

Parallel Operation of Transformers with Different Voltage Ratio

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Abstract

The power transformers can operate in parallel when changing the sources for the consumer supply without interrupting the power supply. The article describes the way transformers with different voltage ratio until 0.5% of the geometric mean of the voltage ratio can operate in parallel without damaging the windings of the transformers due to the equalisation current. There are studied also parallel operation of transformers with different power with power ratio of maximum 1:3 and of the transformers with different impedance voltage with maximum ratio until $\pm 10\%$ of the arithmetic mean and the maximum power limit for each transformer due to his impedance voltage. The possibility for parallel operation of transformer with different voltage ratio was determined through mathematical calculation. In the article is presented an example for parallel operation of two transformers of 25MVA and different voltage ratio 110/20 kV and 110/21 kV.

Keywords

transformer, parallel operation, impedance voltage, voltage ratio

1. Introduction

Three-phase transformers are connecting different voltage levels of the electric network and can operate in parallel when switching between different energy sources in the grid without interrupting the electricity supply to consumers.

So far the research in this domain shows that to operate in parallel two transformers some conditions must be fulfilled:

- The difference between the transformer ratio divided with the geometric mean of the transformer ratio must not exceed 0.5 % [3];
- The vector group of the transformers must be the same [1, 2];
- The ratio of the apparent power of the transformers must not be less than 1/3;
- The ratio of impedance voltage of the transformers must not be more than 10% [3 - 6].

The article aims to analyse the parallel operation conditions for usual distribution transformers under non ideal conditions. These cases are often met during operation, so if in the parallel operation vector diagram is not a perfect match in the secondary circuit will be a potential difference and also the power transformer loading will be different.

2. Parallel Operation of Different Voltage Ratio Transformers

During parallel operation of the transformers with different voltage ratio, a potential difference will appear between the secondary windings, which during operation will create an equalizing current that will flow between the secondary windings of the transformers.

The transformation ratio of a transformer is defined by the formula:

$$K_T = \frac{U_1}{U_2}, \quad (1)$$

where: K_T - the voltage ratio;
 U_1 - primary voltage;
 U_2 - secondary voltage.

In the figure 1 is presented the parallel operation of two monophasic transformers and the electrical signals and elements that determines this particular function regime.

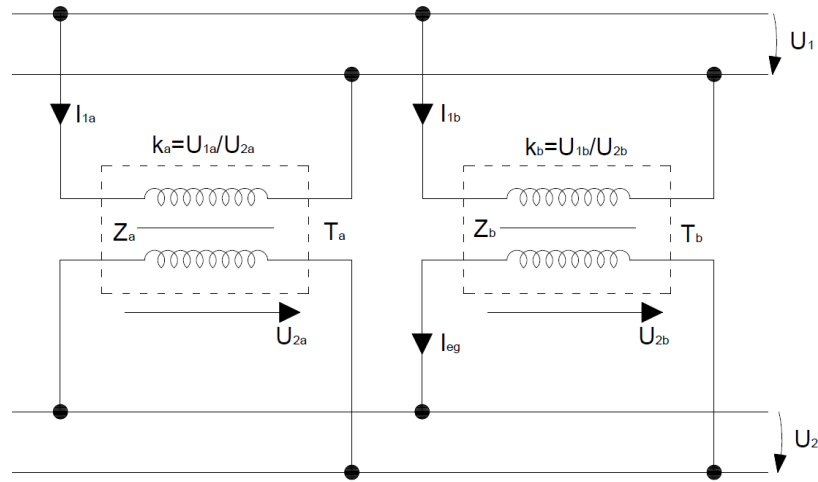


Fig. 1. The parallel operation diagram of two monophasic transformers

The potential difference which appears during parallel operation is calculated as the difference between the voltages that appears in the secondary circuits of the transformers:

$$\Delta U = U_{2b} - U_{2a} . \quad (2)$$

If there will be a potential difference between the secondary circuits of the transformers, in the secondary circuits of both transformers will flow an equalizing current which is calculated after the following formula:

$$I_{eg} = \frac{U_{2b} - U_{2a}}{Z_a + Z_b} . \quad (3)$$

If the voltage ratio of the transformers are not identical, the potential difference between the secondary circuits of the transformers will be different from 0 and there will exist an equalizing current in the secondary circuits [5, 6].

