Method Of Determining The Most Economical Transformer

Jovce Doneski[1] and Nikolce Acevski[2]

Abstract - **Whenever offers are received from several manufacturers it is essential to compare the efficiency of the transformers as well as their technical features, their quality and their reliability. The efficiency of a transformer is measured in terms of its purchase price and the cost of losses occurring during operation.**

Key words - **No-load loss, load loss, transformer loss evaluation.**

1. INTRODUCTION

To permit the manufacturer of design the most economical transformer for his customer's needs, the latter must provide the data required for calculating efficiency. With this data, the manufacturer can determine and offer the transformer with the lowest overall costs during its expected service life.

2. TECHNICAL APPRAISAL

Most of the characteristics of industrial transformers are specified in national or international product standards for distribution transformers. The application of standards can be legally required, or by specific reference in the purchase contract.

For distribution transformers purchased in the European Union, three levels of standards are applicable:

- World-wide standards (IEC, ISO)
- European standards and regulations (EN, HD)
- National standards (e.g. DIN, BSI, NBN, NF)

European Harmonisation Documents (HD) are initiated if there is a need for a European standard. The draft HD is a compilation of the different national standards on the subject. The HD is finalized by eliminating as many national differences as possible. Usually, the HD is the predecessor of an European standard (EN), which must be adopted as a national standard in the EU member countries. Thus, purchase orders which refer to national standards (EN) are compatible with European standards (EN) and/or harmonisation documents (HD). Among the many international standards for distribution transformers, two main European Harmonisation Documents specify energy efficiency levels:

- HD 428: Three phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV;
- HD 538: Three phase dry-type distribution transformers 50 Hz, from 100 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV.

Table 2 gives the limits for load losses fore some important types of oil-immersed and dry-type distribution transformers according to HD 428.1 and HD 538.1 for the preferred rated power range of the transformers. For oil-filled distribution transformers, the HD allows a choice of energy efficiency levels, A, B and C. The no-load losses (iron losses) for the same range of transformers are given below. For oil-filled transformers, the HD offers a choice between three efficiency levels, A', B' and C'.

HD 428 therefore allows customers to choose between three levels of no-load losses and three levels of load losses. In principle, there are a total of 9 possible combinations, ranging from the lowest efficiency, (B-A'), to the highest, (C-C'), which may be regarded as providing a high practical standard of energy efficiency for a distribution transformer. There appears to be a "league table" of national standards for distribution transformer losses specified by the electricity utilities of various European countries. Switzerland and Scandinavian countries are said to set the highest standards, with France and Italy amongst the lowest (A-A'). Others are somewhere in the middle.

Table 1. League table for distribution transformer efficiency levels in Europe

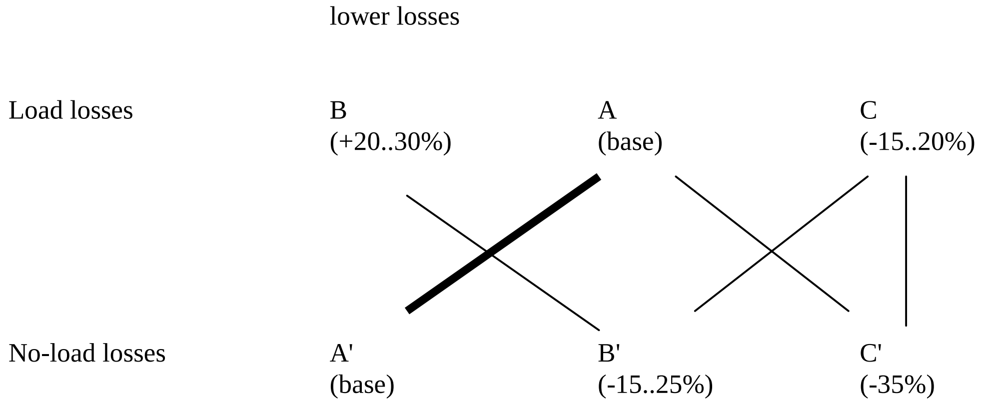
Country	Utility Distribution Transformer Loss Levels
Belgium	C-C'
France	A-A' and B-B'
Germany	A-C' and B-A' and C-C'
Italy	B-C'
Netherlands	Better than C-C'
Spain	50% meet C-C'
UK	Uses capitalization values

[1] Jovce Doneski is with the EMO OHRID Transformer Factory,
P.O. BOX 118, 6000 Ohrid, Macedonia,
E-mail: djovce@yahoo.com
[2] Nikolce Acevski is with Faculty of Technical Sciences,
I. L. Ribar bb, 7000 Bitola, Macedonia,
E-mail: nikola.acevski@mofk.gov.mk

