Parallel Operation Of Transformers - Conditions, Application And Economics

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Abstract - **Parallel operation means transformers connected to the same power systems on the input side and on the output side. There are two forms of parallel operation: in parallel with bus, and in parallel with system. This paper deals with the conditions of the parallel operation of transformers, as well as the conditions for the parallel operation with minimum power losses, i.e. optimal parallel operation.**

Key words - **Three phase transformer, vector group, equalizing current, impedance voltage, parallel operation.**

1. GENERAL REQUIREMENTS FOR PARALLEL OPERATION

1.1. Vector groups of similar phase displacement

The connections of three-phase transformers mean the interconnections of the phase windings on the input or output sides to form star, delta or zigzag connections. The vector group is a notation indicating the connection of the phases of two windings of a transformer and their relative phase displacement. Transformers with vector groups of similar phase displacement are suitable for parallel operation. The terminals with similar notation must be interconnected. However, it is also possible to operate certain other transformers with vector groups of different phase displacement in parallel if the phase connections are interchanged appropriately. Fig. 1 shows the possible connections for parallel operation of transformers with the commonly used numerical indices 5 and 11.

1.2. Approximately equal voltage ratio and tapping range

When the voltage ratios are equal, the total load is distributed between the parallel-connected transformers in direct proportion to the transformer powers and in inverse proportion to their impedance voltages. When the input voltages of two parallel-connected voltage transformers are equal, and the output voltage unequal, an equalizing current flows through both transformers; it can be determined from the following approximate formula:

$$I_{\mathrm{Equal\,Tr1}} \approx \frac{|\Delta u|}{u_{Z(r)1} + u_{Z(r)2} \cdot \dfrac{S_{r1}}{S_{r2}}} \cdot 100 \qquad (1)$$

$I_{\mathrm{Equal\,Tr1}}$ - Equalizing current as % of rated current of transformer 1

$|\Delta u|$ - Absolute value of voltage difference as % of output voltage of transformer 1 at no-load

$u_{Z(r)1}$, $u_{Z(r)2}$ - Impedance voltages at rated current or for certain tappings and/or deviations from the rated induction for transformers 1 and 2

$\dfrac{S_{r1}}{S_{r2}}$ - Ratio of rated powers

The equalizing current is completely independent of the load and of the distribution thereof; it also flows when there is no load.

When there is load, the load current is added geometrically to the equalizing current. If the load current has an inductive power factor, this results in an increased total current in the transformer with the higher secondary voltage and a decreased total current in that transformer with the lower secondary voltage.

Example 1:

	No-load output voltage [V]	Rated power [kVA]	Impedance voltage (at rated current) [%]
Tr. 1	400	250	4
Tr. 2	390	400	4

$$|\Delta u| = \left| \frac{400-390}{400} 100 \right| = 2.5\ \%$$

$$\frac{S_{r1}}{S_{r2}} = \frac{250}{400} = 0.625$$

$$I_{\mathrm{Equal\,Tr1}} \approx \frac{2.5}{4 + 4 \cdot 0.625} \cdot 100 \approx 38.5\%$$

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In example 1, it is unfortunately the smaller transformer which has the higher secondary voltage and therefore must carry the higher total current. Referring to this example, this means that when the equalizing current is 38.5%, a load current of only 61.5% is permitted in order for the rated current of transformer 1 (=100%) not to be exceeded. Therefore, the whole transformer set can be operated at only 61.5% of its total power of 250+400=650 kVA, i.e. approximately 400 kVA. When the load power factor is less than 0.9, this approximate calculation gives sufficiently accurate values, but when the power factor exceeds 0.9 the increasing vectorial differential raises the permitted total power.

Under certain circumstances, changing the setting of the tapping switch on one transformer can improve the load capacity. If, in the case of the 250 kVA transformer in example 1, it were possible to select a higher tapping on the high-voltage side (e.g. 5% more turns), it would give a low voltage reduced by 1/1.05, i.e. 381 V instead of 400 V, owing to the reduced induction with connection to the same high voltage. If this method were to produce too low a distribution voltage, an alternative (if possible) would be to select a lower tapping on the high-voltage side of the 400 kVA transformer (e.g. 5% fewer turns) which would give a low voltage increased by 1/0.95, i.e. 411 V instead of 390 V, owing to the greater noise, core temperature rise and no-load current).

When the voltage setting is changed it must be remembered that the impedance voltage also changes. With EMO transformers conforming to IEC, indirect voltage adjustment associated with a change in induction alters the impedance voltage in approximate proportion to the percentage of increased or decreased turns. The calculations of example 1 are now repeated using a 5% lower tapping on the high voltage winding on the 400 kVA transformer (example 2).

