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Distribution Network Load Distribution Strategy Considering the Economy of Parallel Transformers

Yanguang Huang
Central Testing and Researches Institute
Guangzhou Power Supply Bureau
Guangdong Power Grid Corporation
Guangzhou, China

Yanan Cai, Youyuan Wang, Hang Liu
State Key Laboratory of Power Transmission Equipment & System Security and New Technology
School of Electrical Engineering, Chongqing University
Chongqing, China
caiyanan@cqu.edu.cn

***Abstract*—The distribution transformer plays a key role in distribution network. It undertakes the task of the voltage transformation, energy distribution. But a lot of loss of the transformer in operation has affected the economy of the distribution network. Therefore in order to save energy, it is essential to consider the transformer economical operation mode during distribution network load distribution. Combining with the comprehensive power loss curve and critical load of transformer in parallel, the interval of economic operation of transformers in different operation modes is deduced in this paper. Then the unavailability of transformers in different operation mode is calculated. The distribution network load distribution model is proposed which takes distribution network reliability, the economy of parallel transformers and load balancing as the object function. The topological structure, load capacity and operating limits are given as the restriction conditions. Using optimization algorithm to analyze the model, the appropriate transformer operation mode and the load distribution scheme can be determined. What's more, a simple double power distribution network is used to show the steps of the distribution network load distribution considering the transformer economic operation mode. It makes clear that the model can determine the transformer operation mode and the load distribution strategy. The optimization results contribute to improving the distribution network reliability and economy.**

Keywords*—economic operation of transformer; comprehensive power loss; style; reliability; load balancing

I. INTRODUCTION

With environmental and energy problems increasingly serious, many countries around the world are committed to the development of the new energy. Meanwhile, they also advocate energy saving in every field. Electricity is one of the important and indispensable resources. However, there is massive energy loss in the process of power production and transmission. Therefore, the power industry energy-saving task brooks no delay. Main energy loss in electric power industry contains coal consumption and the network loss. Network loss includes line loss and transformer loss. As essential equipment, the distribution transformer undertakes the vital task of voltage transformation and power distribution in the power distribution system. Nevertheless, transformers loss occupies a large proportion of the distribution network loss. Thus it is inevitable to take some measures to reduce the transformer loss. This will do good to safety and economy of the distribution network.

Economic operation mode of transformer is an operation mode that transformer power loss is minimized on the basis of ensuring safe and reliable operation and meeting the demand of power supply. In addition, load balancing can reduce the life loss of the transformers when the electric load is close to or more than the rated capacity of transformer. At present, scholars at home and abroad do much research about the distribution network loss reduction problem. Reference [1-2] discussed transformer economical operation problem and yet it was not applied to the distribution network. Reference [3] studies about load distribution of multiple distribution substations. However, this reference didn't take the operation modes of several transformers in a substation into account. AS a result, combining distribution network load distribution with the transformer operation mode is of feasibility and necessary.

Distribution network load distribution strategy considering the economy of parallel transformers is put forward in this paper. It is emphasized that the object of study are all double winding transformer. A distribution network load distribution model is proposed which takes distribution network reliability, transformer economic operation and load balancing as the object function. Expected energy not supplied (EENS), comprehensive power loss of transformer and the maximum difference among the load factor are regarded as the evaluation indicators of distribution network reliability, transformer economic operation and load balancing, respectively. Constraint conditions include topological structure, load capacity operating limits and so on. Using optimization algorithm to analyze the model, the appropriate transformer operation modes and the on-off states can be determined.

II. ECONOMIC OPERATION OF TRANSFORMER

A. Transformer Power Loss

Transformer loss in the process of power transmission covers active loss and reactive power loss. In general, the formulas of no-load loss P_{0z}, rated load loss P_{kz} and comprehensive power loss ΔP_Z are expressed as

$$\Delta P_{0z} = P_0 + K_Q Q_0 \quad (1)$$

$$\Delta P_{kz} = P_k + K_Q Q_k \quad (2)$$

$$\Delta P_Z = P_{0z} + \beta^2 P_{kz} \quad (3)$$

where: P_0 - no-load power consumption (kW),

P_k - rated load power loss (kW),

Q_0 - no-load excitation loss (kvar),

Q_k - rated leakage loss (kvar),

K_Q - reactive economic equivalent (kW/kvar),

$\beta = S / S_N$ - average load rate,

S - load capacity (kVA),

S_N - rated power (kVA).

