A Coordinated Optimization Method of SNOP and Tie Switch Operation Simultaneously Based on Cost in Active Distribution Network

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ABSTRACT

Soft Open Point (SOP) refers to a power electronic device installed in place of a normally-open point in a distribution network. The application of SOP will greatly promote the economy, flexibility and controllability of the distribution network. However, due to the high investment of SOP and operation cost of switch, the coordinated operation of SOP and switch needs to be considered. In this paper, a coordinated optimization method of SOP and tie switch operation simultaneously based on cost is proposed for the operation of active distribution system. Firstly, this paper builds a coordinated operation optimization model for SOP and switch considering action costs. Then, a conic model conversion is proposed and mixed-integer second-order cone programming is used to solve the model with efficiency and convergence. Finally, case studies on IEEE 33-node test feeder are used to verify the proposed coordinated optimization method.

INTRODUCTION

The development and application of smart distribution network and renewable resource generation technologies is pushing forward the reform of distribution & utilization pattern and operation management mechanism [1]. As a novel power electronic device, Soft Open Point (SOP), emerges to replace the normally-open point in distribution network. Compared with traditional tie switch, the power flow controlled by SOP is in an accurate and flexible way. It can realize real-time active power flow optimization and reactive power compensation, which effectively responds to the volatility brought by DG and load. However, traditional tie switch cannot be completely replaced by SOP in a short time in terms of the high investment. The operation optimization of distributed network containing both of them needs to be taken into account.

Considering the power losses and current surge caused by switching events, the traditional tie switch can't operate frequently. By contrast, SOP is capable of changing transmitted power and operation state, which offers a feasible solution to overvoltage and overload. In this case, the time series model of coordinated optimization of traditional tie switch and SOP is needed.

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Reference [2] studied the basic principle and model of the SOP, while reference [3, 4] carried on the simulation analysis of steady-state and transient characteristics of

SOP, respectively, which will provide a foundation for the coordinated optimization for SOP and tie switch.

This paper proposes a coordinated optimization method for SOP and tie switch considering action costs. The conic programming is employed to convert the original model into a mixed integer second order conic programming model. The effectiveness of the optimization model and algorithm is verified on the modified IEEE 33-node system.

MODELING OF DISTRIBUTION NETWORK COORDINATED OPERATION WITH SOP AND TIE SWITCHES

In this section, considering the action costs of tie switch and power losses of SOP, the mathematical model of distribution network coordinated operation with SOP and tie switch is formulated.

Objective function

This paper takes the minimization of active power losses as the objective function, which is formulated as

$$\min f = \min\left(W^{\mathrm{SWI,loss}} + W^{\mathrm{NET,loss}} + W^{\mathrm{SOP,loss}}\right) \tag{1}$$

The overall active power losses of distribution network are composed of the following three parts.

1) $W^{\mathrm{SWI,loss}}$: equivalent losses of action costs caused by switches

$$W^{\mathrm{SWI,loss}} = C^{\mathrm{SWI}} \sum_{t=1}^{N^{\mathrm{T}}} \sum_{ij\in\Omega_b} \left|\alpha_{t,ij} - \alpha_{t-1,ij}\right| \tag{2}$$

Where Ω_b is the set of branches. N^{T} is the cycle of coordinated operation optimization. C^{SWI} is the equivalent coefficient of action costs caused by switches. $\alpha_{t,ij}$ denotes the switch status in period t, and $\alpha_{t,ij}$ is 0 when the switch is open while $\alpha_{t,ij}$ is 1 when the switch is closed.

2) $W^{\mathrm{NET,loss}}$: power losses of distribution network

$$W^{\mathrm{NET,loss}} = \sum_{t=1}^{N^{\mathrm{T}}} \sum_{ij\in\Omega_b} r_{ij} I_{t.ij}^2 \Delta t \tag{3}$$

Where $I_{t,ij}$ denotes the current from bus i to bus j in period t. Denote $z_{ij} = r_{ij} + \mathbf{i}x_{ij}$ as the complex impedance of the line connecting bus i and bus j.

