Specific Issues of Equivalent Longitudinal Resistances Calculation for Three Windings Transformers

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Abstract. Accomplishing the aspirations of electrical power engineering consists, nowadays, in accurately determining the operating modes. Knowing the parameters of network elements is imperative for accurate solving the power flow regimes. This paper addresses unitarily the calculation of longitudinal resistance of three windings transformers and autotransformers, considering its rated parameters, and discussing the validity of relations demonstrated in detail.
Keywords**:** transformer, three windings, accurately determining, parameters.

Aspecte specifice ale calculării valorii ecivalente a rezistenței longitudinale a transformnatoarelor cu trei înfăşurări

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Rezumat. Realizarea aspirațiile ingineriei electrice constă în zilele noastre în determinarea cu precizie a modurile de operare. Cunoaşterea parametrilor elementelor de rețea este un imperativ pentru rezolvarea corectă a problemei determinării regimurilor de schimb de putere în rețea. În această lucrare se examinează minuțios problema determinării prin calcul a rezistenței longitudinale a transformatoarelor şi autotransformatoare cu trei înfăşurări, luând în considerare parametrii evaluați; se prezintă rezultatele discutării valabilității relațiilor obținute de calcul.
Cuvinte cheie: transformator, trei înfăşurări, precizie, parametrii.

Особенности расчета продольного эквивалентного сопротивления трехобмоточных трансформаторов

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Аннотация. Достижения поставленных целей при расчете режимов в электрических цепях (сетях) в значительной степени зависит от точности определения параметров элементов этих цепей. Знание значений параметров является обязательным условием для правильного расчета режима обмена мощностью в сетях. В данной работе рассматривается задача определения значения продольного эквивалентного сопротивления трехобмоточных трансформаторов и автотрансформаторов. Выполнен анализ корректности полученных расчетных соотношений.
Ключевые слова**:** трансформатор, три обмотки, точность, параметры.

Introduction

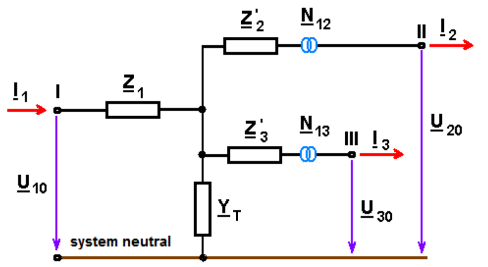
In the current stage of electrical power systems development, transformers and autotransformers with three windings have gained wide spread use. This requires accurate knowledge of their parameters, and deep understanding of the various operating modes of the power system as well [1 - 4].

1. Equivalent scheme

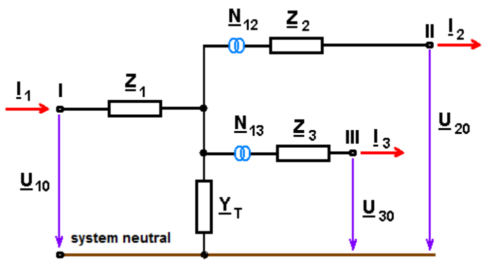
Transformers are passive elements of electric networks and are represented by equivalent schemes with concentrated and constant parameters. (fig. 1. a, b).

Equivalent schemes described below are recommended [2,4] due to the fact that the calculation of the node stores the actual voltage due to the complex processing operators N_{12}, N_{13}.

When calculating the equivalent diagram elements require some necessary tests to determine the parameters of transformers and autotransformers with three windings.



a. with range related to the same voltage



b. with range related to different voltages

Fig.1. Equivalent schemes of three winding transformers

2. Three-winding transformer tests

These tests are described in literature such as:

- **empty test**

Transformers with three windings, the empty test is performed as transformers with two windings and consists of primary winding nominal supply voltage $\mathbf{U_{n1}}$, determining the sizes:

$\mathbf{i_0}$ - current nominal idling percentage (relative to voltage $\mathbf{U_{n1}}$ primary winding and $\mathbf{S_{n1}}$ nominal apparent power source);

$\mathbf{\Delta P_0}$ - active power losses at nominal load (relative to the primary winding voltage $\mathbf{U_{n1}}$ and $\mathbf{S_{n1}}$ nominal apparent power source).

