DNIPRO UNIVERSITY of TECHNOLOGY 1899

Mining of Mineral Deposits
ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)
Journal homepage http://mining.in.ua
Volume 13 (2019), Issue 2, pp. 1-16

UDC 621.314.2 https://doi.org/10.33271/mining13.02.001

ECONOMIC CRITERIA FOR OPTIMIZING THE NUMBER AND LOAD FACTOR OF MINING TRANSFORMERS

D. Pasculescu[1], L. Pana[1], V.M. Pasculescu[2*], F. Deliu[3]

[1]*University of Petrosani, Petrosani, Romania*
[2]*National Institute for Research and Development in Mine Safety and Protection to Explosion – INSEMEX, Petrosani, Romania*
[3]*"Mircea cel Batran" Naval Academy, Constanta, Romania*
**Corresponding author: e-mail vlad.pasculescu@insemex.ro, tel. +40765616288*

ABSTRACT

Purpose. This article discusses how to choose the optimal number and load factor, respectively the economic power in the first year of mining power transformers operation. The analysis is carried out based on technical-economic criteria. In this regard, two economic criteria are proposed for a detailed analysis, namely the minimum updated total expenses criterion and the minimum power and energy losses criterion.

Methods. For determining the number and the optimal load factor, the paper presents mathematical models for the two eco-nomic criteria used. The results obtained by the presented methods are simulated using Matlab for several series of under-ground mining transformers. Also, it is assumed that the load remains constant over the year.

Findings. The article confirms the possibility of using the analyzed economic criteria for establishing the optimal number of mining transformers as well as the optimal load factor, respectively the optimal power for the first year of operation. The difficulty of the research is related to the loss time assessment. Also, the paper presents the performed comparative analysis of the two implications.

Originality. This research provides a novel approach, by the detailed presentation of the two criteria used for describing the objective functions which have to be minimized in order to gain the optimum, referring strictly to mining transformers, which represents a novelty for power engineering in mining.

Practical implications. The methods described in the article can be successfully used in the case of new mining power networks which are going to be designed, and in the case of those currently in operation. Economic criteria analysed also provide results for the economical regime of mining transformers which corresponds to minimum energy loss. Therefore, this case also results in significant energy savings, i.e. lower economic criteria used.

Keywords: *economic criteria, load factor, loss time, mining transformer, optimal power*

1. INTRODUCTION

In order to determine the optimal number and power of electric transformers in underground power stations, it is mainly sought to obtain the most technically and economically convenient parameters (Song, Rinne, & van Wageningen, 2013; Jonek-Kowalska & Tchorzewski, 2016; Peralta, Sasmito, & Kumral, 2016; Dubinski, Prusek, & Turek, 2017). In this respect, it is necessary to draw up a study based on the following elements:

– daily load curve for one work day and one rest day, during typical consumption periods, summer and winter;

– annual load curve;

– curve of the classified annual loads;

– the total maximum load, calculated from the data on the load curves, plus the technological losses in the low or medium voltage electrical networks and in the transformers.

In order to determine the optimal number and power of the electrical transformers with which underground electrical distribution stations are equipped, the technical-economic and safety criteria in the power supply of the mining consumers are used (Beshta 2012; Choi, Lee, Lee, Lee, & Kang, 2018). The safety level required in the power supply of underground consumers connected to a mining transformer station is achieved, if a reserve of power is created in terms of the number of installed transformers.

A problem that still needs to be considered when choosing the size of the transformers is the evolution of the load over time, in which case two types of compromises have to be taken into account (Zlender & Kravanja, 2011; Basu, 2017; Erdogan, Cigla, Topal, & Yavuz, 2017):

© 2019. D. Pasculescu, L. Pana, V.M. Pasculescu, F. Deliu. Published by the Dnipro University of Technology on behalf of Mining of Mineral Deposits.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/),
which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

– statically, if the load to be provided remains approximately constant and a compromise has to be made between choosing a higher power transformer that has a lower recovery cost on the installed kVA and a greater number of transformers running in parallel (only for transformation and distribution stations at the surface), which reduces the reserve needed because the consequences of a transformation unit failure are reduced;

– from a dynamic point of view, taking into account the increase in the load over time, the relevant problem is to know for how many years a transformer has to be installed. If the number of years is low, the cost of replacing transformers will also increase, and if the number of years is high, higher power transformers that will need to be installed to avoid these frequent replacements also incur large expenses.

There is also an optimal compromise in this area. In this context, the problem of normalizing the power steps of transformers also arises because it is not advisable to use a number of different types of devices, both in terms of manufacturing costs (serial effect) and maintenance costs in respect to a certain number of devices of each type (Doneva, Despodov, Mirakovski, Hadzi-Nikolova, & Mijalkovski, 2015; Krawczyk, Majer, & Krzemien, 2016; Cichy, Sakowicz, & Kaminski, 2018).

Finally, some limitations of technical nature have to be mentioned, such as: maximum number of gauges that cannot be exceeded due to the difficult underground transport conditions; maximum short-circuit powers at lower voltage levels a.s.o., which can lead to choosing values lower than the optimal ones, resulting in the above compromises.

As it has been shown in this paper, establishing the optimum operating mode for a transformer is not such a simple problem. As a result, the analysis underlying evaluation of offers for the purchase of transformers is not easy either.

2. STATIC PROBLEM OF DETERMINING THE OPTIMUM NUMBER OF TRANSFORMERS CORRESPONDING TO A MINIMUM ANNUAL COST

The first problem to be analysed is that of determining the optimal number of transformers to be installed in an underground distribution station in a given year. To begin with, we assume that the power to be provided by the underground distribution station remains approximately constant over time and that the power of the transformers is not subject to certain technical and safety restrictions (Meira, Ruschetti, Alvarez, & Verucchi, 2018).

In accordance with the general theory of the design and construction of underground and surface power transformers, it can be considered that the active material within the same series of transformers, power losses related to the idle operation of the transformer and the losses in short-circuit regime operation are generally grouped around a characteristic that varies once with the apparent nominal power of the transformer to the β power, according to equation (1):

$$Y = K \cdot S_{nT}^{\beta}, \tag{1}$$

where:

Y – characteristic to which reference is made (loss of power in idle operation, loss of power in short-circuit operation etc.);

S_{nT} – the nominal apparent power of the transformer in kVA;

K – coefficient or proportionality factor specific to each characteristic, an exponent that can take the value 2/3 or 3/4 for some series of transformers.

Similarly, as mentioned above, it is considered that the cost of the transformer follows the same law of variation. To determine the optimal number of transformers from a transformer station, we will assume the following:

S – the maximum consumption served by the transformation or distribution station, MW;

S_{nT} – the apparent nominal power of the transformer installed in the transformer or distribution station, MVA;

N – number of transformers installed in a power distribution station;

C_T – the cost of a power transformer S_{nT}, €;

C_{ct} – the cost of a transformer cell from a transformer or distribution station, €;

γ_k – the equivalent annual cost of a Joule loss megawatt at the annual load peak, €/MW;

γ_0 – the annual cost of a megawatt of losses, constant throughout the year (iron losses in transformers), €/MW.

2.1. Analytical expression of transformers cost

The following transformer cost variation law according to size was admitted:

$$C_T = C_{T0} \cdot \left(\frac{S_{nT}}{S_{T0}} \right)^{\beta} = \alpha_T \cdot S_{nT}^{\beta}, \tag{2}$$

where:

C_{T0} – cost of a power transformer S_{T0}.

This law in S^{β}_{nT}, results from the fact for a given induction and current density, the mass of a transformer varies sensitively with the β power from the nominal apparent power of the transformer.

2.2. Active power losses in idle operation

The law that gives the variation of active power loss in idle operation, depending on the nominal apparent power of the transformer, is in a first approximation of the same form as the preceding one:

$$\Delta P_{Fe} = \Delta P_{Fe0} \cdot \left(\frac{S_{nT}}{S_{T0}} \right)^{\beta} = \alpha_0 \cdot S_{nT}^{\beta} \ . \tag{3}$$

2.3. Active power losses in short-circuit operation

For a given transformer family (i.e. for transformers having the same primary and secondary voltages), the resistance R varies sensibly, inversely proportional to the apparent rated power of the transformer:

$$R \cdot S_{nT} = R_0 \cdot S_{T0} \, . \tag{4}$$

Joule power losses (ΔP_k) for the annual load peak or the active power losses in short-circuit operation in a transformer are calculated based on the following equations:

$$\Delta P_k = \frac{R \cdot S^2}{U^2 \cdot n^2} = \frac{R_0 \cdot S_{T0}}{U^2} \cdot \frac{S^2}{n^2 \cdot S_{nT}} = \alpha_k \cdot \frac{S^2}{n^2 \cdot S_{nT}}, \tag{5}$$

or:

$$\Delta P_k = \Delta P_{k0} \cdot \left(\frac{S_{nT}}{S_{T0}} \right)^{\beta} = \alpha_k \cdot S_{nT}^{\beta} . \quad (6)$$

2.4. Analytical expression of annual investment costs and power losses

Next, if a is the update rate, the annual global investment costs and power losses are:

$$C = n \cdot a \cdot \left(C_T + C_{ct} \right) + n \cdot \Delta P_0 \cdot \gamma_0 + n \cdot \Delta P_k \cdot \gamma_k . \quad (7)$$

If the relations (2), (3) and (6) are replaced in the analytical expression (7), it results in:

$$C = n \cdot a \cdot C_{ct} + n \cdot \left(a \cdot \alpha_T + \alpha_0 \cdot \gamma_0 \right) \times \times S_{nT}^{2/3} + \alpha_k \cdot \gamma_k \cdot \frac{S^2}{n \cdot S_{nT}} . \quad (8)$$

In order to simplify the power supply safety issue, it is assumed in this calculation that the supply of the consumers at load peak can be ensured by other means in the case of the transformer unavailability, taking into account the following equation:

$$1.25 \cdot \left(n - 1 \right) \cdot S_{nT} = S , \quad (9)$$

where:

1.25 is the maximum admitted overload factor for a transformer in case of failure.

