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ANALYSIS OF EFFICIENCY OF POWER TRANSFORMERS WINDINGS CONNECTION GROUPS DETERMINATION

The paper analysis the efficiency of methods intended for definition connection group of power transformer windings: direct method, method of two voltmeters and direct current method .The device for definition of connection group using the method of direct current allows to define connection group automatically with minimum losses of time.

Key words: *power transformer, winding connection group*

For parallel operation of the transformers the coincidence of winding connection groups is necessary. That is why, at the stage of manufacture, operation and maintenance of power transformers there appears the necessity to determine connection group which depend on bias angle of linear e. m. f vectors of high and low voltage windings of similar phases transformers, as well as mutual applying and placement of windings on the transformer. In cases, when the winding is connected in triangle, the angular bias depends on the method of phase connection while forming the triangle (a-y or a-z). To define the direction of winding by external appearance, it is necessary to know the location of the beginning and the end of the winding.

In accordance with the State Standard (ГОСТ 11677-85) the beginning of the phases of low voltage winding are labeled by letters A, B, C, end – by letters – X, Y, Z, and high voltage windings – a, b, c and x, y, z, correspondingly.

If we know the beginning of the winding and its end, the direction of its winding is determined in the following way: if we look at the winding from the side of its beginning, then, in case of turns direction counterclockwise the winding will be called left winding, and if the direction of the turns is clockwise – the winding will be called right.

For three-phase transformers with two windings (State Standard ГОСТ 11675-85) the following symbols are used for designation of winding circuits and their connection groups:

a) Y/Y_1-0: high voltage winding, Y – connected, low voltage winding, Y – connected, with the neutral available; group – O;

b) Y/ Δ – 11: high voltage winding γ - connected, low-voltage winding, delta-connected; group 11;

c) Y_l/ Δ -11: high voltage winding, γ - connected, with the neutral available; low-voltage winding - delta-connected; group 11;

d) Y/Z_l-11: high voltage winding, γ – connected; low-voltage winding - Z – connected, with the neutral available, group 11;

e) Δ Y_l-11: high voltage winding, delta-connected, low-voltage winding - γ – connected, with the neutral available, group 11.

Connection in parallel of two transformers with different connection groups results in the advent of equalizing current, its value depends on the difference between shift angles of e. m. f. vectors of both transformers:

$$I_{com} = \frac{20 \cdot \sin\frac{\alpha}{2}}{\frac{U_{\kappa 1}}{I_1} + \frac{U_{\kappa 2}}{I_2}}\ , \tag{1}$$

where α – shift angle between e. m. f. of both transformers; U_{s1}, U_{s2} – short-circuit voltage of transformers; I_1, I_2 – nominal currents, A.

If we assume that two transformers with equal short-circuit voltage, for instance 5%, and of the same power and equal currents are connected in parallel, then formula (1) after transformations will be:

$$I_{com} = 20 \cdot I \cdot \sin(\frac{\alpha}{2}). \tag{2}$$

It follows from the expression (2), that if the error is committed while factory tests, and instead of group 0 connection, the transformer is manufactured with group 6 connection, then in the process of its connection in parallel with the transformer of 0 connection group , equalizing current will be:

$$I_{com} = 20 \cdot I \cdot \sin(\frac{180}{2}) = 20 \cdot I_{nom}. \tag{3}$$

Hence the error in determination of windings connection group will cause the failure of the transformer, when the transformer is connected in parallel with the transformer having another connection group.

Connection group of winding can be verified using one of the following methods [1]:

Direct method (phase-meter);

Method of two voltmeters;

Bridge method, used for verification of transformation ratio;

Direct current method.

The correctness of labeling of transformer bushings is controlled simultaneously with group control.

1. Phase-meter method

Testing of connection group using the phase-meter is called direct method, since the given method enables to define directly the shift angle between primary and secondary E. M. F.

If the scale of four-quadrant single-phase phase-meter is calibrated in hours divisions, then deviation of the arrow will indicate connection group in hours notation.

The most suitable for testing is four-quadrant phase-meter with 360° scale of Э-500 type.

Parallel winding of the phase-meter is connected to linear voltage from the side of low voltage supply, and series – to linear voltage of high voltage winding. Depending on the characteristic of the transformers. parallel winding of phase-meter can be connected across voltage transformer TV and series winding is always connected across the resistor R [1].

Resistor R is selected proceeding from the characteristics of the phase-meter and test conditions; the current passing in series winding must not exceed nominal current of the phase-meter.

