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TECHNICAL LOSSES CAUSED BY POOR POWER QUALITY IN ELECTRICAL NETWORKS WITH NONLINEAR CONSUMERS

VALENTIN STEFANESCU[1], FRANCISC IOAN HATHAZI[2], GABRIELA RATĂ[3], CONSTANTIN UNGUREANU[3]

Keywords: Electrical networks; Transformation station; Power quality analyzer; Energy losses; Current harmonics.

The main subject of this article is the calculation of additional energy losses due to current harmonics generated by nonlinear consumers. The calculations were performed using a mathematical formula derived from specialized literature and applied in the present study, in a novel manner, to an electrical supply network serving an assembly of oil wells. The primary effect of this article is to draw attention to nonlinear consumers who generate current harmonics and, in doing so, implicitly incur energy losses for the DSO.

1. ABSTRACT

The article presents a case study that represents a complex calculation modality for estimating power and energy losses within electrical distribution networks when serving nonlinear consumers. The networks considered are contaminated with harmonics and current asymmetry. The study is based on the monitoring of the currents and the distortions of the total current harmonics on each phase of an underground medium voltage power line, which supplies an entire ensemble of industrial oil wells, producing disruptions in the public network. The calculation has been performed for a scheduled analysis during an entire week of autumn.

2. INTRODUCTION

In the last years, the increasing number of nonlinear loads and power electronic devices for utility and customers are becoming sources of degradation of power quality. Power quality is a complex issue of great actuality in the power system. It covers all aspects of power system engineering, from transmission and distribution level analyses to end-user problems. Both the consumer and the supplier of electrical energy are interested in monitoring power quality at the point of common coupling (PCC). Poor power quality has adverse effects on network equipment, consumers and power systems. It has a significant impact on the losses and further increases the losses of the distribution network also.

Power quality issues are studied in the context of the power loss issue [1].

The studies on the power quality issues of the medium-voltage distribution network loss are not very thorough and most of the existing studies have studied the losses when a certain kind of power quality exists. In fact, the medium-voltage distribution network can contain many types of power quality problems. Therefore, it is important to study the additional losses of the medium-voltage distribution network when multiple power quality disturbances exist [2].

Additional power loss is caused by the non-sinusoidal currents and voltages as well as by the asymmetry in the power system components.

Several publications describe the technical and economic impact of harmonics and asymmetries on energy losses in power systems. An approach on evaluation of system losses due to harmonics in medium voltage distribution networks is presented in [3].

Reference [4] analyzed the extra losses caused by harmonic distortion, unbalance and low power factor in the cables and transformers of an industrial installation.

An analysis of the dependence between poor power quality and the additional costs associated with increased energy consumption for a typical industry is described in [5].

Some similarities regarding the power quality parameters, between this case study and other scientific articles can be found in [6, 7].

The total power transported along an electrical line has three components: active, reactive and deformed. The active power represents the quantity of usable electricity and the other two express the non-usable part. Although it may not have a practical activity, the reactive power is still necessary for magnetization, control and commutation, but the deformed power has no usage. The voltage harmonics are being supervised by the electrical energy distribution operators, as the supervisory activities upon the power supply is their direct and exclusive responsibility. The electrical energy users are to be held accountable for the harmonic currents.

The control of the voltage harmonics is discussed in the Romanian Performance Standard for the Electrical Power Distribution Service, and the harmonic currents' control is approached in the regulatory legislation PE 143/94. From the perspective of the attitude of the Distribution Operators towards the mandatory performance standard, the Electrical power quality analyzer fit out within the power supply network monitors just the voltage harmonics, without taking into consideration the current ones. Generally, it is being measured the total voltage harmonic distortion and it is being signaled the possible deviations. In contrast to the lines, within the transformers it is calculated the additional active power losses due to the abnormal regime, taking into consideration just the voltage harmonics, without bearing in mind the current ones. Given the fact that this paper as also, in the general case of transport and distribution of electrical power systems, the total distortion of the voltage harmonics fits the norm, the losses of the electrical transformer, within the upstream of the analyzed portion of the network, weren't calculated.

