Operation and Optimization Technologies of Active Distribution Network with Multi-terminal Soft Open Points

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ABSTRACT

The increasing penetration of distributed generators (DGs) exacerbates the power fluctuation and the risk of voltage violations in active distribution networks (ADNs). The conventional regulation devices limited by the physical constraints are difficult to meet the requirement of rapid operation and optimization when DGs fluctuate frequently. Soft open point (SOP) is a flexible power electronic device, which can provide an accurate active and reactive power flow control. The multi-terminal SOPs further enable the flexible connection among multiple feeders, effectively extending the adjustment range of the power flow. In this paper, the potential benefits of using multi-terminal SOPs are investigated to improve the performance of pilot distribution networks constructed in Tianjin, China. By accurately adjusting the power flow among feeders, the multi-terminal SOPs can effectively improve the operation performance of the pilot project, including power loss reduction, feeder load balancing, voltage violation mitigation and reliability improvement.

Index Terms*—active distribution network (ADN), multi-terminal soft open point, operation optimization, pilot project*

Nomenclature

Sets

Ω_b	Set of all branches
Ω_s	Set of fault scenarios

Indexes

i, j, h	Indices of nodes
ij	Indices of branches
t	Indices of time periods
s	Indices of fault scenarios

Variables

$P_{t,i}, Q_{t,i}$	Total active/reactive power injection of node i in period t
$P_{t,ij}, Q_{t,ij}$	Active/reactive power flow of branch ij in period t
$I_{t,ij}$	Current magnitude of branch ij in period t
$U_{t,i}$	Voltage magnitude at node i in period t
$P_{t,i}^{\mathrm{L}}, Q_{t,i}^{\mathrm{L}}$	Active/reactive power load at node i in period t
$P_{t,i}^{\mathrm{DG}}$, $Q_{t,i}^{\mathrm{DG}}$	Active/reactive power injection by DG at node i in period t
$P_{t,i}^{\mathrm{DG,re}}$	Forecasted value of DG outputs at node i in period t
$P_{t,i}^{\mathrm{SOP}}, P_{t,j}^{\mathrm{SOP}}, P_{t,h}^{\mathrm{SOP}}, P_{t,m}^{\mathrm{SOP}}$	Active power injection by SOP at node i , j, h and m in period t
$Q_{t,i}^{\mathrm{SOP}}, Q_{t,j}^{\mathrm{SOP}}, Q_{t,h}^{\mathrm{SOP}}, Q_{t,m}^{\mathrm{SOP}}$	Reactive power injection by SOP at node i , j, h and m in period t
$P_{t,i}^{\mathrm{SOP,L}}, P_{t,j}^{\mathrm{SOP,L}}, P_{t,h}^{\mathrm{SOP,L}}, P_{t,m}^{\mathrm{SOP,L}}$	Active power losses of the converter at node i , j, h and m in period t
$S_i^{\mathrm{SOP}}, S_j^{\mathrm{SOP}}, S_h^{\mathrm{SOP}}, S_m^{\mathrm{SOP}}$	Capacity of the converter of SOP at node i , j, h and m
T_s	Annual outage time under fault scenario s
μ_s	Coefficient associated with the recovery level of load

Parameters

S_i^{DG}	Capacity limit of DG at node i
N_N	Total number of the nodes
R_{ij}, X_{ij}	Resistance and reactance of branch ij
$U_i^{\max}$, $U_i^{\min}$	Upper/lower limit of the desired voltage range
I_{ij}^{rate}	Rated current value of branch ij
$A_i^{\mathrm{SOP}}, A_j^{\mathrm{SOP}}, A_h^{\mathrm{SOP}}, A_m^{\mathrm{SOP}}$	Loss coefficient of the converter at node i , j, h and m
$I_{ij}^{\max}$	Upper limit of the current
$Q_i^{\mathrm{DG,max}}, Q_i^{\mathrm{DG,min}}$	Upper/lower limit of the reactive power output of DG at node i
λ_s	Average failure rate of scenario s
U_0	Reference voltage in the $\mathrm{U_{ac}}\theta$ control strategy of SOP

1. INTRODUCTION

The increasing penetration of distributed generators (DGs) exacerbates the power fluctuation and the risk of voltage violations in active distribution networks (ADNs) [1]. The conventional regulation devices such as on-load tap changer (OLTC) and capacitor banks (CBs), limited by the physical constraints are difficult to meet the requirement of rapid operation and optimization when DGs fluctuate frequently [2].

