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Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received November 5, 2020, accepted November 13, 2020, date of publication November 20, 2020,
date of current version December 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3039552

Soft Open Point in Distribution Networks

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This work was supported by the Business Finland through the SolarX Research Project under Grant 6844/31/2018.

ABSTRACT The main objective of this article is to present a comprehensive review of soft open point (SOP), an emerging power electronics technology to maximize future distribution networks' (DNs) resiliency and flexibility as well as increase hosting capacity for distributed energy resources like photovoltaics and electric vehicles. The SOP is currently an active area of research and ongoing development of new control techniques for SOP and optimization algorithm for the optimal use of SOP in DNs produces new techniques until DN operators use it comprehensively in their systems. The motivation for this work is to present the research that has been completed for the SOP and summarize the duties of SOP in DNs according to the literature and propose advanced duties for SOP according to modern standards. Finally, future research directions are mentioned to pave the way for research in the coming years to drive the DNs towards more flexibility and 'Robust' from controllability, stability, and protection structure point of view.

INDEX TERMS Distribution networks, grid-connected converters, power electronics, soft open point, normally open points.

I. INTRODUCTION

Operation of the Distribution networks (DNs) is getting complex as more distributed energy resources (DERs) are installed along with the penetration of electric vehicles and demand-side resources. DNs gets overloaded from time to time due to different load types and intermittent nature of DERs connected to the feeders. As a result, voltage fluctuations occur in the network and need to be compensated to mitigate the voltage fluctuation. Presently, reactive power compensation devices like switched shunt capacitor banks (CBs) and on-load tap changer (OLTC) is used in DNs to mitigate the voltage violation within the network. But the response of these traditional devices is slower and not acceptable for the need of fast voltage control due to the penetration of DERs in DNs. Recently also more advanced power electronics (PEs) devices such as dynamic voltage conditioner [1] is proposed.

In traditional radially operated electricity DNs, back-up connection points between medium voltage (MV) feeders with remotely operated switch disconnects are typically called as normally open points (NOPs). In the future, these NOPs could be replaced by soft open points (SOPs) equipped with rapidly controllable PEs converters. The SOP is also termed as "SIPLINK" [2], "DC-link" [3]–[5], "MV direct current (dc) link (MVdc-link)" [6], Soft multi-state open point (SMOP) [7], Loop Balance Controller (LBC) [8], Soft normally-open point "SNOP" [9], [10] and "Back-to-back (BTB) system" [11] in the literature. The SOP is typically installed between two feeders integrated with large-scale of DER penetration in radial DNs where two converters are connected in back to back (B2B) mode. The basic topology of SOP is given in Fig. 1 as a single line diagram in DNs. Here the SOP in MV and low voltage (LV) DNs named MV-SOP and LV-SOP, respectively. In Fig. 1, only one LV DN from MV DN feeder is shown as an example and other LV DNs from the MV feeder are represented as load. Meshed DNs is not preferable as it needs sophisticated and costly protection arrangement to function whereas radial DNs is more preferred for its simplicity. The placement of SOP best suit at the feeder branch ends in radial type as they will be able to supply maximum loads during the isolation of a fault. SOP gives the advantage of both radial DNs having simple protection system and meshed DNs with higher reliability. SOP can serve the purposes without changing the current topology of the radial type of DNs. SOPs can be connected to the feeders

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The associate editor coordinating the review of this manuscript and approving it for publication was Ning Kang.

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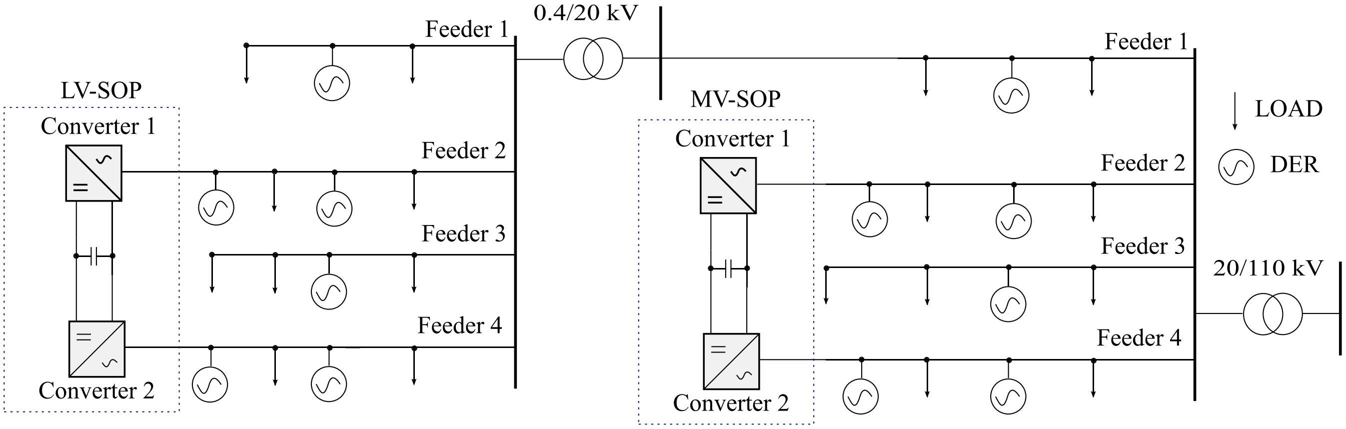

FIGURE 1. Basic topology and placement of SOP in DNs.

from the same substation of the equal voltage level. Also, it is possible to connect feeders by an SOP from different substations of distinct voltage levels as SOP can control the voltage level at each feeder independently. Potentially, SOPs could e.g. improve the local voltage profile, control the active power (P) and reactive power (Q) flows or limit fault currents to maximize the DERs hosting capacity of DNs.

In DNs, the term 'Flexibility' defines the capability of a system to regulate the controllable devices to adapt the uncertainties in the system due to DERs [12]. Flexibility allows the system to maintain high-quality performance by adapting to the operating environment. Possibility of coordination of SOP with devices like OLTC and tie switches will increase the flexibility of the system as SOP will aid these slow act devices to act fast. In [13], the cost-benefit of SOP in DNs by increasing the flexibility in the network is given where the option value of SOP is justified by a multistage stochastic framework. Results show that SOP helps to achieve a reduction in expected investment cost and operational cost. There are no standards that define the functions of SOP, but standards related to grid-connected converters for power quality improvements can be taken as a reference to define the duties of SOP.

The main goals of this article are:

- Conducting a comprehensive review of SOP from the beginning of the technology to the latest research till now.
- Defining the duties of SOP according to modern standards, existing literature, and future research directions.
- Explicitly mentioning the pros and cons of existing methodology regarding SOP and direction for future works.

According to the literature review, no previous work has been done on a comprehensive review of SOP technology, no standards is there to mention the duties of SOP and explicitly mentioning the future research possibility. At first, a general review of power electronics technologies in DNs along with SOP is presented. We then proceed with the SOP in present DNs and classification of SOP topologies. Then the functions of the SOP are defined according to IEEE standards, existing literature, and future research proposal. After that, basic control algorithm of SOP, control of SOP during normal and abnormal grid condition and optimization problems related to the operation of SOP in DNs is presented. The paper is finished by summing up some of the future research directions and conclusions at the end.

II. POWER ELECTRONICS IN DNs

Currently, OLTC does the automatic voltage control in MV DNs, which is primarily for unidirectional power flow. But the penetration of DERs in DNs needs bidirectional power flow control and demands the introduction of PEs technologies. Large-scale DERs are mostly connected at MV level as related types of equipment are lower in cost compared to the high voltage (HV) DNs. This introduction of DERs in MV level has a significant effect on the voltage profile. The use of PEs technology has been mostly in transmission networks and normally known as flexible alternating current transmission system (FACTS) devices. The research focus on PEs devices in DNs was not significant until the penetration of DERs in MV and LV DNs has forced to introduce new innovative PEs technology in DNs. In the following sections, some of the important PEs technology in DNs level are discussed briefly.

A. SOFT OPEN POINT

The main goals of SOP are load balancing within connected feeders by maintaining the voltage level within the limits and supply restoration (SR) after a fault in unfaulted parts of the feeders. SR is a process of supplying the power to the unfaulty part of the feeders which is out of the service immediately after the fault part is isolated. SOP provides faster SR process after a fault as it operates within few millisecond to restore the power supply whereas NOP takes hundreds of milliseconds. SOP also exhibit the function of other PEs devices like Static synchronous compensator (STATCOM), OLTC, shunt CB, Unified power flow controller (UPFC) and active power filter. Performance comparison of PEs technology like STATCOM, SOP, static series synchronous Compensators and UPFC in DNs for different conditions are considered in [14] and results show that SOP provides the greatest flexibility in DNs than other PEs devices. The operation principles of SOP during normal, balanced and unbalanced fault conditions are given in [15], [16] for power flow and SR control modes. These can be considered as the basic operation of SOP. Other benefits of SOP are:

- Improve the regulation of power flow in DNs within feeders for load balancing.
- The action of SOP is faster than the NOP as SOP is based on electronic switches where NOP is based on mechanical switches.
- Power quality will be improved by means of harmonics and unbalance current compensation and voltage support capability.
- Reduces the fault propagation by limiting the fault current as SOP is able to disconnect the fault side feeder within a few milliseconds in order to limit fault current propagation [15], [16].

B. UNIFIED POWER FLOW CONTROLLER

UPFC is a power electronics-based FACTS device that is mainly used in the transmission system to control P and Q flow through the transmission networks and basic topology of UPFC is shown in Fig. 2 [17]. UPFC is based on two converters, connected through a dc-link capacitor. In Fig. 2, left-side converter is connected in shunt across a parallel transformer and right-side converter is connected in series through a series transformer. The main function of the series converter is to control the magnitude and angle of the injected ac voltage to the line by controlling P and Q at the point of common coupling 1 (PCC^1). PCC is a point where the converter and grid are connected together. The shunt converter provides P needed by the series converter and independently compensates the Q at the PCC 2 (PCC^2). Here Z_T is the transmission line impedance.

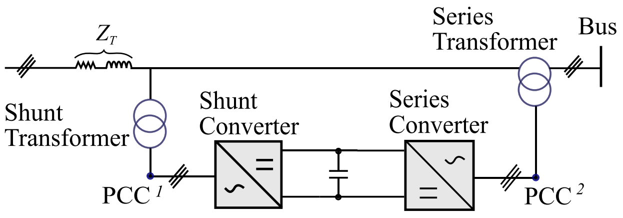

FIGURE 2. Basic topology of UPFC in transmission networks.

