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Abstract: This paper proposes an optimal power flow calculation method of minimum three-phase unbalance of distribution network based on split-phase SNOP breakers. First, a new circuit design of split-phase SNOP breakers is proposed, and its corresponding mathematical modeling is also established. Then, an optimal power flow calculation model of minimum three-phase unbalance of distribution network is developed, based on split-phase SNOP mathematical modeling. The model has 3 objective functions, minimum unbalanced three-phase active load, minimum unbalanced three-phase voltage magnitudes and minimum active power loss of distribution systems. The constraints are included power flow constraints and split-phase SNOP operation constraints. And the relative dominant method is used for transforming dual objectives to one objective, and the immune genetic algorithm is hired for solving. Finally, the effectiveness of the proposed model is verified by simulation analysis of a practical distribution network with 5 feeders.

1. Introduction

The unbalanced three-phase voltage problem of distribution systems, unbalanced load may cause asymmetric operation of the distribution network. Asymmetric operation of the distribution network not only increases the power loss and decreases transfer efficiency, but also causes bad impacts on voltage quality of overloading phases in the distribution network. Reactive power compensation can deal with three-phase unbalanced problems of the distribution network, and it’s mainly including two ways. The first is the split-phase reactive compensation at the low voltage sides of distribution transformers, and the other one is these reactive power sources at the distribution network. But for the first manner, it has limited compensation for unbalanced voltage and can’t compensate for three-phase unbalanced load at the low pressure side completely. And the second method offers three-phase symmetric compensations for non-neutral grounding system by using static compensator, but it can neither cope with power source unbalanced, nor deal with coordinated inhibition of unbalanced voltage at many buses in the distribution network. Currently, we can take full advantage of advanced power electronic technology, and develop a flexible, reliable, high-efficiency and high-quality soft distribution network for increasing the high operation efficiency and power distribution reliability, and maintaining high power quality like voltage unbalanced and harmonic wave.

Soft normally open point (SNOP) is the key soft control device in the distribution network. This SNOP device is an all-computer-controlled power electronic device, which can be instead of the traditional interconnection switch. And, SNOP can realize flexible regulation of active transmission among 10kV feeders and provide independent reactive compensation for multiple 10kV feeders. Moreover, SNOP has certain independent control for three-phase power, which can do split-phase control on active power transmission and reactive power compensation at two sides. Flexible adjustment of three-phase power based on split-phase SNOP among 10kV feeders can relieve unbalanced three-phase power flow and three-phase voltage magnitudes in the distribution network effectively, and eliminating overloading problems of single-phase lines, equipment damages caused by over-high phase voltage magnitude, etc.

The future distribution network is developing toward electronic power generation and flexible regulation. 10kV feeders in the soft distribution network are connected by split-phase SNOP breakers, which can achieve mutual active and reactive power support among feeders and thereby relieve the unbalanced three-phase active problem and the unbalanced bus voltage magnitude problem. In this paper, the three-phase power control ability of split-phase SNOP breakers is analyzed, and we then deduce the active and reactive power regulation range of split-phase SNOP breakers. Furthermore, a three-phase power control optimization model of distribution network based on split-phase SNOP breakers is established. In this model, we proposes a three-phase power control for minimizing the sum of unbalanced three-phase active power and unbalanced three-phase voltage. The immune genetic algorithm is hired for solving this optimization model. Finally, it is verified effectively by a practical 10 kV distribution network.

2. Three-phase power control characteristics and ranges of a split-phase SNOP

2.1. Three-phase power control characteristics of a split-phase SNOP breaker

SNOP breakers have excellent control ability and flexible power regulation ability because of embedded power electronic components. In Fig.1, two feeders are connected by a split-phase SNOP. There are two voltage source converters (VSCs) at two sides of this split-phase SNOP, which share one DC bus. VSC-I and VSC-II are composed by the modularized multilevel structure. Each phase is formed by a series connection of 1 electric reactor and N sub-modules. It can be seen from Fig.1 that active and reactive power which are injected by VSC-I and VSC-II into feeders are $P^{r}_{\mathrm{T,SNOP}}$ and $Q^{r}_{\mathrm{T,SNOP}}$, where r=I or II which are corresponding to VSC-I and VSC-II, and T=A, B and C, which are corresponding to the three phases. When three-phase network and load parameters are unbalanced, the SNOP breakers can make split-phase regulation of active and reactive power for enhancing power quality and operation efficiency.

For three-phase active power of VSC-I and VSC-II, active power input and output of SNOP breakers are balanced, which maintaining steady voltage of the DC bus. Besides, active power loss of SNOP breakers is also considered. Therefore, active balance equations of SNOP breakers are:

$$\begin{cases}\sum\limits_{\mathrm{T=A,B,C}} P^{\mathrm{I}}_{\mathrm{T,SNOP}} + P^{\mathrm{I}}_{\mathrm{L,SNOP}} \sum\limits_{\mathrm{T=A,B,C}} P^{\mathrm{II}}_{\mathrm{T,SNOP}} + P^{\mathrm{II}}_{\mathrm{L,SNOP}} = 0 \\ P^{\mathrm{r}}_{\mathrm{L,SNOP}} = aS^{\mathrm{r}}_{\mathrm{L,SNOP}} + b\sqrt{S^{\mathrm{r}}_{\mathrm{L,SNOP}}} + P_{\mathrm{L0,SNOP}},\ r\text{=I, II}\end{cases} \tag{1}$$

where $P^{\mathrm{r}}_{\mathrm{L,SNOP}}$ and $S^{\mathrm{r}}_{\mathrm{L,SNOP}}$ are the active power loss and complex power of VSC-I and VSC-II. a and b are active power loss coefficients. $P_{\mathrm{L0,SNOP}}$ is the inherent active power loss.

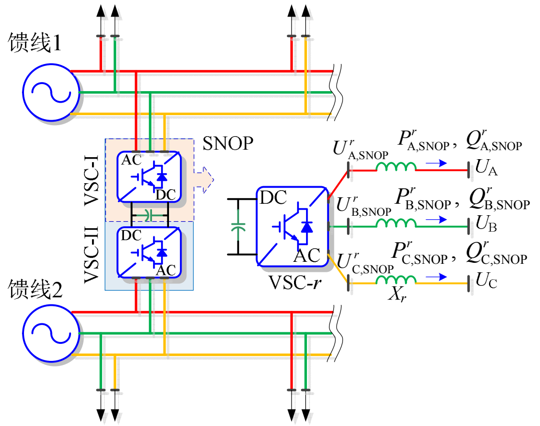


Fig. 1 *Two feeders connected by a split-phase SNOP breaker*

In three-phase power control process of split-phase SNOP breakers, active power balance equations at two sides need be satisfied. Reactive control can absorb or inject reactive power under practical operation demand. However, complex power in different phases should not exceed the capacity of SNOP breakers.