If S_{nT} is replaced by its expression in terms of S, the value of the annual cost is:

$$C = K \cdot \left(A \cdot n + B \cdot n \cdot S_{nT}^{2/3} + C \cdot \frac{S^2}{n \cdot S_{nT}} \right), \quad (10)$$

where:

$$A = 1.15 \cdot a \cdot C_{ct} ;$$
$$B = a \cdot \alpha_T + \alpha_0 \cdot \gamma_0 ; , \quad (11)$$
$$C = 1.43 \cdot \alpha_k \cdot \gamma_k ,$$

and K, being a factor resulting from the calculations performed, has a value of 0.69.

After performing the replacements, the expression of the annual cost can be written as follows:

$$C = K \cdot \left(A \cdot n + B \cdot n \cdot \frac{S^{2/3}}{\left(n - 1 \right)^{2/3}} + C \cdot \frac{n-1}{n} \cdot S \right) . \quad (12)$$

The number of transformers which delivers the minimum cost, assuming the function is continuous, will be defined by equation (13):

$$\frac{dC}{dn} = K \cdot \left(A + B \cdot S^{2/3} \cdot \frac{n-3}{3 \cdot \left(n - 1 \right)^{2/3}} + C \cdot \frac{S}{n^2} \right) = 0 . \quad (13)$$

This relationship shows that n cannot be more than 3 and that the coefficients A, B and C are positive. In practice, it can be verified that the value of the minimum cost is always obtained for $n = 2$.

If the function $F(S)$ is considered to be equal to the annual cost difference corresponding to $n = 2$ and $n = 3$, it results in the following:

$$F\left(S \right) = K \cdot \left(A - 0.11 \cdot B \cdot S^{2/3} + C \cdot \frac{S}{6} \right) . \quad (14)$$

The minimum of this function is:

$$S_{\min} = \left(0.44 \cdot \frac{B}{C} \right)^3 . \quad (15)$$

It can be noted that $F(S_{\min})$ is always close to the value $K \cdot A \cdot C > 0$.

Finally, it is mentioned that the optimal number of transformers in a transformer station is two or three, depending on the safety criteria adopted, and that a larger number of power transformers can only result from technical conditions independent of the economic optimum.

3. DETERMINATION OF MINING TRANSFORMERS OPTIMAL POWER BASED ON ECONOMIC CRITERIA

In order to determine the optimum power of a transformer, namely the setting of the initial values for the first year of operation (load cofactor at its lower limit $k_{l.\inf}$) of loads at the annual load peak, the following optimization criteria can be used, namely (Pasculescu, Vlasin, Florea, & Suvar, 2017; Pasculescu, Vlasin, Suvar, & Lupu, 2017):

– minimum updated total expenses (CTA), which takes into account both the cost of the transformer and the loss of power and energy. If the update rate is not taken into account, there is a particular case consisting in minimizing the annual calculation costs;

– minimum power and energy losses (CPW), in which case the cost of the transformer is neglected.

In the case of a transformer, an economic operation period is defined as the number of years until its maximum load level increases about 1.6 times the initial value, considered economically optimal for the first year since installation (Pasculescu, Lupu, Pasculescu, Inisconi, & Suvar, 2012; Chueco, Lopez, & Bobadilla, 2015; Gouda & El Dein, 2015; Vagonova, & Volosheniuk, 2012).

The “n” number of years for one of these economic intervals of the transformer depends primarily on the value of the increase in the annual load peak during that period and can be approximated with sufficient accuracy based on the equation (16):

$$\left(1 + r \right)^n = 1.6 , \quad (16)$$

where:

r – coefficient that takes into account the dynamics of the load during the considered period.

3.1. Minimum updated total expenses criterion

The analytical expression of the updated total expenses (CTA) determined for the purchase, installation and operation of a power transformer at a certain load regime over a period of n years can be determined as:

$$CTA_n = \frac{T_n}{T_{20}} \cdot \left(C_T + C_0 \cdot \Delta P_0 + C_k \cdot \Delta P_{kn} \cdot \left(\frac{S_{M1}}{S_{nT}} \right)^2 \right), \quad (17)$$

where:

$$C_0 = C_p + C_W \cdot T_f \cdot T_{20}; \\ C_k = C_P + C_W \cdot \tau \cdot T_{20} \cdot m_r, \quad (18)$$

where:

CTA_n – the sum of total updated expenses for a period of n operation years, €/an;

T_n – updated size of operation duration of n years expressed as:

$$T_n = \sum_{x=1}^{n} (1+a)^{-x}, \quad (19)$$

where:

C_T – cost of the transformer, including its installation costs, €;

C_0 – updated cost of an iron power loss unit for a period of n years of operation, €/kW;

ΔP_0 – active power losses in the iron (power losses during idle operation) of the transformer, kW;

C_k – updated cost of a short-circuit active power loss unit by assuming an increase rate r of the annual load peak, €/kW;

ΔP_{kn} – nominal power losses in short-circuit operation (transformer operating at nominal load), kW;

C_P – specific cost of the power installed in base-equivalent electrical power plants, in up-to-date values, €/kW;

C_W – the average cost on the system of kilowatt-hour losses calculated for the MV/LV station, €/kWh;

S_{M1} – maximum apparent power for the first year of operation of the transformer, kVA;

S_{nT} – nominal apparent power of the transformer, kVA;

m_r – load multiplier expressed by relationship (20):

$$m_r = \frac{1}{(1+a) \cdot T_n} \cdot \sum_{m=0}^{n-1} \frac{(1+r)^{2m}}{(1+a)^m}, \quad (20)$$

where:

r – the rate of increase in annual load peaks in that period, and a the update rate. If $r = 0$ and $n = 20$ years are considered, the load multiplier $m_r = 1$;

τ – the calculation time of the annual energy technology losses in h/year, whose value can be taken from diagrams or can be calculated with equation (21) or (22):

$$\tau = T_{SM} \frac{10000 + T_{SM}}{27520 - T_{SM}}, \quad (21)$$

or:

$$\tau = 8760 \cdot \left(0.124 + T_{SM} \cdot 10^{-4} \right)^2, \quad (22)$$

where:

T_{SM} – duration of using the apparent maximum annual power, expressed in h/year, which can also be approximated with sufficient accuracy by the relation (23):

$$T_{SM} = 1.03 \cdot \frac{\sqrt{W_{P1}^2 + W_{Q1}^2}}{S_{M1}}, \quad (23)$$

where:

W_{P1} şi W_{Q1} – estimates of the total active energy and the total reactive energy expected to be transited through the transformer during its first year of operation;

T_f – transformer running time, in h.

The loss of active power in idle operation, short-circuit active power losses as well as the cost of the transformer can be replaced according to the current hypothesis, depending on some specific values related to the nominal load of the transformer (S_{nT}), to the power β, as follows:

$$C_T = \alpha_T \cdot S_{nT}{}^{\beta}; \\ \Delta P_0 = \alpha_0 \cdot S_{nT}{}^{\beta}; \\ \Delta P_k = \alpha_k \cdot S_{nT}{}^{\beta}. \quad (24)$$

If the relationships (24) are substituted in relation (17), and the value of β is considered 2/3, then:

$$CTA_n = \frac{T_n}{T_{20}} \cdot \left((\alpha_T + \alpha_0 \cdot C_0) \cdot S_{nT^{2/3}} + \right. \\ \left. + \alpha_k \cdot C_k \cdot \frac{S_{M1}{}^2}{S_{nT^{4/3}}} \right). \quad (25)$$

In order to determine the optimal nominal power, at which the minimum total updated expenses are reached, the order I derivative is calculated according to the S_{nT} and the expression is obtained:

$$\frac{d(CTA_n)}{dS_{nT}} = \frac{2}{3} \cdot \frac{1}{S_{nT}^{1/3}} \cdot \frac{T_n}{T_{20}} \cdot \left(\left(\alpha_T + \alpha_0 \cdot C_0 \right) - \right. \\ \left. -2 \cdot \alpha_k \cdot C_k \cdot \left(\frac{S_{M1}}{S_{nT}} \right)^2 \right); \; \frac{d(CTA_n)}{dS_{nT}} = 0. \quad (26)$$

The analytical expression of the optimum load factor ($k_{l.\inf}$) corresponding to the annual load peak, after solving the equation (26) is:

$$k_{l.\inf} = \frac{S_{M1}}{S_{nT}} = 0.707 \sqrt{\frac{\alpha_T + \alpha_0 \cdot C_0}{\alpha_k \cdot C_k}}. \quad (27)$$

Finally, if the relationships (18) are replaced in relation (27), the following analytical calculation expression is used for calculating the optimal initial loads corresponding to the annual peak load:

$$k_{l.\inf} = 0.707 \sqrt{\frac{\alpha_T + \alpha_0 \cdot (C_P + T_f \cdot T_{20} \cdot C_W)}{\alpha_k \cdot (C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r)}}. \quad (28)$$

The analytical expression of the optimal power corresponding to the first year of operation (S_{M1}) of a transformer is:

$$S_{M1} = 0.707 \cdot S_{nT} \sqrt{\frac{\alpha_T + \alpha_0 \cdot (C_P + T_f \cdot T_{20} \cdot C_W)}{\alpha_k \cdot (C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r)}}. \quad (29)$$

In the second case, where β is considered to have value 3/4, the analytical expression of the total updated expenses is:

$$CTA_n = \frac{T_n}{T_{20}} \cdot \left(\left(\alpha_T + \alpha_0 \cdot C_0 \right) \cdot S_{nT}^{3/4} + \alpha_k \cdot C_k \cdot \frac{S_{M1}^2}{S_{nT}^{5/4}} \right). \quad (30)$$

In order to determine the optimum nominal apparent power, the lower limit load factor, for which the total updated expenses are minimal, similarly to the above-mentioned case, i.e. the order I derivative is cancelled in relation to S_{nT} and obtained via:

$$\begin{gathered} \frac{d\left(CTA_n\right)}{dS_{nT}} = \frac{1}{4} \cdot \frac{1}{S_{nT}^{1/4}} \cdot \frac{T_n}{T_{20}} \cdot \left(3 \cdot \left(\alpha_T + \alpha_0 \cdot C_0 \right) - \right. \\ \left. -5 \cdot \alpha_k \cdot C_k \cdot \left(\frac{S_{M1}}{S_{nT}} \right)^2 \right); \ \frac{d\left(CTA_n\right)}{dS_{nT}} = 0. \end{gathered} \quad , \quad (31)$$

