A PLANNING METHOD OF ON-LOAD CAPACITY REGULATING DISTRIBUTION TRANSFORMERS IN URBAN DISTRIBUTION NETWORKS AFTER ELECTRIC ENERGY REPLACEMENT

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ABSTRACT

Replacing conventional distribution transformers with on-load capacity regulating distribution transformers reasonably can effectively cope with the high peak-valley difference of load after electric energy replacement and reduce the no-load loss of distribution transformers. Thus, in order to reduce the loss of distribution transformers in urban distribution network after electric energy replacement, this paper proposed a planning method of on-load capacity regulating distribution transformers. Then, the distribution transformer planning of electric energy replacement points in an urban distribution network was carried out by this method. The examples showed that the planning method has a strong feasibility and of great guiding significance to distribution transformer planning in urban distribution network after electric energy replacement and promotion of on-load capacity regulating distribution transformers.

INTRODUCTION

In order to reduce emission of pollutants and construct an urban air environment with green development, replacing oil, coal, and gas with electric energy on the load side, called electric energy replacement in China, is promoted by national energy department. Under the background of electric energy replacement, valley/peak difference of electrical load in distribution network continuously increases, significantly rising no-load loss of distribution transformers, which is adverse to economical operation of distribution network. On-load capacity regulating distribution transformer has two capacities, which has been used to deal with the load with great valley/peak difference in rural area[1], so transforming conventional distribution transformers into on-load capacity regulating distribution transformers can effectively solve power loss problem caused by electric energy replacement.

In this paper, the planning of on-load capacity regulating distribution transformers in urban distribution network after electric energy replacement was studied. Firstly, according to loss relation between on-load capacity regulating distribution transformers and conventional distribution transformers, three characteristic indexes of annual continuous apparent power curve and replacing criterion for on-load capacity regulating distribution transformer were put forward, and a set of distribution transformer replaceable points was obtained. Then, based on cost benefit analysis, a planning model of on-load capacity regulating distribution transformers which consists of investment profitability index within the life cycle, investment cost recouping index and annual capacity regulating cost index was put forward. Finally the branch and bound method was used to solve the planning model within replaceable point set to obtain planning scheme of distribution transformers.

REPLACING CRITERION FOR ON-LOAD CAPACITY REGULATING DISTRIBUTION TRANSFORMERS

Active loss of distribution transformer consists of no-load loss caused by excitation conductance and load loss caused by winding resistance and it's the main part of loss in distribution network. For conventional distribution transformer, its active loss $P^{n}_{loss}(t)$ can be calculated according to the following equation:

$$P_{loss}^{n}(t) = P_0 + \frac{P_k \cdot S^2(t)}{S_N^2} \tag{1}$$

Where S_N is rated capacity of distribution transformer, P_0 and P_k are no-load loss and short-circuit loss of distribution transformer and S(t) is apparent power of distribution transformer load.

On-load capacity regulating distribution transformer has two capacities and can automatically switch capacity through on-load capacity regulating switch according to actual load. Then active loss $P^{c}_{loss}(t)$ of on-load capacity regulating distribution transformer is obtained as such

$$P_{loss}^{c}(t) = \begin{cases} P_{0L} + \dfrac{P_{kL} \cdot S^2(t)}{S_{NL}^2}, S(t) < S_c \\ P_{0H} + \dfrac{P_{kH} \cdot S^2(t)}{S_{NH}^2}, S(t) \geq S_c \end{cases} \tag{2}$$

Where S_{NH} and S_{NL} are large and small rated capacities of on-load capacity regulating distribution transformer; S_c is critical capacity regulating load of on-load capacity regulating distribution transformer, and its value is acquired through theoretical calculation [2]. P_{0H} and P_{0L} are no-load losses of on-load capacity regulating distribution transformer under large-capacity and small-capacity operations respectively, and P_{kH} and P_{kL} are short-circuit losses under large-capacity and small-capacity operations of on-load capacity regulating distribution transformer respectively.