$$S^{r}_{\mathrm{T,SNOP}} = \sqrt{{P^{r}_{\mathrm{T,SNOP}}}^{2} + {Q^{r}_{\mathrm{T,SNOP}}}^{2}} \le S_{\mathrm{n,SNOP}},\ \mathrm{T=A,\,B,\,C} \tag{2}$$

where $S_{\mathrm{n,SNOP}}$ is three phases of VSC capacities in this SNOP. In Fig.1, U_{A}, U_{B} and U_{C} are the three-phase voltage magnitudes at the feeder side. $U^{r}_{\mathrm{A,SNOP}}$, $U^{r}_{\mathrm{B,SNOP}}$ and $U^{r}_{\mathrm{C,SNOP}}$ are the voltage magnitudes at the VSC side, respectively. X_{r} is the equivalent reactance at two sides. Actually, SNOP's three-phase power control is by adjusting the three-phase voltage at the VSC side. If the voltage's phase at the feeder side is taken as the reference, the active and reactive power which are injected by VSC are

$$\begin{cases} P^{r}_{\mathrm{T,SNOP}} = \dfrac{U^{r}_{\mathrm{T,SNOP}} U_{\mathrm{T}}}{X_r} \sin \delta^{r}_{\mathrm{T}} \\ Q^{r}_{\mathrm{T,SNOP}} = \dfrac{U^{r}_{\mathrm{T,SNOP}} U_{\mathrm{T}} \cos \delta^{r}_{\mathrm{T}} - {U_{\mathrm{T}}}^{2}}{X_r},\ \mathrm{T=A,\,B,\,C} \end{cases} \tag{3}$$

where δ_{T} is the phase for the VSC voltage of a SNOP breaker which is leading than the voltage phase at the feeder side. To ensure safe operation of VSC, the voltage magnitude and phase of VSC must be constrained in the given ranges.

$$\begin{cases} U^{r}_{\mathrm{T,SNOPmin}} \le U^{r}_{\mathrm{T,SNOP}} \le U^{r}_{\mathrm{T,SNOPmax}} \\ \delta^{r}_{\mathrm{Tmin}} \le \delta^{r}_{\mathrm{T}} \le \delta^{r}_{\mathrm{Tmax}},\ \mathrm{T=A,\,B,\,C} \end{cases} \tag{4}$$

where $U^{r}_{\mathrm{T,SNOPmax}}$, $U^{r}_{\mathrm{T,SNOPmin}}$, δ_{Tmax} and δ_{Tmin} are the upper and lower limits of voltage magnitude and phase of VSC, respectively. The upper and lower limits of active and reactive power can be gained by substituting the equation (4) into the equation (3). In the following, they can be combined with SNOP capacity as determined by equation (2), and thus the active and reactive capacity constraints of SNOP could be obtained, as shown in Fig.2.

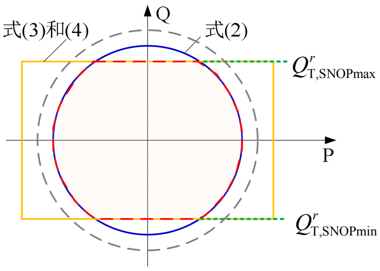


Fig. 2 *Active and reactive capacity constraints of a SNOP breaker*

It can be seen from Fig.2 that the active power constraint of SNOP is determined by capacity, while the reactive power constraint is determined by capacity, voltage magnitude and voltage phase at the side of VSC. This is because the active power injected by VSC into feeders is proportional to voltage magnitude and voltage phase of VSC, according to the equation (3). The equivalent reactance X_{r} is generally 0.1～0.25p.u. The corresponding upper and lower boundaries of active power are far higher than the capacity of VSC. And the injected reactive power is proportional to the difference in voltage magnitudes between the VSC and the 10kV feeder. The determined upper and lower boundary of reactive power are lower than capacity of VSC. Hence, the output reactive power constraint of SNOP is

$$\underline{Q^{r}_{\mathrm{T,SNOP}}} \le Q^{r}_{\mathrm{T,SNOP}} \le \overline{Q^{r}_{\mathrm{T,SNOP}}},\ \mathrm{T=A,\,B,\,C} \tag{5}$$

The upper boundary ($\overline{Q^j_{\mathrm{T,SNOP},i}}$) and the lower boundary ($\underline{Q^j_{\mathrm{T,SNOP},i}}$) of the reactive power in the equation (5) could be gained by substituting upper and lower boundaries of VSC voltage magnitude and voltage phase into the equation (3). In the three-phase asymmetric distribution system, the three-phase active power and reactive power of SNOP breakers may not be balanced. This may cause the asymmetric currents injecting into 10kV feeders.

Since a large amount of distribution networks are non-neutral grounding systems in China, the zero-sequence components of the injected currents by SNOP breakers are zero. This can be expressed as

$$\frac{P^r_{\mathrm{A,SNOP}}+\mathrm{j}Q^r_{\mathrm{A,SNOP}}}{\dot{U}_{\mathrm{A}}}+\frac{P^r_{\mathrm{B,SNOP}}+\mathrm{j}Q^r_{\mathrm{B,SNOP}}}{\dot{U}_{\mathrm{B}}}+\frac{P^r_{\mathrm{C,SNOP}}+\mathrm{j}Q^r_{\mathrm{C,SNOP}}}{\dot{U}_{\mathrm{C}}}=0 \tag{6}$$

Under this circumstance, the three-phase active power and reactive power of SNOP breakers couldn't be controlled independently. Instead, they have a strong relationship between active power and reactive power of SNOP breakers. It is assumed that there is an infinite power source connected to the beginning of a 10kV feeder, and the corresponding three-phase voltage is defined as $U_{\mathrm{A}}=U$, $U_{\mathrm{B}}=U\mathrm{e}^{-\mathrm{j}2\pi/3}$ and $U_{\mathrm{C}}=U\mathrm{e}^{\mathrm{j}2\pi/3}$. The three-phase active power and reactive power of SNOP breakers can meet the following equation (7) if the three-phase voltage is substituted into the equation (6).

$$\begin{cases} P^r_{\mathrm{C,SNOP}}=\dfrac{P^r_{\mathrm{A,SNOP}}+P^r_{\mathrm{B,SNOP}}}{2}+\dfrac{\sqrt{3}(Q^r_{\mathrm{A,SNOP}}-Q^r_{\mathrm{B,SNOP}})}{2} \\ \qquad\quad =P^r_{\mathrm{A,SNOP}}-1/2\,\Delta P^r_{\mathrm{AB}}+\sqrt{3}/2\,\Delta Q^r_{\mathrm{AB}} \\ Q^r_{\mathrm{C,SNOP}}=\dfrac{Q^r_{\mathrm{A,SNOP}}+Q^r_{\mathrm{B,SNOP}}}{2}+\dfrac{\sqrt{3}(P^r_{\mathrm{B,SNOP}}-P^r_{\mathrm{A,SNOP}})}{2} \\ \qquad\quad =Q^r_{\mathrm{A,SNOP}}-1/2\,\Delta Q^r_{\mathrm{AB}}-\sqrt{3}/2\,\Delta P^r_{\mathrm{AB}} \end{cases} \tag{7}$$

where the difference between phase A and phase B in active power and reactive power are $\Delta P^r_{\mathrm{AB}}=P^r_{\mathrm{A,SNOP}}-P^r_{\mathrm{B,SNOP}}$ and $\Delta Q^r_{\mathrm{AB}}=Q^r_{\mathrm{A,SNOP}}-Q^r_{\mathrm{B,SNOP}}$. Among three phases injected by SNOP breakers, only two phases could be adjusted independently. Both active power and reactive power of the rest one phase must be coordinated with those of previous two phases, which is in order to ensure no zero-sequence components in the currents injected by SNOP breakers. In the equation (7), the active power and reactive power from the phase C is the same with from phase A and phase B, when $\Delta P^r_{\mathrm{AB}}=0$ and $\Delta Q^r_{\mathrm{AB}}=0$. Similarly, there is also a relationship in the active power and reactive power between from the phase B and active power and from both phase A and phase C could be deduced below.

