discussing its limitations. From this, is introduced a new metaheuristic, called Fuzzy Evolutionary Particle Swarm Optimization, based in the Swarm Intelligence Principles and Evolution Strategies, which is extended to fuzzy domain to modeling a multi-objective optimization, by mean of a fuzzy fitness function. A simulation on a real system is presented, and advantages of this approach respect to the Classical Simulated Annealing and Particle Swarm metaheuristics, selected between the most representatives, are evidenced.

Introduction

Metaheuristics algorithms are widely recognized as one of more practical and success approaches to solve combinatorial problems [1–3]. However, the original formulations have been oriented to mono-objective optimizations. Many proposal of extensions to multi-objective domain have been established, but each formulation has showed particular advantages and limitations, in general, over certain kind of problems. Such is the case of Phase Balancing in Low Voltage Electric Distribution Systems (LVEDS), when a classic programming approach is not addressed to solve it. The balance is referred to the loads in the feeders of a LV network in an EDS. The classic approach, has demonstrated significant limitations, as will be discussed. For this reason, a metaheuristic approach is an alternative that may produce very good results.

There are a significant number of metaheuristics, such as Tabu Search (TS) [4], Simulated Annealing (SA) [5], Ant Colony Optimization (ACO) [6] and Particle Swarm Optimization (PSO) [7,8], that have been proposed to solve specific combinatorial problems, with a great success. However, there are two aspects that remain in discussion: (a) How model a best multi-objective metaheuristic and (b) How design a self-adaptive metaheuristic, with the less number of external parameters as possible (if were possible, none). This paper presents a new multi-objective metaheuristic, called Fuzzy Evolutionary Particle Swarm Optimization (FEPSO), which results can to drive towards a general model, capable to overcome the two aspects mentioned. The problem of Phase Balancing, under a multi-objective formulation, is, then, considered to simulations with the aim of comparing the performance of FEPSO with respect to a classical metaheuristic. Among the most representative metaheuristics was selected Simulated Annealing (SA), which will be extended to the fuzzy domain to define a multi-objective version of SA, that will be called FSA. The selection of SA is not arbitrary, but respond to fact of to separate two strategies very different that can be observed in the metaheuristics algorithms: in the first, that supported SA, the evolution of the solution algorithm, is simulated using probabilistic sampling techniques, supported by successive generation of states of energy, corresponding to solutions of the combinatorial optimization. In the second, that supported FEPSO, such evolution is based in the denominated Swarm Principles. These concepts will be presented in section 'The metaheuristics simulated annealing and Particle Swarm Optimization'.

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The work is organized as follows: in section 'The Phase Balancing problem in Low Voltage Feeder System', the problem of Phase Balancing is presented. It discussing the no desired effects of a high unbalance degree on the LV feeders system. A model supported in Linear Integer-Mixed Programming is presented, to observe and discussing its limitations. Then, a multi-objective formulation for the problem, according with the purpose of simulations by metaheuristics algorithm, is presented. In section 'The metaheuristics simulated annealing and Particle Swarm Optimization', the essential of the metaheuristics SA and PSO, are described. In section 'The metaheuristic Evolutionary Particle Swarm Optimization (EPSO)', the first approach towards the contribution of this paper, the metaheuristic Evolutionary Particle Swarm Optimization (EPSO), is presented. Section 'Static fuzzy decision and fuzzy fitness function' is focused in the formulation of a fuzzy fitness function, supported in the static decision-making in fuzzy environment principle, formulated by Bellman and Zadeh [9]. From this, in section 'Simulation on the real LV feeder system', the multi-objective metaheuristics FSA and FEPSO, in the specific context of Phase Balancing problem considered in section 'The Phase Balancing problem in Low Voltage Feeder System', are introduced. Finally, in section 'Simulation on the real LV feeder system', a simulation of the two fuzzy metaheuristics on the same real LV feeders system is presented, and its results are compared and discussed. In section 'Conclusions', the most important conclusions of this work, are presented.

The Phase Balancing problem in Low Voltage Feeder System

The most LV networks of an EDS are three-phase systems. Feeders loads in a LV network, for low incomes residential areas, are commonly single-phase. Original feeders system design, depends on accuracy of the given load data, there always will be certain unbalance degree and it must be as low as possible.

