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Benefits analysis of Soft Open Points for electrical distribution network operation

Wanyu Cao [a], Jianzhong Wu [a,*], Nick Jenkins [a], Chengshan Wang [b], Timothy Green [c]

[a] Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
[b] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
[c] School of Engineering, Imperial College London, London, UK

HIGHLIGHTS

- An analysis framework was developed to quantify the operational benefits.
- The framework considers both network reconfiguration and SOP control.
- Benefits were analyzed through both quantitative and sensitivity analysis.

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ABSTRACT

Soft Open Points (SOPs) are power electronic devices installed in place of normally-open points in electrical power distribution networks. They are able to provide active power flow control, reactive power compensation and voltage regulation under normal network operating conditions, as well as fast fault isolation and supply restoration under abnormal conditions. A steady state analysis framework was developed to quantify the operational benefits of a distribution network with SOPs under normal network operating conditions. A generic power injection model was developed and used to determine the optimal SOP operation using an improved Powell's Direct Set method. Physical limits and power losses of the SOP device (based on back to back voltage-source converters) were considered in the model. Distribution network reconfiguration algorithms, with and without SOPs, were developed and used to identify the benefits of using SOPs. Test results on a 33-bus distribution network compared the benefits of using SOPs, traditional network reconfiguration and the combination of both. The results showed that using only one SOP achieved a similar improvement in network operation compared to the case of using network reconfiguration with all branches equipped with remotely controlled switches. A combination of SOP control and network reconfiguration provided the optimal network operation.

1. Introduction

The widespread use of distributed energy resources, e.g., distributed generators (DG), energy storage and controllable loads, is being promoted by many countries. This can lead to operation problems including excessive fault level as well as violations of thermal and voltage limits [1,2]. Power utilities have conventionally used expensive and time consuming approaches such as building new circuits to maintain the quality of power supply. However, there are also alternative operational measures being investigated, aiming at reliable and cost-efficient operation of distribution networks [3], e.g., network reconfiguration and increasing use of power electronic devices.

In a distribution network, there are usually a number of normally-open points connecting adjacent feeders. These normally-open points (switches) are able to be closed (while opening other switches) to reconfigure the network and achieve load transfer between feeders. Under normal operating conditions, extensive research has been conducted into network reconfiguration for optimal network operation (e.g., load balancing, loss minimization and improved voltage profiles) [4,5]. However, practical applications of automatic network reconfiguration are presently very limited due to the high cost of remotely-controlled switches, the associated ICT (information and communication technologies) infrastructure, and maintenance of hardware/software.

* Corresponding author.
E-mail addresses: CaoW5@Cardiff.ac.uk (W. Cao), WuJ5@cardiff.ac.uk (J. Wu), JenkinsN6@cardiff.ac.uk (N. Jenkins), cswang@tju.edu.cn (C. Wang), t.green@imperial.ac.uk (T. Green).

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An alternative solution to improve distribution network operation, without requiring network topology changes, is the use of power electronic devices. Power electronic devices enable more efficient use of existing network capacity by controlling power flows in an accurate and flexible way [6]. A wealth of information exists on the use of these devices in the transmission network for bulk power transfer [7]. Recently, installing power electronic devices in place of normally-open points in a distribution network, namely 'Soft' Open Points (SOPs), has been investigated [8,9]. Instead of simply opening/closing normally-open points, these devices are able to control load transfer and optimize network voltage profile by providing fast, dynamic and continuous real/reactive power flow control between feeders [8].

Previous studies have investigated the use of power electronic devices at the normally-open points to facilitate distribution network operation [10,11]. In [10], a unified power flow controller was developed to regulate network voltage with minimum line losses in a simple loop network (with two feeders), and experimental results were presented to verify its effectiveness. Field tests of installing back-to-back converters between adjacent feeders were reported in [11]. Power flow was balanced which in turn led to reduced line losses and improved network voltages. Although the benefits of installing individual SOP for network operation have been investigated in a simple two-feeder network together with the controller design and simulation, methodologies for benefit quantification, i.e., steady state analysis of distribution networks with SOPs were not addressed and the advantages of the more widespread use of these devices in distribution networks have not been explored.

To fill this gap, a method to quantify the operational benefits of a distribution network with SOPs was developed, for power loss minimization, feeder load balancing and voltage profile improvement. A generic model of an SOP for steady state analysis was developed, which takes into account both physical limitations and internal power losses of the back-to-back voltage-source converters of a typical SOP device. Based on the SOP model, an improved Powell's Direct Set method was developed to obtain the optimal SOP operation. This method determines a good initial approximation of the SOP operation based on simplified power flow equations, which significantly reduces the computation burden. The performance of traditional network reconfiguration was compared to using SOPs. A method that combines SOP control and network reconfiguration was developed to identify the benefits. In addition, the benefits of using SOPs in distribution networks with DG connections were also investigated.

