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Optimal integrated planning of MV–LV distribution systems using DPSO

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ABSTRACT

A new technique for optimal planning of MV and LV segments of a distribution system is presented in this paper. The main goal is to find optimally distribution transformer and substation locations and ratings, as well as, the route and type of Medium Voltage (MV) and Low Voltage (LV) feeders. The proposed technique is applicable to both uniform and non-uniform load densities areas. In this method, the planning area is divided into regions with relatively uniform load density such as urban, semi-urban, sub-urban. Each of regions is divided into zones, called LV zone. Each LV zone is supplied by an MV/LV transformer. The dimensions of LV zones are found based on the average load of each region. The placement and rating of MV/LV transformers, the type and route of LV conductors in an LV zone all depend on its loads' location and power. Regarding the placement and rating of MV/LV transformers in planning area and the space of regions, the dimensions of a zone which is supplied by a HV/MV transformer, called MV zone, is determined. Additionally, the location and rating of HV/MV transformers as well as the feeder's routes and types are calculated. Since the dimensions of an LV zone influence the associated length of MV feeder, the MV feeder cost needs to be included in the total cost associated with the LV zone. This requires the MV feeder type to be known to calculate the corresponding cost. However, the MV feeder type is determined as an output from MV zone planning. As a result, an iterative based method is proposed to consider this common element in computations to develop integrated planning of both LV and MV zones. It is observed that the iterative technique quickly converges to the same results as the exhaustive search method.

Discrete particle swarm optimization (DPSO) method is employed for solving the planning problem. The results are compared with nonlinear programming, genetic algorithm and exhaustive search methods. It is observed that DPSO is as accurate as the exhaustive search method for integrated planning of MV–LV distribution systems while its computation time is significantly lower.

1. Introduction

A distribution system consists of MV and LV networks. Although the LV network cost, to some extent, is comparable with the MV network cost, the majority of the published papers in this field are dedicated to the planning of MV networks [1–6] rather than LV networks [7–10]. Furthermore, there are only a few papers that consider both MV and LV networks [11–13]. The optimal planning of either of these networks separately will not lead to an accurate result. Since the dimensions of an LV network determine the associated length of MV feeder, this element should be included in the total cost associated with both LV and MV networks so both of these networks should be planned simultaneously as considered in this paper.

Most of the papers referred above use a continuous cost function to model the cost of distribution system components, LV conductors, distribution transformers, MV feeders and substations. Only a few authors used the discrete cost function [3,7,10,14]. Due to the rounding process, the accuracy of the solution decreases with continuous cost functions. Therefore, a discrete cost function based on realistic discrete data, collected from the distribution system elements, is used in this paper.

Selection of an appropriate optimization method for the optimal planning of distribution systems (OPDS) is crucial. The classical branch and bound techniques are employed for planning distribution networks in [2,11,15–17]. Although these procedures can lead to minimum objective function value, they require excessive computation time owing to their combinatorial complexity. As a result, some other approaches have been presented to improve computational efficiency. Amongst these, the heuristic methods are extensively applied in the literature [3–11]. The particle swarm optimization (PSO) is one of the heuristic methods [18,19]. In this paper, PSO is employed to solve the OPDS problem. Due to the discreteness of the cost function, a Discrete PSO, called DPSO, is used.

A comprehensive optimal planning of distribution systems for the urban/semi-urban areas is presented in this paper. Both MV and LV networks are optimized and the optimal location and size

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of transformers and substations, as well as, the route and type of MV and LV feeders are obtained. This work is aimed at Greenfield sites where the location of specific loads or substations is not pre-assigned. In this work, the cost of the distribution system elements is not assumed to be continuous, but discrete. The employed objective function consists of the capital cost, loss cost and reliability cost. The voltage drop and feeder current are incorporated as constraints in the optimization procedure.

2. Problem formulation

The main objective of the optimal planning of distribution systems is to minimize the cost of substations, transformers, MV feeders and LV conductors; while the bus voltage and feeder current are maintained within acceptable ranges.

To accommodate these, the objective function (OF) as the net present value of total cost is defined as

$$OF = C_{CAPITAL} + \sum_{t=1}^{T} \frac{C_{O\&M} + C_{INTERRUPTION} + C_{LOSS}}{(1+r)^t} + SP \quad (1)$$

where $C_{CAPITAL}$ is the total capital cost, $C_{O\&M}$ is the total operation and maintenance cost, $C_{INTERRUPTION}$ is the interruption cost, C_{LOSS} is the loss cost, r is the discount rate, T is the number of years in the study timeframe, and SP is the penalty factor.

