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CALCULATION OF POWER LOSSES IN UNBALANCED AND HARMONIC POLLUTED ELECTRIC NETWORKS

Gabriel V. POP, Mircea CHINDRIŞ, Radu BINDIU

Technical University of Cluj – Napoca, Gabriel.Pop@eps.utcluj.ro

Abstract **– Today, the electric power systems have a working state characterized by the existence of electromagnetic perturbations. Nonlinear devices are becoming a bigger part of electrical load in industrial and commercial networks.**
The modern electronic equipment and technologies existing to the domestic and industrial consumers, and the modern artificial lighting sources whose working principle is based on electric arc discharging represent the main cause of the harmonic pollution. The unbalanced loads are also presented in great number.
The paper presents a method for determination of power losses in electrical networks working in different conditions: balanced and harmonic polluted, unbalanced but not harmonic polluted, and unbalanced and harmonic polluted.
An evaluation of the economic impact produced by the pollution level is performed for several typical electric conductors.

Keywords: *electric networks, power losses, unbalance, harmonic polluted state*

1. INTRODUCTION

Low voltage electrical distribution networks now supplies an increasing number of nonlinear and unbalanced consumers, which causes a permanent unbalanced and harmonic polluted operating state[1].
Households have in possession many advanced electronic devices, such as radio and TV receivers, computers, printers, etc, which may cause the operating polluted state.
On the other hand, industrial consumers use more equipment based on power electronics due to their lower electricity consumption and improved quality.
The modern artificial lighting sources, whose working principle is based on electric arc discharging, represents the main cause of the harmonic pollution. The unbalanced loads are also presented in great number.
As a result, in the distribution electric system two main sources of electromagnetic disturbances are existing: harmonic currents injected by non-linear loads and the unbalance of the current systems produced by unbalanced loads, respectively. The current and voltage waveforms have reached a very high level of distortion.
Losses in the generation, transmission and distribution parts of any power system, occur during the process of consumers supplying. The level of energy losses ranges between 10 % and 15 % from the energy produced by the power plants, depending on the structure of the electrical network, working conditions etc.
In spite of the above-mentioned aspects, the power engineers calculate the power losses considering a sinusoidal balanced regime; this approach can lead to the undersizing of the network's elements, especially lines and cables. In the operation stage, it can generate many malfunctions or even failure of the entire power system.
In order to implement an accurate design of a power network, in concordance with its real working regime and to obtain for calculated power losses values closed to reality, it is necessary to perform complex accurate calculations, taking into consideration many parameters

2. POWER LOSSES VARIATION

Power losses have an important role in the design and operation of electrical networks. In the first phase, power losses are calculated considering a sinusoidal and balanced state of functioning. This can result in overload of electrical conductors, especially the neutral conductor, leading to degradation or even to their destruction. In operation the power losses have a strong economic importance.
To determine the optimal operating state and the oprimal cables cross section in the design, operation and further development process of electrical lines, a few aspects have to be taken into account:

- the energy losses ranges;
- the harmonic pollution and unbalanced degree for voltage and current waves;
- all technical and functional parameters for

electrical lines.

Calculation of power losses enable the user to evaluate:
- the costs of electricity transmission;
- the assessment of efficiency measures to reduce power losses;
- the optimal voltage level;
- the compensation of reactive power.

2.1. Losses in balance and sinusoidal state[6]

Symmetric and sinusoidal regime is characterized by the following:
• wave form for voltage and current is sinusoidal;
• symmetrical system of voltages and currents.

In electrical lines due to the passage of current through the impedance $\underline{Z} = R + jX$, power losses can be calculated:

$$\Delta P = \frac{P^2 + Q^2}{U^2} \cdot R\,[MW]; \qquad (1)$$

where:

P, Q - active power [MW] respectively reactive power [MVar];

U – end user voltage.

Taking into account that:

$$I^2 = \frac{S^2}{3U^2} \cdot 10^{-3}\,[A] \qquad (2)$$

and

$$S^2 = P^2 + Q^2\,[MVA] \qquad (3)$$

the equation (1) becomes:

$$\Delta P = 3 \cdot I^2 \cdot R\,[W]. \qquad (4)$$

If the power losses calculated in the case of a real operating system (harmonic polluted and unbalanced) are reported to the power losses calculated in a symmetrical and sinusoidal, it will be obtained the growth of power losses, given by the equation (5):

$$\varepsilon_{\Delta P} = \frac{\Delta P_{total} - \Delta P}{\Delta P} \qquad (5)$$

where:

ΔP_{total} - power losses when the system is unbalanced and harmonic polluted;

ΔP - power losses when the system is symmetrical and sinusoidal.