By solving the equation (31), the analytical expression of the optimal load factor ($k_{l.\inf}$) at the annual load peak with $\beta = 3/4$.

$$k_{l.\inf} = \frac{S_{M1}}{S_{nT}} = 0.775 \sqrt{\frac{\alpha_T + \alpha_0 C_0}{\alpha_k \cdot C_k}} . \quad (32)$$

If the relations (18) are substituted in relation (32), the following analytical expression of the optimum initial loads at the annual load peak is obtained:

$$k_{l.\inf} = 0.775 \sqrt{\frac{\alpha_T + \alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W \right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r \right)}} . \quad (33)$$

This equation is used for determining the analytical expression of the optimal power in the first year of a transformer operation:

$$S_{M1} = 0.775 \cdot S_{nT} \sqrt{\frac{\alpha_T + \alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W \right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r \right)}} . \quad (34)$$

The optimum loading coefficient ($k_{l.\inf}$) at the annual load peak, in respect to the optimal power in the first year of operation of a transformer, is determined on the basis of the CTA criterion by equation (35):

$$\begin{gathered} k_{l.\inf} = \frac{S_{M1}}{S_{nT}} = \xi \sqrt{\frac{\alpha_T + \alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W \right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r \right)}}; \\ S_{M1} = \xi \cdot S_{nT} \sqrt{\frac{\alpha_T + \alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W \right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r \right)}}, \end{gathered} \quad . \quad (35)$$

where:

ξ – a coefficient with the value of 0.707 or 0.775 depending on the value taken into account β, namely 2/3 or 3/4.

For the current series of transformers in explosion-proof construction (TT – AN), the value of the final load, indicated for the transformer with an immediately higher step, is determined by equation (36):

$$k_{l.\sup} = 1.6 \cdot k_{l.\inf} \Rightarrow \frac{k_{l.\sup}}{k_{l.\inf}} = 1.6 . \quad (36)$$

Figure 1, using equation (35), presents the variation of the optimal load factor for different values of the kilowatt-hour losses cost C_W.

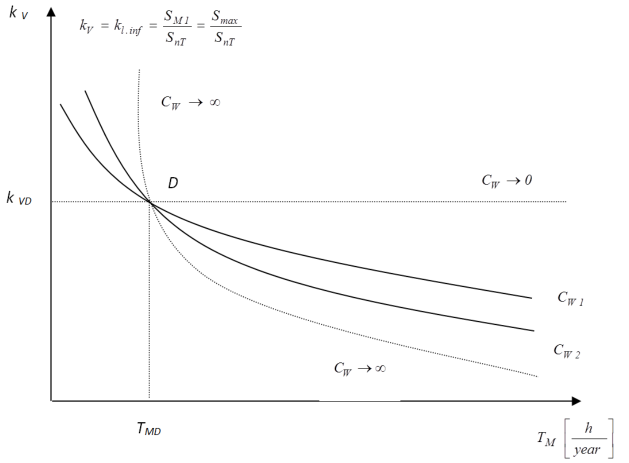

Figure 1. Economic loads for the annual load peak, for the series of TT – AN transformers

It can be seen from the diagram that all the characteristics of different specific values of the C_W kilowatt-hour losses cost pass through a fixed point denoted by D, in which the derivative of the lower limit load factor relative to C_W is cancelled:

$$\frac{dk_{l.\inf}}{dC_W} = 0 . \quad (37)$$

In this way, we may determine the ordinate and the abscissa of point D.

$$\tau_D = \frac{\alpha_0 \cdot T_f \cdot C_P}{\alpha_T + \alpha_0 \cdot m_r \cdot C_P} . \quad (38)$$

The value of the ordinate of point D is obtained from relations (28) and (33), if the kilowatt-hour energy loss cost is considered $C_W = 0$.

$$k_{l.D} = \xi \sqrt{\frac{\alpha_T + \alpha_0 \cdot C_P}{\alpha_k \cdot C_P}} . \quad (39)$$

Data for τ_D and $k_{l.D}$ are obtained by replacing the parameters of the respective relations with numerical values.

Values of parameters τ_D and $k_{l.D}$ will be calculated at the end of this section where some case studies will be analysed for different transformers in the series TT – AN.

As the specific energy losses cost C_W grows, the optimal load factor at peak decrease or increase depending on the number of usage hours of the maximum load T_{SM} is higher or lower than $T_{\max.D}$ calculated using equation (40):

$$T_{\max.D} = 10^4 \sqrt{\frac{\tau_D}{8760}} - 1240 . \quad (40)$$

In the hypothesis of a minimum total updated expenses, the theoretical field of variation of the optimum load at peak in Figure 1 is limited by two characteristics.

One of the characteristics corresponds to the kilowatt-hour losses cost equal to zero:

$$k_{l.\inf} = \lim_{C_W \to 0}\left(\xi\sqrt{\frac{\alpha_T + \alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W\right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r\right)}}\right) = \\ = \xi\sqrt{\frac{\alpha_T + C_P \cdot \alpha_0}{C_P \cdot \alpha_k}}. \quad (41)$$

Respectively, for the second characteristic we obtain the following equation:

$$k_{l.\inf} = \lim_{C_W \to \infty}\left(\xi\sqrt{\frac{\alpha_T + \alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W\right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r\right)}}\right) = \\ = \xi\sqrt{\frac{\alpha_0 \cdot T_f}{\alpha_k \cdot \tau \cdot m_r}}, \quad (42)$$

where:

ξ can be 0.707 or 0.775 depending on the performed assumption, namely the value considered for β of 2/3 or 3/4.

The main case studies will be presented below to highlight the manner of application of the method under analysis based on the CTA criterion in order to determine the optimal load factor and the optimum power of the TT – AN mining transformers with different transformation ratios.

3.1.1. Case study 1

Figure 2a – 2f show the values of the initial economic loads for different values of the kilowatt-hour losses cost C_W and parameters of the current series of TT – AN explosion-proof mining power transformers.

The economic power (S_{M1}) and the optimum load factor ($k_V = k_{l.\inf}$) for the TT – AN 6/0.4 kV series of transformers were determined considering $m_r = 1$ for the two assumptions analysed according to the value of β.

In the first case, we considered $\beta = 0.66$, and in the second case $\beta = 0.75$. We also considered the increase rate of the annual peak loads $r = 0$, so the load is assumed to be constant over a year. The abscissa of the intersection point D, and, respectively, the ordinate of the intersection point D, were calculated for $m_r = 1$.

The intersection point D of the three characteristics, which correspond to the different specific cost values of the kilowatt-hour losses cost C_W, was not shown on the graphs below to avoid too bulky figures. This was highlighted in Figure 1.

The number of hours of the annual maximum load use corresponding to the intersection point D, ($T_{\max.D} = T_D$), was determined by equation (39). The calculation time of the annual technological losses τ was calculated by equation (22).

The results obtained from the simulation as well as the input data for the parameters of the transformers analysed are summarized in Table 1.

The graphs shown in Figure 2a – 2f were plotted using the Matlab-Simulink software package for the TT – AN transformer series with 250, 400 and 500 kVA nominal powers, and the transformation ratio 6/0.4 kV, taking into account the annual growth rate r of the load peaks.

The economic power of the transformer is, in fact, the maximum value of a constant power over the duration of the operation which, when transiting through the transformer, produces minimum power losses. Low-loss transformers use more and better materials for their construction and are thus initially more expensive than low-cost transformers. For distribution and power transformers, which operate continuously and most frequently in loaded condition, this consideration is especially important. By stipulating loss evaluation figures in the transformer inquiry, the manufacturer receives the necessary incentive to provide a loss-optimized transformer rather than the low-cost model.

It can also be observed that with the increase in the specific power losses cost (C_W), the optimal load factor at the annual load peak (k_V) decreases or increases, depending on the variation in the use time of the maximum annual load. In the case studies presented in this section, the value of the specific cost of power installed in base equivalent stations in updated values is C_P = 1250 €/kW respective to the real value of the specific power losses cost C_W 0.06 €/kWh.

3.1.2. Case study 2

Figure 3a – 3d show the values of the initial economic loads for different values of the kilowatt-hour losses cost C_W and of the parameters of the current series TT – AN 6/0.69 kV explosion-proof mining power transformers.

The results obtained from the simulation as well as the input data for the parameters of the transformers analysed are summarized in Table 2.

The graphs shown in Figure 3a – 3d were plotted using the Matlab-Simulink software package for the TT – AN transformer series with 400 and 500 kVA nominal powers, and the transformation ratio 6/0.69 kV, not taking into account the annual growth rate r of the load peaks.

A simplified method for a quick evaluation of different quoted transformer losses involves the following assumptions:

– the transformers operate continuously;

– the transformers operate at a partial load, but this partial load is constant;

– additional cost and inflation factors are not considered;

– demand charges are based on 100% load.

3.1.3. Case study 3

Figure 4a – 4f show the values of the initial economic loads for different values of the kilowatt-hour losses cost C_W and the parameters of the current series TT – AN 6/1.05 kV explosion-proof mining power transformers.

The results obtained from the simulation as well as the input data for the parameters of the transformers analyzed are summarized in Table 3. The graphs shown in Figure 4a – 4f were plotted using the Matlab-Simulink software package for the TT – AN transformer series with 250, 400 and 630 kVA nominal powers, and the transformation ratio 6/1.05 kV, not taking into account the annual growth rate r of the load peaks.

The equations used to determine the optimum power, respective to the optimal load factors at the annual load peak are the same as for the case studies presented before.

