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DETERMINING ADDITIONAL POWER AND ENERGY LOSSES IN LOW VOLTAGE ELECTRICITY DISTRIBUTION NETWORKS OPERATED IN DISTORTED AND UNBALANCED OPERATION STATES

BY

BOGDAN NEAGU*, GHEORGHE GEORGESCU and OVIDIU IVANOV

Technical University “Gheorghe Asachi” of Iaşi,
Faculty of Electrical Engineering

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Abstract. The normal operation of electricity distribution networks (EDN), particularly at the low voltage level, is generally modelled in literature using steady unbalanced and asymmetrical (distorted) states. The effect is a lower quality of supply for the various consumer categories connected directly in these networks. Using as benchmark an existing LV distribution network from Romania, this paper proposes a methodology and a software application for computing the additional active power and energy losses occurring in the phase and neutral wires. The significant increase of neutral wire current is also emphasized.

Key words: electricity distribution network; asymmetry; harmonics; power and energy losses.

1. Introduction

In a three-phase power system with sinusoidal AC supply, the ideal operating states are symmetrical on all three phases, with phase currents equal

*Corresponding author: *e-mail*: bogdan.neagu@tuiasi.ro

in modulus and out of phase with $2\pi/3$ radians, as shown in Fig. 1. Any difference in modulus and/or angle leads, obviously, to an asymmetrical operating state (Fig. 2). In theoretical load flow studies, for computing the unknown state variables, the operating conditions of the studied power system are considered ideal, *i.e.* the operation state is symmetrical and sinusoidal.

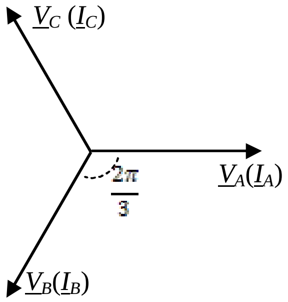

Fig. 1 – Symmetrical operation.

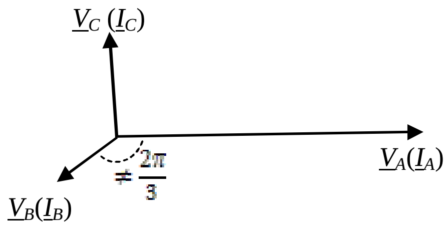

Fig. 2 – Asymmetrical operation.

An asymmetrical voltage system applied to a balanced or unbalanced electrical network leads to asymmetrical current flows.

The voltages at the synchronous machine busbars from large power plants is generally symmetrical, because of their physical characteristics and operation procedures. For this reason, large power plants do not contribute to asymmetry occurrence. Even for the particular case of asynchronous generators, used nowadays in some wind turbine designs, a symmetrical three-phase voltage system is obtained. However, when distributed generation (DG) is used intensively, or in some cases of peak load generation, this scenario changes. It should be noted that many of these small DG units, such as photovoltaic panels, are connected to LV distribution grids through electronic single-phase inverters. Because the connection points of these devices are important for minimizing the short-circuit current, voltage asymmetry is possible, relatively higher than in the case of connecting these PV panels in the high voltage grid.

According to several literature studies, (Eremia *et al.*, 2006; Golovanov *et al.*, 2007; Georgescu *et al.*, 2008; Neagu *et. al.*, 2012), the main causes for asymmetrical voltage and currents in power system components are: different impedances on the three phases of electricity transmission and distribution circuits; unbalanced phase loads; large multiple single-phase, unevenly distributed, simultaneous power demand; the presence of large two-phase consumers (electrical furnaces, electrical railroad traction etc.) unbalanced three-phase loads and others.

Obviously, an asymmetrical voltage system applied to a balanced or unbalanced electrical network leads to asymmetrical current, thus to asymmetrical operation states.

At the same time, the public electricity distribution networks supply a significant number of residential consumers and a small number of industrial consumers with relatively low power demand. Generally, all these consumers are non-linear and unevenly distributed on the three phases of the LV network. In this paper and in other works from the literature (Chicco *et al.*, 2011; Georgescu *et al.*, 2001; Hanzelka *et al.*, 2004; Neagu *et al.*, 2012), the presence of voltage and current harmonics was identified in LV networks, after extended instantaneous or interval recordings and measurement campaigns, which confirmed that the operating conditions in these networks are indeed distorted and asymmetrical.

2. The General Characteristic of Area Distribution Systems and the Consumer Categories Supplied with Electricity in these Networks

In Romania, the public electricity distribution systems use two voltage levels: medium voltage (MV – 6, 10, 20 kV) and low voltage (LV – 400 V). In the present free market conditions, the expansion and upgrading of distribution systems and the restructuring of existing electricity distribution infrastructure becomes of increasingly greater importance, after the significant consumption shifting to MV and LV levels seen in the last years. The estimate number of the consumers supplied from the Romanian EDNs, published by the Romanian Regulatory Authority for Energy, is impressive: around 9 million. 8,380,000 of these are residential consumers; 20,000 are tertiary or large non-residential; 600,000 are small and medium non-residential consumers (Georgescu *et al.*, 2001; Georgescu *et al.*, 2008; Georgescu *et al.*, 2016; Neagu *et al.*, 2016). At the same time, the improved quality of supply, higher supply capacity, improved energy transfer efficiency and loss reduction requirements became tougher for electricity distribution utilities.