This sample measurement schemes are consistent technical rules in force, depending on the number of phases of transformers and are unitary power transformer manufacturers. The relations are associated calculation unit sizes and $\mathbf{\Delta P_0}$ him.

- **Short-circuit(s) test**

These samples can be achieved in two ways:
a) pairs of windings, third winding being empty;
b) simultaneous charging of three windings without exceeding their nominal charge.

Short variants of questionable evidence in the following ways:

- The value of testing costs;
- Duration of the tests;
- Accuracy in calculating transformer parameters using experimental data of test results for short.

The variant is preferred by most manufacturers a) pairs of windings for reasons of greater precision in determining the longitudinal parameters of transformer windings three.

When this preference is a need to make three different short samples [5 to 10].

Admittedly, three-phase transformer windings are noted by (i, j, k) as follows:

- 1 - primary winding (high voltage) with a rated voltage Un1 apparent power Sn1;
- 2 - the secondary coil (MV), rated voltage Un2 apparent power Sn2;
- 3 - tertiary winding (low voltage), nominal voltage Un3 and apparent power Sn3.

The sample circuit denoted by 1-2 proceed as follows: bypasses winding 1 (3 remaining empty winding) and apply a voltage called short circuit voltage defined by the expression usc, Usc 1-2 = usc 1-2 / (100·Un 1) at the terminals of the winding 1, so that the intensity of the current in the windings 1 and 2 (the short-circuit) does not exceed its nominal value.

Similarly proceed and short samples 1-3 and 2-3 to which the short-circuit voltage Usc 1-3 and Usc 2-3 as defined in the test circuit 1-2.

The three-phase system, they can cause either between phases or between phase and neutral winding system.

i. Short-circuit on windings pairs test – a)

Making a short sample - pair of coils - is determined:

$u_{sc\ 1\text{-}2}$ - Percentage of short circuit rated voltage windings pair 1-2, in%;

$u_{sc\ 1\text{-}3}$ - Percentage of short circuit rated voltage windings pair 1-3, in%;

$u_{sc\ 1\text{-}3}$ - Percentage of short circuit rated voltage windings pair 2-3, in%;

$\Delta P_{sc\ 1\text{-}2}$ - short nominal losses for the pair of coils 1-2, in W.

$\Delta P_{sc\ 1\text{-}3}$ - short nominal losses for the pair of coils 1-2, in W.

$\Delta P_{sc\ 2\text{-}3}$ - short nominal losses for the pair of coils 2-3, in W.

The experimental values listed and defined above relate to the rated voltage of winding 1, U_{n1} and the nominal apparent power of the winding 1 S_{n1}.

After this sequence of values such reports can be obtained catalog sizes that can be used to calculate the transformer with three windings parameters:

$u'_{sc\ 1\text{-}2}$ - rated voltage short circuit percentage (relative) per pair of coils 1-2, in%;

$u'_{sc\ 1\text{-}3}$ - nominal voltage short circuit percentage (relative) per pair of coils 1-3, in%;

$u'_{sc\ 2\text{-}3}$ - rated voltage short circuit percentage (relative) per pair of coils 2-3, in%;

$\Delta P'_{sc\ 1\text{-}2}$ - rated short-circuit losses (reported) on the pair of coils 1-2, in W.

$\Delta P'_{sc\ 3\text{-}1}$ - nominal short-circuit losses (reported) on the pair of coils 1-3, in W.

$\Delta P'_{sc\ 2\text{-}3}$ - short nominal losses (reported) on the pair of coils 2-3, in W.

