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Maximizing hosting capacity of renewable energy sources in distribution networks: A multi-objective and scenario-based approach

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ABSTRACT

Due to the development of renewable energy sources (RESs), maximization of hosting capacity (HC) of RESs has gained significant interest in the existing and future power systems. HC maximization should be performed considering various technical constraints like power flow equations, limits on the distribution feeders' voltages and currents, as well as economic constraints such as the cost of energy procurement from the upstream network and power generation by RESs. RESs are volatile and uncertain in nature. Thus, it is necessary to handle their inherent uncertainties in the HC maximization problem. Wind power is now the fastest growing RESs around the world. Hence, in this paper a stochastic multi-objective optimization model is proposed to maximize the distribution network's HC for wind power and minimize the energy procurement costs in a wind integrated power system. The following objective functions are considered: 1) Cost of the purchased energy from upstream network (to be minimized) and 2) Operation and maintenance cost of wind farms. The proposed model is examined on a standard radial 69 bus distribution feeder and a practical 152 bus distribution system. The numerical results substantiate that the proposed model is an effective tool for distribution network operators (DNOs) to consider both technical and economic aspects of distribution network's HC for RESs.

1. Introduction

Distribution networks have been developed under vertically integrated patterns with little or no generation units installed in medium and low voltage levels. Calculation of distribution networks' hosting capacity (HC) for renewable energy sources (RESs) is an effective tool to determine the most suitable locations and capacities for the installation of RESs. Hence, the investments will be guided toward the critical and most effective nodes of the grid.

Beneficial integration of RESs into distribution networks, as well as large-scale renewable power injection into transmission systems impose considerable challenges to the existing methods for power system planning and operation. Wind power is the fastest growing and popular form of RESs [1], which has gained the attention of researchers around the world in recent years. The wind power HC of a distribution network is limited by power quality and reliability concerns.

Distribution network operator (DNO) and RES owners (RESO) may not have the same strategies or benefits, which would result in the conflict of interests between DNO and RESO. For example, DNO is interested to attract more wind power generation capacity in his/her network under control, which leads RESO to sell more energy and DNO to receive more connection fees. However, this issue may increase energy losses, which is undesirable for DNO.

In this paper, the aims of both DNO and RESO are considered simultaneously through a multi-objective optimization framework. Thus, this work focuses on maximizing HC in distribution networks as well as minimizing the production cost of RESs. A mid-term horizon (i.e. a one year period) is considered which explores how a distribution network should be operated and how much capacity of wind turbines should be optimally installed in order to attract more wind power generation capacity without deteriorating the network efficiency and operational constraints.

1.1. Literature review

Various studies have been carried out for optimal sizing and sitting of wind power or generally RESs. Optimal power flow (OPF)-based approaches are proposed to determine the available HC for DGs [2] and wind power [3] in distribution networks. Genetic

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Nomenclature

Sets

NB	Set of system buses
NB_b	Set of buses connected to bus b
NB_w	Set of buses for wind turbines installation
NS	Set of all possible scenarios
NO	Set of objective functions in the multi-objective optimization problem
NB_{PQ}	Set of system PQ buses

Indices

K	Index of objective functions
b	Index of bus numbers
s	Index of scenario numbers
ℓ	Index of transmission lines
Sl	Index of slack bus

Parameters

π_s	Probability of scenario s
π_d	Probability of demand scenario d
π_w	Probability of wind power generation scenario w
$Y_{bj}\angle\gamma_{bj}$	Magnitude/angle of the bj-th element of Y_{BUS} matrix (pu/radian)
$P_b^{G,\min}/P_b^{G,\max}$	Minimum/maximum limits of active power in slack bus
$Q_b^{G,\min}/Q_b^{G,\max}$	Minimum/maximum limits of reactive power of slack bus at bus b
$P_{b,s}^D$	Expected real power load of b-th bus in scenario s
$Q_{b,s}^D$	Expected reactive power load of b-th bus in scenario s
$V_b^{\min}/V_b^{\max}$	Minimum/maximum limits of voltage magnitude at b-th bus
$S_\ell^{\max}$	Maximum transfer capacity of line ℓ
v	Wind speed in m/s
v_{in}^c/v_{out}^c	Cut-in/out speed of wind turbine in m/s
v_{rated}	Rated speed of wind turbine in m/s
P_w^{avl}	Available wind power generation
$I_b^{W,\min}/I_b^{W,\max}$	Minimum/maximum number of wind turbines connected to node b
$\cos(\varphi_{lag,b})/\cos(\varphi_{lead,b})$	Lag/lead power factor limits of the wind farms located at node b
$\underline{\alpha}_b^W$	Lower limit coefficient of reactive power generation by a wind farm
$\overline{\alpha}_b^W$	Upper limit coefficient of reactive power generation by a wind farm
ζ_b^W	Percentage of wind power rated capacity realized in scenario s at bus b
Λ_b^W	Rated capacity of the wind farm installed at bus b
λ_b^W	Operation and maintenance (O&M) cost of the wind farm connected to bus b
λ_b^P	Cost of purchased energy from upstream network