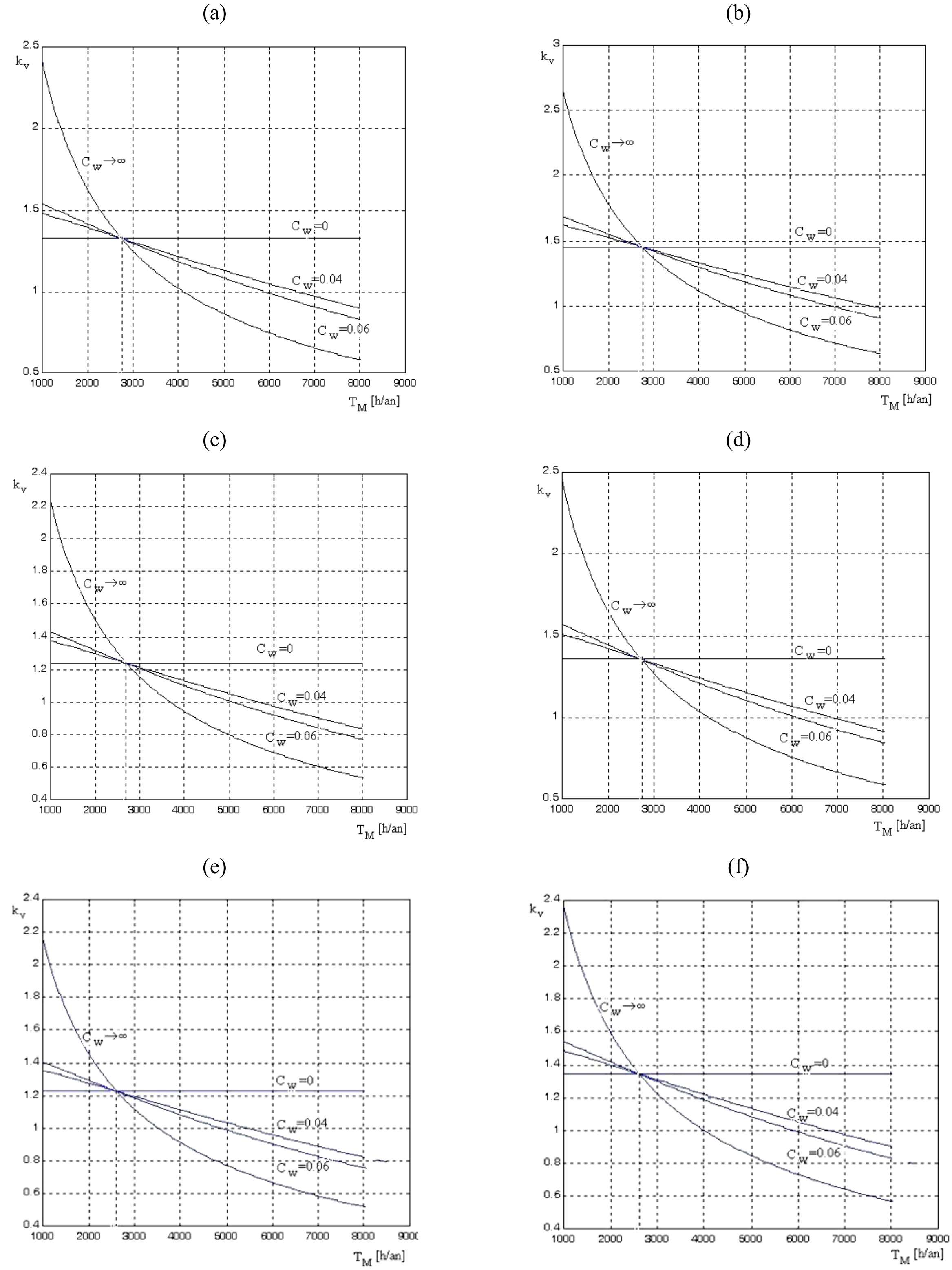

Figure 2. Economic loads for the annual load peak, determined based on the CTA criterion, for series of transformers type TT – AN 6/0.4 kV: (a) S_{nT} = 250 kVA, β = 0.66; (b) S_{nT} = 250 kVA, β = 0.75; (c) S_{nT} = 400 kVA, β = 0.66; (d) S_{nT} = 400 kVA, β = 0.75; (e) S_{nT} = 500 kVA, β = 0.66; (f) S_{nT} = 500 kVA, β = 0.75

Table 1. Input data and simulation results for the parameters of transformers type TT – AN 6/0.4 kV

S_{nT} [kVA]	U_1/U_2 [kV/kV]	ΔP_0 [kW]	ΔP_k [kW]	C_T [€]	β				τ_D [h/year]	T_D [h/year]
					0.66	0.75	0.66	0.75		
					$k_{ID} = k_{VD}$		S_{M1}			
250	6/0.4	1.3	2.3	8500	1.33	1.45	332.5	362.5	1406	2766
400	6/0.4	1.5	3.1	10000	1.24	1.36	496	544	1383.2	2733.6
500	6/0.4	1.63	3.6	11500	1.22	1.34	610	670	1318.4	2639.5

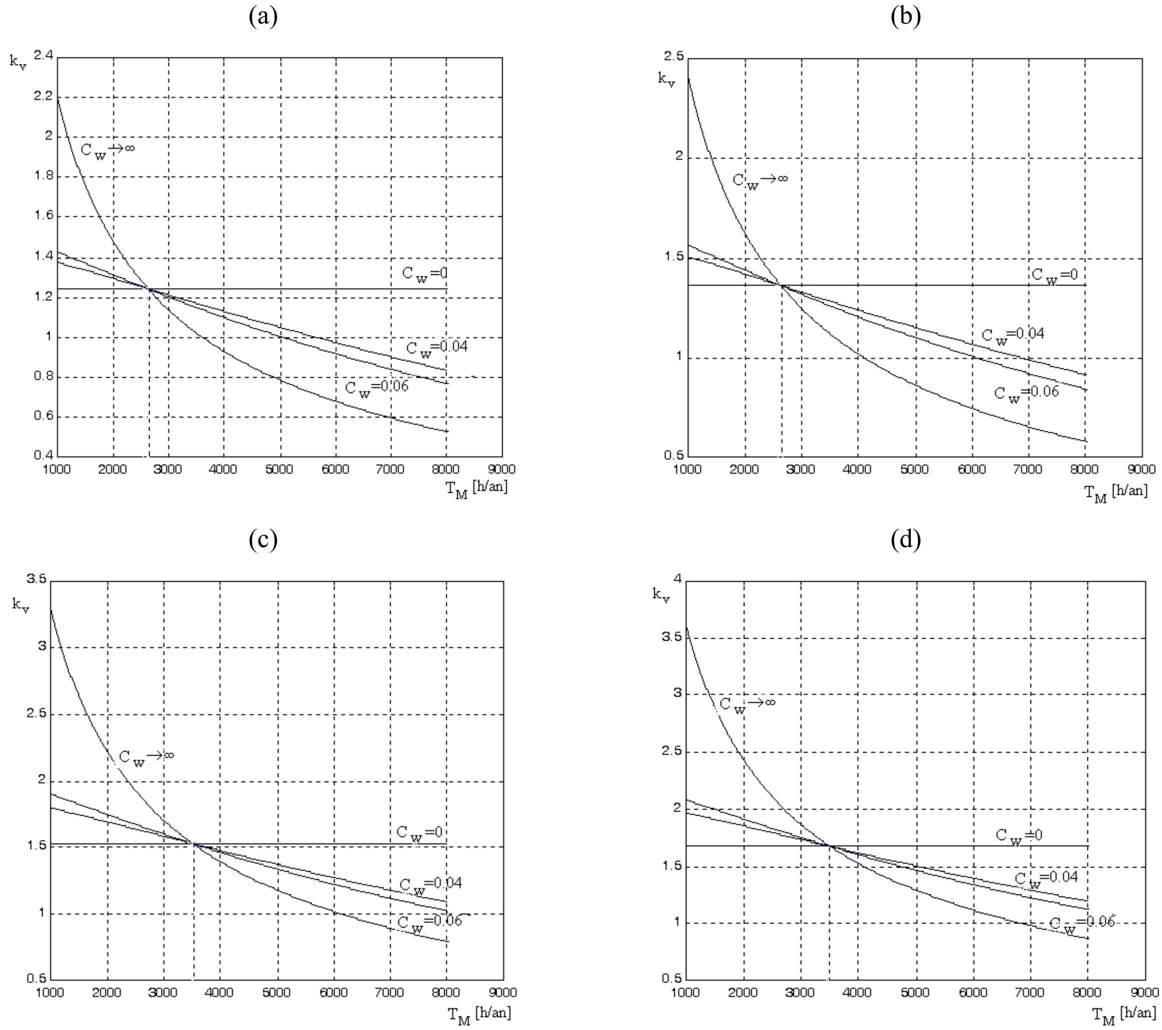

Figure 3. Economic loads for the annual load peak, determined based on the CTA criterion, for series of transformers type TT – AN 6/0.69 kV: (a) S_{nT} = 400 kVA, β = 0.66; (b) S_{nT} = 400 kVA, β = 0.75; (c) S_{nT} = 500 kVA, β = 0.66; (d) S_{nT} = 500 kVA, β = 0.75

Table 2. Input data and simulation results for the parameters of transformers type TT – AN 6/0.69 kV

S_{nT} [kVA]	U_1/U_2 [kV/kV]	ΔP_0 [kW]	ΔP_k [kW]	C_T [€]	β				τ_D [h/year]	T_D [h/year]
					0.66	0.75	0.66	0.75		
					$k_{lD} = k_{VD}$		S_{M1}			
400	6/0.69	1.5	3.2	10000	1.24	1.36	496	544	1327	2652
500	6/0.69	2.75	2.6	11750	1.53	1.67	765	835	1983	3517.5

The quality of a transformer is based on the quality of all processes that are necessary – from the project initiation to the project completion.

As an example, the added cost of loss-optimized transformers can in most cases be recovered via savings in energy use in less than three years.

In the case studies presented above, we considered all types of mining transformers from the series TT – AN of 6/0.4, 6/0.69 and 6/1.05 kV used in the power distribution systems of Romanian underground mining units.

At the same time, based on the graphs, the optimal power of the TT – AN mining transformers can be determined.