3) $W^{\mathrm{SOP,loss}}$: operation power losses of SOP

$$W^{\mathrm{SOP,loss}} = \sum_{t=1}^{N^{\mathrm{T}}} \sum_{i=1}^{N^{\mathrm{N}}} A_i^{\mathrm{SOP}} \left|P_{t,i}^{\mathrm{SOP}}\right| \Delta t \tag{4}$$

Where N^{N} denotes the number of SOP. A_i^{SOP} denotes the loss coefficient of SOP. $P_{t,i}^{\text{SOP}}$ is the transmitted active power of SOP at node i in period t.

Radical distribution network constraints

$$\alpha_{t,ij} = \beta_{t,ij} + \beta_{t,ji} \tag{5}$$

$$\sum_{j\in\Omega(i)} \beta_{t,ij} = 1,\ \forall i \in N \setminus N_S \tag{6}$$

$$\sum_{j\in\Omega(i)} \beta_{t,ij} = 0,\ \forall i \in N_S \tag{7}$$

$$\alpha_{t,ij} \in \{0,1\},\ 0 \le \beta_{t,ij} \le 1,\ 0 \le \beta_{t,ji} \le 1 \tag{8}$$

Let N^{S} denote the subset of buses which are substations and $\Omega(i)$ be the set of all adjacent nodes of bus i. Since the binary variable $\alpha_{t,ij}$ is not directional, each switch status of the line is also associated with two continuous line orientation variables $\beta_{t,ij}$ and $\beta_{t,ji}$, representing the direction of power flow [5].

System power flow constraints

$$\sum_{ji\in\Omega_b} \alpha_{t,ji}\left(P_{t,ji} - r_{ji} I_{t,ji}^2\right) + P_{t,i} = \sum_{ik\in\Omega_b} \alpha_{t,ik} P_{t,ik} \tag{9}$$

$$\sum_{ji\in\Omega_b} \alpha_{t,ji}\left(Q_{t,ji} - x_{ji} I_{t,ji}^2\right) + Q_{t,i} = \sum_{ik\in\Omega_b} \alpha_{t,ik} Q_{t,ik} \tag{10}$$

$$P_{t,i} = P_{t,i}^{\text{DG}} + P_{t,i}^{\text{SOP}} - P_{t,i}^{\text{LOAD}} \tag{11}$$

$$Q_{t,i} = Q_{t,i}^{\text{DG}} + Q_{t,i}^{\text{SOP}} - Q_{t,i}^{\text{LOAD}} \tag{12}$$

$$I_{t,ij}^2 U_{t,i}^2 = P_{t,ij}^2 + Q_{t,ij}^2 \tag{13}$$

$$\begin{aligned} &U_{t,i}^2 - U_{t,j}^2 - 2\left(r_{ij} P_{t,ij} + x_{ij} Q_{t,ij}\right) \\ &\quad + \left(r_{ij}^2 + x_{ij}^2\right) I_{t,ij}^2 + \text{M}\left(1 - \alpha_{t,ij}\right) \ge 0 \end{aligned} \tag{14}$$

$$\begin{aligned} &U_{t,i}^2 - U_{t,j}^2 - 2\left(r_{ij} P_{t,ij} + x_{ij} Q_{t,ij}\right) \\ &\quad + \left(r_{ij}^2 + x_{ij}^2\right) I_{t,ij}^2 - \text{M}\left(1 - \alpha_{t,ij}\right) \le 0 \end{aligned} \tag{15}$$

