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DISTORTING STATE ANALYSIS IN ELECTRIC ENERGY DISTRIBUTION NETWORKS

BY

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Abstract. In present, technological condition, the distorting (non-sinusoidal) state appearance in public distribution networks is inevitable, because any non-linear or parametric circuit element represents a harmonic source, and the decrease of negative effects produced by this state is an essential issue. Under these circumstances, the paper presents distorted state parameters computation methodology and software application for complete and complex analyses. On the strength of recorded measurements with different monitoring systems based on Alpha-meters and harmonic analysers, the distorting state parameters for some substation from Iaşi County, was computed. The results can be used by the specialists to adopting important decisions for public distribution network planning, development and operation.

Key words: harmonics; distorting state; total harmonic distortion coefficient.

1. Introduction

The intensive power electronic usage, the advanced technologies and equipment introduction using some nonlinear devices especially, has resulted in

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the pollution intensification with harmonics of power networks from low (LV) and medium voltage (MV) public distribution systems caused by the stronger appearance of distorting states. Under these conditions, their operation lead to increased voltage and current distortion curves in power systems, with disturbing effects on electrical equipment designed for sinusoidal state operation (Georgescu *et al.*, 2009).

By public distribution networks are supplied with electric energy receivers, and households and third-party consumers (*i.e.* commercial, social-cultural, public services, small industrial consumers), located in a rural or urban habitable area (Georgescu *et al.*, 2008). Regarding LV and MV three-phase networks, because it cannot be ensured for a long interval a three phases symmetrical load, these utilities usually real operating state is an unbalanced non-sinusoidal periodical steady-state.

The appearance of the non-sinusoidal (distorting) state in public distribution systems is inevitable under present technological conditions, because any element of a nonlinear or parametric circuit represents a harmonic source. The response signal of such an element, excited by a sinusoidal signal, is a non-sinusoidal periodical signal.

The contribution issue of each distorting element to harmonic currents flow is frequently encountered in the literature, and attempts have been made to set more specific rules, responding to issue complexity. Moreover, the too severe setting rules can lead to unjustified economic costs, required for consumer adaptation. Furthermore, an ethical problem appears concerning the responsibilities of power customers and suppliers.

2. Harmonic Sources and Distorting State Effects on Electric Energy Distribution Networks

In power distribution systems, the distortion state or harmonic distortion derives from the voltage wave distortion, so that the spectral analysis brings out multiple fundamental frequencies (Arumugam *et al.*, 2011). Then, voltages and currents are not perfectly sinusoidal, since certain electrical devices, absorbing non-sinusoidal currents, spread them by distorting, at the same time, the voltage wave. These distortions are spread through electric energy network.

In the public power supply systems, the distortion state is produced by the distorting elements generating or amplifying harmonic voltages and currents. Such distorting elements can be divided as follows:

a) Elements which, supplied with rigorously sinusoidal voltages or currents, produce distorting phenomena (arc furnaces, welding devices, rectifiers and, more generally, any highly nonlinear circuit element).

b) Elements which do not generate distorting phenomena, but which, being supplied with distorting currents, amplify this distortion. This category includes electrical lines when their own inductances and capacitances form oscillating circuits, whose frequencies may coincide with the one of the harmonic currents produced by elements generating distorting phenomena.

In addition, distortion state sources can also be classified as follows:

a) Harmonic voltage sources, represented by sources producing non-sinusoidal electromotive voltages. For such sources, voltage and current waves are alternately symmetrical and, consequently, contain only uneven harmonics. Even harmonics are mainly generated by harmonic current sources. The mutual dependency between current and voltage harmonics is strongly influenced both by the reactance and the configuration of the electrical network, and by the resonance phenomena that may appear under certain circumstances.

b) Harmonic current sources, represented by distorting elements which, in a sinusoidal voltage state, usually introduce superior harmonics into the current absorbed from the electrical distribution network. As for the values of the harmonic voltages generated in the source connection point, these are proportional to the intensities of the generated harmonic currents, as well as to the values of the equivalent impedances of the electrical network

Also, all power electronic converters used in different types of electronic systems can increase harmonic disturbances by injecting harmonic currents directly into power system (Ko *et al.*, 2011). From the above, should be noted that the sources responsible for distortion state can exist both in the energy suppliers' and the consumers' electrical networks (Georgescu *et al.*, 2006).

