Citation for final published version:

Jiang, Xun , Zhou, Yue , Ming, Wenlong , Yang, Peng and Wu, Jianzhong 2022. An overview of soft open points in electricity distribution networks. IEEE Transactions on Smart Grid 13 (3) , pp. 1899-1910. 10.1109/TSG.2022.3148599

Publishers page: http://doi.org/10.1109/TSG.2022.3148599

An Overview of Soft Open Points in Electricity Distribution Networks

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Abstract— **Soft open points (SOPs) are power electronic devices that are usually placed at normally open points of electricity distribution networks to provide flexible power control to the networks. This paper gives a comprehensive overview of both academic research and industrial practice on SOPs in electricity distribution networks. The topologies of SOPs as multi-functional power electronic devices are identified and compared, which include back-to-back voltage source converters, multi-terminal voltage source converters, unified power flow controllers, and direct AC-to-AC modular multilevel converters. The academic research is reviewed in three aspects, i.e., benefit quantification, control, and optimal siting and sizing of SOPs. The benefit quantification indices are categorized into feeder load balancing, voltage profile improvement, power losses reduction, three-phase balancing and DG hosting capacity enhancement. The control of SOPs is summarized as a three-level control structure, where the system-level and converter-level control are further discussed. For optimal siting and sizing of SOPs, problem formulation and solution methods are analyzed. Besides the academic research, practical industrial projects of SOPs worldwide are also summarized. Finally, opportunities of research and industrial application of SOPs are discussed.**

Index Terms—**Soft open point, distribution network, topology, benefit quantification, control, siting and sizing.**

I. INTRODUCTION

Electricity distribution networks are facing unprecedented challenges. The large-scale deployment of new electricity demand, such as electrified heat and transport, will significantly increase the peak demand of distribution networks [1]–[3]. The increasing connection of low-carbon distributed generators, such as photovoltaic (PV) panels and wind turbines, may incur violations of voltage and thermal limits of distribution networks [4]. Moreover, there are great uncertainties in local power generation and consumption, and traditional regulation methods, such as on-load tap changers of transformers, cannot satisfy the requirements for real-time continuous regulation [5]. To host the increasing power demand and generation, major investment will be required in network reinforcement and aging assets replacement, which will be very costly and time-consuming. An alternative method is to actively utilize the flexibility in distributed generation (DG), flexible demand and network devices to manage the network constraints in real time [6], [7].

Soft open points (SOPs) are power electronic devices that are usually placed at normally open points of electricity distribution networks to provide flexible and accurate power and voltage control to the networks. With great real-time power controllability, they have been verified promising in dealing with the aforementioned challenges of distribution networks. These distribution-level power electronics are invented and named as Siemens multifunctional power link (SIPLINK) by Siemens AG in Germany in 2001 [8]. The name of SOPs was used in [9] in 2010, emphasizing on the replacement of normally open points in distribution networks. Since its inception, different names were also used to describe such type of devices although they may have different focuses, such as DC-link [10], DC interlink [11], MVDC-link [12], [13], soft multi-state open point （SMOP） [14], loop balance controller (LBC) [15], [16], back-to-back active power controller (APC) [17], back-to-back system [7], [18], flexible interconnection device (FID) [19], partition flexible interconnection converter station (PFICS) [20], etc. Among these names, SOPs have been widely accepted by researchers and will be used in this paper.

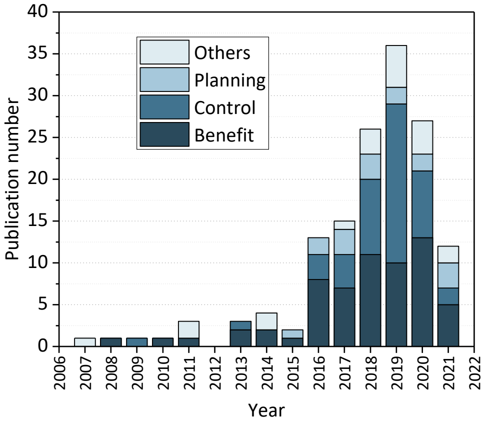

Fig. 1. Annual number of SOP related publications since 2007. (The statistical data are based on searching the core collection of Web of Science. As a result, a total of 145 relevant academic papers are identified up to May 2021.)

Fig. 1 shows the annual number of academic publications related to SOPs since 2007. It can be seen from Fig. 1 that the number of publications for SOPs has experienced a great

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This work was supported in part by China Scholarship Council and in part by the Engineering and Physical Sciences Research Council, U.K., under Grant EP/T021969/1. (Corresponding author: Wenlong Ming)

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increase since 2016. In general, benefit quantification, control and planning of SOPs are the three main research topics so far, while interests in other topics such as protection of SOPs have begun to increase in the last 4 years. It should be mentioned that some of the studies on benefit quantification of SOPs adopt control methods to maximize one or more benefits. However, these studies are included in the category of "benefit" instead of "control" since the main goal of these studies are to analyze the benefits of SOPs in the distribution networks. By contrast, the studies focusing on designing control strategies or providing control loops or modulation waves for SOPs are categorized into "control".

The research in SOPs has been conducted for over 10 years and attracted lots of interest in recent 5 years, but there is rare review [21] published in this area. In [21], the implementing challenges are discussed, in particular the duties of SOPs are proposed according to modern standards. In addition, SOP topologies, SOP control methods during normal/abnormal network conditions and optimization problems in distribution networks with SOPs are also comprehensively reviewed [21]. In our study, the existing research in SOPs is reviewed from different perspectives, although the topics of topology, benefits and control of SOPs, which have been partially reviewed in [21], are also discussed. To distinguish the contributions from [21], the main contributions of our study are summarized as follows:

1) The similarities and differences among different SOP topologies are distinguished and the pros and cons of these features are analyzed in detail.

