POWER FACTOR IN INSTALLATIONS WITH NON-LINEAR RECEIVERS AND HEATING ELEMENTS OF THE POWER CABLES OF THE VARIOUS EQUIPMENT

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The paper presents an analysis based on experimental data of the non-sinusoidal situation from an installation supplied in three-phase low-voltage alternating current. The analysis was designed to determine how the power factor varies and the operation of the capacitor bank used to improve it. It was found that the presence of harmonic distortions shows relatively large differences between the value of the power factor (calculated as the ratio between active power and apparent power) PF and $\cos\varphi$ *(cosine of the phase shift angle between the fundamental components of voltage and current curves). As harmonic distortion regimes cause additional dissipation in the power conductors, a calculation method for heating the cables was also presented, the simulation being performed on the type of cable for which the operating parameters were recorded.*

Keywords: non-sinusoidal situation, power factor, heating of power cables

1. Introduction

Modern electrical equipment, which uses commutation elements, introduces distortions and harmonics of current and voltage in the supply network, respectively, causing an increase in active power losses, overcurrent in three-phase networks and heating of conductors, overvoltage in network nodes or equipment terminals and disturbances. in their operation. The authors studied these phenomena on an industrial user who was found a strong non-sinusoidal regime, accompanied by the accentuated heating of some electrical conductors in various areas, to highlight the disturbances and establish a calculation methodology for the additional thermal effect that occurs. The first records showed the presence of strong non-sinusoidal currents. Under these conditions, the need for one-week monitoring was established to have complete information.

Measurements were also made to analyse the shape of the absorbed electric current. The analysed scheme comprises two departures, each of which

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feeds strongly nonlinear receptors. The measurements were performed on the low voltage secondary circuit of the power supply transformer of the analysed section. In the analysis of voltage and current distortions, it is necessary to consider differently, the two notions regarding the power factor. For the analysis of the user's operation, the following main electrical quantities were monitored: variation of rms value of phase voltages, variation of rms value of electric current on tree phases, variation of voltage distortion factor, variation of harmonic level of order 5 & 7, variation of imbalance, variation long-term flickering factor and the occurrence of transient situations.

2. Analysis of experimental data

The recording of voltage and electric current phasors highlighted a correct phase sequence of voltages and electric currents (fig. 1).

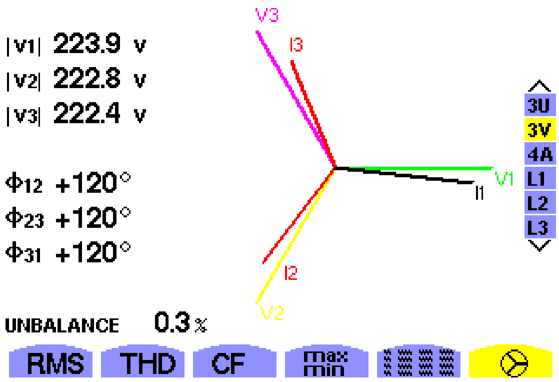


Fig. 1 - Phase sequence of voltage and current phasors.

At the time of recording, the electric current phasors indicated an inductive phase shift for the fundamental harmonic. The phase origin was taken as the voltage phasor from phase 1, and according to the current norms, the phase sequence analysis is performed for the phasors corresponding to the fundamental harmonic [1,2]. The initial recording of the voltage curves on the three phases and of the corresponding electric currents showed a strongly distorted shape of them.

Fig. 2 shows the shape of the L1 phase voltages, when a voltage peak was recorded on the oscilloscope for a very short period. Fig. 3 shows the shape of the electric currents on phase L2, similar on all three phases, during two periods.

