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Active distribution networks planning with high penetration of wind power

Geev Mokryani*, Yim Fun Hu, Prashant Pillai, Haile-Selassie Rajamani

School of Electrical Engineering and Computer Science, University of Bradford, Bradford BD7 1 DP, UK

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ABSTRACT

In this paper, a stochastic method for active distribution networks planning within a distribution market environment considering multi-configuration of wind turbines is proposed. Multi-configuration multi-scenario market-based optimal power flow is used to maximize the social welfare considering uncertainties related to wind speed and load demand and different operational status of wind turbines (multiple-wind turbine configurations). Scenario-based approach is used to model the abovementioned uncertainties. The method evaluates the impact of multiple-wind turbine configurations and active network management schemes on the amount of wind power that can be injected into the grid, the distribution locational marginal prices throughout the network and on the social welfare. The effectiveness of the proposed method is demonstrated with 16-bus UK generic distribution system. It was shown that multi-wind turbine configurations under active network management schemes, including coordinated voltage control and adaptive power factor control, can increase the amount of wind power that can be injected into the grid; therefore, the distribution locational marginal prices reduce throughout the network significantly.

1. Introduction

1.1. Motivation and approach

The connection of large amounts of renewable energy sources (RES) to distribution networks introduces many technical and economic challenges to distribution network operators (DNOs). Therefore, DNOs have to develop a rational operating strategy taking into account dispatching distributed generators (DGs), interrupting loads, and purchasing power from the wholesale market while keeping the system security. DNOs, in some cases, play the retailers role which buy power on the wholesale market at volatile prices and sell it again at fixed tariffs to small consumers. DNOs and retailers are separate market entities with different purposes, networks, and sizes [1]. However, assuming that the objective of DNOs is to maximize their benefits, two different regulatory cases can be taken into account: 1) DG-owning DNO – allowed to own DG and can exploit the financial benefits brought by considering new generation as an option for the investment in distribution network, 2) Unbundled DNO – forbidden from DG ownership but can maximize benefits based on a number of incentives. European Directive 2003/54/EC defines the technical and legal existing restrictions among different market actors of European electricity markets. In particular, it forms the unbundling regulations that DNOs have to be unbundled from generation interests, thus, forbidding DNOs from DG ownership. It splits the electricity distribution from retail supply where distribution utilities are not responsible to sell power to customers [2,3]. By introducing DGs in distribution systems, the planning for investment in distribution networks to meet the future load growth and its related infrastructures can be deferred [4]. On the other hand, emerging active network management (ANM) schemes have proved to be advantageous for DNOs, compared to passive network management [5]. ANM schemes can increase the operation of the assets of network that allow the distribution networks to accommodate more DGs within the existing infrastructure and therefore, defer or avoid expensive network upgrades. The main ANM schemes include coordinated voltage control (CVC) of on load tap changers (OLTCs) and voltage regulators, adaptive power factor control (PFC) of DGs and energy curtailment [5–7].

This paper provides a novel approach for DNOs to evaluate the

* Corresponding author.
E-mail addresses: g.mokryani@bradford.ac.uk (G. Mokryani), y.f.hu@bradford.ac.uk (Y.F. Hu), p.pillai@bradford.ac.uk (P. Pillai), h.s.rajamani@bradford.ac.uk (H.-S. Rajamani).

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Nomenclature

Sets and indices

i,j	Index of system buses running from 1 to NB
w	Index of wind turbine
G	Index of substation
D	Index of loads
t	Index of energy block offered by wind turbines running from 1 to NT
q	Index of energy bids submitted by loads running from 1 to NQ
s	Index of scenarios running from 1 to NS
c	Index of configurations running from 1 to NC
y	Index of years running from 1 to NY

Variables

$(P/Q)^{w}_{i,t,s,c,y}$	Active/reactive power generated by wind turbines at bus i, block t, scenario s, configuration c and year y in MW/MVAr
$(P/Q)^{G}_{i,t,c,y}$	Active/reactive power at substation, block t, configuration c and year y in MW/MVAr
$V_{i,s,c,y}/\delta_{i,s,c,y}$	Voltage/voltage angle at bus i, scenario s, configuration c and year y in Volt/Radian
$\phi^{w}_{i,s,c,y}$	Power factor angle of WTs at bus i, scenario s, configuration c and year y in radian
T_{ij}	Tap magnitude of OLTC