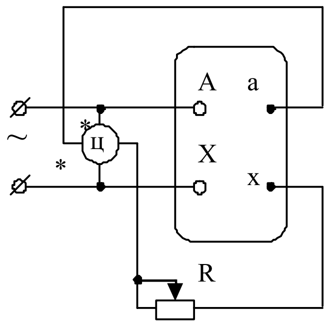
The voltage, supplied to parallel winding of the phase-mater must not exceed its nominal value.

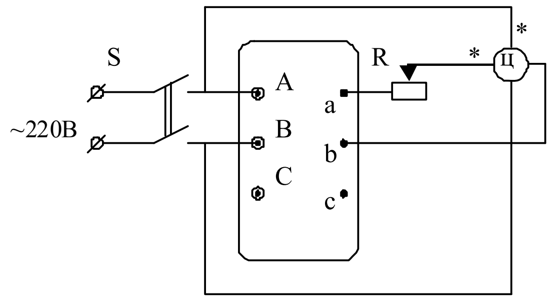
While checking connection groups of three-phase transformers winding at least two tests are to be carried out (for two pairs of corresponding linear inputs).

Complete circuit of the phase- mater is regularly tested before putting into operation, connection groups are already known, and in the same circuit, in which the phase-mater functions while testing.

When connection groups of windings are to be defined applying phase-mater method, it is necessary to check the correctness of interlacing of three-phase voltage supplied to transformer windings; in order to avoid errors

The simplest and most convenient method to check coupling groups is by means of special phase indicator of Э-500/2 type.





a) single-phase transformer; b) three-phase transformer.

Fig. 1. Circuit for checking of connection group of power transformer winding by means of direct method.

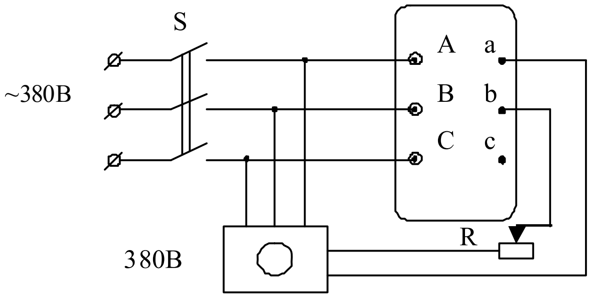


Fig. . Determination of connection group, applying universal phase indicator of Э-500/2 type.

2. Method of two voltmeters

The method is based on combination of vector diagrams of primary and secondary e. m. f and measurement of voltages between corresponding inputs with further comparison of these voltages with calculated ones. Common practice is to connect the terminals of the same phases of HV and LV windings (in practical applications inputs A and a are connected).

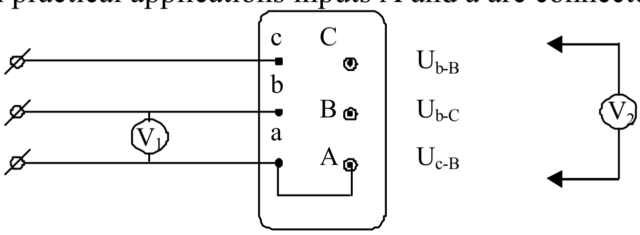


Fig. 3. Circuit for testing transformer connection group using the method of two voltmeters.

For verification of winding connection group it is necessary to define voltage and inputs b – B, b – C and c – B of combined vector diagrams. These voltages are compared with the voltages determined by formular of the Table 1. [1]

Table 1.

Determination of winding connection groups using the method of two voltmeters by means of group transformation ratio

WCG	$\frac{U_{b-B}}{U_{lv}}$	$\frac{U_{b-C}}{U_{lv}}$	$\frac{U_{c-B}}{U_{lv}}$
0	$K-1$	$\sqrt{1-K+K^2}$	$\sqrt{1-K+K^2}$
1	$\sqrt{1-\sqrt{3}\cdot K+K^2}$	$\sqrt{1-\sqrt{3}\cdot K+K^2}$	$\sqrt{1+K^2}$
2	$\sqrt{1-K+K^2}$	$K-1$	$\sqrt{1+K+K^2}$
3	$\sqrt{1+K^2}$	$\sqrt{1-\sqrt{3}\cdot K+K^2}$	$\sqrt{1+\sqrt{3}\cdot K+K^2}$