Example 2:

	No-load output voltage [V]	Rated power [kVA]	Impedance voltage (at rated current) [%]
Tr.1	400	250	4
Tr. 2	411	400	3.8 (≈ 95% of 4)

$$|\Delta u| = \left| \frac{400-411}{400} 100 \right| = 2.75\ \%$$

$$\frac{S_{r1}}{S_{r2}} = \frac{250}{400} = 0.625$$

$$I_{\mathrm{Equal\,Tr1}} \approx \frac{2.75}{4+3.8\cdot 0.625} \cdot 100 \approx 43\%$$

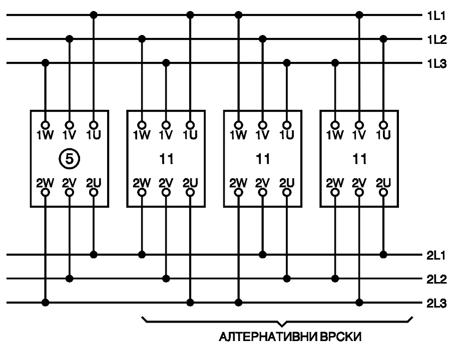
Now, that transformer 2 has the higher no-load secondary voltage, it carries the combined load current and equalizing current and therefore determines the permitted total load of the parallel units.

The equalizing current referred to transformer 2 then becomes:

$$I_{\mathrm{Equal\,Tr2}} = I_{\mathrm{Equal\,Tr1}} \cdot \frac{S_{r1}}{S_{r2}} \tag{2}$$

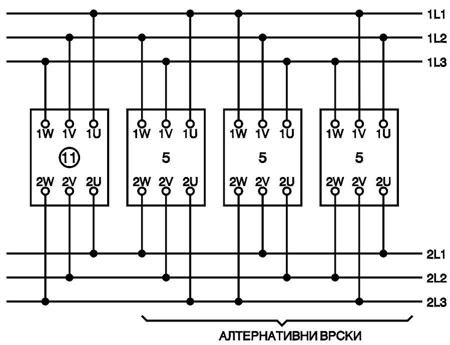
$$I_{\mathrm{Equal\,Tr2}} = 43 \cdot \frac{250}{400} = 26.9\%$$

The permitted load current for transformer 2 is therefore 100%-26.9%=73.1% of the rated current. Consequently, when the load power factor is less than 0.9 (cosφ<0.9), the transformer set can be operated approximately 73.1% of its total power of 650 kVA, i.e. roughly 475 kVA.



1L1, 1L2, 1L3 - High voltage
2L1, 2L2, 2L3 - Required index 5

Alternative connections



1L1, 1L2, 1L3 - High voltage
2L1, 2L2, 2L3 - Required index 11

Alternative connections

Fig. 1 Alternative connections for the parallel operation of transformers with vector-group numerical indices 5 and 11

1.3. Approximately equal impedance voltage

The impedance voltages of the individual transformers should not deviate by more than ±10% from the mean value of all the transformers to be operated in parallel. If $S_{r1}, S_{r2}, \ldots\ldots, S_{rp}$ are the rated powers of the parallel transformers, and $u_{Z(r)1}, u_{Z(r)2}, \ldots\ldots, u_{Z(r)p}$ are their impedance voltages at rated current (the lowest subscript 1 corresponding to the lowest impedance voltage etc.) the maximum possible total load S can be worked out according to the following approximation formula:

$$S \approx S_{r1} + S_{r2} \cdot \frac{u_{Z(r)1}}{u_{Z(r)2}}$$

$$+ S_{r3} \frac{u_{Z(r)1}}{u_{Z(r)3}} + ... + S_{rp} \cdot \frac{u_{Z(r)1}}{u_{Z(r)p}} \qquad (3)$$

At identical rated power levels, the part loads are inversely proportional to the impedance voltages.

Example 3:

	Rated power [kVA]	Impedance voltage (at rated current) [%]
Tr. 1	250	3.6
Tr. 2	250	4.0
Tr. 3	250	4.4
$\text{Transformer 1} \quad 250 \cdot \frac{3.6}{3.6} = 250\,\text{kVA}$ (100% of S_r)		
$\text{Transformer 2} \quad 250 \cdot \frac{3.6}{4.0} = 225\,\text{kVA}$ (90% of S_r)		
$\text{Transformer 3} \quad 250 \cdot \frac{3.6}{4.4} = 205\,\text{kVA}$ (82% of S_r)		
Total load S=380 kVA (=91% of theoretical total power of 3x250=750 kVA)		

Whereas transformer 1 can carry 100% load, transformer 2 can only be operated at 90% of rated load and transformer 3 at only 82%. The transformer with the lower impedance voltage carries more load than that with the higher impedance voltage.

Deviations in the impedance voltage between 10% and 20% are generally still economically acceptable if the transformer with the lower rated power has the higher impedance voltage. In the opposite case even a 1:3 ratio of the powers of the parallel-connected transformers can lead to uneconomical operation.

As a remedial measure, a paralleling reactor can be connected on series with the too highly loaded transformer, e.g. on the low-voltage side. Its function is simply to increase the impedance voltage, and it is not suitable for limiting the short-circuit current owing to the saturation of the reactor core which occurs.

Perfectly satisfactory parallel operation is possible under the above-mentioned conditions.