$$\Delta_K \% = \frac{K_a - K_b}{\sqrt{K_a \cdot K_b}} \cdot 100 \leq 0.5\% . \quad (3)$$

2.1. Problems

Determine if the following two windings three-phase transformers can operate in parallel. If yes, please explain the conditions and calculate the equalising current. The primary voltage is 116 kV.

The parameters for the first transformer are: $S_{na}=25$ MVA, $U_{1na}=110$ kV, $U_{2na}=20$ kV, $u_{sca}=11\%$, voltage variation $\pm 9 \times 1.78\%$, vector group YNd 11.

The parameters for the second transformer are: $S_{nb}=25$ MVA, $U_{1nb}=110$ kV, $U_{2nb}=21$ kV, $u_{scb}=11\%$, voltage variation $\pm 9 \times 1.78\%$, vector group YNd 11.

We calculate the voltage ratio of the transformers. The transformers are functioning on median plot (no 10):

$$K_a = \frac{U_{1na}}{U_{2na}} = \frac{110}{20} = 5.5$$

$$K_b = \frac{U_{1nb}}{U_{2nb}} = \frac{110}{21} = 5.238$$

The percentage difference of the transformer ratio divided by the geometric mean of the transformer ratios will be:

$$\Delta_K \% = \frac{K_a - K_b}{\sqrt{K_a \cdot K_b}} \cdot 100$$

$$\Delta_K \% = \frac{5.5 - 5.238}{\sqrt{5.5 \cdot 5.238}} \cdot 100 = 4.8795\%$$

$$\Delta_K \% \geq 0.5\%.$$

The two transformers Ta and Tb cannot function in parallel.

To easy understand the problem will be considered the tables with the plots of the two transformers and the voltage ratio calculated.

Table 1. Tables with transformers plot
Trafo 1(a) Trafo 2(b)

Plot	U1b (kV)	U2b (kV)	Kb	Plot	U1a (kV)	U2a (kV)	Ka
1	127,622	21	6,077	1	127,622	20	6,381
2	125,664		5,984	2	125,664		6,283
3	123,706		5,891	3	123,706		6,185
4	121,748		5,798	4	121,748		6,087
5	119,790		5,704	5	119,790		5,990
6	117,832		5,611	6	117,832		5,892
7	115,874		5,518	7	115,874		5,794
8	113,916		5,425	8	113,916		5,696
9	111,958		5,331	9	111,958		5,598
10	110,000		5,238	10	110,000		5,500
11	108,042		5,145	11	108,042		5,402
12	106,084		5,052	12	106,084		5,304
13	104,126		4,958	13	104,126		5,206
14	102,168		4,865	14	102,168		5,108
15	100,210		4,772	15	100,210		5,011
16	98,252		4,679	16	98,252		4,913
17	96,294		4,585	17	96,294		4,815
18	94,336		4,492	18	94,336		4,717
19	92,378		4,399	19	92,378		4,619

For the two transformers to operate in parallel, it is necessary that the second transformer's (110/21 kV) plot to be set on no 7. The first transformer will function on median plot. Generally, is valid any combination in which the first transformer's plot is set with three plots up like the second transformer.

Will check the relation of the two transformers' transformer ratio.

$$\Delta_K \% = \frac{K_b - K_a}{\sqrt{K_a \cdot K_b}} \cdot 100$$

$$\Delta_K \% = \frac{5.518 - 5.5}{\sqrt{5.518 \cdot 5.5}} \cdot 100 = 0.323\%$$

$$\Delta_K \% \leq 0.5\%.$$

This means that the two transformers can operate in parallel due to transformer ratio.