Actually, the main sources of low power harmonics in public distribution systems are represented by fluorescent lighting, TV-sets, computers, printers, faxes, copying machines and, more and more often, the whole range of appliances. All these receivers have input supply systems for electrical devices with switch-mode-power-supply commuting sources. The major issues of these receivers are mostly related to the variety of connection points in the power distribution systems, with implications for current flow (Varvara *et al.*, 2009).

The main effects of distribution systems operating in a distortion state are the followings: active power losses increasing; overvoltages appearance in power network nodes and in appliance terminals; overcurrents; malfunctioning of measuring devices, protection and automation devices, counters, measuring transformers, remote-controlled devices; increase of noise produced by electrical machines; phone distortions, etc. (Georgescu *et al.*, 2008).

3. Distorting State Parameters Determination

Typically, the harmonics analysis from a distribution network involves the parameters determination for non-sinusoidal signals (voltages and currents), which are measured with modern monitoring systems, digital electronic meters, *i.e.* Alpha-meters produced by ABB (Fig. 1), and different harmonic analysers such as Fluke 343 shown in Fig. 2 (www.eamc.ro/Assets/poze/fluke_435).

The *voltage and current harmonics levels* are estimated with coefficients γ_u and γ_i, calculated for each single phase and defined accordingly

$$\gamma_u = \frac{U_k}{U_1} \cdot 100,\ [\%]; \qquad \gamma_i = \frac{I_k}{I_1} \cdot 100,\ [\%], \tag{1}$$

where: U_k, I_k are k-order harmonic for voltage and current, respectively; U_1, I_1 – 1st harmonic (the fundamental one).

Fig. 1 – ABB Alpha Power + Meter.

Fig. 2 – Fluke 343.

The Total Harmonic Distortion Coefficient (THD) in voltage and current is calculated for each phase and defined by relations

$$\mathrm{THD}_u = \frac{\sqrt{\sum_{k=2}^{\infty} U_k^2}}{U_1} \cdot 100,\ [\%]; \qquad \mathrm{THD}_i = \frac{\sqrt{\sum_{k=2}^{\infty} I_k^2}}{I_1} \cdot 100,\ [\%]. \tag{2}$$

The Root Mean Square (RMS) in voltage and current for non-sinusoidal values is defined with the expressions

$$U = \sqrt{\sum_{k=0}^{\infty} U_k^2},\ [\mathrm{V}]; \qquad I = \sqrt{\sum_{k=0}^{\infty} I_k^2},\ [\mathrm{A}]. \tag{3}$$

From (3) are known the voltage and current harmonic levels, γ_{umk} and γ_{imk} ($m = a, b, c$ – phase index, k – harmonic order) and the actual values U_m, I_m; the fundamental amplitudes can be calculated as follows:

$$U_{1m}=\frac{100U_m}{\sqrt{100^2+\sum_{k=2}^{15}\gamma_{umk}^2}},\ [\text{V}];\qquad I_{1m}=\frac{100I_m}{\sqrt{100^2+\sum_{k=2}^{15}\gamma_{imk}^2}},\ [\text{A}].\tag{4}$$

The actual values of each voltage and current harmonic are calculated with the following relations:

$$U_{km}=\gamma_{ukm}U_{1m},\ [\text{V}],\quad I_{km}=\gamma_{ikm}I_{1m},\ [\text{A}];\ \ (m=a,b,c;\ \ k=2,3,\ldots,15).\tag{5}$$

For each phase, the U_d (voltage) and I_d (current) residual distortion value can be determined with the formulae

$$U_d=\sqrt{\sum_{k=2}^{15}U_k^2},\ \ [\text{V}];\quad I_d=\sqrt{\sum_{k=2}^{15}I_k^2},\ \ [\text{A}].\tag{6}$$

