ADAPTIVE SERVICE RESTORATION STRATEGY OF DISTRIBUTION NETWORKS WITH DISTRIBUTED ENERGY RESOURCES AND SOFT OPEN POINTS

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ABSTRACT

Soft Open Point (SOP) is a type of power-electronic devices which can replace the traditional tie switches (TSes). This paper proposes an adaptive service restoration strategy by coordinating and optimal dispatching SOPs, Energy Storage (ES) Systems, Distributed Generations (DGs) and TSes to adapt to different combinations of load and DG output in the distribution network. With the convex relaxation approach, the service restoration problem can be transformed into easily-resolved second-order cone programming (SOCP). Finally, case studies on the IEEE 33-node system are used to verify the effectiveness of the proposed model and approach. For fault scenarios, the coordinated operation of SOPs, ESs, DGs, and closing corresponding TSes can realize the adaptive service restoration in an active distribution network.

INTRODUCTION

The integration of distributed energy resources (DERs) brings new opportunities and challenges to power distribution networks (DNs). DERs include renewable distributed generations (DGs), such as photovoltaic power and wind power. Considering the uncertainties of renewable power output and load consumption [1], constraints e.g. over/under voltage issue [2] become significant. In addition, power flows can be bidirectional due to the fluctuations of DG output and demand.

Soft open points (SOPs) as novel power-electronic devices can replace traditional tie switch to increase operational performance to cope with the above issues from high penetration levels of DERs [6-15]. In [6,7] three basic topologies of SOP were proposed including back-to-back voltage-source converters (B2B VSCs), unified power flow controller (UPFC), static synchronous series compensator (SSSC). Under normal operational conditions, SOP can control power flows and compensate reactive power. Under fault conditions, SOP can effectively isolate fault areas. Therefore, SOP can increase flexibility, reliability and economy of the power plant operation of the distribution network.

However, the design of SOP in terms of service restoration strategy for the distribution networks is challenging and state-of-the-art techniques are limited to aspects of SOP allocation, optimal dispatching, and control methods. In a distribution system planning area, SOP coordinates with energy storage and can partly replace the DC link capacitor [8]. The work in [9] uses Wasserstein distance to create several typical scenarios to Optimally Plan for SOP Locating and Sizing. In terms of optimal dispatching, SOP can balance feeders' load and improve voltage quality [10,11]. In [12], a mixed optimization algorithm based on convex optimization and simulate annealing is designed for integrated optimization of SOP and loop switches in distribution networks. Meanwhile, a time series model of distribution networks is built to maximize the effectiveness of investments and operation. In [13], it is suggested that network reconfiguration incorporating SOP control is more secure and reliable than network reconfiguration only.

During service restoration, distribution systems have higher real and reactive power demand. SOP has the advantages of high speed and real-time power transmission and can accommodate distribution systems to changes of DG output [14,15]. In [16], a novel power flow algorithm is designed using second-order cone programming which can calculate complex system and reduce network losses. In contrast to traditional distribution network with tie switches, a distribution network with SOP can more quickly and securely provide power to blackout loads. Meanwhile, flexible reactive power adjustment ability of SOP can enhance voltage quality. Otherwise, when the system has high power demand or DG cannot supply sufficient amount of power, SOP cannot compensate required reactive power due to limited transmission capacity. Thus, SOP should cooperate with ES, DGs, and TSes.

This paper proposes an adaptive service restoration strategy of distribution networks with DGs and SOPs, and achieve service restoration under multiple load levels. This paper will discuss following questions with a modified IEEE 33-node system.

- Faults at different durations
- Different service restoration strategy
- Different DG output and load level

The main contributions of this paper are as follows:

i) The influence of faults with different durations on the network with SOP at distribution levels are surveyed. The decision matrix method is used for the establishment of an appropriate optimization objective function, which includes the minimum weight of the lost load, minimum DG curtailments, and minimum network loss. Modeling method of power electronic devices is studied especially, SOPs, DGs, and ESs during service restoration.

ii) For a distribution system with SOP, its service restoration can be achieved by optimizing the topology and the outputs of SOPs and DGs simultaneously. Using second-order cone programming (SOCP) to simplify the solving process of the mixed integer non-convex programming problem of the model [17]. To formulate the convex MIQP (mixed integer quadratic program)model, the main idea is to convert the non-convex models of branch currents and the currents of SOPs, DGs ES, and loads into the linear models, since the objective is quadratic and convex, and other constraints are linear.