2. Steady state analysis of Soft Open Points

Fig. 1a shows a typical location of an SOP which allows the power electronic device to control active power flow between connected feeders and supply or absorb reactive power at its interface terminals under normal operation conditions.

2.1. Modeling of Soft Open Points

A generic power injection model of SOP was developed. This model considers SOP terminal power injections and hence enables straightforward incorporation of SOPs into existing power flow analysis algorithms without considering the detailed controller design.

Fig. 1b shows the representation of an SOP model with real and reactive power, injecting into feeders I and J through both terminals. Taking these power injections as decision variables, the power flow in feeder I is calculated by the following set of recursive equations [12]:

$$P_i = P_{i-1} - P_{Loss(i-1,i)} - P_{L,i} = P_{i-1} - \frac{r_{i-1}}{|V_{i-1}|^2} \cdot \left(P_{i-1}^2 + Q_{i-1}^2\right) - P_{L,i} \tag{1.i}$$

$$Q_i = Q_{i-1} - Q_{Loss(i-1,i)} - Q_{L,i} = Q_{i-1} - \frac{x_{i-1}}{|V_{i-1}|^2} \cdot \left(P_{i-1}^2 + Q_{i-1}^2\right) - Q_{L,i} \tag{1.ii}$$

$$|V_i|^2 = |V_{i-1}|^2 - 2 \cdot (r_{i-1}P_{i-1} + x_iQ_i) + \frac{(r_{i-1}^2 + x_{i-1}^2)}{|V_{i-1}|^2} \cdot \left(P_{i-1}^2 + Q_{i-1}^2\right) \tag{1.iii}$$

with boundary conditions:

$$\left|P_n + P_{S\_inj}^I\right| = P_{Loss(n,sI)} \tag{2}$$

$$\left|Q_n + Q_{S\_inj}^I\right| = Q_{Loss(n,sI)} \tag{3}$$

where P represents active power, Q reactive power, V nodal voltage, r resistance and x reactance. Subscript $Loss$ denotes line losses, and L denotes load. The variables and parameters are shown in Fig. 1b. Similar recursive power flow equations with boundary conditions are applied to feeder J.

To consider the internal losses of the SOP equipment, the following equality constraint of power balance is used:

$$P_{S\_inj}^I + P_{S\_inj}^J + P_{SOP,Loss} = 0 \tag{4}$$

where $P_{SOP,Loss}$ denotes the internal power losses of the whole SOP device.

Various types of power electronic devices can be implemented as an SOP, such as unified power-flow controllers, back to back and multi-terminal voltage-source converters [9]. In this paper, the back-to-back voltage-source converters (back-to-back) were

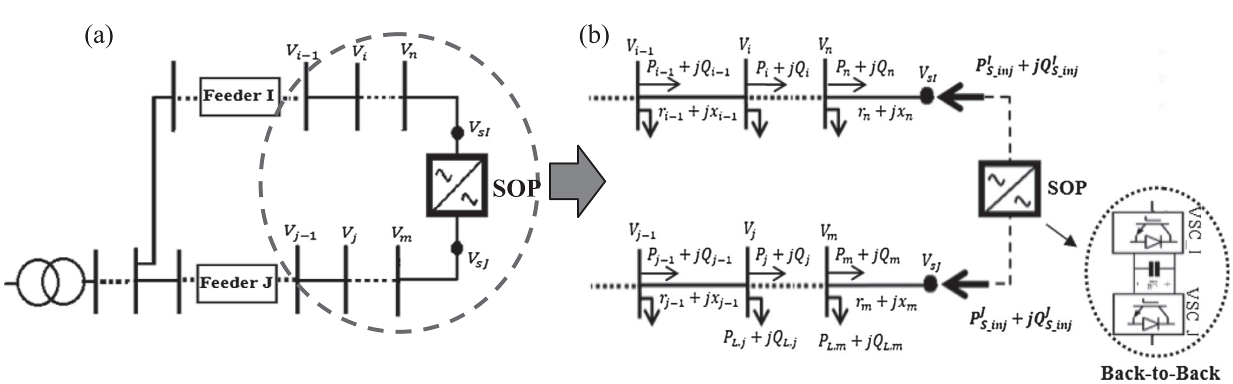

Fig. 1. (a) Simple distribution network with an SOP and (b) power injection model of SOP for distribution network power flow control.