The value of K_Q is related to transformer position and power factor. According to [4], K_Q is equal to 0.10 in the paper.

B. Loss of the Transformer in Parallel

Transformer parallel operation is defined as an operation mode that the primary windings of two or more transformers connect with the same bus and the secondary windings link to another bus. Nevertheless, it is really not that some transformers randomly chosen can run in parallel. The transformer parallel running must satisfy four conditions:

1) The winding connection must be in the same mode;

2) The ratio of the voltage conversion must be same;

3) The short-circuit voltage must be approximate;

4) The capacity ratio is universally less than 3:1.

The effect of n double winding transformers in parallel operation is equivalent to a combined transformer. The rated capacity, no-load loss and rated load loss of the combined transformer are the sum of those of n transformers separately. Then the rated capacity S_{Nn} and comprehensive power loss P_{zn} of n double winding transformers in parallel operation are expressed as follows:

$$S_{Nn} = \sum_{i=1}^{n} S_{Ni} \quad (4)$$

$$P_{0zn} = P_{0n} + K_Q Q_{0n} = \sum_{i=1}^{n} P_{0zi} \quad (5)$$

$$P_{kzn} = P_{kn} + K_Q Q_{kn} = \sum_{i=1}^{n} P_{kzi} \quad (6)$$

$$P_{zn} = P_{0zn} + \beta^2 P_{kzn} = \sum_{i=1}^{n} \left(P_{0zi} + \beta^2 P_{kzi} \right) \quad (7)$$

where: n - number of parallel transformers, i=1, 2, 3, ···, m,

P_{0zn} - total no-load loss of parallel transformers (kW),

P_{kzn} - total rated load loss of parallel transformers (kW),

S_{Ni} - rated capacity of the i^{th} transformer (kVA),

P_{0zi} - no-load loss of the i^{th} transformer (kW),

P_{kzi} - rated load loss of the i^{th} transformer (kW).

C. Transformer Economic Operation Mode

Assuming there are n transformers in a substation, there would be (2^n-1) kinds of transformer operation modes. The transformer economic operation mode is one of them in which the total comprehensive power loss of the transformer is minimum. The critical point method is adopted to determine transformer economic operation interval in this paper. It is necessary to enumerate the possible operation mode of n transformers. The next step is to describe the comprehensive power loss curves under various operation modes. The transformer economic operation mode can be chosen when load is different. Then it is prone to calculate the critical load.

There are two transformer comprehensive power loss curves in the operation modes like I and II in Fig. 1. The intersection is the critical load of the two transformer operation modes. The critical load S_{lz} is calculated as

$$S_{lz} = \sqrt{\frac{(P_{0z})_{\text{I}} - (P_{0z\text{I}})_{\text{II}}}{\left(\frac{P_{kz}}{S_N^{\,2}}\right)_{\text{II}} - \left(\frac{P_{kz}}{S_N^{\,2}}\right)_{\text{I}}}} \quad (8)$$

where: I, II - transformer operation modes.

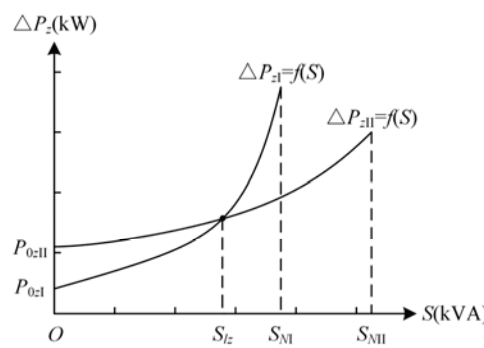

Fig. 1. Transformer comprehensive power loss characteristic curve under different operation mode.

As a result, it is obvious to identify the economic operation interval of the transformer:

1) If $0 < S < S_{lz}$, transformers ought to run in mode I;

2) If $S_{lz} < S < S_{NII}$, transformers ought to run in mode II.

III. THE DISTRIBUTION NETWORK LOAD DISTRIBUTION CONSIDERING THE ECONOMY OF PARALLEL TRANSFORMERS

The distribution network load distribution is a multi-objective nonlinear hybrid optimization problem. When the load on lines are constant, it is normal to change the state of switch to adjust the transformer load. The object of study of the traditional distribution network load distribution strategy is the substations with a single transformer. This paper is about to do research about the load distribution of the substation with more than one transformer.