UPFC research is related mostly to transmission networks and few research has been done for UPFC in the DNs, where it is known as distribution-UPFC (D-UPFC). D-UPFC performs the function of an autotransformer, controls the voltage of the DNs during voltage sags and swells in [18], where the location of the D-UPFC is after the pole transformer and connects with the load side. D-UPFC as a centralized controlled device in DNs performs the regulation of load voltage and loss minimization in a single loop formed by two feeders from the same substation, single loop formed by two feeders from two different substations and multiple loops formed by three feeders from same substation in [19], [20]. Experimental results show that D-UPFC helps to maintain the node voltage within the limit in all types of loop mentioned above along with loss minimization. Compare to SOP, D-UPFC also helps to connect two feeders to control the power flow and maintain the voltage profile within the feeders during normal condition. But connection of multiple feeders by D-UPFC and performance of D-UPFC is not been evaluated during faults in DNs, which needs more attention.

C. SMART TRANSFORMER

Smart transformer (ST) is also known as "Solid-State Transformer (SST)" and introduction of SST was in 1968. ST has the ability to control the bidirectional power flow and works as a communication hub between grid and microgrid. As a result, ST is known as 'Energy Router' as it resembles the duties of router in an internet network and works as a communication hub to regulate data within the local grid and data center.

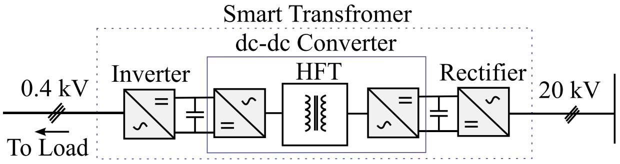

FIGURE 3. Basic Configuration of smart trandormer in DNs.

The three-stage configuration is the most popular and suitable for ST as it makes the dc-link connectivity available as shown in Fig. 3 [21]. The three-stage configuration has three-power electronics module stage hierarchically as the rectifier, dc-dc converter which incorporates a high-frequency transformer (HFT), and inverter. The modular architecture of the ST has better aspects than non-modular and semi-modular architecture [22], [23]. By means of ST, there is isolation between the grid side and load side, which prevents load side low power factor and harmonic pollution to affect overall DNs and eventually minimize the overall loss in the DNs [24]. The purpose of ST is P and Q control, harmonic compensation, voltage support, work as active filter, reverse power flow limitation and optimization of energy flow.

The integration of DERs and battery energy storage (ES) using the dc-link of ST is an excellent feature. Also, the microgrid can be represented as an individual controllable entity to the grid using the dc-link. As a result, the utility grid doesn't need to communicate with the microgrid elements and only needs to communicate with the ST [25]. This results is the increment of flexibility for power transfer within the microgrid and utility grid.

The performance of an ST in smart grid environment has been experimentally demonstrated for LV DNs in [26].

Hardware implementation combines energy regulation devices along with the control platform for communication purposes. The result shows the acceptable performance for Q compensation, voltage regulation, and microgrid integration but the efficiency of the ST is far away from the conventional transformers. The efficiency of the proposed ST is around 92% for dc load and 84%–88% for both ac and dc load. Although, the targetable efficiency for the transformer is about higher than 97%. According to several international standards, the distribution transformers have efficiency over 99% and target efficiency for ST in literature is around 96%-98% [23]. In addition, the weight of the transformer is also a major issue according to the efficiency of the transformer.

TABLE 1. Functions of PE Devices in DNs.

Functions	D-UPFC	ST	SOP
Reactive power compensation	Yes	Yes	Yes
Active Power Control	Yes	Yes	Yes
Load balancing	Yes	Yes	Yes
Number of Converters	Two	One to Three	Two or more
Fault Isolation Capability	No	No	Yes
Connected number of Feeders	One or more	One or more	Two or more
Location in DNs	After pole transformer in DNs feeder	Replacing the pole Transformer	Typically at the End of the Feeders
Bidirectional Power Flow	No	Yes	Yes

Table 1 summarizes the function of PEs technologies in the DNs level and it can be seen that SOP can perform most of the functions and can replace the other PEs technologies to minimize the cost in DNs. Also, UPFC and ST analysis is confined within balanced power system conditions and typical voltage fluctuations like voltage sags and swells. But their operation during abnormal conditions like balanced and unbalanced fault has not been considered or defined in previous works in literature.

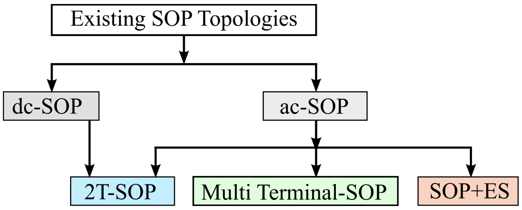

FIGURE 4. Classification of SOP topology.

III. EXISTING SOP TOPOLOGIES

SOP can be divided into two categories- ac-SOP and dc-SOP, depending on the type of ac and dc DNs, respectively. SOP is classified into three categories based on the topology as two-terminal SOP (2T-SOP), multi-terminal SOP (MT-SOP) and SOP with ES named as SOP+ES. Fig. 4 shows the classification of SOP.

A. 2T-SOP

The basic SOP as mentioned earlier in section I, contain two B2B converters and will be called as two-terminal SOP (2T-SOP) in this article and showed in Fig. 1.

B. MT-SOP

The basic 2T-SOP has been improved to enhance the performance of SOP as three-terminal (3T-SOP) shown in Fig. 5, where three feeders are connected together by SOP. Here in Fig. 5 the SOP is shown for MV DNs for simplicity and is same for LV DNs. The idea of 3T-SOP can be enhanced to connect more feeders and called as of MT-SOP. The purpose of the MT-SOP is to connect the most vulnerable feeders having large-scale of DERs and loads in the DNs to balance the power flow within the feeders.

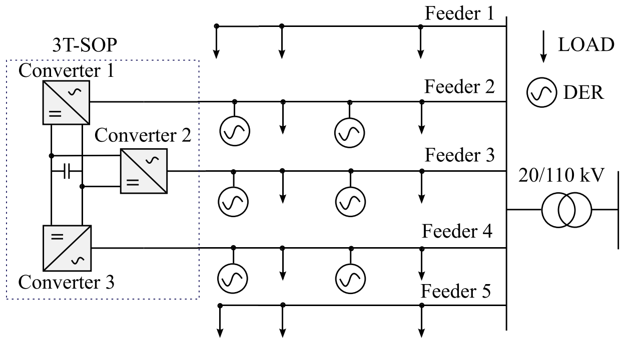

FIGURE 5. Basic topology of 3T-SOP in DNs.

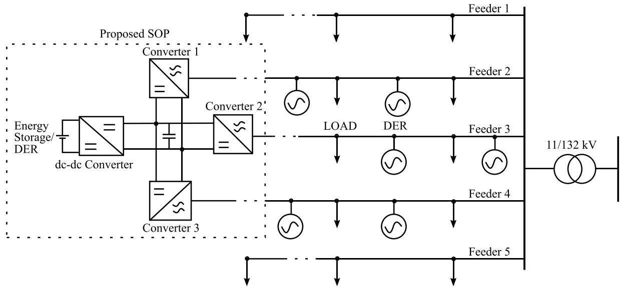

FIGURE 6. Basic topology of SOP+ES.

C. SOP+ES

SOP with ES or DERs connected in the dc-link is also an exciting novel topology for SOP technology, will be called as SOP+ES and it is showed in Fig. 6. The maximum hosting capacity (MHC) of DERs in DNs is enhanced for having SOP+ES instead of other SOPs, which is demonstrated in [27]. SOP+ES helps to aggregate the ES in one place rather than placing them scattered in the DNs. Also, the cost of putting an ES system will be less, as ES is a must need for modern DNs due to the intermittent nature of connected DERs. SOP based on voltage source converter (VSC) along with bidirectional Dual active bridge (DAB) dc-dc converter with ES coupled in dc-link is considered for SOP+ES application in [28] and sizing of ES connected in the dc-link is discussed in [29]. DAB converter output voltage is controlled by one of the VSCs as it is responsible for the control of the dc-link voltage (u^{dc}).

D. dc-SOP

The concept of dc-SOP is first introduced in [30] in a hybrid ac/dc DNs along with ac-SOP. The dc-SOP is based on a bidirectional dc-dc converter having a HFT and two VSCs as shown in Fig. 7, connected between two MV dc feeders. The dc-SOP provides P flow control and voltage regulation capability. One of the VSCs controls the dc power flow and other controls the ac power through the transformer and can switch functions when needed during fault conditions on both sides of the feeder.

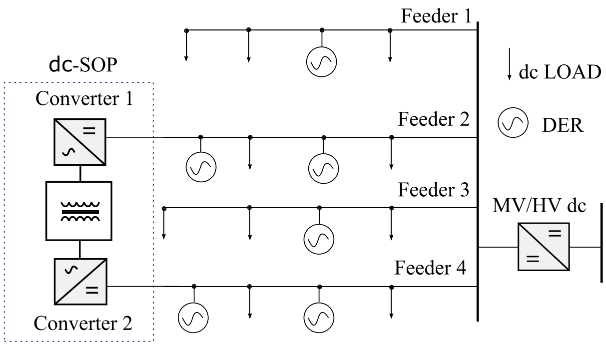

FIGURE 7. Basic topology of dc-SOP.

E. SOP CONFIGURATION AND CONVERTERS

The converters of SOP are connected in B2B mode for 2T-SOP having bidirectional power flow control ability and many suitable converter options are available. Among them, two-level VSC [15], [16] is vastly used for SOP and modular multilevel converter (MMC) is used by some literature, where MMC is consider for its' lower switching loss and HV quality [31]. B2B modular multilevel matrix converter (M^3C) and MMC as SOP are considered in [32] and their operating areas for P and Q exchange ability are evaluated for 2T-SOP. Simulation results shows that the operating range of MMC is much wider than M^3C as the converter of SOP. Also UPFC configuration as SOP [29], cascaded H-bridge (CHB) and multi-active bridge (MAB) converters [34] are considered for SOP. Topologies like neutral-point-clamped three-level converter can also be considered in future. Table 2 summarizes the SOP configurations along with converters type used in the literature.

IV. IMPLEMENTATION CHALLENGES OF SOP IN DNs

The main challenges regarding SOP to implement in DNs are the size and cost of SOP, functions of SOP in DNs, economic analysis of SOP, and how SOP can affect the protection scheme. These challenges are explained in the following sections.