3.2. Minimum power and energy losses criterion

Minimum power and energy loss (CPW) represents another optimisation criterion which is obtained via the analytical expression of CTA from equation (17) not taking into account the specific investment cost for power transformers $C_T = 0$, resulting in:

$$CPW_n = \frac{T_n}{T_{20}} \cdot \left(C_0 \cdot \Delta P_0 + C_k \cdot \Delta P_{kn} \cdot \left(\frac{S_{M1}}{S_{nT}} \right)^2 \right). \quad (43)$$

By analogy with the CTA criterion, following the same steps, the calculation relation of the optimum load factor to the annual load peak for a transformer is determined:

$$k_{l.\inf} = \frac{S_{M1}}{S_{nT}} = \xi \sqrt{\frac{\alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W \right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r \right)}}. \quad (44)$$

where:

ξ is 0.707 or 0.775 depending on the performed assumption.

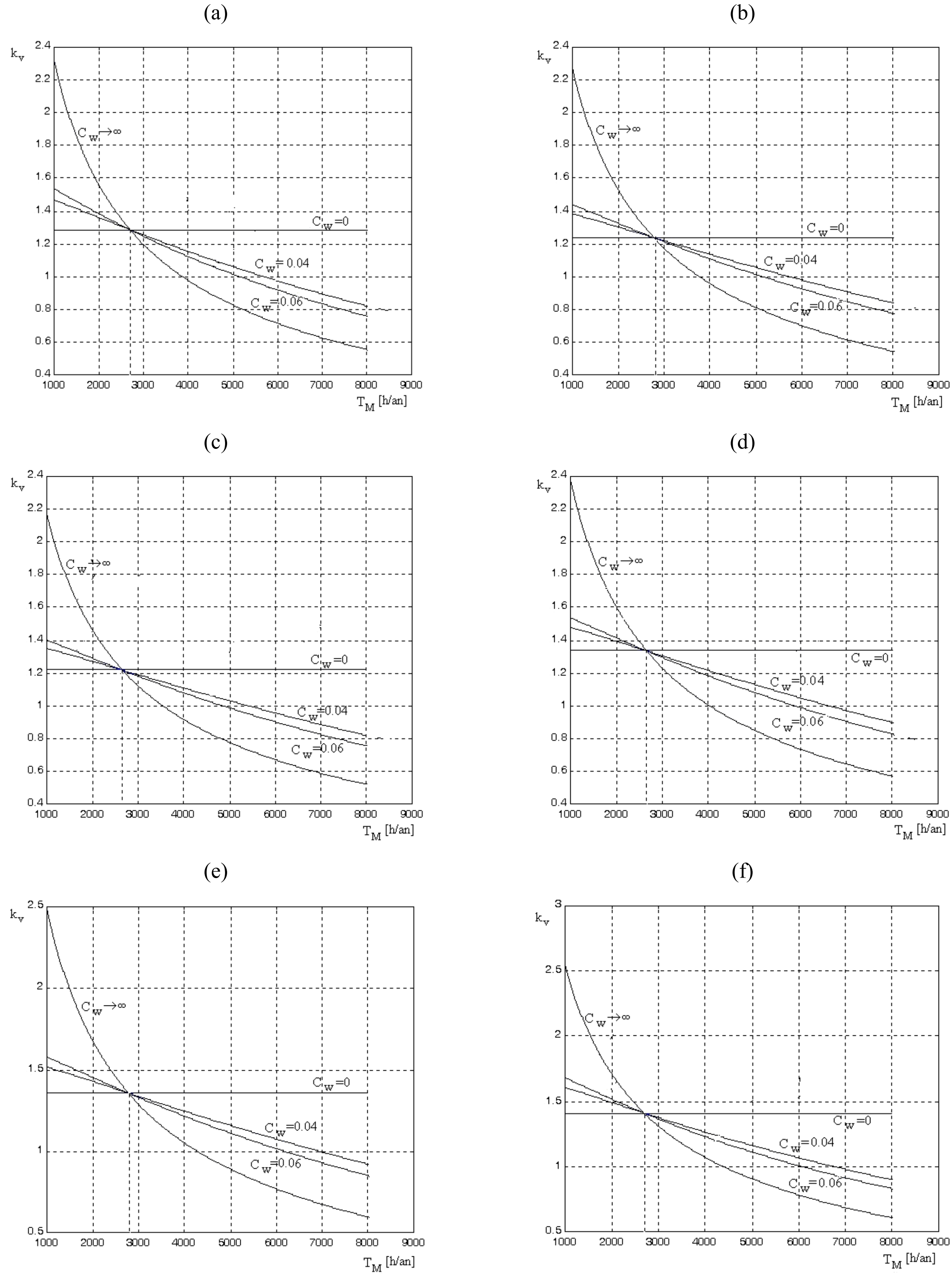

Figure 4. Economic loads for the annual load peak, determined based on the CTA criterion, for series of transformers type TT – AN 6/1.05 kV: (a) S_{nT} = 250 kVA, β = 0.66; (b) S_{nT} = 250 kVA, β = 0.75; (c) S_{nT} = 400 kVA, β = 0.66; (d) S_{nT} = 400 kVA, β = 0.75; (e) S_{nT} = 630 kVA, β = 0.66; (f) S_{nT} = 630 kVA, β = 0.75

Table 3. Input data and simulation results for the parameters of transformers type TT – AN 6/0.4 kV

S_{nT} [kVA]	U_1/U_2 [kV/kV]	ΔP_0 [kW]	ΔP_k [kW]	C_T [€]	β				τ_D [h/year]	T_D [h/year]
					0.66	0.75	0.66	0.75		
					$k_{ID} = k_{VD}$		S_{M1}			
250	6/1.05	1.3	2.5	8750	1.28	1.41	320	352.5	1372	2717
400	6/1.05	1.6	3.5	11000	1.22	1.34	488	536	1347.7	2682.3
630	6/1.05	2.1	4.2	13500	1.24	1.36	781.2	856.8	1426	2795

The abscissa of point D (Fig. 1) is:

$$\tau_D = \frac{\alpha_0 \cdot T_f \cdot C_P}{\alpha_0 \cdot m_r \cdot C_P} = \frac{T_f}{m_r}, \quad (45)$$

for $r = 0$ and $m_r = 1$, the above equation becoming:

$$\tau_D = T_f . \quad (46)$$

With the help of S_{M1} which takes into account both the characteristics of the transformers and the load curves, we can find the degree of utilization of the economic capacity for which the losses are minimal. Similar to the CTA criterion, in the case of minimal expenses for total loss of power and electricity, the theoretical range of the optimal load at the annual load peak in Figure 1 is limited by two characteristics. One of the characteristics corresponds to zero kilowatt-hour loss cost of zero and is:

$$k_{l.D} = \lim_{C_W \to 0}\left(\xi\sqrt{\frac{\alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W\right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r\right)}}\right) = \xi\sqrt{\frac{\alpha_0}{\alpha_k}}, \quad (47)$$

respectively for the second characteristic we have:

$$k_{l.D} = \lim_{C_W \to \infty}\left(\xi\sqrt{\frac{\alpha_0 \cdot \left(C_P + T_f \cdot T_{20} \cdot C_W\right)}{\alpha_k \cdot \left(C_P + \tau \cdot T_{20} \cdot C_W \cdot m_r\right)}}\right) = \xi\sqrt{\frac{\alpha_0 \cdot T_f}{\alpha_k \cdot \tau \cdot m_r}}. \quad (48)$$

From the analysis of the CTA, CPW criteria for determining the optimal charging coefficient of the transformer distribution networks, is derived based on the value of S_{M1} set on a random basis.

3.2.1. Case study 1

Figure 5a – 5f present the initial values of the optimal load factors ($k_{l.\inf}$) for the series of TT – AN mining transformers of 6/0.4 kV and the final maximum load values ($k_{l.sap}$) for which it is advisable to replace with an immediately higher power rating, calculated with the CTA method and the CPW method.

As can be seen from the following diagrams, the initial values of the load factors in the hypothesis of a minimum CPW result in about 25% lower value than the assumed minimum of total updated expenses.

The optimal load factors ($k_{l.\inf} = k_{l.i}$, $k_{l.sup} = \underline{k_{l.s}}$) were calculated on the basis of the current cost of the kilowatt-hour electricity losses, respectively with $C_W = 0.06$ €/kWh. The load is considered constant over time, so the load multiplier is $m_r = 1$. The input data for 6/0.4 kV TT – AN type transformers are shown in Table 1.

3.2.2. Case study 2

Figure 6a – 6d present the values of the initial and final economic loads for the annual load peaks ($k_{l.\inf} = k_{l.i}$, $k_{l.sup} = k_{l.s}$), neglecting the growth rate r of the load (for $\boldsymbol{r} = 0$ (results $m_r = 1$) for the current series of TT – AN transformers of 6/0.69 kV depending on the maximum annual load usage time T_M, by using also the two optimization criteria analysed in this section, namely: the CTA criterion and the CPW criterion.

The graphs in Figure 6a – 6d were plotted using the Matlab-Simulink software package. The input data for 6/0.69 kV TT – AN transformer parameters are synthesized in Table 2.

It can also be noted that the energy losses during idling are of great importance, although the value of the power loss is 18 – 25% of the value of the losses associated with the maximum duration of the load.

This is generally due to charging under the rated power of the transformer, which is usually $1 < k_{l.\inf} = S_{M1}/S_{nT} < 3.2$ and τ between 2500 and 5000 h/yr.

In the case of the TT – AN mining transformer of 6/0.69 kV, 500 kVA resulted in the loss ratio $\Delta P_0/\ \Delta P_k = 1.02$, because iron losses are higher than copper losses.

For values of the fill coefficient 0.35 and 0.6, the economic load factor value is 87.46 and 96.25% respectively. In this situation, it will not operate at such loads as it is very dangerous during charge peaks, which exceed the transformer power, have $S_{\max} = 2.5 S_{nT}$. Also, it will be watched in operation that the transformer will operate at a lower limit load. If the transformer operates at the calculated economic load factor [1.2, 1.5], the energy losses are high (ΔW_a = [90.79, 131.17] kWh/day).

