Applied Energy 189 (2017) 301–309

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Optimal siting and sizing of soft open points in active electrical distribution networks

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## HIGHLIGHTS

- A model to optimal siting and sizing of SOPs was proposed considering DG impacts.
- The problem was converted to an MISOCP model with improved accuracy and convergence.
- Economic benefits and algorithm validation were given for different scale systems.

## ARTICLE INFO

*Article history:*
Received 13 September 2016
Received in revised form 12 December 2016
Accepted 14 December 2016

*Keywords:*
Active electrical distribution network
Soft open points (SOPs)
Optimal siting and sizing
Operation scenario generation
Mixed integer second-order cone programming (MISOCP)

## ABSTRACT

Soft open points (SOPs) are power electronic devices installed to replace normally open points in active electrical distribution systems. SOPs can provide active/reactive power flow control and voltage regulation under normal operating conditions as well as fast fault isolation and supply restoration under abnormal conditions. The application of SOPs can improve the controllability of distribution systems, thus further enhances the economy, flexibility and reliability of the grid. In this paper, considering the long-term operation characteristics of distributed generation, a mixed integer non-linear optimization problem is formulated to optimally determine the siting and sizing of SOPs based on the typical operation scenarios generated by Wasserstein distance. It is then transformed to and solved as a mixed integer second-order programming model. Finally, case studies on the IEEE 33-node system and Taiwan Power Company distribution system are used to verify the effectiveness and efficiency of the proposed method.


**Contents**



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http://dx.doi.org/10.1016/j.apenergy.2016.12.075

## 1. Introduction

In recent years, an increasing number of distributed generators (DG), such as wind turbines (WT) and photovoltaic (PV) arrays, have been integrated into electrical distribution systems. The integration of DG is able to contribute to the power loss reduction [1], power supply reliability improvement [2], economic promotion [3], reduction of $CO_2$ emission, etc. [4,5], while posing new challenges to the planning and operation of distribution systems as well, such as a higher risk of network congestion [6] and voltage violation [7], and bi-directional power flow [8]. Traditional distribution systems cannot effectively address the problems caused by the high penetration of intermittent DG because of their limited regulation means. Soft open points (SOPs) are power electronic devices which replace normally open points (NOPs), effectively covering the lack of power adjustment ability in a distribution system. Instead of simply opening/closing NOPs, SOPs can further balance load flow and optimize the network voltage profile by providing fast, dynamic and continuous active/reactive power flow control among the feeders. Meanwhile, due to the isolation of DC link and instantaneous control of currents, the short-circuit current brought by SOP is limited and different from the traditional fault characteristics [9]. Coordinated with the protection of distribution network, the duration of fault isolation and supply restoration can be shortened. The application of SOPs enhances the controllability of distribution power flows to improve the system operation with a better economy, flexibility and reliability [10].

Previous studies have investigated both steady-state and transient performances of SOPs to facilitate distribution network operation [11–16]. In [11,12], the concept and topology of SOPs were proposed. Three types of topologies were defined, including back-to-back voltage source converter (B2B VSC), unified power flow controller (UPFC) and static series synchronous compensator (SSSC). In [13], based on the traditional B2B VSCs, the DC capacitor was replaced by battery energy storage, which further enhanced the regulating range of the studied SOP. In [14], the applications of SOPs were analysed and verified in terms of DG accommodation, feeder load balance and voltage profile improvement. In [15,16], considering the system fault transient process, different control modes of SOPs during a fault and post-fault period were investigated. Compared with NOPs, SOPs have more reliable power control, and can even realize real-time optimal control of the distribution network. When a fault occurs, the fault recovery mode of SOPs is used for power supply of the load out of service. However, SOPs are mainly based on fully controlled power electronic devices, leading to higher capital and maintenance costs. Therefore, it is necessary to optimize the siting and sizing of SOPs to maximize the benefits of capital and operation.