2) The quantification indices are identified for the evaluation of SOP performance considering different operation and planning targets of distribution networks, which also lay the foundation for the optimal control and optimal siting and sizing of SOPs in distribution networks.

3) The control of SOPs, comparing to [21], is further structured in three levels including the system-level, converter-level, and switching-level control. The different control goals and strategies for SOPs in these three levels and the interfaces between the levels are analyzed.

4) The optimal siting and sizing of SOPs in distribution networks were generally formulated as optimization problems in previous studies. The differences in the optimization models formulated and the corresponding solution algorithms are summarized.

5) Industrial SOP projects worldwide are comprehensively reviewed and summarized in two categories: projects within public distribution networks and projects between public distribution networks and grid edge networks.

The rest of this paper is organized as follows. Section II introduces the different topologies of SOPs. The three main research topics, i.e., benefit quantification, control, and optimal planning of SOPs, are discussed in Section III, Section IV and Section V respectively. Section VI summarizes the existing industrial projects of SOPs worldwide. In Section VII, three promising future developments of SOPs are discussed. Finally, conclusions are given in Section VIII.

II. TOPOLOGIES OF SOFT OPEN POINTS

SOPs are usually used for connecting different AC feeders or buses of an electricity distribution network. The main function of SOPs is AC/AC conversion and accordingly there are four different topologies for SOPs, as shown in Fig. 2. These topologies include back-to-back voltage source converters (VSCs), multi-terminal VSCs [22], unified power flow controller (UPFC) [23], [24] and direct AC-to-AC modular multilevel converter (MMC) [25].

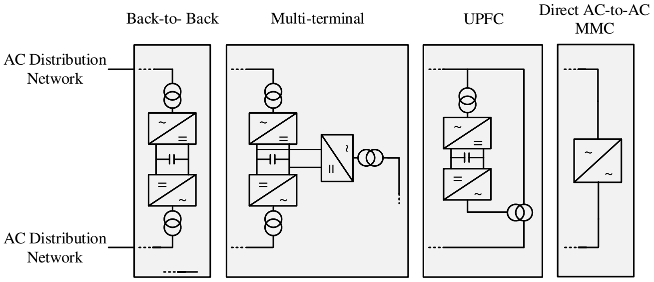

Fig. 2. Different topologies of SOPs.

Different from direct AC-to-AC MMC, back-to-back VSCs, multi-terminal VSCs and UPFC are three typical indirect AC-to-AC topologies of SOPs. These three typical topologies exploit multiple VSCs to achieve AC/AC conversion between connected feeders. The main advantages for using VSCs to build SOPs are threefold [26]: 1) the freedom to operate with any combination of active and reactive power; 2) the ability to limit fault current; 3) the possibility to supply isolated areas of a network and even provide the black-start capability. For these typical topologies, VSCs are connected through a common DC bus. The DC bus is very short so that there is no overhead lines or cables separating the VSCs. This enables high DC current and low DC voltage, thus reducing the insulation requirement and favouring a compact design for SOPs. Through the DC bus, energy storage can be easily connected to provide more flexibility for the operation of distribution networks [27]–[30]. At the interfaces of each VSC with the connected AC feeders, coupling transformers are usually equipped.

Despite the similarities in multi-VSC configuration, there are some different features among these three typical topologies. A major difference lies in whether the connected distribution networks are isolated by the DC bus. As shown in Fig. 2, due to the intermediate AC/DC conversion stage, connection between asynchronous distribution networks is viable for back-to-back and multi-terminal VSC based SOPs. Under abnormal network conditions, the fault on one feeder can also be isolated from other feeders by the DC bus. For a UPFC based SOP in comparison, it consists of two VSCs with one in series and the other in shunt, and the feeders interconnected with it are not isolated by the DC bus. Therefore, the connected distribution networks are required to be synchronous and the fault on one feeder will affect the other unless an effective control strategy is developed. However, a UPFC based SOP is able to control power flows greater than its rating (for example, 1MVA rated UPFC based SOP can control maximum 10MVA power exchange between the feeders in Fig. 2). Thus, the cost of this type of SOPs can be largely reduced. To make back-to-back type and multi-terminal type of SOPs more competitive in the cost, transformerless topologies are proved to be feasible [15], [31].

J. Pereda et al [18] proposed direct AC-to-AC MMC as an SOP topology, with the idea of keeping the advantage of MMC and simultaneously reducing its cost when applied in distribution networks. For high-voltage direct current transmission, MMC has been proved to be a promising VSC topology due to its high efficiency, fault tolerant operation, and low total harmonic distortion [32], [33]. However, when applied in distribution networks, it occupies big space and has high cost compared to two-level or three-level converters. To solve this problem, the direct MMC topology is an attractive solution. Compared to back-to-back MMC, a direct MMC based SOP has no DC bus and has the same number of semiconductors but half the number of capacitors and inductors, which can reduce the installation space and overall cost. However, it has an important drawback that the currents in the connected two feeders are not independent. The coupling of the currents between the two feeders entails a coupled reactive power and results in a limitation of the converter to assist only one feeder at a time when unbalance voltage or harmonic compensation is desired [18]. These limitations are expected to be addressed by control and hardware development hereafter.

Recently, new topologies of SOPs keep emerging. For example, the development in transformerless UPFC topology is promising to further reduce the cost of SOPs [34], [35]. In addition, SOP topologies with DC/DC converters will be exploited when considering the connection between AC distribution networks and DC networks. Since these topologies have not been well developed yet, they will be discussed in Section VII as future development.

III. MODELLING AND BENEFIT QUANTIFICATION OF SOFT OPEN POINTS

In this section, a generic steady-state model of SOPs and various indices for quantifying the benefits of SOPs in distribution networks are given. The model and quantification indices have been widely used in the analysis of distribution networks with SOPs, laying the foundation for the optimal system-level control of SOPs in Section IV and the optimal siting and sizing of SOPs in Section V. It should be mentioned that due to the space limitations this section does not give the SOP models for all the topologies shown in Section III. Instead, the generic model for SOPs with back-to-back VSCs and multi-terminal VSCs topologies (two commonly used topologies in both research and practice) is given, while the models of SOPs with direct AC-to-AC MMC topology and UPFC topology refer to [25] and [36], respectively.

