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Weight Comparison of Oil and Dry Type Distribution Transformers

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Abstract**—**Reducing the weight of transformers while providing good performance, cost reduction and increased efficiency is important. Weight is one of the most significant factors in all electrical machines, and as such, many transformer design parameters are related to weight calculations. This study presents a comparison of the weight of oil type transformers and dry type transformer weight. Oil type transformers are mainly used in industry; however, dry type transformers are becoming more widespread in recent years. MATLAB is typically used for designing transformers and design parameters (rated voltages, core loss, etc.) along with design in ANSYS Maxwell. Similar to other studies, this study presented that the dry type transformer option is limited. Moreover, the commonly-used 50 kVA distribution transformers in the industry are oil type and dry type transformers are designed and considered in terms of weight. Currently, the preference for low-cost oil-type transformers would change if costs for dry-type transformer were more competitive. The aim of this study was to compare the weight of transformers, which is a substantial cost factor, and to provide an evaluation about increasing the use of dry type transformers.

Keywords**—**Weight, oil-type transformers, dry-type transformers.

I. Introduction

ELECTRICAL energy is the most consumed energy type in the world [1]. Electric energy generation, transmission, distribution and consumption processes are typically done through electrical machinery called transformers. Regardless of where they are used, they are always the same in terms of principle and generally, they are formed from two windings isolated against each other and the soil. These windings are upon iron core [2]. Most of the energy applied to the inputs of transformers transmits as electrical energy without changing the nature of the electricity. For this reason, energy conversion does not occur like in other electrical machinery, and only in the transformers structure, where a small amount of energy is changed and converted into heat energy [3].

When designing transformers, losses are first calculated in the weight calculation due to the apparent power. As in all electrical machines, power loss also occurs in transformers. The most important difference in transformers from other electrical machines is that they do not have moving parts and so there are no wind and frictional losses. As such, losses are less and productivity is high [2]. The power losses in transformers come in two forms:

- Iron Loss
- Copper Loss

Iron losses in transformers consist of eddy and hysteresis losses. Eddy losses are the losses caused by eddy currents induced on the transformer core. Hysteresis losses emerge in the form of heat as a result of the friction of molecules with each other during the change in direction of eddy molecules depending on the transformer eddy currents [4]. Copper losses occur on the windings of a transformer core.

II. Losses, Efficiency and Weight Calculation in Transformer

The calculation of weight using basic mathematical methods is described in [2]. In order to make weight calculations, iron and copper losses in transformers are obtained by using the characteristics given in Figs. 1 and 2.

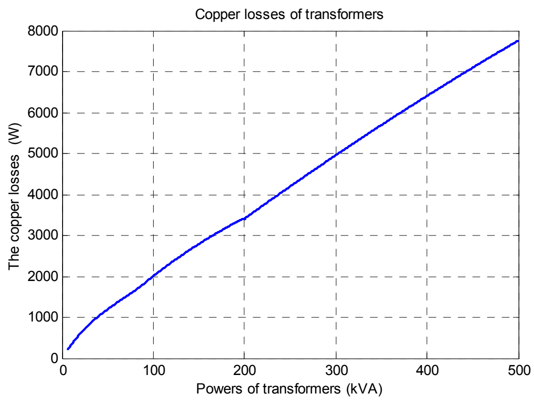

Fig. 1 Copper loss depending on apparent transformer power [3]

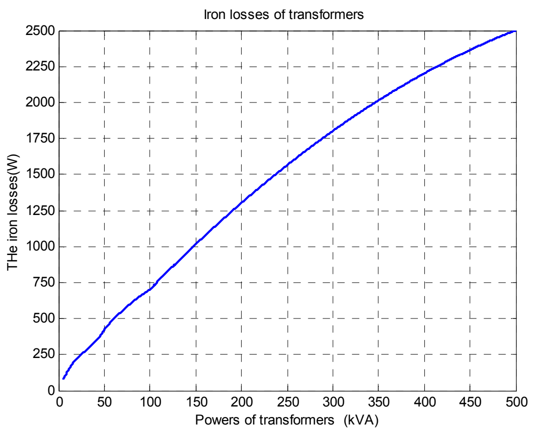

Fig. 2 Iron losses depending on apparent transformer power [3]