3. CALCULATION METHOD

The analysis starts from a mathematical expression related to the electrical power quality, a concept that must be respected by both DSOs and consumers. More precisely, from this mathematical expression in [8] results the additional power losses in a medium voltage power line, produced by the simultaneous action of the nonsinusoidal and unbalanced conditions.

[1] Society of Power Engineers in Romania
[2] University of Oradea, Faculty of Electrical Engineering and Information Technology, Oradea, Romania.
[3] „Ștefan cel Mare" University of Suceava, Faculty of Electrical Engineering and Computer Science, Suceava, Romania.
E-mails: valentin.stefanescu86@yahoo.com, ihathazi@uoradea.ro, gabriela.rata@usm.ro, costel@usm.ro

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$$\Delta P = \left[3 \cdot (I^+)^2 + 3 \cdot (I^-)^2 + \sqrt{2} \cdot \sum_{h=1}^{\infty} \sqrt{h} \cdot I_h^2\right] \cdot \cdot r - \Delta P_0 \quad (1)$$

where ΔP are the additional active power losses due to nonsymmetrical deforming steady state;

the relations in [9, 10]:

$$I_1 = \left[\frac{1}{1 + (THD)^2}\right]^{0.5} \quad (2)$$

where THD is the total harmonic distortion related to each phase and measured by the analyzer during a week (Fig. 3).