A. *Mathematical Model of SOPs*

The steady-state model of SOPs is normally developed as the power injection model, which involves the power injections at SOP terminals and hence enables straightforward incorporation of SOPs into existing power flow analysis without the need of considering detailed controller design. The mathematical model of an SOP is shown in (1)-(4), expressing the active power exchange, power losses, power constraints and voltage constraints of the SOP respectively.

$$\sum_{i=1}^{N_T}\left(P_i^{SOP}+P_i^{SOP,\mathrm{L}}\right)=0 \tag{1}$$

$$P_i^{SOP,L}=A_i^{SOP}\sqrt{\left(P_i^{SOP}\right)^2+\left(Q_i^{SOP}\right)^2} \tag{2}$$

$$\sqrt{\left(P_i^{SOP}\right)^2+\left(Q_i^{SOP}\right)^2}\le S_i^{SOP} \tag{3}$$

$$V^{\min}\le V_i^{SOP}\le V^{\max} \tag{4}$$

N_T is the number of the terminals of the SOP. P_i^{SOP} and Q_i^{SOP} are active power and reactive power injections from the *i*th terminal of the SOP to the connected points of the network. $P_i^{SOP,\mathrm{L}}$ is the power losses of the *i*th converter of the SOP whereas A_i^{SOP} is the losses coefficient. S_i^{SOP} is the capacity of the *i*th converter of the SOP. V_i^{SOP} denotes the voltage of the network at the *i*th terminal of SOP, normally restrained by the minimum allowed network voltage $V^{\min}$ and the maximum allowed network voltage $V^{\max}$ at the SOP terminals. The setting for $V^{\min}$ and $V^{\max}$ can be customized according to different network conditions. Under normal network condition, $V^{\min}$ and $V^{\max}$ are usually defined as the minimum and maximum allowed voltages of the network [37], while in fault conditions, SOPs can serve for voltage support and $V^{\min}$ is suggested to be set as 1.0 p.u. [38], [39].

B. *Benefit Quantification of SOPs*

SOPs can provide accurate and fast active and reactive power flow control, which can bring great benefits to electricity distribution networks. Under normal operation of distribution networks, SOPs can help balance the power loads between connected feeders, improve the voltage profile [11], [40], and/or reduce the overall power losses [41]–[43]. These three benefits are comprehensively considered in [37], [44]–[46] and compared in [13], [47].

In addition, SOPs can increase DG penetration [29], [48], [49] and participate in congestion management [50], [51]. Under three-phase unbalanced operation condition of the network, SOPs can mitigate the three-phase unbalance [52], [53]. When a fault occurs, SOPs can detect the presence of an unbalanced fault [52], help isolate the fault area and split the distribution network into separate self-sufficient partitions [38]. They can also achieve fast supply restoration [39], [54]–[57] resulting in the reliability improvement of the network [58].

Quantifying the benefits of SOPs is important for SOP owners to learn their value in an intuitive and comparable way. Moreover, the quantification indices can be selected as objective functions in the optimization problems for the optimal control and the optimal siting and sizing of SOPs in distribution networks, which will be detailed in Section IV and Section V respectively. Due to the importance of benefit quantification for SOPs, this section summarizes the existing quantification indices.

The identified indices, although with different unit and function, can be used for evaluating the benefits of SOPs considering different operation targets of distribution system operators separately. Moreover, multiple indices can be used as objectives in a multi-objective optimization model for a comprehensive evaluation of the benefits of SOPs. A straightforward way is to weight and summate these indices in one objective function after their standardization. Based on Pareto-dominance principle [13], [37], a set of solutions with equal interests amongst different objectives can be further obtained and the trade-off between different SOP benefits can be considered. By comparing the values of these indices, technologies used in distribution networks, including SOPs and other technologies such as network reconfiguration and on-load tap changers, can be compared quantitatively.

1) Feeder Load Balancing

Feeder load balancing of a distribution network can be represented by the line utilization index – feeder load balancing (FLB), which can be defined either in the form of the branch currents [37], [46], [47], or in the form of apparent power flow [13]. The index represented by the branch currents is shown in (5), while the index represented by the power flow is described as (6) or (7).

$$FLB = \sum_{k=1}^{N_{branch}} \left(\frac{I_k}{I_{k-rated}} \right)^2 \tag{5}$$

I_k is the current flowing through branch k, and $I_{\text{k-rated}}$ is the rated current of branch k. N_{branch} is the total number of branches.

$$FLB = \sum_{k=1}^{N_{\text{branch}}} \left(\frac{S_k}{S_{k,\text{rated}}} \right)^2 \tag{6}$$

S_k is the apparent power flow in branch k, and $S_{k,\text{rated}}$ is the rated capacity of the branch.

$$FLB = \sqrt{\frac{1}{N_{branch}} \sum_{k=1}^{N_{\text{branch}}} \left(\frac{S_k}{S_{k,\text{rated}}} \right)^2} \tag{7}$$

The index shown in (7), divided by the total number of branches, reflects the average degree of utilization of all branches in the distribution network.

2) Voltage Profile Improvement

Voltage profile index (VPI) is commonly used to measure the voltage improvement of a distribution network. The index reflects the degree of dispersion of all bus voltages from the nominal values, which is described as the following forms.

$$VPI = \sqrt{\frac{1}{N_{bus}} \sum_{i=1}^{N_{bus}} \left(V_i - V_{i,\text{ref}} \right)^2} \tag{8}$$

$$VPI = \sum_{i=1}^{N_{bus}} \left(|V_i| - |V_{i,ref}| \right)^2 \tag{9}$$

$$VPI = \sum_{i=1}^{N_{bus}} \left| V_i - V_{i,ref} \right| \tag{10}$$

V_i and $V_{i,ref}$ are the real and nominal voltage magnitudes at bus i. N_{bus} is the total number of buses. Equation (8) adopts the form of the standard deviation of the bus voltages [13], while it is more simplified in (9) [47] and (10) [37].

