Analysis of the effect of characteristic parameters of a distribution transformer on economic management of electric power transmission in low-voltage networks

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The paper presents an attempt of mathematical description of the effect of, among others, such parameters of modern energetic transformers as magnetizing current or power loss in the core on the power loss and reactive power, in case of power transmission in the distribution networks, particularly of low-voltage.

1. Introduction

The Law of April 15, 2011, on "Energetic effectiveness" defines the goals in the range of economic energy management. The Law recommends, among others, auditing the energetic effectiveness of various objects, with a view to make efforts aimed at energy saving. The energy should be saved, among others, in result of purchasing and exchanging of a new device or its modernization, in case it meets no requirements related to energy saving. In order to improve the energy effectiveness the Law specifies, among others, such undertakings as delimiting the reactive power flux, delimiting the network losses in linear wireways and transformer power loss. New kinds of transformer sheets designed for power transformers are directly conducive not only to reduction of power loss in transformer core but to significant reduction of the magnetizing current (the no-load current) or reactive power input under transformer no-load condition. Unfortunately, the winding power loss, i.e. a so-called full-load loss, cannot be reduced in practice. The energetic transformers, particularly the ones provided with adjusted number of the winding turns under voltage-free condition, belong to technical objects of the highest durability and reliability. Therefore, they are exchanged for new ones of improved operational parameters only rarely. High durability of the transformers, significantly exceeding 30 years that is assumed at the designing stage, does not encourage to replace them with new transformers of more advantageous parameters ensuring electric energy savings. Desistance from exchanging the transformers is justified by the lack of financial means and low supply on the market. Even a new standard "Standardized voltages IEC" introduced in 1999 did not speed up the process of exchanging of the transformers, in spite of the fact that the network rated voltage has been changed from 220/380 V to 230/400 V. The change of rated voltage of the alternate current network forced the change in rated voltage of energetic transformers from 230/400 V to 242/420 V. Allowable voltage deviation amounting to ±10% defined by the standard appeared to be insufficient reason for exchanging the transformers of former values of rated voltages and former values of the parameters. The transformer manufacturers keep offering the units that do not meet the requirements of the binding standard. It should be noticed that the AC motors and generators designed for the generating sets are also manufactured inconsistently with the binding standard. In such a condition the requirements of the "Law of Energetic Effectiveness" are difficult to be implemented with regard to replacing the devices with the ones of lower energy consumption.

2. Basic relationships helpful in calculating the power loss and reactive power input

In case of the transformers one should discern the power loss in the core, called a loss in no-load state (ΔP_0), and the power loss in the winding, called a full-load loss ΔP_{obc}). The sum of these losses is decisive for the power loss in the transformer and, in consequence, for efficiency of the power transformation. The transformer efficiency is given by the formula (1):

$$\eta = \frac{S_n \cos\varphi}{S_n \cos\varphi + \Delta P_0 + \Delta P_{obc}} \tag{1}$$

where: $S_n\cos\varphi$ – is the output power (P_{od}), ΔP_0 represents the no-load loss, and ΔP_{obc} the full-load loss.

The value of the no-load state loss has a large significance for the transformer operation, since it lasts practically unchanged during the whole time when the transformer is connected to the source of supply. On the other hand, the full-load loss depends on the transformer load that is determined by the current intensity and the power factor. This loss depends on resistance of the winding which, in turn, depends on the winding temperature. Rated full-load loss is usually specified for the temperature +75°C. The full-load loss depends on the square of current intensity, i.e. ΔP_{obc} is proportional to I^2. In the transformers manufactured at present the no-load loss is small as compared to the full-load loss, e.g. of the range slightly exceeding twenty percent. The relatively small power losses of the transformers result in high efficiency, reaching usually 98-99 percent. The transformer efficiency is not reckoned among the rated parameters of a transformer, as it is not constant, since it depends on the transformer load with the active power. One can say that for the case of rated apparent power the transformer operational efficiency depends on the power load factor.

The maximum efficiency of a transformer may be determined according to the equation (2):

$$\eta_{max} = \frac{S_n \cos\varphi}{S_n \cos\varphi + 2\Delta P_0} \tag{2}$$

Nevertheless, practical significance of the maximum efficiency of a transformer is rather low, since the efficiency occurs at the load power remarkably below the rated power. Therefore, operation of the transformer charged with the power corresponding to its maximum efficiency is not justified economically. Value of this power may be calculated from the formula (3):

$$S = S_n \sqrt{\frac{\Delta P_0}{\Delta P_{obc}}} \tag{3}$$

Figure 1 depicts the effect of transformer no-load loss (ΔP_0) on the power value at which the maximum efficiency occurs. Should the no-load loss be equal to the full-load loss, the maximum efficiency would occur at the rated power.