3.2.3. Case study 3

Figure 7a – 7f present the values of the initial and final economic loads for the annual load peaks ($k_{l.\inf} = k_{l.i}$, $k_{l.sup} = k_{l.s}$), neglecting the growth rate r of the load for the current series of TT – AN transformers of 6/1.05 kV depending on the maximum annual load usage time T_M, by using the two optimization criteria CTA and the CPW. If the growth rate of the annual load peaks is not taken into account, the initial loading coefficient resulting from the calculation, regardless of the analysis criteria presented in this paper (CTA and CPW), will be taken less, in order to leave a reserve in case of future consumption increase.

In other terms, knowing that for the calculation of the optimal load capacity of the transformers, the maximum power enters the first year of exploitation, we can conclude that in determining this power (and thus the load factor), two elements must be taken into account:

– the loss factor calculation value, which as has been shown, typically has a value different from the actual value;

– the value of the iron and copper losses of the transformer (ΔP_0, ΔP_k), which also differ depending on the different types of transformers, or which may undergo changes over time as a result of repairs, for the same types of transformers.

The calculated charge is hypothetical because the actual load in operation is different from the one resulting from the calculations made for different types of transformers. If the real load is equal to the calculated value, this would be valid for a short time [1, 2], or the CTA calculation is done over a long time [20, 30], during which the load will certainly be varied within certain limits, compared to the initial load (optimum load factor in the first year of operation).

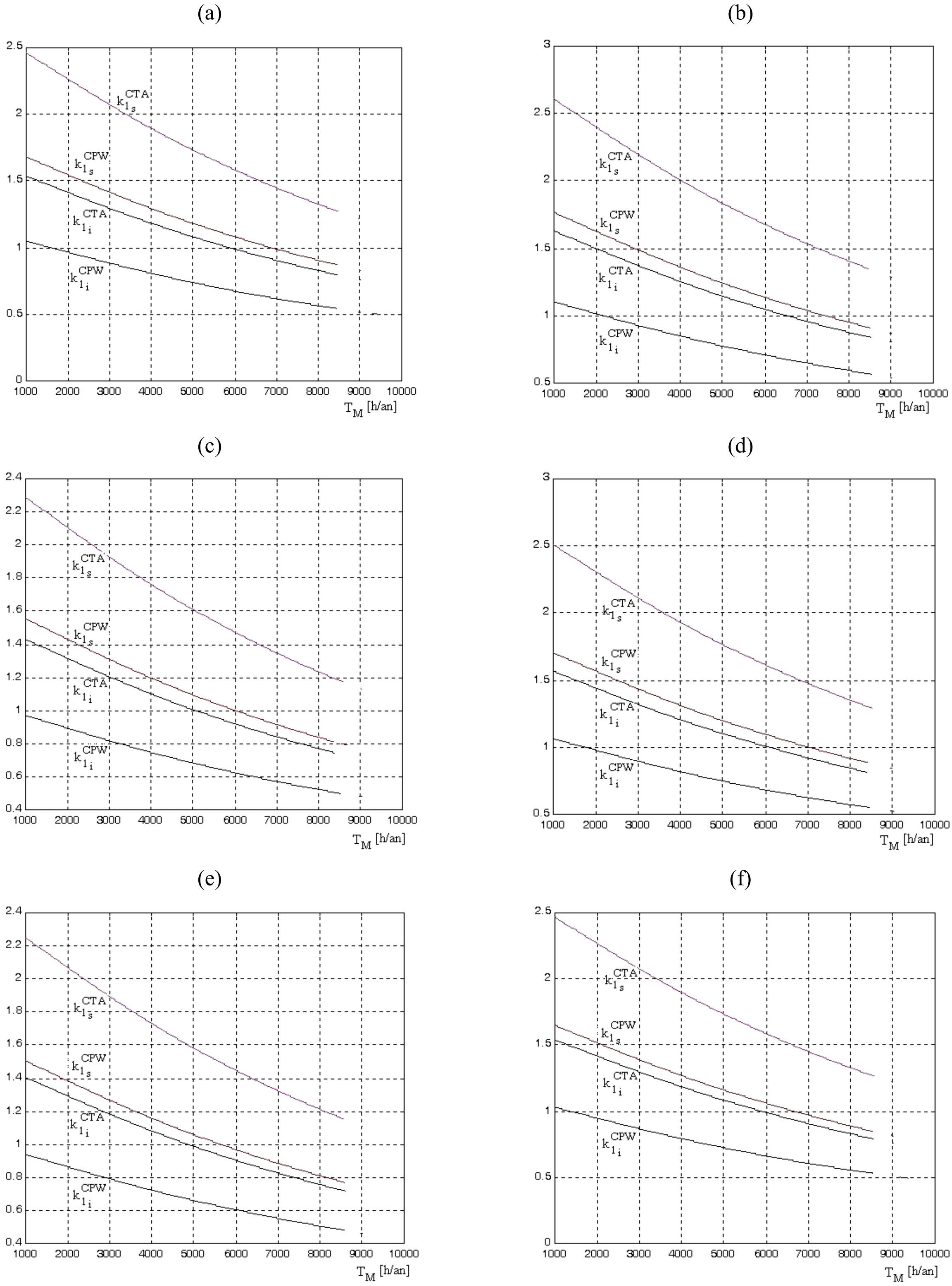

Figure 5. Economic loads for annual load peaks, determined based on the CTA and CPW criteria, for the current series of transformers type TT – AN, of 6/0.4 kV: (a) S_{nT} = 250 kVA, β = 0.66; (b) S_{nT} = 250 kVA, β = 0.75; (c) S_{nT} = 400 kVA, β = 0.66; (d) S_{nT} = 400 kVA, β = 0.75; (e) S_{nT} = 500 kVA, β = 0.66; (f) S_{nT} = 500 kVA, β = 0.75

The lower the transformer load, the higher the chance of overloading in case of failure. The graphs in Figure 7a – 7f were plotted using the Matlab-Simulink software package. The input data for 6/0.69 kV TT – AN transformer parameters are synthesized in Table 3.

The current transformer series manufactured in Romania have the ratio $\Delta P_0/\Delta P_k$ = [0.15, 0.2], in the case of normal TTU – NL transformers, being in this way relatively economical for any type of load curve. In the case of TT – AN type mining transformers, the ratio of losses is much higher, with a value of $\Delta P_0/\Delta P_k$ = [0.45, 1.05], their optimal operating regime being obtained for load curves with higher filling factors.

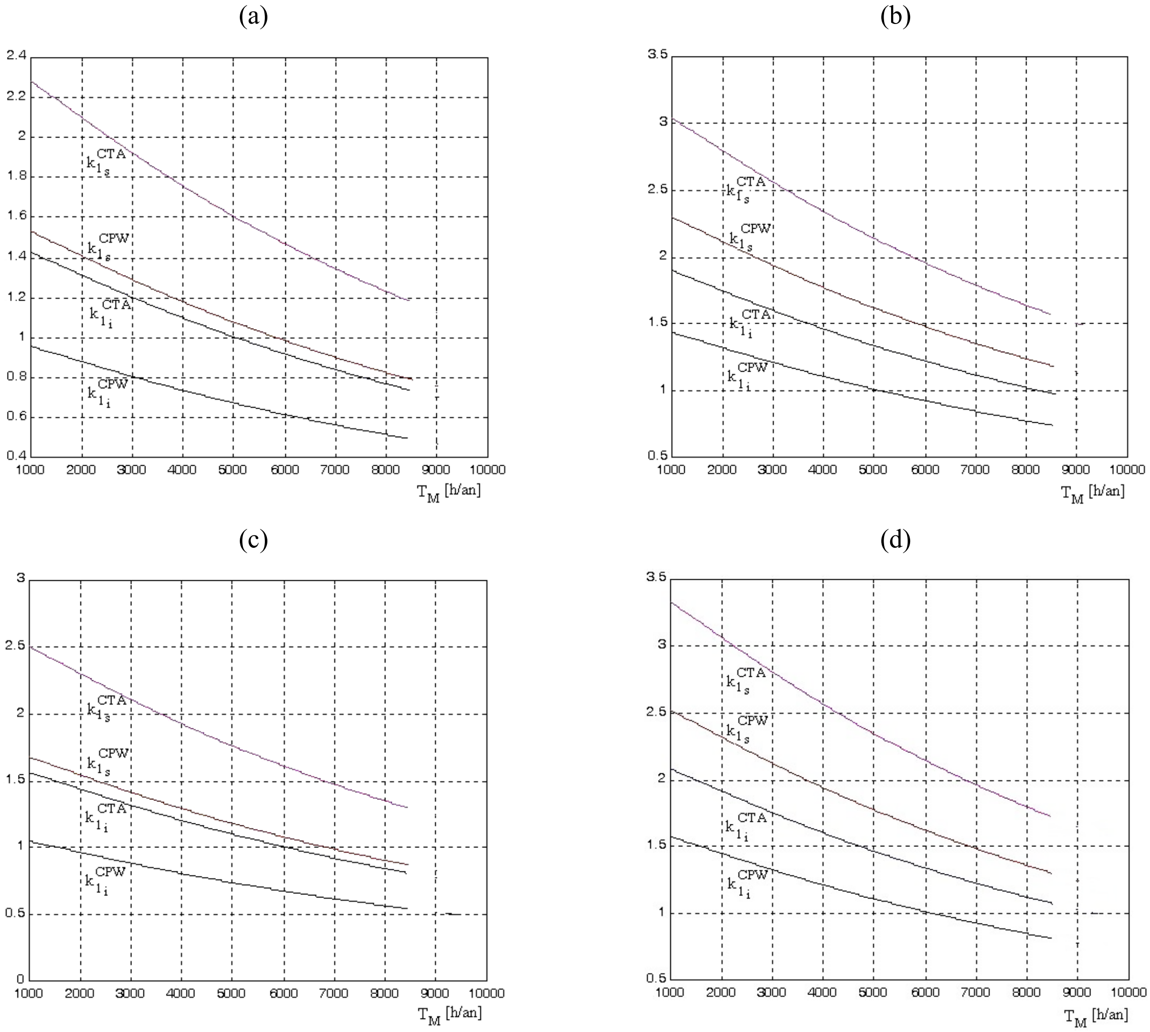

Figure 6. Economic loads for annual load peaks, determined based on the CTA and CPW criteria, for the current series of transformers type TT – AN, of 6/0.69 kV: (a) S_{nT} = 400 kVA, β = 0.66; (b) S_{nT} = 400 kVA, β = 0.75; (c) S_{nT} = 400 kVA, β = 0.66; (d) S_{nT} = 500 kVA, β = 0.75

4. CONCLUSIONS

The central theme of this paper is determination of the optimal number and optimal coefficient of power transformers incineration in underground mining.