We will calculate the secondary voltages base on the transformer ratio and on the primary voltage of 116 kV.

$$U_{2a} = \frac{U_1}{K_a} = \frac{116}{5.5} = 21.091 \text{ (kV)}$$

$$U_{2b} = \frac{U_1}{K_b} = \frac{116}{5.518} = 21.022 \text{ (kV)}$$

$$\Delta E = U_{2b} - U_{2a} = 0.069 \text{ (kV)}$$

With the input data we will calculate the internal impedance of the two transformers.

$$Z_a = \frac{u_{sca} \cdot U_{1na}^2}{100 \cdot S_{na}}$$

$$Z_a = \frac{11 \cdot 110^2 \cdot 10^6}{100 \cdot 25 \cdot 10^6} \text{ (kV)}$$

$$Z_a = 53.24 \text{ (}\Omega\text{)}$$

$$Z_b = \frac{u_{scb} \cdot U_{1nb}^2}{100 \cdot S_{nb}}$$

$$Z_b = \frac{11 \cdot 110^2 \cdot 10^6}{100 \cdot 25 \cdot 10^6} \text{ (kV)}$$

$$Z_b = 53.24 \text{ (}\Omega\text{)}$$

The equalising current which will flow in the secondary circuits of the transformers will have the following value:

$$I_{eg} = \frac{U_{2b} - U_{2a}}{Z_a + Z_b}$$

$$I_{eg} = \frac{21.091 - 21.022}{53.24 + 53.24} = 0.648 \text{ (A)}$$

3. Parallel Operation of Transformers with Different Impedance Voltage

The loading of transformers operating in parallel depends on their impedance voltage. Also, the impedance voltage is dependent on the apparent power of the transformers. Considering this, it is desirable to have equal impedance voltages for optimal operation, otherwise we will have an asymmetric distribution of loads, respectively the transformer with a lower impedance voltage will be overloaded [3, 5, 6].

For the two parallel transformers represented in figure 1, we can write the following equations considering Ohm's law in the primary circuit:

$$U_1 = Z_a \cdot I_{1a}; \quad (4a)$$

$$U_1 = Z_b \cdot I_{1b}, \quad (4b)$$

and it results

$$Z_a \cdot I_{1a} = Z_b \cdot I_{1b}, \quad (5)$$

or we can write the relation (5) as ratio:

$$\frac{I_{1a}}{I_{1b}} = \frac{Z_b}{Z_a}. \quad (6)$$

To demonstrate the relationship between the power transformer load and the related impedance voltage, we start from the previous relation in which the first ratio is multiplied both in the denominator and in the numerator by the primary voltage, and the second ratio is divided in both the numerator and denominator with primary voltage:

$$\frac{S_a}{S_b} = \frac{\frac{Z_{scb} \cdot I_{Na} \cdot 100}{U_1} \cdot \frac{I_{Nb}}{I_{Na}}}{\frac{Z_{sca} \cdot I_{Nb} \cdot 100}{U_1}}. \quad (7)$$

If we use in the previous relation the impedance voltage formula, it will become:

$$\frac{S_a}{S_b} = \frac{u_{sca}[\%]}{u_{scb}[\%]} \cdot \frac{I_{Nb}}{I_{Na}}. \quad (8)$$

If we amplify the previous relation with U_1 we will find the following relation:

$$\frac{S_a}{S_b} = \frac{u_{sca}[\%] S_{Nb}}{u_{scb}[\%] S_{Na}} \quad (9)$$

Using relation (9) we can calculate the load on each transformer, considering the total load,

$$S = S_a + S_b, \quad (10)$$

where S – Total Apparent Power.