The problem of optimal installation sites and capacities of SOPs consists of not only continuous variables such as voltages and currents of a distribution network, but also discrete variables such as the locations and capacities of SOPs. It is a mixed integer nonlinear programming problem (MINLP). Meanwhile, the connection of DG will change the power flow of a distribution system, bringing more challenges to the siting and sizing of the SOPs. Therefore, the long-term operation characteristics of DG should be considered. Furthermore, the number of decision variables and constraints is increasing rapidly with the system scale, making the problem solving difficult and time-consuming. Heuristic methods such as genetic algorithm, simulated annealing and particle swarm algorithm are usually used to solve such problem. Ref. [17] used a genetic algorithm to determine the active distribution network expansion planning, in which the rewiring, network reconfiguration, new protection devices and DG installation were considered. Recently, some mathematical programming methods are also adopted to solve the problem. In [18], a convex formulation of AC optimal power flow was used to define a mixed integer second-order cone programming (MISOCP) model to optimally site and size the energy storage systems in the distribution network.

In this paper, an MISOCP model is proposed to optimally determine the siting and sizing of SOPs. First, the yearly DG operation characteristics are considered in this model using scenario generation method based on the Wasserstein distance [19]. For the typical scenarios generated, to minimize the annual expense of the overall distribution system, a model was developed to optimally determine the installation sites and capacities of SOPs while considering the constraints of the radial distribution system, system power flow, system security and operation of the SOPs, which is essentially an MINLP problem. Furthermore, a conic conversion is used to transform the original MINLP model into an MISOCP model. Finally, the effectiveness and efficiency of the proposed method are verified on the IEEE 33-node system and Taiwan Power Company (TPC) distribution system.

The main contributions are summarized as follows: (1) Taking the long-term operational characteristics of DG and network topology changes into account, a model was developed to optimally determine the siting and sizing of SOPs to minimize the annual expense of the overall distribution system including capital cost and annual operational cost of the SOP, and annual energy loss cost of the distribution system. (2) The siting and sizing of SOPs is a large-scale MINLP problem, which cannot be efficiently solved. Firstly, we reduce the size of the original problem using Wasserstein distance based scenario generation method. Then by applying the linearization and conic relaxation, the original nonconvex MINLP model is converted into an MISOCP model, which guarantee a global optimality with moderate computational burden.

The reminder of the paper is organized as follows. Section 2 introduces the optimization model to site and size SOPs in an active electrical distribution network. The original problem is converted into an MISOCP model by the linearization and conic relaxation in Section 3. Case studies are given in Section 4 to verify the effectiveness and efficiency of the proposed method. Section 5 concludes this paper with a discussion.

## 2. Optimization model to site and size SOPs in an active electrical distribution network

### 2.1. Typical operation scenario generation

In order to consider DG influence on the installation sites and capacities of SOPs, the probability density functions (PDFs) generated based on the historical data is used [20]. And the discrete PDF distribution is used instead of a continuous distribution, which is called scenario generation. In this paper, a method based on the Wasserstein distance is adopted to generate typical operation scenarios so as to reduce the computational burden in the optimization process.

Assuming that a continuous PDF of variable $x$ is $f(x)$, $S$ discrete scenarios is used to approximate $f(x)$. The typical scenario $z_s$ ($s = 1, 2, \ldots, S$) is obtained as follows:

$$\int_{-\infty}^{z_s} f(x)^{\frac{1}{2}} dx = \frac{s-1}{2S} \int_{-\infty}^{+\infty} f(x)^{\frac{1}{2}} dx \quad (1)$$

The probability $p_s$ of a scenario is calculated as follows:

$$\begin{cases} p_s = \int_{\frac{z_{s-1}+z_s}{2}}^{\frac{z_s+z_{s+1}}{2}} f(x)dx, \quad s = 1, 2, \ldots, S \\ p_1 = \int_{\frac{z_0+z_1}{2}}^{\frac{z_1+z_2}{2}} f(x)dx \\ p_S = \int_{\frac{z_{S-1}+z_S}{2}}^{\frac{z_S+z_{S+1}}{2}} f(x)dx \end{cases} \quad (2)$$