Soft open point (SOP) [3] is a new power electronic device to replace tie switches, which can provide an accurate active and reactive power flow control between connected feeders. Based on the conventional dual-terminal SOPs, the multi-terminal SOPs further enable the flexible connection among feeders, effectively extending the adjustment range of power flow [4].

Previous studies have investigated the benefits of SOPs to facilitate the operation of ADNs. Ref. [5] analysed the basic principle and advantages of SOPs. Considering the coordination of SOPs and conventional regulation devices, voltage violations were effectively eliminated in [6]. In [7], the benefits of multi-terminal SOPs were presented on the improvement of system flexibility.

In this paper, we focus on the application of multi-terminal SOPs to improve the performance of the pilot distribution networks. The overall contributions are summarized as follows:

1) The basic principle and the mathematical model of multi-terminal SOPs are analyzed. Then the operation optimization method with multi-terminal SOPs is further proposed for ADNs. Various optimization objectives are considered in the proposed model, including power loss reduction, feeder load balancing, voltage violation mitigation and reliability improvement.

2) The potential benefits of multi-terminal SOPs have been demonstrated in a pilot project constructed in Tianjin, China. By accurately adjusting the power flow among feeders, the multi-terminal SOPs can effectively reduce the power losses, balance the feeder loading, mitigate the voltage violations and improve the reliability of power supply in pilot distribution networks.

The remainder of this paper is organized as follows. Section 2 introduces the basic principle and mathematical model of multi-terminal SOPs. The operation optimization model with multi-terminal SOPs of ADNs is formulated in Section 3. The application of multi-terminal SOPs in the pilot project is presented in Section 4. Conclusion is stated in Section 5.

2. PRINCIPLE AND MATHAMATICAL MODEL OF MULTI-TERMINAL SOPS

2.1 Principle of multi-terminal SOPs

Multi-terminal SOPs are composed of several groups of AC/DC converters, of which the DC side is connected in parallel to the same bus. The integration of multi-terminal SOPs in ADNs is shown in Fig.1. The multi-terminal SOP enables the flexible connection of multiple feeders, leading to the high controllability of system operation and improving reliability of power supply.

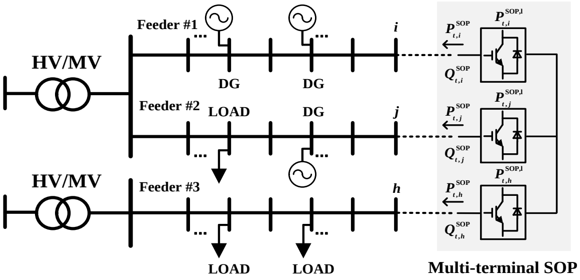


Fig. 1 *Integration of multi-terminal SOPs in ADNs.*

2.2 Mathematical model of multi-terminal SOPs

The controllable variables for multi-terminal SOPs consist of active power transmissions and reactive power outputs of converters. Although the operation efficiency of each converter is sufficiently high, losses inevitably arise when a large-scale power transfer occurs. A loss coefficient is considered in the model. PQ-PQ-V$_{\mathbf{dc}}$Q control is selected as the control mode, the operation constraints of multi-terminal SOPs are expressed as follows:

