Electrical Power and Energy Systems 106 (2019) 146–157

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A decomposition approach for integrated planning of primary and secondary distribution networks considering distributed generation

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ARTICLE INFO

Keywords:
Bilevel model
Distributed generation
Distribution system planning
Primary and secondary networks
Tabu search algorithm

ABSTRACT

This paper presents a new model for optimal integrated planning of medium and low voltage distribution systems with penetration of distributed generation (DG) in the low voltage network. The proposed bilevel model takes into account in the upper and the lower levels, the medium and low voltage network planning respectively. This approach considers as conflict between these two agents (upper and lower levels), the size and location of the distribution transformers (DT), *i.e.* the incidence in both networks of the power flow circulating from the primary to the secondary system. The main objective of this approach is to find a joint global solution that establishes a balance to benefit the planning of both networks, by decomposing the problem in two subproblems (or levels). The upper and lower levels involve the costs of installing and upgrading the new and existing elements (branches, DT, substations and DG) and the cost of the energy technical losses. This problem is formulated as a mixed integer non-linear model, and is solved using a tabu search algorithm (TSA). To verify the efficiency of the proposed methodology, three cases of study are compared: (i) traditional integrated planning, (ii) bilevel integrated planning and (iii) bilevel integrated planning with DG in the LV network. The obtained results show the importance of considering both networks in a simultaneous way in the electric distribution system planning, which allows finding answers of lower global costs.

1. Introduction

Distribution system planning (DSP) is known as the set of strategies that allow to determine how many, where and when an electric element (or elements) could be installed in the network, in order to satisfy the growing demand in a defined time horizon [1]. Traditionally the DSP has considered the installation of new elements as electrical circuits (medium and low voltage - MV/LV), sources (substations and DTs) and the upgrading of the size of existing elements in both voltage levels [1–21]. Due to the combinatorial nature of the DSP problem (NP-complete), this has been usually solved separately for both voltage levels (primary and secondary), which has reduced the search space of the problem. According to this, several methodologies and different mathematical models have been used in order to solve this problem. However, the number of investigations in this topic is greater on the primary DSP [1–11] than on the secondary DSP [12–17], and a few consider the integrated planning of both networks [18–21].

In the last years, the interest of the electric sector by the connection of DGs and energy storage systems (ESS) in the electrical networks has increased considerably, due to the technical and economic benefits [5,6,8,21–24]. Initially the DGs were used to solve operative problems. Subsequently, due to the great obtained impacts, they were incorporated into the DSP problem. Despite the positive impacts that the DGs present, only a work considers these elements in the integrated planning of primary and secondary networks [21]. The main difference between the works mentioned before and the approach proposed in this research consists on a new bilevel mathematical model, which is used to represent in a simultaneous way the integrated planning of both networks (primary and secondary) by decomposing the problem in two subproblems (or levels). Additionally, penetration of DG in the LV network is considered. It was decided to use DGs in this voltage level, because it was desired to observe the impact of a small-scale penetration given that in countries like Colombia, there are laws that encourage this type of connections to the network.

A bilevel formulation is a hierarchical optimization model that involves two levels (agents) known as upper (leader) and lower

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https://doi.org/10.1016/j.ijepes.2018.09.040
Received 18 October 2017; Received in revised form 14 August 2018; Accepted 24 September 2018

Nomenclature

Parameters

$C_{ij,p}^{EP}$	fixed cost to expand the capacity of an existing primary feeder between nodes i–j, type p ["$"]
$C_{ij,c}^{ES}$	fixed cost to expand the capacity of an existing secondary circuit between nodes i–j, type c ["$"]
$C_{i,s}^{ESS}$	fixed cost to expand the capacity of an existing substation at node i, type s ["$"]
$C_{i,d}^{ND}$	fixed cost of a new DT at node i, type d ["$"]
$C_{i,g}^{NG}$	fixed cost of a new DG at node i, type g ["$"]
$C_{ij,p}^{NP}$	fixed cost of a new primary feeder between nodes i–j, type p ["$"]
$C_{ij,c}^{NS}$	fixed cost of a new secondary circuit between nodes i–j, type c ["$"]
$C_{i,s}^{NSS}$	fixed cost of a new substation at node i, type s ["$"]
$I_{ij,c}^{max}$	maximum current limit of a secondary wire type c [A]
$I_{ij,p}^{max}$	maximum current limit of a primary wire type p [A]
nL	number of levels of the load duration curve
R_{ij}^{p}	resistance of the primary feeder between nodes i–j, type p [Ω]
R_{ij}^{s}	resistance of the secondary circuit between nodes i–j, type s [Ω]
$S_{i,d}^{cu}$	power losses in the copper of a DT at node i, type d
$S_{i,d}^{fe}$	power losses in the iron of a DT at node i, type d
$S_{i,d}^{max}$	maximum power limit of a DT type d [kVA]
$S_{i,g}^{max}$	maximum power limit of a DG type g [kVA]
$S_{i,s}^{max}$	maximum power limit of a substation type s [MVA]
$S_{i,l}^{SD}$	secondary demand at node i, for a load level l [kVA]
V_{i}^{max}	maximum voltage limit at node i [kV]
V_{i-abcn}^{max}	maximum voltage limit at secondary node i, on phases a, b, c, and neutral [kV]
V_{i}^{min}	minimum voltage limit at node i [kV]
V_{i-abcn}^{min}	minimum voltage limit at secondary node i, on phases a, b, c, and neutral [kV]