TABLE 2. Converters and configuration of SOP.

Configuration of SOP	Converter Type	Reference
B2B	VSC	Most of the literature
	MMC	[7], [31], [32], [33], [51], [63], [64]
	M^3C	[32]
	Electric Spring	[76]
	CHB, MAB	[34]
UPFC configuration as SOP	VSC	[29], [76]

A. SIZING OF SOP

The maximum size of SOP doesn't entirely depend on the amount of DERs penetration but mostly on the requirement of power need to supply the connected loads during the isolation of a fault [10]. Voltage variation is smaller when SOP rating is high for a network but inadequate size and cost of the SOP is also a limitation [35].

B. DUTIES OF SOP DURING NORMAL AND ABNORMAL CONDITION IN DNs

The SOP is a grid-connected converter and the main purpose is to improve the power quality of the DNs. An IEEE Guide for the application of PEs for power quality improvement of DNs [36] and [37] mention the responsibilities of PEs converter like dynamic voltage restorer, static voltage regulator, static transfer switch and distribution STATCOM. Standards like IEEE1547-2018 [36], [38] and operations perform by SOP mentioned in literatures are considered to define the operation standard of SOP in DNs, are given in Table 3.

The duties for SOP+ES can be extended as it has the ability to supply P according to the need at PCC, are given in Table 4. According to the modern grid codes and several standards, the strictest continuous operation limits for frequency (f) is around 47.5–52 Hz and the most extreme f limits is 46.5–53.5 Hz [39]. Control of f in feeders connected by SOP is very important to maintain the stability of the power system during normal and abnormal operations like phase-angle jump. During short-duration unbalanced faults, Fault ride through (FRT) operation by SOP can be performed by injecting an unbalanced reactive current by the inverter at the faulted feeder. Positive sequence reactive current injection is needed to boost the positive sequence voltage and negative sequence reactive current injection is needed to mitigate the negative sequence voltage during an unbalanced fault condition. As a result, phase voltages and currents at the PCC can be kept within the desired limit. Other functions of SOP like fault identification [40] can also be included in the duties of SOP.

C. SOP AND PROTECTION SYSTEM CONFIGURATION

The existing fault protection configuration in DNs is current based protection, where protection devices work according to the current through the line. But DERs connected into

TABLE 3. SOP operation standard according to IEEE standards and literature.

Duty	Description of the Duty	Condition	Ref.
Power flow control	SOP should have the ability to manage the load balance within feeders by controlling the output P and Q during normal conditions	Normal	[15], [16]
Voltage Regulation	Dynamic voltage support by means of supplying or absorbing reactive power in Volt\Var mode	Normal	clause 5.3 [38], clause 6.3 [36]
Supply restoration	SOP should supply the power to the unfaulty part of the feeders which was out of the service immediately after the fault part is isolated. It should also restore the connection with grid after the fault is cleared by the protection system in DNs.	Abnormal	[15]
Voltage disturbance Ride Through	Minimization of the total power losses, the voltage, and current unbalanced conditions	Abnormal	clause 6.4.2 [38], clause 6.2 [36]
Low-voltage Ride-through (LVRT)	For temporary low-voltage disturbance, SOP should have LVRT capability, should maintain synchronism with grid, should not trip and restore the voltage at PCC	Abnormal	clause 6.4.2.3 [38], clause 6.2 [36]
High-voltage Ride-through (HVRT)	For temporary low-voltage disturbance, SOP should have HVRT capability, should maintain synchronism with grid, should not trip and restore the voltage at PCC	Abnormal	clause 6.4.2.3 [38], clause 6.2 [36]

TABLE 4. SOP+ES operation standard according to IEEE1547-2018 standard and according to future research direction.

Duty	Description of the Duty	Condition	Ref.
Frequency disturbance ride-through (FDRT)	For temporary frequency disturbance, SOP should have FDRT capability, should maintain synchronism with grid, should not trip and restore the frequency at PCC	Abnormal	clause 6.5.2 [38], clause 6.2 [36]
Fault Ride Through (FRT)	For temporary unbalanced faults, SOP should have FRT capability, should maintain synchronism with grid, should not trip and restore the voltage at PCC	Abnormal	According to future research direction

the grid contribute the fault current during a fault in DNs, as a result, the malfunction of relay protection and automatic reclosing function failure can occur and lead to a permanent fault [41]. The fault current contribution from DERs can be regulated within the limit of the existing protection system due to the current control loop of converters in SOP, which helps to reduce the faults affect in DNs. SOP can also be used to perform FRT operation to limit the fault current as mentioned in Table 4. In [42], an algorithm based on outer power and inner current control loop along with an error suppressor control method to limit the contribution of fault current from SOP is given for the accurate operation of feeder automation system to support the faulty feeder during a short term balanced faults. A protection scheme named as ‘Asset guarding’ is defined in [43] to protect the SOP from the network and also protect the network from the operation of SOP in normal condition. SOP should deliver the voltage within the defined limit and also maintain the current within limits in feeder and the transformer.

D. ECONOMIC ANALYSIS OF SOP AND CONVERTER EFFICIENCY

One of the main challenges to implement SOP in DNs is the recognition of economic benefit in terms of installation and maintenance cost of SOP compared to the traditional network. Economic analysis of SOP installation and maintenance is presented in [44] to show the benefit of SOP. SOP helps to reduce the annual cost of the DNs compared to the DNs without SOP and it is cost effective to install SOP according to the analysis. An optimization model is proposed in [45] to find the optimal size and location of SOP to minimize the annual cost of the DNs includes capital cost, yearly energy loss, and the operational cost of SOP. Simulation results on a modified IEEE 33-node network and a real DNs model considering the penetration of DERs shows that the SOP helps to reduce the total annual cost by 29.7% and 23.6% compared to the network without SOP. The results presented in the literature to show the benefit of the SOP are all based on simulation. To get an actual view of the economic benefit it is needed to verify the result in real DNs, which has not been mentioned in any literature till now.

The efficiency of SOP is discussed in literature in terms of power loss and cost minimization. In most of the cases the advantage of SOP to reduce the operational cost and power loss minimization is considered by considering the SOP efficiency. Most of the paper has considered the efficiency of SOP as 98% [45], [46]. The efficiency of converters mostly depend on the operating load which is given in [47].

V. CONTROL METHODS FOR SOP IN DNs

The control of SOP is different than other grid-connected converters as SOP is connected at least with two feeders. Fig. 8 shows a basic block diagram of SOP where two converters are controlled in closed-loop control method having multiple loops to achieve optimal performance during normal and abnormal grid conditions. The superscript 1 and 2 represents the left side and right side converters and their corresponding parameters, respectively in Fig. 8. The Q control of each converter is independent which depends on the power rating of the converter and P flow is dependent on both converters.

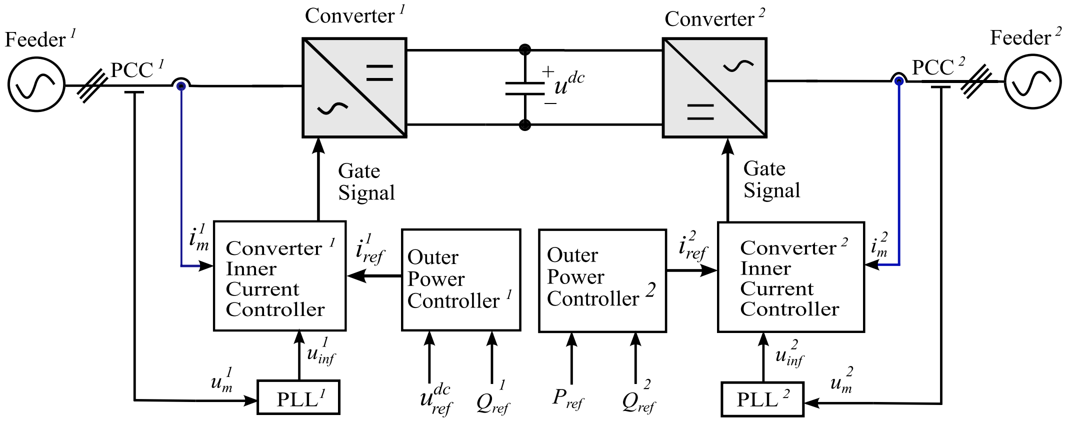

FIGURE 8. **Block diagram for the control of 2T-SOP in DNs.**

Each converter in Fig. 8 has mainly three control block, named as outer power control loop, inner current control loop and phase-locked loop (PLL). The PCC voltage (u_m) between SOP and feeder's and line current (i_m) are usually main feedback parameters in multiple loop control method. The outer power control loop takes the power references as active power reference (P_{ref}), reactive power reference (Q_{ref}), dc-link voltage reference (u_{ref}^{dc}) as input and generates the current references (i_{ref}) for inner current control loop, where P_{ref} and u_{ref}^{dc} can be given either of the converters, depend on the control algorithm. Then, informations of u_m from PLL is given as input to the inner current control loop, which finally generates the pulse width modulated (PWM) gate signal for the transistors of the converters.

The PLL is one of the major control blocks and plays important role for grid-voltage synchronization algorithm which extracts the accurate information of PCC voltage as phase angle, f, and positive- and negative-sequence value of the voltage by means of PLL. This information helps to generate the current references, which ultimately produce P and Q according to the reference and plays one of the major parts to control the SOP. In Fig. 8, (u_{inf}) is the information of PCC voltage extracted by PLL.

A. CONTROL OF SOP DURING NORMAL CONDITION

Control of SOP during normal grid condition is known as power flow mode control where the main objective is to deliver required P and Q to maintain the voltage level within the acceptable range and balancing the load between the connected feeders. The traditional vector control method in synchronous d–q reference frame based on proportional-integral (PI) controller is the most used technique for the control of three-phase VSCs for its acceptable performance [48] and used in most of the literature to control the converters of SOP.

SOP based on two VSC in B2B mode is given in [6], [15], [16], [49], [50] where two VSCs control u^{dc} and P, separately along with independent Q control i.e. one in P–Q and another one in u^{dc}–Q control mode. In this mode of operation, both VSC are working in current source mode.

A new control technique named as switch-mode is proposed in [35]. The objective of the switch mode control technique is to maintain the zero voltage difference between two PCC voltages to balance the operation of the connected feeders, although the detail control algorithm in d–q reference frame is not given. Simulation results in [35] show that switch mode control is suitable for urban radial type network during normal condition as it helps to achieve optimal power flow regulation and less voltage variation.

