DISTRIBUTION TRANSFORMERS WITH WINDINGS MADE OF ALUMINUM CONDUCTOR

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Short content

This paper takes into consideration geometrical shape of distribution transformers with windings made of copper conductors and of aluminum conductors.
It is shown that transformers with windings made of aluminum conductors are higher but with smaller length and width, than those with windings made of copper conductors. Based on these dimensions it follows that in transformer stations, transformers with windings made of copper conductors could be replaced by transformers with windings made of aluminum conductors if, there is enough height in transformer stations.
The reasons for this study are Technical Recommendations of Electrical Authority of Serbia, according to which distribution transformers are with windings made of copper conductor, so in EAS Transformer Stations there are no transformers with windings made of aluminum. However this is not the case in the world. There are developed countries where the situation is opposite; they are using more transformers with windings made of aluminum.
This paper shows that there are economic reasons for use of transformers with windings made of aluminum. By use of insulation with higher dielectric strength even for transformers for distribution voltage levels it was achieved that transformers with windings made of aluminum conductors are with better efficiency. Better efficiency is the result of lower loss of active energy in the magnetic core due to lower mass of magnetic steel. Lower mass of core steel is the result of geometrical change of shape of the transformer, so electromechanical force is lower for transformers with aluminum windings when optimal solution is achieved. It is opposite for transformers with copper windings. It is interesting that total mass of transformer is lower, because specific mass of aluminum is more than three times lower than specific mass of copper.
Total Transformer price is affected not only by price of materials but with other factors, so it is not possible to make conclusion about total transformer price in this paper. It is evident, that by development of production technology of transformers with aluminum windings, favorable results could be expected. It comes out that use of distribution transformers with windings made of aluminum conductor depends more on manufacturers than on users. For the same buying price, transformer with aluminum windings is more economic because it has higher efficiency.

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Influence of spacing between windings

Geometrical shape of distribution transformers mostly depends on geometrical shape of magnetic core with windings. Other elements, such as coolers, could influence it more. If there are special requirements usually, the ratio between length and width of transformer is changed. The paper [1] takes into consideration the influence of spacing between windings to reduce height and mass of active part. However, it was about windings made of copper, so this paper studies the case when windings are made of aluminum conductor.
We will start, as in [1], from approximate relation for inductive component of impedance u_x. This part is repeated in order to get the whole picture.

$$u_x = \frac{0.414 \cdot P \cdot D_{sr}}{E_1^2 \cdot h}\left(\delta + \frac{a+b}{3}\right) \tag{1}$$

Where (figure 1):

- P - Nominal Transformer Rating
- D_{sr} - Mean diameter of both windings
- E_1 - Electromechanical Force
- H - Winding height
- δ - Distance between windings
- a - Width of low voltage winding LV
- b - Width of high voltage winding HV

Therefore, the distance between windings δ will be:

$$\delta = \frac{u_x \cdot E_1^2 \cdot h}{0.414 \cdot P \cdot D_{sr}} - \frac{a+b}{3} \tag{2}$$

Because the values P, E_1, and u_x are constant it comes out:

$$\delta = k\frac{h}{D_{sr}} - \frac{a+b}{3} \tag{3}$$

Where:

$$k = \frac{u_x \cdot E_1^2}{0.414 \cdot P} \tag{4}$$

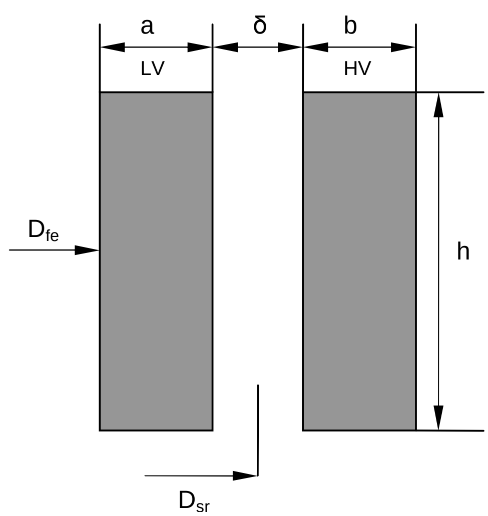

Figure 1 - Cross-section of high and low voltage windings

As shown in figure 1 $a \cdot b = S_{LV}$ and $b \cdot h = S_{HV}$ are axial cross sections of high and low voltage windings. Geometrical shapes of cross sections are rectangular. The rectangulars are lengthened, because height of winding is much larger than winding width. Cross sections S_{LV} and S_{HV} depend on number of coils in LV and HV winding as well as on cross sections of conductors, therefore $S_{LV} = N_{LV} \cdot s_{CuLV}$ and $S_{HV} = N_{HV} \cdot s_{CuHV}$. Electromagnetic force is constant so the number of coils is constant, and because we are taking into consideration transformer of known power, cross sections of conductors are constant. Therefore, geometrical shape of conductor could be changed without changing cross section of winding. Now equation for δ can be written as follows:

$$\delta = k\frac{h}{D_{sr}} - \frac{S_{LV} + S_{HV}}{3h} \qquad (5)$$

Because $a = S_{LV}/h$, and $b = S_{HV}/h$. It is possible to introduce also constant:

$$k_1 = \frac{S_{LV} + S_{HV}}{3} \qquad (6)$$

So relation for δ becomes:

$$\delta = k\frac{h}{D_{sr}} - \frac{k_1}{h} \qquad (7)$$

This relation shows that if the distance between *LV* and *HV* winding is smaller, the height of windings is lower. Windings cross sections are constant, and their shape is lengthened rectangular, so the height of windings, *h*, will be changed in absolute value much more than windings widths *a* and *b* for the same cross section. This is valid if mean diameter D_{sr} is constant, so the necessity of taking into consideration diameter D_{sr} is obvious.

Value of mean diameter can be written as follows:

$$D_{sr} = \frac{2D_{Fe} + 3a + 3\delta + b}{2} \qquad (8)$$

Where D_{Fe} is diameter of circle for placement of magnetic core and this diameter is constant for exact electromechanical force. The value *δ* will decrease and values of *a* and *b* will increase. Total change in absolute value is small, so increase of diameter D_{sr} is also small. Relation u_x (1) has in denominator $E_1^2 \cdot h$, so if we decrease *h* much, we should increase E_1 so that the value of u_x remains constant. This is because constant value of u_x cannot be achieved only by changing the values of *a* and *b*. The increase of the electromechanical force [1] results in larger cross section of magnetic core leg, but also decreases number of coils in windings. Decrease of number of coils decreases mass of conductor, so current density in conductors can be increased and mass of conductor can be decreased. It should be noted that current density is limited by short circuit conditions JUS N.H1.015, both in case of copper and aluminum conductor.

Windings made of aluminum conductor

For determined transformer rating, active losses are defined by regulations, i.e. JUS, IEC and others, and are independent of material from which the windings are made.
Active losses, in windings made of copper conductor, can be calculated as follows:

$$P_{cu} = m_{cu} \cdot \Delta_{cu}^2 \cdot k_{cu} \qquad (9)$$

Where:

P_{cu} – Active losses
m_{cu} – Copper conductor mass
Δ_{cu} – 3,76 A/mm2 – Current density limited by short circuit conditions JUS N.H1.015 when windings are made of copper conductor and when impedance is 4%.

$k_{cu} = \frac{\rho_{cu75}}{\gamma_{cu}} = 2.42$ – Coefficient of losses for copper conductor

ρ_{cu75} = 0.0217 $\left[\frac{\Omega mm^2}{m}\right]$ Specific electric resistance at 75°C

γ_{cu} = 8.96 $\left[\frac{kg}{dm^3}\right]$ Specific mass

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So:

$$P_{cu} = m_{cu} \cdot 3.76^2 \cdot 2.42 \quad (10)$$

Also active losses in windings made by aluminum conductor:

$$P_{al} = m_{al} \cdot \Delta_{al}^2 \cdot k_{al}$$

Where:

P_{al} - active losses
m_{al} - aluminum conductor mass
Δ_{al} = 2,08 A/mm2 – current density limited by short circuit conditions JUS N.H1.015 when windings are made of aluminum conductor and when impedance is 4%.

$k_{al} = \frac{\rho_{al75}}{\gamma_{al}} = 12.6$ - Coefficient of losses for aluminum conductor

ρ_{al75} = 0.0303 $\left[\frac{\Omega mm^2}{m}\right]$ specific electric resistance at 75°C.

γ_{al} = 2.7 $\left[\frac{kg}{dm^3}\right]$ specific mass.