2.2. Losses in unbalanced and sinusoidal state[4][6]

The unbalanced state of functioning is determined by unequal distribution of loads on system phases due to unbalanced consumers or different impedances on each system phases.

This operation state is characterized by different values of electric current in three phase system.

In electric networks, the unbalance of currents cause additional power losses, energy respectively.

The equation of power losses in low voltage electric lines with four conductors operating in unbalanced state is:

$$\Delta P = (I_1^2 + I_2^2 + I_3^2) \cdot R_{ph} + I_N^2 \cdot R_N \qquad (6)$$

where:

R_{ph} – phase conductors resistance;

R_N – neutral conductor resistance

When the system is unbalanced and not harmonic polluted, the growth of power losses depends on negative sequence (k_I^-) and zero sequence (k_I^0) factors for current systems; it is presented in following equation:

$$\varepsilon_{\Delta P} = k_I^{-2} + k_I^{02} \cdot (1 + 3 \cdot \frac{R_N}{R_{ph}}) \qquad (7)$$

where:

$\varepsilon_{\Delta P}$ - relative power losses;

k_I^- - negative sequence factor for currents;

k_I^0 - zero sequence factor for currents.

Determination of relative power losses was made for different cross sections of the phase conductors and neutral conductor (the ratio of the cross sections).

In this purpose, six cases were chosen which correspond to the standards; their ratio between cross sections has the values:

$$\frac{s_{phase}}{s_{neutral}} = 1; 1{,}36; 1{,}56; 1{,}71; 2; 2{,}18 \qquad (8)$$

In the following figures (Fig. 1, Fig. 2, and Fig. 3) are presented the variation of relative power losses when the ratio between cross section of phase and neutral conductors have different values (1, 1.36 and 2); also the negative respectively zero sequence factors for currents ranges between 0 and 50 %.

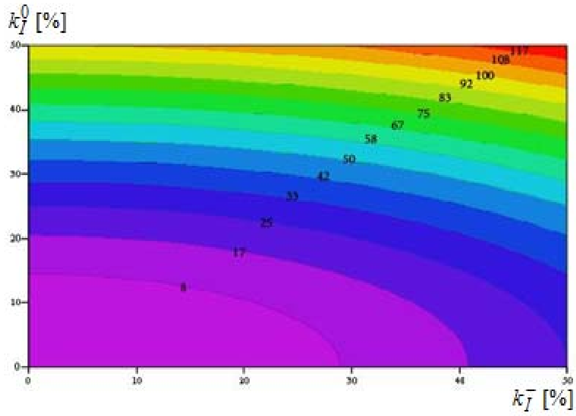

Figure 1: Relative power losses variation for $s_{ph} / s_n = 1$ in function of k_I^- and k_I^0

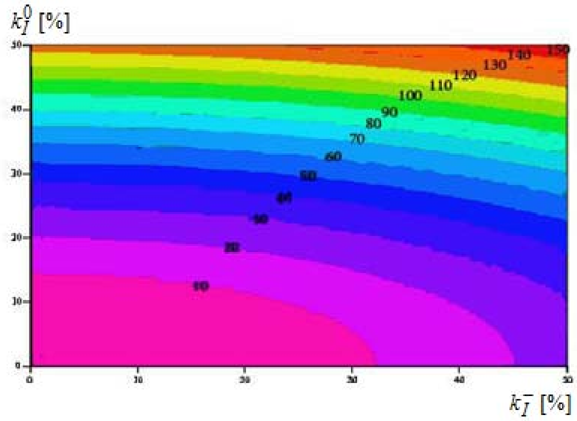

Figure 2: Relative power losses variation for s_{ph} / s_n =1.36 in function of k_I^- and k_I^0