2. ECONOMICS OF PARALLEL OPERATION

When a group of several parallel-connected transformers is subjected to a varying load over a specified period of time, minimum total losses can be attained by the connection or disconnection of individual transformers. The load loss varies as the square of the load, i.e. the sum of the load loss and the no-load loss when the load is distributed between several transformers can be less (under certain circumstances) than when only a few transformers are used.

In order to avoid a complicated comparison of the losses of the parallel-connected transformers, the part-load at which the switching-in of a further identical transformer (the p^{th} transformer) becomes economical can be calculated as follows:

$$\text{Part} - \text{load factor} \quad n = \frac{\text{Part load}}{\text{Rated power}} \qquad (4)$$

Power of the group:

$$S_{group} = n \cdot S_r \qquad (5)$$

S_r - Rated power of the individual transformer

The part load factor for the economical switching-in of a further identical transformer (the p^{th} transformer) can be calculated using the following formula:

$$n = \sqrt{\frac{p \cdot (p-1) \cdot P_0}{P_k}} \qquad (6)$$

p - number of transformers to be connected in parallel

Calculation example for three identical EMO transformers to be connected in parallel:

Rated data		
Rated power	S_r	630 kVA
No-load ratio	u_r	10/0.4 kV
Vector group		Dyn 5
Rated frequency	f_r	50 Hz
No-load losses	P_0	1300 W
Load losses	P_k	6500 W
Impedance voltage at rated current	u_{Zr}	4 %

with p = 2

$$n = \sqrt{\frac{2 \cdot 1 \cdot 1300}{6500}} = 0.632$$

$$S_{group} = 0.632 \cdot 630 = 398\,\text{kVA}$$

with p = 3

$$n = \sqrt{\frac{3 \cdot 2 \cdot 1300}{6500}} = 1.095$$

$$S_{group} = 1.095 \cdot 630 = 690\,\text{kVA}$$

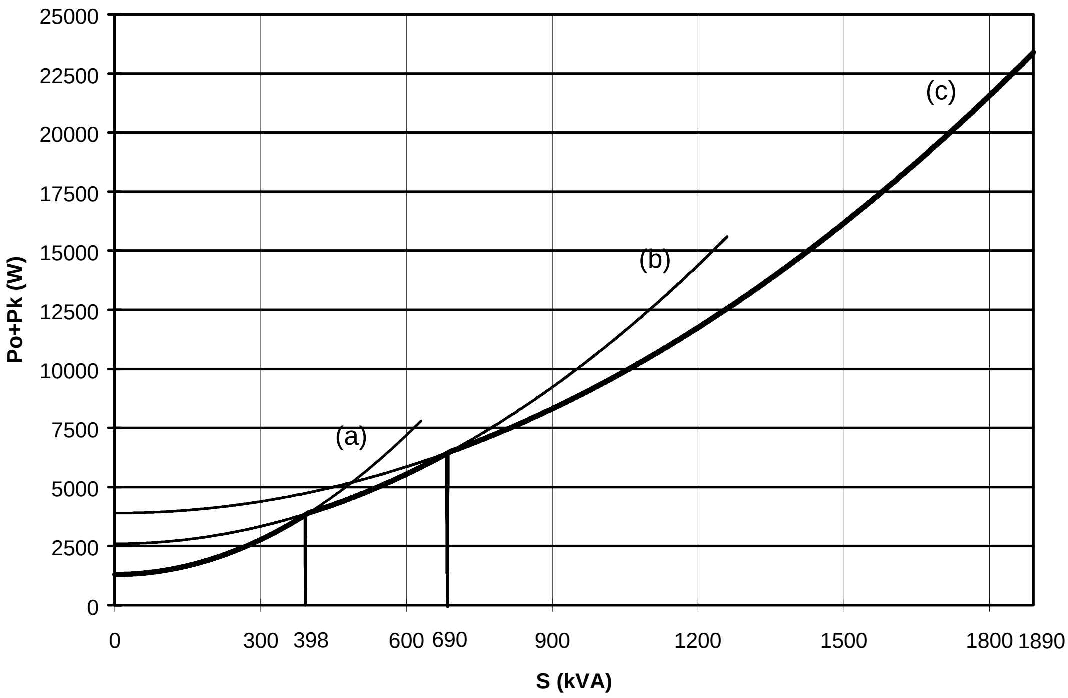


Fig. 2 Curves of total losses of parallel-connected 630 kVA transformers:
(a) 1 transformer; (b) 2 transformers; (c) 3 transformers

Therefore, it is most economical to switch in the second transformer at 398 kVA and the third at 690 kVA, a figure precisely 11.5% over the rated power of one transformer. This is also shown in the diagram (Fig. 2).

3. CONCLUSION

By determining the total losses of parallel connected transformers it is possible to establish the transformers' limit load. During such load, the operation of one transformer is switched to parallel operation of two, three etc. transformers, in order to enable minimum total losses, i.e. parallel operation to be economical.

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