A. Modeling

The power supply reliability of distribution network is the first requirement for distribution network load distribution. At the same time, economic operation of transformer and load balancing are supposed to be under consideration. So the establishment of the model is to ensure distribution network reliability, enhance the transformer running economy and balance the load. The research framework is shown in Fig. 2. This paper takes EENS, comprehensive power loss and the maximum load factor difference as the indicator of reliability, operation economy and load balancing degree, respectively.

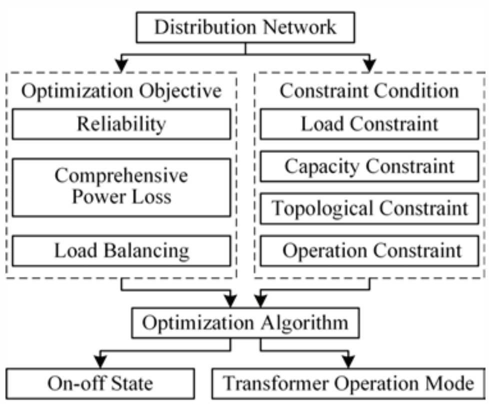

Fig. 2. Research framework.

Equation (9) is the function of the optimization objective in Fig. 2.

$$\begin{cases} \min & EENS \\ \min & \Delta P_z \\ \min & \Delta\beta \end{cases} \tag{9}$$

Because of the fixed position of transformers and switches and some other conditions, there are some constraints in the model.

1) Load constraint: The sum of each substation load is equal to the sum of all load in the distribution network. That is to say, each supply can gain power from one, and only one ,substation.

2) Capacity constraint: Each section of the load must be less than the maximum allowable load.

3) Topological constraint: Power transformers, lines and switches are interconnected in the fixed connection relation.

4) Operation constraint: There is no closed loop in the network.

B. Distribution Network Reliability Evaluation

The common evaluation indexes about the distribution network reliability are system average interruption duration index, system average interruption frequency index and EENS, etc. EENS is selected to evaluate the distribution network reliability in the paper owing to the fusion of much information such as failure frequency, interruption duration and severity consequences[5]. EENS is computed by

$$EENS=\sum_{j=1}^{m} U_j P_j T \left(kW \cdot h/a\right) \tag{10}$$

where: m - number of substations in the distribution network,

U_j - Unavailability of the j^{th} substation,

P_j - active power of the load in jth substation (kW),

T - work time of the load (h).

Transformers running in parallel can be regarded as a parallel system. Thus the unavailability of the parallel transformers is deduced by the definition of parallel network. A parallel system consisting of two repairable components is shown in Fig. 3 [6].

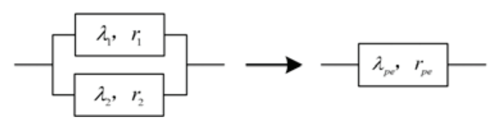

Fig. 3. Parallel network equivalent diagram.

The unavailability of the system is given by

$$\lambda_{pe} = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \tag{11}$$

$$r_{pe} = \frac{r_1 r_2}{r_1 + r_2} \tag{12}$$

$$U_{pe} = \frac{\lambda_{pe}}{\lambda_{pe} + \dfrac{1}{r_{pe}}} \approx \lambda_{pe} \cdot r_{pe} \tag{13}$$

where: λ_{pe} - failure rate of the parallel system (times per year),

r_{pe} - repair time of the parallel system (h),

λ_i - failure rate of the i^{th} transformer (times per year),

r_i - repair time of the i^{th} transformer (h). i=1,2.

IV. Example and Analysis

A simple double side load power distribution network is used as an example to develop the distribution network load distribution strategy considering the parallel transformer economical operation. Fig. 4 is the simplified topological structure of the distribution network. The parameters of transformers and load are shown in TABEL I and II, respectively.

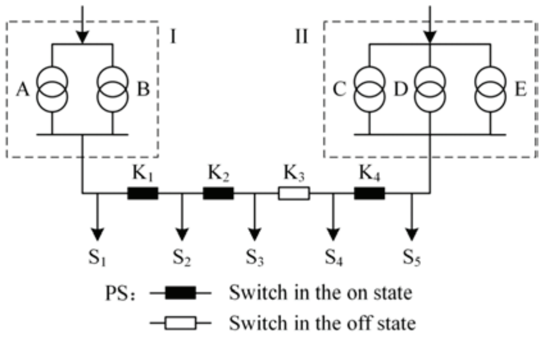

Fig. 4. The simplified topological structure of the distribution network.