It points out that it is strictly necessary to unify these parameters by reference to which depends on the ratio of windings apparent power proved both impedance voltage and short-circuit active losses. In addition impedance voltage depends on the ratio of nominal voltage windings are shorted

ii. Short-circuit test with simultaneous windings loading – b)

This option is rarely used, as required explicitly by the beneficiary of the three windings transformer; these maximum active power losses are measured.

It stresses that the short-circuit voltage of the three winding transformer is given only to the first variant testing and recorded in order of decreasing the rated value of voltages:

- windings 1-2: high voltage - medium voltage;
- windings 1-3: high voltage - low voltage;
- windings 2-3: medium voltage - low voltage,

stating the power at which the calculation were made.

The short-circuit losses are given in the same order as the impedance voltage with the same mention over power to which they were determined.

It is stated for maximum losses, short version simultaneously tested windings, provided it is defined according to the relationship that defines just prior assumptions losses in short everything ΔP_{sc} rated maximum.

During test of idling and short-circuit is necessary to give indications about the alleged incidents, which may prevent subsequent failure of the transformers (transformers with two windings).

Also during simultaneous short-circuit test of windings further incidents may occur due to the synchronous operation of the three windings, which can be detected and remedied without destroying the transformer [11 - 16].

The figure and other characteristics of the transformer, namely:

- nominal voltages (U_{1n}, U_{2n}, U_{3n});
- nominal apparent power on each wrapper (S_{1n}, S_{2n}, S_{3n});
- their reports against the greatest power N_{12}, N_{13}, according to Table 1.

Parameters must be considered for calculation, that in all cases $s_{n1} = 100\%$ and nominal power density of secondary windings 2 and 3 relative to the primary winding 1 are represented by the general ratio:

$$100\% / s_{n2}\% / s_{n3}\%, \tag{1}$$

and which may be found most commonly as in table 1:

Table I. Three - windings transformers, listed by winding loads

Transformer type	Rated power of each winding, % from $s_{n\,1}$ of winding 1*)		
-	$s_{n\,1}$**)	$s_{n\,2}$***)	$s_{n\,3}$****)
I	100	100	100
II	100	100	66,(6)
	100	66,(6)	100
III	100	66,(6)	66,(6)
IV	100	66,(6)	33,(3)
TID*****)	100	50	50

*) maximum power winding (usually, high voltage)
**) high voltage winding– hv
***) medium voltage winding– mv
****) low voltage winding– lv
*****) TID divided windings transformer (with equal rated voltages)

Thus are being defined a multitude of three-winding transformers.

3. Windings resistances with known maximum short-circuit losses

Total active losses [14÷19] in short-circuit ΔP_{sc} tot are determined with the following equation:

$$\Delta P_{sc\,tot} = \frac{R_1 \cdot S_1^2 + R_2' \cdot S_2^2 + R_3' \cdot S_3^2}{U_{n1}^2} \tag{2}$$

with respect to the primary.

Consider the balance of apparent power on three windings transformers:

$$S_1 - (S_2 + S_3) = 0 \tag{3}$$

Given the Lagrange multipliers method to find the optimum position (2) the optimized condition of equality (3), yield the following equivalent function

$$\Phi = \Delta P_{sc\,tot} - \lambda \cdot \left[S_1 - \left(S_2 + S_3 \right) \right] \tag{4}$$

Extreme conditions are found when cancels the first-order derivatives of the function (4) in relation to the variables S_1, S_2, S_3. By performing these operations and putting windings are subjected to corresponding nominal loads, it follows that:

$$R_1 \cdot S_{n1} = R_2' \cdot S_{n2} = R_2' \cdot S_{n3} \tag{5}$$

Interpretation of relations (5) follows from the principle of operation of the transformer, the existence of a single voltage value on a single spiral, for all windings.

