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Evaluation of load division among transformers of different capacities in the grounded wye–delta and open wye–open delta banks under balanced loading and various power factor conditions

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Abstract

This paper evaluates the load division among transformers of different capacities in the grounded wye–delta and open wye–open delta banks under balanced loading and various power factor conditions. In some contingency cases two or three single-phase transformers of different kVA ratings are connected as a three-phase transformer bank to provide three-phase service for critical customers. In these cases, the load division among transformers becomes unequal and results in an unbalanced distribution system. The results of this study corroborate power company experience. Even when both three-phase sources and loads of the bank are balanced, the load division among transformers is unequal if transformers of different capacities are used in a bank, or an open wye–open delta connection is adopted.

Keywords: Load division; Open wye–open delta connection; Grounded wye–delta bank

1. Introduction

In some contingency cases, two or three single-phase transformers of different kVA ratings are connected as a three-phase transformer bank to provide three-phase service for critical customers. In these cases, the load division among transformers becomes unequal, resulting in an unbalanced distribution system.

The distribution systems of the Taiwan Power Company (Taipower) are usually three-phase four-wire multi-grounded systems in which a great number of open wye–open delta transformer banks are used to serve single-phase lighting loads and three-phase power customers simultaneously. For economic reasons and to improve the utilization of the transformers, the open wye–open delta banks are commonly composed of two transformers of different capacities. The transformer with the larger capacity is called the lighting-leg transformer, and the one with the smaller capacity is called the power-leg transformer. All the power of the single-phase lighting loads is supplied from the lighting-leg transformer and the three-phase power loads are served by both lighting-leg and power-leg transformers. In this case, the load division between these two transformers is unequal even when their loads are three-phase balanced. To understand the load division among transformers in a three-phase bank and keep the transformers from being damaged, it is necessary to evaluate the load division in detail.

For the purpose of improving accuracy and dependability while doing the system analysis, detailed mathematical models for critical distribution elements, such as feeders, transformers and loads, have been developed [1–8]. Once these mathematical models have been implemented into a three-phase power flow program, a distribution system can be accurately simulated. In some situations, these detailed models make program convergence difficult. Hence, a criterion for evaluating the individual phase load of a transformer bank was proposed. The criterion provides an alternative to solving this kind of problem [9,10].

In this paper, a straightforward approach that is based on the basic relationships between primary and secondary voltages and currents and transformer impedance, is used. The load division among transformers in the bank can be easily obtained. The load division among transformers and the system unbalance, which was caused by the transformers of different capacities being used in a bank, were investigated. The results confirmed power company experience, even when both three-phase sources and loads of the transformer bank are balanced.

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Nomenclature

$S_{3\phi}$ balanced three-phase load of the specified transformer bank
kVA_a, kVA_b, kVA_c kVA ratings of the single-phase transformers in the bank
N_p, N_s turns of the primary and secondary windings of the single-phase transformers in the transformer bank
a turns ratio of the single-phase transformers in the bank
V_{AN}, V_{BN}, V_{CN} balanced source voltages for phases a, b, and c, respectively, of the primary windings of the transformer bank
V_{ab}, V_{bc}, V_{ca} voltages across the secondary windings of the transformer bank, for phases a, b, and c, respectively
E_{AN}, E_{BN}, E_{CN} induced voltages on the primary windings of the transformer bank, for phases a, b, and c, respectively
E_{ab}, E_{bc}, E_{ca} induced voltages on the secondary windings of the transformer bank, for phases a, b, and c, respectively
I_A, I_B, I_C currents through the primary windings of the transformer bank, for phases a, b, and c, respectively
I_{ba}, I_{cb}, I_{ac} currents through the secondary windings of the transformer bank, for phases a, b, and c, respectively
I_a, I_b, I_c load currents, for phases a, b, and c, respectively
Z_A, Z_B, Z_C leakage impedances of the primary windings of the transformer bank, for phases a, b, and c, respectively
Z_a, Z_b, Z_c leakage impedances of the secondary windings of the transformer bank, for phases a, b, and c, respectively
Z_{ta}, Z_{tb}, Z_{tc} equivalent leakage impedances of the single-phase transformers in the transformer bank; refers to the secondary side of the bank
Z_L load impedance per phase
α an operator, $\alpha = \angle 120°$

2. General formulation of load division

Fig. 1 illustrates a schematic diagram of a grounded wye–delta transformer bank providing three-phase three-wire service for a balanced three-phase load. The capacities of the transformers in the bank may be the same or different. When one of the transformers is removed, the transformer bank becomes an open wye–open delta connection and can continue to serve the three-phase load at a reduced capacity. Assume that all transformers have the same turns ratio a (= N_p/N_s), identical frequency ratings, identical voltage ratings and identical tap settings. The source voltages, V_{AN}, V_{BN}, V_{CN} of the bank are assumed to be balanced. That is

$$V_{AN} = |V_{AN}|\angle 0°,\ V_{BN} = \alpha^2 V_{AN},\ V_{CN} = \alpha V_{AN}$$

For the grounded wye–delta bank as shown in Fig. 1

$$\begin{bmatrix} E_{AN} \\ E_{BN} \\ E_{CN} \end{bmatrix} = a \begin{bmatrix} E_{ab} \\ E_{bc} \\ E_{ca} \end{bmatrix} \quad (1)$$

and

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \frac{1}{a} \begin{bmatrix} I_{ba} \\ I_{cb} \\ I_{ac} \end{bmatrix} \quad (2)$$

The relationship between phase voltages, induced voltages and leakage impedances for the grounded wye-connected primary of the bank is

$$\begin{bmatrix} E_{AN} \\ E_{BN} \\ E_{CN} \end{bmatrix} = \begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} - \begin{bmatrix} Z_A & 0 & 0 \\ 0 & Z_B & 0 \\ 0 & 0 & Z_C \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (3)$$

and, for the delta-connected secondary

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} I_{ba} \\ I_{cb} \\ I_{ac} \end{bmatrix}. \quad (4)$$

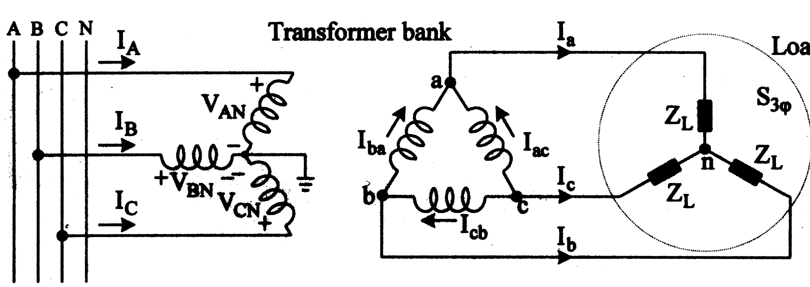

Fig. 1. Schematic diagram of a grounded wye–delta transformer bank providing three-phase three-wire service for a balanced three-phase load.