MODELING OF SERVICE RESTORATION DISTRIBUTION NETWORK WITH SOP

Control mode of SOP and the adaptive service restoration strategy

The topology of SOP in this paper is standard back-to-back voltage-source converters (VSCs) as shown in Fig.1.

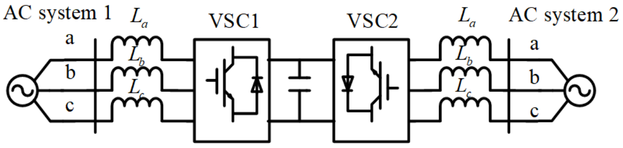

Fig.1 Back-to-back VSC-based SOP

Table 1 gives control modes of SOP. After the fault-side VSC of SOP finished close restart and step-up under *Vf* mode, the distribution network step in service restoration stage.

Table 1 Control modes of VSC-based SOP

Distribution network state		VSC of SOP
Norm operation		*PQ* mode
		$V_{dc}Q$ mode
Service restoration	Fault side connect to the system by tie switches	*PQ* mode (fault side)
		$V_{dc}Q$ mode (unfaulty side)
	Fault side connect to the system by SOP	*Vf* mode (fault side）
		$V_{dc}Q$ mode (unfaulty side)

In service restoration stage, optimize energy storages and transmission power of SOP firstly. If the voltage exceeds the upper limit, DG output should be reduced. Finishing above process, objective function should be calculated. If all lost load is restored, that proof SOP cooperates with ES can adapt the change of new operation status of the system. Meanwhile, the distribution network should keep original topology, and all lost load is connected to the main grid by SOP. Otherwise, all lost load is not restored. That means tie switches should be operated. Furthermore, SOP, ES and tie switches should be optimized at the same time. The control mode of the fault side VSC of SOP will transfer from *Vf* to *PQ*. The flow chart of the adaptive service restoration strategy is shown in Fig.2. Control modes of SOP under system fault condition are shown in Fig.3.

Modelling of service restoration of DN with SOP

Objective function

In the service restoration, the objective function consists a total minimum weight of the lost load, minimum DG curtailments, and minimum network loss. The optimization variables include the DG power and circuit breakers states.

$$f_1 = \min \sum_{k=1}^{N} \alpha_k P_k \tag{1}$$

$$f_2 = \min \sum_{i=1}^{M} P_i^{DG} \tag{2}$$

$$f_3 = \min \sum_{t=1}^{T} \sum_{i,j=1}^{B} R_{ij} I_{ij}^2 \tag{3}$$

where P_k are lost load of node k; α_k are important degree of node k, loads are divided into 3 levels; N is a set of power loss load; M is a set of lost disconnected DGs; B is a set of nodes in the distribution network, ,T is the total fault time; $P_{t,\,ij}$ and $Q_{t,\,ij}$ denote the real and reactive powers of branch at time t; R_{ij} is the resistance of branch ij; $U_{t,\,j}$ is voltage of the node j.

In this paper, the decision matrix method is used to transform the multi-objective function into a single objective function. The objective function of the original multi-objective problem can be transformed into:

$$f = \min(\omega_1 f_1{'} + \omega_2 f_2{'} + \omega_3 f_3{'}) \tag{4}$$

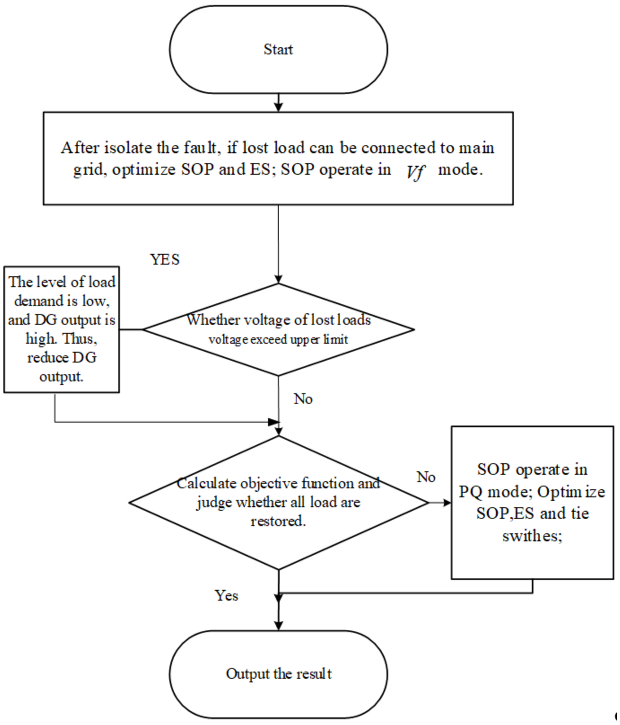

Fig.2 Flow chart of the proposed adaptive recovery strategy

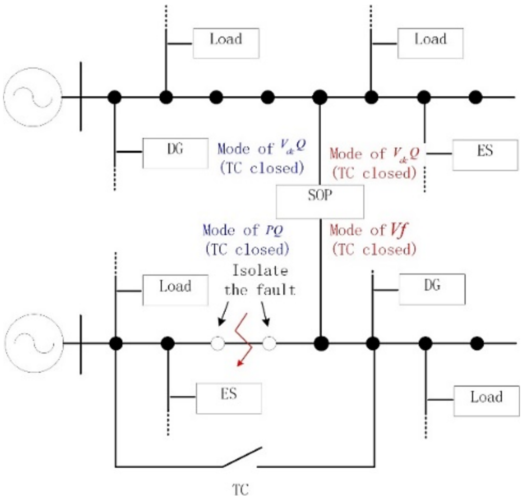

Fig.3 Schematic of the control mode of SOP under fault condition

where, f_1, f_2, and f_3 are normalized to $f_1{'}$, $f_2{'}$, and $f_3{'}$ (i.e., the conversion to the interval [0,1]) to eliminate the effect on the optimization results due to the difference in the magnitude of each target function's value. Also, the judgment matrix is used [17].

$$J = \begin{bmatrix} 1 & 5 & 7 \\ \frac{1}{5} & 1 & 3 \\ \frac{1}{7} & \frac{1}{3} & 1 \end{bmatrix} \tag{5}$$

After matrix processing, the weight vectors of each target are obtained as follow.

$$[\omega_1 \quad \omega_2 \quad \omega_3] = [0.7655 \quad 0.1600 \quad 0.0745] \tag{6}$$

A. Constraint of network topology

After reconfiguration, the network is still considered as radial.

B. SOP power limit

Active and reactive power outputs of VSCs should meet VSC capacity restrictions.

$$\begin{cases} P_{i,t}^{SOP} + P_{j,t}^{SOP} = 0 \\ (P_{i,t}^{SOP})^2 + (Q_{i,t}^{SOP})^2 \le (S_{ij}^{SOP})^2 \\ (P_{j,t}^{SOP})^2 + (Q_{j,t}^{SOP})^2 \le (S_{ij}^{SOP})^2 \end{cases} \tag{7}$$

where $P_{i,t}^{SOP}$ and$P_{j,t}^{SOP}$ are active powers of SOP at time *t*, SOP connects node *i* and node *j*; $Q_{j,t}^{SOP}$and $Q_{j,t}^{SOP}$arereactive powers of SOP at time t; S_{ij}^{SOP} is the capacity of SOP.

C. Constraints of energy storage

$$\begin{cases} \mathrm{P}_{t,i}^{ES,\mathrm{c}} \le \mathrm{P}_{t,i}^{ES} \le \mathrm{P}_{t,i}^{ES,\mathrm{d}} \\ E_{t,i} = E_{t-1,i} + \mathrm{P}_{t,i}^{ES,} \\ E_i^{\mathrm{ES}} \bullet SOC_{i,\min} \le E_{t,i} \le E_i^{\mathrm{ES}} \bullet SOC_{i,\max} \end{cases} \tag{8}$$

where $P_{t,i}{}^{ES}$ is the charge power or discharge power; $P_{t,i}{}^{ES,c}$ and $P_{t,i}{}^{ES,d}$ are the charging power limit or discharge power limit at time t; $E_{t,i}$ is the state energy storage present state; $E_i{}^{ES}$ is the energy storage capacity; $SOC_{i,\min}$ and $SOC_{i,\max}$ are the minimum and maximum states of charge.