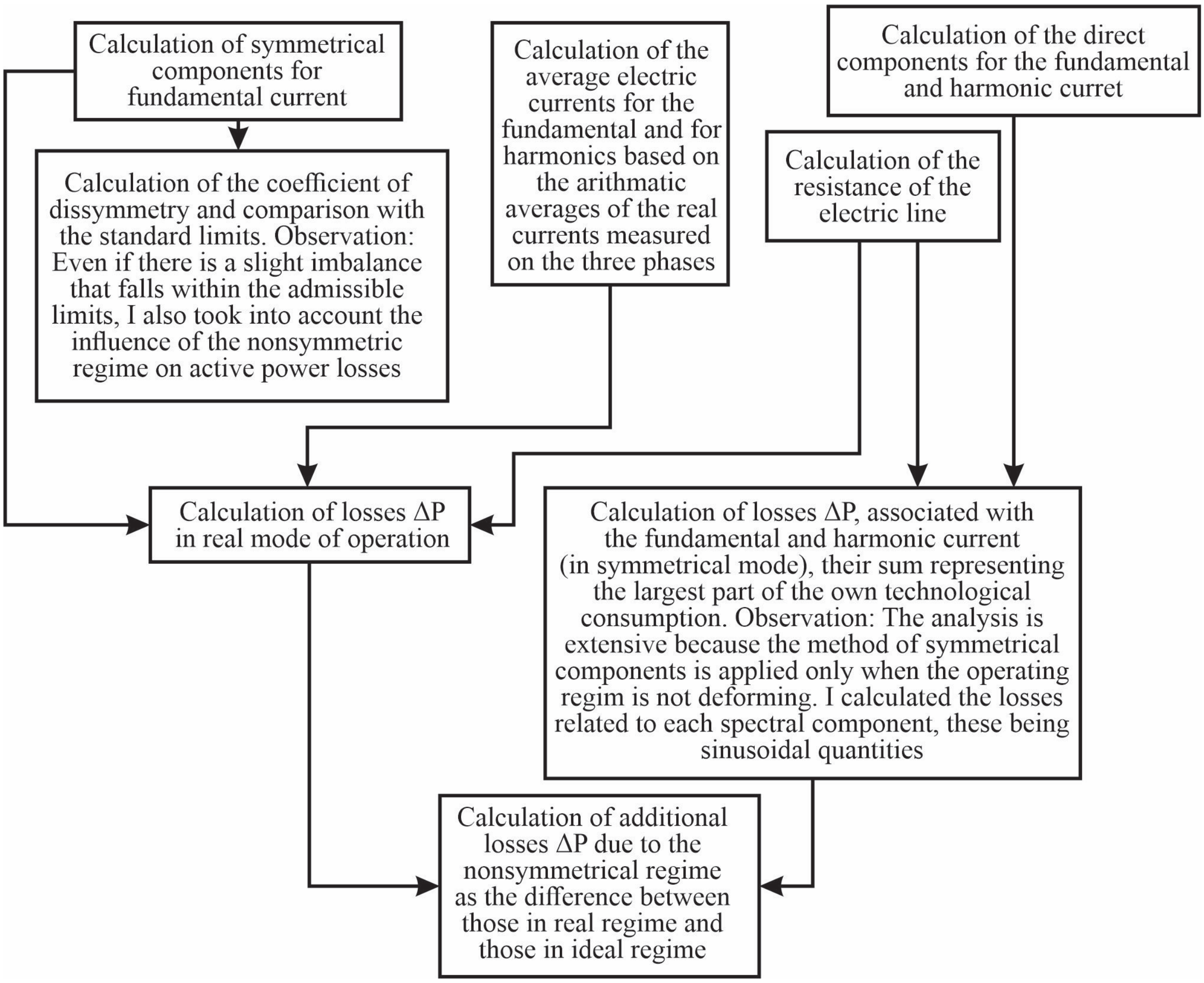

Fig. 1. – Diagram of calculation stages.

I^+, I^- – direct sequence component and inverse sequence component of the fundamental current;

h – harmonic order;

I_h – h order current harmonic;

r – resistance of the electric line;

ΔP_0 – total losses of active power in symmetrical sinusoidal steady state.

ΔP_0 losses correspond to the maximal allowed values for the harmonic currents.

In this paper, the losses of active power due to the abnormal operating conditions of the electrical distribution networks are analyzed using a real case encountered in the operation of electrical power systems.

The study carried out is based on the monitoring of currents and total harmonic current distortions on each phase of an underground medium voltage power line that feeds an industrial assembly of oil wells that introduces disturbances in the public network.

The fundamental currents on each phase calculated using

The power quality analyzer has been mounted through measuring transformers in a medium voltage switchgear panel of the transformation station located in the nearby of the oil wells. The currents based on which this analysis was performed are the actual measured currents without needing to be multiplied by any constant or transformation ratio.

The electrical wiring diagram of the power quality analyzer installed in the 20 kV system of the analyzed transformation station is shown below.

The term „transformation station” was used instead of „transformer substation” because the feeder connection installation contains HV/MV equipment, not MV/LV.

The current harmonics (in p.u.) have been calculated using the relation [9, 10]:

$$I_h = \frac{\alpha I_1}{h} \quad (3)$$

where h =3, 5, 7, 9, 11, 13, 15, 19, 21, 23, 25 is the harmonic order, and α is given by relation [9, 10]:

$$\alpha = \frac{(THD)}{0.463} \qquad (4)$$

The intensities of the fundamental currents and the harmonics corresponding to each phase were calculated by the product of their values in p.u. and the RMS values measured by the analyzer which are presented in Fig. 2.

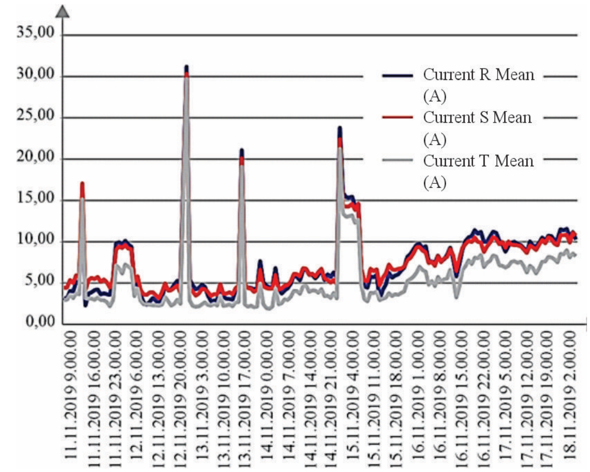

Fig. 2 – The graphical representation of the phase currents measured by the analyzer during a week.