3) Power Losses Reduction

Power losses reduction is one of the key benefits brought by the SOPs for distribution networks. Power losses index (PLI), as shown in (11), is usually calculated for evaluating this benefit and is of great significance for the cost evaluation [13], [37].

$$PLI = \sum_{k=1}^{N_{\text{branch}}} I_k^2 \times r_k = \sum_{k=1}^{N_{branch}} \frac{P_k^2 + Q_k^2}{|V_k|^2} \times r_k \tag{11}$$

r_k is the resistance of branch k. P_k and Q_k are the active and reactive power flow through branch k. In [47], energy losses is also adopted as a quantification index by adding up the power losses during a certain period of time.

4) Three-phase Balancing

Distribution networks are usually unbalanced due to the asymmetric three-phase line configuration and a large number of single-phase power loads. The asymmetric integration of DGs will further exacerbate the three-phase unbalanced condition in a distribution network. The unbalanced operation of the network will cause inefficient utilization of network assets and increase losses. The negative sequence components of the unbalanced voltages may also result in distribution equipment operating in an abnormal condition.

SOPs are able to rapidly regulate the three-phase active and reactive power flow to mitigate the three-phase unbalance. In [52], the three-phase balancing indices are proposed in (12) and (13), while in [53] the index for voltage unbalance adopts a different form as shown in (14).

$$f^{\text{V}} = \sum_{i=1}^{N_{\text{N}}} \sum_{\varphi=a}^{c} \left| V_{\varphi,i} - \frac{1}{3} \left(V_{a,i} + V_{b,i} + V_{c,i} \right) \right| \tag{12}$$

$$f^{\text{I}} = \sum_{\varphi=a}^{c} \left| I_{\varphi,0} - \frac{1}{3} \left(I_{a,0} + I_{b,0} + I_{c,0} \right) \right| \tag{13}$$

$$f^{\text{V}} = \sum_{i=1}^{N_{\text{N}}} \sum_{\varphi=a}^{c} \left| |V_{\varphi,i}|^2 - \frac{1}{3} \left(|V_{a,i}|^2 + |V_{b,i}|^2 + |V_{c,i}|^2 \right) \right| \tag{14}$$

f^V and f^I are the index of the voltage unbalanced condition of the network and the current unbalanced condition of the substation. $V_{\varphi,I}$ is the complex voltage on phase φ (φ=a, b, c) at busbar i. $I_{\varphi,0}$ denotes the complex current on phase φ of the substation outlet.

5) DG hosting Capacity Enhancement

With the strong power and voltage controllability, SOPs are able to coordinate the DG resources connected to the feeders (or networks) and mitigate voltage violation to enable more DG connected to distribution networks. Hosting capacity (HC) [29], [49] is used for quantitatively evaluating this benefit:

$$HC = \sum_{i=1}^{N_{\text{N}}} S_i^{\text{DG}} \tag{15}$$

S_i^{DG} is the capacity of DG at busbar i.

Alternatively, DG penetration level (PL) [59] can also be used for quantitative evaluation. One of the widely used DG penetration level definitions is shown below:

$$PL = \frac{\sum_{i \in G} P_{gi}}{P_{\text{max-load}}} \tag{16}$$

P_{gi} denotes the active power injection from the DG unit at busbar I, and G is the set of DG units. $P_{\text{max-load}}$ is the maximum loading of the network under study.

6) Supply Restoration

After traditional protection relay acts when a fault happens, SOPs in the distribution network can be controlled for restoring the out-of-service power loads from outages. Restored active power load (RAPL) [39], [54]–[57] is normally used for quantifying the performance of SOPs in supply restoration of the distribution network:

$$RAPL = \sum_{i=1}^{N_{bus}} \lambda_i \pi_i P_i^L \tag{17}$$

λ_i is the coefficient associated with the recovery level of load at bus i, where $\lambda_i \in [0,1]$. π_i is the weighting factor of the load at bus i depending on its importance. P_i^L is the active power load at bus I, which can be further expressed as the sum of the three-phase active power at each bus in the unbalanced distribution network [38]. In [38], [56], [57], the restored active power load during the restoration period is also accumulated for the evaluation of the benefits of SOPs.

It is noteworthy that the indices *5)* DG hosting capacity enhancement and *6)* supply restoration are normally maximized in the optimal operation of the distribution network with SOPs, while the indices *1)* feeder load balancing, *2)* voltage profile improvement, *3)* power losses reduction and *4)* three-phase balancing are minimized. Multiple quantification indices above can also be used simultaneously for the optimal operation (or planning) of distribution networks with SOPs.

IV. CONTROL OF SOFT OPEN POINTS

A. Control Structure of Soft Open Points

Fig. 3 shows the control structure of SOPs. The control for SOPs encompasses three levels: system-level, converter-level, and switching-level.

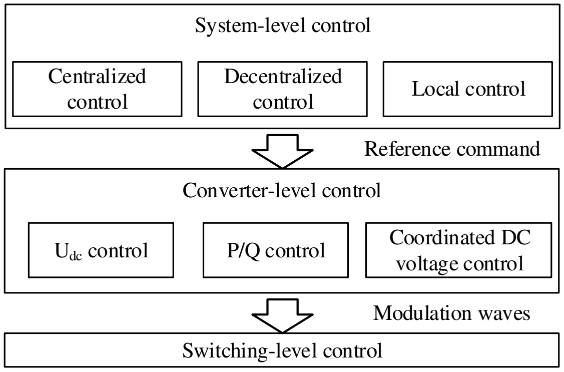

Fig. 3. Control structure of SOPs.