WCG	$\frac{U_{b-B}}{U_{lv}}$	$\frac{U_{b-C}}{U_{lv}}$	$\frac{U_{c-B}}{U_{lv}}$
4	$\sqrt{1+K+K^2}$	$\sqrt{1-K+K^2}$	$K+1$
5	$\sqrt{1+\sqrt{3}\cdot K+K^2}$	$\sqrt{1+K^2}$	$\sqrt{1+\sqrt{3}\cdot K+K^2}$
6	$K+1$	$\sqrt{1+K+K^2}$	$\sqrt{1+K+K^2}$
7	$\sqrt{1+\sqrt{3}\cdot K+K^2}$	$\sqrt{1+\sqrt{3}\cdot K+K^2}$	$\sqrt{1+K^2}$
8	$\sqrt{1+K+K^2}$	$K+1$	$\sqrt{1-K+K^2}$
9	$\sqrt{1+K^2}$	$\sqrt{1+\sqrt{3}\cdot K+K^2}$	$\sqrt{1-\sqrt{3}\cdot K+K^2}$
10	$\sqrt{1-K+K^2}$	$\sqrt{1+K+K^2}$	$K-1$
11	$\sqrt{1-\sqrt{3}\cdot K+K^2}$	$\sqrt{1+K^2}$	$\sqrt{1-\sqrt{3}\cdot K+K^2}$

Note; K - transformation ratio of the transformer

While on-site testing of the installation the connection group is not defined, only its correspondence to certificate data is checked. That is why, in these conditions simpler method of two voltmeters is used, i. e., the supply voltage is connected to HV winding, but not to LV winding.

There is no need to measure all the voltages and calculate them by the formulas of Table 1, it is sufficient to compare them with supplied voltage U B-C and with the data, given in Table 2; depending on the fact if they are greater, equal or smaller than the linear voltage (we will denote them by letter "b", "p", "m") and define the coupling group of the winding. For such an experiment it is convenient to use the circuit with one voltmeter (Fig 4).

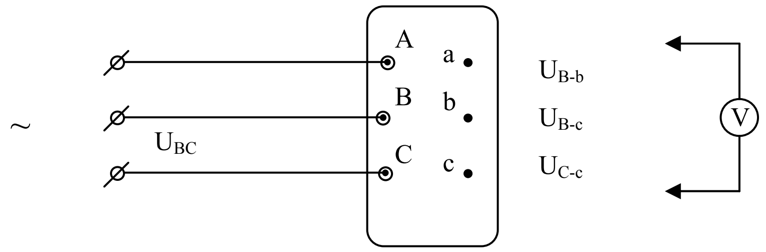


Fig 4. Circuit for winding connection group test , applying one voltmeter.

Table 2.

Determination of winding connection group, applying one voltmeter

Index.	WCG											
	0	1	2	3	4	5	6	7	8	9	0	11
Comparison of measured voltage with supplied voltage.												
B-b	м	м	м	р	б	б	б	б	б	р	м	м
B-c	м	р	б	б	б	б	б	р	м	м	м	м
C-c	м	м	м	м	м	р	б	б	б	б	б	р

While supplying the circuit of the voltmeters from non-symmetric three phase network, the errors can be made while determining connection group. For taking into consideration non-symmetry calculation formulas are used (see Table 3)

$$\left.\begin{aligned}\Delta_1 &= \frac{U_{AB}}{U_{cp}} - 1;\\ \Delta_2 &= \frac{U_{BC}}{U_{cp}} - 1;\\ \Delta_3 &= \frac{U_{CA}}{U_{cp}} - 1,\end{aligned}\right\} \tag{4}$$

where

$$U_{avr} = \frac{U_{AB} + U_{BC} + U_{CA}}{3}, \tag{5}$$

Algebraic sum $\sum\Delta$ always equals zero.

Table 3

Calculation formulas for determination of winding connection groups in case of non-symmetrical supply

WCG	Group Coefficient	Calculation formula
0	$\frac{U_{B-b}}{U_{lv}}$	$(K-1)(1+\Delta_1)$
	$\frac{U_{B-c}}{U_{lv}}$	$\sqrt{1-K(1-4\Delta_2)+K^2(1+2\Delta_3)+2\Delta_1}$
	$\frac{U_{C-b}}{U_{lv}}$	$\sqrt{1-K(1-4\Delta_2)+K^2(1+2\Delta_1)+2\Delta_3}$
11	$\frac{U_{B-b}}{U_{lv}}$	$\sqrt{1-\sqrt{3}\cdot K[1+\frac{4}{3}(\Delta_1-\Delta_3)]+K^2(1+2\Delta_1)-2\Delta_3}$
	$\frac{U_{B-c}}{U_{lv}}$	$\sqrt{1-2{,}32\cdot K(\Delta_2-\Delta_1)+K^2(1+2\Delta_3)-2\Delta_3}$
	$\frac{U_{C-b}}{U_{lv}}$	$\sqrt{1-\sqrt{3}\cdot K[1+\frac{4}{3}(\Delta_1-\Delta_2)]+K^2(1+2\Delta_1)-2\Delta_2}$

3. Direct current method

Using this method direct current pulse is sent to terminals AB, BC and AC of HV winding, and signs of induced e. m. t are fixed at terminals ab, bc and ac. The conclusions regarding connection group are made by the results of comparison of obtained signs of induced e. m. t with the Table of group index.