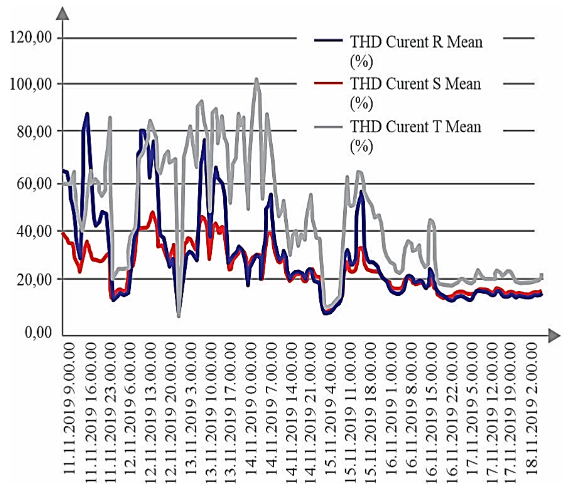

Fig. 3 – The graphical representation of THD measured by the analyzer during a week.

Next, the fundamental fractions of the current harmonics for each phase are calculated and compared with the compatibility limit levels, as specified in the national standard PE 143/94 [11].

To determine the number of deviations of the harmonics from the imposed maximum limit, it was calculated the Isc/Is ratio.

The short circuit current is given by the relation:

$$I_{sc} = E/Z_k \; = (c \cdot U_n/\sqrt{3})/Z_k \qquad (5)$$

where: c=1.1 is the maximum voltage factor chosen for Un = 20 kV and

$$Z_k = \sqrt{(R_S + R_L)^2 + (X_S + X_L)^2} \qquad (6)$$

is the short circuit impedance

The calculated short-circuit impedance is Z_k=2.039 Ohm.

The calculated short-circuit current is I_{sc}= 6.23 kA. I_S is the average current of the supply line and is calculated with the relation:

$$I_s = (I_R + I_S + I_T)/3 \qquad (7)$$

for each value of the phase currents measured by the analyzer (Fig. 2).

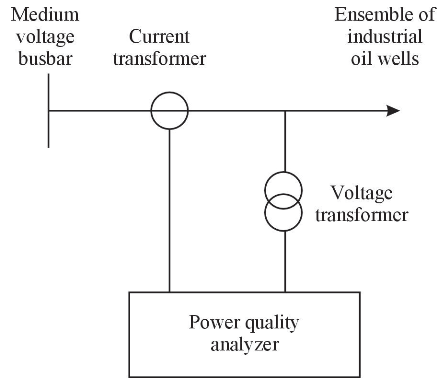

Fig. 4 – Electrical wiring diagram of the power quality analyzer.

Because in three-phase networks without neutral conductor the third order harmonic currents and their multiples are eliminated, we will analyze only the harmonic currents of rank 5,7,11,13,17,19,23,25.

In Fig. 5 the value of the fundamental current for each phase for one week was graphically represented, and in Fig. 6-8 represent the 5th, 7th and 11th order harmonics.

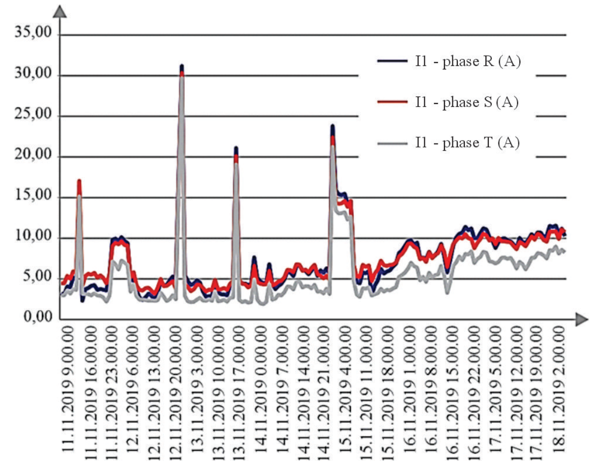

Fig. 5 – Graphical representation of fundamental currents in a week, calculated with the relation (2).

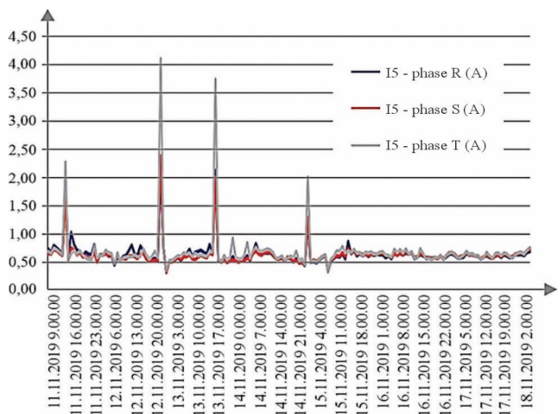

Fig. 6 – Graphical representation of I5 corresponding to each phase in the week, calculated from the relation (3).