In order to compare loss characteristics of on-load capacity regulating distribution transformer and conventional distribution transformer, saved active loss $\triangle P_{loss}(t)$ and annual saved active loss $\triangle P_{loss}$ after conventional distribution transformer is replaced by on-load capacity regulating distribution transformer are obtained according to (1) and (2) as follows

$$\Delta P_{loss}(t)=\begin{cases} P_0 - P_{0L} + (\frac{P_k}{S_N^2} - \frac{P_{kL}}{S_{NL}^2}) \cdot S^2(t), S(t) < S_c \\ P_0 - P_{0H} + (\frac{P_k}{S_N^2} - \frac{P_{kH}}{S_{NH}^2}) \cdot S^2(t), S(t) \geq S_c \end{cases} \quad (3)$$

$$\Delta P_{loss} = \sum_{1}^{8760} \Delta P_{loss}(t)\tau = (P_0 - P_{0H})t_H + (\frac{P_k}{S_N^2} - \frac{P_{kH}}{S_{NH}^2}) \sum_{1}^{8760} S_H^2(t)\tau \quad (4)$$
$$+ (P_0 - P_{0L})t_L + (\frac{P_k}{S_N^2} - \frac{P_{kL}}{S_{NL}^2}) \sum_{1}^{8760} S_L^2(t)\tau$$

Where t_H is annual operation time of on-load capacity regulating distribution transformer under large-capacity operation, t_L is annual operation time of on-load capacity regulating distribution transformer under small-capacity operation, τ is equal to 1h, $S_H(t)$ and $S_L(t)$ are apparent powers of on-load capacity regulating distribution transformer under large-capacity and small-capacity operations, and their values are determined according to the following equation.

$$S_H(t)=\begin{cases} 0, & S(t) < S_c \\ S(t), & S(t) \geq S_c \end{cases}; \quad S_L(t) = \begin{cases} 0, & S(t) \geq S_c \\ S(t), & S(t) < S_c \end{cases} \quad (5)$$

When annual active loss of on-load capacity regulating distribution transformer is lower than that of the conventional distribution transformer, i.e. annual saved active loss is greater than 0, on-load capacity regulating distribution transformer is used to replace conventional distribution transformer. From (4) the annual saved active loss is related to annual electrical load, so whether to replace conventional distribution transformer with on-load capacity regulating distribution transformer is decided by annual electrical load characteristics. In order to characterize the annual electrical load, three characteristic indexes—high load mean square value μ, low load mean square value ν and annual operation time ratio λ of annual continuous apparent power curves were put forward in this paper.

(1) High load mean square value μ

The load higher than critical capacity regulating load of on-load capacity regulating distribution transformer is called high load, and on-load capacity regulating distribution transformer operates in large-capacity status under high load. In order to measure load level of on-load capacity regulating distribution transformer in large-capacity operation, high load mean square value is defined as follow according to annual continuous apparent power curve

$$\mu = \frac{1}{t_H} \sum_{1}^{8760} S_H^2(t)\tau = \frac{1}{f^{-1}(S_c)} \sum_{1}^{f^{-1}(S_c)} f^2(t)\tau \quad (6)$$

Where $f(t)$ is annual continuous apparent power curve function and $f^{-1}(t)$ is inverse function of $f(t)$. In annual continuous apparent power curve, the aggregated duration of load greater than S_c is the large-capacity operation time t_H, so t_H can be changed to $f^{-1}(S_c)$ for variable reduce.

(2) Low load mean square value ν

The load lower than critical capacity regulating load of on-load capacity regulating distribution transformer is called low load, on-load capacity regulating distribution transformer operates in small-capacity status under low load. Low load operation time is equal to the time obtained by reducing high load operation time from annual electrification time of distribution transformer, so low load mean square value is obtained as

$$\nu = \frac{1}{t_L} \sum_{1}^{8760} S_L^2(t)\tau = \frac{1}{f^{-1}(S_{\min}) - f^{-1}(S_c)} \sum_{f^{-1}(S_c)}^{f^{-1}(S_{\min})} f^2(t)\tau \quad (7)$$

Where t_M is annual electrification time of distribution transformer, $S_{\min}$ is minimum apparent power. Similarly, the aggregated duration of load greater than $S_{\min}$ is the annual electrification time t_M, so t_M can be changed to $f^{-1}(S_{\min})$ for variable reduce.