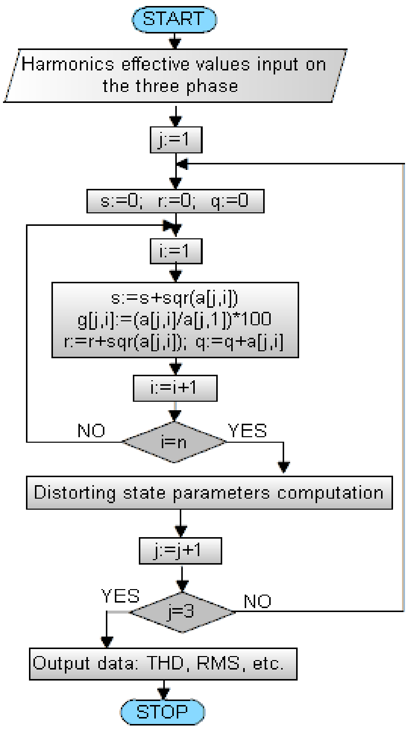

Fig. 3 – The proposed application flowchart.

For harmonics indicators computation, in the paper a specialized application was developed, within the measurements provided by Alpha three-phase electronic meters, harmonic analysers or other monitoring systems, starting from effective and fundamental voltage or current harmonics values. For this purpose, the corresponding flowchart is shown in Fig. 3.

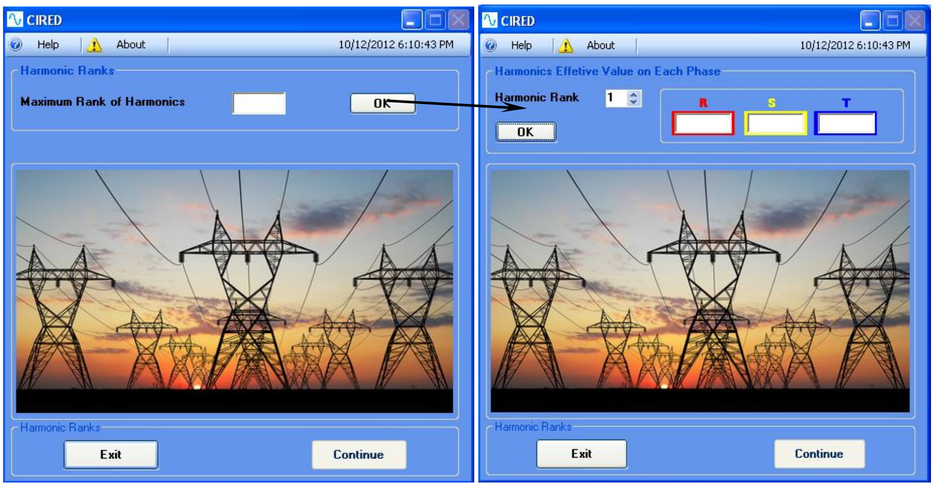

Fig. 4 – Input data windows.