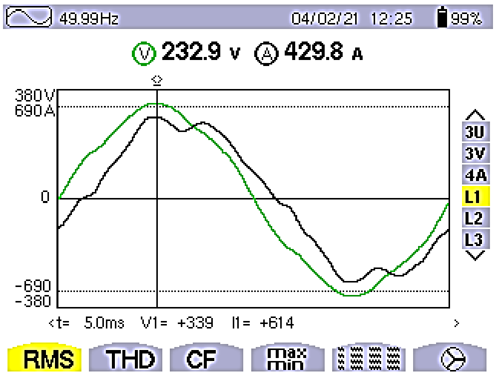


Fig.2 - The shape of the L1 phase voltages (marked in green) and current (marked in black) Start of monitoring period

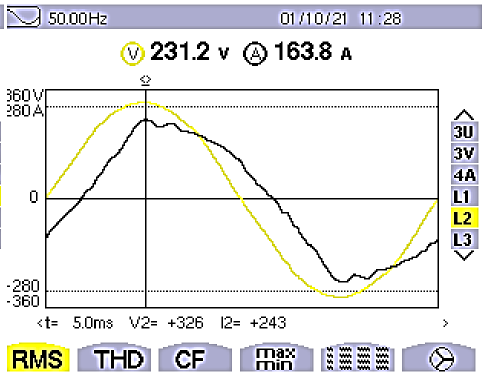
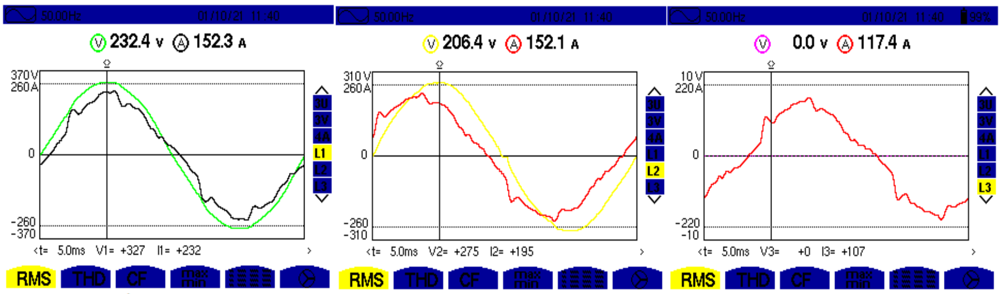


Fig.3 - The shape of the L2 phase voltages (marked in yellow) and current (marked in black) End of monitoring period

The differences between the zero value crossings of electric current curves, on the three phases, are indicated in Fig. 4 (a, b, c). Given the distortion of the analysed curves, a phase shift specific to sinusoidal quantities cannot be defined.



a) Phase L1 b) Phase L2 c) Phase L3

Fig. 4 - Voltage and current curves on the three phases.

The strong distortion of the curves and the distance from the sinusoidal shape is determined by the large number of frequency converters used to power the electric drive motors, which are not equipped with systems to limit the level of distortion. Fig. 5 shows the shape of the voltage curve at the supply bars and the electric current absorbed by a circuit that supplies a 6-pulse electronic converter attached to an electric drive motor (example needed to be able to observe the possible causes of the appearance of a non-sinusoidal situation in others dedicated industrial electronic devices, too) [1,3,4]

Fig. 5 - The shape of the voltage curve and the current curve absorbed by a frequency converter.

To obtain the information necessary for the analysis of the consumer operation mode, the following main electrical quantities were monitored: the variation of the rms value of the phase voltages (Fig. 6), the variation of the electric current rms value on the tree phases (Fig. 7), the variation of the voltage distortion factor (Fig. 8), the variation of the order 5 harmonic level (Fig. 9), the variation of the asymmetry factor (Fig. 10) and the variation of the long-term factor flicker *Plt* (Fig. 11) [1,5].

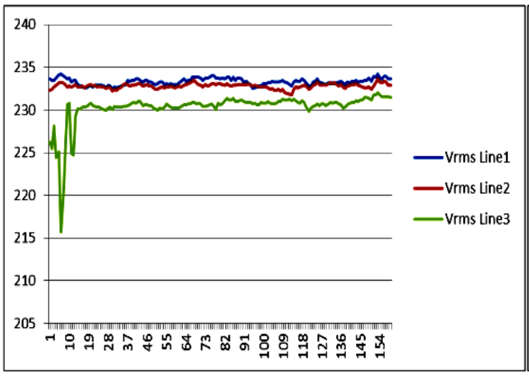


Fig. 6 - Variation of the rms value of the voltage on the three phases.

