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Optimal siting and sizing of distributed generation in distribution systems with PV solar farm utilized as STATCOM (PV-STATCOM)

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HIGHLIGHTS

- PV-STATCOM is originally considered in DGs' optimal siting and sizing problems.
- WVSAI is firstly used to quantify PV-STATCOMs' fast voltage support ability.
- A modified DGs' optimal siting and sizing model is proposed.
- An exact SOCP relaxation is utilized to process the proposed model.

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ABSTRACT

According to the recently proposed concept of PV-STATCOM that utilizes photovoltaic (PV) inverter as STATCOM, PV solar farm plays an increasingly important role in providing fast reactive power compensation, especially during the voltage recovery processes under voltage sag or post-fault conditions. To relieve the enormous economic losses caused by the inefficiency in voltage recovery scenario, the reactive power fast response characteristic of PV should be adequately considered in optimal siting and sizing of distributed generation. In this paper, a weighted voltage support ability index (WVSAI) based on sensitivity analysis has been firstly used to quantify the influence of PV-STATCOM on voltage recovery efficiency under voltage sag or post-fault conditions. With the WVSAI added to traditional distributed generator (DG) planning constraints, a modified optimal siting and sizing model is proposed for the targets of minimizing the total annual cost associated with the DGs to be planned. The proposed model is classified into the type of mixed integer nonlinear programming (MINLP) and then relaxed by second order cone programming (SOCP). After relaxation, commercial solver CPLEX through YALMIP platform is used to solve the relaxed model. The proposed model has been applied in IEEE 33-bus distribution system under scenarios with different WVSAI restrictions. Based on the optimal solutions of DGs' siting and sizing, PSCAD simulation tool is used to emulate voltage recovery processes of a specific sensitive load under voltage sag, and thus demonstrates the feasibility and effectiveness of the proposed model.

1. Introduction

With the worldwide exhaustion of fossil fuels and deregulation of power industry, the integration technology of distributed generator (DG) has attracted rapidly increased attention during the past decade. As a complement to centralized generation, the employment of DGs has many positive effects on power systems, especially on distribution systems with long power-supply distance and weak network structure, such as shifting the peak loads, reducing the network losses, improving the voltage profiles, enhancing the system reliability and so on [1–4]. However, these positive effects largely depend on the optimal deployment of DGs. Inappropriate siting and sizing of DGs always lead to a low utilization of DG investment. In extremes, system indices could be even worse after DG integration. Therefore, with the rapid growth of DG penetration in distribution systems, researches on the optimal siting and sizing of DGs have great significance.

The optimal siting and sizing of DGs in distribution systems have been investigated in the literatures from different perspectives. Firstly, viewed from the DG modeling methods, most researches regard dispatchable DGs (e.g. micro-turbines, biomass and fuel cells) as firm

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Nomenclature

Sets

Ω_N set of buses in the distribution system
Ω_L set of branches in the distribution system
Ω_{PQ} set of PQ buses
Ω_I set of PV-STATCOM installation buses
Ω_C set of PV-STATCOM candidate buses
Ω_{SE} set of sensitive load buses
$u(i)/u(j)$ set of downstream buses connected with bus i/j
$v(j)$ set of upstream buses connected with bus j

Parameters

s_{max} upper bound of solar irradiance at a given time (kW/m^2)
μ_g mean of the historical solar irradiance data for time segment g
σ_g standard deviation of the historical solar irradiance data for time segment g
N number of solar irradiance states corresponding to each time segment
$s_{k\text{-max}}/s_{k\text{-min}}$ upper/lower bound of solar irradiance state k (kW/m^2)
s_{rated} PV's rated solar irradiance (kW/m^2)
$P_{s\text{-rated}}$ PV's rated active power output (kW)
S_{rated} rated capacity of the installed PV inverter (kVA)
d discount rate
y_{PV}/y_{MT} economic life of PV/MT (year)
N_{bus} number of buses in the distribution system
c_{PV}^I/c_{MT}^I per-unit capacity investment cost of PV/MT ($/kW)
$c_{PV}^{O\&M}/c_{MT}^{O\&M}$ per-unit O&M cost of PV/MT ($/kWh)
Δt span of each time segment (h)
c_{MT}^F per-unit fuel cost of MT ($/kWh)
c_{em} tax cost of per-unit CO_2 emission ($/g)
ρ_{em} CO_2 emission caused by per-unit power generation (g/kWh)
c^L per-unit cost of network losses ($/kWh)
R_{ij}/X_{ij} resistance/reactance of branch from i to j (kΩ)
U_{min}/U_{max} permitted minimum/maximum limit of voltage magnitude (kV)
$I_{ij,max}$ upper limit of branch current from i to j (A)
$S_{PV}^{unit}/S_{MT}^{unit}$ available unit capacity of PV/MT to be installed (kW)
$pf_{PV,min}$ permitted minimum limit of PV's power factor
$WVSAI^{ref}$ reference value of WVSAI
p^{ref} reference value of PV penetration
$P_{load,i}$ annual peak load at bus i (kW)

