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Voltage regulation-oriented co-planning of distributed generation and battery storage in active distribution networks

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ABSTRACT

Active Distribution Networks (ADNs) are featured by large-scale integration of distributed generation (DG) and energy storage. This paper proposes a novel two-layer co-planning method for optimal placement of inverter-interfaced DG and battery energy storage (BES) units towards enhanced voltage regulation functions in an ADN. The outer-later model determines the planning decision of DG units and the inverter sizing, location, and capacities of BES units, respectively; the inner-layer model corresponds to the operation decision which aims to optimally schedule the BES's charging/discharging and reactive power from inverters for voltage regulation support considering the conservation voltage reduction (CVR). The Taguchi's Orthogonal Array Testing (TOAT) is used to select a small number of scenarios to represent the DG power output uncertainties. The load is represented by a time-varying ZIP load model. The proposed model is tested on a modified IEEE 33-bus radial distribution system and the results to validate the effectiveness of the proposed method.

1. Introduction

1.1. Background and motivation

In recent years, the renewable energy-based distributed generation (DG) has been rapidly integrated into active distribution networks (ADN) [1]. However, the growing penetration of renewable energy resources also induces significant technical challenges to the power grid, such as voltage violation and fluctuation problems. Energy storage systems (ESS) can effectively mitigate the uncertainty caused by renewable energies and provide voltage regulation support [2]. Nowadays, the DG resources are often accompanied with small-scale energy storage system in an ADN, especially battery energy storage (BES) units [3], which is expected to become cheaper in the future. Moreover, the power-electronics inverters of the DGs are designed to provide near-real-time active power curtailment, reactive power and voltage regulation services [4,5]. The location and capacity of DG and BESs substantially affect the operation efficiency of the ADN. Thus, the optimal planning of DG and BES is needed for harvesting their combined participation in ADN operation.

1.2. Related works

DG and BES expansion planning in distribution network has attracted significant research interests in the literature. However, most previous works focus on the separate BES or DG allocation optimization [6–8], or BES's optimal integration given existing DG resources [9–12]. Some recent works start to consider the co-planning problem of DG and BESs. Ref. [13] proposes a stochastic planning method for ESS and wind power generators, and main characteristics of BES such as charging/discharging strategy, and depth of discharge are considered. Ref. [14] proposes an optimal allocation scheme for DG and ESS in a micro-grid to minimize the investment cost and operation cost. In [15], an optimal planning model was presented considering the installation and scheduling of DG in conjunction with BES for enhancing system reliability and stability. Ref. [15] presents a multi-stage optimal planning of renewable energy resources aiming to maximize the renewable power utilization level, reactive power resources are also taken into account. Among the existing literature [6–13], DG uncertainty modeling can be mainly classified into three types: 1) stochastic scenarios, 2) uncertainty set, and 3) probabilistic model. Solution methods including sensitivity analysis, classic programming and meta-heuristic algorithms have been adopted for solving the planning and operation problem. However, the reactive power utilization and voltage regulation support capability

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Nomenclature

Indices

t, T	Index and total number of time intervals
Δt	Time duration of each time interval

Sets

Φ	Set of system buses
L_{BES}	Set of candidate system buses for BES installation

Parameters

$P^{\xi}_{buy,t}$	Power bought from external grid at time t in scenario $\mathscr{E}$ (MW)
$P^{\xi}_{DG,t}$	Active power output at time t in scenario $\mathscr{E}$(MW)
$P^{\xi}_{load,t}$	Load demand at time t in scenario $\mathscr{E}$ (MW)
P_{ni},Q_{ni}	Active and reactive load power of bus i at the rated voltage and frequency (MW/MVar)
I_{ij}	Current output of line ij (A)
v_i,v_n	Voltage of bus i and nominal voltage of the system (V)
P_{li},Q_{li}	Active/reactive power at bus number i (MW/MVar)
$C^{\xi}_{bat,i,t}$	Energy stored in ith battery at time t in scenario $\mathscr{E}$ (MWh)
$PF^{\xi}_{i,t}$	Power factors of bus i at time t in scenario $\mathscr{E}$
r_{ij},x_{ij}	Line resistance and reactance between bus i and j
G_{ij},B_{ij}	Conductance and susceptance matrix between bus i and j
MP_t	Price for purchasing power from external grid($/MW)
C_{dep}	BES depreciation cost for per unit($/MW)
d	Interest rate

Outer Layer Decision Variables

$P^{i}_{bat\max}$	Rated power capacity of ith BSS (MW/h)
S^{i}_{DG}	Apparent power capacity of ith DG inverter (MVar)