Active power and energy losses occur inevitably in operation, in all network components. Together with increasing the supply capacity, the active power and energy loss reduction is an essential requirement for a reasonable or optimal EDN operation, and final consumers and electricity utilities see it as a major ongoing objective.

The LV distribution systems are the three-phase, two-phase and single-phase networks, in overhead and cable configuration. Three-phase networks generally use three active power wires and a neutral wire. The connection is in star configuration with grounded neutral.

As presented in the previous paragraphs, and for other physical reasons, the ideal sinusoidal state does not occur in real operation conditions. In reality, the operating state is distorted, the ideal fundamental sine voltage and current waves being polluted with harmonics (Chicco *et al.*, 2011; Georgescu *et al.*, 2016; Golovanov *et al.*, 2003; Hanzelka *et al.*, 2004; Neagu *et al.*, 2012).

At the same time, the LV distribution systems supply a relatively high number of three-phase and two-phase unbalanced consumers with somewhat high power demand, and a very high number of single-phase small consumers, usually with uneven distribution on the three phases.

Taking into account these aspects, it is obvious that electricity distribution systems are operated in distorted and unbalanced states. For this reason, the three-phase currents system is both unbalanced and asymmetrical, and there is a current flow on the neutral wire, obtained as the phasor sum of active wire currents.

In such asymmetrical and unbalanced operating states, a series of negative effects will certainly occur, which were extensively studied in the literature. It was said that the neutral wire current flow is ‘the place where all negative consequences gather’ in LV distribution systems.

This paper analyzes only the aspects regarding the increase or occurrence of additional active power and energy losses in LV networks which are normally operated in unbalanced and distorted conditions, for the most operating states occurring during the year.

3. The Evaluation of Additional Power and Energy Losses Occurring in LV Electricity Distribution Systems Operated in Distorted States

The urban public electricity distribution systems are in a continuous and gradual upgrading process and supply a minor number of small industrial consumers and an increasing number of residential consumers. Both these industrial and residential consumers use sophisticated receptors which, among others, cause distorted operation states and voltage and current harmonics thorough the entire period of the year.

In order to perform an analysis regarding the quality of the electricity flown through EDNs and to emphasize the distorted asymmetrical operating states occurring in these networks, both in the literature and in (Georgescu *et al.*, 2016), a significant number of measurements and recordings have been carried out in LV EDNs, in various points and on several feeders. For direct measurements, the CA8334 (Chauvin Arnaux) analyzers have been used in this study, which provide a thorough energy quality analysis, compatible with the SR EN 50160 and IEC 6100–4–30 standards.

In the literature (Chindriş *et al.*, 2005; Eremia *et al.*, 2006; Georgescu *et al.*, 2008; Georgescu *et al.*, 2016; Neagu *et al.*, 2016), for studying the distorted asymmetrical operation conditions in electrical networks, the harmonic analysis is used, which basically consists in the computation of magnitudes and phases of the fundamental wave and of the harmonics which are integer multiples of the fundamental wavelength that propagate in an electrical network. In this regard, a periodical function $\alpha(t)$ can be represented over a period as a piecewise smooth function, that can be decomposed in a trigonometric series written as:

$$\alpha\left(t\right)=A_0+\sum_{n=1}^{\infty}B_{hm}\sin\left(h\omega t\right)+\sum_{k=1}^{\infty}C_{hm}\cos\left(h\omega t\right), \tag{1}$$

where: for h = 1 the fundamental wave is obtained, while for h = 2, 3, 4,… the corresponding order harmonics are found, and A_0 is a constant.

In a three-phase electrical network with balanced phase loading, operated in a sinusoidal state, the active power losses that occur in the phase wires can be computed with an equation written as:

$$\Delta P_{\sin} = 3 r_f I_1^2 , \tag{2}$$

where: r_f is the resistance of a phase wire, and I_1 is the phase current flow.

If the LV electricity distribution network has a balanced load distribution on all three phases, which are supplying nonlinear receptors, a distorted operating state will inevitably occur.

For these situations, several cases which are considered to be close to real network operation conditions were analysed. A number of simplifying assumptions were adopted, in which the skin effect and the frequency-resistance variation was neglected. Given the known amplitudes and range of the harmonics most frequently encountered in distribution networks, these approximations will lead acceptable errors in the mathematical model used to compute the power and energy losses.