If we use the last relation in relation (8) we can find:

$$S_a = \frac{S}{\frac{S_{Na}}{u_{sca}} + \frac{S_{Nb}}{u_{scb}}} \cdot \frac{S_{Na}}{u_{sca}}, \quad (11)$$

$$S_a = \frac{C}{u_{sca}}, \quad (12)$$

where C is a constant

It can be observed that in a parallel transformer operation the transformer loading is inversely proportional to its impedance voltage. Thus, if two transformers of different apparent powers are operating in parallel, the lower power must have a higher impedance voltage in order to equalize the loading power on the two transformers. Otherwise, a limitation must be made because the two transformers will not load in the same way and thus the assembly will be able to give to the consumers a lower power than the sum of their nominal apparent powers [5].

3.1. Problem

Determine if the following three-phase transformers with two windings can be put in parallel and if so, determine the power with which each transformer is loaded considering that the load they have to supply is 32 MVA.

The first transformer parameters are: $S_{na}=25$ MVA, $U_{1na}=110$ kV, $U_{2na}=20$ kV, $u_{sca}=11\%$, voltage variation $\pm 9 \times 1.78\%$, vector group YNd 11.

The second transformer parameters are: $S_{nb}=16$ MVA, $U_{1nb}=110$ kV, $U_{2nb}=20$ kV, $u_{scb}=10.5\%$, voltage variation $\pm 9 \times 1.78\%$, vector group YNd 11.

The ratio between the apparent powers of the transformers must not be greater than 1:3.

The impedance voltages must not differ by more than 10%. If we take into account 10% of the lower short-circuit voltage, we get 11.55%. The short-circuit voltage of the first transformer falls between 10.5% and 11.55%.

Using the input data and considering the relation (10) we can calculate the loading on the two transformers:

$$S_a = \frac{S}{\frac{S_{na}}{u_{sca}} + \frac{S_{nb}}{u_{scb}}} \cdot \frac{S_{Na}}{u_{sca}}$$

$$S_a = \frac{32 \cdot 10^6}{\frac{25}{11} + \frac{16}{10.5}} \cdot \frac{25 \cdot 10^6}{11} = 19.16 \text{ MVA}$$

The calculated value for the loading of the first transformer in percentage is 76.62%.

$$S_b = \frac{S}{\frac{S_{na}}{u_{sca}} + \frac{S_{nb}}{u_{scb}}} \cdot \frac{S_{Nb}}{u_{scb}}$$

$$S_b = \frac{32 \cdot 10^6}{\frac{25}{11} + \frac{16}{10.5}} \cdot \frac{16 \cdot 10^6}{10.5} = 12.84 \text{ MVA}$$

The calculated value for the loading of the second transformer in percentage is 80.27%.

We can conclude that the transformer with low impedance voltage will have more loading. So, the loading of the transformer during parallel operation is inversely proportional with his impedance voltage.

4. Conclusions

The article describes the conditions under which two transformers can operate in parallel even if they do not have all the same characteristics.

It has been demonstrated through mathematical calculations that two transformers with different transformation ratio can be put in parallel without affecting their integrity due to the circulation in the secondary of a high value equalization current.

The reduction of the equalization current and respectively falling within the allowed limit of 0.5% for the difference of the transformation ratios compared to their geometric mean was achieved by switching the plot of one of the transformers in order to achieve the optimal parallel operation conditions.

In the analysis of the parallel operation of transformers with different impedance voltage, it was demonstrated by calculations that the transformer with a higher impedance voltage will have a lower load. It is well known that the impedance voltage is higher as the apparent power of the transformers increases. We can operate in parallel transformers with a ratio between their powers of maximum 3:1, but the difference between their impedance voltages of maximum $\pm 10\%$.

Placing two or more transformers in parallel saves the operator from passing through zero and having interruptions in the case of switching from one source to another.

It is important for the operator to know very well the characteristics of the equipment, especially when they are put in parallel for the first time and when checks and calculations must be made to determine the optimal conditions for parallel operation.

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