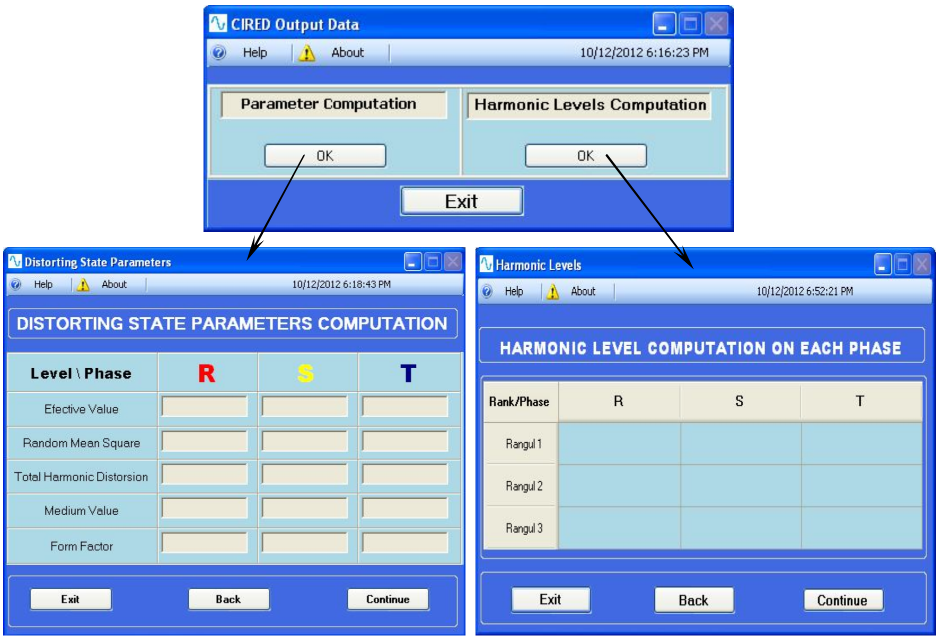

Fig. 5 – Output data windows.

Based on the algorithm and flowchart above presented, an application software was implemented, called CIRED, having a dialogue interface with a strong conversational character. The program is developed in C # language andperforms the distorting state characteristic parameters computation. CIRED can be run on any Windows system, being a useful tool for both specialists operating in power distribution utilities and to prepare future specialists in distribution systems.

Then, CIRED can calculate the distorting state recorded in a network with the expressions presented in the previous sections. Thus, the input data consist of harmonic current or voltage maximum rank (RMS values measured on each phase and for each harmonic voltage and/or current rank), and can be added as shown in Fig. 4.

The user access the “Continue” button after program execution and a new form appears, presented in Fig. 5, where can choose the desired results concerning the distorting state analysis, with the two possibility by accessing "OK", namely: *specific parameter* and *harmonic levels* computation.

4. Case Example

For example, the proposed software (CIRED) was applied for different monitored substation from Iaşi urban distribution, in order to determine the current and voltage harmonics parameters and with their attempts a harmonics time evolution analysis, *i.e*. 2005 and 2011 years. Thus, for both voltage and current harmonics estimation of the substation feeders the following values were determined: the non-sinusoidal effective value, the fundamental and all up to 15 harmonic effective values, total harmonic distortion coefficients, random mean square, and the time evolution of these values, based on available data held by regional electricity distribution company.

Table 1
Parameters of the Distortion State Pertaining to Voltage in 2005

	PT11			PT63			PT68			PT413		
	R	S	T	R	S	T	R	S	T	R	S	T
U, [V]	229.8	229.5	230.1	233.9	233.1	232.0	225.3	224.2	224.4	227.7	227.9	227.4
U_1, [V]	225.37	225.54	225.32	231.95	231.25	230.94	214.16	212.72	213.24	223.55	223.44	224.03
U_2, [%]	0.69	0.77	1.31	0.65	0.81	0.35	0.81	2.04	1.41	0.83	0.78	1.48
U_3, [%]	1.60	1.65	1.76	0.99	0.99	1.08	1.11	0.40	0.23	1.36	2.36	1.25
U_4, [%]	0.20	0.95	1.22	0.16	1.25	1.06	0.25	0.06	0.95	0.15	0.91	1.03
U_5, [%]	1.35	1.33	2.99	4.10	2.22	3.48	2.33	3.80	2.87	1.16	2.05	1.16
U_6, [%]	0.11	0.68	0.70	0.09	1.45	0.90	0.25	0.72	0.63	0.17	0.80	1.34
U_7, [%]	2.52	2.89	2.68	1.76	0.43	0.90	1.99	2.42	0.91	3.59	0.96	2.75
U_8, [%]	0.18	1.49	0.58	0.11	0.60	1.08	0.04	0.38	0.57	0.08	0.58	1.45
U_9, [%]	0.65	1.06	1.44	0.69	1.68	0.43	0.66	1.40	0.78	0.80	1.20	0.60
U_{10}, [%]	0.13	1.06	1.10	0.11	1.36	1.15	0.08	0.65	1.02	0.17	1.38	1.09
U_{11}, [%]	0.81	0.56	1.91	0.12	0.90	0.90	1.02	1.48	2.11	1.00	1.98	1.85
U_{12}, [%]	0.02	0.90	1.49	0.07	1.52	1.33	0.06	0.25	1.30	0.02	0.93	0.89
U_{13}, [%]	0.67	1.28	1.19	0.18	0.92	0.76	1.28	1.42	0.68	0.64	1.40	1.07
U_{14}, [%]	0.20	1.56	0.97	0.16	1.52	1.15	0.19	0.46	1.42	0.17	1.54	0.67
U_{15}, [%]	0.32	1.47	0.99	0.62	0.92	1.27	0.21	0.63	1.49	0.31	1.00	1.72

Thus, the paper presents results regarding the distorting state parameters for only four substations. Tables 1 and 2 present the features of the distortion state pertaining to voltage for the 2005 and 2011 years, respectively, in a working day.