In the analyses performed for evaluating the additional active power and energy losses occurring in LV feeders as consequence of the distorted operating states, several cases or scenarios were considered, as follows: *Scenario 1* – the phase current contains the fundamental (I_1) and a multiple of three harmonic (I_{3h}) wavelength; *Scenario 2* – the phase current contains the fundamental (I_1), a multiple of three harmonic (I_{3h}), and a not multiple of three order harmonic ($I_{\neq 3h}$) wavelength; *Scenario 3* – besides the fundamental wave (I_1), the phase current contains a multiple of three (I_{3h}), and the $3h$ + 1 and $3h$ + 2 harmonic wavelengths (I_{3h+1} and I_{3h+2}).

It must be noted that the multiple of three order harmonics are present in the neutral wire, while the others are not.

For the three proposed scenarios, Tables 1,...,3 provides the equations for computing the power losses in distorted state, the additional power losses, and the percent power loss increase in distorted state.

Table 1

The Equations Used for the Power Losses, the Additional Power Losses and the Percent Power Loss Increase in EDNs Operated in Distorted State in First Scenario

State type	Symmetrical state	Distorted states- Scenario 1
Active power losses	$\Delta P_{\sin} = 3 \cdot r_f \cdot I_1^2$	$\Delta P_{defor} = 3 \cdot r_f \cdot \left(I_1^2 + I_{3h}^2\right) + r_n \cdot \left(3 \cdot I_{3h}\right)^2$ or $\Delta P_{defor} = 3 \cdot r_f \cdot \left[I_1^2 + (1+3\phi) \cdot I_{3h}^2\right]$
Additional active power losses	–	$\Delta P_{\sup l} = \Delta P_{defor} - \Delta P_{\sin}$
Percent loss increase (%)	–	$\varepsilon_{\Delta P} = \frac{\Delta P_{defor} - \Delta P_1}{\Delta P_1} \cdot 100 [\%]$ $\varepsilon_{\Delta P} = (1 + 3 \cdot \phi) \cdot \gamma_{3h}^2 \cdot 100 \ [\%]$

Table 2
The Equations Used for the Power Losses, the Additional Power Losses and the Percent Power Loss Increase in EDNs Operated in Distorted State in Second Scenario

State type	Symmetrical state	Distorted states- Scenario 2
Active power losses	$\Delta P_{\sin} = 3 \cdot r_f \cdot I_1^2$	$\Delta P_{defor} = 3 \cdot \left(I_1^2 + I_{3h}^2 + I_{\neq 3h}^2\right) \cdot r_f + \left(3 \cdot I_{3h}\right)^2 \cdot r_n$ or $\Delta P_{defor} = 3 \cdot \left[I_1^2 + I_{\neq 3h}^2 + (1+3\cdot\phi) \cdot I_{3h}^2\right] \cdot r_f$
Additional active power losses	–	$\Delta P_{\sup l} = \Delta P_{defor} - \Delta P_{\sin}$
Percent loss increase (%)	–	$\varepsilon_{\Delta P} = \left(1+3\cdot\phi+\beta^2\right)\cdot\gamma_{3h}^2 \cdot 100[\%]$

Table 3
The Equations Used for the Power Losses, the Additional Power Losses and the Percent Power Loss Increase in EDNs Operated in Distorted State in Third Scenario

State type	Symmetrical state	Distorted states- Scenario 3
Active power losses	$\Delta P_{\sin} = 3 \cdot r_f \cdot I_1^2$	$\Delta P_{defor} = 3 \cdot \left(I_1^2 + I_{3h}^2 + I_{3h+1}^2 + I_{3h+2}^2\right) \cdot r_f + \left(3 \cdot I_{3h}\right)^2 \cdot r_n$ or $\Delta P_{defor} = 3 \cdot [I_1^2 + I_{3h+1}^2 + I_{3h+2}^2 + (1+3\cdot\phi) \cdot I_{3h}^2] \cdot r_f$
Additional active power losses	–	$\Delta P_{\sup l} = \Delta P_{defor} - \Delta P_{\sin}$
Percent loss increase (%)	–	$\varepsilon_{\Delta P} = \left(1+3\cdot\phi+\beta_1^2+\beta_2^2\right)\cdot\gamma_{3h}^2 \cdot 100[\%]$

The notations used in Tables 1,...,3 are the following: r_f – the phase wire resistance; r_n – the neutral wire resistance; I_1 – the RMS value of the phase current; $\phi = r_n / r_f$ – the ratio between the neutral wire and the active wires resistance; $\beta = I_{\neq 3h} / I_{3h}$ – the ratio between the harmonic which is not multiple of three order ($I_{\neq 3h}$) and the multiple of the multiple of three order harmonic (I_{3h}); $\beta_1 = I_{3h+1} / I_{3h}$ şi $\beta_2 = I_{3h+2} / I_{3h}$ – the ratios between the harmonics which are not multiple of three order, $3h+1$ and $3h+2$, and the multiple of three order harmonic; $\gamma_{3h} = I_{3h}/I_1$ – the weight of the multiple of three order harmonic in the fundamental wave.