Variables

$V_{b,s}$	Voltage magnitude of bus b in scenario s
$\theta_{b,s}$	Voltage angle of bus b in scenario s
$S_{\ell,s}$	Power flow of ℓ-th branch in scenario s
$P_{b,s}^G$	Active power production of slack bus in scenario s
$P_{b,s}^W/Q_{b,s}^W$	Active/reactive power produced by wind farm in scenario s
$Q_{b,s}^G$	Reactive power production of slack bus in scenario s
I_b^W	Hosting capacity step (number of wind turbines) at bus b
F_k	Individual value of the k-th conflicting objective function
$\overline{F}_k$	Normalized value of the k-th objective function

Functions

EPC	Expected purchased energy cost from upstream network ($/MWh)
$EPC^{\min}/EPC^{\max}$	Minimum/maximum value for EPC ($/MWh)
EWC	Expected operation and maintenance cost of wind farm ($/MWh)
$EWC^{\min}/EWC^{\max}$	Minimum/maximum value of EWC ($/MWh)

algorithm (GA) [4], as well as combined OPF and GA [3], have been used to optimal allocation of RESs in distribution networks. In Ref. [5], a multi-period OPF approach was developed which utilizes active network management (ANM) design in static/dynamic reconfigurations. The proposed approach aims to find the optimal location and maximize the size of RES (especially wind power generation) under thermal and voltage constraints in a distribution network.

In addition, active/reactive management strategies (AMSs/RMSs) such as wind power curtailment (with limiting overcurrent or overvoltage) [5–8], reactive power compensation [7,8], voltage control using interconnected on load tap changers [5,7], or even control of wind turbines' power factor (PF) [5] are utilized to maximize the HC of distributed generations (DGs) or wind farms in distribution systems. In Ref. [8], curtailment option was used to allow for more wind or solar power capacity to be connected to a distribution network when an overcurrent or an overvoltage occurred. In this regard, the concepts of “hard curtailment” and “soft curtailment” were introduced.

These AMSs are incorporated into optimization problems for satisfying special objectives. For example, in Ref. [7], the objectives are to maximize the net benefits of DNO and RESO, or in Ref. [5], the overall capacity of DGs was maximized under technical and environmental constraints that could be hosted by the distribution system. In Ref. [9], a procedure was presented for HC assessment considering harmonic distortions on transmission and distribution systems.

Limitations of local HC due to the constraints such as steady-state bus voltage were investigated in Ref. [10] by applying the proposed approach on the real Spanish transmission system. Accurate dimensioning of battery energy storage systems (BESS) and quantifying the grid limitations were proposed in Ref. [11]. In Ref. [12], the technical and economic benefits of various strategies to increase the HC of a low voltage grid in Germany for photovoltaic (PV) generation were studied. The results of these strategies were compared with those of two conventional approaches, i.e. traditional grid reinforcement and control of distribution transformer equipped with OLTC. In Ref. [13], a methodology was proposed for determination of maximum DG capacity in radial low-voltage feeders. The introduced approach determines the maximum DG capacity that could be installed at a fixed point in the feeder for which the voltage is kept within a safe band in critical scenarios such as low load/high power generation scenarios. In Ref. [14], a decentralized scheme was proposed for voltage control in distribution networks, which aimed to maximize the DGs' active power production and avoid their disconnection due to the violation of