Applied Energy 188 (2017) 140–150

Contents lists available at ScienceDirect

Applied Energy

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

Optimal location and capacity planning for distributed generation with independent power production and self-generation

Lesiba Mokgonyana [a], Jiangfeng Zhang [b,*], Hailong Li [c], Yihua Hu [d]

[a] Department of Electronic and Electrical Engineering, University of Strathclyde, UK
[b] School of Electrical, Mechanical and Mechatronic Systems, University of Technology Sydney, Australia
[c] School of Business, Society and Engineering, Mälardalen University, Sweden
[d] Department of Electrical Engineering and Electronics, University of Liverpool, UK

HIGHLIGHTS

- A distributed generation location and capacity optimal planning model is proposed.
- Independent power production (IPP) and self-generation (SG) are studied.
- A profit increase of up to 23.7% can be achieved under the new model.

ARTICLE INFO

Article history:
Received 28 August 2016
Received in revised form 8 November 2016
Accepted 29 November 2016

Keywords:
Distribution company
Distributed generation
Distribution network
Profit maximization
Quota obligation

ABSTRACT

This paper proposes a planning model for power distribution companies (DISCOs) to maximize profit. The model determines optimal network location and capacity for renewable energy source, which are categorized as independent power production (IPP) and self-generation (SG). IPP refers to generators owned by third-party investors and linked to a quota obligation mechanism. SG encompasses smaller generators, supported by feed-in tariffs, that produce energy for local consumption, exporting any surplus generation to the distribution network. The obtained optimal planning model is able to evaluate network capacity to maximize profit when the DISCO is obliged to provide network access to SG and IPP. Distinct parts of the objective function, owing to the definition of SG, are revenue erosion, recovery as well as the cost of excess energy. Together with the quota mechanism for IPP, the combination of all profit components creates a connection trade-off between IPP and SG for networks with limited capacity. The effectiveness of the model is tested on 33- and 69-bus test distribution systems and compared to standard models that maximize generation capacity with predefined capacity diffusion. Simulation results demonstrate the model outperforms the standard models in satisfying the following binding constraints: minimum IPP capacity and SG net energy. It is further revealed that integrating SG and IPP with the proposed model increases profit by up to 23.7%, adding an improvement of 8% over a feasible standard model.

1. Introduction

Policy makers around the world are implementing measures to accelerate the connection of renewable energy sources (RESs) in order to meet low carbon or sustainability objectives. As such, the number of countries that have some form of target setting for utilizing renewable energy has reached 164 as of 2015 [1]. Furthermore, 59 jurisdictions have targets that are legally binding. However, with increasing commitment comes concerns over the promotion of RESs. For example, distribution companies (DISCOs) risk losing profits while customers bear the cost of the related support schemes. Therefore, cost effective planning considering the locations and capacities of renewable distributed generation (DG) connections is necessary to deal with these key challenges.

There are plenty of studies on the grid connection of new DG. Approaches described in [2–6], determine locations and sizes of DG units to optimize savings arising from deferral of network upgrades, losses, reliability, and other technical objectives. It is found in [7,8] that there are additional financial benefits of DG connection in the form of use-of-system charges, capacity and loss reduction incentives overseen by regulators.

* Corresponding author.
E-mail addresses: lesiba.mokgonyana@strath.ac.uk (L. Mokgonyana), jiangfeng.zhang@uts.edu.au (J. Zhang), hailong.li@mdh.se (H. Li), y.hu35@liverpool.ac.uk (Y. Hu).

http://dx.doi.org/10.1016/j.apenergy.2016.11.125
0306-2619/

DG planning is carried out in diverse contexts [9–14]. In [9] the profit of a DISCO is maximized by strategic sizing and placement of third-party DG while maintaining project viability. This approach is in line with many instances whereby the DISCO coordinates generation by other producers [15,16]. The models proposed in [10,11] minimize the cost of power purchased from generation companies (GENCOs), capital and operating costs of DG units owned by the DISCO, and the costs of network operation and unserved power. In [12], the objective is to maximize social welfare among DISCOs and GENCOs, and to maximize profit for the DG owner. The interaction between a DG owner and DISCO can also be treated as a bi-level problem whereby the DG owners profits are maximized first, followed second by the DISCOs cost of energy [13]. The work presented in [14] models the role of a central planning authority aiming to encourage GENCOs and local DISCOs achieve predefined targets for RESs. The resulting incentives ensure viability of a mix of various technology investments.