Over time, the analysis of the real operating states of distribution networks has been approached from different aspects by several researchers (Chindriş *et al.*, 2005; Eremia *et al.*, 2006; Georgescu *et al.*, 2008). In the works published by the authors of this paper (Georgescu *et al.*, 2016; Neagu *et al.*, 2016), based on an extended instantaneous and interval measurement campaign carried out with CA 8334 analyzers installed in different locations in LV electrical networks from Romania, the presence of distorted and asymmetrical operating states was confirmed. At the same time, the most frequent voltage and current harmonics and the highest relative amplitude harmonics (with regard to the fundamental wave amplitude) were identified:

a) the 3, 5, 7, 11 odd order and the 2 and 4 even order harmonics for current;

b) the odd order harmonics, 3, 5 and 7, for voltages.

For the real distribution network used in the paper, the percent active power loss increase was computed for the MV/LV substation transformer and on the main LV feeder sections, and was found to be of 10,...,18%, in the different scenarios considered, during a time interval that does not include the consumption peak hours. The obvious conclusion is that, for all distorted and asymmetric operating states occurring in LV EDNs over the course of a year, the percent loss increases will reduce the energy transfer efficiency in these networks.

4. Methodology and Software Tool for Evaluating the Additional Power Losses in LV Distribution Networks Operated in Asymmetrical and Distorted State

For studying the asymmetrical states of three-phase electrical networks, the symmetrical components (Fortescue's) theorem is frequently used, which states that any asymmetrical three-phase system of sinusoidal signals can be decomposed into three symmetrical systems: positive (+), negative (–) and zero (0), also known as sequence systems. As an example, Fig. 3 shows the phasor decomposition of an asymmetrical three-phase current system into three symmetrical systems. Each of the three systems has three phasors of equal length. In the zero-sequence system, the phasors are parallel and in phase, while in the positive and negative systems, the phasors are out of phase with $2\pi/3$ in direct and inverse succession (Eremia *et al.*, 2006; Georgescu *et al.*, 2001).

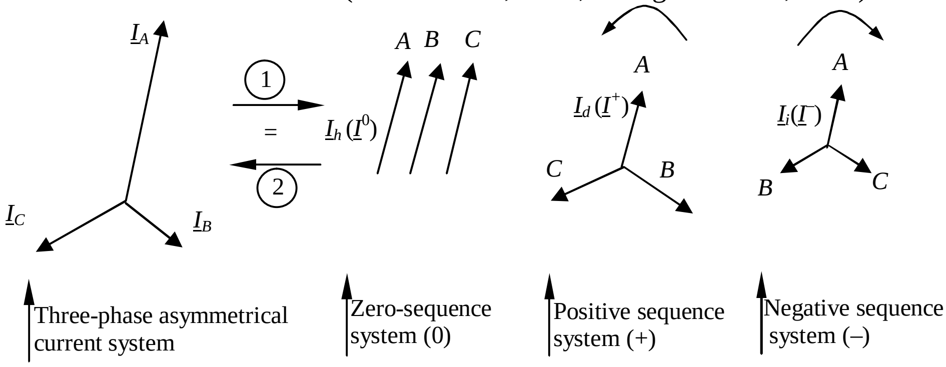

Fig. 3 – An example of decomposing an asymmetrical three phase current system into three symmetrical systems.

It follows that, in asymmetrical or unbalanced state, the asymmetrical current system that flows through the three-phase LV feeders can be decomposed into three symmetric systems of direct, inverse and zero sequence. The zero-sequence currents, being parallel and in phase, can flow through the neutral wire, when 4-wire feeders are used. Thus, in a three-phase unbalanced electrical network operated in sinusoidal state, the total active power loss can be computed with:

$$\Delta P_{\Sigma} = \Delta P_A + \Delta P_B + \Delta P_C + \Delta P_n$$

or (3)

$$\Delta P_{\Sigma} = 3 \cdot r_f \cdot \left(I_A^2 + I_B^2 + I_C^2\right) + r_n \cdot I_n^2$$

where: ΔP_A, ΔP_B, ΔP_C – the active power losses on each phase wire, and ΔP_n – the active power losses in the neutral wire.

By denoting with $\phi = r_n / r_f$ the ratio between the resistance of the neutral and phase wires, the following equation ensues for computing the neutral wire active power losses:

$$\Delta P_n = \phi r_f I_n^2 . \tag{4}$$

With (3) and (4), the total active power losses in the network can be computed as follows:

$$\Delta P_{\Sigma} = 3 r_f \left(I_A^2 + I_B^2 + I_C^2\right) + \phi r_f I_n^2 . \tag{5}$$