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Iron loss P_{fe} and copper loss P_{cu} are obtained from Figs. 1 and 2 according to the apparent power of transformers and apparent power S:

$$S = \sqrt{3} * U * I \text{ (VA)} \tag{1}$$

$$\xi = \frac{P_{cu}}{P_{fe}} \tag{2}$$

ξ is obtained as loss rate. After this, specific copper loss

$$p_{cu} = 2.7s^2 \text{ (Watt / kg)} \tag{3}$$

is obtained. Here, the current density value is s, 2.2< s <3.5 [5]. Specific copper loss is:

$$p_{fe} = p_{10}\xi_2 \left(\frac{B}{10^4}\right)^2 \text{(Watt / kg)} \tag{4}$$

And here, p_{10}; loss factor, ξ_2; additional loss factor occurs as a result of the processing of sheets, *B* is core induction in transformers (Tesla). One of the important calculations in transformer design includes the iron section. The iron section is obtained by [3]:

$$q_{fe} = C\sqrt{\frac{10^3 S}{3f}} \text{ (cm}^2\text{)} \tag{5}$$

Here, q_{fe}, iron section (cm^2), *f, frequency*. *C* is a transformer iron section suitability factor.

The C value is 4<C<6 for oil transformers [6] and 5.9<C<10.6 for dry type transformers [3]. C and s values are fixed values in design. The yoke leg section q_{fej} must be 20% more than the leg section,

$$q_{fej} = q_{fe}.1{,}2 \text{ (cm}^2\text{)} \tag{6}$$

Primary and secondary winding sections q_1, q_2 and the number of turns w_1, w_2, and average winding length are shown in L_{m1}, L_{m2} (7)-(13):

$$q_1 = \frac{I_1}{s} \text{ (mm}^2\text{)} \tag{7}$$

$$q_2 = \frac{I_2}{s} \text{ (mm}^2\text{)} \tag{8}$$

$$w_1 = \frac{U_1}{\sqrt{3}.4{,}44.f.\emptyset.10^{-8}} \tag{9}$$

$$w_2 = \frac{U_2}{\sqrt{3}.4{,}44.f.\emptyset.10^{-8}} \tag{10}$$

$$L_{m1} = \pi.D_{m1} \quad \text{(cm)} \tag{11}$$

$$L_{m2} = \pi.D_{m2} \quad \text{(cm)} \tag{12}$$

$$D_{m2}=D+2(\Delta_2+\delta_2)+\alpha_2 \tag{13}$$

$$D_{m1}=D_{m2}+\alpha_2+2(\Delta_1+\delta_1)+\alpha_1 \tag{14}$$

Here, D_{m1} and D_{m2} are respectively the average primary winding and average secondary winding diameters. Δ_1, δ_1 (cm) are respectively the primary insulating cylinder thickness and oil channel width Δ_2, δ_2 (cm) secondary cylinder thickness and if oil channel width and α_1, α_2, primary and secondary voltage are winding channels

Magnetic flux occurred in the windings ϕ,

$$\phi = q_{fe}.B \text{ (Maxwell)} \tag{15}$$

The diameter of the iron core is obtained as:

$$D = \sqrt{\frac{4q_{fe}}{0.677\pi}} \text{ (cm)} \tag{16}$$

With the values obtained here, the total weight of transformer G_T is equal to the total of iron weight G_{fe} and copper weight G_{cu}:

$$G_T=G_{cu}+G_{fe} \text{ (kg)} \tag{17}$$

Copper weight is the total of the primary winding copper weight G_{cu1} and secondary winding copper weights G_{cu2}. This is also expressed as:

$$G_{cu}= G_{cu1}+ G_{cu2} \text{ (kg)} \tag{18}$$

Iron weight is equal to the total of the weights in three legs G_{feb} and yoke weight G_{fej}:

$$G_{fe}= G_{feb}+ G_{fej} \text{ (kg)} \tag{19}$$

From here:

$$G_{cu1}=3.10\text{-}5 *\delta_{cu}*w_1*q_1*Lm_1 \tag{20}$$

$$G_{cu2}=3.10\text{-}5 *\delta_{cu}*w_2*q_2*Lm_2 \tag{21}$$

$$G_{feb}=3.10\text{-}3 *\delta_{fe}*q_{fe}*L_s \tag{22}$$

$$G_{fej}=3.10\text{-}3 * \delta_{fe}*q_{fej}.2\,(2M+0{,}8D) \tag{23}$$

The δ_{cu}, δ_{fe} values are respectively copper and iron specific weight.

The length between the axis of the legs is M, the width of the window is a , and the height of window L_s a are found by:

$$M = 0.851D + a \text{ (cm)} \tag{24}$$

$$L_s = \frac{2w_1 I_1}{A_s} \text{ (cm)} \tag{25}$$

$$a = \frac{4w_1\, q_1}{100k_{cu}\, L_s} \text{ (cm)} \tag{26}$$

Here k_{cu} is a window copper filling factor. This value is obtained in Fig. 4 As (A/cm) is specific ampere turn.