The drawback of the given method is large amount of experiments (three) and measurements (nine). In order to simplify the process of group determination of power transformer windings the investigations were carried out, which allowed to determine the connection group of windings, carrying out only one experiment [2,3,4]

Table 4

Signs of induced EMF on LV side while supplying HV side of power transformer LW winding

Connection Group of Windings	Winding LV		
	ab	bc	ca
1	-	+	+
2	0	+	+
3	+	+	+
4	+	0	+
5	+	-	+
6	+	-	0
7	+	-	-
8	0	-	-
9	-	-	-
10	-	0	-
11	-	+	-
0	-	+	0

To determine connection groups of transformer windings it is necessary to carry out only one experiment. This can be performed applying special connecting circuit of DC supply to terminals of HV winding of power transformer depending on the method of connection of its windings. As a result of theoretical and experimental research it was determined that if the connection of positive pole of the source to phase bushing B, and negative pole – phase bushing A of HV winding of power transformer is taken as base connection circuit, then, irrespectively of coupling method of its winding while testing we obtain correspondence between the number of WCG and combinations of three signs of induced EMF. In case of winding connection Δ/У this version of connection remains in case of У/У(Δ) – additionally the jumper is installed between bushing A and C, and in case of Δ/Δ the jumper is installed between B and C. Table 4 contains the signs of induced EMF for different connection circuits of DC source.

Using these regularities several devices intended for determination of connection groups of transformer windings were developed and manufactured. These devices have some advantages as compared with similar devices:

1. For determination of connection groups only one experiment must be performed;
2. All intermediate operations to be performed outside the device, are excluded;
3. There is no need in application of the connection groups indication Table;
4. Device can be used for connection group determination in any connecting circuits of transformer windings.

Fig 5 shows the structural diagram of the device, intended for determination the transformer connection group. The device consists of DC source, start button (SB), connection circuit switch , limiting unit of input signals voltage levels, optoelectronic converter of TTL levels, registers unit, decoder and indication unit, as well as auxiliary elements, necessary to provide the device operation in automatic mode.

The device operates in the following manner: its terminals A, B, C and a, b, c are connected to corresponding terminals of HV and LV windings of power transformer. The switch of connection circuit is set in required position. The device is ready for operation.

