Parallel operation of transformers in practice

Natasa D. Mojsoska[1]

Abstract— **In this paper is analyzed the parallel operation of two or more transformers when there is not fulfilled two conditions $u_{kI} \neq u_{kII}$ and $k_{12I} \neq k_{12II}$. The phase diagram is given. It is explained the differences between theory and practice. Also are referred the other conditions that influence on decision the type of transformer which should work on parallel operation. Conclusion is given for what are the most important values for analyses of the parallel operation. I must mention that this work is only small part of a whole project for researching the parallel operation of two transformers in practice, the conditions, distribution of rated powers, max allowed power, equalizing currents est.**

Keywords—**Transformer, Parallel operation, Impedance voltage, Transformation ratio.**

I. INTRODUCTION

When technical and economical justifications exist, total power which had to be transferred to the consumers of EES is split to more transformers units. In practice at substations in Macedonia there are two and more transformers in parallel operation. Causes for this situation could be following:

- increasing of the loading of substation caused by turning on new consumers or resizing the capacity of the old one
- construction of the substation was in more phases in a long period
- variable loading depends on certain timeline period (peak loading, overloading, winter loading etc)
- one transformer is back up in case of breakdown or blow of the first transformer

All this provides continuality, reliability and security in supplying with electrical energy to the consumers and also maintenance costs are lower.

II. CONDITIONS FOR PARALLEL OPERATION OF TRANSFORMERS

In theory is provided that optimal parallel operation of transformers can be done if are fulfilled following conditions:

1. rated voltages of primary windings of all trans-formers in parallel operation to be equal to network voltage Eq.(1)

$$U_{1I} = U_{1II} = U_{1III} = \ldots\ldots\ldots\ldots = U_{1n} = U_m \qquad (1)$$

2. rated voltages of primary windings of all trans-formers in parallel operation to be equal to network voltage Eq.(2)

$$U_{1I} = U_{1II} = U_{1III} = \ldots\ldots\ldots\ldots = U_{1n} = U_m \qquad (2)$$

3. rated voltages of secondary windings of all transformers to be equal Eq.(3)

$$U_{2I} = U_{2II} = U_{2III} = \ldots\ldots\ldots\ldots = U_{2n} \qquad (3)$$

This condition is come down to equality of transformation ratios of transformers Eq. (4)

$$k_{12I} = k_{12II} = k_{12III} = \ldots\ldots\ldots\ldots = k_{12n} \qquad (4)$$

where:

$$k_{12I} = \frac{U_{1I}}{U_{2I}}, \quad k_{12II} = \frac{U_{1II}}{U_{2II}}, \ldots, \quad k_{12n} = \frac{U_{1n}}{U_{2n}}$$

4. the phase displacement between the primary and secondary winding should be the same i.e. the transformer connections should have the same clock hour figure
5. equality of impedance voltages Eq.(5)

$$u_{kI} = u_{kII} = u_{kIII} = \ldots\ldots\ldots\ldots = u_k \qquad (5)$$

or the components of active and reactive impedance voltage to be equal Eqs. (6) and (7)

$$u_{kaI} = u_{kaII} = u_{kaIII} = \ldots\ldots\ldots\ldots = u_{kan} \qquad (6)$$

$$u_{k\sigma I} = u_{k\sigma II} = u_{k\sigma III} = \ldots\ldots\ldots\ldots = u_{k\sigma n} \qquad (7)$$

From all recent analyses, both theoretical and practical, the conclusion is that parallel operation of transformers is possible if completely is fulfilled the condition that transformers should have the same or appropriate clock hour figure, while with the other conditions (equality of secondary voltages, impedance voltages and transformation ratios) is allowed certain tolerance which is limited by defined frames.

III. ALLOWED FRAMES OF TOLERANCE

A. Transformation ratio

If the condition for equality of transformation ratios is not fulfilled allowed frames are:

- for transformers with transformation ratios $\mathbf{k_{12} \leq 3}$ and for transformers for self necessities is allowed $\mathbf{\Delta k \leq 1\%}$, Eq. (8):

$$\Delta k = \frac{k_{12II} - k_{12I}}{k}.100 \qquad (8)$$

where:

$$k = \sqrt{k_{12II} . k_{12I}} \qquad (9)$$

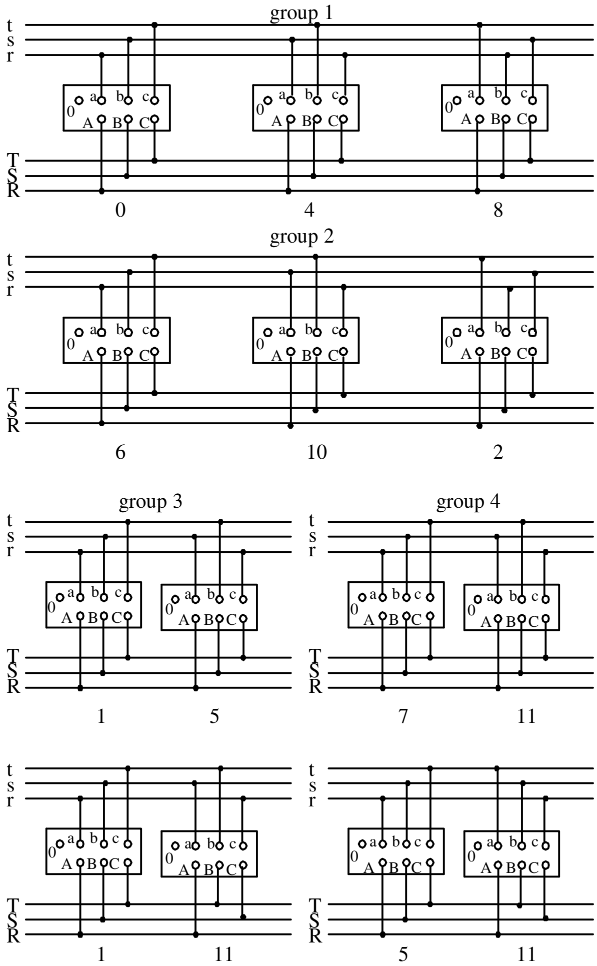
- for others transformers $\mathbf{\Delta k \leq 0.5\%}$.

In cases when transformers which should work in parallel operation are from even or odd class of connection group, but do not belong to the same group, parallel operation is possible to be done. Even groups of connection are 0 and 6 and odd are 5 and 11. Even figures of combination are Yy, Dd and Dz and odd are Yd, Dy and Yz.

Connections of transformers are split at 4 groups:

[1] Natasa D. Mojsoska is with the Faculty of Technical Sciences, I.L.Ribar bb. 7000 Bitola, Macedonia E-mail: natmojso@freemail.com.mk

group 1	clock hour	0	4	8
group 2	clock hour	2	6	10
group 3	clock hour	1	5	
group 4	clock hour	7	11	



All mention connections are given on the following Fig. 1.

Fig. 1. Survey of connection groups of transformers in parallel operation

B. Impedance voltage

Tolerance of impedance voltage of each transformer in parallel operation should be within the limits of **±10%** from middle arithmetical value of others transformers Eqs. (10) and (11).

$$u_{ksr} = \frac{u_{kI} + u_{kII}}{2} \tag{10}$$

$$\Delta u_{kI} = \frac{u_{kI} - u_{ksr}}{u_{ksr}} \cdot 100 \le (\pm 10)\% \tag{11}$$

$$\Delta u_{kII} = \frac{u_{kII} - u_{ksr}}{u_{ksr}} \cdot 100 \le (\pm 10)\% \tag{12}$$

It is recommended transformer with lower power to have bigger impedance voltage and conversely. Also ratio of rated powers of the biggest and the smallest transformer should not exceed **3:1**

IV. Parallel operation of transformers with different transformation ratios and impedance voltages

Some authors have made analyses of parallel operation of transformers with presumption that only one of conditions for optimal work is not fulfilled, while the others are. In practice the most common case is when two or all transformers working in parallel operation do not satisfy two conditions at the same time ($k_{12I} \neq k_{12II}$ and $u_{kI} \neq u_{kII}$).

In this paper work the subject of analyses is parallel work of two transformers with different transformation ratios and impedance voltages. Phase diagram of these transformers is given on Fig. 2.

For this concrete case presumptions are:

$$U_{1I} = U_{1II} = U_m$$

$$k_{12I} < k_{12II} \quad \Rightarrow \quad U_{2nI} > U_{2nII}$$

$$u_{kI} < u_{kII}$$

$$S_{nI} > S_{nII} \quad \Rightarrow \quad I_{opI} > I_{opII}$$

First transformer is mark with I and second with II.