$$-\text{M}\alpha_{t,ij} \le P_{t,ij} \le \text{M}\alpha_{t,ij} \tag{16}$$

$$-\text{M}\alpha_{t,ij} \le Q_{t,ij} \le \text{M}\alpha_{t,ij} \tag{17}$$

$$0 \le I_{t,ij}^2 \le \text{M}\alpha_{t,ij} \tag{18}$$

Equations (9) and (10) represent the law of conservation of power at each bus i in period t, where $P_{t,ij}$ and $Q_{t,ij}$ denote the real and reactive power from bus i to bus j in period t respectively. $P_{t,i}$ and $Q_{t,i}$ denote the real and reactive power injection at bus i in period t respectively. Equations (11) and (12) indicate the power injection at each bus i. Let $P_{t,i}^{\text{DG}}$, $P_{s,i}^{\text{LD}}$ and $P_{s,i}^{\text{SOP}}$ represent the real power generated by DG, real power consumption and real power delivered by SOP in period t, respectively. Let $Q_{t,i}^{\text{DG}}$, $Q_{s,i}^{\text{LD}}$ and $Q_{s,i}^{\text{SOP}}$ represent the reactive power generated by DG, reactive power consumption and reactive power delivered by SOP in period t, respectively. The current magnitude of each line can be determined by using Equation (13), where $U_{t,i}$ denotes the complex voltage of bus i in period t. Equations (14)-(15) represent Ohm's law over each link (i, j). Disjunctive parameter M is a sufficiently large constant, denoting the bounds of the variable [6].

System operation constraints

$$(U_i^{\min})^2 \le U_{t,i}^2 \le (U_i^{\max})^2 \tag{19}$$

$$0 \le I_{t,ij}^2 \le (I_{ij}^{\max})^2 \tag{20}$$

Where $U_i^{\max}$ and $U_i^{\min}$ are the upper and lower limits of voltage amplitude at node i, respectively. Let $I_{ij}^{\max}$ denote the upper limit of current amplitude of line ij.

SOP operation constraints

$$P_{t,i}^{\text{SOP}} + P_{t,j}^{\text{SOP}} + A_i^{\text{SOP}}\left|P_{t,i}^{\text{SOP}}\right| + A_j^{\text{SOP}}\left|P_{t,j}^{\text{SOP}}\right| = 0 \tag{21}$$

$$Q_i^{\min} \le Q_{t,i}^{\text{SOP}} \le Q_i^{\max} \tag{22}$$

$$Q_j^{\min} \le Q_{t,j}^{\text{SOP}} \le Q_j^{\max} \tag{23}$$

$$\sqrt{\left(P_{t,i}^{\text{SOP}}\right)^2 + \left(Q_{t,i}^{\text{SOP}}\right)^2} \le S_{ij}^{\text{SOP}} \tag{24}$$

$$\sqrt{\left(P_{t,j}^{\text{SOP}}\right)^2 + \left(Q_{t,j}^{\text{SOP}}\right)^2} \le S_{ij}^{\text{SOP}} \tag{25}$$

Where $Q_i^{\min}$ and $Q_i^{\max}$ are the upper and lower limits of reactive power of SOP connected to bus i. S_{ij}^{SOP} is the upper capacity limit of SOP connected to bus i.

The variables in above-mentioned model include the installing location and capacity of SOP, the switch state and the transmitted active and reactive power of SOP in each period. As a consequence, Equations (1)-(28) form the optimization model of distribution network coordinated operation with SOP and switches.

CONIC MODEL CONVERSION

Second-order cone programming (SOCP) is essentially convex programming mathematically, which can be regarded as the generalization of both linear and nonlinear programming [7]. SOCP can solve the problem of minimum linear objective function based on convex cone in the linear space. It has an excellent performance of global optimality and computational efficiency. The SOCP standard form can be written as:

$$\min\{\boldsymbol{c}^T \boldsymbol{x} \mid \boldsymbol{A}\boldsymbol{x} = \boldsymbol{b}, \boldsymbol{x} \in \boldsymbol{K}\} \tag{26}$$

As shown above, the second-order cone programming has very strict demands on the mathematical formulation. The objective function must be a linear function of decision variable $\boldsymbol{x}$ and its feasible region is composed of linear equality constraints and convex cone constraints. The above-mentioned optimization model is described with numerous nonlinear functions, such as the square representation of voltage amplitude and current amplitude. Firstly, it needs to introduce additional variables for each bus and line, respectively, to realize the linearization of nonlinear functions by means of variable substitution.