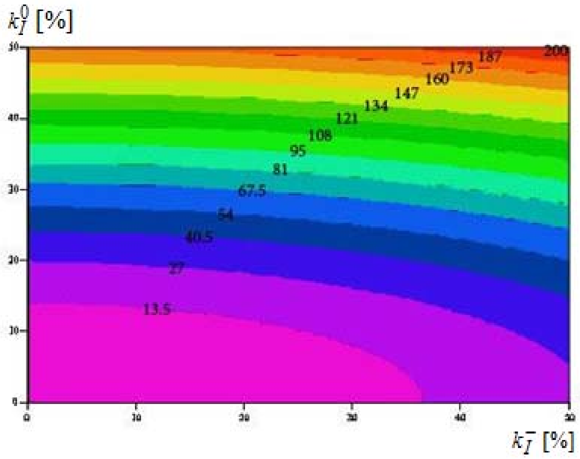

Figure 3: Relative power losses variation for s_{ph} / s_n =2 in function of k_I^- and k_I^0

2.3. Losses in balance and nonsinusoidal state[2][3]

To analyze the harmonic polluted state is necessary to decompose nonsinusoidal waves in Fourier series, achieving, first of all, a sinusoidal waveform with fundamental frequency of 50 Hz and another number of sinusoidal waves where the frequencies, in general, are multiples of the fundamental frequency, called harmonics currents. Their number can be very high, reaching up to order 50, but the share in the real wave gradually decreases (the most important are the harmonics up to order 17, 19).

A negative consequence of the existence of harmonics is the increasing of the rms value of the currents, compared to the fundamental component, leading to increased power and energy losses.

The rms value of the current is given by the equation:

$$I_{ef} = \sqrt{I_f^2 + \sum_{k=2}^{n} I_k^2}, \qquad (9)$$

where:

I_f - rms value for fundamental current;

$\sum_{k=2}^{n} I_k^2$ - it refers to the full spectrum of harmonics.

The relationship that determines the power losses in this case is:

$$\Delta P = 3 \cdot R_f \cdot I_{ef}^2, \qquad (10)$$

where:

R_f - value conductor resistance corresponding to the frequency of 50 Hz

Since the resistance of conductors increases with increasing frequency (due to the skin effect), the equation (10) become complicated, and losses are determined using the equation (11):

$$\Delta P = 3 \cdot \left(R_{f1} \cdot I_1^2 + \sum_{k=2}^{n} R_{fk} \cdot I_k^2 \right) \qquad (11)$$

where:

k- represent the harmonic order for current.

Determination of relative power losses depending on the total distortion factor of the currents was done with following equation:

$$\varepsilon_{\Delta P} = THD_I^{\ 2} + \frac{R_N}{R_{ph}} \cdot \frac{\sum I_{3k}^{\ 2}}{I_1^{\ 2}} \qquad (12)$$

where:

$\varepsilon_{\Delta P}$ - relative power losses;

THD_I - Total Harmonic Distortion Factor for currents;

R_N - neutral conductor resistance;

R_{ph} - phase conductors resistance;

I_{3k} - rms value of the current of order 3k, k=1,2,…;

I_1 - rms value of the fundamental current in phase conductors.

In the following figures (Fig. 4, Fig. 5, and Fig. 6) is presented the variation of relative power losses when the ratio between cross section of phase conductor and neutral conductor have different values (1, 1.36 and 2); also Total Harmonic Distortion Factor for currents takes values between 5 and 100 % and the share of harmonics of rank 3k from total harmonics takes values of 10%, 30%, 50%, 70% and 90%.

2.4 Losses in unbalance and nonsinusoidal state[5]

The unbalance and nonsinusoidal state is the existing operating system in the national power grid. It is characterized by nonsinusoidal wave forms and unbalanced for voltages and for currents .

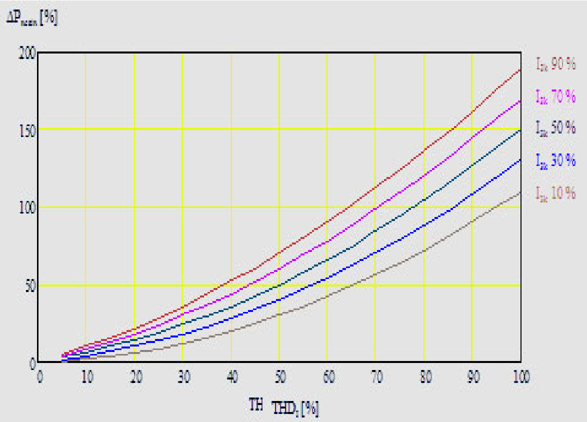

Figure 4: Relative power losses variation for $s_{ph} / s_n = 1$ in function of THD_I and I_{3k}