$$\begin{cases} P^r_{\mathrm{B,SNOP}}=P^r_{\mathrm{A,SNOP}}+1/2\,\Delta P^r_{\mathrm{CA}}+\sqrt{3}/2\,\Delta Q^r_{\mathrm{CA}} \\ Q^r_{\mathrm{B,SNOP}}=Q^r_{\mathrm{A,SNOP}}+1/2\,\Delta Q^r_{\mathrm{CA}}-\sqrt{3}/2\,\Delta P^r_{\mathrm{CA}} \end{cases} \tag{8}$$

When both three-phase active power and reactive power of SNOP breakers meet capacity constraints of VSC simultaneously, active and reactive capacities of phase A have to meet not only constraints in equations (2) and (5), but also the capacity constraint of phase C in the equation (7) and the capacity constraint of phase B in the equation (8). Similarly, active power and reactive power of the rest two phases have to meet multiple capacity constraints, as seen in Fig.3. As a result, the injected three-phase unbalanced power to 10kV feeders by SNOP breakers can improve power quality and enhance operation efficiency of the asymmetric distribution network. However, it may narrow the allowable regulating power ranges of different phases. Therefore, we need to fully consider there have differences in active and reactive capacity constraints of different phases, and we could better obtain how much active power and compensated reactive power can be specified by SNOP breakers.

2.2. Regulating ranges of split-phase SNOP breakers under unbalanced voltages

We suppose that there are $U'_{\mathrm{A}}=U$, $U'_{\mathrm{B}}=1/\eta_{\mathrm{B}}U\mathrm{e}^{-\mathrm{j}(2\pi/3-\sigma_{\mathrm{B}})}$ and $U'_{\mathrm{C}}=1/\eta_{\mathrm{C}}U\mathrm{e}^{\mathrm{j}(2\pi/3+\sigma_{\mathrm{C}})}$ when a SNOP breaker is connected into a 10kVfeeder with unbalanced three phase voltage. And thus, they are substituted into the equation (6), and we get

$$\begin{aligned} &\frac{P^r_{\mathrm{A,SNOP}}+\mathrm{j}Q^r_{\mathrm{A,SNOP}}}{\dot{U}_{\mathrm{A}}}+\frac{\eta_{\mathrm{B}}e^{-\sigma_{\mathrm{B}}}(P^r_{\mathrm{B,SNOP}}+\mathrm{j}Q^r_{\mathrm{B,SNOP}})}{\dot{U}_{\mathrm{B}}} \\ &\qquad +\frac{\eta_C e^{-\sigma_{\mathrm{C}}}(P^r_{\mathrm{C,SNOP}}+\mathrm{j}Q^r_{\mathrm{C,SNOP}})}{\dot{U}_{\mathrm{C}}}=0 \end{aligned} \tag{9}$$

By multiplying the asymmetry factors $\eta_{\mathrm{B}}\mathrm{e}^{-\mathrm{j}\sigma_{\mathrm{B}}}$ and $\eta_{\mathrm{C}}\mathrm{e}^{-\mathrm{j}\sigma_{\mathrm{C}}}$ and corresponding complex power, updated power of phases B and C could be gained

$$\begin{cases} P^{r'}_{\mathrm{B,SNOP}}+\mathrm{j}Q^{r'}_{\mathrm{B,SNOP}}=\eta_{\mathrm{B}}e^{-\sigma_{\mathrm{B}}}(P^r_{\mathrm{B,SNOP}}+\mathrm{j}Q^r_{\mathrm{B,SNOP}}) \\ P^{r'}_{\mathrm{C,SNOP}}+\mathrm{j}Q^{r'}_{\mathrm{C,SNOP}}=\eta_C e^{-\sigma_{\mathrm{C}}}(P^r_{\mathrm{C,SNOP}}+\mathrm{j}Q^r_{\mathrm{C,SNOP}}) \end{cases} \tag{10}$$

If power of phases B and C is updated in the equation (9), the equation (9) is the same with the equation (6). Hence, the power of phase A and updated power of phases B and C are satisfied with equation (7) and equation (8). The power constraint of phase A of the SNOP under unbalanced voltage is

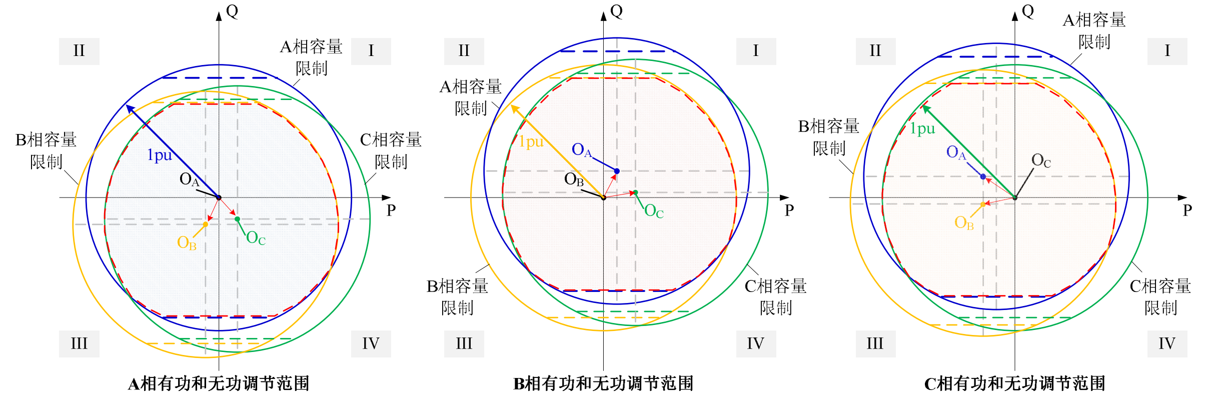
$$\begin{cases} \sqrt{\begin{aligned}&(P^r_{\mathrm{A,SNOP}}-1/2\,\Delta P^{r'}_{\mathrm{AB}}+\sqrt{3}/2\,\Delta Q^{r'}_{\mathrm{AB}})^2\\ &+(Q^r_{\mathrm{A,SNOP}}-1/2\,\Delta Q^{r'}_{\mathrm{AB}}-\sqrt{3}/2\,\Delta Q^{r'}_{\mathrm{AB}})^2\end{aligned}}\le\eta_C S_{\mathrm{n,SNOP}} \\ \sqrt{\begin{aligned}&(P^r_{\mathrm{A,SNOP}}+1/2\,\Delta P^{r'}_{\mathrm{CA}}+\sqrt{3}/2\,\Delta Q^{r'}_{\mathrm{CA}})^2\\ &+(Q^r_{\mathrm{A,SNOP}}+1/2\,\Delta Q^{r'}_{\mathrm{CA}}-\sqrt{3}/2\,\Delta Q^{r'}_{\mathrm{CA}})^2\end{aligned}}\le\eta_B S_{\mathrm{n,SNOP}} \end{cases} \tag{11}$$