For generalization purposes, a situation was considered when the three-phase LV system supplies *n* nonlinear and almost identical single-phase receptors. Such consumptions can represent residential loads from apartment blocks with the same type of domestic utilities infrastructure (Georgescu *et al.*, 2008). These non-linear receptors usually have an uneven distribution on the three phases, denoted with n_A, n_B and n_C (where $n = n_A + n_B + n_C$). Also, the current taken by these receptors from the distribution network is distorted and contains three harmonics, of 3*h*, 3*h* + 1 and 3*h* + 2 orders. With these assumptions, the currents on the three phases can be written as:

$$\begin{aligned} \underline{I}_A &= n_A \underline{I}_1 \left[1 + \left(1 + \beta_1 + \beta_2\right)\gamma_{3h}\right] = \underline{k}_A \underline{I}_1; \\ \underline{I}_B &= n_B \underline{I}_1 \left[a^2 + \left(1 + \beta_1 a^2 + \beta_2 a\right)\gamma_{3h}\right] = \underline{k}_B \underline{I}_1; \\ \underline{I}_C &= n_C \underline{I}_1 \left[a + \left(1 + \beta_1 a + \beta_2 a^2\right)\gamma_{3h}\right] = \underline{k}_C \underline{I}_1, \end{aligned} \tag{6}$$

where: I_1 is the RMS value of the fundamental wave of the current taken by a non-linear receptor; $a = -(1/2) + \mathrm{j}\left(\sqrt{3}/2\right)$, $a^2 = -(1/2) - \mathrm{j}\left(\sqrt{3}/2\right)$ – the rotation operators (Steinmetz).

The neutral wire current ($\underline{I}_n$) can be computed with:

$$\begin{aligned} \underline{I}_n = \Big\{ &\left(n_A + n_B a^2 + n_C a\right) + \gamma_{3h}\Big[\left(1 + \beta_1 + \beta_2\right) n_A + \left(1 + \beta_1 a^2 + \beta_2 a\right) n_B + \\ &+ \left(1 + \beta_1 a + \beta_2 a^2\right) n_C \Big]\Big\} \underline{I}_1 = \underline{k}_n \underline{I}_1 . \end{aligned} \tag{7}$$

Taking into account the adopted assumptions and the above mathematical model, the percent active power loss increase in LV distribution networks operated in asymmetrical and distorted states, with regard to the balanced states ($\varepsilon_{\Delta P}= 100(\Delta P_{\Sigma} - \Delta P_{\sin})/\Delta P_{\sin}$), can be computed with:

$$\varepsilon_{\Delta P} = \frac{k_A^2 + k_B^2 + k_C^2 + \phi k_n^2 - \left(n^2/3\right)}{n^2/3} \times 100, \ [\%]. \quad (8)$$

For automatically computing the additional active power losses which occur in LV network components, in asymmetrical and distorted states, the RENESDEF (Rețele Electrice în regim NESimetric şi DEFormant – Electrical Networks in Asymmetrical and Distorted State) software tool was created, which provides a complex analysis of all scenarios encountered in the normal operation of public LV distribution networks. The RENESDEF software was built in JAVA, with several subroutines managed through an easy-to-use graphical interface. Given the rapid technological advances seen lately in electronics, online and offline EDN monitoring and computing power, intelligent metering devices connected through optic fiber can be successfully used for monitoring, storing and transmitting state values (voltages, currents) which describe the asymmetrical and distorted operating states occurring in electricity distribution networks.

The input data required by the RENESDEF software are: the general parameters of the studied network (topology, wire types and cross-sections, feeder lengths), recorded and measured values (RMS currents and voltages on phase and neutral wires, harmonic amplitudes up to the 50^{th} order, computed with regard to the fundamental wave amplitude).

The results provided by the RENESDEF application are:

- ✓ The active power losses in balanced sinusoidal steady state, in absolute values;
- ✓ The active power losses in asymmetrical distorted states, corresponding to the scenarios considered in the paper, in absolute values, computed using combinations of harmonic amplitudes measured in the network;
- ✓ The additional power losses in asymmetrical distorted states, corresponding to the scenarios considered in the paper, in percent values, computed by using combinations of harmonic amplitudes measured in the network

5. Case Study

For emphasizing the approach proposed in this paper and the capabilities of the RENESDEF software, a real public LV electricity distribution network supplied by a MV/LV transformer was analysed. Its one-line diagram is depicted in Fig. 4, together with the physical data for the feeders (cable type, cross-section and length). This EDN has 6 LV feeders operated in radial configuration, and supplies apartment buildings, a food store, an office building and a mobile communications antenna. The network points in which the CA 8334 analyzers were installed for voltage and current monitoring are marked on the one-line diagram: the LV busbar of the transformer (1), and the main sections of each LV feeder (2,...,7).