The capital cost is composed of the purchase and installation cost of distribution substations, transformers, MV feeders, and LV conductors. The operation and maintenance costs involve fixing, inspection, maintenance, and replacements of parts (see Tables A1 and A2 in Appendix A). The interruption cost has two components – the cost related to the duration of interruptions and that related to the number of interruptions. The summation of these two costs is taken as the interruption cost. The duration based interruption cost is the multiplication of the cost for the average interruption duration in a year (in terms of minutes) and the average interruption duration. The average interruption duration can be found using the multiplication of SAIDI (System Average Interruption Duration Index), as a reliability index, and the number of customers. Similarly, the number based interruption cost is found by the multiplication of SAIFI (System Average Interruption Frequency Index), the cost of average interruption number per customer, and the number of customers. The cost of average interruption duration and number per customer is provided by the local electrical company. Based on the above description, the total cost of interruption is calculated using (2).

$$C_{INTERRUPTION} = W_{SAIDI} \times SAIDI + W_{SAIFI} \times SAIFI \quad (2)$$

$$W_{SAIDI} = NC \times C_{ID} \quad (3)$$

$$W_{SAIFI} = NC \times C_{IN} \quad (4)$$

where W_{SAIDI} and W_{SAIFI} are the reliability weight factors, C_{ID} and C_{IN} are the cost of average interruption number per customer ($/interruption) and the cost of average interruption duration per customer ($/min), respectively. NC is the number of customers served.

The loss cost is expressed in (5). In this, the loss cost has two parts – the energy loss cost which is proportional to the cost per MWh and the peak power cost which is proportional to the cost saving per MW reduction in the peak power.

$$C_{LOSS} = P_{LOSS} \times (k_{PL} + k_L \times 8760 \times lsf) \quad (5)$$

where P_{LOSS} is the loss power, k_{PL} is the saving per MW reduction in the peak power, k_L is the cost per MWh, and lsf is the loss load factor. The constraints include bus voltages and feeder currents. The bus voltage (V_{bus}) should be maintained within the standard level.

$$V_{\min} \le V_{bus} \le V_{\max} \quad (6)$$

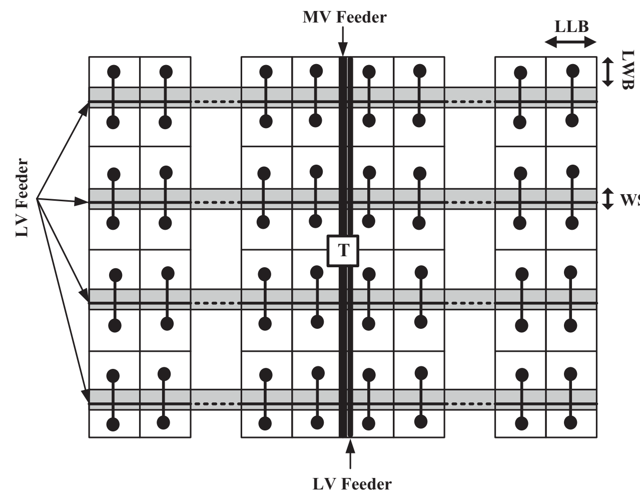

Fig. 1. Typical distribution transformer service area (LV Zone).

The feeder current (I_{fi}) should be less than the feeder rated current (I_{fi}^{rated}) in the ith feeder.

$$I_{fi} \le I_{fi}^{rated} \quad (7)$$

The Static Penalty method is used in this paper to include the constraints. In this method, the constraints are incorporated in the objective function with a penalty factor, called SP, in (1). If all constraints are satisfied, SP will be zero. Otherwise, SP is set as a large number and is added to the objective function to exclude the relevant solution from the search space [20].

3. Methodology

The proposed methodology covers planning both LV and MV networks. For planning distribution systems around a city, typically the electrical load density decreases from downtown towards the rural areas. Given this, the proposed procedure starts by dividing the planning area into the regions with fairly uniform load density: urban, semi-urban, sub-urban, etc. Within each region, the optimization considers LV zones, each of which is supplied by an MV/LV transformer whose rating is determined by the power of loads, located in the corresponding LV zone. As optimizing variables, the dimensions of LV zones along with the placement and rating of MV/LV transformers and the route and type of LV feeders are optimized using the loads' powers and configuration. In the next step, another type of zone, called MV zone, is constituted to supply MV/LV transformers, located in LV zones, using a HV/MV transformer. The dimensions of MV zones along with the placement and rating of HV/MV transformers and the route and type of MV feeders are optimized in this step. These zones are defined in the following sub-sections.

3.1. LV network

In this methodology, each customer is assumed to occupy a rectangular block, called load block, with a specific power demand. The dimensions of these blocks and their power consumption are related to the average load density of the region. Subsequently, a rectangular service area, composed of these load blocks that are supplied by a distribution transformer, is formed. This service area, called the LV zone, is shaped in an arrangement as shown in Fig. 1. In this figure, a distribution transformer "T" supplies several customers. The white blocks are the customers and the grey parts are the streets. The length and the width of each load block are denoted