D. Power flow constraints

$$\begin{cases} \sum\limits_{k\in\Psi_i} P_{t,ik} = \sum\limits_{j\in\Phi_i} (P_{t,ji} - R_{ji}(I_{t,ji})^2) + P_{t,i} \\ \qquad\qquad\qquad\qquad\qquad\qquad i,j,k \in B \\ \sum\limits_{k\in\Psi_i} Q_{t,ik} = \sum\limits_{j\in\Phi_i} (Q_{t,ji} - X_{ji}(I_{t,ji})^2) + Q_{t,i} \end{cases} \tag{9}$$

$$\begin{cases} P_{t,i} = P_{t,i}^{\mathrm{REG}} + P_{t,i}^{ES} + P_{t,i}^{SOP} - P_{t,i}^{\mathrm{LOAD}} \\ Q_{t,i} = Q_{t,i}^{\mathrm{REG}} + Q_{t,i}^{ES} + Q_{t,i}^{SOP} - Q_{t,i}^{\mathrm{LOAD}} \end{cases} \tag{10}$$

$$(U_{t,i})^2 = (U_{t,j})^2 - 2\left(R_{ji}P_{t,ji} + X_{ji}Q_{t,ji}\right) + \left(R_{ji}^2 + X_{ji}^2\right)\left(I_{t,ji}\right)^2 \tag{11}$$

where Φ_i is the set of the head nodes from the system whose terminal node is *i*; Ψ_i is the set of the terminal nodes from the system whose head node is *i*; R_{ji} and X_{ji} are the resistance and reactance of branch *ij*; $P_{t,ji}$ and $Q_{t,ji}$ are the active and reactive powers from node *j* to node *i*; $P_{t,i}$ and $Q_{t,i}$ are active and reactive power injections of node *i*; $Q_{t,i}{}^{ES}$ is the reactive power of energy storages; $I_{t,ji}$ is the current amplitude from node *j* to node *i*.

The constraints of DG output

$$\begin{cases} 0 \le P_{t,i}^{\mathrm{DG}} \le P_{t,i}^{MAX} \\ 0 \le Q_{t,i}^{\mathrm{DG}} \le Q_{t,i}^{MAX} \end{cases} \quad i \in B \tag{12}$$

where $P_{t,i}{}^{MAX}$ and $Q_{t,i}{}^{MAX}$ are the maximum active and maximum reactive powers of DG of node i at time t

The voltage constraint is

$$U_{i\min} < U_{t,i} < U_{i\max} \tag{13}$$

where $U_{i\min}$ and $U_{i\max}$ are the lower and upper voltage limits of node *i*. In addition,

$$I_{t,ij} \le I_{ij\max} \tag{14}$$

where $I_{ij\max}$ are upper current limits of branch *ij*.

OPTIMIZATION ALGORITHM

Second-order cone transforming of objectives

The standard form of second-order cone programming model can be formulated as follows:

$$\begin{cases} \min\ c^T x \\ \text{s.t.}\ \ Ax = b \\ \qquad x \in K \end{cases} \tag{15}$$

$$K = \left\{ x \in R^m : 2x_1x_2 \ge \sum_{l=3}^{m} x_l^2, x_1, x_2 \ge 0 \right\} \tag{16}$$

with $(I_{t,ij})^2$ and $(U_{t,i})^2$ replaced by $I_{2,t,ij}$ and $U_{2,t,i}$, f_3 in the object can be expressed as follows:

$$f_3 = \min \sum_{t=1}^{T} \sum_{i,j=1}^{B} R_{ij} I_{2,t,ij} \tag{17}$$

$$I_{2,t,ij} = \frac{(P_{t,ij})^2 + (Q_{t,ij})^2}{U_{2,t,ij}} i,j \in B \tag{18}$$

Equation (18) can be further loosed and transformed into the form of SOCP.

$$\left\| \begin{bmatrix} 2P_{ij} & 2Q_{ij} & I_{2,ij} - U_{2,ij} \end{bmatrix}^T \right\|_2 \le I_{2,ij} + U_{2,ij} \tag{19}$$