The system-level control of SOPs is based on the measured states of the distribution network and subject to communication conditions and computational requirements. Corresponding to different conditions, different system-level control strategies are developed, which can be categorized into centralized, decentralized, and local control strategies (or their mix). In the system-level control, reference values such as active power and reactive power reference values, are determined and are sent to the converter-level control.

According to different reference commands (active power, reactive power, or DC voltage reference), converter-level control can vary. At this level, DC voltage control or active power control are applied at the DC side of SOPs, while reactive power control or AC voltage control are at the AC side. It is noteworthy that at least one converter should be selected to control the DC voltage. For multi-terminal SOPs, coordinated DC voltage control method is normally used.

Modulation waves are generated from the converter-level control for switches (e.g., Insulated Gate Bipolar Transistors) of SOPs. This section will focus on the system-level and converter-level control of SOPs only.

B. System-level Control

1) Centralized Control

The centralized control requires sufficient measurements of the distribution network through fast and reliable communication. Usually, the historical or forecasted power load and solar/wind generation are needed. Based on these measurements, the optimal control strategies of SOPs are normally derived by using optimization models, of which the objective functions can be selected from the quantification indices in Section III depending on different operation targets of distribution system operators.

Due to the nonlinearity of power flow equations and SOP constraints in the optimization models, the optimal control of SOPs is nonlinear programming, which can be directly solved by the primal-dual interior-point algorithm [39], the Powell's Direct Set method [46] or intelligent algorithms such as meta-heuristic algorithm [41], particle swarm algorithm [37] and genetic algorithm [19], [55]. To achieve global optimality and computation efficiency, the original problems can also be converted to and solved as convex optimization problems (e.g., second-order cone programming [38], [40], [50], [54] or semidefinite programming [51], [52]). Considering the uncertainty of distributed energy resources in the distribution network, the chance-constrained programming embedded nonlinear optimization model is formulated for SOP control [57]. However, a large number of scenarios are required to fully characterize the uncertain power output of renewable resources, making the model computationally difficult. A further robust optimization model is formulated for the robust operation of SOPs [44], [53]. Instead of requiring the historical data or probability distribution of the power output of renewable resources, this method requires only the range of the power output. The obtained control strategy of SOPs is conservative, and the network constraints can be satisfied under the uncertainty conditions.

Besides the conventional optimization-based centralized control for SOPs, X. Xing et al [60] develops a rolling horizon operation model for networks with SOPs on the basis of model predictive control. In [61] and [62], model predictive control is only used for inner-day/intra-day control of SOPs, combined with other methods separately for real-time control.

Despite the fact that the global optimal operation strategies of SOPs might be obtained under centralized control, the heavy communication burden and complex global optimization might hinder the fast response of SOPs against the frequent power/voltage fluctuations in the network. Moreover, there may be privacy and security concerns in centralized control, resulting in potential data unavailability. In comparison, decentralized and local control methods can fix these problems.

2) Decentralized Control

Compared to centralized control, decentralized control usually has the advantages of higher computation efficiency and stronger reliability, only based on local information of each area and boundary interaction among connected areas. Therefore, decentralized control methods are usually more suitable for SOPs to provide responses in real time.

To achieve decentralized control, H. Ji et al [63] firstly split a distribution network into multiple partitions based on voltage-to-power sensitivity analysis, assigning DGs as the partition centers and SOPs or distribution lines as the components between partitions. After network partition, the alternating direction method of multiplier algorithm is applied to realize the decentralized optimization of the exchange power among connected areas. Different from [63], J. Zhao et al [64] consider SOPs as the centers of each partition and divide the network into sub-areas using a clustering method. This allows independent power control of SOPs in each partition by using an optimization model for intra-area voltage control. If some nodal voltages still exceed the expected range after the intra-area autonomy, the alternating direction method of multiplier algorithm will be further used to improve the operation strategies of SOPs by inter-area coordination [64].

3) Local Control

Local control for SOPs is implemented based on local information, for example the measurements of the bus voltage at each port of SOPs. Despite the difficulty to obtain the global optimal control strategy for SOPs, fast responses can be provided in real time.

To realize local control of SOPs, droop control methods are usually used [65]–[67]. In [66], an improved control strategy is further proposed to adjust the droop control coefficient in real time according to the rated active power and the value of active power variation. Optimization methods could also be used for local control of SOPs. In [68], an optimization model to minimize the apparent power of SOPs is adopted based on the local voltage data of the common connection point. Apart from the above two methods, Q-V curve is also exploited for local control of the reactive power output of SOPs. The parameters of the Q-V curve is determined by optimization using the day-ahead forecasted data of electricity power load and solar/wind generation [69].

C. Converter-level Control

Converter-level control aims to use control loops to generate modulation waves for the ultimate control of SOPs, using the reference values provided (e.g., from the system-level control) as the input to the controllers. Under normal network operating conditions, a dual closed-loop current-controlled strategy is popular because it can not only provide de-coupled control of active and reactive power components, but also inherently limits the converter current during network faults.

The dual closed loop consists of the outer power control loop, the inner current control loop and the phase locked loop[67], [70]–[72]. In the outer power control loop, one converter operates with V_{dc}-Q control scheme where the DC voltage error and reactive power error are transformed into the reference d–q current components through the PI controllers. Other converters normally use P-Q control scheme for active and reactive power control. Under P-Q control scheme, it is in the same way that active and reactive power errors are transformed into the reference d-q current components. In the inner current control loop, the d-q current errors are ultimately transformed into the modulation waves for switches of SOPs. For the dual closed-loop current-control, the phase locked loop is important for synchronizing the output voltage of SOPs with the AC network voltage. Besides the reactive power control at the AC side of SOPs, AC voltage control can also be selected [72] in the dual closed loop.