Parameters

α	Load growth rate
β	Operational status of each WT
$\beta_{i,c}$	Operational status of WTs at bus i and configuration c
c	Scale coefficient
v	Wind speed in m/s
v_m	Mean value of wind speed in m/s
v_{ci}/v_{co}	Cut-in/cut-off wind speed in m/s
v_r	Rated wind speed in m/s
π_s	Probability of state s
$(P/Q)^{D}_{i,q,s,y}$	Active/reactive consumption of loads at bus i, block q, scenario s, configuration c and year y in MW/MVAr
$V^{\min}_i/V^{\max}_i$	Min/max voltage at each bus in Volt
$\delta^{\min}_i/\delta^{\max}_i$	Min/max voltage angle at each bus
$Q^{w,\min}_i/Q^{w,\max}_i$	Min/max reactive of WTs at bus in MVAr
$P^{w}_{i,rated}$	WTs rated active power in MW
$\gamma^{w}_{i,s,c}$	Percentage of active power generated by WTs at scenario s and configuration c
$P^{G,\min}_i/P^{G,\max}_i$	Min/max active power at substation in MW
$Q^{G,\min}_i/Q^{G,\max}_i$	Min/max reactive power at substation in MVAr
$C^{D}_{i,q}$	Price for the energy bid q at bus i submitted by load D in £/MWh
$C^{w}_{i,t}$	Price for the energy selling t at bus i by WT w in £/MWh
$C^{G}_{i,t}$	Price for the energy selling t at substation in £/MWh
G_{ij}/B_{ij}	Real/imaginary part of the element in the admittance matrix corresponding to the ith row and jth column in mho
$I^{\max}_{ij}$	Maximum current flow of wires in A

amount of wind power that can be injected into the distribution network over the planning horizon considering: 1) capability curve of doubly fed induction generator (DFIG)-based wind turbines (WTs), 2) uncertainties related to the stochastic variations of wind power generation and load demand, 3) multiple-WT configurations and 4) ANM schemes including CVC and PFC. The method also characterizes the impact of the abovementioned factors on the distribution-locational marginal prices (D-LMPs). Multi-configuration multi-scenario market-based optimal power flow (MMMOPF) is utilized to maximize the social welfare (SW) considering abovementioned uncertainties. A distribution market model, called the DNO acquisition market, is presented here under a distribution market structure based on pool and bilateral contracts within DNO's control area. It is assumed that WTs and loads are owned or managed by the DG-owning DNO [8]. Here, the DNO is defined as the market operator of the DNO acquisition market, which determines the price estimation and the optimization process for the hourly acquisition of active power [9].

1.2. Literature review

Lots of studies have been reported on the benefits of ANM and its applications. Some of them revealed implementations, and experiences of ANM [10,11], online ANM application [12,13], and ANM challenges for network operators [14]. The cost-benefit analysis of investments and operation costs for various combinations of ANM schemes and techno-economic evaluation are studied in Refs. [15–17] and compared with passive network management scheme. Generally, it is found that as the DG penetration increases, the investment costs of ANM schemes become more viable and justifiable. Also, several works have been carried out about the planning and operation of distribution networks with integration of DGs [18,19]. In Ref. [18], the authors proposed a cost based model to allocate DGs in distribution networks to minimize DG investment and total operation costs. In Ref. [19], a method for optimal placement of WTs in distribution networks to minimize annual energy losses has been proposed. However, these studies also did not consider the distribution market environment as well as the effect of multi DG-configurations which considerably impact the allocations and amount of connected DG capacity.

1.3. Contributions

The gap that this paper tries to fill is how the combination of multi-WT configurations and ANM schemes can impact on the total dispatched energy of WTs and D-LMPs within a distribution market environment. To the best of the authors' knowledge, no stochastic method for the planning of active distribution networks within a distribution market environment considering multiple-WT configurations and capability curve of DFIG-based WTs and ANM schemes has been reported in the literature. The dynamic nature of the power system operation has not been taken into account in the conventional planning studies with integration of DGs. For example, in Refs. [5–7] and [20–22], the authors have not addressed the impact on the overall DG penetration level when one or more existing DGs are absent. Moreover, the presence of a distribution market environment has not been addressed in the abovementioned studies. One of the innovative contributions of this paper is proposing a novel MMMOPF-based planning approach which considers the operational status of WTs at the planning stage, and assesses the dispatched energy of WTs considering various multi-configurations within the DNO market environment which has not been addressed so far. It also provides detailed analysis and results on how multiple-WT configurations and ANM