Variables

$\sigma_{ij,p}^{EP}$	binary decision variable to expand the capacity of an existing primary feeder between nodes i–j, type p
$\sigma_{ij,c}^{ES}$	binary decision variable to expand the capacity of an existing secondary circuit between nodes i–j, type c
$\sigma_{i,s}^{ESS}$	binary decision variable to expand the capacity of an existing substation at node i, type s
$\sigma_{i,d}^{ND}$	binary decision variable to install a new DT at node i, type d
$\sigma_{i,g}^{NG}$	binary decision variable to install a new DG at node i, type g
$\sigma_{ij,p}^{NP}$	binary decision variable to install a new primary feeder between nodes i–j, type p
$\sigma_{ij,c}^{NS}$	binary decision variable to install a new secondary circuit between nodes i–j, type c
$\sigma_{i,s}^{NSS}$	binary decision variable to install a new substation at node i, type s
$I_{ij,l}$	current flow on primary branch i–j, for a load level l [A]
$I_{ij,l}^{abcn}$	current flow on secondary branch i–j, on phases a, b, c, and neutral, for a load level l [A]
$S_{i,l}^{DT}$	power injected to a DT at node i, for a load level l [kVA]
$S_{i,l}^{G}$	power injected by a DG at node i, for a load level l [kVA]
$S_{i,l}^{S}$	power injected by a substation at node i, for a load level l [MVA]
$V_{i,l}$	bus voltage at primary node i, for a load level l [kV]
$V_{i,l}^{abcn}$	bus voltage at secondary node i, on phases a, b, c, and neutral, for a load level l [kV]

Sets

Ω_{DT}	set of new and existing DT
Ω_{EP}	set of existing primary feeders
Ω_{ES}	set of existing secondary circuits
Ω_{ESS}	set of existing substations
Ω_{ip}	set of nodes connected with node i of primary network
Ω_{is}	set of nodes connected with node i of secondary circuit
Ω_{ND}	set of new DT
Ω_{NG}	set of new DG
Ω_{NL}	set of the number of levels of the load duration curve
Ω_{NP}	set of new primary feeders
Ω_{NS}	set of new secondary circuits
Ω_{NSS}	set of new substations
Ω_{PF}	set of new and existing primary feeders
Ω_{PN}	set of nodes of primary networks
Ω_{SC}	set of new and existing secondary circuits
Ω_{SN}	set of nodes of secondary circuits
Ω_{SS}	set of new and existing substations
Ω_{TD}	set of types of DT
Ω_{TG}	set of types of DG
Ω_{TP}	set of types of primary feeders
Ω_{TS}	set of types of secondary circuits
Ω_{TSS}	set of types of substations.

(follower). In this kind of problem, each level is an optimization model composed by an objective function and its respective set of constrains. One of its main characteristics is the conflict between these two agents, where the decisions of one affect the decisions of the other [25]. In the proposed methodology in this work, the upper level is the planning of medium voltage distribution system (leader) and the lower level is the planning of the low voltage distribution system (follower). Generally, the distribution networks of the medium and low voltage belong to the same owner, and it is possible to think that there is no conflict between the participating agents (actually only one agent). However, the conflict in this work is treated according to the location and dimensioning of the DT, which affects the power flows that circulate from the MV to the LV network. This situation is reflected in the technical and economic aspects in the planning of both systems.

A suitable location of a DT for a secondary network may be inappropriate for the medium voltage network, causing an inadequate sizing of their electric elements. On the other hand, the location of the DT (from the point of view of the MV system), can affect the technical losses at the LV network, which would increase the costs of the project. Similarly, the size of DT impacts directly the technical aspects of both networks. A nominal value of a DT, imposes technical requirements in the low voltage network in order to comply aspects of voltage regulation and low technical losses. To avoid these situations, the bilevel model proposed considers the interaction of the two networks in a simultaneous way, allowing to find a joint global solution that guarantees an equilibrium in the planning between the two networks.

In a bilevel optimization model, the leader realizes a first movement anticipating the decision of the follower [25–30]. After that, the follower takes a decision based on the movement of the leader. In Fig. 1, the movements employed in this work between both levels are observed. In this figure, the leader (primary DSP) proposes a location and size for the DT ($S_{i,d}^{max}$) and the follower (secondary DSP) reacts to this strategy. In other words, the secondary network is planned using the movement of the leader, which causes different values of the required power to feed the LV load. Once the optimization problem of the LV is solved, the follower returns to the leader the power quantity used for