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Low voltage distribution planning considering micro distributed generation

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ABSTRACT

This paper presents further advances to the low voltage distribution optimization problem by considering micro distributed generation injected by costumers. To this purpose the proposed model presented in [1] has been improved including aspects such as the evaluation of three-phase power losses, system reliability evaluation and mainly the impact of micro distributed generation (micro DG) on the overall process of Low Voltage (LV) network planning. Finally, results are shown on the application of the algorithm on a test and real urban networks.

1. Introduction

Electric power systems are undergoing a profound change driven by a number of requirements. There is the need for environmental compliance, energy efficiency and the consumer role in determining its own level of consumption. Also, an improved grid reliability and costumer quality service is needed by way of augmenting infrastructure as well as operational efficiencies. The changes that are happening are particularly significant for the electrical distribution network, where presently a global tendency exists, known as Distributed Generation (DG) [2], to allow electric energy injection by end-customers, electrical industries or from third parties.

This presents two major advantages. Firstly, it allows an efficient use of energy by the way of using energy surplus from industries connected to the net fostering also non-conventional energy generation, and secondly energy injection close to the load allows an improvement on consumers quality service due to an efficient energy transport [3,4]. The advantages of DG in distribution networks are: it provides base load operating in parallel with the distribution network, it provides energy during peak load, it supports the distribution network, it improves power supply quality eliminating fluctuations, it serves as backup to ensure uninterrupted electricity supply and it is a self-supply using renewable energies [5].

These facts are also worldwide supported [6] by facilitating some regulatory aspects associated to the integration of DG to electric networks. In Chile, in particular, this can be seen on modifications introduced on existing laws [7,8], pointing out incentives and procedures for energy injection on electrical networks.

This reflects the fact that more and more small *power plants*, between 1 kW and 5 kW are used at residential consumer level, based on the available Renewable Energy (RE) sources [9], with micro-generation power plants technologies such as fuel cells, mini hydro (run-of-the-river), small wind turbines, photovoltaic panels or small scale fossil fuel generation [2]. Therefore, the results of the LV networks planning will not only be influenced by equipment and operational costs, but also by the growing importance of reliability and the networks injected micro generated energy [10].

Today, optimization of electric power systems design and operation is necessary. Regarding location, size and quantity of supply for sub-transmission substations for high to medium voltage (HV/MV) the problem is solved mainly by the following methods: Branch and Bound, Heuristic method, Non Linear Programming, Quadratic Mixed Integer Programming, Expert Systems, Genetic Algorithms, Fuzzy Models and Set Techniques, Neural-Tabu Search and Evolutionary Programming, among others [11,12].

On the other hand, articles approaching the design of low voltage networks and siting of medium to low voltage step-down transformers (MV/LV) are few. In [13], a dynamic programming algorithm is proposed and in [14] the same problem is solved using Voronoi's Diagram and Tabu Search. In [1], a genetic algorithm is used to solve this problem optimizing a cost function considering

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investments and operational costs of the electric network with good results.

This article augments and improves the work presented in [1], extending the solution to the question of size, quantity and siting of distribution transformers (DT). More practical aspects, which best represent the current trend of low voltage networks, are included in the model: the effect of micro distributed generation injected by residential consumers, the three-phase losses of the system to consider unbalance of these networks, as well as the effects on system reliability.

2. Problem formulation

Low voltage electric networks are designed for energy supply of mainly residential type loads through distribution transformers (DT). Their quantity, size and location depend on network characteristics, that is, power demand and quantity of loads, geographic distribution, and also the possibility of micro generation by some consumers. These are all elements subject of economic assessment.

In this work as in [1], the set of low voltage loads and micro distributed generation (the geographical location, average power demand and power factor), the future or existing paths, the electrical conductors of the low voltage network and the medium voltage power lines are considered known. From the economic point of view, the location, size and quantity question of DTs can be stated as (1):

Minimize Tc_{PV} subject to technical constraints

$$\begin{aligned} &\text{where } T_{cPV}(C) = I(C) + O_{cPV}(C) \\ &\text{with } C = C(q, l, s),\ q : \{1 \ldots \infty\}, \quad l \in L, s \in S \end{aligned} \tag{1}$$

Tc_{PV}(C) is the total cost at present value, $I(C)$ is the investment and $Oc_{PV}(C)$ is the operational cost at present value, all for a C DT configuration. C is the DT configuration for q DT installed in l positions and s standardized sizes. L and S represent feasible locations and sizes, respectively.

