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# Distributed energy storage planning in soft open point based active distribution networks incorporating network reconfiguration and DG reactive power capability

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## HIGHLIGHTS

- An optimal planning model for DESSs in SOP-based active distribution networks is proposed.
- The power flow controllability of SOP is modeled and optimally coordinated with DESS operation.
- Inverter-based DG reactive power capability and short-term network reconfiguration at the hourly timescale are incorporated in the planning.
- The proposed DESS planning model is formulated as a computationally efficient MISOCP problem.

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## ABSTRACT

The integration of high-penetration distributed generators (DGs) with smart inverters and the emerging power electronics technology of soft open points provide increased controllability and flexibility to the operation of active distribution networks. Existing works on distributed energy storage planning have not fully considered the coordinated operation of these new power electronic devices with distributed energy storage systems, leading to less economic investment decisions. This paper proposes an optimal planning model of distributed energy storage systems in active distribution networks incorporating soft open points and reactive power capability of DGs. The reactive power capability of DG inverters and on load tap changers are considered in the Volt/VAR control. Moreover, soft open points are modeled to provide flexible active and reactive power control on the associated feeders. Hourly network reconfiguration is conducted to optimize the power flow by changing the network topology. A mixed-integer second-order cone programming model is formulated to optimally determine the locations and energy/power capacities of distributed energy storage systems. Finally, the effectiveness of the proposed model is validated on a modified IEEE 33-node distribution network. Considering soft open points, DG reactive power capability, and network reconfiguration, the results demonstrate the optimal distributed energy storage systems planning obtained by the proposed model achieves better economic solution.

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## 1. Introduction

### 1.1. Motivation and aims

Driven by increasing penetrations of distributed generators (DGs), such as wind turbines (WTs) and photovoltaics (PVs), the traditional distribution system is evolving towards active distribution network (ADN) [1]. The intermittency and variability of high-penetration renewables impose new challenges to the operation of ADN. It is a consensus that distributed energy storage system (DESS) is effective in accommodating high-penetration DGs and providing more flexibility to the distribution system operation [2,3]. The deployment of DESSs can mitigate the power fluctuations of volatile generation of distributed generators and maintain the secure operation of distribution systems. However, DESSs are expensive at present and the foreseeable future and they need to be managed and deployed effectively to minimize the total investment cost while meeting the system requirements [4]. In active distribution networks, the integration of advanced power electronics technology provides flexible controls and operation to the ADN. The deployment of DESS should account for the coordination with the emerging active network management.

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## Nomenclature

| | |
|---|---|
| $\mathcal{SOP}$ | set of soft open points (SOPs) |
| $\mathcal{DG}$ | set of distributed generators (DGs) |
| $\mathcal{DS}$ | set of distributed energy storage systems (DESSs) |
| $\mathcal{N}$ | set of all the nodes in the network |
| $\mathcal{N}_f$ | set of substation nodes |
| $\mathcal{D}$ | set of all the distribution lines |
| $\mathcal{N}(i)$ | set of nodes connected to node $i$ |
| $P_{i,t}^{SOP}$ | active power of SOP at time $t$ |
| $Q_{i,t}^{SOP}$ | reactive power of SOP at time $t$ |
| $S_{v,1}^{SOP}$ | capacity of voltage source converter 1 of SOP $v$ |
| $S_{v,2}^{SOP}$ | capacity of voltage source converter 2 of SOP $v$ |
| $P_{i,t,\max}^{DG}$ | maximum power output of DG $i$ at time $t$ |
| $S_{i,t}^{DG}$ | inverter capacity of DG $i$ |
| $P_{i,t}^{DG}$ | active power output of DG $i$ at time $t$ |
| $Q_{i,t}^{DG}$ | reactive power output of DG $i$ at time $t$ |
| $\kappa_{i,\min}$ | power factor requirement of DG $i$ |
| $P_{i,t}^{DS,+}$ | charging active power of DESS $i$ at time $t$ |
| $P_{i,t}^{DS,-}$ | discharging active power of DESS $i$ at time $t$ |
| $P_{i,\max}^{DS,c}$ | charging power limit of DESS $i$ |
| $P_{i,\max}^{DS,d}$ | discharging power limit of DESS $i$ |
| $SOC_{i,\min}$ | minimum state of charge limit of DESS $i$ |
| $SOC_{i,\max}$ | maximum state of charge limit of DESS $i$ |
| $SOC_{i,t}$ | state of charge of DESS $i$ at time $t$ |
| $E_{i,t}$ | energy stored in DESS $i$ at time $t$ |
| $E_i^{DS}$ | energy capacity of DESS $i$ |
| $\eta_i^c$ | charging efficiency of DESS $i$ |
| $\eta_i^d$ | discharging efficiency of DESS $i$ |
| $P_{i,t}^L$ | active power load at node $i$ |
| $Q_{i,t}^L$ | reactive power load at node $i$ |
| $\alpha_{ij,t}$ | binary variable indicating the status of the line between node $i$ and $j$ at $t$ |
| $n_s$ | maximum number of line switching |
| $P_t^S$ | active power at the substation |
| $Q_t^S$ | reactive power at the substation |
| $S_{sub}$ | power capacity of the substation |
| $y_i$ | power capacity of DESS at node $i$ |
| $z_i$ | energy capacity of DESS at node $i$ |
| $C_p$ | annualized cost for 1 kW power capacity of DESS |
| $C_e$ | annualized cost for 1 kWh energy capacity of DESS |
| $V_{i,t}$ | voltage of node $i$ at time $t$ |
| $V_{i,\min}$ | minimum voltage level of node $i$ |
| $V_{i,max}$ | maximum voltage level of node $i$ |
| $I_{ij,t}$ | current on line $i$-$j$ at time $t$ |
| $r_{ij}$ | resistance of line $i$-$j$ |
| $x_{ij}$ | reactance of line $i$-$j$ |
| $P_{ij,t}^f$ | active power flow on line $i$-$j$ at time $t$ |
| $Q_{ij,t}^f$ | reactive power flow on line $i$-$j$ at time $t$ |
| $pr(i)$ | set of parent nodes of node $i$ |
| $cr(i)$ | set of children nodes of node $i$ |
| $P_{DS}^{Bgt}$ | total power capacity of DESS in the planning budget |
| $E_{DS}^{Bgt}$ | total energy capacity of DESS in the planning budget |
| $\delta_i$ | binary variable indicating the location of DESS $i$ |
| $\lambda_t$ | time of use electricity price at time $t$ |