where $\Delta P^{r'}_{\mathrm{AB}}$ and $\Delta Q^{r'}_{\mathrm{AB}}$ are differences between active power and reactive power of phase A and updated active power and reactive power of phases B and C.

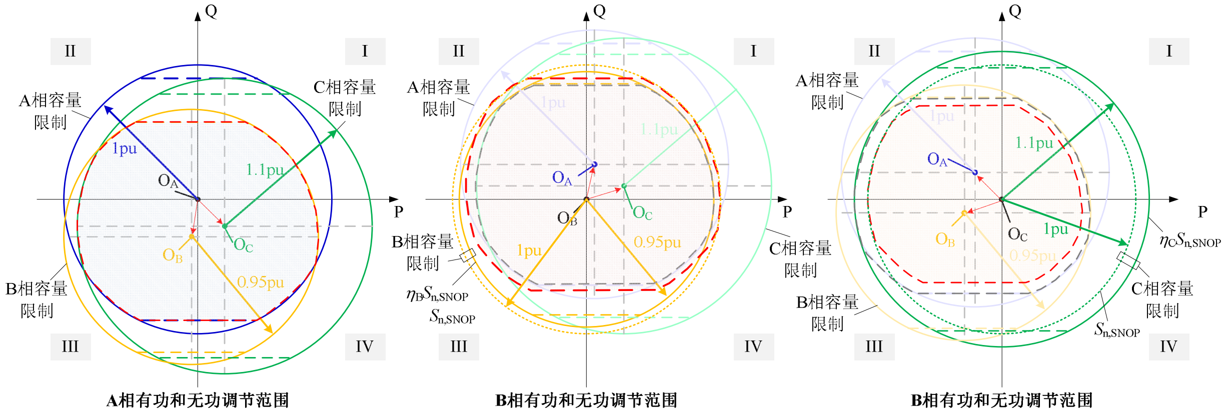
In addition, power constraints of phases B and C of the SNOP under unbalanced voltage can be further deduced. We suppose that $\Delta P^r_{\mathrm{AB}}=0.1$pu, $\Delta Q^r_{\mathrm{AB}}=0.2$pu, $S_{\mathrm{n,SNOP}}=1$pu, $\eta_{\mathrm{B}}\mathrm{e}^{-\mathrm{j}\sigma_{\mathrm{B}}}=0.95\mathrm{e}^{-\mathrm{j}6^\circ}$ and $\eta_{\mathrm{C}}\mathrm{e}^{-\mathrm{j}\sigma_{\mathrm{C}}}=1.1\mathrm{e}^{-\mathrm{j}3^\circ}$. Then, regulating ranges of active power and reactive power under balanced voltages and unbalanced voltages can be concluded, as seen in Fig.3.

When active power and reactive power of each of three-phase is different, the corresponding regulating ranges are all narrowed into the irregular intersection area, which is truncated in the circles of three-phase power constraints. Under three-phase balanced voltage circumstance as seen in Fig.3(a), the upper and lower reactive power truncated lines of three-phase power regulating area are the reactive power boundaries of phase B and A, respectively. Likewise, the regulating areas of three phases are the same. However, these centers of regulating ranges of split-phase SNOP breakers could be deviated, if regulating ranges of three-phase power are changed. The relative positions of their centers are determined by power differences between phase A and phase B as well as the zero-sequence current.

Under three-phase unbalanced voltage in Fig.3(b), due to unbalanced voltage magnitudes and phases between phase B and phase C, these three-phase regulating ranges are the intersection area of three truncated circles with different lengths of radius. Actually, the regulating power areas of phase B and phase C are gained by expanding or narrowing the corresponding regulating power ranges by $1/\eta_B$ or $1/\eta_C$ ($\eta_B<1$ and $\eta_C>1$), respectively. Under unbalanced voltage circumstance, the regulating power range will be narrowed if this phase's voltage grows up, while the regulating power range will be expanded if this phase's voltage gets down.



(a) Balanced three-phase voltage



(b) Unbalanced three-phase voltage

Fig. 3 Regulating power ranges of a split-phase SNOP breaker under balanced and unbalanced voltage conditions

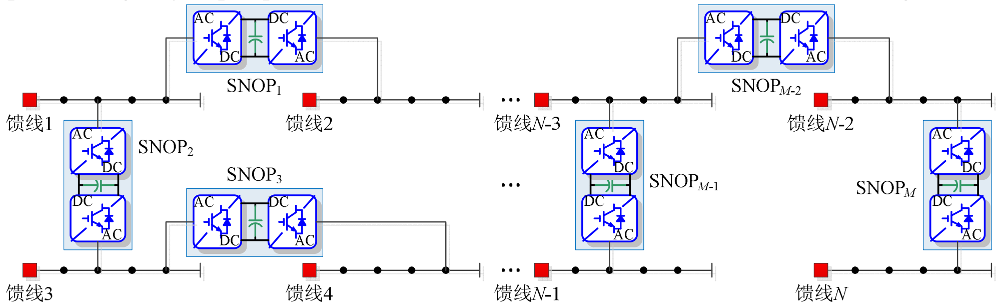


Fig. 4 Structure of feeders with M split-phase SNOP breakers

3. Three-phase power optimal control model based on split-phase SNOP breakers

An optimal power flow model of distribution networks based on split-phase SNOP breakers is established, according to power regulating characteristics of split-phase SNOP breakers and the required minimum three-phase unbalanced of distribution network operation. As a result, this model not only can satisfy distributing load balance and provide effective reactive power supporting, but also can deal with the three-phase asymmetry problems in the distribution networks as well. The Fig.4 shows N 10kV feeders which are connected by M split-phase SNOP breakers in the distribution network. Combined with this figure, we use three-phase active power $P^r_{A,SNOP}$, $P^r_{B,SNOP}$ and $P^r_{C,SNOP}$ and three-phase reactive power $Q^{r}_{A,SNOP}$, $Q^{r}_{B,SNOP}$ and $Q^{r}_{B,SNOP}$ of M split-phase SNOP breakers as optimization variables. Besides, the total unbalanced amounts of three-phase active power of N feeders and three-phase voltage should be minimized as optimization objectives. Therefore, a three-phase power optimal control model based on the split-phase SNOP can be established below.