(3) Annual operation time ratio λ

Annual operation time ratio represents high/low load operation time difference, and it's decided by annual continuous apparent power curve and critical capacity regulating load of on-load capacity regulating distribution transformer.

$$\lambda = \frac{t_L}{t_H} = \frac{t_M - t_H}{t_H} = \frac{f^{-1}(S_{\min}) - f^{-1}(S_c)}{f^{-1}(S_c)} \quad (8)$$

Then based on high load mean square value μ, low load mean square value ν and annual operation time ratio λ, replacing criterion for on-load capacity regulating distribution transformers is obtained according to (4).

$$\begin{cases} h(\mu, \nu, \lambda) = k_1 + k_2 \cdot \mu + k_3 \cdot \lambda + k_4 \cdot \lambda \cdot \nu > 0 \\ k_1 = P_0 - P_{0H}, k_2 = \frac{P_k}{S_N^2} - \frac{P_{kH}}{S_{NH}^2}, k_3 = P_0 - P_{0L}, k_4 = \frac{P_k}{S_N^2} - \frac{P_{kL}}{S_{NL}^2} \end{cases} \quad (9)$$

Where k_1, k_2, k_3 and k_4 are loss difference coefficients between conventional distribution transformer and on-load capacity regulating distribution transformer. It's noteworthy that this criterion is a necessary condition but not sufficient condition for replacing conventional distribution transformers with on-load capacity regulating distribution transformers, i.e. cost benefit of replacing with on-load capacity regulating distribution transformers should be further considered to decide whether to replace the distribution transformers.

PLANNING METHOD OF ON-LOAD CAPACITY REGULATING DISTRIBUTION TRANSFORMERS IN URBAN DISTRIBUTION NETWORK AFTER ELECTRIC ENERGY REPLACEMENT

Cost benefit analysis of replacing with on-load capacity regulating distribution transformer

In order to measure cost benefit of replacing conventional distribution transformer with on-load capacity regulating distribution transformer, setting the life cycle of distribution transformers as 20 years[3], three cost benefit indexes—investment profitability index F_E within the life cycle, investment cost recouping index F_T and capacity regulating cost index F_C—are proposed.

(1) Investment profitability index F_E within the life cycle

On-load capacity regulating distribution transformer has higher acquisition price and operations & maintenance cost and lower active loss when compared with conventional distribution transformer[4]. Therefore, in order to characterize economic benefit created by on-load capacity regulating distribution transformer replacing conventional distribution transformer during the life cycle, investment profitability index F_E within the life cycle is proposed in this paper as:

$$F_E = \phi_{price}\sum_{\mathrm{i}=1}^{20}\Delta P_{loss.i} - 20\cdot C_{cap} - (\chi_{price} - \theta_{price}) \quad (10)$$

Where subscript i represents the parameter in the i (th) year. χ_{price} is the price of on-load capacity regulating distribution transformer. When the capacity of distribution transformer is not enough for the load, θ_{price} is the price of conventional distribution transformer planned, when the capacity is enough, θ_{price} is 0. ϕ_{price} is hourly electric charge. C_{cap} is the average annual operations & maintenance cost of on-load capacity regulating switch.

(2) Investment cost recouping index F_T

Reconstruction investment is needed when conventional distribution transformers are replaced by on-load capacity regulating distribution transformers. The investment cost includes acquisition cost and operations & maintenance cost of distribution transformers. When the on-load capacity regulating distribution transformer is put into operation, electric charge saving brought by reduction of active loss will be taken as the means of recouping reconstruction investment cost. But reconstruction fund of distribution network is limited and in consideration of investment payback period of the reconstruction fund, the cost-recovering time is taken as investment cost recouping index F_T evaluating replacing with on-load capacity regulating distribution transformer.

$$\sum_{1}^{F_T}\Delta P_{loss}(t)\tau = \frac{\chi_{\mathrm{price}} + 20\cdot C_{cap} - \theta_{\mathrm{price}}}{\phi_{\mathrm{price}}} \quad (11)$$

(3) Capacity regulating cost index F_C

On-load capacity regulating switch is an important constituent part of on-load capacity regulating distribution transformer, and its service life is related to switching times of transformer capacity, i.e. the greater the switching times of transformer capacity, the more easily the on-load capacity regulating switch suffers from a fault. So the load's requirement for switching times of on-load capacity regulating switch is incorporated into cost benefit analysis of replacing with on-load capacity regulating distribution transformer, and capacity regulating cost index F_C is defined as follow

$$F_C = \frac{R_{price}}{n}\cdot\sum_{t=1}^{8760\times 20}\left|N_{T,t} - N_{T,t-1}\right| \quad (12)$$

Where $N_{T,t}$ is operating state of on-load capacity regulating distribution transformer, $N_{T,t}$=1 expresses that it operates in large-capacity status while $N_{T,t}$=0 means that it operates in small-capacity status; R_{price} is the price of on-load capacity regulating switch; n is the maximum switching times of on-load capacity regulating switch.