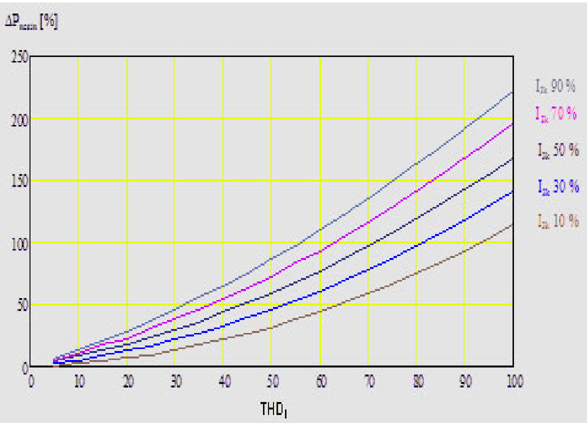

Figure 5: Relative power losses variation for $s_{ph} / s_n = 1.36$ and in function of THD_I and I_{3k}

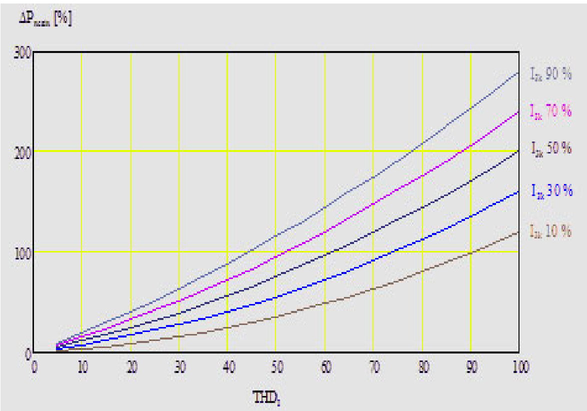

Figure 6: Relative power losses variation for $s_{ph} / s_n = 2$ and in function of THD_I and I_{3k}

In an unbalanced and harmonic polluted state, the three-phase current system, decomposed in Fourier series, leads to a sum of harmonic unbalanced currents. Every unbalanced harmonic current can be decomposed in 3 symmetric systems; e special category is the triplen harmonics existing in each phase and gathering into the neutral conductor.

The calculation of power losses is done by the following equation:

$$\Delta P_{total} = \Delta P_A + \Delta P_B + \Delta P_C \quad [W], \tag{13}$$

where:

$$\Delta P_A = \sum_{k=1}^{n} R_{ph} \cdot I_{kA}^2 \, [W] \text{ - power losses on phase A;}$$

$$\Delta P_B = \sum_{k=1}^{n} R_{ph} \cdot I_{kB}^2 [W] \text{ - power losses on phase B;}$$

$$\Delta P_C = \sum_{k=1}^{n} R_{ph} \cdot I_{kC}^2 [W] \text{ - power losses on phase C.}$$

In case of a neutral conductor to the power losses will be added the power losses occurring in the neutral conductor. Those power losses can be calculated using the following equation:

$$\Delta P_N = \sum_{k=1}^{n} R_N \cdot I_{kN}^2 \, [W] \tag{14}$$

where:

R_{ph}, R_N - phase conductors resistance, respectively neutral;

$I_{kA}, I_{kB}, I_{kC}, I_{kN}$ - represent rms value of the current harmonics on each phase separately, and neutral conductor respectively, in [A].

3. REDUCING POWER LOSSES UNDER UNBALANCED AND NONSINUSOIDAL STATE[7]

In operation, distribution networks are presenting a dynamic functioning (unbalanced and harmonic polluted), witch is different than the ideal operating state. As shown in the previous paragraph, the main negative effect of this operating state is increased power losses (due to increased rms value of current) and overload of the neutral conductor.

The analysis was made for low (U<1kV) and medium voltage (1kV<U<35kV) electrical networks (both underground and overhead electric lines).

The following presents a study that shows the variation of power losses for different type of cables like ACYABY, overhead electric line ACSR and medium voltage cable N2XS.

3.1. ACYABY Cable

This cable type is used in electricity distribution networks suitable for installation in the ground, in cable ducts or in indoor and outdoor mounting conditions.

For this type of cable power losses are presented bellow; for the phase and neutral cross sections of 3x240+120 mm^2, respectively 4x240 mm^2.