1) Objective functions

Unbalanced three-phase load, unbalanced network parameters or unbalanced power sources in high level voltages may have many influences on three-phase voltages. Thus, we have established three objective functions. The 1st objective function is to minimize the total unbalanced amounts of three-phase active power, and the 2nd objective function is used for decreasing unbalanced amounts of three-phase voltage magnitudes. Moreover, split-phase SNOP breakers can also provide reactive power compensation, and lead to reduce active power loss of distribution networks. Hence, the third objective function is the minimization of active power loss.

The unbalanced amounts of three-phase active power in N feeders is expressed by F_1. Then, the 1st objective function is

$$\begin{aligned} &\min F_1 = G \\ G = &\sum_{j=1}^{N} | P^{j}_{\mathrm{A,LOAD}} + \sum P^{j}_{\mathrm{A,SNOP}} - (P^{j}_{\mathrm{B,LOAD}} + \sum P^{j}_{\mathrm{B,SNOP}}) | \\ &+ \sum_{j=1}^{N} | P^{j}_{\mathrm{B,LOAD}} + \sum P^{j}_{\mathrm{B,SNOP}} - (P^{j}_{\mathrm{C,LOAD}} + \sum P^{j}_{\mathrm{C,SNOP}}) | \\ &+ \sum_{j=1}^{N} | P^{j}_{\mathrm{A,LOAD}} + \sum P^{j}_{\mathrm{A,SNOP}} - (P^{j}_{\mathrm{C,LOAD}} + \sum P^{j}_{\mathrm{C,SNOP}}) | \end{aligned} \tag{12}$$

where $P^{j}_{\mathrm{A,LOAD}}$, $P^{j}_{\mathrm{B,LOAD}}$ and $P^{j}_{\mathrm{C,LOAD}}$ are the total active power loads of phase A and phase C of the 10kV feeder j in the region. $\sum P^{j}_{\mathrm{A,SNOP}}$, $\sum P^{j}_{\mathrm{B,SNOP}}$ and $\sum P^{j}_{\mathrm{C,SNOP}}$ are the outputting active power of phase A, B and C of all SNOP breakers connecting to the feeder j.

The unbalanced amounts of three-phase voltage magnitudes in this region are expressed by F_2. Then, the corresponding 2nd objective function is

$$\begin{aligned} &\min F_2 = H \\ H = &\sum_{j=1}^{N}\sum_{i=1}^{n_{bj}} | U^{j}_{\mathrm{A},i} - U^{j}_{\mathrm{B},i} | + \sum_{j=1}^{N}\sum_{i=1}^{n_{bj}} | U^{j}_{\mathrm{A},i} - U^{j}_{\mathrm{C},i} | \\ &+ \sum_{j=1}^{N}\sum_{i=1}^{n_{bj}} | U^{j}_{\mathrm{C},i} - U^{j}_{\mathrm{B},i} | \end{aligned} \tag{13}$$

where $U^{j}_{\mathrm{A},i}$ is the voltage magnitude of phase A at bus i of the 10kV feeder j, $U^{j}_{\mathrm{B},i}$ and $U^{j}_{\mathrm{C},i}$ are voltage magnitudes of phase B and phase C at bus i of the 10kV feeder j. n_{bj} is the total number of buses in the feeder j.

It is possible to reduce active power loss of all 10kV feeders in the network, and increase economic operation by using the split-phase reactive compensation of SNOP breakers. The third objective function is

$$\min F_3 = P_{\mathrm{loss}} \tag{14}$$

where P_{loss} is the total active power loss of all 10kV feeders in the network.

2) Constraints

Three-phase power flow constraints of distribution networks and split-phase voltage security constraints are shown below.

$$g(P^{j}_{\mathrm{T,SNOP},i}, Q^{j}_{\mathrm{T,SNOP},i}, P^{j}_{\mathrm{T,LOAD},i}, Q^{j}_{\mathrm{T,LOAD},i})=0 \tag{15}$$

$$\underline{U_{\mathrm{n}}} \le U^{j}_{\mathrm{T},i} \le \overline{U_{\mathrm{n}}} \tag{16}$$

where g is the three-phase power flow equation of distribution network in this region. $P^{j}_{\mathrm{T,SNOP},i}$, $Q^{j}_{\mathrm{T,SNOP},i}$, $P^{j}_{\mathrm{T,LOAD},i}$ and $Q^{j}_{\mathrm{T,LOAD},i}$ are the outputting power and absorbing power of the SNOP breaker at bus i of the 10kV feeder j. $U^{j}_{\mathrm{T},i}$ is the voltage magnitude at bus i of the 10kV feeder j, and T=A, B or C. $\underline{U_{\mathrm{n}}}$ and $\overline{U_{\mathrm{n}}}$ are the lower and upper security boundary of voltage magnitudes, respectively.

Besides, M split-phase SNOP breakers in the distribution network have to satisfy active power balance constraints (1), three-phase capacity constraint (3), and reactive power compensation constraint (5). Additionally, the three-phase power unbalanced constraint which is deduced by the zero-sequence currents of SNOP breakers under unbalanced voltage condition.

$$\begin{cases} \Delta P^{j}_{\mathrm{CA,SNOP},i} + 1/2\,\Delta P^{j}_{\mathrm{AB,SNOP},i} - \sqrt{3}/2\,\Delta Q^{j}_{\mathrm{AB,SNOP},i} = 0 \\ \Delta Q^{j}_{\mathrm{CA,SNOP},i} + 1/2\,\Delta Q^{j}_{\mathrm{AB,SNOP},i} + \sqrt{3}/2\,\Delta P^{j}_{\mathrm{AB,SNOP},i} = 0 \end{cases} \tag{17}$$

where $\Delta P^{j}_{\mathrm{AB,SNOP},i}$, $\Delta Q^{j}_{\mathrm{AB,SNOP},i}$, $\Delta P^{j}_{\mathrm{CA,LOAD},i}$ and $\Delta Q^{j}_{\mathrm{AB,LOAD},i}$ are power differences between phase A and B and between phase C and phase A by asymmetric factors of SNOP breakers at bus i of the 10kV feeder j, respectively.

$$\begin{cases} \Delta P^{j}_{\mathrm{AB,SNOP},i} + \mathrm{j}\Delta Q^{j}_{\mathrm{AB,SNOP},i} \\ = \eta_{\mathrm{A}} e^{-\sigma_{\mathrm{A}}} (P^{j}_{\mathrm{A,SNOP},i} + \mathrm{j}Q^{j}_{\mathrm{A,SNOP},i}) - \eta_{\mathrm{B}} e^{-\sigma_{\mathrm{B}}} (P^{j}_{\mathrm{B,SNOP},i} + \mathrm{j}Q^{j}_{\mathrm{B,SNOP},i}) \\ \Delta P^{j}_{\mathrm{CA,SNOP},i} + \mathrm{j}\Delta Q^{j}_{\mathrm{CA,SNOP},i} \\ = \eta_{\mathrm{C}} e^{-\sigma_{\mathrm{C}}} (P^{j}_{\mathrm{C,SNOP},i} + \mathrm{j}Q^{j}_{\mathrm{C,SNOP},i}) - \eta_{\mathrm{A}} e^{-\sigma_{\mathrm{A}}} (P^{j}_{\mathrm{A,SNOP},i} + \mathrm{j}Q^{j}_{\mathrm{A,SNOP},i}) \end{cases} \tag{18}$$

In the established optimal three-phase power control model in the distribution network, three-phase active power and reactive power at two sides of each SNOP breakers are used as optimization variables. The minimizing objectives are unbalanced amounts of three-phase active load of all feeders and unbalanced amounts of three-phase voltage of all buses. The constraints are included nonlinear power flow constraints and SNOP breaker capacity constraints as well as unbalanced power constraint of SNOP breakers.