Variables

s solar irradiance (kW/m^2)
α, β shape parameters of Beta distribution
$prob(S_k)$ probability that solar irradiance falls in state k
P_s/Q_s PV's active/reactive power output under solar irradiance s (kW/kVar)
C^I DGs' annualized investment cost ($)
$C_{t,k}^{O\&M}$ DGs' O&M cost corresponding to state k in time segment t ($)
$C_{t,k}^F$ DGs' fuel cost corresponding to state k in time segment t ($)
$C_{t,k}^C$ DGs' CO_2 emission cost corresponding to state k in time segment t ($)
$C_{t,k}^L$ network losses cost corresponding to state k in time segment t ($)
$prob(S_{t,k})$ probability that solar irradiance of time segment t falls in state k
R_{PV}, R_{MT} auxiliary variable in calculation of C^I
$S_{PV,i}^{rated}/S_{MT,i}^{rated}$ installed capacity of PV/MT at bus i (kW)
$P_{PV,i}/P_{MT,i}$ active power output of PV/MT at bus i under the designated state (kW)
I_{ij} branch current from i to j under the designated state (A)
P_{ij}/Q_{ij} active/reactive power in branch from i to j under the designated state (kW/kVar)
U_i voltage magnitude at bus i under the designated state (kV)
P_j/Q_j equivalent active/reactive power demand at bus j under the designated state (kW/kVar)
$N_{PV,i}/N_{MT,i}$ integer variable that indicates the installation number of PV/MT at bus i
$pf_{PV,i}$ power factor of PV at node i
$VSAI_i$ voltage support ability index at bus i
$WVSAI_i$ weighted voltage support ability index at bus i
$\overline{U_i}$, $\overline{I_{ij}}$ auxiliary variable in SOCP relaxation
d_{ij} deviation variable used in exactness verification of SOCP relaxation

generation, whose outputs are considered to be constant at a specific time segment [5,6]. While for non-dispatchable DGs, such as photovoltaic (PV) and wind turbines, their outputs are uncertain and hard to be described due to the randomness and intermittency of environmental factors (e.g. solar irradiance and wind speed) [7]. Fuzzy set theory and stochastic theory are respectively used to model the uncertain outputs of DGs in [8–11]. Based on the probability density functions of solar irradiance and wind speed, a state discretization method has been utilized in [6,12], which relieves the complexity of optimization model and makes it easy to be solved. Secondly, in terms of the optimization objectives, the previous researches focus on various targets according to different planning scenarios. In [13], only network losses are considered in the objective function for determining the optimal allocation scheme of DGs. In addition to network losses, total costs for DG investment, DG operation and maintenance (O & M), purchase of power by distribution companies from transmission companies are fully considered in [14]. In [15,16], the interruption of power-supply has been transformed into reliability cost and added to the objective function. In [17], maximizing voltage stability margin and minimizing grid power losses are considered at the same time to find the global optimal solution for DGs' allocation. To meet the growth of load demand, distribution system expansion scenarios are considered in [18,19], which aim to minimize DGs' investment and operation cost as well as the payment for expanding substations and adding new feeders. Thirdly, reviewing from the respect of solution algorithms, mathematical methods and intelligence search techniques are always utilized in solving the optimization models of DG planning. Mathematical methods are more reliable to find global optimal solutions but always not directly applicable for DG planning problems due to the complexity and non-convexity of optimization models. To simplify the model and make it easy to be solved by mathematical methods, a piecewise linear approximation is utilized in [20] and then the original mixed integer nonlinear programming (MINLP) model is transformed into mixed integer linear programming (MILP) model. In [21,22], second order cone programming (SOCP) relaxation is presented, through which the optimization model is convexified and then solved with commercial optimization solvers. It should be noted that most commercial optimization solvers like CPLEX, MOSEK, GUROBI, adopt appropriate mathematical methods as solution algorithms. Intelligence search techniques are easy to be used and always capable for solving troublesome optimization models, but they are time-consuming and easily lead to local optimal solutions instead of global optimal solutions. Genetic algorithm (GA),