Planning model of on-load capacity regulating distribution transformers in urban distribution network after electric energy replacement

In reality, distribution transformer upgrading and reconstruction fund which matches electric energy replacement is usually limited, and replacing can't be implemented for all distribution transformer replaceable points. On the condition that only one distribution transformer is accessed to each electric energy replacement point, distribution transformer replaceable point set Ω is obtained according to replacing criterion for on-load capacity regulating distribution transformers as shown in (9), and the replaceable points in set Ω are taken as optimization variables to construct on-load capacity regulating distribution transformer planning model in urban distribution network. Optimization variable x_{j} is the state about whether conventional distribution transformer in position j is replaced by on-load capacity regulating distribution transformer. If it's equal to 1, it means that the conventional distribution transformer is replaced by on-load capacity regulating distribution transformer; and if it's equal to 0, it means no replacing, and then

$$x_j \in \{0,1\} \quad j\in\Omega \quad (13)$$

From cost benefit analysis of replacing with on-load capacity regulating distribution transformer, it can be known that optimal planning scheme of distribution transformers needs to realize maximum investment profitability index F_{E} within the life cycle as well as minimum investment cost recouping index F_{T} and capacity regulating cost index F_{C}. The multi-objective optimization [5,6] is used to establish the planning model of on-load capacity regulating distribution transformers in urban distribution network after electric energy replacement. Therefore, normalized weighing of the above indexes is implemented to obtain comprehensive benefit index F which is taken as objective function of the planning model.

$$\max F = \sum_{j\in\Omega}\left((w_E\frac{F_{E,j}}{\max\{F_E\}} - w_T\frac{F_{T,j}}{\max\{F_T\}} - w_C\frac{F_{C,j}}{\max\{F_C\}})\cdot x_j\right) \quad (14)$$

Where w_E, w_T and w_C are weighing coefficients of three cost benefit indexes respectively and they are constants within 0~1. Pecking-order comparison method is used to determine weighing coefficient w_E, w_T and w_C, according to the importance of three cost benefit indexes.

Moreover, distribution transformer upgrading and reconstruction which matches electric energy replacement needs to satisfy overall investment constraint. So the total sum of capacity expansion cost of conventional distribution transformers, acquisition cost of on-load capacity regulating distribution transformers and incremental operations & maintenance cost within the life cycle should be smaller than total investment E of distribution transformers.

$$\sum_{j\in\Omega}\left((\chi_{price,j}+C_{M,j})\cdot x_j+\theta_{\text{price},j}\cdot(1-x_j)\right)+\sum_{j\in\Phi,j\notin\Omega}\theta_{\text{price},j}\le E \quad (15)$$

Where subscript j represents the parameter corresponding to position j, and capacity upgrading set Φ is the set of the distribution transformers that can't satisfy the load after electric energy replacement. To sum up, planning model of on-load capacity regulating distribution transformer in urban distribution network after electric energy replacement is as follow.

$$\max F=\sum_{j\in\Omega}\left((w_E\frac{F_{E,j}}{\max\{F_E\}}-w_T\frac{F_{T,j}}{\max\{F_T\}}-w_C\frac{F_{C,j}}{\max\{F_C\}})\cdot x_j\right) \quad (16)$$

$$s.t.\ \begin{cases}\sum_{j\in\Omega}\left((\chi_{price,j}+C_{M,j})\cdot x_j+\theta_{\text{price},j}\cdot(1-x_j)\right)+\sum_{j\in\Phi,j\notin\Omega}\theta_{\text{price},j}\le E\\ x_j\in\{0,1\}\quad j\in\Omega\end{cases}$$

CASE STUDY

Electric energy replacement is implemented for multiple loads in a large-scale 10kV urban distribution network in one area on MATLAB R2012a. This 10kV distribution network totally has 55 nodes and 8 electric energy replacement points, where node 6, 11, 16, 23, 25 and 39 are electric energy replacement points for hot pot, node 53 is electric automobile and electric bus charging station and node 35 is electric energy replacement point in small-scale glass manufacturing industry. Node 1 at high-voltage side of the main transformer in 110kV substation is set as a balancing bus, and node 2 at low-voltage side is installed with reactive compensating capacitor, and concrete topology structure is seen in Fig. 1.