Inner Layer Decision Variables

$p^{\xi}_{ch,i,t}$	Charging power of ith BES at time t for scenario $\mathscr{E}$(MW)
$Q^{\xi}_{DG,i,t}$	Reactive power output of ith DG's inverter (MVar)
ξ, S	Index and numbers for total scenarios
i, j	Index of system load points
L_{DG}	Set of candidate system buses for DG installation
f_l	Power flow on line l (MW)
SOC^{ξ}_{t}	State-of-charge of battery at time t in scenario $\mathscr{E}$
$I_{ij,\max}$	Maximum current output of line ij(A)
$v_{\min}$,$v_{\max}$	Minimum and maximum voltage limitations(v)
$f^{\max}_{l}$,$f^{\min}_{l}$	Minimum and maximum Power flow limitations
$Tap^{\min}$,$Tap^{\max}$	Maximum and minimum positions of OLTC
P^{ξ}_{loss}	Power loss at time t in scenario $\mathscr{E}$ (MW)
C_E	Capital cost of BES per unit ($MWh)
C_{DG}	Capital cost of DG real power capacity ($MW)
C_S	Capital cost of DG inverter apparent power capacity ($MVar)
$C_{O,BESS}$	Operation & maintenance cost per day for BESs ($/MWh)
$C_{O,DG}$	Operation & maintenance cost per day for DG units ($/MWh)
η_{ch},η_{dis}	BES Storage charging and discharging efficiency
η_{loss}	Cost for power loss ($MW)
$C^{i}_{bat\max}$	Rated energy capacity of ith BSS (MW)
$P^{i}_{DG,rated}$	The rated capacity of ith DG units (MW)
$p^{\xi}_{dis,i,t}$	Discharging power of ith BES at time t for scenario $\mathscr{E}$(MW)
$Q^{\xi}_{DG,i,t}$	Reactive power output of ith DG's inverter (MVar)

from DG inverters are rarely considered in all the aforementioned works.

Due to the advancement of power electronics and control technology, the inverter interfaced DGs are capable to provide reactive power compensation. The DG inverters are attracting attention for providing voltage regulation supports based on its fast and flexible reactive power injection/consumption capability [16]. Generally, the active and reactive output power are based on DG inverter rating and type. Nowadays, the concept of DG "inverter over-sizing" has been considered in practice to make further use of inverter's reactive power capacity [17,18].

Besides, conservation voltage reduction (CVR) is an energy saving scheme to reduce the voltage magnitude to the minimum allowable range to reduce the load demand [19]. The implementation of CVR brings benefits for utilities such as: peak-load shaving, power loss reduction for transformers and incentives from governments and increased social welfare from environmental perspective [20]. Recently the increasing penetration of PV in the distribution grid has largely prompted the CVR implementation. Considering the radial topology and the high R/X ratio of a distribution network, the DG power fluctuation may strongly affect the voltage profile. It is reported that more energy savings can be achieved while implementing CVR and DG simultaneously [21]. Many studies have been carried out discussing CVR operation effects [21–24]. The author in [21] proposes a two-stage stochastic optimization framework taking account of DG placement and CVR implementation simultaneously. In [22], the potential impacts of CVR with DG active/reactive power control was analyzed under different renewable energy penetration levels. Ref. [23] presents a closed loop control scheme for CVR implementation in DN by controlling the on-load-tap changer (OLTC), voltage regulators, PV inverters and capacitor banks. In our previous work [24], a stochastic optimal BES planning framework considering conservation voltage reduction (CVR) is proposed for ADN with abundant renewable energy resources. However, none of the above works study the coordinated voltage control support from DG and BES for CVR in the planning aspects, and there is a lack of consideration of inverter over-sizing and its participation of voltage regulation.

1.3. Contribution and outline of this paper

This paper proposes a new method for collaborative planning of DG units and BES units towards enhanced voltage regulation in an ADN. The contributions of this paper can be summarized as follows:

1. A two-layer renewable DG/BESs joint expansion planning model is formulated from the system operator's and asset owner's perspective. In the outer layer, the planning decision including the placement of DG generation, inverter sizing, location and capacity of BES units are optimized; in the inner layer, the daily operation decisions such as OLTC positions, charging and discharging power of BES, and reactive power output of DG inverters are optimized on hourly basis.
2. For enhanced voltage control and CVR purposes, this paper considers the potential of inverter over-sizing design at the planning stage, and the full utilization mode of the reactive power output of DG inverters during each time periods in the operation stage.
3. To achieve higher CVR effects of DG/BES co-planning, the voltage regulation by the coordination of DG inverters, BES and existing voltage regulation devices (OLTC) are discussed to maximize the