$$P_{t,i}^{\mathrm{SOP}} + P_{t,j}^{\mathrm{SOP}} + P_{t,h}^{\mathrm{SOP}} + P_{t,m}^{\mathrm{SOP}} + P_{t,i}^{\mathrm{SOP,L}} + P_{t,j}^{\mathrm{SOP,L}} + P_{t,h}^{\mathrm{SOP,L}} + P_{t,m}^{\mathrm{SOP,L}} = 0 \qquad (1.a)$$

$$P_{t,i}^{\mathrm{SOP,L}} = A_i^{\mathrm{SOP}} \sqrt{\left(P_{t,i}^{\mathrm{SOP}}\right)^2 + \left(Q_{t,i}^{\mathrm{SOP}}\right)^2} \qquad (1.b)$$

$$P_{t,j}^{\mathrm{SOP,L}} = A_j^{\mathrm{SOP}} \sqrt{\left(P_{t,j}^{\mathrm{SOP}}\right)^2 + \left(Q_{t,j}^{\mathrm{SOP}}\right)^2} \qquad (1.c)$$

$$P_{t,h}^{\mathrm{SOP,L}} = A_h^{\mathrm{SOP}} \sqrt{\left(P_{t,h}^{\mathrm{SOP}}\right)^2 + \left(Q_{t,h}^{\mathrm{SOP}}\right)^2} \qquad (1.d)$$

$$P_{t,m}^{\mathrm{SOP,L}} = A_m^{\mathrm{SOP}} \sqrt{\left(P_{t,m}^{\mathrm{SOP}}\right)^2 + \left(Q_{t,m}^{\mathrm{SOP}}\right)^2} \qquad (1.e)$$

$$\sqrt{(P_{t,i}^{\mathrm{SOP}})^2 + (Q_{t,i}^{\mathrm{SOP}})^2} \le S_i^{\mathrm{SOP}} \qquad (1.f)$$

$$\sqrt{(P_{t,j}^{\mathrm{SOP}})^2 + (Q_{t,j}^{\mathrm{SOP}})^2} \le S_j^{\mathrm{SOP}} \qquad (1.g)$$

$$\sqrt{(P_{t,h}^{\mathrm{SOP}})^2 + (Q_{t,h}^{\mathrm{SOP}})^2} \le S_h^{\mathrm{SOP}} \qquad (1.h)$$

$$\sqrt{(P_{t,m}^{\mathrm{SOP}})^2 + (Q_{t,m}^{\mathrm{SOP}})^2} \le S_m^{\mathrm{SOP}} \qquad (1.i)$$

The active power transmission constraint is shown in constraint (1.a) and the power loss of it is considered in constraints (1.b) - (1.e). Constraints (1.f) - (1.i) show the capacity limit of multi-terminal SOPs.

3. OPERATION OPTIMIZATION OF ADNS WITH MULTI-TERMINAL SOPS

Various optimization objectives are considered in the proposed operation method of ADNs with multi-terminal SOPs, including power loss reduction, feeder load balancing, voltage violation mitigation and reliability improvement.

3.1 Power loss reduction

The power losses of networks can be reduced by the adjustment of multi-terminal SOPs.

1) Objective function

$$\min f = \sum\nolimits_{ij\in\Omega_\mathrm{b}} R_{ij} I_{t,ij}^2 \qquad (2)$$

Operation constraints consist of system operation constraints (3), system secure constraints (4), DG operation constraints (5) and multi-terminal SOPs operation constraints (6).

2) System operation constraints

$$\sum\nolimits_{ij\in\Omega_\mathrm{b}}\left(P_{t,ij} - R_{ij}I_{t,ij}^2\right) + P_{t,j} = \sum\nolimits_{jh\in\Omega_\mathrm{b}} P_{t,jh} \qquad (3.a)$$

$$\sum\nolimits_{ij\in\Omega_\mathrm{b}}\left(Q_{t,ij} - X_{ij}I_{t,ij}^2\right) + Q_{t,j} = \sum\nolimits_{jh\in\Omega_\mathrm{b}} Q_{t,jh} \qquad (3.b)$$