Second-order cone transforming of constraints

The constraint of network reconfiguration in the second-order cone programming model is formulated as follows:

$$\begin{cases} \sum \alpha_{ij} = n - n_f & i,j \in B \\ \beta_{ij} + \beta_{ji} = \alpha_{ij} & i,j \in B \\ \sum\limits_{j\in N(\mathrm{i})} \beta_{ij} = 1 & \forall i \in N / N_f \quad i,j \in B \end{cases} \tag{20}$$

where α_{ij} is a Boolean variable, referring to the switch status between node *i* and node *j*; n_f is the number of head nodes; β_{ij} is an auxiliary Boolean variable, and if node *i* is the parent node of node *j*, β_{ij} is 1, and if not, β_{ij} is 0; *N* is the node set; N_f is the head node.

With $(I_{ij})^2$ and $(U_i)^2$ replaced by $I_{2,t,ij}$ and $U_{2,t,i}$, the constraints of power flow and node voltage can be transformed and expressed as equations (21)-(22). Especially, the Big M Method [18] is employed to reflect the impact of network reconfiguration during the transforming.

$$\begin{cases} \sum\limits_{k\in\Psi_i^{AC}} P_{t,ik} = \sum\limits_{j\in\Phi_i^{AC}} (P_{t,ji} - R_{t,ji}I_{2,t,ji}) + P_{t,i} \\ \sum\limits_{k\in\Psi_i^{AC}} Q_{t,ik} = \sum\limits_{j\in\Phi_i^{AC}} (Q_{t,ji} - X_{t,ji}I_{2,t,ji}) + Q_{t,i} \end{cases} \tag{21}$$
$$i,j,k \in B^{AC}$$

$$\begin{gathered} -(1-\alpha_{ij})\mathrm{M} \le U_{2,\mathrm{t},j} - (U_{2,\mathrm{t},i} - 2\left(R_{ij}P_{t,ij} + X_{ij}Q_{t,ij}\right) \\ +\left(R_{ij}^2 + X_{ij}^2\right)I_{2,t,ij}) \le (1-\alpha_{ij})\mathrm{M} \\ \mathrm{i,j} \in B \end{gathered} \tag{22}$$

The operation constraints of SOPs can be transformed into rotation cone constraints.

$$P_{i,t}^{SOP} + Q_{i,t}^{SOP} \le 2\frac{S_{ij}^{SOP}}{\sqrt{2}}\frac{S_{ij}^{SOP}}{\sqrt{2}} \tag{23}$$

CASE STUDY

In this section, a distribution network as shown in Fig. 4 is used as a test system to analyze and verify the proposed model and algorithm. The system is an improved IEEE 33-node systems with one SOP. Three PVs are installed at nodes 22, 25 and 33 with capacities of 500 kW, 300 kW, and 400 kW, respectively. Three 200 kW WTs are installed at nodes 6, 16, and 19. The total base load is 3715 kW and 2300 MVar. The voltage of the substation transformer is

12.66kV. There are 32 normal closed switches and 5 normal open tie switches. In this modified system, the capacity of the SOP is 300 kVA and replace the original tie-line switch on Line 18–33. The voltage range of all nodes is set to [0.95, 1.05] p.u. The current range of main line (1-18) is 400A. The current range of branch line (19-22,23-25,23-33) is 200A. The current range of tie switches (8-21,12-22,9-15,25-29) is 100A. The DGs are required to operate with a power factor is 0.95. Locations and capacities of ESs are indicated in Table 2. The initial state of charge of ESs is 0.2. Priorities of the loads are indicated in Table 3. This program is coded by YALMIP [19] The optimization method proposed is implemented with MATLAB R2016a, and the operating environment is Intel i5-5200 2.2GHz CPU, 8GB RAM.