Apart from the classic dual closed loop for outer power control and the inner current control, an adaptive voltage droop outer-loop control and a sliding mode inner-loop control with feedback linearization are further proposed in [73], which shows better steady-state performance with less fluctuation in the controlled active/reactive power and DC voltage.

V. OPTIMAL SITING AND SIZING OF SOFT OPEN POINTS

Optimal siting and sizing of SOPs in distribution networks is reviewed and discussed in this section. Since only the topology of back-to-back VSCs has been used in the existing studies on SOP siting and sizing, the selection of SOP topologies is not discussed yet can be a future research topic.

The siting and sizing of SOPs can be well formulated as an optimization model, which is proved to be able to be solved by various effective algorithms in the corresponding studies. In this section, the optimization problem for siting and sizing of SOPs is described in two parts: problem formulation (including decision variables, objective functions and constraints) and the algorithms to solve the problem.

A. Problem Formulation

1) Decision Variables

The basic decision variables of the optimal siting and sizing problem for SOPs can be categorized into planning variables and operation variables. The planning variables include the installation sites and sizes of SOPs, while the operation variables encompass the active/reactive power injections from SOPs in each scenario or for each time period.

To achieve a better performance of the operation of a distribution network and to reduce the overall cost, other electrical devices or smart technologies are often used with SOPs simultaneously. The electrical devices include but not limited to the switches of the network [74], DGs [75]–[77], energy storage [75], and capacitor banks [77]. Therefore, the states of the switches, the sites and sizes of DGs, energy storages and capacitor banks are also considered as decision variables in these articles. In addition, I. Konstantelos et al [78] combine SOPs with other smart technologies (demand side response and coordinated voltage control), of which the planning variables and operation variables are also decision variables in the planning problem.

2) Objective Functions

In existing studies, the objective of siting and sizing of SOPs is to minimize the overall cost including the investment, maintenance, and operation-related cost within the planning horizon. Optimal siting and sizing of SOPs is to find the best trade-off between the investment/maintenance cost and the operation benefits. The total investment/maintenance cost is usually converted into annual cost by timing the capital recovery factor or the present value factor [74]–[77]. Among the benefits summarized in Section III, power losses reduction can be easily converted into monetary value considering the price of electricity and is commonly considered as a term in the objective function of the optimization problem for SOP siting and sizing [74], [75]. In addition to the consideration of power losses, an alternative is to consider the cost of the electricity purchased from the upstream grid in the objective function [76], [77].

3) *Constraints*

The constraints for the planning problem of SOPs encompass SOP power constraints, power flow equations, network constraints and constraints of other electrical devices. In [74], [76], the constraints of SOP capacity are also considered, where SOP in each candidate location is assumed to be constituted by multiple modules or units.

In respect of SOP power constraints, the apparent power output from each SOP terminal should be within the SOP capacity. In [76], [78], an upper limit on reactive power output of SOPs is also considered individually. For power flow equations, distflow branch model [74] is usually used due to the radial topology of the distribution network. As for network constraints, they are comprised of voltage limits and branch current (or branch power) limits. Constraints of other devices or technologies can refer to the correlated papers and will not be focused in this study.

4) *Single-level/Bi-level Optimization*

The optimal siting and sizing problem of SOPs can be formulated in a single-level [74], [75], [78] or a bi-level optimization model [76], [77]. Compared to the single-level optimization model, the bi-level one consists of an upper-level optimization model and a lower-level optimization model. The upper-level optimization model optimizes the planning variables (sites and capacities of SOPs and other electrical components) and sends them to the lower level. Then based on these optimized results from the upper level, the operation variables (for example power output of SOPs) are optimized and then the cost-related objective in the lower-level optimization process is fed back to the upper level. The two procedures iterate to achieve better results.

In general, the formulation of the single-level optimization follows those presented in the above three subsections, while the formulation of the bi-level optimization differs in three parts. Firstly, despite the investment cost, operation related cost in many cases is also involved in the objective function in the upper level, which will be calculated in the lower-level optimization process. Secondly, in the lower-level optimization model, different quantification indices in Section III can be weighted and summated as the objective function. The weights for different indices can be decided through analytic hierarchy process [76]. Thirdly, the constraints considered by the upper level only include the location and capacity constraints of SOPs and other aforementioned electrical devices, such as DGs, energy storage and capacitor banks, while the other constraints are considered in the lower level.

B. *Algorithms of the Optimization Problem*

The optimal siting and sizing problem of SOPs is a mixed integer nonlinear optimization problem, which is difficult to converge into the global optimum and computationally inefficient. One effective algorithm to solve this optimization problem is firstly to transform the original model to a mixed integer second-order cone programming model, and then solve it by commercial solvers like CPLEX [74] and MOSEK [76]. Considering the uncertainties of power output of DGs and the power load, a chance-constrained programming model can be embedded in the original model, where genetic algorithm is proved to be effective for solving the problem [77].

The algorithms for the transformation between single-level optimization problem and bi-level problem can also be used. In [76], the bi-level optimization model is transformed into a single-level model based on the strong duality theory of conic optimization [79]. In [75], on the contrary, the single-level optimization problem is converted to an investment decision-making master problem with integer variables and an operation optimal sub-problem with continuous variables by the Benders decomposition method.

VI. INDUSTRIAL PROJECTS OF SOFT OPEN POINTS

Industrial projects of SOPs have already been carried out across the globe. In this section, 18 major projects are selected for investigation, whose information are publicly available. Among these projects, Germany, the UK and China are the three countries leading the industrial development of this technology as shown in Fig. 4.

According to the types of distribution networks where SOPs are installed, the applications of SOPs can be classified into two categories: within public distribution networks and between public and grid edge distribution networks.