For fulfilling the condition of extreme conditioning is required that between windings load the apparent power must be satisfied requesting windings in this sample to be as different from each other, some may be nominal charge, as follow:

$$|S_1| \neq |S_2| \neq |S_3| \tag{6}$$

If the load coefficients are associated to the 2 and 3 windings, thus

$$k_1 = \frac{S_2}{S_1}\ ;\ k_2 = \frac{S_3}{S_1} \tag{7}$$

The values of nominal coefficients defined in equation (7), are

$$k_{n1} = \frac{s_{n2}}{100}\ ;\ k_{n2} = \frac{s_{n3}}{100} \tag{8}$$

Equation (6) is replaced in (3) and it results:

$$k_1 + k_2 = 1 \tag{9}$$

The maximum active losses in short-circuit $\Delta P_{sc\ tot\ max}$, are obtained using equation (9) in the condition (6) for transformers in table 1, obtaining:

- **transformer type I**

$$k_1 = 1 \rightarrow \begin{cases} s_{n1} = 100 \\ s_{n2} = 100 \end{cases} ;\ k_2 = 0 \tag{10}$$

maximum losses in copper are obtained by charging 1 and 2 windings at nominal values and leaving empty the 3 winding;

$$k_1 = 0\ ;\ k_2 = 1 \rightarrow \begin{cases} s_{n1} = 100 \\ s_{n3} = 100 \end{cases} \tag{11}$$

or when windings 1 and 3 are loaded at nominal values and leaving empty the 2 winding;

$$s_{n2} = 100\ ;\ s_{n3} = 100 \tag{12}$$

or when windings 2 and 3 are loaded at nominal values and leaving empty the 1 winding;

- **transformer type II a**

$$k_1 = 1 \rightarrow \begin{cases} s_{n1} = 100 \\ s_{n2} = 100 \end{cases} ;\ k_2 = 0 \tag{13}$$

maximum losses in copper are obtained by charging windings 1 and 2 at rated values and leaving empty the winding 3;

- **transformer type II – b**

$$k_1 = 1 \rightarrow \begin{cases} s_{n1} = 100 \\ s_{n2} = 100 \end{cases} ;\ k_2 = 0 \tag{14}$$

maximum losses in copper are obtained by charging windings 1 and 3 at rated values and leaving empty the winding 2;

- **transformer type III**

$$k_1 = \frac{2}{3} \rightarrow \begin{cases} s_{n1} = 100 \\ s_{n2} = \frac{200}{3} \end{cases} ;\ k_2 = \frac{1}{3} \rightarrow s_3 = = \frac{100}{3} \leq s_{n3} = \frac{200}{3} \tag{15}$$

maximum losses in copper are obtained by charging windings 1 and 2 at rated values and winding 3 being charged at 50 % of the rated power

$$k_2=\frac{2}{3}\rightarrow\begin{cases}s_{n1}=100\\ s_{n3}=\frac{200}{3}\end{cases};\ k_1=\frac{1}{3}\rightarrow s_2= \quad (16)$$
$$=\frac{100}{3}\le s_{n2}=\frac{200}{3}$$

maximum losses in copper are obtained by charging windings 1 and 3 at rated values and winding 2 being charged at 50 % of the rated power

- **transformer type IV**

$$k_1=\frac{2}{3}\rightarrow\begin{cases}s_{n1}=100\\ s_{n2}=\frac{200}{3}\end{cases};\ k_2=\frac{1}{3}\rightarrow\begin{cases}s_{n1}=100\\ s_{n3}=\frac{100}{3}\end{cases} \quad (17)$$

maximum losses in copper are obtained by charging at the rated values all the windings.

- **V type transformer – TID**

$$k_1=\frac{1}{2}\rightarrow\begin{cases}s_{n1}=100\\ s_{n2}=50\end{cases};\ k_2=\frac{1}{2}\rightarrow\begin{cases}s_{n1}=100\\ s_{n3}=50\end{cases} \quad (18)$$

maximum losses in copper are obtained by charging all of the windings to their rated values.