The efficiency of a transformer is:

$$\eta = \frac{S}{S+P_k} \tag{27}$$

Here P_k total copper, P_{cu} and total iron losses express P_{fe} [8].

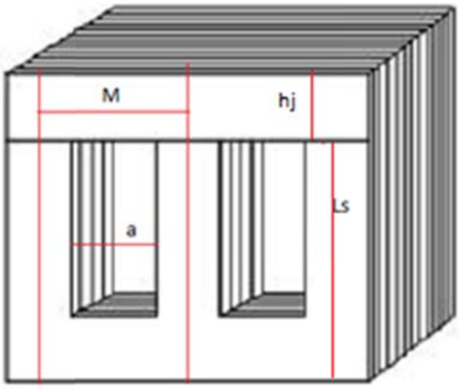


Fig. 3 Transformer iron body dimensions [7]

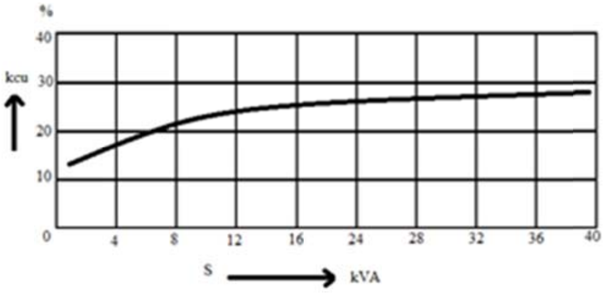
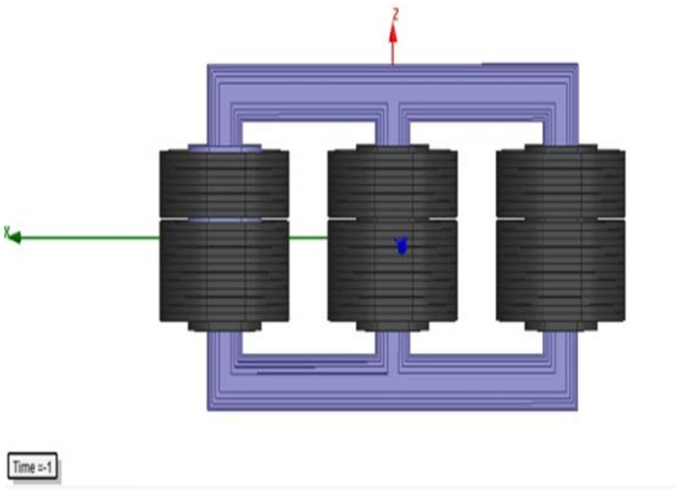


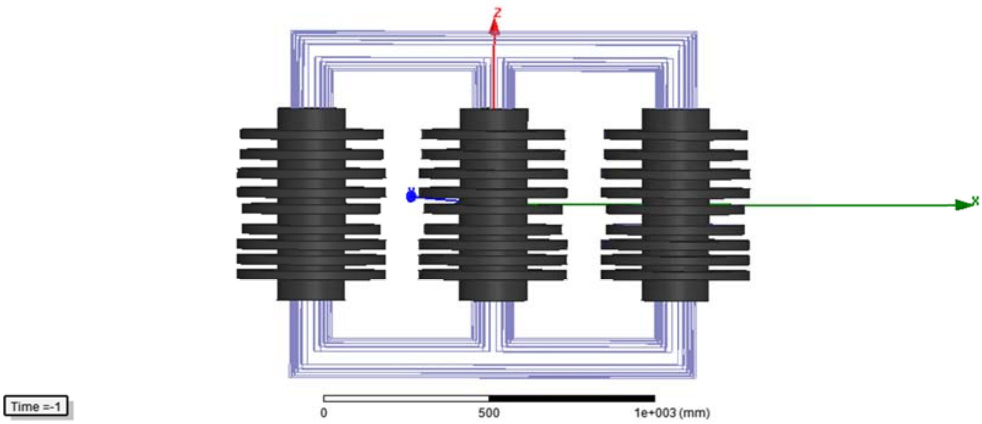
Fig. 4 Windows Cooper filling factor [2]

III. Weight Values of Transformers and Evaluation

Fig. 5 shows an oil type and dry type transformer where the ANSYS Maxwell schemes are given. ANSYS Maxwell analysis indicates the difference between the weights of the transformers. Core loss of transformers schemes are given in Maxwell. One of the important parameter of weight calculation is core loss of transformers which are shown in Fig. 6.