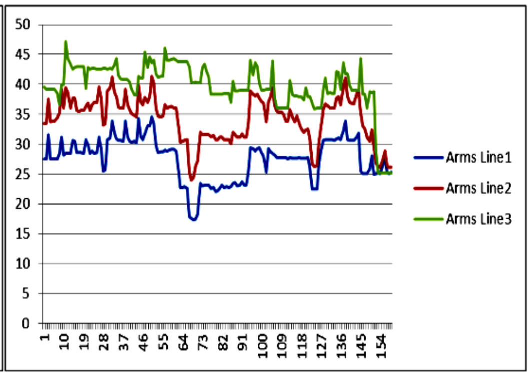


Fig.7 - The variation of the rms value of the electric current on the three phases

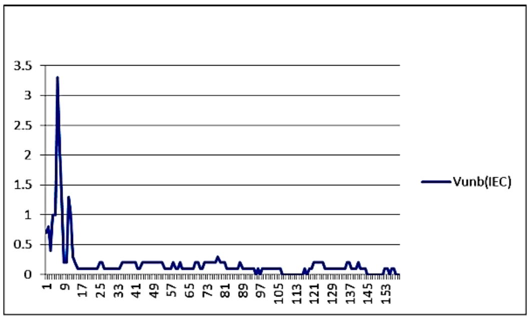


Fig.8 - Variation of voltage distortion factor

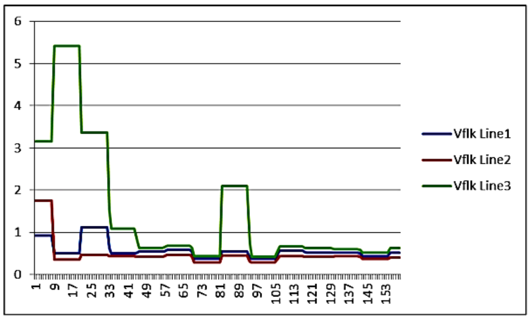


Fig.9 - Variation in the level of voltage harmonics of order 5.

In the first minutes of Phase 3 (Line3) registration, several transients appear which should not normally be considered. The analysis of the data in Fig. 6 highlights the fact that the voltage varies within wide limits (minimum value 215 V and maximum value 235 V), the actual value of the voltages on the three phases being within the allowed limits (230 ± 10%) [1,6]. The data in Fig. 7 indicate a wide variation in the rms value of the electric current on each phase, but the well-sized power supply system does not lead to unacceptable voltage dips during the working performance.

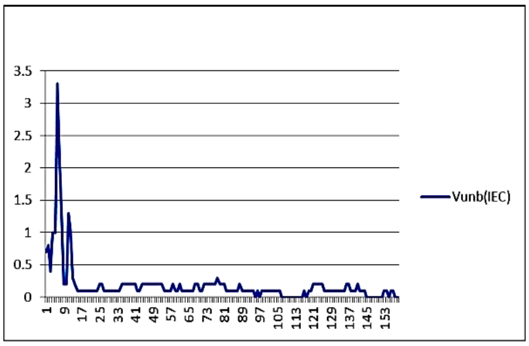


Fig. 10 - Variation of the negative unbalance factor

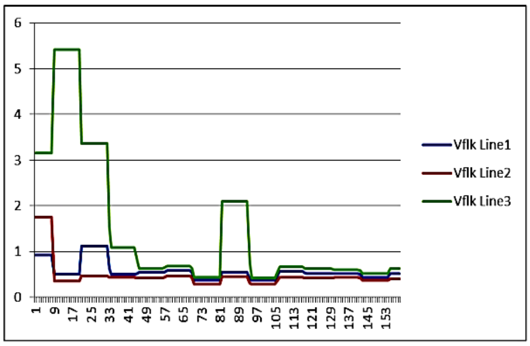


Fig.11 - Variation in voltage fluctuation level (long-term factor P_{lt} - flicker effect).