4. Case Study

4.1. Basic data

The optimal three-phase power control of split-phase SNOP breakers in a 10kV urban distribution network was analyzed on MATLAB R2012a. This network covered five feeders which were connected by four interconnection switches, as shown in Fig.5. These four interconnection switches were replaced by split-phase SNOP breakers. All buses at five feeders were numbered by the uniform sequence. Maximum reactive power compensation and rated capacity of split-phase SNOP breakers were shown in Table 1. In this case, the base power and nominal voltage were set at 1.0MVA and 10kV, respectively. The first bus number of each feeders was used as the balancing node.

Table 1 Capacities of split-phase SNOP breakers

SNOP No.	Capacity/MVA	Upper boundary of reactive power/MVar	Lower boundary of reactive power/MVar
1	3.0	0.5	-0.5
2	3.0	0.5	-0.5
3	3.0	0.5	-0.5
4	3.0	0.5	-0.5

The measured load data of five feeders were came from 11:35 a.m., July 26th, 2016 on the monitoring control system (SCADA). The total loads of all feeders were shown in Table 2. In the simulation, the safe 220V single-phase voltage range was between +7% ~-10% of the nominal voltage, which is between 0.9~1.07 p.u.. Additionally, the immune genetic algorithm (IGA) was adopted. The total number of antibodies, the mutation probability, the selective probability and the maximum generations of immune genetic evolution were set as 40, 0.15, 0.5 and 100, respectively.

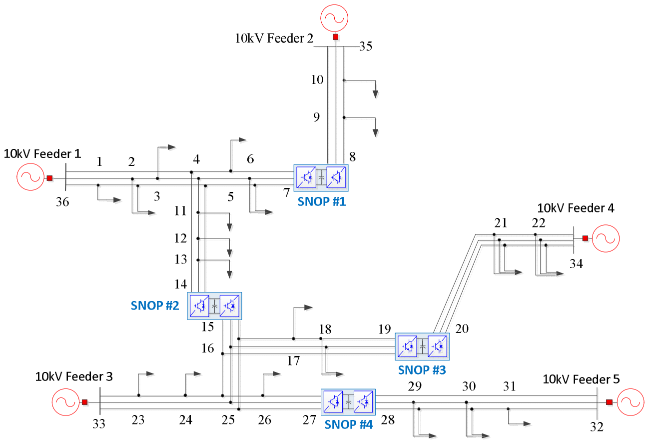


Fig. 5 *An urban distribution system with split-phase SNOP breakers*

Table 2 Total loads of each feeder

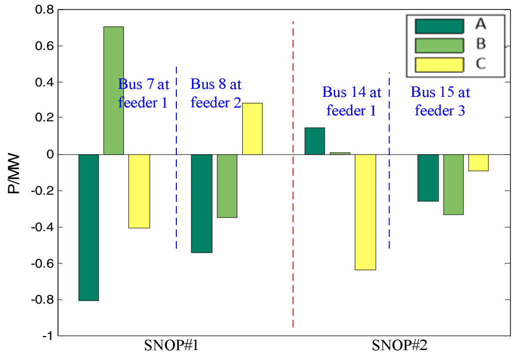
Feeder No.	Loads of phase A /pu	Loads of phase B /pu	Loads of phase C /pu
1	1.426 + j1.125	2.749 + j1.312	1.206 + j0.415
2	0	0	4.725 + j0.513
3	8.203 + j1.015	4.263 + j1.002	0
4	3.796 + j0.431	5.51 + j0.692	3.209 + j0.73
5	0	5.075 + j0.243	1.519+j0.997

4.2. Analysis of test results

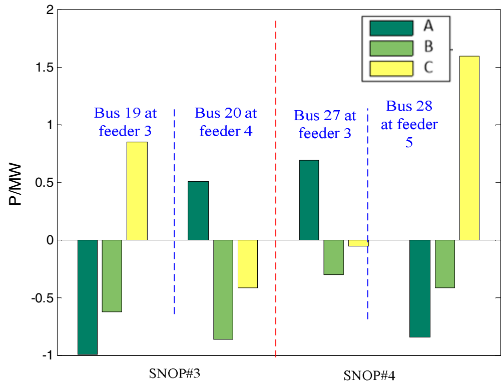
① **Simulation power results of SNOP breakers**

Optimal outputting active power of SNOP #1, #2, #3 and #4 gained from the proposed model are shown in Fig.6. In this figure, positive active power were absorbed from 10kV feeders, which was indicated as loads; negative active power were injected by 10kV feeders, which was indicated as power sources. It can be seen from Fig.6(a) and Table 2 that SNOP#1 injected active power of phase B and phase C at bus 7 of the 10kV feeder 1. And it absorbed active power of phase A and phase B at bus 8 of the 10kV feeder 2, and injected active power of phase C. In fact, the feeder 2 only had load of phase C. Therefore, this solution had injected into active power of phase C, and absorbed active power of phase A and B. This had finally balanced three-phase load of the 10kV feeder 2 as much as possible.

We could also found that active power of phase A injected from SNOP#2 was successfully dealt with overloading problem of phase A in the feeder 3, according to active power transmission solution of the 10kV feeder 1 and 3. Meanwhile, because the 10kV feeder 3 had no load of phase C, SNOP#2 had to output active power of phase C in order to maintain three-phase load balance of the 10kV feeder 3 as much as possible.



(a) SNOP#1and #2



(b) SNOP#3 and #4

Fig. 6 *Optimal three-phase active power solution*

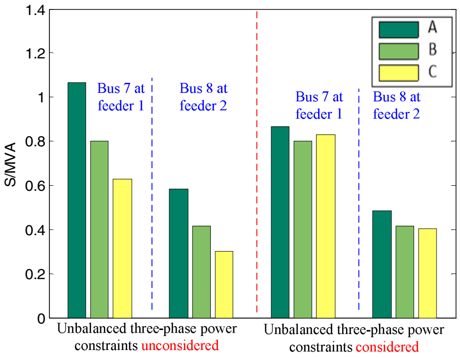
As for SNOP#3, it injected active power of phase B at bus 20, and absorbed active power of phase A and C, owing that the active total load of phase B in the feeder 4 was higher than the active load of phase A and C. This had eventually balanced the three-phase load of the feeder 4.