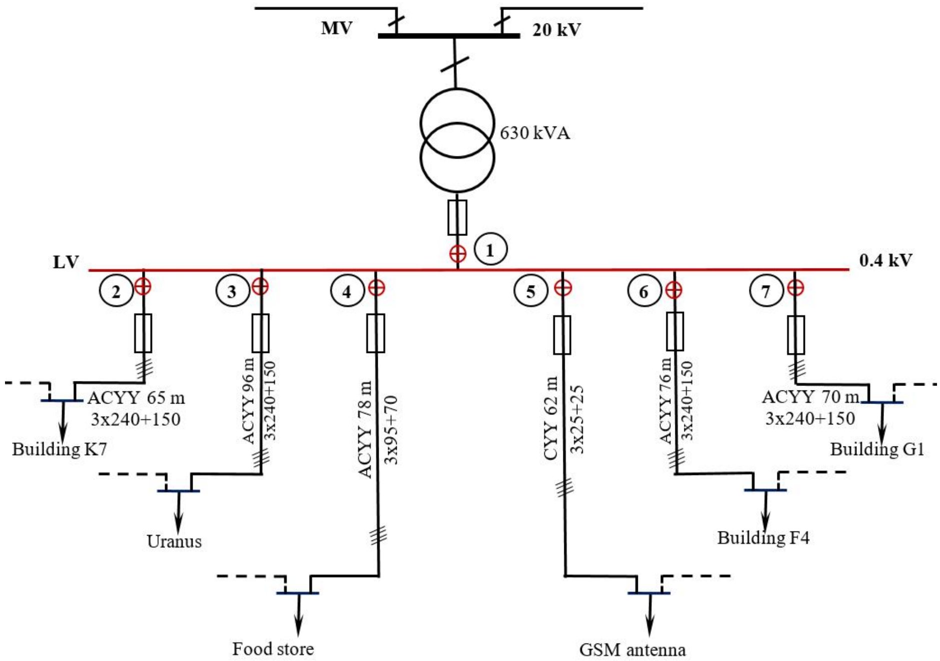

Fig. 4 – The one-line diagram of the LV distribution network used in the case study.

After analyzing the input data and the results of an extended recording campaign of instantaneous and interval measurements, carried out in the LV distribution networks belonging to the e-on Moldova Distributie power utility, using the aforementioned analyzers, and considering the theoretical findings presented in this paper, it becomes obvious that the operating states of these networks are asymmetrical and distorted on all the monitored LV feeders. Based on the data collected during the measurement campaign in the benchmark LV network, it has been found that that the phase loadings and currents are not equal, as it can be seen in Fig. 5. Harmonics are also present in the current waves, with higher amplitudes for the odd 3, 5, 7, 11 and even 2 and 4th orders. As examples, in Fig. 6 is shown the evolution of the 3rd order harmonic on the first feeder, which supplies the apartment building K7 (measurement point 2 in the one-line diagram), while Fig. 7,...,9 show the 5th, 7th and 11th order harmonics recorded in the same measurement point.

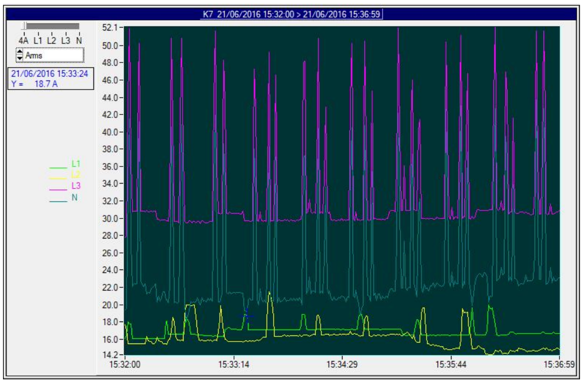

Fig. 5 – The RMS current values measured on the first section of the three-phase feeder which supplies the apartment building K7.

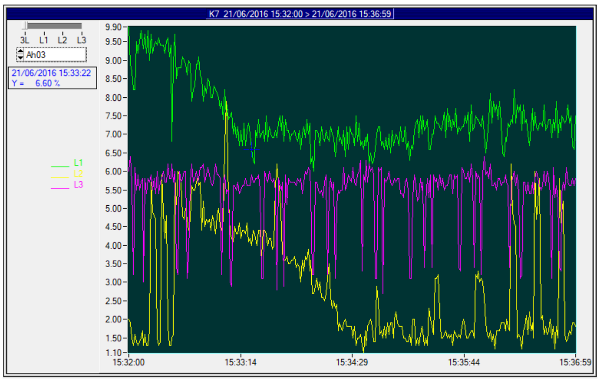

Fig. 6 – The 3rd order harmonic recorded on the first sections of the feeder which supplies the apartment building K7.

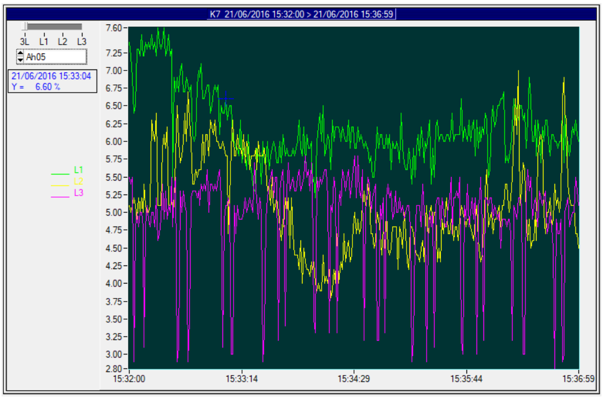

Fig. 7 – The 5th order harmonic recorded on the first sections of the feeder which supplies the apartment building K7.