The distortion factor on the supply voltage curves exceeds the permissible limits (maximum 8%) during the transients on phase 3 [1,3]. The harmonic analysis of the voltage (fig.12) and electric current curves (fig. 13) indicated that the most important harmonic component is the one of rank 5. In this sense, the variation of the rank 5 harmonic was monitored (fig. 12).

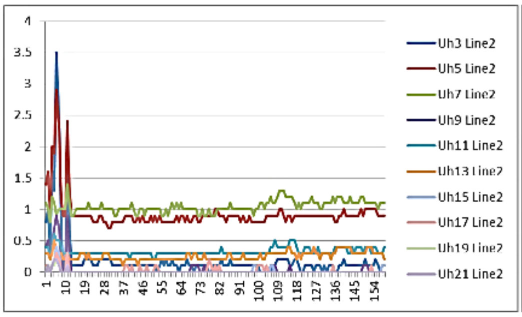


Fig. 12 - Harmonic spectrum of voltage curves on phase 3 (similar on Phase 1 and 2).

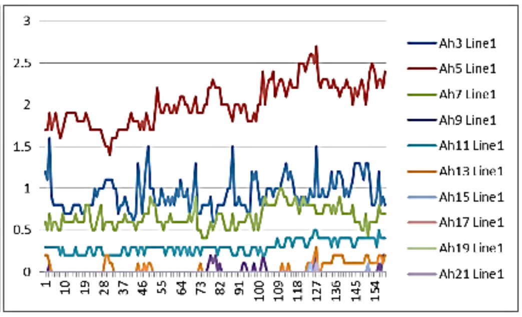


Fig. 13 - Harmonic spectrum of electric current curves on phase 1 (like all phases).

The data in Fig. 12 indicate that the 5th grade harmonic exceeds the permitted limits in terms of electrical quality (5% allowable value) during the transients [1,5]. The unbalance analysis of the power supply system indicated that the negative factor, calculated as the ratio between the negative phase voltage component and the positive component is within the limits imposed by the energy quality standards. electrical (permissible value 2%) [1,6]. This is also confirmed by the analysis of the compliance with the established limits, indicated in Fig. 10. Wide range variations in the rms value of the electric current required the analysis of the existence of voltage fluctuations. Monitoring referred to the long-term flicker indicator P_{lt}, calculated as an aggregation of short-term flicker values over a two-hour interval.

The recorded data (Fig. 11) indicate that for most of the working time, the level of voltage fluctuations was within the allowed limits (allowed value P_{lt} <1, in 95% of the time). Some values that exceed the allowed limits (Fig. 15) are due, in most cases, to important transient regimes in the power supply network. The small number of events of this type allows the assessment of the adequate quality of electricity, from the point of view of voltage fluctuations. The values indicated in Fig. 13 show that the 5th order harmonics in the phase current curve, at the time of determination, have the highest values (18.4%, representing 230.1 A).

This information can also be found in the tables on events in the form of voltage dips (fig. 14), corresponding to the same time interval in which voltage fluctuations were found, which determined the long-term flicker effect.

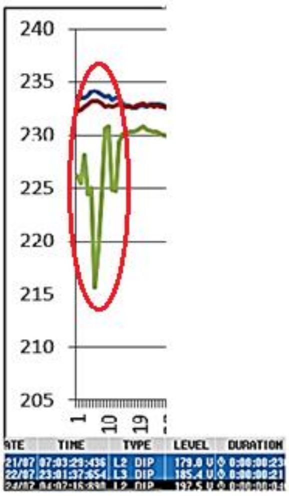


Fig. 14 - Voltage dips during monitoring.