Resistance-reactance R/X ratio data of lines in DNs is used to generate the P_{ref}, Q_{ref}, u_{ref}^{dc} in [51] for voltage support during balanced voltage drop. In [51], 3T-SOP is based on half-bridge MMC where two MMCs are working in P–Q and another one in u^{dc}–Q control mode. Voltage support depends on the injection of active and reactive current based on the various values of the R/X ratio where voltage magnitude changes on the values of the R/X ratio. 3T-SOP based on half-bridge MMC for u^{dc} and power flow control based on d–q reference frame is given in [31], [33]. Droop control strategy is proposed to adjust the droop coefficient according to the active power demand in real-time for DNs [31]. Here MMCs are responsible for P and Q control along with droop control for the network. The proposed method is more sensitive to power and u^{dc} fluctuation compared to the system that has a conventional droop control technique.

The average model of the converter used in the simulation model to develop the control algorithm for SOP is a major drawback for most of the literature mentioned above. The switching model of the converter is more beneficial over the average model for real-time utilization of power converters in the simulation model [52]. A detail model of the converter is given in [16] and one of the main contributions is the introduction of a zero component controller in the inner current control loop to mitigate the dc offset to the injected current due to impedance mismatch between two feeders in three-phase four-wire system. Also, an independent volt/Var droop control method is proposed to generate Q_{ref} for the SOP.

B. CONTROL OF SOP DURING ABNORMAL CONDITION

During a fault in any one of the feeders connected by SOP, the function of SOP includes SR, fault current limitation, u^{dc} fluctuation control and can be extended to FRT during short-term faults and frequency control as mentioned in the proposed standard above.

1) SUPPLY RESTORATION MODE CONTROL

During SR mode, the power supply is restored for the isolated loads in the faulty feeder connected by SOP, where the converter of this side acts in voltage source mode to supply required voltage along with stable frequency. Another converter connected with unfaulty feeders, is in normal current source mode of operation. After the clearance of the fault, the converter again goes back to its normal current source mode. In [15], SR mode is given for a 2T-SOP, where VSC connected with faulty feeder act as voltage source and other VSC controlled in u^{dc}–Q mode.

2) CONTROL OF DC-LINK VOLTAGE OSCILLATION

One of the main goals of SOP control is the smooth operation of u^{dc} during power fluctuations and abnormal conditions to control the P flow accurately. Oscillations in u^{dc} could result oscillations in power delivered by SOP and not acceptable.

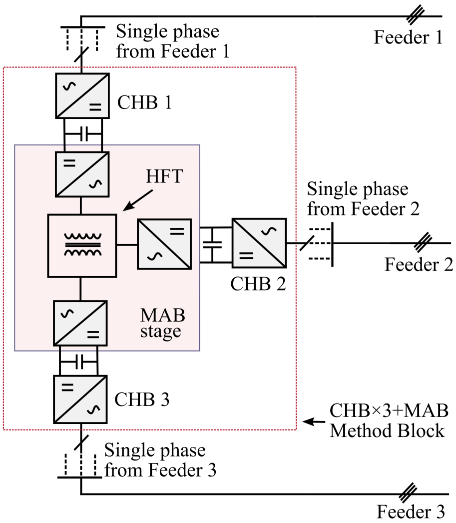

FIGURE 9. Simplified block diagram of CHB×3+MAB method for a single phase line.

The u^{dc} control during power fluctuation is studied in [34] for a modularized structural ST based 3T-SOP consisting of CHB and MAB converter. The combination of these two converters named as CHB×3+MAB method, which was introduced previously in [11], [53]–[58]. In the CHB×3+MAB method, three bidirectional converter stages named CHB are needed for each phase of a feeder and three phases from three feeders are connected in the MAB stage based on bidirectional dc/dc converter incorporating an HFT, as shown Fig. 9. Here, Fig. 9 represents the CHB×3+MAB method block needed for a single-phase connection. A similar three individual blocks are needed for three-phases to connect with 3T-SOP. MAB block manages the power transfer between three terminals of CHBs and balances the u^{dc} of each phase. The three CHB blocks also control the u^{dc}, whereas in other methods u^{dc} is controlled by individual CHB, which is vulnerable to system failure. Therefore, u^{dc} is controlled by three CHB along with MAB and called CHB×3+MAB method. One of the main advantages of this method is that it secures stability by maintaining the u^{dc} if any of the feeders are down or failed due to fault. Also, this method is useful for LV DNs as each phase can be controlled individually. Although, due to the use of many PEs converters, the cost of the proposed system can be one of the main drawbacks along with the complexity of the control algorithm.

A bidirectional B2B VSC named as synchronverter introduced in [59], used as SOP in [60]. The converter resembles the function of a synchronous machine having the ability to supply loads and voltage regulation by controlling the output voltage, power angle, and f. A control algorithm based on the synchronverter control principle in d–q reference frame for u^{dc} and fault current control is given for fault conditions. Simulation results in [60] are given for normal and extreme abnormal conditions having fast load and DERs supply change, where feeder voltage and u^{dc} are maintained within the limit but the frequency is not within accepted range going below 46 Hz.

3) FAULT CURRENT LIMITATION

The contribution towards fault current by DERs during a fault in DNs is one of the common issues and fault current contribution by DERs depends on the type of DERs [61]. Simulation results in [61] for a fault in a busbar demonstrate the fault current regulation capability of SOP. During a fault, two feeders from the busbar are connected by a tie switch to exchange the power from heavily loaded feeder to lightly loaded where fault current in one of the feeders exceeds the protection system ratings due to contribution by DERs and another feeder. For the case of SOP instead of tie switch, results show that SOP can prevent the rise of fault current in one of the feeders due to the contribution from another feeder and DERs. Thanks to the current limiting ability of the current control loop of converters in the SOP.

4) FAULT IDENTIFICATION

Identification of fault i.e. Fault index by utilizing SOP is given in [40], [62]. Fault index can only provide the information of the fault i.e. does any fault occurred or not, but cannot provide the information about the fault type. The performance of SOP to identify the fault during unbalanced fault condition is evaluated for three types of short-time faults in [40] and results show that the three-phase fault is most dangerous as saturation current flows at PCC. The fault duration is chosen lower than the time required for the protection devices in DNs to isolate the feeder and no action is taken by SOP to mitigate the fault at the PCC. In [62], Fault index is defined by measuring the positive- and negative-sequence current at the PCC during an unbalanced temporary fault. Results show that during an L-G fault of a period of 0.6 s, Fault index has the ability to identify the fault within a cycle (0.02 s) and switching of transistors can be blocked immediately, whereas the conventional system takes up to 30 cycles (0.6 s) to detect the fault.

5) FAULT RIDE THROUGH

FRT application by SOP based on a B2B half-bridge MMC is proposed in [63]. The simulation result is given for unbalance current compensation using negative sequence current compensation method during unbalanced faults. But there are oscillations in u^{dc} and P, due to 2ω oscillation, which affects the power flow on the feeders and advanced PLL is needed to mitigate the 2ω oscillation.

6) FREQUENCY CONTROL

In [64], an adaptive droop control technique based on variable droop coefficient is proposed to control the f and the MT-SOP is based on MMC. The adaptive droop control technique is based on the "Virtual Inertia" of the dc-link of the SOP, where there is a proportional relationship between dc voltage and ac output power of SOP. For the simulation experiment, SOP is connected to four terminal and different control objectives are defined for four MMC. Results show that adaptive droop control helps to maintain the f stable during a change in active power and load in a network, but abnormal condition is not considered.

All of the methods mentioned above use conventional PLL blocks in the control algorithms. Conventional PLL performs well during balanced condition but their performance is not acceptable during unbalanced conditions due to the "Double frequency oscillation" and can be termed as 2ω oscillation [65], [66]. The 2ω oscillation arises due to the coupling of the positive and negative voltage sequences during unbalanced conditions. To overcome this problem, three grid-voltage synchronization algorithms in d–q reference frame has been evaluated in [67] during unbalanced conditions and results show that decoupled double synchronous reference frame PLL performs faster than other synchronization methods. A synchronization algorithm having the technique of adaptively tuning the control parameter of PLL according to the fault at PCC for the faster and accurate response of grid-connected converters is proposed in [68]. Adaptive tuning of the control parameter is taken into consideration, as the parameter of the proposed algorithm can be tuned according to the type of fault and provides a faster response than other conventional PLL, is required for PLL in SOP.

The summary of the control of SOP during normal and abnormal grid conditions is given in Fig. 10. Control of SOP during abnormal condition needs more research to satisfy the operation standard of SOP given in section IV to satisfy modern standards.

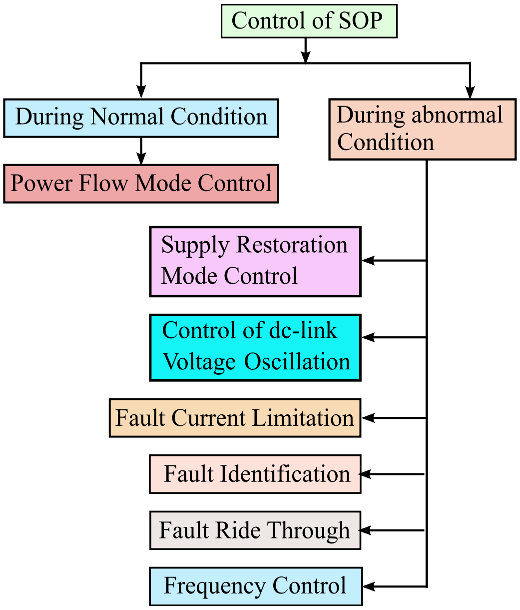

FIGURE 10. Summary of Control of SOP in DNs.

VI. OPTIMIZATION OF DNs CONSIDERING SOP

The optimization of DNs is obtained by solving optimization problems to optimize the use of resources like CB, OLTC, NOP, SOP, etc in an efficient approach. Optimization algorithms are formulated to solve optimization problems and many optimization methods are used to solve the problems. Optimization algorithms have been formulated incorporating the functions provided by SOP in numerous literatures. In an optimization algorithm, the response of SOP is taken as fast and accurate for P and Q supply and other operations performed by SOP in the normal balanced condition in most of the literature. So, the optimization algorithm has been developed by focusing on normal power system conditions and does not consider fault conditions. The purpose of this section is to present the various type of optimization problems mentioned in the literature, the objectives, and the objective functions along with results in a brief. At first, the optimization problems regarding MV DNs are presented according to the optimization objectives. Then a few optimization problems regarding voltage unbalance mitigation in three-phases for LV DNs are given.