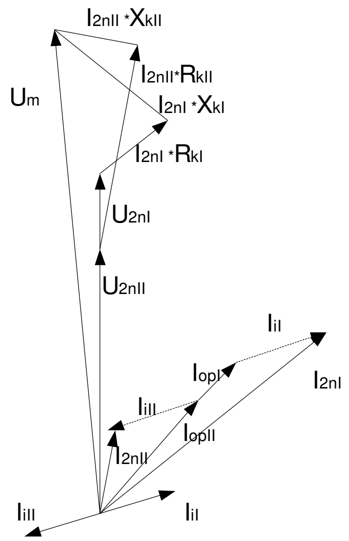


Fig. 2. Phase diagram of two transformers in parallel operation with different k_{12} and u_k

U_{2nI} is secondary voltage of the first transformer working in parallel operation

U_{2nII} is secondary voltage of the second transformer

I_{iI} is equalizing current of the first transformer

I_{iII} is equalizing current of the second transformer

I_{2nI} is rated current of the first transformer

I_{2nII} is rated current of the second transformer

I_{opI} is current of loading of the first transformer

I_{opII} is current of loading of the second transformer

U_m is voltage of network.

Because transformation ratios of transformers are not equal consequently difference in the secondary voltages Δu (%) exists. That difference will cause equalizing current to flow between the transformers. Phase diagram show that equalizing current increase current of loading of the first transformer I_{opI} and decrease current of loading of the second transformer I_{opII}. This caused difference at values of the rated currents I_{2nI} and $I_{2nII.}$ Voltage of network U_m is primary voltage for both transformers. But presumption that $k_{12I} < k_{12II}$ means that there is difference in secondary voltages and different voltage drop at firs and second transformer. They are $I_{2nI} \cdot R_{kI}$ ohmic voltage drop, $I_{2nI} \cdot X_{kI}$ reactive voltage drop for first transformer and $I_{2nII} \cdot R_{kII}$ ohmic voltage drop, $I_{2nII} \cdot X_{kII}$ reactive voltage drop for second transformer.

The values of the current are given in the following Eqs. (13) and (14) in % from the rated currents of individual transformer.

$$i_{iI}(\%) = \frac{I_{iI}}{I_{2nI}} \cdot 100 = \frac{\Delta k}{u_{kI} + u_{kII} \cdot \frac{P_{nI}}{P_{nII}}} \cdot 100 \qquad (13)$$

$$i_{iII}(\%) = \frac{I_{iII}}{I_{2nII}} \cdot 100 = \frac{\Delta k}{u_{kII} + u_{kI} \cdot \frac{P_{nII}}{P_{nI}}} \cdot 100 \qquad (14)$$

In worst case allowed values are:

$$P_{nI} : P_{nII} = 3 : 1$$

$$\Delta k = 1\% \qquad \Rightarrow \qquad u_{kI} = 0.9 \cdot u_{kII}$$

With substitution of this values in Eqs. (13) and (14) the results are given in Eqs. (15) and (16):

$$i_{iI} = \frac{0.26}{u_{kII}}(\%) = \frac{0.23}{u_{kI}}(\%) \qquad (15)$$

$$i_{iII} = \frac{0.77}{u_{kII}}(\%) = \frac{0.75}{u_{kI}}(\%) \qquad (16)$$

Because impedance voltages are moving in frames from 3 to 10 equalizing currents will be about from 0.23% to 2.6% from rated currents.

V. PARALLEL OPERATION OF TRANSFORMERS IN PRACTICE

Mainly in practice we have slightly different picture about parallel operation of transformers.

With turning on of one transformer within parallel operation with already existing transformer necessary power of the group has played important role. For ex. if we have transformer with power of 100kVA and necessary power which should provide the group is 128kVA in that case we can not installed transformer with that power of 28kVA because that special design will be too expensive and economically unprofitable. So it should be installed transformer with standard power or in this case the smallest is with 50kVa. Totally installed power will be 150kVA. Because of unfulfilled conditions for parallel work with calculation can be find allowed max power those transformers which are connected can transmit in the aggregate with none of them being overloaded.

So as a first condition for parallel operation of these transformers is following:

If by limiting caused by any of basic conditions would be limited max power of the group under 100kVA in that case there is not necessity of installation the second transformer because that power we already have it.

In practice transformer with bigger rated power has bigger impedance voltage. It can be get with measuring of voltage when no-load and flown have rated current between the transformer windings.

From other side different manufacturers produced transformers with same rated power but different impedance voltages [4] from 3.7% to 5% which is a big difference.

It is also important how will be divided the power among individual transformers Eq. (17).

$$S_I = S_{nI} \cdot \frac{u_k}{u_{kI}} \qquad (17)$$

where

$$u_k = \frac{S}{\frac{S_{nI}}{u_{kI}} + \frac{S_{nII}}{u_{kII}} + \ldots} \qquad (18)$$

The main issue is max power Eq. (18) that transformers can transmit in the aggregate with none of them being overloaded:

$$S_{max} = S_{nI} \cdot \frac{u_{kn}}{u_{kI}} + S_{nII} \cdot \frac{u_{kn}}{u_{kII}} + \ldots \qquad (19)$$

where:

u_{kn} is the smallest of all impedance voltages of the individual transformers

S_{max} is max allowed power that transformers can transmit in the aggregate with none of them being overloaded

Calculation is made from S_{max} how divided this power to each of transformers and value of efficiency Eq. (20) of the whole group is found:

$$\eta = \frac{S_{max}}{S} \qquad (20)$$

η is coefficient of efficiency of the whole group.