So:

$$P_{al} = m_{al} \cdot 2.08^2 \cdot 12.6 \quad (11)$$

It is possible to make relation between active losses in windings when they are made of copper and aluminum conductor.

$$\frac{P_{cu}}{P_{al}} = \frac{m_{cu} \cdot 3.76^2 \cdot 2.42}{m_{al} \cdot 2.08^2 \cdot 12.6} \quad (12)$$

Because $P_{cu} = P_{al}$, ratio between masses of copper and aluminum conductor will be:

$$m_{al} = 0.627 m_{cu} \quad (13)$$

It is possible to determine ratio of volumes of copper and aluminum conductors, as ratio of specific masses is:

$$\frac{\gamma_{cu}}{\gamma_{al}} = \frac{8.96}{2.7} = 3.318 \quad (14)$$

So:

$$V_{al} = 0.627 \cdot 3.318\, V_{cu}$$
$$V_{al} = 2.08\, V_{cu} \quad (15)$$

Aluminum conductor volume is larger. So the dimensions of magnetic core window will be larger causing the bigger core mass. Influence of bigger core mass on transformer price is approximately in proportion with decrease of price of winding made of aluminum conductor. This is the reason why manufacturers have no interest, in respect to the price of material, to make transformers with windings made of aluminum conductor. Overall dimensions of transformer can remain unchanged, although there are differences in dimensions, which can be corrected by changing dimensions of coolers. Coolers maintain total surface necessary for taking away thermal energy, but it is possible to decrease rib depth on corrugated tank by decreasing number of ribs, est.

Lower mass of magnetic core

This variant is achieved by decreasing up to 50% theoretical electromechanical force [1] per coil of winding. Lower electromechanical force decreases cross section of magnetic core, as given in relation:

$$E_1 = 222 \cdot B_m \cdot S_{Fe} \cdot 10^{-4} \quad (16)$$

Where:

E_1 – Electromechanical force per coil
B_m = 1,7 T – Density of magnet induction when material of magnetic core is well used
S_{Fe} – Magnetic core cross section

Magnetic core mass is decreased due to smaller cross section. However, lower electromechanical force increases the number of coils in windings made of aluminum conductor. Increased number of coils corresponds to larger magnetic core window, through which windings are passing. Larger window increases mass of magnetic core, so the effect reached by smaller magnetic core cross section is a bit decreased. On the other hand, there is increase in mass of aluminum conductor for two reasons. The first is increase of number of windings on the coil and the second is decrease of aluminum conductor cross section due to decrease of current density in conductor in order to achieve guaranteed losses.

Geometrical shape of transformer is changed. Due to lower electromechanical force, windings are higher, mean diameter D_{sr} is smaller and widths of windings *a* and *b*, are smaller, in order to achieve guaranteed value of impedance. Value δ, relation 2, is defined in accordance to its influence on magnetic core mass and with technical solution for exact voltage level. The result is significantly lower magnetic core mass, so with magnetic flux density of 1,7T smaller active energy losses than guaranteed, can be achieved. Aluminum conductor mass is approximately equal to the mass of copper conductor, but the price of aluminum is much lower. The transformer is much higher.

Conclusion

Economic factor and possibility of further development are most important for evaluation of presented concept about distribution transformer with windings made of aluminum. For users this transformer is better than transformer with copper windings, because it has better efficiency, i.e. lower losses of active energy in magnetic core. For manufacturers it is more favorable due to lower prices of materials.

There is no answer, here, how much larger height (up to 15%) will be a problem, particularly if there is need for replacement of transformer.

Development of Distribution Network is in direction of reduction of energy losses, so there is need for transformers with considerably lower losses of active energy. For comparison, transformer rated 630kVA, per JUS recommendation, has the losses of active energy, in magnetic core 1300W +15%, and in windings 6500W +15%. However, there are Distribution Networks who are asking for transformers with losses in magnetic core 540W and in the windings 5250W. The selling price of transformers with lower losses is higher, and there is capitalization formula in order to examine economy of exploitation. Calculations show that transformers with windings made of aluminum wire will have lower cost of materials even with these characteristics. It comes out that for economy reasons use of transformers with windings made of aluminum conductors should be permitted by EPS regulations.

Key Words

Transformer, winding, conductor, copper, aluminum, price

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