A. VOLTAGE PROFILE IMPROVEMENT AND POWER LOSS MINIMIZATION DURING NORMAL CONDITIONS

Voltage profile maintenance refers to keep the voltage profile within the acceptable range mentioned by DN operators. Many optimization algorithms were proposed in the literature having the main objective to improve the voltage profile in feeders. The SOP connected within feeders performs its main duty by delivering the required P and Q demand by the optimization algorithm. Some of the important optimization problems are discussed below.

Network Reconfiguration (NR) in DNs is a technique of altering the state of the switch (open/close) to obtain the optimal power flow by satisfying the network operational objective. the optimization problem for NR using SOP is proposed in [69], [70]. The multi-objective functions are minimizing the power loss, load balancing and maximizing the DER penetration level. Results show that the NR method using SOP outperforms the NR method which does not use the SOP. The multi-objectives of the optimization algorithm in [71]–[73] are to maintain the voltage profile and minimize the power system loss. For [71], [72] the optimization objective functions are minimizing the size and find the optimal location of DER and SOP in DNs. The optimization objective functions in [73] are minimizing the active power loss and feeder load balancing. Results in [71] show a 10% power loss reduction and a 12.6% voltage deviation index improvement for systems having SOP than without SOP.

In [75], an optimization method is formulated using the ''Jacobian matrix'', based on voltage and current 'sensitivity' to analyze P and Q injection by SOP during variable load and generation situations. Optimization objectives are voltage profile improvement, feeder load balancing and energy loss minimization where objective functions lead to the optimal dispatch of the SOP's P and Q. The optimization model helps to reduce the power loss, improve the voltage profile along with load balancing and increase the DERs hosting capacity according to the simulation result in [75]. A Biconvex optimization problem is formulated to improve the voltage profile by minimizing the voltage deviation in [76]. In [76], SOP and DERs converters are considered as Q injection capability and series impedance, respectively. A new type of SOP using Electric Spring [77], normally used in series within distribution feeder and load is introduced in [76] as SOP. Different IEEE node networks were evaluated for the proposed method and simulation results showed that the voltage profile improved during light and heavy loadings.

The SOP+ES topology has also been considered in [78] for an optimization problem. The objectives are to minimize P loss and improve the voltage profile of the DNs. The objective functions are minimizing the losses of the network, converters of SOP and ES. Simulation results in [78] show that the proposed model exhibits less power loss compared to the networks having no SOP or SOP+ES.

Load balancing within feeders and voltage profile maintenance are the main optimization objectives in [10]. The objective functions are loss minimization and feeder load balancing considering the penetration of DERs. Simulation results for the real DNs model of the UK are given for the proposed optimization algorithm. The comparisons of SOP performance with other solutions like static VAR compensator, OLTC, and dynamic OLTC are given for urban, rural and mixed DNs types. Results show that SOP combined with OLTC in a network helps to achieve the highest DERs penetration along with an acceptable voltage level. But the economic feasibility for the installation of two devices together in DNs needs to be investigated. MT-SOP is considered in [79] having the optimization goals to maintain the feeder load balancing and increase the economic efficiency of the DNs. Interval control based load balance technique is used in [79]. Simulation results on the modified IEEE 33-node network show that 3T-SOP helps to maintain the current loading for each feeder within the desired level by properly maintaining the P and Q flow within the network. Feeder load unbalanced condition and total power loss have been reduced by 18.30% and 39.10%, respectively compared to the network without SOP and with high photovoltaic (PV) penetration.

B. VOLTAGE PROFILE MAINTENANCE DURING FAULT CONDITION

Most of the optimization problems studied in the literature are formulated for normal balanced conditions rather than fault conditions. Voltage profile maintenance of supplied voltage after a fault using SR method is considered as an objective for the optimization problems in [80]. Multiple Microgrids named as networked microgrids (NMGs) connected by SOP along with the grid in DNs are considered in [74] to design a SR model. Routing repair crews (RRC) and mobile battery-carried vehicles (MBCV) are also considered along with SOP-NMGs for the fast restoration of loads during outages in DNs. The objective of the algorithm is the fast restoration of high-priority loads. The function of the optimization problems are to maximize the P supply for the restored loads in [74], [80] . Simulation results in [80] show the high efficient capability of the proposed SR model for the amount of load restored after a fault compared with the mechanical tie switches. Simulation results in [74] for the modified IEEE-33 node network showed that the network with RRC, MBCV, and SOP-NMGs perform faster load restoration during outages than other network conditions without the SOP. Three connected IEEE-69 node network is also considered to verify the proposed algorithm in [74] and the result shows that network with SOP-NMGs helps to restore the loads faster by 31% compared to the network without SOP-NMGs. Self-healing capability of active distribution network through SR employing multiple SOP is given in [81]. Main focus is to assess the effect of SR for overlapped areas of two SOP and location of SOP and capacity of SOP are also consider to formulate the optimization problem. Simulation results shows that multiple SOP aids SR process significantly when faults happen in a node where two terminals of SOP is located in that node.

Islanding operation during faults in DNs based on SOP along with the coordination of DERs and ES is considered in [82]. The objective function of the proposed robust optimization algorithm is the maximization of P to the restored loads after the isolation. During a fault, both feeders are isolated from the main grid. One of the VSC of SOP works in u_{dc}-Q control mode in which feeder controllable DERs and ES are connected. In other feeders where no controllable DERs and ES are not connected, the VSC2 works in u-f control mode to control the voltage and frequency in that feeder after the isolation. Simulation results on a modified IEEE 33-node network show that the proposed optimization algorithm based on coordinated control of SOP, DERs, and ES helps to restore 82.2% load of the isolated network after a fault. Also, a comparison between the proposed optimization method and deterministic optimal operation method shows that during the worst case of PV uncertainties the proposed method helps to restore 87.35% load while the deterministic optimal operation method restores 80.35% load.

C. CAPABILITY EVALUATION OF SOP FOR DER HOSTING CAPACITY IN DNs

One of the ultimate objectives for the use of SOP in DNs is the MHC of DERs in DNs and every other objective revolves around this objective. Optimization algorithms were formulated to evaluate the hosting capacity of DERs in DNs considering SOP in [27], [70], [83] and the objective function is to maximize the hosting capacity of DERs. Simulation results in [83] showed an increment of 48.54% of hosting capacity of DERs with SOP in the example network than without SOP. A "Flexibility evaluation model" is developed in [27] and evaluate to compare the benefit of 2T-SOP, 3T-SOP, and SOP+ES. Results showed that SOP+ES helps to increase the hosting capacity by 16.84% contrast to a network without SOP and also outperformed the other SOP topology.

The robust optimization method is proposed in [84] to cope up with the uncertainty of PVs to mitigate the voltage limit violation. The simulation result for a modified IEE-33 network shows that the robust optimization helps to maintain the network voltage magnitude within the defined limit with the help of SOP compared to the deterministic optimal operation method that violates the voltage magnitude limit during the penetration of PV power during peak hour.

A decentralized control based on an alternating direction method of multipliers (ADMM) algorithm is proposed in [46] to improve the efficiency of the optimization calculation having the objective function as the minimization of voltage deviation in each sub-network. Decentralized control interprets to divide the DNs areas into sub-networks under local controllers. SOP is taken as the center of sub-networks to implement decentralized control. Each sub-network is controlled by SOP depending on the intra-area measurements and nodes voltage-to-power sensitivity. Then if needed, the operation strategies are improved by inter-area communication between sub-networks. IEEE-33 node network has been divided into four sub-networks having four SOP for the simulation purpose and results show that the proposed algorithm maintains the minimum voltage deviation during 0-140% DERs penetrations compared to other conventional techniques.

D. OPERATION COST MINIMIZATION OF DNs

The total operating cost of DNs can be reduced by utilizing SOP as it helps to balance the power flow within the connected feeders. As a result, power loss will be reduced significantly and existing cable and other protection arrangements need not be modified due to the penetration of DERs as the current in the feeders can be maintained within the limit, thanks to SOP. Also, the introduction of SOP in DNs can increase the operation cost for the DN operators as SOP itself is a PE device and needs sophisticated control algorithms. Therefore, one of the major objectives should be the cost minimization to help DN operators to install SOP not to increase the overall cost but decrease it. An optimization model based on two-level programming having the objective functions to minimize the annual power loss and the total cost is proposed in [85]. The objective is to find the influence of SOP on the annual cost of DNs. A modified IEEE-node 33 having five SOP for different power ratings has been simulated to verify the proposed model and results showed that location and size of SOP have a significant effect on annual power loss and total cost of the system. Voltage and VAR control (VVC) method is proposed based on the coordinated operation of SOP, OLTC and CBs for DNs in [44]. SOP controls the P and Q flow to provide real time fast response to mitigate the voltage violation caused by DERs whether OLTC and CBs adjust Q to avoid frequent action in long term basis. Simulation results on a modified IEEE 33-node network shows that proposed optimization algorithm based on coordinated VVC control of SOP, OLTC and CBs helps to reduce the operating cost significantly compare to the conventional control of OLTC and CBs along with VVC control for SOP.

E. OPTIMAL PLACEMENT OF DERs AND SOP IN DNs

The placement of SOP or other PE devices mainly depends on the geographical distance, weekly connected areas, node voltage control ability, branch currents and also the maximum amount of load that could be supplied by the SOP after the isolation during a fault. Placement of DERs in arbitrary or clustered form along with SOP placement in DNs is analyzed in [70]. Simulation results showed that placement of DERs in clustered form near SOP helps to obtain MHC of DERs. An optimization algorithm is proposed in [86] to find the optimal location of DERs, SOP, and CBs for reactive power supply. The proposed algorithm was tested using the IEEE33-node. Results showed that the proposed algorithms help to place more DERs in the network and reduce the use of CB, which ultimately reduces the total operating cost.

F. MITIGATION OF UNBALANCE CONDITION WITHIN THREE-PHASES IN LV DNs

Power flow in LV DNs is normally unbalanced because of asymmetric three-phase line arrangement and a huge amount of single-phase loads [62]. In four-wire three-phase LV DNs, the three-phase voltage from the source is divided into three separate single-phase lines which goes to the load, are different in the manner in terms of load in each phase. As a result, the loads consume different current and the voltage level for three separate phases will not be as same and unbalanced. Therefore, the investigation is needed to be done in the LV DNs level on a three lines design instead of a single line analysis.