For each bus $i, j \in N$, let $\tilde{U}_{t,i}$ denote the square of the magnitude of its complex voltage, and let $\tilde{I}_{t,ij}$ denote the square of the magnitude of the complex current. Then, with substituting the new optimization variables $\tilde{U}_{t,i}$ and $\tilde{I}_{t,ij}$ into the branch flow model, the objective function and nonlinear constraints become linear except the equality constraints (13). To cast them as second order cone constraints, these nonlinear equality constraints are relaxed to the inequality constraints [8]

$$I_{t,ij}^2 U_{t,i}^2 \geq P_{t,ij}^2 + Q_{t,ij}^2 \quad (27)$$

The corresponding second-order cone programming (SOCP) formulation is:

$$\left\| \begin{matrix} 2P_{t,ij} & 2Q_{t,ij} & \tilde{I}_{t,ij} - \tilde{U}_{t,i} \end{matrix} \right\|_2 \leq \tilde{I}_{t,ij} + \tilde{U}_{t,i} \quad (28)$$

As for the capacity constraints of SOP, it is transformed into the following form in accordance with requirements of SOCP [9].

$$\left(P_{t,i}^{SOP}\right)^2 + \left(Q_{t,i}^{SOP}\right)^2 \leq 2 * \frac{S_{ij}^{SOP}}{\sqrt{2}} * \frac{S_{ij}^{SOP}}{\sqrt{2}} \quad (29)$$

$$\left(P_{t,j}^{SOP}\right)^2 + \left(Q_{t,j}^{SOP}\right)^2 \leq 2 * \frac{S_{ij}^{SOP}}{\sqrt{2}} * \frac{S_{ij}^{SOP}}{\sqrt{2}} \quad (30)$$

Equations (29) and (30) are equivalent to the original constraints (24) and (25) while meeting the requirement of rotated quadratic cone form.

As for the absolute terms $\left|P_{t,i}^{SOP}\right|$ and $\left|P_{t,j}^{SOP}\right|$ in (21), auxiliary variables $\left|M_{t,i}^{SOP}\right|$ and $\left|M_{t,j}^{SOP}\right|$ are introduced to represent and linearize them, as shown in follows.

$$M_{t,i}^{SOP} \geq 0, \quad M_{t,j}^{SOP} \geq 0 \quad (34)$$

$$M_{t,i}^{SOP} \geq P_{t,i}^{SOP}, \quad M_{t,i}^{SOP} \geq -P_{t,i}^{SOP} \quad (35)$$

$$M_{t,j}^{SOP} \geq P_{t,j}^{SOP}, \quad M_{t,j}^{SOP} \geq -P_{t,j}^{SOP} \quad (36)$$

After convex relaxation and conic conversion [10], the mixed inter second-order cone optimization model of distribution network coordinated operation with SOP and switches is formulated.

CASE STUDY

In this section, the effectiveness of the optimization model and conic convertion is verified on the modified IEEE 33-node test feeder. The test case is shown in Figure 1.

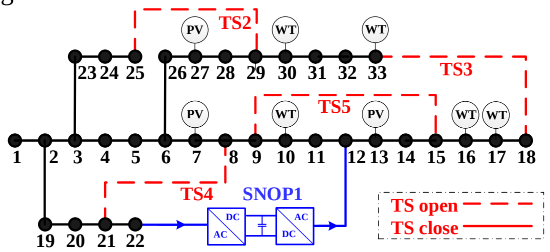


Figure 1. Structure of the IEEE 33-node test feeder

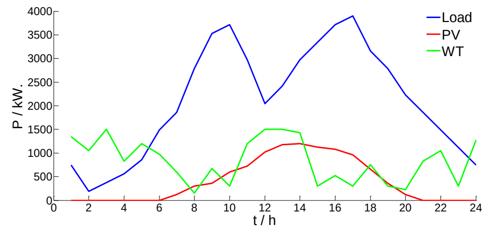


Figure 2. Daily operation curve of DGs and loads

In order to consider the impact of distributed generation, five groups of wind turbines and three groups of photovoltaic systems are accessed into IEEE 33-node test feeder. The main parameters are shown in Table 1. Taking one hour as a unit time period, daily DGs and loads operation curve is obtained by load forecasting, as shown in Figure 2. One group of SOP is accessed into the distribution network, with the capacity of 1000kVA. Assuming that the loss coefficient of SOP is 0.0199.