3. Proposed solution

The solution proposed in this paper is based on [1], and incorporates several modifications to improve the results, such as micro DG, three-phase analysis of the problem and a system reliability evaluation through energy not supplied (ENS).

One of the aspects defining the investments and operational costs of this problem is the configuration C and, as such, it is necessary to determine q, l and s. This work, considers that for a given quantity q of DTs, with l locations or sites, the size s of each DT is calculated by a three-phase power load flow considering the assigned load or power injection on the proposed low voltage network. This allows assessing the average demand requirements for the transformer and also to evaluate the technical constraints of the system.

A three-phase load flow was considered so to take into account typical unbalances of low voltage networks. It also considers a factor for the over dimensioning required for the expected demand growth over the period of analysis, together with an overload factor to prevent loss of life do to the peak demand.

The *DT* cost will be established from a database of real values, which considers standard sizes and equipment installation found in the market. Once the *DT* size is determined, the core losses can be assessed and by considering the utilization factor, the corresponding proportion of copper losses may be established. These values will be translated into energy costs at present values. The evaluation of line construction costs is possible considering the proposed low voltage network and the required paths from each *DT* to the MV lines for its supply.

3.1. Investments

In this paper investment are calculated considering the costs of each distribution transformer, including its costs for installation $DTc(C)$, medium voltage line construction $LMVc(C)$ from the original layout to the installation position and finally low voltage lines construction $LLVc(C)$ as in [1]. Eqs. (2–7) allow the previous calculations.

$$I(C) = DTc(C) + LMVc(C) + LLVc(C) \tag{2}$$

$$DTc(C) = \sum_{i=1}^{q} pT_i\{SDT_i\} \tag{3}$$

$$SDT_i = \overline{D_i(kVA)} \cdot k \tag{4}$$

$$k = \frac{(1+g)^T}{f_L \cdot f_{OL}} \tag{5}$$

$$LMVc(C) = L_{MV}(m) \cdot pLMV \tag{6}$$

$$LLVc(C) = L_{LV}(m) \cdot pLLV \tag{7}$$

q, number of installed DTs; SDT_i, selected DT I; pT_i, price of the SDT_i; $\overline{D_i(kVA)}$, average demand in kVA supplied for i DT; K, over sizing factor; f_L, load factor of the systems; f_{OL}, overload factor of the DT; g, annual growth rate of load; T, number of years in the study; $L_{MV}(m)$, length of the MV line in meters; $L_{LV}(m)$, length of the LV line in meters; $pLMV$, MV line construction price in \$/m; $pLLV$, LV line construction price in \$/m.

3.2. Operational costs

The operational costs $Oc_{PV}(C)$ consider the costs of energy loss of low voltage lines $eLLVc(C)$, plus the energy loss of each transformer $eLDTc(C)$ valued at present values for a fixed quantity of years of project plus the energy not supplied cost $ENSc$(C) at present values for a fixed quantity of years of project.

The energy not supplied is a reliability index used to evaluate the expected lost energy due to the unavailability of the system [15]. Generally the cost associated to the ENS is calculated multiplying this value for the price of energy of the systems and a penalty factor that usually is used to compensate the customers. Eqs. (8–12) show these calculations. Maintenance costs have not been considered due to their low economic impact in reduced time projects and low labor involved. If a growing demand over the period of analysis is considered, losses will be roughly determined increasing them proportionally with demand.

$$Oc_{PV}(C) = eLLVc_{PV}(C) + eLDTc_{PV}(C) + ENSc(C) \tag{8}$$

$$eLLVc_{PV}(C) = 8760 \cdot p \cdot \sum_{j=1}^{T} TLLLV(C) \frac{(1+g)^j}{(1+r)^j} \tag{9}$$

$$eLDTc_{PV}(C) = 8760 \cdot \sum_{j=1}^{T} \left(\sum_{i=1}^{q} [Lo_i + Lcu_i \cdot F_u \cdot (1+g)^{2j}] \right) \cdot \frac{1}{(1+r)^j} \tag{10}$$

$$ENSc(C) = Pe \cdot ENS(C) \cdot p \cdot \frac{(1+g)^j}{(1+r)^j} \tag{11}$$