In order to mitigate the three-phase unbalance situation in LV DNs, the minimization of the "Power system voltage unbalance rate (PVUR)" specified in IEEE STD 112-1991 [87], is the objective function for the optimization model in [88]. The PVUR defines the percentage of

TABLE 5. Summary of optimization problems considering SOP in DNs.

Optimization Objectives	Optimization Objective Functions	Ref.	Optimized Network for simulation purpose	Type of SOP
Voltage profile improvement and P loss minimization	Minimizing the size and find the optimal location of DER and SOP	[71], [72]	IEEE 33- and 69-node	2T
	Minimizing the active power loss, minimizing the load balancing index and maximizing the DER penetration level	[69], [70]	IEEE 33-node	
	Minimizing the active power loss and feeder load balancing	[73]		
Voltage profile improvement, feeder load balancing and energy loss minimization	Objective functions lead to the optimal dispatch of the SOP's P and Q	[75]	Example DN	
	Minimization of feeder load unbalance condition and total power loss	[79]	IEEE 33-node	3T
Voltage profile improvement	Minimization of voltage deviation	[76]	IEEE 15-, 33- and 69-node	2T
	Minimizing the active power loss, converters of SOP and ES	[78]	IEEE 33-node	SOP+ES
Voltage profile improvement and feeder load balancing	Minimizing the active power loss and feeder load balancing	[10]	Real DN model of UK	2T
Voltage profile maintainace during SR mode	Maximization of Psupply of restored loads	[80], [74], [81], [82]	IEEE 33-node	
Capability evaluation of SOP for DER Hosting Capacity in DNs	Maximizing the hosting Capacity of DERs	[83]		
		[26]		2T, 3T and SOP+ES
	Minimization of voltage deviation	[84]		2T
Finding the influence of SOP on the annual cost	Minimizing the annual cost and power losses	[85], [86], [44]		
Finding the optimal location of DER and SOP in DN				
Mitigate of unbalance condition within three-phases	Minimizing the Power system voltage unbalance rate	[88]	IEEE 33- and 37-node	
	Minimization of the total power losses, the voltage, and current unbalanced conditions	[89]	IEEE 33- and 123-node	

voltage deviation in a phase from the average voltage in a three-phase system. IEEE 33- and the IEEE 37-node network are connected by a 2T-SOP and are simulated to verify the proposed model. SOP required is taken as supporting three single-phase separately i.e. each phase is connected with three separate converters by both of the SOP. The result shows that PVUR was 0.724 and 0.515 for non-optimized and optimized network cases, respectively which is an increase of 30% by choosing the best location and size of SOP. Mitigation of three-phase unbalance conditions to reduce the power loss by SOP in DNs is the goal of the proposed optimization algorithm in [89]. Three single-phase SOP modules are assumed for three-phase SOP topology. The objective functions are taken as the weighted combination of minimizing the voltage and current unbalanced condition including the total power loss. An Unbalance index [90] is used to evaluate the unbalanced condition at each node. Simulation results on a modified IEEE 33-node network show that the proposed optimization algorithm helps to reduce the total power loss and unbalance conditions by 65.98% and 66.67%, respectively compared to the network without SOP. The proposed method is also applied to a modified IEEE 123-node network to verify the method in a large network. The result shows that SOP helps to reduce the total power loss and unbalance conditions significantly during the maximum penetration of PV sources compared to the network without SOP and also the network with ES instead of SOP.

The summary of the optimization algorithms for different optimization objectives discussed above, is given in Table 5. One of the important aspect from all the methods mentioned above, is that the optimization parameters P and Q output of SOP play the major role for the optimal operation of the proposed algorithms. Also, 2T-SOP are considered in most of the optimization algorithms.

VII. FUTURE RESEARCH DIRECTIONS

The research till now related to SOP, are mostly focused on optimization algorithm using SOP but research on SOP converter topologies and control needs much more improvements. Also, optimization algorithm problem demonstration result is based on simulation result and hardly any experimental data and result is presented. Some of the key future research directions are mentioned below:

- Most of the research is related to balanced voltage conditions. However, the performance of SOP is very crucial according to the modern standards as it is connected to the grid and can follow the summarized duties and referred standards mentioned in Table 3 and Table 4 in section IV for SOP. Also, all of the literature has considered fixed control parameters for the control algorithm of SOP. However, we need to consider unbalanced and harmonic polluted voltage conditions where fixed control parameters do not provide expected outcomes as modern standards. So, adaptive control algorithms are needed to control the parameters adaptively for enhancing the performance of SOP.
- Most of the research are related to MV DNs. However, operation of SOP in LV three-phase four wire DNs need to be investigated as protection system in this level is more vulnerable than MV level and need more vigorous research.
- The conventional protection system along with SOP needs to be integrated for fast and effective fault analysis and make the distribution automation system smarter.
- An accurate and fast action time frame for the SR process can be one of the research goals to achieve than current SR techniques.
- The efficiency of the converters in SOP is taken as flat 98% during the calculation of power loss and cost minimization in most of the literature. However, the losses of converters in SOP can have a significant effect on overall power losses and accurate efficiency of converters needed to be considered in future research and also mentioned in section IV.D. Also, the efficiency of the converters in SOP in different voltage level is not assessed by any literature and need to be considered in the future.
- Basic PLL is used in the control algorithm of SOP for all the literature mentioned above. However, the performance of PLL is not acceptable during unbalanced conditions as mentioned in section V.B. So, advanced PLL is needed to be considered to derive the control algorithm for SOP control during unbalanced power system conditions.
- Control methods like combined voltage-dependent P and Q control ($Q(U)/P(U)$) mentioned in [91] to control the grid-connected PV inverters can also be explored to develop more robust control algorithms for SOP.
- LVRT, HVRT, FDRT and FRT operation of SOP during short-duration balanced and unbalanced faults need to be considered according the Table 3 in section IV.B.
- The propagation of voltage sag through regular three-phase transformer used in the DNs give rise to new types of voltage sags [92], [93] and also needs to be considered to evaluate the performance of SOP.
- The introduction of SOP in DNs doesn't require reconfiguration of the network, but the existing distributed automation system needs to be adjusted for the protection devices to interact with the SOP. The synchronized operation of the protection system is not discussed explicitly in most of the previous research and should be a major area of research for the implementation of SOP in existing DNs.
- The use of SOP in MV DNs is experimented as a pilot project in the UK [94], [95] and China [96] only. Performance of SOP need to be verified in real network situation to test the capability of SOP along with advance algorithms.

VIII. CONCLUSION

A comprehensive review of SOP starting with the configuration of SOP, control of SOP, network optimization using SOP is presented in this article. The inclusion of SOP in DNs is a must to increase the flexibility and DERs hosting capacity of DNs. Most of the research till now has been done in the field of the optimization problem for DNs incorporating SOP in the network. The control of SOP has been solved until now for normal conditions and SR is the process during faults. Also, SOP needs to follow the defined duties in section IV during abnormal conditions to satisfy modern grid codes and make a substantial impact in DNs. Also, the operation time and fast response of SOP during these conditions should be a major area of research. Finally, the cost-benefit ratio of implementation of SOP in DNs should be investigated in comparison with other existing PEs technologies.

REFERENCES

[1] H. Hafezi and R. Faranda, "Dynamic voltage conditioner: A new concept for smart low-voltage distribution systems," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7582–7590, Sep. 2018.

[2] J. Flottemesch and M. Rother, "Optimized energy exchange in primary distribution networks with DC links," in *Proc. IEEE Int. Conf. Electr. Utility Deregulation, Restructuring Power Technol.*, Hong Kong, vol. 1, Apr. 2004, pp. 16–108.

[3] C.-Y. Tang, Y.-F. Chen, Y.-M. Chen, and Y.-R. Chang, "DC-link voltage control strategy for three-phase back-to-back active power conditioners," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6306–6316, Oct. 2015.

[4] E. Romero-Ramos, A. Gómez-Expósito, A. Marano-Marcolini, J. M. Maza-Ortega, and J. L. Martinez-Ramos, ''Assessing the loadability of active distribution networks in the presence of DC controllable links,'' *IET Gener., Transmiss. Distrib.*, vol. 5, no. 11, pp. 1105–1113, Nov. 2011.

[5] J. M. Maza-Ortega, M. Barragán-Villarejo, E. Romero-Ramos, A. Marano-Marcolini, and A. Gómez-Expósito, ''Voltage source converter-based topologies to further integrate renewable energy sources in distribution systems,'' *IET Renew. Power Gener.*, vol. 6, no. 6, pp. 435–445, Nov. 2012.

[6] A. Aithal and J. Wu, ''Operation and performance of a medium-voltage DC link,'' *CIRED Open Access Proc. J.*, vol. 2017, no. 1, pp. 1355–1358, Oct. 2017.

[7] J. Song, Y. Zhang, Z. Gao, C. Cao, Z. Wang, and F. Xu, ''Research on topology and control technology of soft multi-state open point with fault isolation capability,'' in *Proc. China Int. Conf. Electr. Distribution (CICED)*, Tianjin, China, Sep. 2018, pp. 1467–1473.

[8] N. Okada, M. Takasaki, H. Sakai, and S. Katoh, ''Development of a 6.6 kV–1 MVA transformerless loop balance controller,'' in *Proc. IEEE Power Electron. Specialists Conf.*, vol. 2, Jun. 2007, pp. 1087–1091.

[9] W. Cao, J. Wu, and N. Jenkins, ''Feeder load balancing in MV distribution networks using soft normally-open points,'' in *Proc. IEEE PES Innov. Smart Grid Technol.*, Europe, Istanbul, Oct. 2014, pp. 1–6.

[10] J. M. Bloemink and T. C. Green, ''Increasing distributed generation penetration using soft normally-open points,'' in *Proc. IEEE PES Gen. Meeting*, Providence, RI, USA, Jul. 2010, pp. 1–8.

[11] H. Akagi and R. Kitada, ''Control and design of a modular multilevel cascade BTB system using bidirectional isolated DC/DC converters,'' *IEEE Trans. Power Electron.*, vol. 26, no. 9, pp. 2457–2464, Sep. 2011.

[12] B. Mohandes, M. S. E. Moursi, N. Hatziargyriou, and S. E. Khatib, ''A review of power system flexibility with high penetration of renewables,'' *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 3140–3155, Jul. 2019.

[13] S. Giannelos, I. Konstantelos, and G. Strbac, ''Option value of soft open points in distribution networks,'' in *Proc. IEEE Eindhoven PowerTech*, Eindhoven, The Netherlands, Jun. 2015, pp. 1–6.