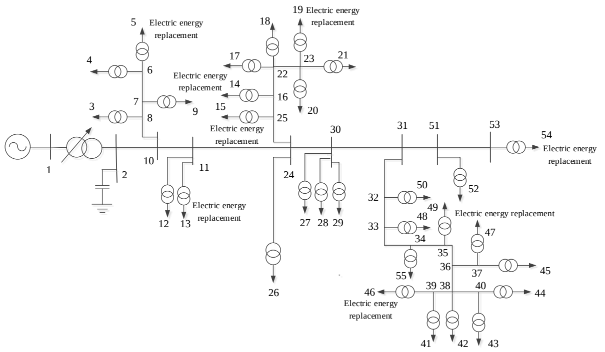

Figure 1. A 55-bus urban distribution network of 10 kV

In order to exclude the interference from distribution transformer manufacturing technique to the results of the case, S11-M.ZT on-load capacity regulating distribution transformers and S11 conventional distribution transformers are chosen as distribution transformers to be selected in this case. Basic parameters of on-load capacity regulating distribution transformers and conventional distribution transformers are obtained according to technical parameter specifications of S11-M.ZT on-load capacity regulating distribution transformers in Q/GDW731-2012 Selection guide for on-load capacity regulating power transformer, technical parameter specifications of S11 conventional distribution transformers in JB/T3837-2010 Identification method of transformer's product type as well as the quotations of distribution transformers from Jinshanmen Electrical Co., Ltd.

It's assumed that total investment E on distribution transformer upgrading and reconstruction under this electric energy replacement is RMB 300,000. Moreover, annual average operations & maintenance costs C_{tap} of on-load capacity regulating switch of on-load capacity regulating distribution transformers with different capacities are approximate, all being set as RMB 200/year. The on-load capacity regulating switch price R_{price} is set as 1/8 of on-load capacity regulating distribution transformer price χ_{price} and its maximum switching times n is 50,000 times. Node 6, 23, 35 and 53 are connected with commercial loads and their electric price ϕ_{price} is RMB 1.13/kWh; node 11, 16, 25 and 39 are connected with residential loads, and their electric price ϕ_{price} is RMB 0.52/kWh. The average annual growth rate of load g is 0.5%. On the basis of internal relation among three cost benefit indexes, the cost benefit index weighing coefficients w_E, w_T and w_C are respectively taken as 0.67, 0.13 and 0.2.

Table 1. Optimal planning scheme of distribution transformers after electric energy replacement

Node	Maximum Prediction Load in 2017/kVA	Planned distribution transformer	Transformation cost
6	300	315(100)	5.4
11	270	No Change	0
16	180	No Change	0
23	360	400(125)	5.9
25	260	No Change	0
35	600	630	6.3
39	300	No Change	0
53	550	630(200)	7.9

According to replacing criterion of on-load capacity regulating distribution transformers, distribution transformer replaceable point set Ω is taken as {6, 11, 23, 53}. Moreover, according to the relation between original distribution transformers and planned capacities, the capacity upgrading set Φ is obtained as {23, 35, 53}. Then branch and bound method in 0-1 integer programming method is used to solve on-load capacity regulating distribution transformer planning model. When comprehensive benefit index F is 0.334, optimal planning scheme for distribution transformers after electric energy replacement is obtained as shown in Tab. 1. This planning scheme has satisfied maximum load requirements predicted in 2017 for all points after electric energy replacement, and total planned investment is RMB 255,000 which is smaller than overall investment namely RMB 300,000. In addition, by replacing three conventional distribution transformers at nodes 6, 23 and 53 with on-load capacity regulating distribution transformers, the distribution network is expected to save

2,584.44 kWh in the first year of electric energy replacement, which is conducive to reducing environmental pollution. Therefore, the construction of on-load capacity regulating distribution transformers matched with electric energy replacement project has equal meaning to electric energy replacement project itself.

CONCLUSION

This paper deduced the replacing criterion for on-load capacity regulating distribution transformers according to the loss relation between on-load capacity regulating distribution transformers and conventional distribution transformers. And then, based on the cost benefit analysis of replacing with on-load capacity regulating distribution transformer, a planning model of on-load capacity regulating distribution transformers in urban distribution network after electric energy replacement was put forward. This method used the replacing criterion for on-load capacity regulating distribution transformers to obtain the set of distribution transformer replaceable points. Then, on the basis of the distribution transformer replaceable points, the planning model of on-load capacity regulating distribution transformers was solved, which avoided the calculation of electric energy replacement points that need not be replaced with on-load capacity regulating distribution transformers, and reduced the calculation amount of distribution transformer planning. The results of examples showed that the planning method proposed in this paper can quickly obtain the optimal planning scheme of distribution transformers in urban distribution network according to the predicted load, effectively reducing the operation loss of distribution transformers after electric energy replacement, and promoting the wide application of on-load capacity regulating distribution transformers.

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