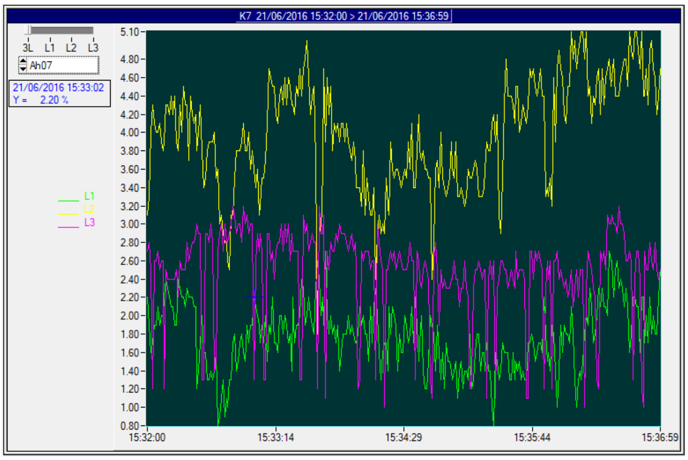

Fig. 8 – The 7th order harmonic recorded on the first sections of the feeder which supplies the apartment building K7.

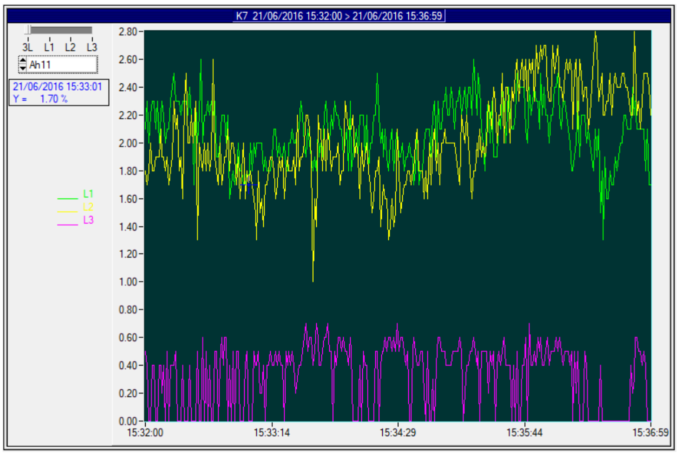

Fig. 9 – The 11th order harmonic recorded on the first sections of the feeder which supplies the apartment building K7.

It should be noted that the time interval in which the measurements were taken in the distribution network was in a working Tuesday, in the summer, outside the peak loading hours, because three feeders supply apartment buildings. In these conditions, the MV/LV transformer was loaded at only 43%, while at peak load, at 21.00-23.00 hours in summer, the transformer loading for residential areas goes up to 60,...,68%, according to earlier tests. Thus, at peak load, the loss increase in asymmetrical and distorted state will exceed 14%.

The additional active power losses occurring in the main LV feeder sections, determined using the instantaneous harmonic current measurements recorded in points (2…7) from Fig. 4, were computed for the third scenario from Table 3, considering the fundamental wave and the most frequent combinations of harmonics detected by the CA 8334 analyzers in the network. In Table 4 are given the results computed by the RENESDEF software tool, regarding the active power losses on each phase of the 6 feeders, while Table 3 gives the additional power losses in distorted states and the percent loss increase.

Table 4

The Active Power Losses in Asymmetrical Distorted State on Each Phase of the Six Feeders from the Network, in the Most Frequent Four Probable Situations

Feeders/ Phases		Scenarios			
		1 (h_3+h_4+h_5)	2 (h_3+h_{11}+h_4)	3 (h_3+h_5+h_7)	4 (h_3+h_7+h_{11})
2	ΔP_A, [W]	4.694	4.372	4.891	4.562
	ΔP_B, [W]	3.136	3.268	3.298	3.434
	ΔP_C, [W]	3.789	3.948	3.966	4.129
	ΔP_n, [W]	0.269	0.294	0.255	0.278
	ΔP, [W]	11.886	11.882	12.410	12.404
3	ΔP_A, [W]	466.76	452.62	487.21	472.77
	ΔP_B, [W]	299.51	305.37	315.94	321.95
	ΔP_C, [W]	397.09	404.63	415.92	423.62
	ΔP_n, [W]	62.19	63.90	59.83	61.48
	ΔP, [W]	1225.54	1226.53	1278.91	1279.82
4	ΔP_A, [W]	1058.48	1000.11	1116.28	1056.32
	ΔP_B, [W]	530.66	552.42	571.81	594.36
	ΔP_C, [W]	822.28	853.98	873.01	905.51
	ΔP_n, [W]	236.14	244.59	228.30	236.45
	ΔP, [W]	2647.57	2651.11	2789.40	2792.64
5	ΔP_A, [W]	8.034	7.897	8.262	8.123
	ΔP_B, [W]	6.520	6.582	6.725	6.788
	ΔP_C, [W]	7.364	7.434	7.582	7.653
	ΔP_n, [W]	0.140	0.145	0.133	0.137
	ΔP, [W]	22.058	22.058	22.701	22.701
6	ΔP_A, [W]	1.692	1.632	1.793	1.731
	ΔP_B, [W]	0.847	0.869	0.919	0.942
	ΔP_C, [W]	1.326	1.359	1.415	1.449
	ΔP_n, [W]	0.473	0.484	0.456	0.466
	ΔP, [W]	4.339	4.344	4.583	4.588
7	ΔP_A, [W]	1.154	1.048	1.210	1.101
	ΔP_B, [W]	0.709	0.752	0.753	0.797
	ΔP_C, [W]	0.900	0.953	0.949	1.004
	ΔP_n, [W]	0.100	0.110	0.095	0.105
	ΔP, [W]	2.862	2.863	3.007	3.007