There are, in general, two options for Phase Balancing: (a) feeders reconfiguration at the system level and (b) phase swapping at the feeder level. The option (b), phase swapping, is a direct and effective way to balance a feeder in terms of phases, and this method will be considered in this work. For the purpose of this paper, LV feeders system will have only single-phase loads. A formulation to the general problem of Phase Balancing, in this context, considering, without loss of generality, only one feeder (principal), can be expressed as follows:

$$Min\left\{Loss_T; I(\Delta u); \left|I^{[o]}\right|_f\right\} \tag{1}$$

Subject to:

$$\left|I^{[R]}\right|_f \leqslant I_{Max} \tag{2}$$

$$\left|I^{[S]}\right|_f \leqslant I_{Max} \tag{3}$$

$$\left|I^{[T]}\right|_f \leqslant I_{Max} \tag{4}$$

where the subindex f, refers the output of substation connected to the principal feeder of the system; $Loss_T$ indicates the total active power loss of system and $I(\Delta u)$ is an index that depends of voltage drops. $\left|I^{[o]}\right|_f$ is the homopolar component of the unbalance intensities system, that satisfy the equation:

$$\left|I^{[R]}\right|_f + \left|I^{[S]}\right|_f + \left|I^{[T]}\right|_f = 3 \times \left|I^{[0]}\right|_f \tag{5}$$

If the system is balanced, then $\left|I^{[0]}\right|_f = 0$.

The subindex $[R]$, $[S]$ and $[T]$, represent each phase of system. In addition, three constraints are imposed: the intensities in each phase at the output, must be less than the phase line capacity, I_{Max}, Eqs. (2)–(4). The problem can be seen as a set of swapping single phase loads or a load assignment to lines. For example, a single phase load can only be assigned to either phase $[R]$, $[S]$ or $[T]$ (see Fig. 1). This assignment should be executed until the objectives (1) are satisfied. This problem is clearly combinatorial: if there are 3 phases and n loads that can be swapping, then the number of states of search space for the solution, is 3^n.

An approach from mathematical programming supported in linear Mixed-Integer Programming

The MIP (Mixed-Integer Programming) model, was presented in [10], and its formulation, to the context of this work, can be stated as follows:

$$Min\left\{\sum_j p_j \times U_j\right\}$$

Subject to :

$$U_j = Max\left\{\sum_j \left|I_f^{[R]} - I_f^{[T]}\right|; \left|I_f^{[S]} - I_f^{[T]}\right|; \left|I_f^{[R]} - I_f^{[S]}\right|\right\} \tag{6}$$

$$I_j^{[\Phi]} = \sum_k I_k^{[\Phi]} + \sum_w \delta_i^{[\Phi]}{}_w \times I_i^{[\Phi]}{}_w \tag{7}$$

$$\sum_w \delta_i^{[\Phi]}{}_w = 1; \quad \forall[\Phi] \in \{R, S, T\} \tag{8}$$

$$\sum_w \delta_i^{[\Phi]}{}_w = 1; \quad \forall[w] \in [1 \ldots nL] \tag{9}$$

$$I_j^{[\Phi]} \leqslant I_{Max\ j} \tag{10}$$

$$\delta_i^{[\Phi]}{}_w \in \{0, 1\}; \quad \forall[i, \Phi] \tag{11}$$

$$\sum_j p_j = 1; \quad \forall[j] \in [1 \ldots nB] \tag{12}$$

From Eq. (6), in the context of this work, it is intend to assign the single-phase loads to the conductors (phases) such that in each branch j, the maximum difference in magnitude between the intensities (taken in pairs of phases), be a minimum. Then U_j becomes in a measure of unbalance degree per branch. To complete the objective, a convex set of weights, indicated as p_j, is externally fixed, by the decision-maker, and, this way, the most simple multi-objective linear programming formulation is proposed. p_j is a subjective value that reflex the importance of unbalance degree, U_j, in the branch j of feeder system. The remaining symbols have the following meaning: Φ is the phase in $\{R, S, T\}$; $\delta_i^{[\Phi]}{}_w$ is a decision variable, (binary) in $\{0, 1\}$, for w-th load connected to phase Φ at node i; nL is the number of loads; nB is the number of branches; I_{Maxj} is the phase line capacity of branch j. In this formulation, Eq. (7) represents the Kirchhoff Law of current at the node i; Eqs. (8), (9) and (11) ensure that each load has assigned (or is connected to) only one phase; the Eq. (5) is the line capacity constraint, and the Eq. (12) is the convex set of branch-weights constraint.

This model has three major limitations: (a) The problem is not linear and its linearization is valid only if the load characteristics are constant-current. In the most real systems, this condition is not observable, (b) the model require the subjective weights, p_j,

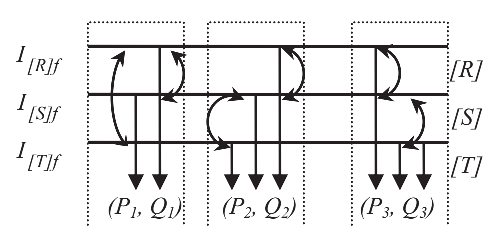

Fig. 1. Single phase loads and balance by phase swapping in some loads.