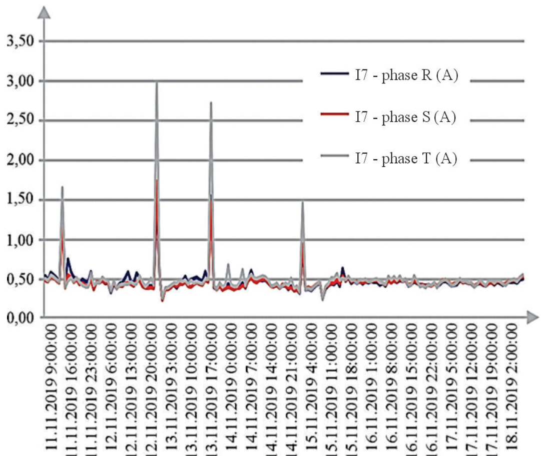

Fig. 7 – Graphical representation of I7 corresponding to each phase in the week, calculated from the relation (3).

Because the ratio differs for each time interval, they were chosen from the table 1 thresholds corresponding to each harmonic.

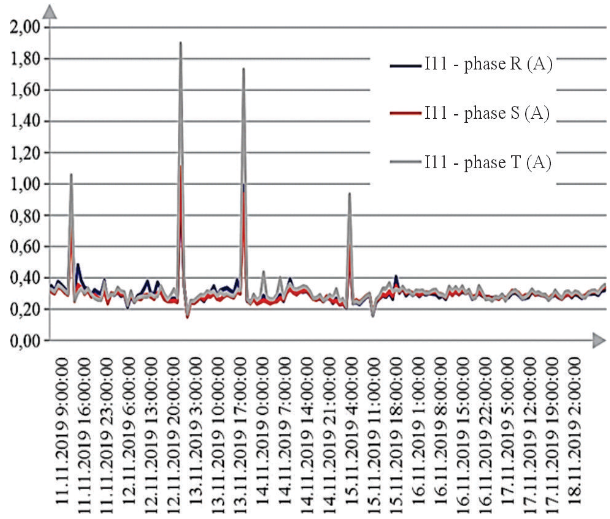

Fig. 8 – Graphical representation of I11 corresponding to each phase in the week, calculated from the relation (3).

The number of deviations of current harmonics from the standard limits must not exceed 5% of the total number of recordings. The ΔP losses have been computed both using measured I_h values and recommended I_h values. The values of the fundamental fractions of the current harmonics that do not fall within the normal limits were reduced to the allowed threshold to calculate the intensities of the current harmonics corresponding to the sinusoidal operating mode. The damage caused by the action of non-symmetrical and deforming operating modes is reflected in the difference between the energy losses in the abnormal regime and those in normal conditions.

Table 1

Compatibility limit levels (in percent of fundamental current) for harmonic currents, according to the national standard PE 143/94 [11]

I_{SC}/I_S	h<11	11≤h<17	17≤h<23	23≤h<35
<20	4.0	2.0	1.5	0.6
20<50	7.0	3.5	2.5	1.0
50<100	10.0	4.5	4.0	1.5
100<1000	12.0	5.5	5.0	2.0
>1000	15.0	7.0	6.0	2.5

The allure of the curves in the graphs for THD and harmonics is approximately the same, depending on maintenance, company activities and other factors regarding the earth’s substrates. The degree of similarity between the graphs is influenced by the fact that the THD was measured and the harmonic currents were calculated.

The assessment of the non-symmetric regime was carried out by calculating the direct and negative sequence electric currents. In the case of three-phase electric lines without a neutral conductor, the zero-sequence component of the current system is zero.