$$U_{t,i}^2 - U_{t,j}^2 + \left(R_{ij}^2 + X_{ij}^2\right)I_{t,ij}^2 = 2\left(R_{ij}P_{t,ij} + X_{ij}Q_{t,ij}\right) \qquad (3.c)$$

$$I_{t,ij}^2 U_{t,i}^2 = P_{t,ij}^2 + Q_{t,ij}^2 \qquad (3.d)$$

$$P_{t,j} = P_{t,j}^{\mathrm{DG}} + P_{t,j}^{\mathrm{SOP}} - P_{t,j}^{\mathrm{L}} \qquad (3.e)$$

$$Q_{t,j} = Q_{t,j}^{\mathrm{DG}} + Q_{t,j}^{\mathrm{SOP}} - Q_{t,j}^{\mathrm{L}} \qquad (3.f)$$

Constraints (3.a) and (3.b) represent the active and reactive power balance of node j in period t, respectively. Ohm's law for branch ij in period t is expressed in (3.c). The current magnitude of each line can be determined using (3.d). Constraints (3.e) and (3.f) indicate the total active and reactive power injection of node j in period t.

3) System secure constraints

$$\left(U_i^{\min}\right)^2 \le U_{t,i}^2 \le \left(U_i^{\max}\right)^2 \qquad (4.a)$$

$$I_{t,ij}^2 \le \left(I_{ij}^{\max}\right)^2 \qquad (4.b)$$

Constraint (4.a) represents the voltage limit of node i in period t. Constraint (4.b) represents the current limit of line ij in period t.

4) DG operation constraints

$$P_{t,i}^{\mathrm{DG}} = P_{t,i}^{\mathrm{DG,re}} \qquad (5.a)$$

$$Q_i^{\mathrm{DG,min}} \le Q_{t,i}^{\mathrm{DG}} \le Q_i^{\mathrm{DG,max}} \qquad (5.b)$$

$$\sqrt{\left(P_{t,i}^{\mathrm{DG}}\right)^2 + \left(Q_{t,i}^{\mathrm{DG}}\right)^2} \le S_i^{\mathrm{DG}} \qquad (5.c)$$

Constraint (5.a) assumes that the active power generated by DGs is equal to the forecasted value. Constraint (5.b) denotes the reactive power constraint of DGs. The capacity constraint of DGs is expressed in (5.c).

5) Multi-terminal SOPs operation constraints

The operation constraints of multi-terminal SOPs are shown in constraint (1).

3.2 Feeder load balance

The unbalanced feeder load of ADNs causes inefficient use of network assets and even network congestion. Multi-terminal SOPs can balance the feeder load unbalanced conditions through the regulation of power flow.

1) Objective function

$$\min f = \sum\nolimits_{ij\in\Omega_\mathrm{b}} \left(\frac{I_{t,ij}}{I_{ij}^{\mathrm{rate}}}\right)^2 \qquad (6)$$

2) Operation constraints

The operation constraints include system operation constraints, system secure constraints, DG operation constraints and multi-terminal SOPs operation constraints, which are expressed in (1) and (3) - (5), respectively.

3.3 Voltage violation mitigation

The minimum voltage deviation is set as the objective function.

1) Objective function

$$\min f = \sum\nolimits_{i=1}^{N_\mathrm{N}} \left|U_{t,i}^2 - 1\right| \qquad (7)$$

2) Operation constraints

The operation constraints include system operation constraints, system secure constraints, DG operation constraints and multi-terminal SOPs operation constraints, which are expressed in (1) and (3) - (5), respectively.

3.4 Reliability improvement

The integration of multi-terminal SOPs can also improve the reliability of ADNs.

1) Objective function

$$\min f = ENS = \sum\nolimits_{s\in\Omega_\mathrm{s}} \lambda_s T_s \mu_s P_{s,i}^{\mathrm{L}} \qquad (8)$$

The index of energy not supplied (ENS) is set as the objective function, which evaluates the level of power outage under fault conditions.