[14] J. M. Bloemink and T. C. Green, ''Benefits of distribution-level power electronics for supporting distributed generation growth,'' *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 911–919, Apr. 2013.

[15] W. Cao, J. Wu, N. Jenkins, C. Wang, and T. Green, ''Operating principle of soft open points for electrical distribution network operation,'' *Appl. Energy*, vol. 164, pp. 245–257, Feb. 2016.

[16] H. Hafezi and H. Laaksonen, ''Autonomous soft open point control for active distribution network voltage level management,'' in *Proc. IEEE Milan PowerTech*, Milan, Italy, Jun. 2019, pp. 1–6.

[17] P. S. Georgilakis and N. D. Hatziargyriou, ''Unified power flow controllers in smart power systems: Models, methods, and future research,'' *IET Smart Grid*, vol. 2, no. 1, pp. 2–10, Mar. 2019.

[18] K. Lee, H. Koizumi, and K. Kurokawa, ''Voltage control of D-UPFC between a clustered PV system and distribution system,'' in *Proc. 37th IEEE Power Electron. Spec. Conf.*, Jeju, South Korea, 2006, pp. 1–5.

[19] M. A. Sayed and T. Takeshita, ''All nodes voltage regulation and line loss minimization in loop distribution systems using UPFC,'' *IEEE Trans. Power Electron.*, vol. 26, no. 6, pp. 1694–1703, Jun. 2011.

[20] M. A. Sayed and T. Takeshita, ''Line loss minimization in isolated substations and multiple loop distribution systems using the UPFC,'' *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 5813–5822, Nov. 2014.

[21] M. A. Hannan, P. J. Ker, M. S. H. Lipu, Z. H. Choi, M. S. A. Rahman, K. M. Muttaqi, and F. Blaabjerg, ''State of the art of solid-state transformers: Advanced topologies, implementation issues, recent progress and improvements,'' *IEEE Access*, vol. 8, pp. 19113–19132, 2020.

[22] M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L. F. Costa, and Z.-X. Zou, ''The smart transformer: Impact on the electric grid and technology challenges,'' *IEEE Ind. Electron. Mag.*, vol. 10, no. 2, pp. 46–58, Jun. 2016.

[23] X. She, R. Burgos, G. Wang, F. Wang, and A. Q. Huang, ''Review of solid state transformer in the distribution system: From components to field application,'' in *Proc. IEEE Energy Convers. Congr. Exposit. (ECCE)*, Raleigh, NC, USA, Sep. 2012, pp. 4077–4084.

[24] S. Falcones, R. Ayyanar, and X. Mao, ''A DC–DC multiport-converter-based solid-state transformer integrating distributed generation and storage,'' *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2192–2203, May 2013.

[25] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, J. M. Guerrero, and L. Vandevelde, ''Voltage-based control of a smart transformer in a microgrid,'' *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1291–1305, Apr. 2013.

[26] X. She, X. Yu, F. Wang, and A. Q. Huang, ''Design and demonstration of a 3.6-kV–120-V/10-kVA solid-state transformer for smart grid application,'' *IEEE Trans. Power Electron.*, vol. 29, no. 8, pp. 3982–3996, Aug. 2014.

[27] H. Ji, C. Wang, P. Li, J. Zhao, G. Song, and J. Wu, ''Quantified flexibility evaluation of soft open points to improve distributed generator penetration in active distribution networks based on difference-of-convex programming,'' *Appl. Energy*, vol. 218, pp. 338–348, May 2018.

[28] F. Attanasio, S. Wasterlain, T. Pidancier, M. Marchesoni, P. Favre-Perrod, and M. Carpita, ''Low voltage soft open point with energy storage: System simulation and prototype preliminary test results,'' in *Proc. Int. Symp. Power Electron., Electr. Drives, Autom. Motion (SPEEDAM)*, Amalfi, Italy, Jun. 2018, pp. 254–261.

[29] J. M. Bloemink and T. C. Green, ''Increasing photovoltaic penetration with local energy storage and soft normally-open points,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Detroit, MI, USA, Jul. 2011, pp. 1–8.

[30] Z. Zhuet, D. Liu, Q. Liao, F. Tang, J. J. Zhang, and H. Jiang, ''Optimal power scheduling for a medium voltage AC/DC hybrid distribution network,'' *Sustainability*, vol. 10, no. 2, pp. 1–22, Jan. 2018.

[31] Y. Cai, Z. Qu, H. Yang, R. Zhao, Y. Lu, and Y. Yang, ''Research on an improved droop control strategy for soft open point,'' in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Jeju, South Korea, Oct. 2018, pp. 2000–2005.

[32] M. Li, H. Yang, R. Zhao, T. Zheng, C. Si, Y. Lu, and Y. Yang, ''Comparative study on the operating area of M^3C and B2B MMC for soft open point application,'' in *Proc. 10th Int. Conf. Power Electron. ECCE Asia (ICPE ECCE Asia)*, Busan, South Korea, 2019, pp. 1205–1212.

[33] Y. Lu, F. Xu, and C. Wang, ''The development and application of a multi-terminal power electronics soft open point device,'' in *Proc. 25th Int. Conf. Electr. Distrib. (CIRED)*, Madrid, Spain, Jun. 2019, pp. 3–6.

[34] S. Ouyang, J. Liu, Y. Yang, X. Chen, S. Song, and H. Wu, ''DC voltage control strategy of three-terminal medium-voltage power electronic transformer-based soft normally open points,'' *IEEE Trans. Ind. Electron.*, vol. 67, no. 5, pp. 3684–3695, May 2020.

[35] P. Favre-Perrod, D. Chloé, A. Mohamed, L. Eggenschwiler, A. Bifrare, P. Thomas, W. Sébastien, and M. Carpita, ''Soft-open points for medium voltage networks—A case study,'' presented at the CIRED 25th Int. Conf. Electr. Distrib., Madrid, Spain, Jun. 2019.

[36] *IEEE Guide for Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV Through 38 kV*, IEEE Standard 1409-2012, Apr. 2012, pp. 1–90, doi: 10.1109/IEEESTD.2012.6190701.

[37] H. Awad and M. H. J. Bollen, ''Power electronics for power quality improvements,'' in *Proc. IEEE Int. Symp. Ind. Electron.*, Jun. 2003, pp. 1129–1136.

[38] *IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems*, IEEE Standard 1547-2018, 2018.

[39] M. Altın, Ö. Göksu, R. Teodorescu, P. Rodriguez, B. Jensen, and L. Helle, ''Overview of recent grid codes for wind power integration,'' in *Proc. 12th Int. Conf. Optim. Elect. Electron. Equip.*, Braşov, Romania, May 2010, pp. 1152–1160.

[40] A. Aithal, G. Li, J. Wu, and J. Yu, ''Performance of an electrical distribution network with soft open point during a grid side AC fault,'' *Appl. Energy*, vol. 227, pp. 262–272, Oct. 2018.

[41] S. Bai, ''Analysis of the influence of distributed generation on distribution network,'' in *Proc. IEEE 4th Inf. Technol. Mechatronics Eng. Conf. (ITOEC)*, Chongqing, China, Dec. 2018, pp. 1477–1480.

[42] A. Aithal, C. Long, W. Cao, J. Wu, and C. E. Ugalde-Loo, ''Impact of soft open point on feeder automation,'' in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Leuven, Belgium, Apr. 2016, pp. 1–6.

[43] N. Bottrell, P. Lang, and T. Green, ''Algorithm for soft open points to solve thermal and voltage constraints in low-voltage distribution networks,'' *CIRED Open Access Proc. J.*, vol. 2017, no. 1, pp. 1567–1570, Oct. 2017.

[44] P. Li, H. Ji, C. Wang, J. Zhao, G. Song, F. Ding, and J. Wu, ''Coordinated control method of voltage and reactive power for active distribution networks based on soft open point,'' *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1430–1442, Oct. 2017.

[45] C. Wang, G. Song, P. Li, H. Ji, J. Zhao, and J. Wu, ''Optimal siting and sizing of soft open points in active electrical distribution networks,'' *Appl. Energy*, vol. 189, pp. 301–309, Mar. 2017.

[46] J. Zhao, M. Yao, H. Yu, G. Song, H. Ji, and P. Li, "Decentralized voltage control strategy of soft open points in active distribution networks based on sensitivity analysis," *Electronics*, vol. 9, no. 2, p. 295, Feb. 2020.

[47] R. Faranda, H. Hafezi, S. Leva, M. Mussetta, and E. Ogliari, "The optimum PV plant for a given solar DC/AC converter," *Energies*, vol. 8, no. 6, pp. 4853–4870, May 2015.

[48] F. Wang, L. Tjernberg, T. Le, A. Mannikoff, and A. Bergman, "An overview introduction of VSC-HVDC: State-of-art and potential applications in electric power systems," presented at the CIGRE Bologna Symp. Electr. Power Syst. Future, Integrating Supergrids Microgrids, Bologna, Italy, Sep. 2011.

[49] Q. Qi, J. Wu, and C. Long, "Multi-objective operation optimization of an electrical distribution network with soft open point," *Appl. Energy*, vol. 208, pp. 734–744, Dec. 2017.

[50] A. R. Jordehi, "Particle swarm optimisation (PSO) for allocation of FACTS devices in electric transmission systems: A review," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1260–1267, Dec. 2015.

[51] Y. Li, X. Pei, Y. Kang, Y. Lu, F. Xu, and C. Wang, "Voltage support strategy of SNOP under fault circumstance," in *Proc. IEEE Appl. Power Electron. Conf. Exposit. (APEC)*, Anaheim, CA, USA, Mar. 2019, pp. 1146–1149.

[52] J. Channegowda, B. Saritha, H. R. Chola, and G. Narayanan, "Comparative evaluation of switching and average models of a DC-DC boost converter for real-time simulation," in *Proc. IEEE Int. Conf. Electron., Comput. Commun. Technol. (CONECCT)*, Bengaluru, India, Jan. 2014, pp. 1–6.

[53] S. Bifaretti, P. Zanchetta, A. Watson, L. Tarisciotti, and J. C. Clare, "Advanced power electronic conversion and control system for universal and flexible power management," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 231–243, Jun. 2011.

[54] B. Zhao, Q. Song, J. Li, and W. Liu, "A modular multilevel DC-link front-to-front DC solid-state transformer based on high-frequency dual active phase shift for HVDC grid integration," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8919–8927, Nov. 2017.