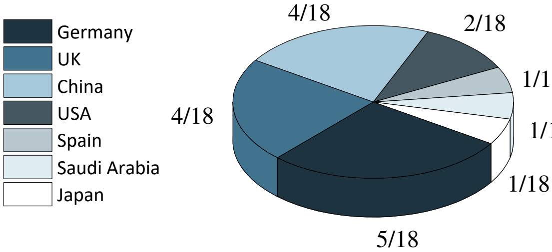

Fig. 4. SOP projects worldwide.

A. *Within Public Distribution Networks*

The most common topology of SOPs connecting two public distribution networks is back-to-back VSCs. This type of SOPs was firstly developed and named as SIPLINK by Siemens AG, which is an industrial manufacturing company in Germany. Since 2001, the SIPLINK series of product were deployed at the switchgear factory in Frankfurt [8], trialled in the “Ulm” project and the “EDISon” project in Germany [80], and used for 50/60 Hz network connection in Saudi Arabia [81]. Besides SIPLINK of Siemens AG, SOPs were also developed and exploited in other countries. In Japan, two distribution lines in a test distribution network were connected by a 6.6kV/1MVA dual-terminal SOP in 2007 for the purpose of load balancing and voltage improvement [15], [16]. In the USA, back-to-back SOPs designed by ABB company in Switzerland were demonstrated in the “Eagle Pass” project in 2011 [82] and “Mackinac HVDC Flow-Control” project in 2014 [83]. In the UK, back-to-back SOP projects funded by the Office of Gas and Electricity Markets (Ofgem) include “Flexible Urban Network-Low Voltage” project led by UK Power Networks (2014-2016) [84], “Network Equilibrium” by Western Power Distribution (2015-2019) [85] and the ongoing “Active Response to Distribution Network Constraints” by UK Power Networks [86]. Apart from Ofgem projects, another dual-terminal SOP project has also been conducted under the “Active Network Management” program of Northern Power Grid in the UK [87]. Particularly in the ongoing “Active Response to Distribution Network Constraints” project, remote control switches will be used in coordination with back-to-back SOPs for automatic reconfiguration to optimize distribution networks.

In addition to back-to-back SOPs, four multi-terminal SOPs were applied in different cities of China since 2018. Depending on whether the connection is for AC or DC networks, these multi-terminal SOPs were configured with either AC/DC converters or DC/DC converters. A three-terminal and a four-terminal SOP with only AC/DC converters were demonstrated [88] in Beijing in 2019 and Suzhou in 2018 [89], respectively. On the other hand, with one or more DC/DC converters connecting to the DC distribution networks, two other multi-terminal SOPs were deployed in Hangzhou in 2018 [90] and Tianjin in 2020 [91], respectively. Connecting the DC bus of an SOP to DC networks makes it easy to integrate DC power load and power generation in public distribution networks. Apart from China, multi-terminal SOPs are also seen in other countries. For example, a three-terminal SOP was trialled in the “Flexible Urban Network-Low Voltage” project in the UK to share capacity between substations.

Besides back-to-back SOPs and multi-terminal SOPs, an UPFC-based SOP is used in the ongoing project “Active Response to Distribution Network Constraints” in the UK [86]. This newly designed SOP will be installed to share power loads and optimize capacity between primary substations. Compared to back-to-back and multi-terminal SOPs, converters of UPFC-based SOPs are partially rated so as to reduce converter cost.

B. Between Public Distribution Networks and Grid Edge Networks

Projects of SOPs were also implemented between public distribution networks and grid edge networks, mainly including shipboard and railway distribution networks.

The shore-to-ship connection through SOPs attributes to the capability of SOPs to connect networks with different frequencies or voltage levels. In “Flender Shipyard” project in 2002, a 1MVA SOP manufactured by Siemens AG enables the power exchange between the shipyard and the shipboard network [80]. It not only enables power supply from the 50 Hz shipyard network to the 50/60Hz on-board network of the vessels, but also the reverse from the marine generator to the shipyard network. In 2007, similar solution was provided for the shipbuilding company FSG in Germany [92]. Through the installed SOP, the 5kV, 50Hz shipyard network could provide ships with different voltages and frequencies (440V/60Hz, 600V/60Hz, 690V/60Hz).

A good example for the SOP implementation between public distribution networks and railway electrification networks is the “E-lobster” project in Spain since 2018. A schematic diagram for this unique SOP is shown in Fig. 5 [93]. The SOP consists of an AC/DC converter connecting to a public distribution network and two DC/DC converters connecting to a railway network and the energy storage system, respectively. Such SOP can capture the regenerative energy of rail braking and use it to charge the energy storage, support the public distribution network, or both. Similarly, the excess of power generation within the public distribution network from renewables but not consumed locally, can also be stored in the energy storage. Therefore, both networks would benefit from this system, being able to reduce electricity losses. Moreover, equipped with the energy storage unit, the surplus energy of both networks can be stored and then used during peak load hours.

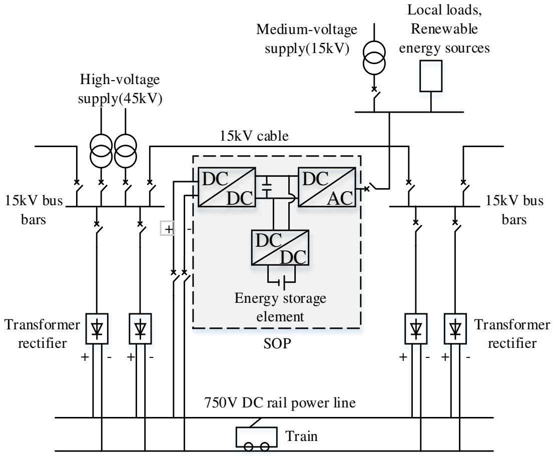

Fig. 5. Application of SOP between public and railway distribution networks.

VII. PROSPECT OF SOFT OPEN POINTS

The opportunities for future research and applications of SOPs are discussed in this section, with its paragraphs corresponding to the prospect of Sections II-VI, respectively.