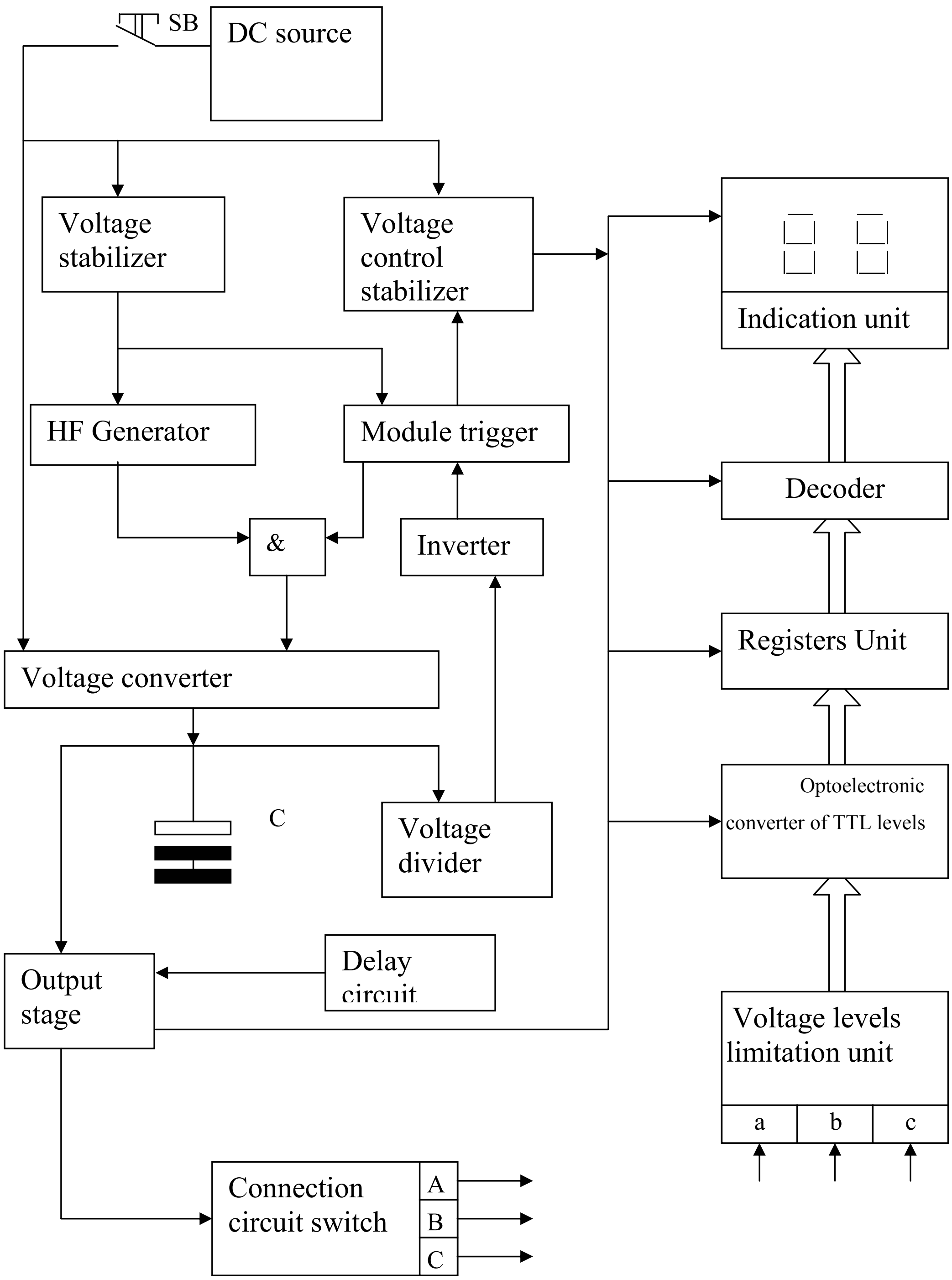


Fig5. Structure diagram of the device, intended for connection groups of transformer windings definition

Start of the device is performed by pressing the start button (SB). Constant voltage +5V from DC supply is sent at the inputs of: voltage stabilizer, voltage control stabilizer and voltage transformer. At the input of high frequency generation (15 KHz) + 5V is sent from the output of voltage stabilizer to start the generator and to the input R of mode trigger, which is set into initial state. From the output $\overline{Q}$ of mode trigger signal "I" is removed, this signal arrives to the second input of logic element "I" and the input of voltage stabilizer. If simultaneously with this signal the signal from high frequency generator arrives at the first input of logic element "I ; then signal to voltage transformer is removed from the output of high frequency generator; starting its operation.

Voltage converter charges discharging capacitor C to voltage of 120V. As soon as capacitor C is charged, the signal is sent to the input S of mode trigger from the positive envelope of capacitor C across voltage divider and inverter.

The trigger is set into another state, signal "O" is removed from its output $\overline{Q}$, that leads to interruption of voltage converter operation.

From the output of voltage control stabilizer +5V supply is sent to indication unit, decoder, delay circuit and optothirystor of the output stage. Within registers unit the supply is sent to inputs S of all triggers and output R; which controls the state of registers unit and trigger. As a result, three other pairs of unit triggers pass into initial state. Delay circuit provides transistor base of output stage with certain time delay, which is sufficient to put into initial state the triggers of register unit. After that the transistor is open, that leads to opening of optothirystor of output stage.

As a result, discharge capacitor C across the input stage and connection circuit switch, discharges into HV winding of power transformer. EMF, induced on HV side arrive into the unit of voltage limitation levels of input signals and into optoelectronic converter of voltage levels of input signals and optoelectronic converter of TTL levels, consisting of six optrons with amplifiers. Signals from its outputs are sent to registers unit, where signs of EMF are fixed by triggers. Signals from registers unit are sent to decoder, which is programming storage unit, the memory of which contains data regarding WCG (see Table 4). After comparison of input signal with the data in programming unit decoder sends the command to indication unit, which consists of two LED matrices, that is , the number ofWCG of power transformer is indicated by indication unit.

Hence, application of such device allows to define reliably and quickly, the number of connection group of transformer windings, that considerably improves the efficiency of the shaff.

Method of bridge

This method of determination is not widely used in practice and is applied while checking of transformation ratio of power transformers at manufacturing plants.

Conclusions

Direct method of connection group determination is not convenient, because it requires the selection of resistor, which is connected in series winding of phasemeter.

Method of two voltmeters requires measurements and calculations for connection group determination and control of supply voltage symmetry.

Method of direct current allows to determine connection group of the transformer performing only one experiment for any circuit with minimum losses of time.

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