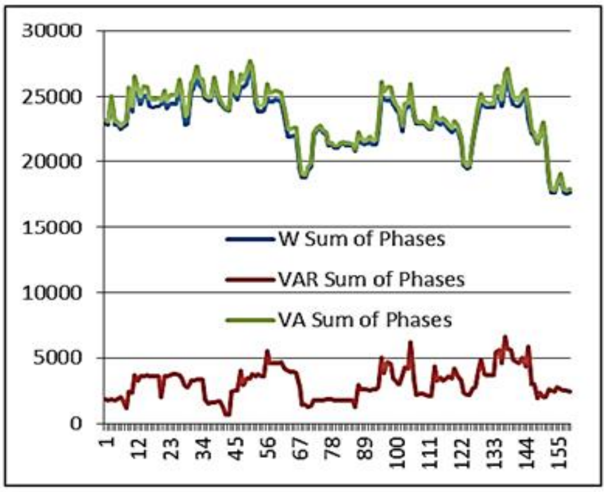


Fig.15 - Powers absorbed by the analysed section, during the monitoring period and

The distortion of the voltage curves is determined by the 5th and 7th harmonics. Figs. 12 and 13 show the spectral values of the voltage and electric currents in the circuit. The corresponding values for the neutral conductor, although important, are not of practical interest because they refer to a reduced rms value of the electric current through this conductor (the electrical quantities are practically symmetrical and the multiple components of order 3 are reduced).

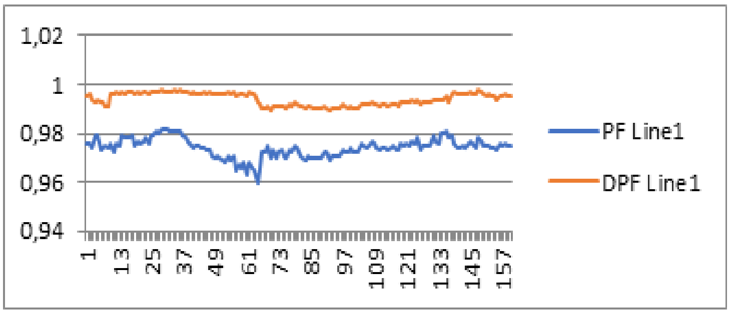
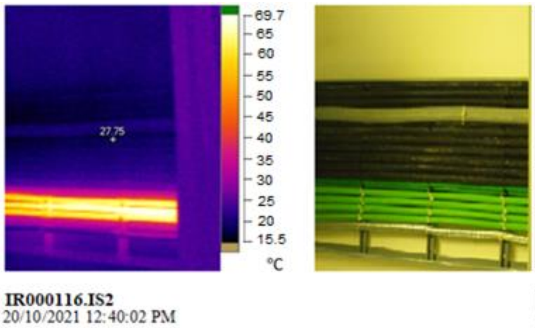


Fig. 16 PF (power factor) versus cos φ (D PF).

The presence of harmonic distortions on the voltage and current curves causes relatively large differences between the value of the power factor (calculated as the ratio between active power and apparent power) *PF* and cos φ (cosines of the phase shift angle between the fundamental components of voltage and current curves). In this sense, in Fig. 15 are presented values of the electric powers in the circuit and in Fig. 16 the comparative variation of PF and cos φ (DPF) on line 1 (behaviour approximately like phases 2 and 3). In Fig. 15, the power indicated in kVAr is the complementary power $\sqrt{Q^2 + D^2}$ in which Q is the reactive power (according to Budeanu's theory [7]), and D is the distortion power. The presence of the distortion power D determines the reduction of the power factor, independent of the presence of the reactive power.