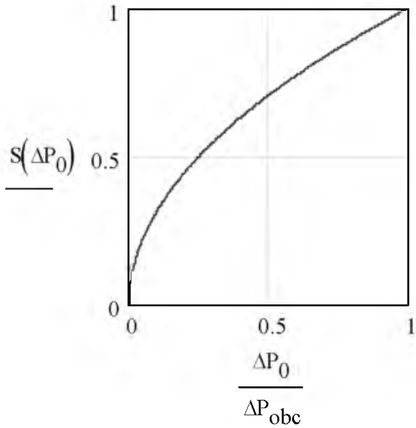

Fig. 1. The effect of no-load loss on the power value at which the maximum efficiency occurs

Since the transformer no-load loss is remarkably less than the full-load loss, the power corresponding to maximum efficiency is significantly lower as compared to the rated power, amounting even one half of the last. Taking into account very high efficiency of the transformers, its maximum value becomes unimportant. If the transformers should operate at the maximum efficiency, the energetic gain would be very small, but the number of the transformers should be doubled at least.

Figure 2 presents the effect of the no-load loss and power factor on the value of maximum efficiency.

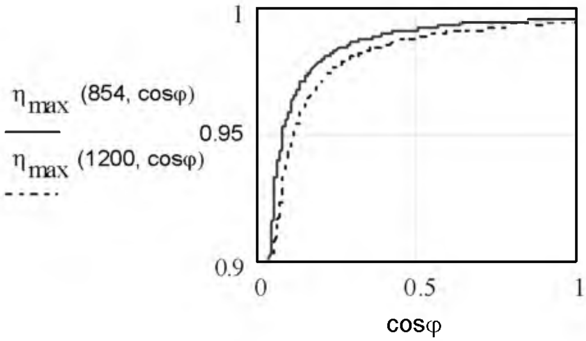

Fig. 2. Dependence of transformer maximum efficiency on the power factor for various values of the no-load loss

Economic features of transformer operation are illustrated by the following data. For example, the transformer of rated power S_n = 400 kVA, no-load state current I_0 = 1.02%, no-load loss P_0 = 854 W, full-load loss ΔP_{obc} = 3967 W, is charged with rated current for the power factor cosφ = 1. Its efficiency will be equal to η = 0.988. Maximum efficiency for the same value of the power factor is equal to 0.996. For cosφ = 0.8 the efficiency drops to 0.995, being still lower at cosφ = 0.7, when it takes the value of 0.983. For older types of transformers these values are still smaller, as the power loss in no-load state is higher. The full-load state loss at 75°C for the above mentioned transformer amounts to 4676 W. Calculation of the transformer efficiency at 75°C and cosφ = 1 gives η = 0.986. This value as smaller than the one calculated for the winding resistance at winding temperature 20°C. Maximum efficiency of this transformer occurs for the power load equal to 0.464 of the rated power.

Taking into account the maximum efficiency the reduction of no-load state loss is disadvantageous, as the higher the no-load state loss the lower the difference between the rated power and the power for which the maximum efficiency occurs. Nevertheless, in general the power loss should be reduced, without regard to maximum efficiency.

In three-phase circuits charged with active power P the current intensity I is calculated according to the relationship (4):

$$I = \frac{P}{\sqrt{3}U\cos\varphi} \tag{4}$$

where U is the phase-to-phase voltage and cosφ is the phase factor. The effect of phase factor on current intensity is shown in Fig. 3.

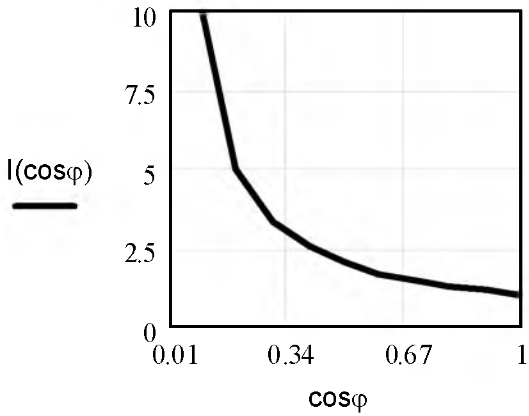

Fig. 3. Relationship between the current intensity and phase factor

The values shown in the figure are expressed in relative units, referred to current intensity at cosφ = 1. The figure gives evidence that for constant value of the active power the current intensity grows with decreasing phase factor, i.e. with the growth of the transmitted reactive power.

The power loss ΔP, among others occurring in the supply network, is calculated from the formula (5):

$$\Delta P = I^2 R \quad (5)$$

where R is for resistance of the part of the electric circuit for which the power loss caused by the current flow I is calculated. The power loss is usually calculated for the resistance value converted to the temperature of 75°C.