2) Operation constraints

The operation constraints consist of (1), (3) - (5), in which the index of time period t is replaced by the index of fault scenario s. Constraints (3.e) - (3.f) are replaced by (9.a) - (9.b), correspondingly.

$$P_{s,j} = P_{s,j}^{\mathrm{DG}} + P_{s,j}^{\mathrm{SOP}} - \mu_s P_{s,j}^{\mathrm{L}} \qquad (9.a)$$

$$Q_{s,j} = Q_{s,j}^{\mathrm{DG}} + Q_{s,j}^{\mathrm{SOP}} - \mu_s Q_{s,j}^{\mathrm{L}} \qquad (9.b)$$

When fault occurs, the terminal of multi-terminal SOPs in the outage area can provide voltage support as shown in constraint (10).

$$\left(U_0\right)^2 \le U_{s,i}^2 \qquad (10)$$

The proposed model mathematically belongs to mixed-integer nonlinear program (MINLP). It can be converted into a mixed integer second-order cone program model (MISOCP), which can be effectively solved.

4. PILOT PROJECT

4.1 Pilot distribution network in Tianjin, China

The potential benefits of multi-terminal SOPs have been demonstrated in a pilot distribution network constructed in Tianjin, China, as shown in Fig. 2. The rated voltage level of distribution network is 10.0 kV. The converter capacity of each terminal of SOPs is set as 1.0 MVA and related active power loss coefficient is set to be 0.01.

To fully consider the impact of high penetration of DGs on power losses and voltage deviation, seven PVs are integrated into networks to simulate the PV to be installed in next few years, whose rated active power reaches almost 80% of peak demand. The capacities of DGs are shown in Table 1, the power factors of DGs are set to be 1.0.

Table 1 Locations and capacities of DGs

Location	2	3	4	6	31	32	44
Capacity (kWh)	200	200	200	100	200	100	200

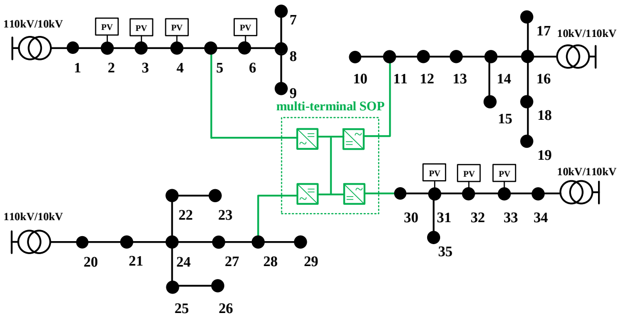


Fig. 2 *Structure of the pilot distribution network in Tianjin.*

4.2 Optimization results analysis

Four scenarios are adopted to analysis the benefits on pilot distribution networks brought by multi-terminal SOPs. The optimization results are shown in Table 2.

Scenario I: The initial operation state of distribution networks is obtained without multi-terminal SOPs integration.

Scenario II: The multi-terminal SOPs are integrated and operated to minimize power losses.

Scenario III: II: The multi-terminal SOPs are integrated and operated to balance feeder load.

Scenario IV: The multi-terminal SOPs are integrated and operated to mitigate voltage violation.

Scenario V: The multi-terminal SOPs are integrated and operated to improve reliability of power supply.

Table 2 Optimization results

Scenario	Power losses (kWh)	Load balance index (p.u.)	Voltage deviation index (p.u.)
I	372.9611	39.6226	8.0197
II	122.6109	61.301	4.271
III	309.8741	28.1838	5.669
IV	140.7243	71.7444	3.5143

Fig. 3 compares the power losses between scenario I and scenario II. The proposed method can effectively reduce the power losses of ADNs by the regulation multi-terminal SOPs. The operation strategy of multi-terminal SOPs in scenario II is shown in Fig. 4.