For a more distorting state comprehensive analysis Table 3 shows the voltage harmonics computed with CIRED application in the four substations on the LV bar level deviating from the values stated in our country's regulation (ANRE, 2002). Also, Figs. 6 and 7 presents also the total harmonic distortion coefficients (THD) and residual distortion value relating to voltage, for each phase of the all analysed four substation (PT 11, PT 63, PT 68 and PT 413), at

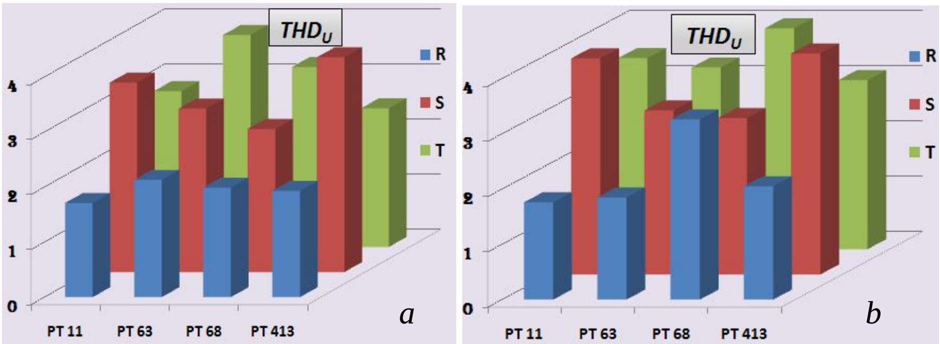

Fig. 6 – The THD values pertaining to voltage for 2005 (*a*) and 2011(*b*) years.

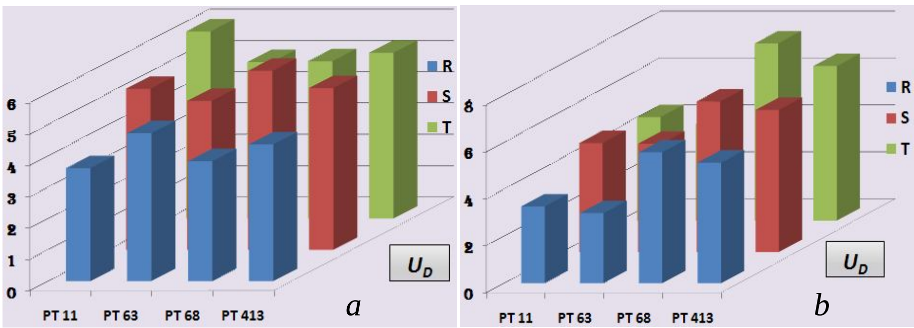

Fig. 7 – The U_D values pertaining to voltage for 2005 (*a*) and 2011(*b*) years.

the 2005 and 2011 year level. At the same time, in Table 3 the values deviating from regulation are marked as follows: light grey for even harmonics, grey background for uneven harmonics and dark grey background for the THD. The data analysis presented in Table 3 leads to the finding of a strong distorting state, installed on most phases and harmonic recorded; this is due to nonlinear receivers supplied with electric energy from the substation analysed.