4. Heating of electrical conductors due to the specific mode of operation of non-linear receivers.

The presence of harmonic distortions in the electrical network is a reality and an increasingly present phenomenon. They are mainly due to electric current electronic equipment using switching power supplies (SMPS) and frequency converters for controlling the speed of electric motors in various applications [5,6,8]. The main effects of these distortions on the power conductors of three-phase machines and electrical appliances are the charging of the neutral conductor by increasing the return current and the apparent increase of the electrical resistance by skin effect. In an unbalanced network with distorting mode, in the neutral conductor there is a potential that determines the appearance of a harmonic current by summing the 3rd harmonics. This determines the appearance of a current that can be up to three times the phase current. In most cases, the neutral conductor in the power conductors has a smaller cross section than the phase conductors, which accentuates its overheating. Apart from the additional heat generated by the electric current through the neutral conductor, the cross-sectional area of the cable is reduced due to the skin effect. All harmonics cause additional losses in the phase conductors but the skin effect, which is negligible at 50 Hz, begins to matter from 350 Hz (7th and higher harmonics). For this reason, the apparent electrical resistance can be up to 60% higher than the direct current electrical resistance of conductor. Fig. 16 shows the IR image of a switching power supply cable. This situation is extremely dangerous because the amount of heat generated by the Joule-Lenz effect is proportional to the square of the current intensity, and in the case of a strongly distorted waves, the heating of the conductor can be much higher than in the case of a normal sinusoidal current [9,10,11,12].



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Calibration Range	-10.00°C to 250.00°C

Main Image Markers

Name	Temperature	Emissivity	Background
Centerpoint	27.75°C	0.95	22.00°C

Fig. 17 - The IR image of a switching power supply cable.

The heating of a three-phase power cables can be estimated from the equivalent conductor model, which is a cable of the same material and has insulation of the same type and size but contains a single conductor with a section equal to the sum of the sections traversed by an electric current and a current. totally equal to the sum of all the currents in the phases as from the neutral conductor (Fig. 18).

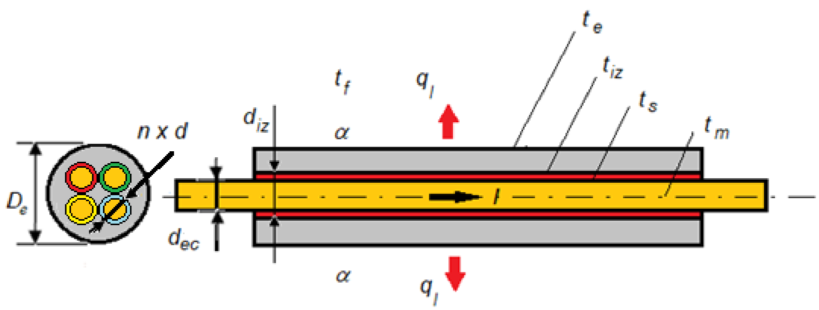

Fig. 18 - The equivalent conductor.

The heat flux generated by the Joule-Lenz dissipative effect, for 1 m length of three-phase cable can be expressed as [9]:

$$\dot{q}_l = 3\rho_c \frac{I_f^2}{A_f}\left(1 + 3k_d \frac{A_f}{A_n}\right) \left[\frac{\mathrm{W}}{\mathrm{m}}\right] \tag{1}$$

where I_f [A] is the phase current, A_f, A_n [m^2] is the phase conductor and neutral conductor areas, respectively, and ρ_c [Ωm] is the electrical resistivity of the conductor material [13,14,15]. The distortion coefficient k_d has values in the range [0 ... 1] depending on the phase unbalance and the shape of the distortions in relation to the perfect sinusoid. It can be expressed in relation with phase current I_f and neutral conductor current I_n by formula:

$$k_d = \left(\frac{I_n}{3I_f}\right)^2 \tag{2}$$

This heat flux must be taken by convection by the ambient air with temperature t_a [°C], according to Newton's law, resulting in the temperature t_e [°C] on the outer surface of the insulation:

$$t_e = t_a + \frac{\dot{q}_l}{\pi D_e \alpha} \ [\mathrm{°C}] \tag{3}$$

The convection coefficient α [W/m^{2}K] has values in the range [2 ... 5], depending on the conditions of the air circulation around it. The heat flux generated inside the metallic conductors is transmitted by conductivity through the thickness of the insulation and as a result, the temperature of the conductors has the expression:

$$t_c = t_e + \frac{\dot{q}_l}{2\pi\lambda_{iz}} \ln\frac{D_e}{d_{ec}} \ [\mathrm{°C}] \tag{4}$$