[55] L. Tarisciotti, P. Zanchetta, A. Watson, P. Wheeler, J. C. Clare, and S. Bifaretti, "Multiobjective modulated model predictive control for a multilevel solid-state transformer," *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, pp. 4051–4060, Sep. 2015.

[56] S. Bifaretti, P. Zanchetta, Y. Fan, F. Iov, and J. Clare, "Power flow control through a multi-level H-bridge based power converter for universal and flexible power management in future electrical grids," in *Proc. 13th Int. Power Electron. Motion Control Conf.*, Poznan, Poland, Sep. 2008, pp. 1771–1778.

[57] S. Ouyang, J. Liu, X. Wang, S. Song, X. Hou, and T. Wu, "A single phase power electronic transformer considering harmonic compensation in scott traction system," in *Proc. 9th Int. Conf. Power Electron. ECCE Asia (ICPE-ECCE Asia)*, Seoul, South Korea, Jun. 2015, pp. 2620–2627.

[58] X. Wang, J. Liu, S. Ouyang, T. Xu, F. Meng, and S. Song, "Control and experiment of an H-bridge-based three-phase three-stage modular power electronic transformer," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2002–2011, Mar. 2016.

[59] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

[60] R. Wu, L. Ran, G. Weiss, and J. Yu, "Control of a synchronverter-based soft open point in a distribution network," *J. Eng.*, vol. 2019, no. 16, pp. 720–727, Mar. 2019.

[61] H. Qin, R. Wu, A. M. Abd-el-Motaleb, L. Ran, X. Deng, and P. Sensarma, "Utilisation of back-to-back VSC in a distribution network with DG," in *Proc. IEEE Int. Conf. Sci. Electr. Eng. (ICSEE)*, Eilat, Israel, Nov. 2016, pp. 1–5.

[62] A. Aithala, G. Lia, and J. Wu, "Grid side unbalanced fault detection using soft open point in an electrical distribution network," in *Proc. 8th Int. Conf. Appl. Energy (ICAE)*, Bejing, China, Oct. 2016, pp. 2859–2864.

[63] Y. Li, X. Pei, Z. Chen, M. Yang, Z. Lyu, and C. Wang, "The steady-state and fault ride-through control strategies of soft normally open point in distribution network," in *Proc. IEEE Energy Convers. Congr. Exposit. (ECCE)*, Portland, OR, USA, Sep. 2018, pp. 1146–1150.

[64] Z. Qu, R. Zhao, Y. Cai, Y. Lu, H. Yang, and Y. Yang, "A variable droop coefficient control of soft open point based on adaptive virtual inertia," in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Jeju, South Korea, Oct. 2018, pp. 2033–2038.

[65] K. S. Fuad, E. Hossain, and M. R. U. Chowdhury, "Grid-voltage synchronization algorithm for grid tied renewable energy sources during adverse grid fault condition," in *Proc. Int. Conf. Innov. Sci., Eng. Technol. (ICISET)*, Dhaka, Bangladesh, Oct. 2016, pp. 1–5.

[66] K. S. Fuad and E. Hossain, "Performance of grid-voltage synchronization algorithms based on frequency-and phase-locked loop during severe grid fault conditions," in *Proc. 3rd Int. Conf. Electr. Eng. Inf. Commun. Technol. (ICEEICT)*, Dhaka, Bangladesh, Sep. 2016, pp. 1–6.

[67] A. Luna, J. Rocabert, J. I. Candela, J. R. Hermoso, R. Teodorescu, F. Blaabjerg, and P. Rodriguez, "Grid voltage synchronization for distributed generation systems under grid fault conditions," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3414–3425, Jul. 2015.

[68] L. Hadjidemetriou, E. Kyriakides, and F. Blaabjerg, "An adaptive tuning mechanism for phase-locked loop algorithms for faster time performance of interconnected renewable energy sources," *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1792–1804, Mar. 2015.

[69] Q. Qi, J. Wu, L. Zhang, and M. Cheng, "Multi-objective optimization of electrical distribution network operation considering reconfiguration and soft open points," *Energy Procedia*, vol. 103, pp. 141–146, Dec. 2016.

[70] Q. Qi and J. Wu, "Increasing distributed generation penetration using network reconfiguration and soft open points," *Energy Procedia*, vol. 105, pp. 2169–2174, May 2017.

[71] C. Han, S. Song, Y. Yoo, J. Lee, G. Jang, and M. Yoon, "Optimal operation of soft-open points for high penetrated distributed generations on distribution networks," in *Proc. 10th Int. Conf. Power Electron. ECCE Asia (ICPE ECCE Asia)*, Busan, South Korea, 2019, pp. 806–812.

[72] M. B. Shafik, G. I. Rashed, H. Chen, M. R. Elkadeem, and S. Wang, "Reconfiguration strategy for active distribution networks with soft open points," in *Proc. 14th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, Xi'an, China, Jun. 2019, pp. 330–334.

[73] W. Cao, J. Wu, N. Jenkins, C. Wang, and T. Green, "Benefits analysis of soft open points for electrical distribution network operation," *Appl. Energy*, vol. 165, pp. 36–47, Mar. 2016.

[74] T. Ding, Z. Wang, W. Jia, B. Chen, C. Chen, and M. Shahidehpour, "Multiperiod distribution system restoration with routing repair crews, mobile electric vehicles, and soft-open-point networked microgrids," *IEEE Trans. Smart Grid*, vol. 11, no. 6, pp. 4795–4808, Nov. 2020, doi: 10.1109/TSG.2020.3001952.

[75] C. Long, J. Wu, L. Thomas, and N. Jenkins, "Optimal operation of soft open points in medium voltage electrical distribution networks with distributed generation," *Appl. Energy*, vol. 184, pp. 427–437, Dec. 2016.

[76] Y. Zheng, Y. Song, and D. J. Hill, "A general coordinated voltage regulation method in distribution networks with soft open points," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020, Art. no. 105571.

[77] S. Y. Hui, C. K. Lee, and F. F. Wu, "Electric springs—A new smart grid technology," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1552–1561, Sep. 2012.

[78] C. Yao, C. Zhou, J. Yu, K. Xu, P. Li, and G. Song, "A sequential optimization method for soft open point integrated with energy storage in active distribution networks," *Energy Procedia*, vol. 145, pp. 528–533, Jul. 2018.

[79] H. Ji, C. Wang, P. Li, J. Zhao, G. Song, F. Ding, and J. Wu, "An enhanced SOCP-based method for feeder load balancing using the multi-terminal soft open point in active distribution networks," *Appl. Energy*, vol. 208, pp. 986–995, Dec. 2017.

[80] P. Li, G. Song, H. Ji, J. Zhao, C. Wang, and J. Wu, "A supply restoration method of distribution system based on soft open point," in *Proc. IEEE Innov. Smart Grid Technol. Asia (ISGT-Asia)*, Melbourne, VIC, Australia, Nov. 2016, pp. 535–539.

[81] P. Li, J. Ji, H. Ji, G. Song, C. Wang, and J. Wu, "Self-healing oriented supply restoration method based on the coordination of multiple SOPs in active distribution networks," *Energy*, vol. 195, Mar. 2020, Art. no. 116968.

[82] H. Ji, C. Wang, P. Li, G. Song, and J. Wu, "SOP-based islanding partition method of active distribution networks considering the characteristics of DG, energy storage system and load," *Energy*, vol. 155, pp. 312–325, Jul. 2018.

[83] H. Ji, P. Li, C. Wang, G. Song, J. Zhao, H. Su, and J. Wu, "A strengthened SOCP-based approach for evaluating the distributed generation hosting capacity with soft open points," *Energy Procedia*, vol. 142, pp. 1947–1952, Dec. 2017.

[84] H. Ji, C. Wang, P. Li, F. Ding, and J. Wu, "Robust operation of soft open points in active distribution networks with high penetration of photovoltaic integration," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 280–289, Jan. 2019.

[85] S. Zhang, L. Zhang, K. Li, H. Zhang, J. Lyu, and H. Cheng, "Multi-objective planning of soft open point in active distribution network based on bi-level programming," in *Proc. IEEE Innov. Smart Grid Technol. Asia (ISGT Asia)*, Chengdu, China, May 2019, pp. 3251–3255.

[86] L. Zhang, C. Shen, Y. Chen, S. Huang, and W. Tang, "Coordinated allocation of distributed generation, capacitor banks and soft open points in active distribution networks considering dispatching results," *Appl. Energy*, vol. 231, pp. 1122–1131, Dec. 2018.

[87] *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators*, IEEE Standard 112-1991, 1991.

[88] H. Xiao, W. Pei, and K. Li, "Optimal sizing and siting of soft open point for improving the three phase unbalance of the distribution network," in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Jeju, South Korea, Oct. 2018, pp. 2080–2084.

[89] P. Li, H. Ji, C. Wang, J. Zhao, G. Song, F. Ding, and J. Wu, "Optimal operation of soft open points in active distribution networks under three-phase unbalanced conditions," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 380–391, Jan. 2019.

[90] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "A three-phase power flow approach for integrated 3-Wire MV and 4-Wire multigrounded LV networks with rooftop solar PV," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1728–1737, May 2013.

[91] S. Weckx, C. Gonzalez, and J. Driesen, "Combined central and local active and reactive power control of PV inverters," *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 776–784, Jul. 2014.

[92] M. Bollen and I. Gu, *Signal Processing for Power Quality Disturbances*. Hoboken, NJ, USA: Wiley, 2006, ch. 8.

[93] M. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions* (Power Engineering Series). Piscataway, NJ, USA: IEEE Press, 2000.

[94] (2017). *Western Power Distribution. Low Carbon Networks Fund Submission From Western Power Distribution—Network Equilibrium*. [Online]. Available: https://www.ofgem.gov.uk/publications-and-updates/low-carbon-networks

[95] (2017). *SP Energy Networks. Electricity NIC Submission: SP Energy Networks—ANGLE-DC*. [Online]. Available: https://www.ofgem.gov.uk/publications-and-updates/electricity

[96] H. Ji, C. Wang, S. Li, G. Song, and H. Yu, "Operation and optimization technologies of active distribution network with multi-terminal soft open points," in *Proc. 25th Int. Conf. Electr. Distrib.*, Madrid, Spain, Jun. 2019, pp. 3–6.

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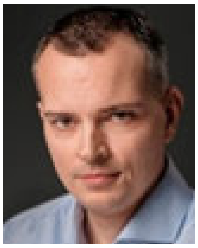

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