Table 2

Parameters of the Distortion State Pertaining to Voltage in 2011

	PT11			PT63			PT68			PT413		
	R	S	T	R	S	T	R	S	T	R	S	T
U, [V]	226.2	227.2	227.3	233.7	233.1	239.2	221.8	223.6	224.5	229.8	230.6	230.6
U_1, [V]	226.17	227.15	227.25	233.3	231.3	239.1	221.3	223.3	224.1	229.7	230.5	230.5
U_2, [%]	0.15	0.81	1.34	0.86	0.81	0.16	0.77	0.61	0.53	0.87	0.62	0.76
U_3, [%]	1.72	2.067	0.591	1.22	0.99	0.98	1.92	2.25	3.22	2.59	2.51	3.08
U_4, [%]	0.04	1.022	1.204	0.25	1.25	0.04	0.19	0.17	0.40	1.01	0.94	1.04
U_5, [%]	1.44	1.908	0.909	1.11	2.22	0.93	3.78	3.75	5.57	1.79	2.67	1.52
U_6, [%]	0.29	0.840	1.431	0.18	1.45	1.53	0.24	0.42	0.47	0.64	0.73	1.38
U_7, [%]	1.81	0.567	0.659	2.43	0.43	1.19	3.27	2.99	3.34	1.97	1.17	4.40
U_8, [%]	0.23	0.613	0.636	0.09	0.60	0.43	0.11	0.82	0.49	0.62	1.31	0.66
U_9, [%]	0.95	1.635	1.29	0.61	1.68	0.57	0.75	1.54	2.04	0.25	1.79	0.76
U_{10}, [%]	0.09	1.362	1.136	0.18	1.36	0.47	0.08	1.72	0.69	1.07	1.29	1.15
U_{11}, [%]	0.75	1.091	1.772	0.44	0.90	0.78	0.62	0.42	0.81	1.21	2.23	1.71
U_{12}, [%]	0.07	1.022	1.499	0.65	1.52	0.43	0.06	0.92	0.78	1.44	1.19	0.94
U_{13}, [%]	0.63	0.908	0.99	2.22	0.92	0.69	0.82	1.49	2.73	0.85	1.91	1.04
U_{14}, [%]	0.03	0.931	0.909	0.21	1.52	0.51	0.08	1.16	2.11	0.66	1.38	0.81
U_{15}, [%]	0.61	1.431	1.408	0.25	0.92	0.40	0.28	1.31	1.32	1.99	1.17	0.89

Table 3

Parameters of the Distortion State Pertaining to Voltage vs. Time Evolution; *Values Deviating from (ANRE, 2002)*

	4 o'clock			10 o'clock			22 o'clock		
	R	S	T	R	S	T	R	S	T
U, [V]	228.9	227.5	230.8	222.8	221.6	223.1	225	224.4	227.2
U_1, [V]	228.8	227.5	230.8	222.77	221.6	223.1	224.94	224.3	227.2
U_2	0.801	0.751	0.323	0.4901	0.222	0.156	1.5746	1.727	0.409
U_3	0.984	1.979	0.923	1.0025	1.329	1.606	0.8098	2.512	2.113
U_4	1.03	0.955	0.138	0.3119	0.066	0.022	1.0347	0.942	0.136
U_5	1.899	1.615	1.362	1.4703	1.219	1.829	2.3619	2.624	1.704
U_6	0.847	1.365	0.254	0.401	0.554	0.29	0.8098	1.144	0.091
U_7	1.716	1.046	0.854	0.4678	0.82	0.892	0.8773	1.077	1.045
U_8	1.693	0.66	0.254	0.1782	0.421	0.156	0.6074	1.054	0.114
U_9	1.053	0.546	0.485	0.8911	0.222	0.758	1.5071	2.086	0.931
U_{10}	1.373	1.137	0.138	2.1163	0.465	0.134	1.1472	1.144	0.091
U_{11}	1.121	0.682	0.277	0.3787	1.595	0.513	1.9795	1.862	1.045
U_{12}	1.007	0.955	0.115	0.0446	0.288	0.067	1.0347	1.099	0.068
U_{13}	1.808	1.024	0.069	0.4901	1.108	0.602	1.1922	1.817	0.954
U_{14}	1.556	1.569	0.162	0.1337	0.51	0.089	1.5521	1.346	0.045
U_{15}	0.847	1.387	0.254	2.1163	0.377	0.357	0.9898	1.525	0.613
THD_U	1.64	3.44	2.92	0.94	2.75	3.2	1.31	2	2.26