From Fig. 6, we saw that SNOP#2 had absorbed abundant load of phase C at bus 15. And there was appearing overload problems of phase A and B in the feeder 3. Therefore, SNOP#4 injected active power of phase A and C at bus 27 in the feeder 3.

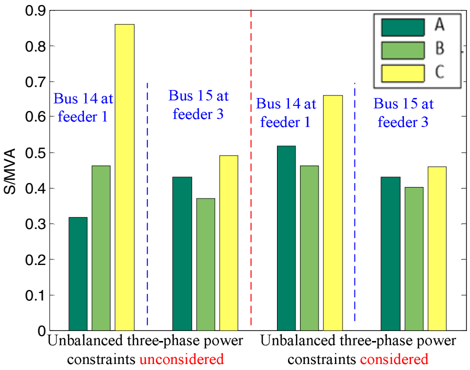
From Fig. 6, the feeder 5 had heavy active power of phase B and no active power of phase A. This was leading SNOP#4 to absorbing active power of phase A and injecting active power of phase B at bus 28. This finally relieved three-phase load unbalanced of the feeder 5.

Three-phase complex power of SNOP#1and #2 without and with constraints (17) and (18), were as shown in Fig. 7. The left sub-figure was the optimal solution without three-phase unbalanced constraints, while the right sub-figure was considered with unbalanced three-phase power constraints.

The optimization results showed that the three-phase complex power difference of SNOP#1and #2 was smaller when unbalanced three-phase power constraints were considered. SNOP#1 between bus 7 and 8 and SNOP #2 between bus 14 and 15 were all achieved the biggest power difference in phase C. Similarly, SNOP#3 and #4 achieved better balance of three-phase power when unbalanced three-phase power constraints were considered. This reflected that the three-phase unbalanced power constraints were helpful for balancing three-phase power of split-phase SNOP breakers. On the contrary, three-phase power control orders of SNOP breakers might be changed frequently if these unbalanced constraints were overlooked. This directly led SNOP breakers to be regulated out of themselves security ranges, and affected balanced control of three-phase load and three-phase voltage.



(a) SNOP#1



(b) SNOP#2

***Fig.* 7** *Optimal three-phase complex power solution*

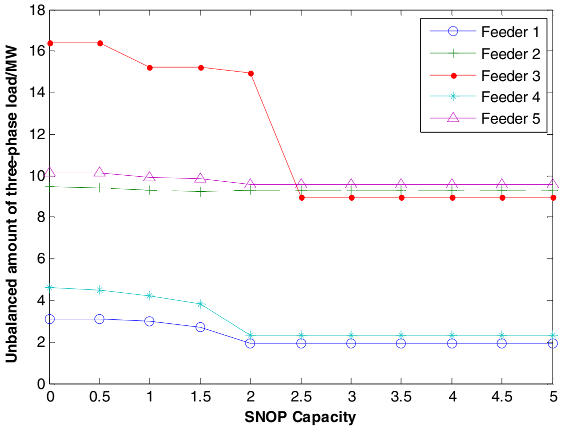
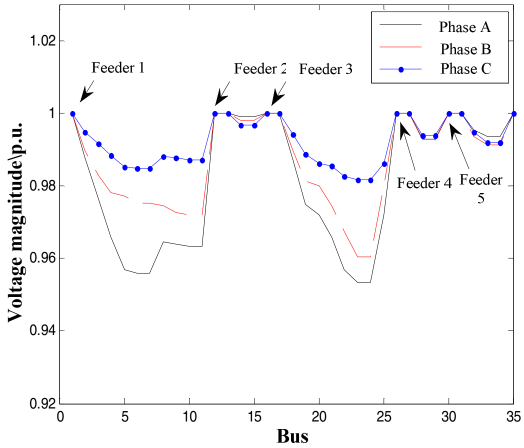


***Fig.* 8** *Relationship between load and SNOP capacity*

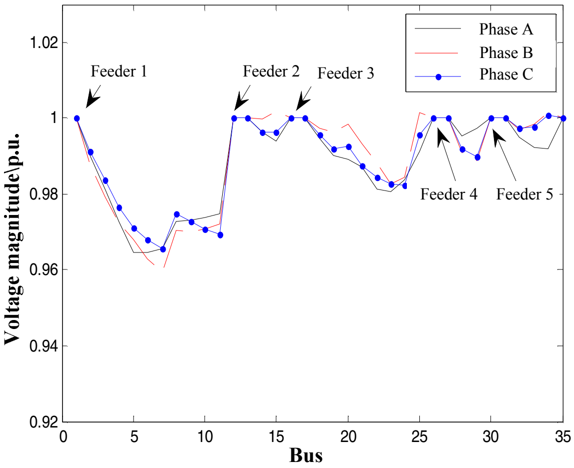
The increasing relationship between three-phase unbalanced load of five feeders and SNOP breakers' capacity is shown in Fig.8. In the figure, a interconnection switch is not replaced by a SNOP breaker if the SNOP breaker capacity is 0. With continuous growth of SNOP breaker capacity, the unbalanced percentage of three-phase load of five feeders decreases continuously and eventually tends to be a stable point. From this point, we see that the three-phase unbalanced load can be relieved if split-phase SNOP breakers were applied in distribution networks. Due to differences in network structures and unbalanced load distributions, the unbalanced load of the feeder 3 fluctuated significantly with the increasing SNOP capacity, and the following significant fluctuation was feeder 4, 1 and 5 successively. And the unbalance load of feeder 2 was changed at the least. Therefore, we could draw a conclusion that SNOP capacity ought to be installed reasonably for active power transmission, and to be distributed effectively for reactive power compensation.

② Simulation results of unbalanced three-phase load

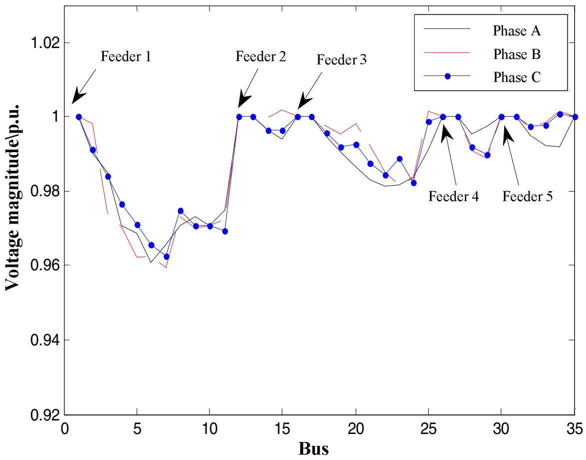
Simulation results of three-phase voltage magnitudes of different feeders were shown in Fig.9. These 1~35 were the numbers of buses in feeders 1~5. Each of the first bus in different feeders was well-marked. The Fig.9 (a), (b) and (c) showed power control solutions under the initial state, proposed model without and with unbalanced three-phase power constraints. We could see that there's serious unbalanced three-phase voltage in feeder 1 and feeder 3 before optimal controls based on split-phase SNOP breakers. But it came to be balanced after optimal controls. This demonstrated that split-phase SNOP breakers can reduce unbalanced amounts of three-phase reactive load and relieved unbalanced three-phase voltage magnitudes in the distribution network.