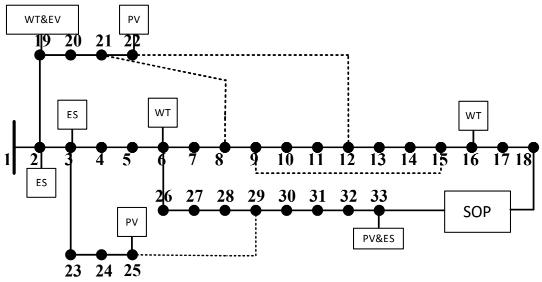

Fig.4 A modified IEEE 33 distribution system with DERs & SOPs

Table 2 Locations and capacities of ESs

Node	2	3	19	33
Power capacity (kW)	120	140	120	280
Energy capacity (kWh)	710	860	720	1700

Table 3 Priorities and controlling types of the loads

Primary load	Second-grade Load	Third-grade Load
2,6,9,13,20,23,26,30,33	The rest	8, 24

Comparison of different scenarios

When a fault happens between Line 7 and Line 8 for one hour. In service restoration, SOP and ES should be optimized at first, and then the distribution network reconfiguration will be considered. In Fig. 5, there are four typical scenarios are used to test the proposed adaptive service strategy, and results are shown in Table 5. In scenario 1, load level is low and DG output is low, because, SOP transmit active power to the system.

In scenario 2, load level is low and DG output is low because SOP transmits less active power to the system and more reactive power to the system. Above all, in the first two scenarios, only optimizing SOP can restore all load. Therefore, there is no need for a network reconfiguration. The SOP should be in *Vf* mode and supply a reference voltage to lost loads. In scenario 3, the load level is high and the DG output is high. Without distribution network reconfiguration, SOP mainly transmits active power.

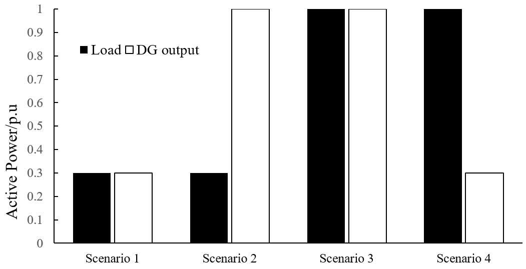

Fig.5 Load and DG output levels of the 4 typical scenarios

Therefore, SOP mainly transmits active power to the system. DG power curtailment happens especially the wind power output (790.55kW of 12000kW). At that time, distribution network topology would be optimized. The result shows that tie switches shoulder the responsibility of active power transmission instead of SOP. SOP have extra ability to supply reactive power. The wind power curtailment phenomenon will be reduced. In scenario 4, the load level is high and the DG output is low. Without distribution network reconfiguration, SOP mainly transmits active power. At that time, distribution network topology would be optimized. The result shows that tie switches shoulder the responsibility of active power transmission instead of SOP. SOP have extra ability to supply reactive power. In scenarios 3-2 and 4-2, SOP should be in PQ mode and supply a reference voltage to lost loads.

Table 4 Comparison of power recovery results under different scenarios

	Active power of lost load (kW)	Reactive power of lost load (kVar)	Real output of PV (kW)	Max output of PV (kW)	Real output of WT (kW)	Max output of WT (kW)	Supplement the reactive power of DG (kVar)	ES output (kW)	Transmission active power of SOP (kW)	Supplement the reactive power of SOP (kVar)	Transmission active power of tie switch (kW)	Transmission reactive power of tie switch (kW)	Power losses (kW)
Scenario1	0.00	0.00	179.98	180.00	238.24	360.00	80.41	197.68	199.07	341.56	0.00	0.00	34.54
Scenario2	0.00	0.00	599.92	600.00	727.28	1200.00	75.84	197.87	67.22	412.30	0.00	0.00	30. 85
Scenario3-1	359.92	206.62	597.91	600.00	790.55	1200.00	90.36	194.27	258.83	303.32	0.00	0.00	21.31
Scenario3-2	0.00	0.00	598.91	600.00	1198.59	1200.00	90.76	195.46	1.02	586.25	1443.30	1217.02	20.23
Scenario4-1	477.12	268.17	179.35	180.00	359.68	360.00	92.77	196.82	271.42	255.57	0.00	0.00	27.59
Scenario4-2	0.00	0.00	178.85	180.00	358.79	360.00	90.93	196.25	1.05	596.96	1475.18	475.85	22.54

(x-1 means without distribution network reconfiguration, x-2 means with distribution network reconfiguration)

Comparison of different cases

There are two cases designed to verify the benefits for coordinated optimization of ESs. When a fault happens between Lines 7 and 8, the outage is to be prolonged for 4 hours. The DG outputs and loads during the service restoration are indicated in Table 5.