Table 2 Distribution transformer loss standards

	Load Losses for Distribution Transformers				No-Load Losses for Distribution Transformers			
RATED POWER	OIL-FILLED (HD 428) UP TO 24kV			DRY TYPE (HD 538)	OIL-FILLED (HD 428) UP TO 24kV			DRY TYPE (HD538)
	LIST A	LIST B	LIST C	12kV PRIMARY	LIST A’	LIST B’	LIST C’	12kV PRIMARY
kVA	W	W	W	W	W	W	W	W
50	1100	1350	875	N/A	190	145	125	N/A
100	1750	2150	1475	2000	320	260	210	440
160	2350	3100	2000	2700	460	375	300	610
250	3250	4200	2750	3500	650	530	425	820
400	4600	6000	3850	4900	930	750	610	1150
630 (4%)	6500	8400	5400	7300	1300	1030	860	1500
630 (6%)	6750	8700	5600	7600	1200	940	800	1370
1000	10500	13000	9500	10000	1700	1400	1100	2000
1600	17000	20000	14000	14000	2600	2200	1700	2800
2500	26500	32000	22000	21000	3800	3200	2500	4300

Table 3



HD 428 defines five preferred combinations of these losses. These combinations are shown in Table 3 where the combination A-A' is chosen as the base case (shown as a bold line - the percentages refer to this combination).

3. DETERMIMING OVERALL COSTS

Overall costs are normally calculated for a one-year period. Consequently, allowance will have to be made for any changes in operating conditions likely to occur during the expected service life of the transformer.

Overall costs can be broken down as follows:

- Capital cost
- Cost of no-load losses
- Cost of short-circuit losses

Any transformer maintenance costs should be included with those of the installation as a whole, so that they will not be included in the present calculations.

3.1. Capital cost K_A

The following formula is used to calculate capital cost:

$$K_A = \frac{A \cdot r}{100} \text{ [Euro p.a.]} \qquad (1)$$

where A is the purchase price of the transformer in Euro and r the redemption factor in % p.a.

The redemption factor r is calculated with the formula:

$$r = \frac{p \cdot q^n}{q^n - 1} \qquad (2)$$

where p - interest rate (% p.a.), $q = 1 + \frac{p}{100}$ - interest factor, n - the depreciation period in years.

The redemption factor r will therefore depend on the interest rate and the depreciation period. The capital cost K_A is therefore equal to the annual amounts required to repay capital A borrowed at an interest rate of p% for a period of n years.

3.2. Cost of no-load loss C_{P0}

No-load losses will give rise to costs throughout the transformer's entire operating life. The annual cost of no-load losses is calculated as follows:

$$K_{P_0} = (k_L + k_a \cdot T_B) \cdot P_0 \ \text{[Euro p.a.]} \qquad (3)$$

where

k_L - cost of power in Euro/kW p.a.;
k_a - energy costs in Euro/kWh;
T_B - operating time in hours p.a. (8760 hours maximum);
P_0 - no-load losses in Kw.

The power costs k_L include the cost of providing electric power (capital and operating costs of the installation) and the costs of power used. These are known to the customer, e.g. from the power supply contarct.

3.3. Cost of short-circuit losses K_{Pk}

The costs incurred through short-circuit losses are somewhat more difficult to calculate since they are in proportion to power squared, and the transformer is subject to wide load fluctuations in the course of a year. Instead of making a curve of the actual load as it occurs in the course of one year, which is quite irregular, the operating times at the various particular power levels are added together (power=ordinate, operating time=abscissa) and shown in an adjusted annual load curve.

At this point it is necessary to introduce some new terms.

The utilization period for the year, T_m, is the period of time during which the transformer would have had to be operated at full load P_{max} (active component corresponding to the adjusted annual load curve) in order to generate the same amount of energy in the year A_W (active component) as it did with the variable load).

The ratio $\frac{T_m}{T_B}$ is the load factor m.

$$m = \frac{T_m}{T_B}; \ m = \frac{A_W}{T_{max.} \cdot T_B} \quad \text{from which it follows}$$

$$T_m = \frac{A_W}{P_{max.}} \ [\text{hours p.a.}] \qquad (4)$$

A_W - year's energy [kWh p.a.];
$P_{max.}$ - peak value of the adjusted annual load curve [kW].

This value $P_{max.}$ [kW] from the adjusted annual load curve is to be converted into $S_{max.}$ [kVA] for the following calculation of the cost of short-circuit losses.

Peak value of the adjusted annual load curve [kVA]

$$S_{max.} = \frac{P_{max.} \ [kW]}{\cos \varphi_{max.}}. \qquad (5)$$

Here is the essential to know the value of $\cos \varphi$ at peak load $P_{max.}$.