(a) Before optimal controls



(b) After optimal controls without unbalanced three-phase power constraints



(c) After optimal controls with unbalanced three-phase power constraints

Fig. 9 *Three-phase voltage before and after optimal controls*

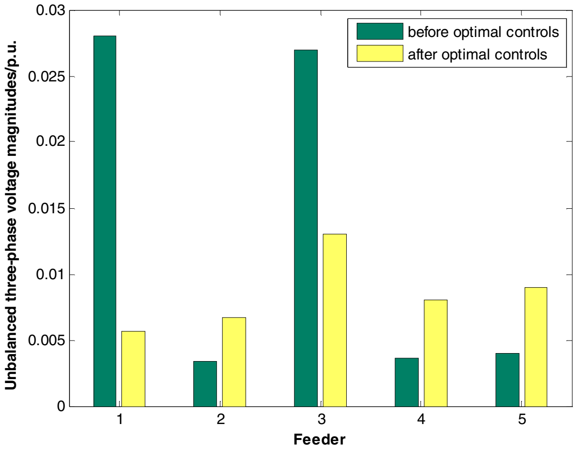


Fig. 10 *Maximum unbalanced three-phase voltage magnitudes before and after optimal controls*

It also could be seen from Fig.9 (b) and Fig.9 (c) that split-phase SNOP breakers could reduce unbalanced amounts of three-phase voltage magnitudes significantly, no matter with and without unbalanced three-phase power constraints. Combined with Fig.7, we found that outputting three-phase power could be better balanced and approached similar control effects on unbalanced three-phase voltage magnitudes , from the optimal power control solution based on SNOP breakers with unbalanced three-phase power constraints.

We selected three-phase voltage magnitudes in these two situations for analyzing, to compare unbalanced amounts of three-phase voltage magnitudes of different feeders before and after this proposed optimal control with unbalanced three-phase power constraints. The maximum unbalanced voltage amounts of each feeder was shown in Fig.10. It was calculated by the maximum phase-voltage magnitude minus the minimum phase-voltage magnitude. In Fig.10, the maximum unbalanced three-phase voltage amount of feeder 1 and 3 had declined sharply after optimal control based on SNOP breakers. The unbalanced three-phase voltage magnitudes of feeder 2, 4 and 5 were increased slightly after the optimal control. We can see that four SNOP breakers in this case offered reactive power compensation mainly for feeder 1 and 3 at the cost of slight unbalance growth of certain three-phase voltage magnitudes of feeder 2, 4 and 5. But the total amount of unbalanced voltage magnitudes in the distribution network could be reduced as a result.

③ Simulation results of active power loss

Active power losses of each feeder before and after the optimal control were shown in Fig.11. It showed that there was less active power loss after the optimal control. The maximum reduction was about 21.53%. This was mainly because split-phase SNOP breakers provided independent three-phase reactive power compensations. In this way, active power loss of each phase could be reduced and kept the active power loss of each feeder being lower than the loss before the optimal control.

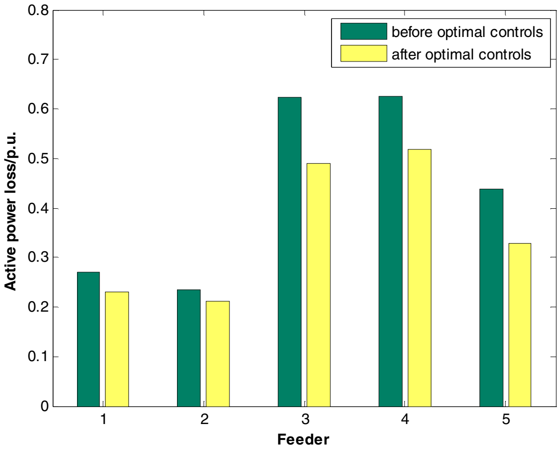


Fig. 11 *Active power loss before and after optimal controls*

Based on analysis on unbalanced loads, unbalanced voltage magnitudes and active power loss of the distribution network, it could significantly reduce three-phase unbalanced active load problems, unbalanced three-phase voltage problems and high active power loss problems in the network, if we used split-phase SNOP breakers to replace the interconnection switches. Besides, split-phase SNOP breakers could still avoid many other operation problems, such as burning of electric devices caused by unbalanced three-phase active power or unbalanced three-phase voltage in the practical distribution system.

5. Conclusion

With the soft interconnection technology development of intelligent distribution networks, a three-phase power optimization control method based on split-phase SNOP breakers is proposed. Research results demonstrate that the proposed method has realized independent three-phase power transmission control of active power and reactive power among multiple-connected feeders by SNOP breakers. This control pattern can eliminate three-phase power unbalance among multiple-connected feeders as much as possible in the final as well. Besides, the in-site reactive power compensation of split-phase SNOP breakers works well and they can really reduce active power losses of each feeder effectively. Overall, split-phase SNOP breakers offer a feasible solution to enhance reliability and maintain high power quality, and provide important significance to keep safe and reliable operation of intelligent distribution networks.

6. Acknowledgements

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7. References

[1] D Thakur P，Singh A K．Unbalance voltage sag fault-type characterization algorithm for recorded waveform [J]．IEEE Transactions on Power Delivery，2013，28(2)：1007-1014．

[2] Cao W，Wu J，Jenkins N，et al．Operating principle of Soft Open Points for electrical distribution network operation [J]．Applied Energy，2016，164：245-257．

[3] Wang C，Song G，Li P，et al．Optimal siting and sizing of soft open points in active electrical distribution networks[J]．Applied Energy，2017，189：301-309．

[4] Cao W，Wu J，Jenkins N，et al．Benefits analysis of Soft Open Points for electrical distribution network operation [J]．Applied Energy，2016，165：36-47．

[5] Xing X，Lin J，Wan C，et al．Model predictive control of LPC-looped active distribution network with high penetration of distributed generation[J]．IEEE Transactions on Sustainable Energy，2017．

[6] Bloemink J M，Green T C．Optimal operation of soft open points in active distribution networks under three-phase unbalanced conditions[J]．IEEE Transactions on Power Delivery，2013，28(2)：911-919．

[7] Li P，Ji H，Wang C，et al．Optimal operation of soft open points in active distribution networks under three-phase unbalanced conditions [J]．IEEE Transactions on Smart Grid，2017．

[8] F. Wang, C. Chen, C. Li, Y. Cao, Y. Li, B. Zhou, X. Dong: 'A multi-stage restoration method for medium-voltage distribution system with DGs', *IEEE Trans. Smart Grid*, to be published

[9] Z. Bie, Y. Lin, G. Li, F. Li: 'Battling the Extreme: A Study on the Power System Resilience', *Proc. IEEE*, 2017, 105, (7), pp. 1253-1266