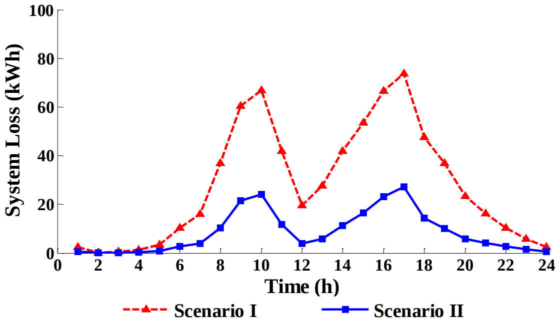
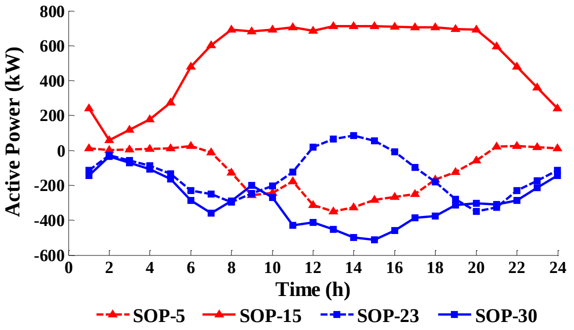
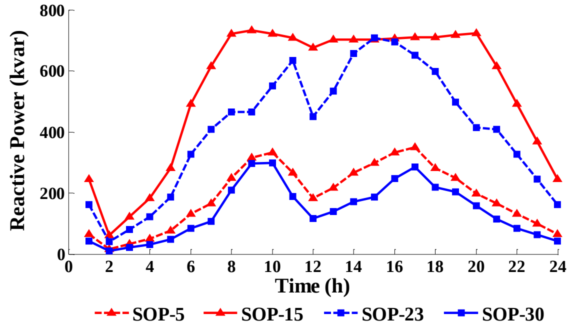


Fig. 3 *Comparison of power losses in scenarios I and II*

The comparison of current loading of line 32-33 between scenario I and scenario III is depicted in Fig. 5. It can be seen that the multi-terminal SOPs can significantly mitigates the feeder load unbalanced condition caused by the DGs with high penetration. The operation strategy of multi-terminal SOPs in scenario III is shown in Fig. 6.



(a) Active power transmission



(b) Reactive power compensation

Fig. 4 *Strategies of multi-terminal SOPs in scenario II*

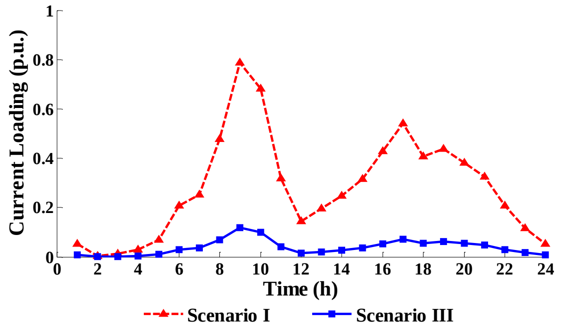
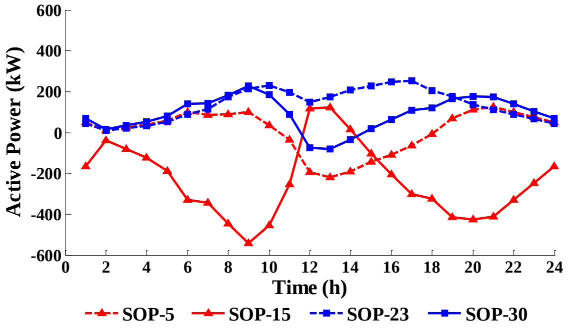
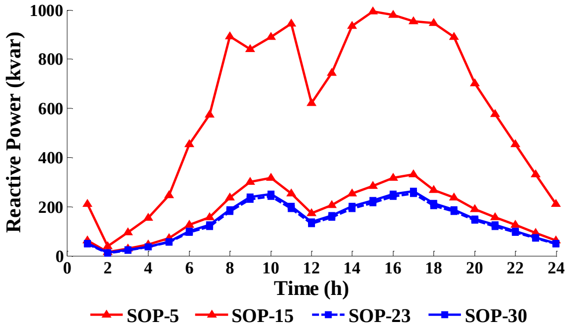