Advanced power electronics technologies are playing an increasing significant role in distribution system operation. The smart inverters enable the flexible control on both active power and reactive power of DGs [5]. The DGs are mostly considered as active power resources. However, the reactive power from the DGs can help manage network congestion, reduce network losses, and improve the voltage profile [6]. It is beneficial to the system operation by utilizing the reactive power capability of DGs. In addition, an emerging power electronic device, soft open points (SOP) [7–8], has attracted attentions in recent years for its strong capability in active/reactive power control among the feeders. SOP is usually installed in place of traditional tie-switch. Different from hard opening/closing the tie-line, SOP can adjust the power flow on the tie-line continuously and optimizes the active/reactive power distribution in ADN [9]. Such distribution-level power electronics have been demonstrated to be supportive to distributed generation growth. These power electronic devices provide enhanced controllability and flexibility to the system operation and alter the operation strategies of ADN.

Network reconfiguration is an effective method to improve the operation efficiency of distribution systems. Traditionally, the network topology remains unchanged for a long-time period, such as a month or a season. However, the changes of operating conditions are more frequent due to the variable power output of renewable energy resources [10]. In ADNs, the advancement of power electronic control devices can realize more frequent short-term network reconfiguration at the hourly timescale. The value of hourly network reconfiguration has been investigated and demonstrated in distribution system with high renewables [11]. It is worthwhile to incorporate network reconfiguration into the normal operation of ADN.

It can be envisioned that the investment on DESSs can be optimized if the advanced devices are fully utilized to coordinate with DESS operation. In this regard, the proposed approach focuses on the development of an integrated optimal planning model to determine the optimal siting and sizing of DESSs in ADNs incorporating soft open points, DG inverters and network reconfiguration.

### 1.2. State-of-the-Art literature review

Many research studies have been conducted on the operation and planning of ADN integrating distributed energy storage systems. [12] proposed a dynamic and multi-objective stochastic optimization model for energy storage system deployment and studied its impact on renewable integration level in distribution systems. A cost-benefit analysis method was used in [13] to optimize the siting and sizing of multiple energy storage in distribution networks to maximize the total net present value. [14] proposed a network-aware approach for energy storage planning and control in the network with high-penetration renewables and obtained approximate solutions to reduce the problem complexity. The design and analysis of electrical energy storage demonstration projects on UK distribution networks were reported in [15]. An expansion planning model of active distribution networks with centralized and distributed energy storage systems was proposed in [16]. However, the reactive power is not explicitly considered. In [6], a distribution system planning strategy is proposed considering the uncertain power output of DGs and their reactive power capability. The proposed model is a non-linear problem and solved by heuristic method. The global optimal solution cannot be guaranteed. In [7], an optimization method for siting and sizing of SOPs in active distribution networks is presented considering network reconfiguration. The DESSs and reactive power capability of DGs are not discussed. In [17], an optimization model is built to determine the optimal locations and capacity of distributed energy storage and

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