The voltage drop at the transformer supplying line and at the transformer itself may be calculated with a similarly simple formula. The voltage drop is determined from the equation (6):

$$\Delta U = I(R\cos\varphi \pm X\sin\varphi) \quad (6)$$

According to the circuit part, for which the voltage drop is calculated, R is for resistance of the line segment or resistance of the transformer winding. Similarly, the reactance X represents inductance either of the line or of the transformer winding.

It is easy to notice that any growth of intensity of the current reaching the transformer is conducive to the increase of power loss in the supplying line. Therefore, the binding regulations require the electric energy customers to absorb possibly low reactive power, i.e. to obey the principle of not exceeding tanφ ≤ 0.4 or to keep cosφ above 0.928, particularly in case of a low-voltage network.

3. Example results of calculation of the reactive power loss, power loss and voltage drop

The value of reactive power absorbed by a transformer, called the magnetizing reactive power, is usually estimated based on the per cent value of the no-load state current. In case of high power transformers this value is usually small, being high in energetic transformers of low power, for which it could even exceed 10 per cent. It gives evidence that the value of magnetizing reactive power of the transformer reaches even 10 per cent of its rated power. In the transformers manufactured at present the no-load state current is usually of the range of 1 per cent, which means that the reactive power absorbed by such a transformer in no-load state is significantly lower. It should be noticed that the reactive power absorbed from the network by a transformer depends on the reactive power absorbed by the receivers supplied from the transformer. Therefore, the phase factor of the transformer must not drop below the level defined by the regulations. Should the phase factor drop too much, the reactive power must be compensated accordingly. The lower phase factor, the higher power loss and voltage drop.

Value of the phase factor significantly affects allowable level of active power of the transformer. In result, the transformer of 400kVA power may be charged with 400kVA active power provided it is not charged with reactive power ($\cos\varphi = 1.0$). In case the value $\tan\varphi = 0.4$ ($\cos\varphi = 0.927$) defined by appropriate regulation is observed, the allowable transformer load must be reduced to 370.4 kW.

Reduction of the phase factor to 0.8 results in the decrease of active power to 325 kW. Further reduction of the phase factor to 0.7 implies the need of active power drop to 289 kW. If in case of larger group of the customers the energy supplier is unable to keep the required value of phase factor, the transformer must be replaced by a new one of higher power or an additional transformer must be added to the system. In both cases the reactive power and power loss will increase. Therefore, compensation of reactive power, that should enable the use of maximum active power of the transformer, is fully justified. The highest use of rated power of the transformer takes place for the phase factor equal to 1. At this value of the phase factor the efficiency is the largest. Taking into account allowable transformer load constrained by the value of rated current, the reactive power should be compensated first of all and, only afterwards, possible use of a transformer of higher power may be considered. In case of the example mentioned above, a transformer of 630 kVA power may be used. Such a transformer will increase the no-load loss e.g. from 940 W through 1250W even to 1650 W, according to transformer manufacturer. The full-load power losses differ for each of the transformers too. In general, in order to analyze the values of power loss and the no-load current a test card should be used, that is enclosed to purchased transformer by some manufacturers. Transformer rated parameters specified by manufacturers in market offers differ each from other and are rather not detailed enough. Very often the information on the winding temperature is missing for which the full-load power loss is specified. Similarly, the values of no-load state current are not always specified.

The transformer voltage drop depends not only on the transformer parameters but on the phase factor too. The rated voltages in the secondary circuit are specified for no-load state of the transformer supplied with rated voltage at its main terminal. Figure 4 presents the effect of the phase factor (the angle φ) on the voltage drop. Figure 5 depicts the effect of the phase factor on the voltage in the secondary circuit. The value 1.57 at this plot corresponds to the angle $\varphi = 90^{o}$. It should be noticed that in case of overcompensating the inductive reactive power the output voltage of the transformer increases.

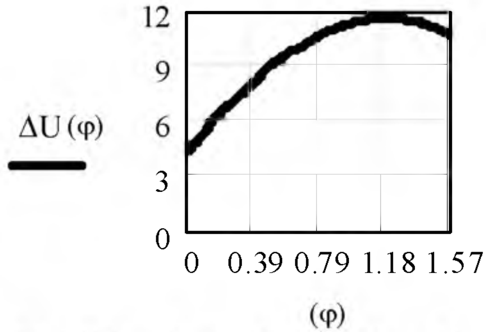

Fig. 4. Voltage drop as a function of the angle φ

Figure 6 shows the effect of phase factor on possible use of rated power, with distinction of the active power P and reactive power Q, for the case of a transformer of rated power $S_n = 1000$ kVA.