The distorting phenomena, inevitable in electric energy distribution systems, have negative effects upon power sources, distribution networks, consumers, measurement systems and protection systems with relay stations. The drawbacks caused by harmonic distortions can be either instantaneous, or proportional to the duration of distortions, depending on the nature of the power receivers supplied from the electrical networks (Davudi *et al.*, 2011). Most often, instantaneous effects can be related to a certain functioning of electronic devices, such as the appearance of pulsing pairs for magnetic actuators. These effects mainly derive either from an important voltage dip, or from the shift in the passing through zero of the voltage wave. As for the effects proportional to the distortions duration, these are generally related to the rotating electrical devices and capacitors heating. Such effects also lead to the appearance of extra power losses in the components of the electrical power supply systems.

While designing process, the possibility of having a distortion state needs to be controlled through the following checkouts (Georgescu *et al.*, 2008):

a) Check on the non-sinusoidal periodical state parameters by computing the harmonic voltages (γ_u) level and the total harmonic distortion (THD_u), depending on the values of the harmonic currents specified by the producer of the devices or measured in similar systems, as well as on the harmonic impedances (Z_n) of the supply network in the respective area.

b) Check on the possible appearance of resonance phenomena when planning to set up a capacitor for reactive power compensation: check on the possible appearance of resonance, *i.e.* both harmonic overvoltages for the circuit made up of the capacitor and of the supply network, the capacitor overload.

To connect a consumer generating harmonic distortions to the electrical network, the most common action to be taken so as to limit the distortion state are the followings (Georgescu *et al.*, 2008; El-Mamlouk *et al.*, 2012):

a) Small distorting power consumers can be connected with no problems to the electrical network.

b) Important distorting power consumers should compensate for the distortion state, usually by setting up harmonic filters. In the case of new systems, these filters are set up when the level of harmonic voltages and of the total distortion coefficient revealed by calculation do not fit the allowed limits set by regulations. For existing systems, setting up filters is necessary when measurements indicate parameters exceeding the non-sinusoidal (distortion) periodical state or when there is a risk of a resonance phenomenon for one of the harmonics produced by this state. When more distorting consumers are connected in a common node to the electrical network and each of them has respected the individual imposed restrictions, while for the whole node the global distortion limit has been exceeded, the electrical energy supplier must take measures in order to diminish the level of these distortions.

5. Conclusions

Due to the existence of a great number of small power nonlinear elements connected in various points of the low voltage distribution network, the manifestation intensity of the distortion state also depends, in a great extent, on the load curve in the respective network node or point. The distorting phenomena, inevitable in distribution systems, have negative effects upon power sources, distribution networks, consumers, measurement systems and protection systems with relay stations

The application developed in this paper is a fast and efficient means of computing the distorting state parameters, the results are useful in the distorting steady-state analysis in electric energy distribution networks, and can help to take important decisions about medium and long term of the electric energy distribution network planning.

Should be noted that the performed analysis from this paper a strong distorting state, installed on most phases and harmonic recorded due to non-linear receivers, are finding.

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ANALIZA REGIMULUI DEFORMANT ÎN REȚELELE DE DISTRIBUȚIE A ENERGIEI ELECTRICE

(Rezumat)

În condițiile tehnologice actuale apariția regimului deformant este inevitabilă în rețelele publice de distribuție deoarece fiecare element de circuit neliniar sau parametric reprezintă o sursă de armonici, o problemă esențială fiind diminuarea efectelor negative produse de funcționarea în acest regim nesinusoidal. În aceste condiții se propune o metodologie şi un program specializat de calcul a indicatorilor care caracterizează regimurile deformante în vederea unei analize cât mai complete şi complexe a acestora. Pe baza măsurătorilor înregistrate de către diversele sisteme de monitorizare care au la bază fie contoarele electronice trifazate de tip Alpha, fie analizoarele de armonici, s-au calculat indicatorii regimului deformant pentru câteva posturi de transformare din județul Iaşi, rezultatele furnizate putând fi utilizate de personalul competent, în vederea adoptării deciziilor privind planificarea, dezvoltarea şi exploatarea rețelelor publice de distribuție a energiei electrice.