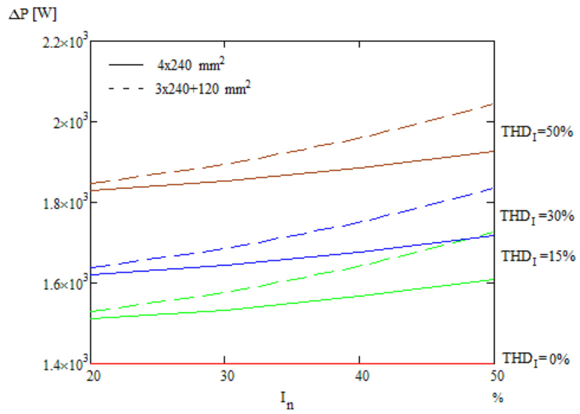

Figure 7: ACYABY Power losses for different values of current in neutral conductor

It can be notice, when the neutral cross section is half of phase cross section, the power losses are increased compare with the case when the phase and neutral cross section are equal, for different share of harmonics and unbalanced currents.

3.2. Electric line ACSR

The power losses for this type of overhead electric line are presented in next figure for different share values of harmonics and unbalanced currents. It is taking in consideration that in first case the cross sections of phase and neutral conductors are equals (95 mm^2) and in the second case the cross section of phase is 95 mm^2 and the neutral cross section is 75 mm^2.

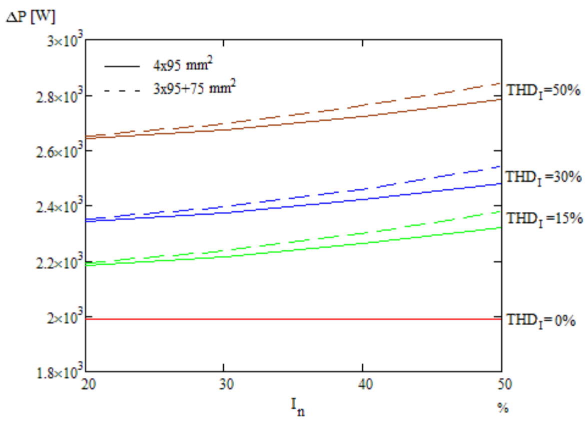

Figure 8: ACSR Power losses for different values of current in neutral conductor

Because of a ratio close to value 1 (1.36) the power losses do not presents significant growth; with the increase of share of harmonics (also the triplen) it is noticed that the power losses in first case (when ratio between cross sections is 1) are smaller than the second case (when ratio between cross sections is 1.36).

3.3. N2XS Cable

It is used in the supply stations of electricity, in cable channels or in the outdoor.
It will use a cable with phase cross section of 120 mm^2 and the neutral cross section will be 120 mm^2 and 70 mm^2.
The growth of power losses when in neutral conductor exists different values for current, for this case, is presented in next figure:

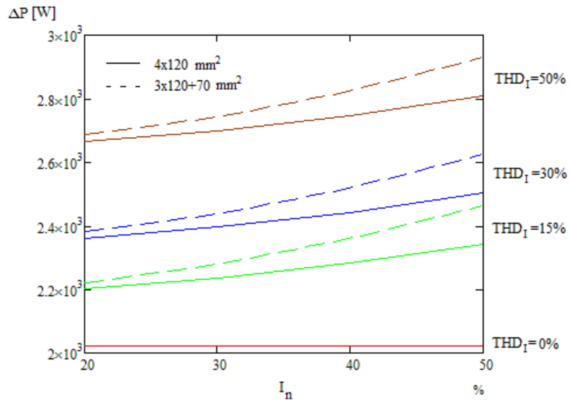

Figure 9: N2XS Power losses for different values of current in neutral conductor

4. INVESTMENT DEPRECIATION IN CABLE[7]

Choosing electrical cables is made in the design phase of electrical networks, when it is considered the ideal operating system. Thus, for electrical networks with four electrical conductors are selected, generally, different types of cables which have the cross section of neutral conductor less than the phase conductors.
A solution to reduce power losses is to replace existing cable with electrical cable containing the cross section of neutral conductor equal or even greater than the phase conductor.
The following a study that shows profitability replacement of different types of cable (ACYABY, electric line ACSR and medium voltage cable N2XS) is presented.
Duration of investment depreciation to replace portions of a ACYABY cable of 100 m is shown in Figure 10. It is noted that the investment recovery is achieved within a maximum period of 5 years if the neutral current share is 20% and decreases to approximately 2 years if the share of neutral current reaches approximately 50% of the current phase.
Determination of power losses and depreciation on investment by replacing an ACSR airline with cross section of phase conductor of 95 mm^2 and cross section for neutral conductor of 70 mm^2 with an ACSR airline with 95 mm^2 for both conductors phase and neutral, was perform in the same way wich was perform for ACYABY cable. Considering the small

difference in price between the two types of electric airlines, the investment is recovered in a short time, less than a year – Fig. 11.