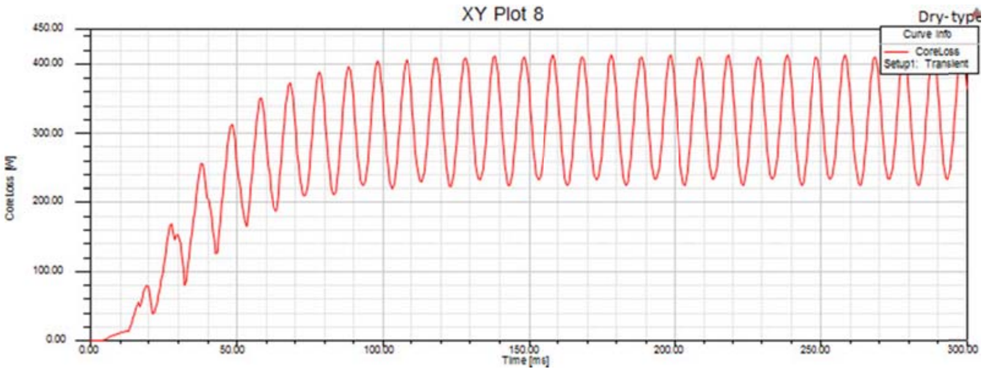


(a)

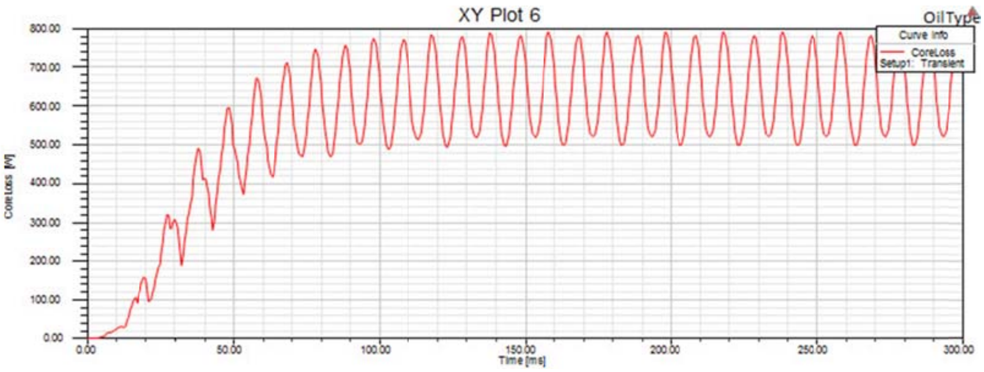


(b)

Fig. 5 (a) Oil Type Transformer (b) Dry Type Transformer



(a)



(b)

Fig. 6 (a) Dry Type, (b) Oil Type Core loss Schemes

TABLE I
THE COMPARISON OF THE PARAMETERS HAVING AN EFFECT IN THE WEIGHT

Variables	Symbol	Unit	Oil type	Dry type	Percentage Change (%)
Iron Section Convenience Factor	C	cm^2*$joule^{-1/2}$	4	4	0
Transformer core diameter	D	cm	159.468	16.8	0,87
Iron section	q_{fe}	cm^2	135.216	137.52	1,7
Efficiency	η	%	95.3	97.4	2,2
Height of the window	L_s	mm	265.44	296.26	11,61
Yoke weight of the transformer	G_{fej}	kg	108.05	92.88	14,03
Secondary winding turn number	w_2	turn	35	40	14,28
Primary winding turn number	w_1	turn	5137	5930	15,43
Current density	s	A/mm^2	3	2	33,33
Transformer three leg weight	G_{feb}	kg	81.83	110.91	35,53
Primary winding section	q_1	mm2	0.1610	0.2465	50
Secondary winding section	q_2	mm2	240.563	360.844	50,02
Total Weight	G_T	kg	217.37	397.01	82,64
Primary winding copper weight	G_{cu1}	kg	15.12	45.88	203,44
Secondary winding copper weight	G_{cu2}	kg	12.35	42.44	243,64
Width of the window	a	cm	83.10	55.862	32,77

As it can be seen in Table I, the effect percentages of the parameters influencing the weight calculations of oil type and dry type transformers are evaluated in the second part. The effectiveness of the parameters influencing weight varies according to the transformer cooling type. Here:

- The *s* current density gets different values depending on the cooling type. This value is between 1.7 and 2 in air-cooled transformers and is between 2.2 and 3.5 in self-cooling oil-type transformers. An increase in this value affects winding cross sections in copper weights.
- L_s window height is determined by obtaining the A_s specific ampere turn in the transformers. According to Table II, A_s increases as power increases in air-cooled transformers.
- The *a* window width values increases depending on the cooling type of the transformer. Window width increases

because of the cooling air channels coming between the windings. An increase in a is effective as it changes radius values in the calculation of iron weight. In (22) and (23), L_s increases, iron leg weight and a increase, and iron yoke weight increases.