The operation modes of transformers in the network are A, B and AB in substation I and C/D/E, CD/CE/DE and CDE in the substation II. In combination with transformer parameters, the comprehensive power loss curves under various operation modes are simulated. As shown in TABLE III, the critical load and unavailability are computed by (8) and (13). The objective function is constructed by (9). Genetic algorithm[7] is used to analysis the model. And then it is facile to get the results. That is, transformer operation mode and switch state is confirmed. The optimization results indicate that Transformer A and B in substation I run in parallel as well as on of the Transformer C/D/E in substation II runs individually. The state of switch K_4 is off and others are on. At this moment, the distribution network work in the best state.

V. Conclusions

1) The transformer comprehensive power loss curve is drawn on the basic of the discipline. The critical load apparent power between each pair of operation modes of numerous transformers can be computed. And it is easy to deduce the transformer economic operation interval.

2) Distribution transformer load distribution model considering the economy of parallel transformers is set up. The optimization goals are distribution network reliability, transformer operation economy and load balancing.

3) The paper takes an example to introduce the model implementation. It is proved that the model is available to reduce the transformer operation loss and balance the load based on ensuring the distribution network reliability.

TABLE I. Transformer Parameters

Substation Number	Transformer Number	Connection Mode	S_N (kVA)	P_0 (kW)	P_k (kW)	Q_0 (kvar)	Q_k (kvar)	I_0 (%)	U_k (%)	λ (times/a)	r (h)
I	A		630	1.30	5.960	7.56	37.80	1.2		0.241	
	B		1000	8.13	8.130	11.00	60.00	1.1		0.318	
	C	Yd11	800	1.52	6.955	9.60	48.00	1.2	6	0.307	170.23
II	D		800	1.52	6.955	9.60	48.00	1.2		0.307	
	E		800	1.52	6.955	9.60	48.00	1.2		0.307	

TABLE II. Load Parameters (T = 6h)

Number	S_1	S_2	S_3	S_4	S_5
Apparent Power (kVA)	249	285	174	351	145
Power Factor	0.447	0.371	0.475	0.376	0.387
Active Power (kW)	111.303	105.735	82.650	131.976	56.115

TABLE III. Economic Operation Area and Unavailability of Transformers

Substation Number	Operation Mode	Economic Operation Area (kVA)	Unavailability (x 10^{-3})
	A	0~279.6295	4.6833
I	B	279.6295~632.0962	6.1796
	AB	632.0962~1630	1.7489
	C/D/E	0~497.8285	5.9658
II	CD/CE/DE	497.8285~862.2643	2.7254
	CDE	862.2643~2400	1.6557

References

[1] J.A.Jardini, C.M.V. Tahan, E.L. Ferrari, S.U. Ahn, “Selection of Distribution Transformers Based on Economic Criteria,” IEEE conference publication, 1997, vol. 6, pp. 14.1-14.5.

[2] Wang Ya-zhong, Shan Xiao-hong, Li Tian-zhu, Zhang Ji-zhong. “Economical operation analysis of more sets parallel operation of the two-winding transformer with the same capacity”, Power System Protection and Control, 2009, vol. 37(4), pp. 93-94.

[3] Cheng Hao-zhong, Gao Ci-wei, Ma Ze-liang, Zhu Zhong-lie, Xu Jin, Wang Xiao-hui, “General Optimized Model of Multi-Objective Electric Power Network Planning,” Journal of Shanghai Jiaotong University, 2004, vol. 38(8), pp. 1229-1237.

[4] Standardization Administration of the People’s Republic of China, GB/T 13462-2008 Economical Operation for Power Transformers, Beijing, China: 2008.

[5] R. Billinton, A. R. Allan. Reliability Evaluation of Power Systems, New York and London: Plenum Press, 1996.

[6] Li Wen-yuan. Risk assessment of power systems: models, methods, and applications. Canada: John Wiley & Sons, 2014.

[7] Li Xiao-ming, Huang Yan-hao, Yin Xiang-gen, “A genetic algorithm based on improvement strategy for power distribution network reconfiguration”, Proceedings of the CSEE, 2004, vol. 24(2), pp. 49-54.