The operating state of the analyzed LV network is asymmetrical and distorted, which leads to asymmetrical phase currents containing multiple of three order harmonics and zero-sequence components. By adding up these currents, the neutral wire current is obtained. Thus, for the main sections of the feeders from Fig. 4, the average instantaneous values of the neutral wire currents are given in Table 5, together with the types of consumers, neutral wire data and the maximum thermal currents.

Table 5
The Additional Active Power Losses in Asymmetrical Distorted State, in the Most Frequent Four Probable Situations

Scenario	Feeder											
	2		3		4		5		6		7	
	W	%	W	%	W	%	W	%	W	%	W	%
1 (h_3+h_4+h_5)	0.44	3.87	76.50	6.66	298.44	12.70	0.430	1.99	0.578	15.37	0.146	5.39
2 (h_3+h_{11}+h_4)	0.44	3.83	77.49	6.74	301.98	12.86	0.430	1.99	0.583	15.51	0.147	5.41
3 (h_3+h_5+h_7)	0.97	8.45	129.87	11.30	440.28	18.74	1.072	4.96	0.823	21.87	0.291	10.71
4 (h_3+h_7+h_{11})	0.96	8.39	130.78	11.38	443.52	18.88	1.072	4.96	0.827	22.00	0.291	10.71

Because the measurements taken from the network and presented in this paper are from a time interval which does not include the peak hours for residential consumers in the summer season (feeders 2, 6 and 7), it is obvious that the neutral wire currents in these feeders will have higher values than those presented in Table 6.

Table 6
The Average Neutral Wire Currents on the LV Feeders

Feeder no.	Consumer category	Wire cross-section [mm^2]	Wire material	Thermal rated current, [A]	Average recorded current, [A]
(2)	Apartment building	150	Al	275	45.76
(3)	Supermarket	150	Al	275	89.32
(4)	Market	70	Al	175	97.18
(5)	GSM antenna	25	Cu	130	18.42
(6)	Apartment building	150	Al	275	38.27
(7)	Apartment building	150	Al	275	32.65

6. Conclusions

In the LV electricity distribution network analyzed in this paper, the real operating state is distorted and asymmetrical, which leads to distorted phase currents, containing multiple of three harmonics, and to the presence of zero-sequence currents. By adding up these zero-sequence currents, the neutral wire currents are obtained. Even if the measurements presented in the paper were taken in time intervals outside the peak hours, the neutral wire currents were high, with the prospect of even higher values in the peak hours, close to the allowed thermal limits of the wires.

At the same time, these asymmetrical and distorted states have a negative influence on the quality of supply and incur additional active power and energy losses in all electricity distribution systems covering a given area.

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DETERMINAREA PIERDERILOR SUPLIMENTARE DE PUTERE ŞI ENERGIE ÎN REŢELELE ELECTRICE DE DISTRIBUŢIE DE JOASĂ TENSIUNE CARE FUNCŢIONEAZĂ ÎN REGIM DEFORMANT ŞI DEZECHILIBRAT

(Rezumat)

Funcţionarea în regimurile permanente normale ale reţelelor electrice de distribuţie (RED), mai ales în cazul celor de joasă tensiune (JT), este abordată, de regulă, în literatura de specialitate, drept regimuri permanente dezechilibrate şi nesinusoidale (deformante). Sunt evidenţiate în acest sens scăderea calităţii energiei electrice furnizate diferitelor categorii de receptoare alimentate direct cu energie electrică din aceste reţele de JT. În cadrul lucrării, pentru o reţea reală existentă de JT este propusă o metodologie şi o aplicaţie de calcul privind apariţia atât a unor pierderi suplimentare de putere şi energie activă în conductoarele de fază, cât şi în conductorul de nul, evidenţiind fenomenul de creştere substanţială a valorilor curenţilor ce străbat conductoarele de nul ale RED.