Currently, in the majority of cases encountered in practice, it is economically feasible for the underground distribution stations to be equipped with as few transformers as possible.

In some cases, when the safety conditions in the power supply require it, or when the consumption exceeds the maximum power of the existing units, several transformer units can be provided in an underground distribution station.

Determining the optimal number and power of transformers by economic criteria refers to all nominal power steps of a series of transformers designed on a unitary basis.

The number of transformers that will equip the transformer station or power plant shall not be greater than three and shall be set in such a way as to ensure continuity in the electricity supply to consumers, according to their category of importance:

– for zero-rated consumers, a 100% reserve is provided;

– in the case of category I important consumers, several transformers will be selected so that each of them will provide the power of category I or zero consumers as the case may be;

– in the case of category II and III consumers of importance, no reserve is foreseen, the continuity of the supply being ensured by network back-up links, where economically indicated.

The above result (n = 2) has been achieved because of unavailability of a single transformer, and given the unavailability of two power transformers, the number of transformers within the power transformation and distribution station is n = 3.

To make the least possible investment, the number of transformers installed in a distribution station must be minimal. In addition to the fact that for average power transformers, the specific cost, expressed in €/kVA, is lower, the reduction in the number of transformers simplifies the configuration of the electrical scheme and implicitly saves switching, measuring and protection equipment, etc.

To make the least possible investment, the number of transformers installed in a distribution station must be minimal. In addition to the fact that for average power transformers, the specific cost, expressed in €/kVA, is lower, the reduction in the number of transformers simplifies the configuration of the electrical scheme and implicitly saves switching, measuring and protection equipment, etc.

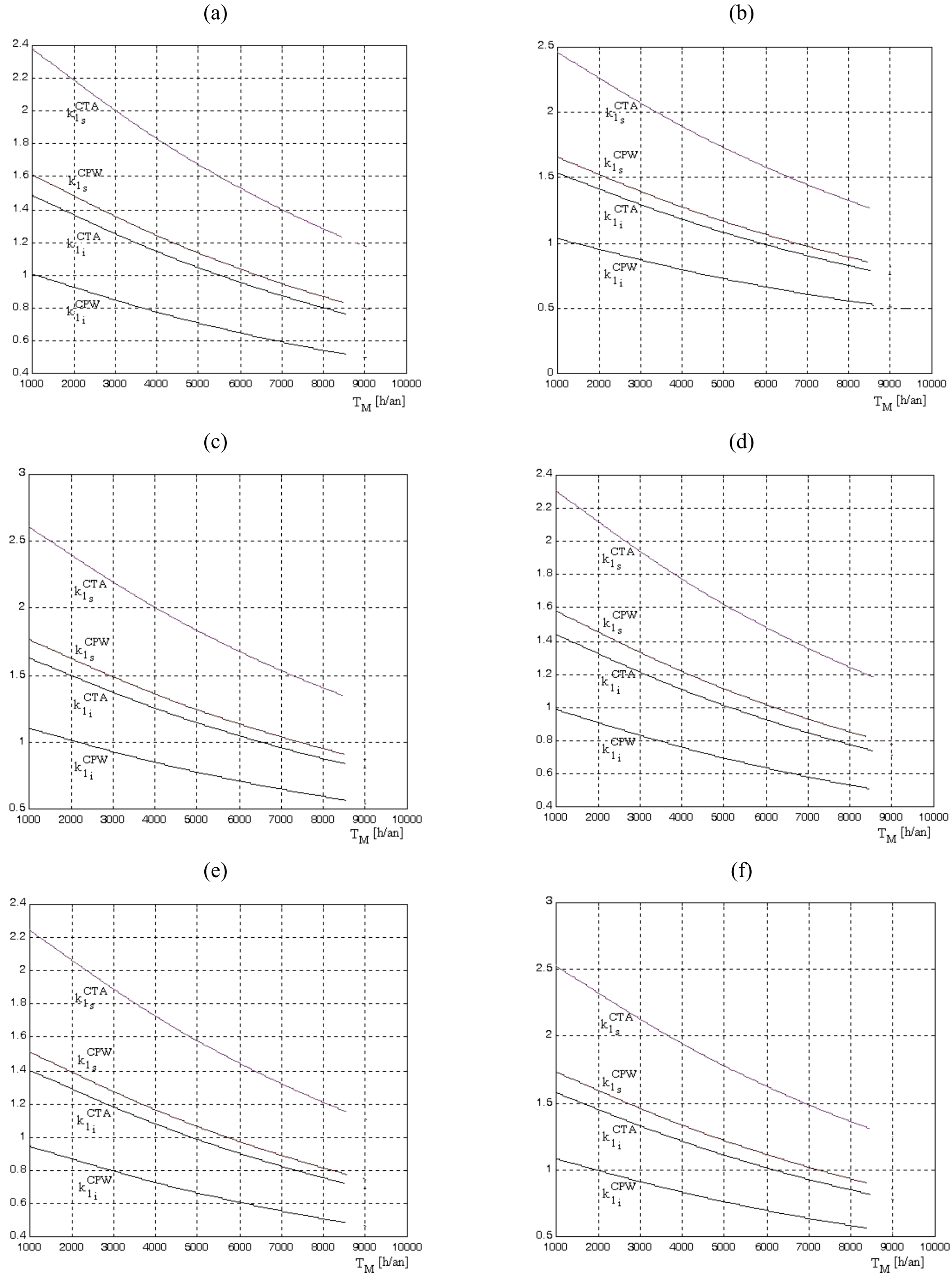

Figure 7. Economic loads for annual load peaks, determined based on the CTA and CPW criteria, for the current series of transformers type TT – AN, of 6/1.05 kV: (a) S_{nT} = 250 kVA, β = 0.66; (b) S_{nT} = 250 kVA, β = 0.75; (c) S_{nT} = 400 kVA, β = 0.66; (d) S_{nT} = 400 kVA, β = 0.75; e) SnT=630 kVA, β=0.66; f) SnT=630 kVA, β=0.75

The optimal use of the transformer charging capacity allows the power to be lowered and thus to save electricity. The operating costs to be considered in the analysis and evaluation of the optimum operation of the transformers are due to power or energy losses. These power or energy losses occur both in transformers and in electrical distribution networks during their operation.

Underground distribution stations should also be analysed from the point of view of the consumer, the environment in which they are located and the configuration of the MV and LV power networks connected to these stations.

Analysis of the load capacity of a transformer is usually done for several purposes:

– for verifying the capacity of an existing transformer in operation to meet the requirements (without overloading in value and duration);

– for comparing the operation regime, performed in relation to the optimum regime of the existing unit;

– for analysing the opportunity of replacing, on economic efficiency criteria, one transformer with another having different technical characteristics (nominal power, power loss in idle and short-circuit operation, idle or magnetized current, short-circuit voltages etc.).

A correct analysis should take into account both the costs of acquiring, installing and maintaining the transformer, as well as the cost of energy losses produced during its operation.

In order to determine whether a transformer meets the requirements of the network, it is obviously necessary to know the consumption characteristics.

As it has been shown in this paper, establishing the optimum operating mode for a transformer is not such a simple problem. As a result, the analysis and the evaluation of offers for the purchase of transformers are also not easy.

If the assessment of acquisition, installation and maintenance costs is simple, the evaluation of power and energy losses and costs becomes a more complicated problem because the following aspects need to be considered when analysing the cost of losses:

– because the load coefficient of a transformer is tracked across the entire range of possible loads, it is normal for the cost loss analysis to be performed across this range;

– this range has to be chosen so that along its entire extent the losses obtained should be as small as possible;

– this range must be chosen so as to use the transformer capacity as much as possible;

– the choice of the optimal load range has to be performed such that over its entire range no load peaks would occur and which would result in hazardous overloads, above the admitted limit.

In all practical cases, the optimal solution is to use the transformer with the nominal power nearest to the theoretical value resulting from the $S_{NT\max}$ calculations.

If transformers differing by no more than half a step from the theoretical optimum are used, CTA increase will not usually exceed 2 and 3%.

If the $S_{nT\max}$ theoretical optimal power would result very closely to a standardized value and would instead be chosen an immediate higher step, then CTA increases by approximately 10 and 12%.

The results obtained from the simulations presented in the case studies show that the values of the load factors, and respectively the optimal power of the mining transformers, are higher than those of the factors from the surface because the ratio of the losses is higher.

ACKNOWLEDGEMENTS

The authors state that this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

REFERENCES

Basu, R. (2017). Evaluation of some renewable energy technologies. *Mining of Mineral Deposits*, *11*(4), 29-37. https://doi.org/10.15407/mining11.04.029

Beshta, O.S. (2012). Electric drives adjustment for improvement of energy efficiency of technological processes. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 98-107.