While the benefits of DG in distribution systems have been widely studied, there is a lack of focus on the implications of renewable energy policies from the DISCO's perspective concerning independent DG units. The formulation in [17] considers capacity expansion planning in the presence of renewable portfolio standards and carbon tax mechanisms. Another study investigates the impact of the aforementioned mechanisms plus feed-in tariffs (FiTs) and emission trading on expansion planning [18]. Although these models take environmental policies into account, they are solved from the perspective of a GENCO. The impact of FiTs, carbon tax and cap-and-trade mechanisms on DG investments by DISCOs and independent investors is studied in [19], with the objective being to maximize the profit from the sale of energy.

In practical settings, DG is categorized as independent power production (IPP) or self-generation (SG) [16]. IPP accounts for relatively large DG units that solely produce electricity, whereas SG represents existing customers seeking to invest in DG, with some energy being consumed on-site. IPP is promoted through a quota obligation scheme [20,21]. The scheme requires that DISCOs supply a portion of their total load with RESs or make an alternative payment to a regulatory body. SG is typically supported by FiT incentive schemes. These schemes offer investors certainty through purchase of power at fixed rates and guaranteed payments over long periods [20,22]. The import and export variability of SG causes changes in revenue from energy sales, whereby revenue erosion is mitigated in several ways including revenue decoupling and lost revenue adjustment mechanisms [23–26]. That means DISCOs recoup the revenue lost due to SG integration from ratepayers. Hence, by promoting DG capacity and locations that maximize profit, the cost carried by ratepayers will be reduced. Under these circumstances, there are financial implications regarding any action the DISCO takes with respect to renewable DG integration. It is therefore crucial to distinguish between IPP and SG.

None of the referenced studies prescribes a model that considers binding RES quotas, the combined network impact of IPP and SG, and the cost and revenue implications for the DISCO in the context of DG location and capacity planning. Therefore, this paper incorporates both IPP and SG to develop an optimization model through which the DISCO enables network access for third-party DG, and responds strategically to renewable energy policy. Given RES quota, network and DG-specific constraints, the model presented herein determines locations and capacities that are allocated to SG and IPP such that the profit of the DISCO is maximized. Distinctly, the objective function encompasses a financial penalty for non-compliance, which varies mainly with IPP deployment, revenue erosion, a cost recovery mechanism for the lost revenue, and cost of energy exported from SG locations. The proposed model is validated on 33- and 69-bus test distribution systems, and compared to standard approaches for maximizing overall DG capacity. Simulation results show there is a trade-off between SG and IPP integration, and that the proposed model provides advantages over standard approaches in terms of profit maximization and DG constraint satisfaction. In fact, the DISCO will achieve an increase of 23.7% in profits in the presence of constrained SG (net energy) and IPP (minimum capacity). This is an improvement of 8% over the standard approaches. Furthermore, the impact of each of the following parameters is analyzed: renewable energy quota, SG net energy limit, revenue recovery rate, energy export rate, and minimum IPP capacity.

The next section provides a description and mathematical model of a DISCO interested in profit maximization in an policy environment promoting RESs integration. Section 3 describes case studies involving 33-bus and 69-bus test distribution systems. Results and analyses are presented in Section 4. Section 5 presents conclusions that are drawn from the study.

2. DG location and capacity planning optimization model

This section presents an optimization model for DG location and capacity planning in terms of IPP and SG.

2.1. Notation

The notation defined below is employed for parameters and variables in the optimization model.

Sets and indices

d,j	bus indices
D	set consisting of all buses in the system
I	set consisting of all candidate IPP buses in the system
i	candidate IPP bus index
k	candidate SG bus index
K	set consisting of all candidate SG buses in the system
t	time interval index
τ	sampling interval of one hour
T	set consisting of all time intervals over the evaluation period

Parameters

C^{e}	wholesale price of electricity (£/MW h)
C^{r}	retail price of electricity (£/MW h)
r^{o}	independent power production quota to be met by DISCO (%)
C^{b}	penalty rate for obligation non-compliance (£/MW h)
C^{rv}	revenue recovery rate (£/MW h)
C^{ee}	DISCO energy export rate (£/MW h)
a_L	total allowed energy generation percentage for SG (%)
$G^{max}_{SG,k}$	maximum allowable capacity for self-generation
$G^{max}_{IPP,i}$	maximum allowable capacity for independent power production
$G^{min}_{IPP,i}$	minimum allowable capacity for independent power production
$S^{max}_{d,j}$	apparent power limit of component between bus d and bus j
$P^{t}_{SGL,k}$	active power demand associated with kth SG and tth time interval (MW)
$P^{t}_{L,d}$	active power demand at dth bus and tth time interval (MW)
$Q^{t}_{L,d}$	reactive power demand at dth bus and tth time interval (MVAr)
G^{t}_{dj}	real part of admittance element between bus d and bus j (mho)
B^{t}_{dj}	imaginary part of admittance element between bus d and bus j (mho)