where λ_{iz} [W/mK] is the thermal conductivity coefficient of the insulation, the equivalent diameter d_{ec} depending on the size of the cross-sectional areas of the conductors [16]:

$$d_{ec} = \sqrt{\frac{4}{\pi}\left(3A_f + A_n\right)} \ [\mathrm{m}] \tag{5}$$

The analysed cables were of ROMCAB type ACYAby 3x150SE + 70RE, being low voltage cables with PVC insulation, with the jacket outer diameter of 46 mm. For this type of cable, a heating calculation was performed, the results being shown in the diagram in Fig. 19. According to the manufacturer's specification, the operating limit is 70 °C, limit that is reached in case of a perfectly sinusoidal regime (k_d = 0; I_n / I_f = 0) for a phase current intensity of 200 A, and the short-circuit limit to over 300 A [17,18].

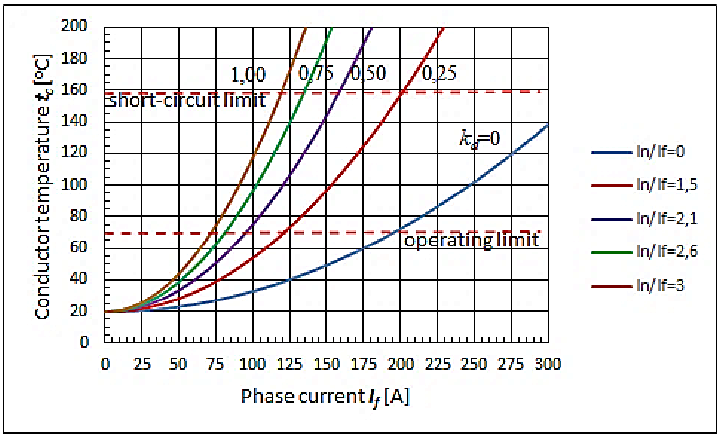

Fig. 19 - ACYAby 3x150SE+70RE three-phase cable heating operating in deforming modes

In the case of distorted current, a strong heating of the cable can be observed. For the most distorted waves (k_d = 1; I_n / I_f = 3) the short circuit limit of 160 °C is reached at about 60% of the maximum current of 200 A allowed for operation [19,20] in case of a perfect sinusoid, and operating limit of 70 °C at about 40% of it.

6. Conclusions

The analysis of the data obtained by monitoring the electrical values during a week, as well as the recordings at a given time, allows the following general conclusions to be drawn:

- the supply voltage at the supply bars is within the parameters allowed from the point of view of the electricity quality standards [1] regarding the frequency, the rms value of the voltage, the unbalance, the flicker level;
- 3 events were recorded in the form of voltage dip (the number of voltage dip is not normalized);
- the analysis section presents an electricity consumption accompanied by important distortion, which determines a low power factor [21,22];
- Improving the power factor by mounting a capacitor bank can be inefficient, given that, for a distorted voltage at the supply bars [23,24], the capacitor bank amplifies the distortion and can lead to a reduction of the power factor;
- the condenser battery can become efficient only if measures are taken to limit the waves distortion that characterizes the consumption in the section [25,26,27,28];
- for the analysis of the behaviour of the capacitor bank in distortion situation it is necessary to consider, differently, the two notions of power factor [28,29]:
  - cosφ - size valid only in the case of purely sinusoidal curves (which are not specific to current industrial consumers), but sometimes extended,

wrongly, in the case of distorted situation; in sinusoidal situation, this value is used for sizing the capacitor bank necessary to compensate the reactive power;

- *PF = P/S,* where the apparent power *S* includes the active power, the reactive power and the distorted power; this value cannot be used for the analysis of reactive power consumption nor for the sizing of the battery necessary to compensate the reactive power [30, 31]; the power factor *PF* may have low values in the conditions of a zero consumption of reactive power, but with important values of the distorted power [1,32];

- in the case of the analysed section, an important share has the distorted power, which requires that the proposed solution be first based on the limitation of the distorted power, by limiting the distortion of the electric current curves and to adopt a solution to limit of reactive power [33,34].

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