Choi, Y.G., Lee, S.W., Lee, H.S., Lee, S.C., & Kang, B. (2018). Increase in power conversion efficiency of bidirectional DC-DC converter using 1:1 transformer and pulse-frequency modulation control. *IEEE Transactions on Power Electronics*, *33*(12), 10539-10549. https://doi.org/10.1109/TPEL.2018.2809682

Chueco, F., Lopez, F., & Bobadilla, M. (2015). Technical and economic evaluation of fluorescent and LED luminaires in underground mining. A case study: New mine level of El Teniente. *Energy and Buildings*, (93), 16-22. https://doi.org/10.1016/j.enbuild.2015.02.022

Cichy, A., Sakowicz, B., & Kaminski, M. (2018). Economic optimization of an underground power cable installation. *IEEE Transactions on Power Delivery*, *33*(3), 1124-1133. https://doi.org/10.1109/tpwrd.2017.2728702

Doneva, N., Despodov, Z., Mirakovski, D., Hadzi-Nikolova, M., & Mijalkovski, S. (2015). Cost analysis in the construction of underground mining structures and opportunities for their reduction. *Rudarsko Geolosko Naftni Zbornik*, *30*(2), 1-12. https://doi.org/10.17794/rgn.2015.2.1

Dubinski, J., Prusek, S., & Turek, M. (2017). Key tasks of science in improving effectiveness of hard coal production in Poland. *Archives of Mining Sciences*, *62*(3), 597-610. https://doi.org/10.1515/amsc-2017-0043

Erdogan, G., Cigla, M., Topal, E., & Yavuz, M. (2017). Implementation and comparison of four stope boundary optimization algorithms in an existing underground mine. *International Journal of Mining Reclamation and Environment*, *31*(6), 389-403. https://doi.org/10.1080/17480930.2017.1331083

Gouda, O.E., & El Dein, A.Z. (2015). Improving underground power distribution capacity using artificial backfill materials. *IET Generation, Transmission & Distribution*, *9*(15), 2180-2187. https://doi.org./10.1049/iet-gtd.2015.0274

Jonek-Kowalska, I., & Tchorzewski, S. (2016). Effectiveness of machinery and equipment in coal mining critical approach to unification and standardization. *Inzynieria Mineralna – Journal of the Polish Mineral Engineering Society*, (2), 99-105.

Krawczyk, P., Majer, M., & Krzemien, J. (2016). Proposal of economic assessment of hard coal mines operation conducted in Polish conditions with the use of cost benefit analysis. *Archives of Mining Sciences*, *61*(4), 875-892. https://doi.org/10.1515/amsc-2016-0058

Meira, M., Ruschetti, C.R., Alvarez, R.E., & Verucchi, C.J. (2018). Power transformers monitoring based on electrical measurements: state of the art. *IET Generation, Transmission and Distribution*, *12*(12), 2805-2815. https://doi.org/10.1049/iet-gtd.2017.2086

Pasculescu, D., Lupu, L., Pasculescu, V., Inisconi, I., & Suvar, M. (2012). Study of electrocution hazards in three-phase electrical networks with ground-isolated neutral point. *Environmental Engineering and Management Journal*, *11*(7), 1267-1271. https://doi.org/10.30638/eemj.2012.154

Pasculescu, V.M., Vlasin, N.I., Suvar, M.C., & Lupu, C. (2017). Decision support system for managing electrical equipment used in hazardous atmospheres. *Environmental Engineering and Management Journal*, *16*(6), 1323-1330. https://doi.org/10.30638/eemj.2017.141

Pasculescu, V.M., Vlasin, N.I., Florea, D., & Suvar, M.C. (2017). Improving the quality of the process for selecting electrical equipment intended to be used in potentially explosive atmospheres. *Quality – Access to Success*, *18*(S1), 97-102.

Peralta, S., Sasmito, A.P., & Kumral, M. (2016). Reliability effect on energy consumption and greenhouse gas emissions of mining hauling fleet towards sustainable mining. *Journal of Sustainable Mining*, *15*(3), 85-94. https://doi.org/10.1016/j.jsm.2016.08.002

Song, Z., Rinne, M., & van Wageningen, A. (2013). A review of real-time optimization in underground mining production. *Journal of the Southern African Institute of Mining and Metallurgy*, *113*(12), 889-897.

Vagonova, O.G., Volosheniuk, V.V. (2012). Mining enterprises' economic strategies as derivatives of nature management in the system of social relations. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 2, 127-134

Zlender, B., & Kravanja, S. (2011). Cost optimization of the underground gas storage. *Engineering Structures*, *33*(9), 2554-2562. https://doi.org/10.1016/j.engstruct.2011.05.001

ЕКОНОМІЧНІ КРИТЕРІЇ ОПТИМІЗАЦІЇ КІЛЬКОСТІ ШАХТНИХ ТРАНСФОРМАТОРІВ ТА ЇХ НАВАНТАЖЕННЯ

Д. Паскулеску, Л. Пана, В.М. Паскулеску, Ф. Деліу

Мета. У статті обговорюється проблема вибору оптимального числа шахтних трансформаторів, визначення коефіцієнта їх навантаження і рентабельності протягом першого року експлуатації.

Методика. Для визначення кількості трансформаторів і оптимального коефіцієнта їх навантаження запропонована математична модель на базі двох використаних економічних критеріїв: мінімальні скориговані загальні витрати та мінімальні втрати потужності й енергії. Отримані результати лягли в основу моделі, побудованої за допомогою Matlab для декількох серій підземних шахтних трансформаторів. Прийнято, що навантаження зберігається постійним протягом року.

Результати. У статті підтверджена можливість використання аналізованих економічних критеріїв для визначення оптимального числа шахтних трансформаторів і оптимального коефіцієнта їх навантаження а, отже, оптимальної потужності протягом першого року їх експлуатації. Складність дослідження полягала в оцінці часових втрат. Крім того, у статті були представлені результати та порівняльний аналіз двох використаних економічних критеріїв. Встановлено, що оптимальним рішенням є використання трансформатора з номінальною потужністю, найближчою до теоретичного значення, отриманого в результаті розрахунків $S_{NT\max}$. Результати, отримані при моделюванні, показують, що значення факторів навантаження, відповідно, оптимальної потужності шахтних трансформаторів, вище, ніж у поверхових, оскільки відношення втрат вище.

Наукова новизна. Дослідження засноване на інноваційному підході, при якому детальне представлення двох критеріїв використано для опису об'єктивних функцій, що підлягають мінімізації, з метою отримання оптимальних рішень для шахтних трансформаторів. Даний підхід є принципово новим у галузі гірничої електроенергетики.

Практична значимість. Методи, запропоновані в статті, можуть бути успішно застосовані як у разі проектування нових шахтних електричних мереж, так і для мереж, які вже перебувають в експлуатації. Аналізовані економічні критерії дозволяють встановити найбільш економічний режим експлуатації шахтних трансформаторів, при якому втрати енергії будуть мінімальні, що, в свою чергу, призведе до її суттєвої економії.

Ключові слова: *економічні критерії, коефіцієнт навантаження, тимчасові втрати, шахтний трансформатор, оптимальна потужність*

ЭКОНОМИЧЕСКИЕ КРИТЕРИИ ОПТИМИЗАЦИИ КОЛИЧЕСТВА ШАХТНЫХ ТРАНСФОРМАТОРОВ И ИХ НАГРУЗКИ

Д. Паскулеску, Л. Пана, В.М. Паскулеску, Ф. Делиу

Цель. В статье обсуждается проблема выбора оптимального числа шахтных трансформаторов, определения коэффициента их нагрузки и рентабельности в течение первого года эксплуатации.

Методика. Для определения количества трансформаторов и оптимального коэффициента их нагрузки предложена математическая модель на базе двух использованных экономических критериях: минимальные скорректированные общие издержки и минимальные потери мощности и энергии. Полученные результаты легли в основу модели, построенной с помощью Matlab для нескольких серий подземных шахтных трансформаторов. Принято, что нагрузка сохраняется постоянной в течение года.

Результаты. В статье подтверждена возможность использования анализируемых экономических критериев для определения оптимального числа шахтных трансформаторов и оптимального коэффициента их нагрузки и, следовательно, оптимальной мощности в течение первого года их эксплуатации. Сложность исследования заключалась в оценке временных потерь. Кроме того, в статье были представлены результаты и сравнительный анализ двух использованных экономических критериев. Установлено, что оптимальным решением является использование трансформатора с номинальной мощностью, ближайшей к теоретическому значению, полученному в результате расчетов $S_{NT\max}$. Результаты, полученные при моделировании, показывают, что значения факторов нагрузки, соответственно, оптимальной мощности шахтных трансформаторов, выше, чем у поверхностных, поскольку отношение потерь выше.

Научная новизна. Исследование основано на инновационном подходе, при котором детальное представление двух критериев использовано для описания объективных функций, подлежащих минимизации с целью получения оптимальных решений для шахтных трансформаторов. Данный подход является принципиально новым в области горной электроэнергетики

Практическая значимость. Методы, предложенные в статье, могут быть успешно применены как в случае проектирования новых шахтных электрических сетей, так и для сетей, уже находящихся в эксплуатации. Анализируемые экономические критерии позволяют установить наиболее экономичный режим эксплуатации шахтных трансформаторов, при котором потери энергии будут минимальны, что, в свою очередь, приведет к ее существенной экономии.

Ключевые слова: *экономические критерии, коэффициент нагрузки, временные потери, шахтный трансформатор, оптимальная мощность*

ARTICLE INFO

Received: 14 December 2018
Accepted: 19 March 2019
Available online: 27 March 2019

ABOUT AUTHORS

Dragos Pasculescu, Doctor in Engineering Sciences – Electrical Engineering, Associate Professor of the Department of Automation, Computers, Electrical Engineering and Power Engineering, University of Petrosani, 20 Universitatii St, 332006, Petrosani, Romania. E-mail: pdragos_74@yahoo.com

Leon Pana, Doctor in Engineering Sciences – Electrical Engineering, Lecturer of the Department of Automation, Computers, Electrical Engineering and Power Engineering, University of Petrosani, 20 Universitatii St, 332006, Petrosani, Romania. E-mail: leon_pana@yahoo.com

Vlad Mihai Pasculescu, Doctor in Engineering Sciences – Mines, Oil and Gas, Senior Researcher and Head of the Laboratory for International Projects and Cooperation, National Institute for Research and Development in Mine Safety and Protection to Explosion – INSEMEX, 32-34 G-ral Vasile Milea St, 332047, Petrosani, Romania. E-mail: vlad.pasculescu@insemex.ro

Florentiu Deliu, Doctor in Engineering Sciences – Power Engineering, Associate Professor and Head of the Department of Electrical Engineering and Naval Electronic, "Mircea cel Batran" Naval Academy, 1 Fulgerului St, 900218, Constanta, Romania. E-mail: florentiu.deliu@anmb.ro