Case 1: the system is optimized by network reconfiguration, with VSC2 and ESs.

Case 2: the system is optimized by network reconfiguration and VSC2, without ESs.

Table 6 shows the result of the service restoration. Without ESs, total restoration power supply of case 2 would significantly decrease compared with case 1. It is worth noting that DG power curtailment will be reduced in case 1. DG can also supply more reactive power in case 1.

Figs. 6 and 7 show that after isolating the fault, SOP takes major responsibility to support outage areas' reactive power. It is apparent that it changed to follow the load's demand. With SOP and ESs, the lost load can get more energy from the grid. DG mainly provide active power. And part of it can be shifted by ESs to the time when the load has a high demand. SOP and grid share the reactive power of loads. Fig.8 shows that ESs were in the charge state at time 1, 2 and 3, and turned to the discharge state at time 4. The reason for this is that ESs from lines need to supply energy for AC peak loads at time 4.

Table 5 DG outputs and loads during the service restoration

Time	1	2	3	4
Load of lines/p.u	0.2	0.7	0.6	1
PV outputs/p.u	1	0.5	1	0.3
WT outputs/p.u	1	0.5	0.2	0.1

Table 6 Results of service restoration

	Active power of lost load (kW)	Reactive power of lost load (kVar)	Real output of PV (kW)	Max output of PV (kW)	Real output of WT (kW)	Max output of WT (kW)	Supplement the reactive power of DG (kVar)	Power losses (kW)
Case 1	0.00	0.00	1677.70	1680.00	2157.90	3240.00	359.35	130.87
Case 2	331.44	190.45	593.16	1680.00	1187.50	3240.00	286.72	131.39

CONCLUSION

Considering integrating high levels of various DERs into the grid, this paper proposes adaptive service restoration strategy of distribution networks with DERs and SOPs to realize the coordination optimization of SOPs, ESs and tie switches. Distribution network scenario classification is described with analysis of various control models of SOPs. Matching analysis is performed between network scenarios and control models of SOPs. Based on the mixed-integer second-order cone programming, lines and the control devices with different characteristics are proposed. Results show that apart from balancing the supply and demand, the ES system scheduling along with network reconfiguration enabled by SOPs can be combined to reduce power losses, restore more lost loads to minimise customer interruptions and customer minutes lost.

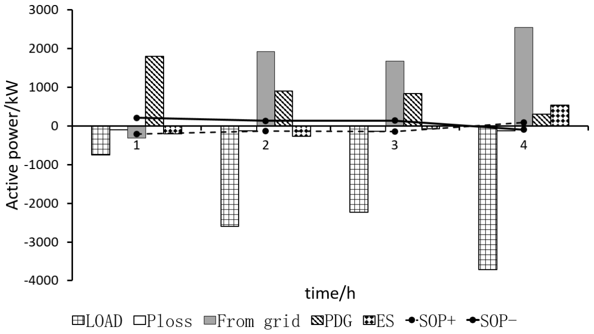

Fig.6 Active power balance during service restoration

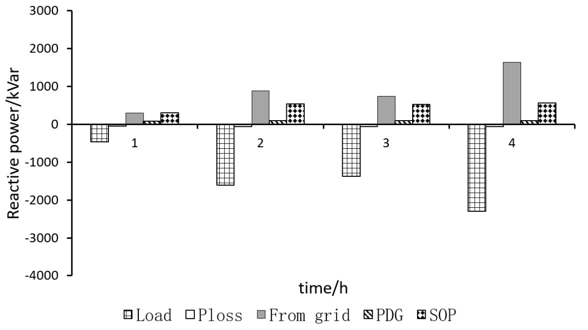

Fig.7 Reactive power balance during service restoration

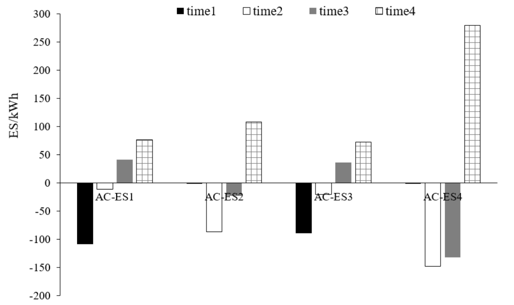

Fig.8 Optimal energy dispatch during service restoration

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