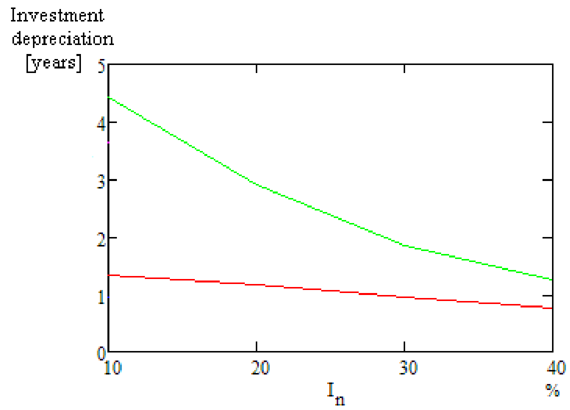

Figure 10: Investment depreciation for ACYABY cable

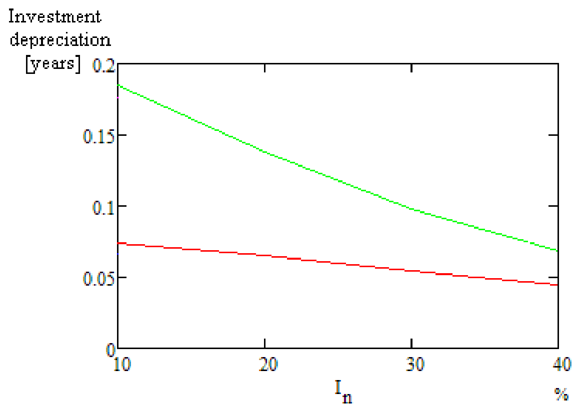

Figure 11: Investment depreciation for ACSR electric airline

Investing for replacing a medium voltage cable N2XS of the type 3x120 + 70 mm^2 with a cable which have the ratio between the phase conductor and the neutral conductor 1 is presented in Fig. 12.

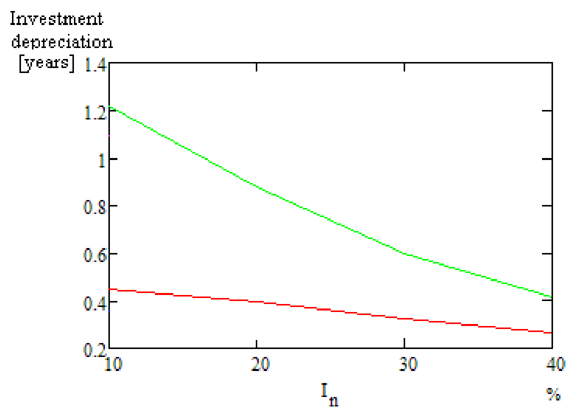

Figure 12: Investment depreciation for N2XS cable

For the evaluation of the economic impact produced by the pollution level some aspects were taken in consideration:

- the operating time is 24 h/day, 365 days/year;
- the price of kWh is 0.14 Euro;
- the actual price for electric cables;
- the anual interest is 12.5%.

4. CONCLUSIONS

Currently, electrical distribution networks operates in an unbalanced and harmonic polluted state. This situation is continually worsening, due to the increasing number of domestic and industrial consumers that containing nonlinear and unbalanced devices.

The main effect of this state of operating is the increasing power losses of electrical lines and operating expenses. A solution to solve this problems is a proper design of new electrical lines and replace existing four conductors cables, which are characterized by cross sections of the neutral conductor smaller than the phase conductors, with electrical conductors which have the neutral conductor cross section corresponding to operating conditions.

The paper presents aspects used to determinate the power losses and their variation, depending on the electricity quality. On the other hand, it underlines the influence of factors which increase the power losses: the harmonic and unbalanced currents, the ratio between phase conductors and neutral conductor cross sections.

Finally an economical aproch was carried out and some results were presented in respect of the investments depreciation for different cables: ACYABY cable, ACSR airline and medium voltage cable N2XS.

Taking into account all matters analysed, it can be seen that the use of cables with neutral cross section equal to the phase conductors cross section is more justified in respect of cable power losses. More than that additional investment in electrical cables can be recovered in a relatively short period of time.

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