Using the geometric method based on solving Napoleon's triangles, for the case of the zero-sequence component, the proposed relations are [12]:

$$I^{+} = \sqrt{\frac{I_{f2} + \sqrt{3I_{f2}^{2} - 6I_{f4}}}{6}} \tag{8}$$

$$I^{-} = \sqrt{\frac{I_{f2} - \sqrt{3I_{f2}^{2} - 6I_{f4}}}{6}} \tag{9}$$

with the notations having the following meanings [12]:

$$I_{f2} = I_1^2 + I_2^2 + I_3^2 \tag{10}$$

$$I_{f4} = I_1^4 + I_2^4 + I_3^4 \tag{11}$$

The asymmetry factor has been calculated by the ratio between the negative sequence component and the direct sequence component of the fundamental current for each time interval. The obtained values must not exceed the admissible limit (2% at low and medium voltage) in 95% of the total recordings. In our case, this limit was not exceeded at all, but in the calculation of active power losses in a normal regime, we considered the fact that there is a slight imbalance.

Next, the hourly losses of active power have been calculated in symmetrical and sinusoidal operating mode within the phases of the analyzed feeder for the fundamental current and the reduced harmonics. Losses represent a sum of power losses because the method of symmetrical components can only be applied in the case of the sinusoidal regime only.

In symmetrical mode, active power losses are calculated using the following formula:

$$\Delta P_{sim} = 3 \cdot R_L \cdot I_d^2 \tag{12}$$

The relation (12) has been used for the fundamental current and for each of the reduced harmonic currents.

In Fig. 9 were graphically represented the total hourly losses of active power in symmetrical and sinusoidal operating mode (ΔP0), due to its power losses, for one week have been represented.

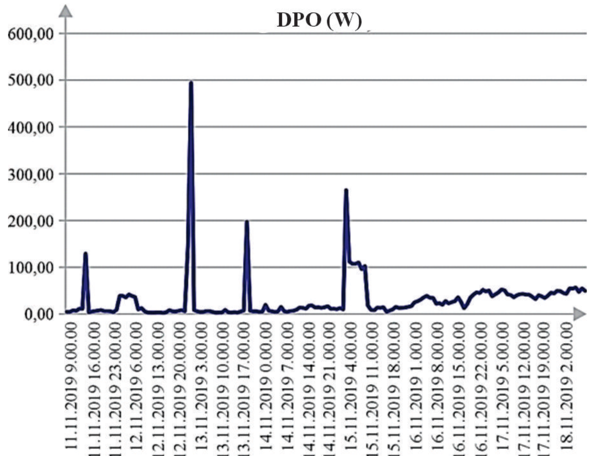

Fig. 9 – Total hourly losses of active power in symmetrical and sinusoidal operating mode, due to power losses.

The total hourly losses of active power in non-symmetrical and deformed steady state for the analyzed power line, due to the non-symmetrical and deforming regime, are calculated with the formula:

$$\left[3\cdot(I^{+})^{2}+3\cdot(I^{-})^{2}+\sqrt{2}\cdot\sum_{h=1}^{\infty}\sqrt{h}\cdot I_{h}^{2}\right]\cdot r \qquad (13)$$

where I^{+}, I^{-} are the direct sequence component, are the negative sequence component of the fundamental current

I_h is the medium harmonic current and h is the rank of the harmonic current.

In Fig.10, the total hourly losses of active power in non-symmetrical and deformed conditions in the analyzed power line, due to the non-symmetrical and deforming regime (ΔPabnormal), for one week are represented.

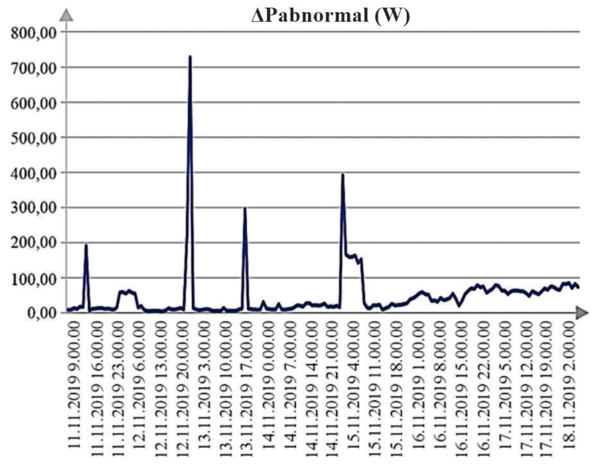

Fig. 10 – Total hourly active power losses during a non-symmetrical and the deforming operating mode.