In many publications, the energy loss factor δ is also introduced to calculate the short-circuit losses more accurately. The energy loss factor δ is a function of the load factor m. For the calculation of the cost of short-circuit losses performed here it certainly suffices to assume that δ is the same as m^2, and than use m^2 instead of δ in calculations. If other influencing factors are introduced, e.g. the inclusion of the tolerances of the stated losses or of the figure for peak load in the adjusted annual load curve $S_{max.}$, this results in deviations which are greater than the inaccuracy of results obtained by the present simplified form of calculation.

The ratio $\frac{S_{max.} \ [kVA]}{S_N \ [kVA]}$ is designated the relative peak load h_r. The short-circuit losses P_k [kW] is proportional to the square of this ration, which can vary considerably from transformer to transformer (distribution transformer, network transformer, generator transformer) and will also depend on the conditions under which the transformer operates. The figure may also vary quite considerably in the course of years of operation, especially in the case of distribution transformers. When purchased, a transformer may have a very low figure for h_r, e.g. 0.5, and by the end of its service life, it may even rise above 1, depending on the type of use.

If the above mentioned figures are known, the cost of annual short-circuit losses may be calculated according to the formula given below:

$$K_{P_k} = (k_L + k_a \cdot m^2 \cdot T_B) \cdot h_r^2 \cdot P_k \ [\text{Euro p.a.}] \qquad (6)$$

The influence of the overlapping factor is ignored here.

Result: The sum total of costs incurred during one year (capital cost K_A cost of no-load losses K_{P0} and short-circuit losses K_{Pk}) are lowest for the most economical transformer. For the sake of completeness, however, it should be pointed out that overall costs should also include the cost of magnetizing reactive power and auxiliary features (cooling installations).

4. THE CAPITALIZATION OF THE COSTS

The convenient method of determining the most economical transformer is used when figures are available for no-load and short-circuit losses. Calculations are again based on annual overall costs.

The annual no-load loss costs K_{P_0} are divided by P_0, the annual short-circuit loss costs are divided by P_k. This yields the annual costs of no-load losses and short-circuit losses per kW, as shown in the formulae below:

$$b_{P_0} = \frac{K_{P_0}}{P_0} = k_L + k_a \cdot T_B \; [\text{Euro/kW p.a.}] \qquad (7)$$

$$b_{P_k} = \frac{K_{P_k}}{P_k} = (k_L + k_a \cdot m^2 \cdot T_B) \cdot h_r^2 \; [\text{Euro/kW p.a.}] \qquad (8)$$

These annual loss costs per kW [P_0 and P_k] are now multiplied by the factor $\frac{100}{r}$. This yields the capitalized value of the annual cost of losses per kW P_0 and P_k for the transformer at date of purchase. Below are given the values applied by the operator for no-load and short-circuit losses:

$$B_{P_0} = b_{P_0} \cdot \frac{100}{r} \; [\text{Euro/kW}] \qquad (9)$$

$$B_{P_k} = b_{P_k} \cdot \frac{100}{r} \; [\text{Euro/kW}] \qquad (10)$$

A direct comparison with the purchase price A of the transformer is now possible since the annual costs of losses were capitalized by multiplication with the factor $\frac{100}{r}$.

The capitalized price for comparison is obtained by adding the transformer's purchase price A, the assessment of the no-load losses · value of no-load losses and assessment of the short-circuit losses · value of short-circuit losses, as follows:

$$K_{VG} = A + B_{P_0} \cdot P_0 + B_{P_k} \cdot P_k \; [\text{Euro}].$$

Example: Distribution transformer 630 kVA, 10/0.4 kV

	Type 1	Type 2
P_0 [kW]	1.3	0.86
P_k [kW]	6.5	5.4
A [Euro]	6175	8160
$B_{P_0} \cdot P_0$ [Euro]	3900	2580
$B_{P_k} \cdot P_k$ [Euro]	9750	8100
K_{VG} [Euro]	19825	**18840**

(Note: $B_{P_0} = 3 \frac{\text{Euro}}{\text{kW}}$; $B_{P_k} = 1.5 \frac{\text{Euro}}{\text{kW}}$)

5. CONCLUSION

The most economical transformer is the one with the lowest total.

$$\begin{pmatrix} \text{Purchase prise} \\ + \\ \text{capitalised cost} \\ \text{of losses} \end{pmatrix}_{\min} = \text{the most economical transformer}$$

Once the transformer manufacturer has assessed the cost of losses, it will possible for him to design the transformer with optimal losses. The other advantage of this method of determining capital value lies in the fact that valuation data does not lead to the disclosure of information relating to the operator's own internal calculations. This method is therefore often given preference over other methods which require records to be kept of the actual annual costs incurred.

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