The proposed model is implemented in MATLAB R2014a scripts, and solved with Mosek 7.0 toolbox. The hardware platform for the simulation is a PC with an Intel Xeon CPU E5-1620 @3.70GHz and a 32GB RAM.

Table 1. The Parameters of DGs

-	WT					PV		
Location	10	16	17	30	33	7	13	27
Capacity /kW	500.0	300.0	200.0	200.0	300.0	500.0	300.0	400.0

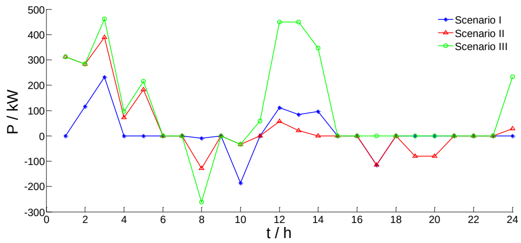
Based on the operation curve of distributed generation and load in Figure 2, we optimize the status of tie switches and the transmitted power of SOP. Three different coefficients of switching cost are set to test the effectiveness of the coordinated optimization model. Three scenarios are selected to analyze the optimization performance of SOP and tie switch.

The loss of entire system without network reconfiguration and SOP is 1239.79kWh. The optimization results are shown in Table 2, and the active and reactive power of SOP are shown in Figure 3. The number of switch action is shown in Figure 4.

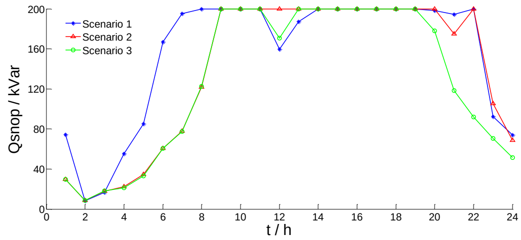
Table 2. Optimization results of different switching costs scenarios

Scenario	I	II	III
Coefficients of switching cost	0.0 (Lower)	5.0 (Medium)	10.0 (High)
Coefficients of SNOP loss	0.0199		
Number of switch action	48	11	1
Net loss / kWh	771.80	835.35	907.51
SOP loss / kWh	19.10	35.81	115.15
Total loss / kWh	790.90	926.16	1022.66

Comparing different schemes, it can be seen that better performance of power loss reduction is obtained by the combination of network reconfiguration and SOP. SOP can adjust its transmitted active power and reactive power compensation dynamically according to the operation condition of the system, enabling to response to the fluctuations of load and distributed generation rapidly.



(a) The active power of SOP



(b) The reactive power of SOP

Figure 3. Optimization results of SOP

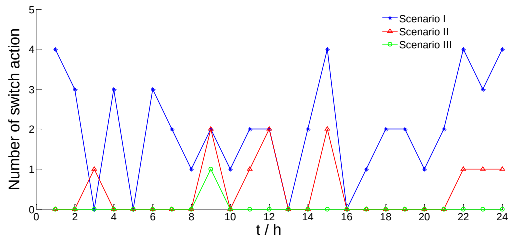


Figure 4. Number of switch action

In conclusion, the operation optimization of SOP is an effective complement for network reconfiguration, which can adjust the real-time power flow control strategy throughout the day. By setting the switch action cost coefficient, the switching frequency is significantly reduced. Combining the optimization of SOP with network reconfiguration, the efficiency of distribution network coordinated operation can be improved significantly.

CONCLUSION

In this paper, a coordinated optimization method of SOP and tie switch operation simultaneously based on cost in active distribution network is proposed, which considers operation cost of switch. Its objective functions and constraints are converted with the application of conic programming, which promotes the solving procedure obviously. In coordination with tie switch, the application of SOP greatly reduces the net loss of distribution network. On the other hand, SOP is an effective tool to avoid the frequent switching of tie switch and prolong its lifetime, which maximizes the investment and operation benefits of distributed network.

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