For the topology of SOPs, the transformerless UPFC topology is promising, which can be achieved by cascade multilevel inverters [34], [35]. Under this innovative topology, the converters are partially rated. The bulky and expensive zigzag transformers, which are required by conventional UPFC for isolation and reaching high power rating with desired voltage waveforms, can also be removed. More attention should be paid to the control design, fault analysis and protection setting of transformerless UPFC based SOPs in the future. Another opportunity is to develop SOPs with reduced components by using emerging wide-bandgap power electronic materials such as silicon carbide (SiC). Owing to the advantages of 10 times higher breakdown electric field in SiC than in the conventional silicon (Si) material [94], it is practically achievable to implement SOP topology with less number of components. For example, simple two-level or three-level converters instead of MMC can be used in medium voltage distribution networks. Moreover, lower conduction losses and switching losses [94] can make SiC competitive in developing highly-efficient SOPs.

Benefit analysis of SOPs in distribution networks is one research focus since their invention. In the existing research, SOPs are expected to improve the performance of distribution networks under normal, three-phase unbalanced or fault conditions. It can be anticipated that in the future distribution networks will face adverse meteorological conditions due to climate change. SOPs in these adverse conditions can play a role in proactive power/voltage control from receiving the early warning signal of the coming event to the stage of post-event power/voltage restoration, which can enhance the network resilience. Compared to the extremely high cost of outages caused by the extreme meteorological events, the cost of SOPs is able to be justified.

From the control perspective, when using centralized control, the millisecond-level power controllability of SOPs is underutilized because centralized control relies heavily on fast and reliable communication and computation which are difficult and expensive to achieve in practical distribution networks. On the other hand, decentralized and local control do not fully utilize the global network information, which may sacrifice the optimality in SOP control. To deal with this dilemma, data-driven methods might be a good solution, which can use centralized methods for training based on the historical data and control SOPs in a decentralized manner, combining the advantages of both centralized and decentralized methods. For example, the multi-agent deep reinforcement learning-based approach for voltage control of distribution networks proposed in [95], [96] can be borrowed for SOP control.

As for optimal siting and sizing of SOPs, the great uncertainties of distributed energy resources are hard to be tackled. In particular, the installation of distributed generation of each customer is usually hard to be predicted, which brings great difficulty to the planning of SOPs. T. Yang et al [97] constructed the steady-state security region for a distribution network as the power injection space, which can quantify the overall hosting capacity of the network. This provides an alternative method to deal with the uncertainties of distributed generation, i.e., modelling the maximum accommodation capability of networks rather than predicting the future development of distributed generation of each customer. In addition to the siting and sizing of SOPs, the performance of SOPs in distribution networks varies with different SOP topologies. In this regard, the selection of SOP topologies can be an important topic in the planning of SOPs in the future.

In the industrial applications of SOPs, the cost justification is required due to the high cost of SOPs. To boost SOP implementation, how to reduce the cost of SOPs and increase the revenue from SOP applications need to be further investigated. New SOP topologies and applications in extreme meteorological conditions are promising, yet practical demonstration of them is indispensable. In addition to cost justification, the protection system for distribution networks with SOPs is imperative. While the self-protecting systems for SOPs are usually well equipped by the manufacturers, the protection of distribution networks under the fault of SOPs is of great concern for distribution system operators.

VIII. CONCLUSION

Existing academic research and industrial projects of SOPs in distribution networks have been comprehensively reviewed in this article. The findings are summarized as follows.

1) Existing SOP topologies include back-to-back VSCs, multi-terminal VSCs, UPFC and direct AC-to-AC MMC. Back-to-back VSCs, multi-terminal VSCs and UPFC are all indirect AC-to-AC topologies, consisting of multiple VSCs through a common DC bus for their connection. However, whether the connected feeders are isolated by the DC bus distinguishes UPFC topology from back-to-back and multi-terminal VSC based topologies. In contrast to indirect AC-to-AC topologies, direct AC-to-AC MMC topology has no intermediate AC/DC conversion stages, thus resulting in lower cost but the coupling of currents between connected feeders brings difficulties to the control and design of such SOP.

2) Academic studies on benefit quantification, control, and optimal siting and sizing of SOPs are summarized. The benefit quantification indices are identified as six categories: feeder load balancing, voltage profile improvement, power losses reduction, three-phase balancing, DG hosting capacity enhancement, and supply restoration. The control of SOPs can be structured as system-level, converter-level, and switching-level control. The system-level control, using centralized, decentralized, or local control strategies, determines the reference values (active power, reactive power, or DC voltage reference) for the converter level control, which generates modulation waves for the switching-level control to control transistors of SOPs. The optimal siting and sizing of SOPs is normally formulated as a single-level or bi-level mixed integer nonlinear optimization problem. The problem can be effectively solved by transforming the original optimization model to a mixed integer second-order cone programming model or by using intelligent algorithms for example genetic algorithm.

3) The practical industrial projects of SOPs worldwide are reviewed and classified as: within public distribution networks, between on-board and shipyard distribution networks and between public and railway distribution networks. Particularly for SOPs applied in public distribution networks, three typical SOP topologies, i.e., back-to-back VSCs, multi-terminal VSCs and UPFC have been demonstrated in existing projects.

4) The opportunities for future research and application of SOPs are identified. Transformerless UPFC and SiC-based two-level/three-level converters are promising topologies of SOPs. Benefit analysis of SOPs appear attractive in three aspects, i.e., network resilience enhancement and climate change adaptation, control of SOPs using data-driven method

and planning of SOPs through the analysis of network hosting capability. For practical SOP applications, cost justification of SOPs and well-developed protection systems need further investigation.

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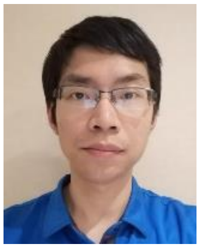

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