A. Mathematical analysis

One of many calculations that are made for this research is given in following example with the final results. Two transformers with following data are taken:

S_{nI}=100kVA	S_{nI}=250kVA
$U_m=U_{1I}=U_{1II}$=10kV	
U_{2I}=395V	U_{2II}=400V
k_{12I}=25.3	k_{12I}=25
u_{kI}=3.7%	u_{kI}=4.1%

According to above mentioned equations the results are given on Eq.(21) and on Table I:

$$S_{max}=325.61\text{kVA} \qquad \Delta k=1.193\% \qquad \eta=0.93 \qquad (21)$$

TABLE I
RESULTS OF MATHEMATICAL CALCULATION
FOR PARALLEL WORK OF TWO TRANSFORMERS

	T I	T II
I_n [A]	146.068	360.84
I_{op} [A]	146.068	325.64
I_i [A]	32.5885	32.5885
i_i [%]	22.31% I_{opI}	10% I_{opII}
I [A]	I_I=113.448	I_{II}=358.22

The scheme of connection of these two transformers with all data is given on Fig. 3.

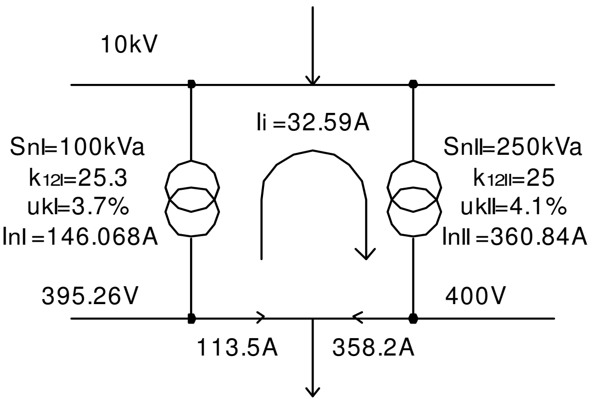


Fig. 3. Scheme of connection of two transformers in parallel operation

I must mention that current limiting for second transformer is necessary. Equalizing current increase the value of current and make it bigger than the current of loading. It can cause smaller max. allowed power S_{max}.

B. Experimental verification

Experimental verification is made on smaller transformers in laboratory with rated power to 3000VA. The results match the calculations.

Purpose of this research are bigger energetic transformers. We demanded a permission from Electro-Bitola to allow measurement at two substations where parallel operation exists. We got information that it will be possible in near future. This measurement will verify our mathematical model for calculating parallel operation.

It is planed the measurement to be performed with measure information system that can follow all relevant data at one substation. All results are on computer or we can get it on flash memory. Then the comparison will be done.

V. CONCLUSION

When we have parallel operation of transformers in substation where already exists two or more transformers analysis can be made in direction of determination of equalizing currents.

In case when in some substation there is necessity of new transformer this calculations are very useful and important. Calculation of max allowed power and divided power of each transformer will give us information about value of rated power that should be selected.

Main goal is proper selection of transformer which will be used more, have bigger coefficient of efficiency of the whole group and have the smallest loses. All this, if is fulfilled it will justify transformer installation. In this paper work subject of wide research is parallel operation of transformers in practice, allowed frames of tolerance of recommended values important for calculation.

As a conclusion from this part the following can be established:

- all limitations caused by allowed deviation does not limit the power under value of rated power of any transformer because there is no need of one of transformers.
- values of equalizing currents to be as lower as possible, so that the losses will be smaller
- the transformers should be chosen from same manufacturers or if it is not possible, the difference between impedance voltages to be smaller
- loses will be smaller if efficiency of each transformer and whole group is bigger.

VI. ACKNOWLEDGEMENT

The measurements on smaller transformers were performed at the Technical Faculty of Bitola, for which the author would like to thank this institution.

Also we acknowledge to “Electro Bitola” – Bitola for their interest about these measurements and their readiness for help in every way.

REFERENCES

[1] M. P. Kostenko, L. M. Piotrovski "Эlektriчeskie машiны" - Leningrad, 1973
[2] Dragutin Kaiser "Elektrotehnički Priručnik" Zagreb, 1964
[3] Prof. d-r Lidija Petkovska "Electrical machines and trans– formers" - lectures, Skopje, 2000.
[4] "Technical handbook" - Rade Koncar, Zagreb, 1984.