Maximum losses in the copper are obtained by replacing equations (5), (7) and taking into account (8) in the (2) expression and results:

$$\Delta P_{sc\,tot\,\max}=\frac{R_1\cdot S_{n1}^2\cdot\left[1+100\cdot\left(\frac{k_1}{s_{n2}}+\frac{k_2}{s_{n3}}\right)\right]}{U_{n1}^2} \quad (19)$$

In conclusion, it results that maximum short-circuit losses are obtained when the power in primary winding is maximum, and its distribution on secondary and tertiary winding is accomplished as unequal.

Taking into account the above computation results the relations for winding resistance, for each type of transformers:

- **type I transformer**

$$R_1=R_2'=R_3'=\frac{\Delta P_{sc\,tot\,\max}\cdot U_{n1}^2}{2\cdot S_{n1}^2} \quad (20)$$

- **type II-a transformer**

$$R_1=R_2'=\frac{2}{3}\cdot R_3'=\frac{\Delta P_{sc\,tot\,\max}\cdot U_{n1}^2}{2\cdot S_{n1}^2} \quad (21)$$

- **type II-b transformer**

$$R_1=\frac{2}{3}\cdot R_2'=R_3'=\frac{\Delta P_{sc\,tot\,\max}\cdot U_{n1}^2}{2\cdot S_{n1}^2} \quad (22)$$

- **type III transformer**

$$R_1=\frac{2}{3}\cdot R_2'=\frac{2}{3}\cdot R_3'=\frac{6\cdot\Delta P_{sc\,tot\,\max}\cdot U_{n1}^2}{11\cdot S_{n1}^2} \quad (23)$$

- **type TIDtransformer**

$$R_1=\frac{R_2'}{2}=\frac{R_3'}{2}=\frac{\Delta P_{sc\,tot\,\max}\cdot U_{n1}^2}{2\cdot S_{n1}^2} \quad (24)$$

4. Calculation of winding resistance in case in which the short circuit losses on windings are known

If the short circuit losses [10÷14] are not reported to the rated power of primary winding, windings resistance are calculated from the following equations:

$$\begin{aligned}P_{sc1-2}&=\left(R_1+R_2'\right)\cdot\left(\frac{S_{n2}}{S_{n1}}\right)^2;\ S_{n2}\le S_{n1}\\ P_{sc1-3}&=\left(R_1+R_3'\right)\cdot\left(\frac{S_{n3}}{S_{n1}}\right)^2;\ S_{n3}\le S_{n1}\\ P_{sc2-3}&=\left(R_2'+R_3'\right)\cdot\left(\frac{S_{n3}}{S_{n1}}\right)^2;\ S_{n3}\le S_{n2}\end{aligned} \quad (25)$$

In case of $S_3 \ge S_2$ the last equations (25) becomes:

$$P_{sc2-3}=\left(R_2'+R_3'\right)\cdot\left(\frac{S_{n2}}{S_{n1}}\right)^2;\ S_{n2}\le S_{n3} \quad (26)$$

Solving the system formed by the equations (25) in relation to R_1, R'_2 and R'_3 are determined the general solution system:

$$R_1 = \left[\Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 + \Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 - \right.$$
$$\left. -\Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 \right] \cdot \frac{U_n^2}{2 \cdot S_{n1}^2};$$
$$R_2' = \left[\Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 + \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 - \right. \quad (27)$$
$$\left. -\Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 \right] \cdot \frac{U_n^2}{2 \cdot S_{n1}^2};$$
$$R_3' = \left[\Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 + \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 - \right.$$
$$\left. -\Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 \right] \cdot \frac{U_n^2}{2 \cdot S_{n1}^2};$$

Or with notations:

$$\Delta P'_{sc1-2} = \Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2;$$
$$\Delta P'_{sc1-3} = \Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2; \quad (28)$$
$$\Delta P'_{sc2-3} = \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2$$

equations system (27) is written with equations (28).