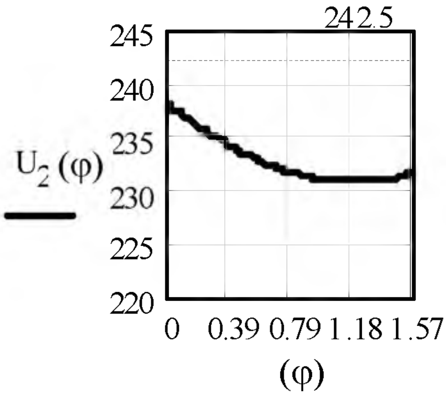

Fig. 5. The effect of the angle φ on secondary voltage

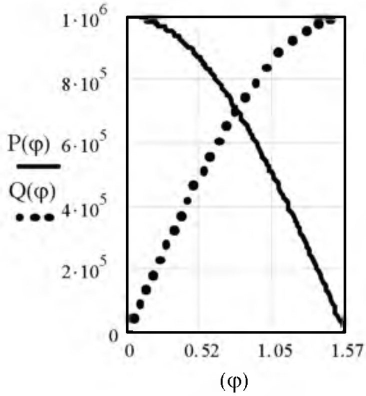

Fig. 6. The effect of phase factor on active power P and reactive power Q of a transformer of rated apparent power S_n = 1000 kVA

Figure 7 shows the effect of phase factor on the transformer voltage drop ΔU(φ), with its active and reactive components.

Table 1 specifies various characteristic values presenting possible use of a transformer of the power 1000 kVA, assuming that rated current flows in its windings. Table 1 includes active power P, reactive power Q, phase factor cosφ, tanφ, the angle φ, transformer voltage drops, and secondary circuit voltages at various values of the phase factor.

The values specified in Table 1 determine the reactive power levels that should be compensated with a view to obtain expected values of the phase factor. For example, when the transformer is charged with 800 kW power at cosφ = 0.8, the use of a capacitor of the power of 230 kVa allows to increase the transformer active power load by 126 kW in order to achieve the value tanφ = 0.4 required by the regulations.

Figure 6 gives evidence that the transformer voltage drop ΔU is the lowest in case of pure resistance load (cosφ=1). For other values of phase factor the voltage drop increases. Voltage drop in medium voltage line follows the changes occurring in the transformer. Current intensity in the transformer primary circuit behaves similarly as in the secondary circuit, with consideration of the transformation ratio, since the no-load currents are low. The more the load current approaches its active character (cosφ approaches unity) the smaller is the difference between current intensities in the primary and secondary circuits. Winding power losses (i.e. so-called full-load power losses) only slightly affect the current intensity in the primary circuit. These losses reduce the efficiency. In effect, in case of a 400 kVA/15/0.42 kV transformer, in which the rated currents in the primary and secondary circuits amount to 14.7 A and 550 A, respectively, the total power loss of the transformer ($\Delta P_j + \Delta P_{obc}$) is equal to 5530W. Current intensity corresponding to this loss is equal to 0.213 A, i.e. 0.14% of the rated current of the primary circuit. One could state that the effect of the current on power loss and voltage drops in the supplying line is negligible.

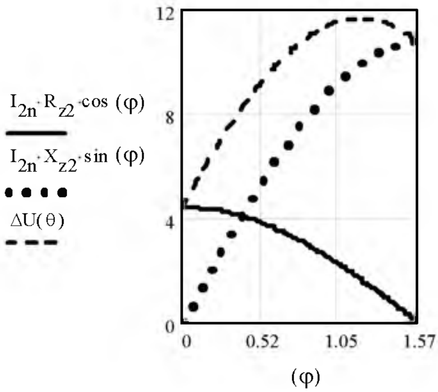

Fig. 7. The effect of phase factor on voltage drop and its components

Table 1. Calculation results of characteristic parameters of the transformer load

P	Q	cosφ	tgφ	φ	ΔU	U_2
[kV]	[kVA]	-	-	-	[V]	[V]
1000	0	1	0	0	4,4	238
926	316	0,92	0,4	22	8,0	234
800	600	0,8	0,75	37	9,9	232
700	430	0,7	1,11	48	11	231

4. Final conclusions

Taking into account reasonable consumption of electric energy any energy saving action may be of significant importance, even the ones related to transformers and energetic lines. Therefore, the modernized high power transformers of reduced power loss and possible low values of no-load current should be used first of all. Any electric equipment manufactured at present and designed for the use in low-voltage networks, as transformers, motors, and generators, should be distinguished by rated voltage values compliant with binding regulations.

References

[1] Jezierski E: Transformatory. WNT 1983.
[2] Ustawa o efektywności energetycznej z 4 marca 2011.