Fig. 5 *Current loading of line 32-33 in scenarios I and III*

The comparison of voltage profile at node 9 between scenario I and scenario IV is shown in Fig. 7. It is shown that the voltage fluctuation caused by the high penetration of DGs is efficiently reduced. The operation strategy of multi-terminal SOPs in scenario II is shown in Fig. 8.



(a) Active power transmission



(b) Reactive power compensation

Fig. 6 *Strategies of multi-terminal SOPs in scenario III*

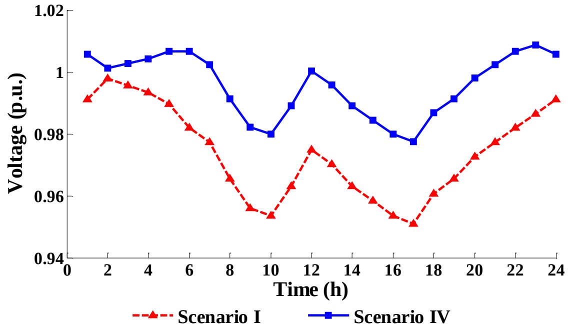
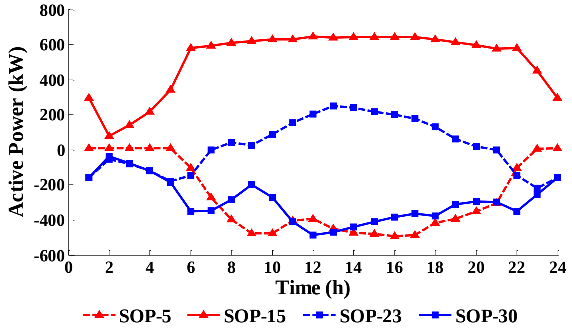
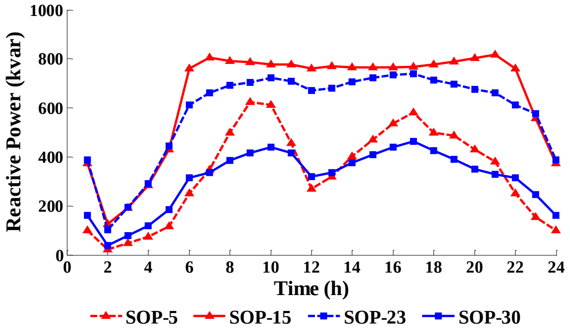


Fig. 7 *Voltage profile at node 9 in scenarios I and IV*



(a) Active power transmission



(b) Reactive power compensation

Fig. 8 *Strategies of multi-terminal SOPs in scenario IV*

The system average interruption duration index (SAIDI) which represents the outage time caused by branch faults and ENS are adopted as the reliability indexes of distribution networks. As shown in Table 3, the integration of the multi-terminal SOPs can effectively improve the reliability of the distribution network.

Table 3 Reliability indexes

Scenario	SAIDI (hour/cust)	ENS (MWh)
I	3.60284	17.53673
V	2.26254	11.01208

As multi-terminal SOPs can realize flexible power exchange among feeders in a large range, the economic efficiency, safety and reliability of the pilot distribution networks are effectively improved by the integration of multi-terminal SOPs.

4 CONCLUSION

Due to the high penetration of DGs, the power fluctuation and voltage violations are becoming severe. This paper discusses the operation optimization strategies of ADN based on multi-terminal SOPs, which is applied to improve the performance of pilot distribution networks constructed in Tianjin, China. Results show that the regulation of multi-terminal SOPs can effectively improve the operation performance of distribution networks, including the power loss reduction, feeder load balancing, voltage violation mitigation and reliability improvement.

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