The additional losses of active power in the analyzed power line, due to the non-symmetrical and deforming regime, have been calculated using the following formula:

$$\Delta P = \Delta P_{abnormal} - \Delta P_{0} \qquad (14)$$

Figure 11 shows the additional active power losses within

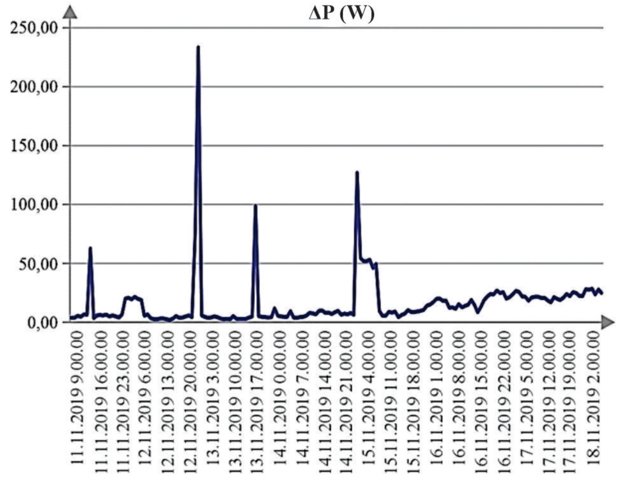

Fig. 11 – Additional active power hourly losses due to the non-symmetrical and deforming regime.

the analyzed power line, due to the non-symmetrical and deforming regime (ΔP), during one week.

4. CONCLUSIONS

Most of the time the additional losses are below 25 W, but there are some higher losses during the working days of the week. These losses represent 0.01% of the consumed power, which is 329.96 kW. The oil wells worked more intensively in the following moments: Monday at 3:00 p.m., Wednesday at 1:00 a.m. and 7:00 p.m. and Friday at 3:00 a.m. The maximum additional losses due to abnormal regimes were recorded on Wednesday at 1:00 a.m. and have a value of 233.36 W. These losses represent 0,02% of the consumed power, which is 1055.91 kW.

The maximum power absorbed by the 20 kV power line for which the calculations were made is approximately 1 MW because the analyzed circuit supplies 10 MV/LV transformer substations, each corresponding to several industrial oil wells.

The additional losses due to abnormal operating modes are very low since this analysis was performed after filters were installed in the installations, not before. This analysis reveals that there are exceedances regarding the power quality in distribution networks managed by DSOs even after nonlinear consumers install filters.

Even if the owners of the industrial park installed filters in advance to limit the deforming regime, the current harmonics still slightly exceed the normalized limits. This aspect also results from the fact that the losses of active electrical energy due to the presence of current harmonics are insignificant from a financial point of view. In the present analysis, the additional losses due to abnormal operating modes represent approximately half of those caused by its power losses. So the influence on the energy efficiency of nonlinear consumers is significant and the total losses can increase a lot for this reason.

Harmonic currents should also be monitored and algorithms capable of signaling their eventual deviations should be implemented. Exceeding certain limits lead to the unnecessary loading of the power grid and the distribution operators will bear the increase in the financial deficit related to the negligent exploitation of the electrical networks.

The originality of this article consists of two issues.

The first refers to the elaboration of a case study considering a relatively complicated general mathematical expression on which no other applications have been conceived before. Like any case study, the calculation method is not necessarily new; however, the content and application are presented in an original form.

The second problem refers to the fact that both harmonics and the direct and inverse components of currents intervene in the general expression of power losses. However, the decomposition of an unbalanced system does not apply in the case of the distorting operating mode.

Therefore, the method of decomposition into symmetrical components was not applied to the total nonsinusoidal current, but to harmonics that have sinusoidal waveforms. The calculation of symmetric components by considering harmonic current is an original method.

Another note of originality is that Fortescue's well-known theorem was not used. Still, the geometric method based on solving Napoleon's triangles was used because the power quality analyzer did not measure the phases of the current harmonics.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Valentin Ștefănescu: conceptualization, establishing restrictions, performing calculations.

Francisc Ioan Hathazi: data consistency analysis, elaboration of the graphical representations.

Gabriela Rață: literature investigation, correlation of the calculation formulas.

Constantin Ungureanu: data organization, elaboration of the calculation diagram.

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