For the case of the system formed by equations (25), the solution is

$$R_1 = \left[\Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 + \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 - \right.$$
$$\left. -\Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 \right] \cdot \frac{U_n^2}{2 \cdot S_{n1}^2};$$
$$R_2' = \left[\Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 + \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 - \right. \quad (29)$$
$$\left. -\Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 \right] \cdot \frac{U_n^2}{2 \cdot S_{n1}^2};$$
$$R_3' = \left[\Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2 + \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 - \right.$$
$$\left. -\Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2 \right] \cdot \frac{U_n^2}{2 \cdot S_{n1}^2};$$

and with notations (30) from below

$$\Delta P'_{sc1-2} = \Delta P_{sc1-2} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2;$$
$$\Delta P'_{sc1-3} = \Delta P_{sc1-3} \cdot \left(\frac{S_{n1}}{S_{n3}}\right)^2; \quad (30)$$
$$\Delta P'_{sc2-3} = \Delta P_{sc2-3} \cdot \left(\frac{S_{n1}}{S_{n2}}\right)^2$$

the system defined by equations (29) becomes:

$$R_1 = \frac{\Delta P'_{sc1-2} + \Delta P'_{sc1-3} - \Delta P'_{sc2-3}}{2} \cdot \left(\frac{U_{n1}}{S_{n1}}\right)^2$$
$$R_2' = \frac{\Delta P'_{sc1-2} + \Delta P'_{sc2-3} - \Delta P'_{sc1-3}}{2} \cdot \left(\frac{U_{n1}}{S_{n1}}\right)^2 \quad (31)$$
$$R_3' = \frac{\Delta P'_{sc1-3} + \Delta P'_{sc2-3} - \Delta P'_{sc1-2}}{2} \cdot \left(\frac{U_{n1}}{S_{n1}}\right)^2$$

Particular types of solutions corresponding to transformer types listed in Table 1 are determined from (27) or (29) through particular mathematical developments. In case of short circuit losses on windings relative to the rated power of the primary - winding, winding resistance calculation will be performed with equations (27) or (29), by putting the following condition:

$$S_{n1} = S_{n2} = S_{n3} \quad (32)$$

These calculation elements are necessary for calculating proper evaluation of longitudinal resistance to determine both the permanent arrangements for the emergency and the associated electrical substations in which they are components.

5. Case studies

Table 2 shows the resistance values of three windings transformers class type TID. For resistance calculation. For resistances calculating, relations from the preceding paragraph were used.

Table 2. TID-type transformers resistances

U_n	S_n	S_1	S_2	S_3	u_{sc}	$\Delta P_{sc\ max}$	ΔP_0	i_0	R_1	R_2	R_3
kV	MVA	%	%	%	%	kW	kW	%	Ω	Ω	Ω
20	25	100	50	50	9.5	125	29	0.7	0.04	0.02	0.02
20	32	100	50	50	11.5	180	33	0.7	0.04	0.02	0.02
20	40	100	50	50	8.5	180	39	0.65	0.02	0.01	0.01
20	40	100	50	50	14	180	39	0.65	0.02	0.01	0.01
20	63	100	50	50	11.5	280	55	0.6	0.01	0.01	0.01
20	80	100	50	50	9.5	330	65	0.6	0.01	0.01	0.01
20	80	100	50	50	14	330	65	0.6	0.01	0.01	0.01
110	25	100	50	50	10.5	120	30	0.7	1.16	0.58	0.58
110	32	100	50	50	10.5	145	40	0.7	0.86	0.43	0.43
110	40	100	50	50	10.5	150	50	0.65	0.57	0.28	0.28
110	40	100	50	50	12	180	40	0.65	0.68	0.34	0.34
110	63	100	50	50	10.5	245	70	0.6	0.37	0.19	0.19
110	80	100	50	50	10.5	310	85	0.6	0.29	0.15	0.15
110	125	100	50	50	10.5	400	120	0.55	0.15	0.08	0.08

6. Conclusions

These calculations were required because transformer construction companies give their characteristics in one of the situations mentioned above, especially up to 100%, (however, up to 80%) as short-circuit loss of windings pairs unreported rated power of the transformer primary side, the rest being of TID-type transformer. These transformers are increasingly being used in the electrical power system in case of renewables.

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