- The windings are selected by high mechanical strength and high cooling options. If transformer power and q_1 increases, primary winding cooling, strength options and copper weight increase.
- Further, when q_2 increases, secondary winding copper weight increases. The windings of dry type have excess turns than windings of oil type transformers.
- Finding w_1, w_2 winding turn significantly changes window width a value and copper weights. Due to the cooling options of dry-type transformers, dry type transformer winding turns are more than those of oil type. If w_1, w_2 increase, primary and secondary weights increase.

TABLE II
AS VALUES (FOR AIR COOLING CORE TYPE TRANSFORMERS) [2]

S (KVA)	0,5	1	2	4	8	10	15	20	25	30
A_s (A/cm)	80	90	100	110	123	127	135	142	147	150

TABLE III
OTHER PARAMETERS USED IN THE DESIGN OF TRANSFORMERS

Variables	Symbol	Unit	Oil type	Dry type	Percentage Change (%)
First winding voltage	U_1	Volt	34500	34500	0
Second winding voltage	U_2	Volt	400	400	0
First winding insulation thickness	Δ_1	cm	2.2	2.2	0
Oil channel width	δ_1	cm	0.1	-	0
Loss factor	p_{10}	-	1.3	1.3	0
Additional losses as a result of processing of the sheets	ξ_2	-	2.2	2.2	0
Temperature	T	^{0}C	75	75	0
Oil channel width	δ_2	cm	0.1	-	0
Specific ampere winding	A_s	A/cm	186.98	162	13.36
Flux density	B	Gauss	12917	11000	14,84
Window copper filling factor	k_{cu}	-	0.15	0.29	93,33
Second winding insulation thickness	Δ_2	cm	1.06	11.24	960,37

Table III shows other parameter values that need to be calculated as they affect the weights of oil-type [5] and dry-type transformers. These parameters reflect transformers power, cooling and strength:

- Δ_1, δ_1 and Δ_2, δ_2 change respectively as directly proportional in primary winding insulation oil channel width and secondary winding insulating thickness and oil channel width in the calculation of winding diameters in transformers. There is an oil channel in the oil-type, but not in dry-type. Insulation thickness is wider in dry-type secondary winding. This effect of thickness indicates in the parameters increasing the weights.
- Δ_1, δ_1 and Δ_2, δ_2 change respectively as directly proportional in primary winding insulation oil channel width and secondary winding insulating thickness and oil channel width in the calculation of winding diameters in transformers. There is an oil channel in the oil-type, but not in dry-type. Insulation thickness is wider in dry-type secondary winding. This indicates the effect of it in the parameters increasing the weights.
- A_s specific ampere winding is high in oil-type and low in dry-type. If A_s increases, L_s decreases, so this reduces iron leg weight.
- B flux density affects magnetic flux. This affects w_1, w_2 winding number values in an inversely proportional way. The oil-type winding number is lower than the dry-type winding number, and from here, the oil-type B value is higher compared to the dry-type winding number.
- k_{cu} filling factor affects the a window in an inversely proportional way. If k_{cu} increases, the a value reduces, and this reduces iron yoke weight. In an oil-type transformer, this value is lower than a dry-type transformer.

IV. CONCLUSIONS

This study compared the weights of oil-type transformers and dry-type transformers. In this comparison, weight effect was investigated to increase the use of dry-type transformers instead of oil-type transformers, which are frequently used in distribution transformers. The average lifespan of transformers is reported to be 7.42 to 20.55 years in relevant standards (IEC C57.91-1995). Previous studies also show that oil-type transformers and dry-type transformers have similar costs throughout their lifespan. Although the costs of these transformers are almost the same, oil-type transformers are more disadvantageous than dry-type transformers. Oil type transformers require regular maintenance leading to environmental pollution because of oil waste, and pose a fire hazard. Currently, however, dry-type transformers are not preferred due to their high costs. As weight is also a determinant factor influential on cost, parameters that may bring about a decrease in weight should be investigated and considered in future studies.

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