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BEHAVIOR OF ELECTRIC TRANSFORMER UNDER NONLINEAR LOAD IN THE SECONDARY WINDING FRACTAL ANALYSIS

BY

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Abstract. This paper is dealing with a double analysis (both frequential and fractal) of electric signals which occur in the primary and secondary windings of transformers which supply heavy nonlinear loads (nonlinearity generated both by the ferromagnetic cores, as component parts of various electromagnetic devices and by widely use of power electronics in the electric drives). The analysis has been performed using two programming mediums: PSIM (for frequential analysis) and MATLAB (for fractal analysis). The goal of this paper is to highlight increasing of distortion degree of current curve, besides the frequent occurrence of current harmonics into the electric networks (usual frequential analysis).

Key words: current harmonics; harmonic pollution; frequential analysis; fractal dimension; distortion degree.

1. Introduction

Widely use of power electronics within the electric drives has led to radical change of signals (in shape, amplitude and frequency) into the energetic system. Since most electromagnetic devices have ferromagnetic cores, used as magnetic field concentrators, this particularity was, till recently, the most powerful source of nonlinearity for voltage and current signals occurring in the

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networks. Along with the emergence of power electronics, the sources of nonlinearity are various, leading to chaos, especially at electric drives level (Chau *et al*., 2011; Nagy *et al*., 1995) and globally, for the energetic system, as a whole.

In these conditions, the Fourier analysis of the multitude of distorted signals within the network proves not to be satisfactory enough to check the abnormal state (away from equilibrium that is away from the sinusoidal signal). Practically, now there is a continuous source-receiver interaction within the energetic system, an interaction that leads to occurrence into the network of superior harmonics (of higher order than the fundamental harmonic) and also of inter-harmonics and intra-harmonics (Chau *et al*., 1997; Chen *et al*., 2000). As a consequence of this continuous interaction, there is an avalanche effect within the energetic system that may lead to drastic decrease in its steadiness. Or, put in other words, an increase of efforts to maintain system's steadiness in the conditions of high efficiency and low environmental impact.

Consequently, finding new methods of analysis is a major need.

Unevenness, as well as the chaotic, random nature of these signals within the energetic system requires a new approach in treating them, closer to discontinuous than continuous, closer to chaos than steady-state and equilibrium (Okafor Nelson Chidiebere, 2012). Such approach is used in this paper to see the distortion degree (unevenness) of signals occurring within the electric networks, for the limited level of receiver-source interaction, for the transformers within the energetic system (these are practically, mini-energetic systems, through similarity criteria, as they bring together the source and the receiver through functionality and structure, in a limited area).

Consequently, in this paper is suggested the use of fractal analysis to evaluate the influence of nonlinear loads connected to the secondary winding of a tree-phase electric transformer on the upwards receivers, in relation to the primary terminals of the transformer. The fractal analysis allows to highlight the distortion degree of signals between transformer output, supplying the nonlinear load and, respectively, transformer input, oriented to the actual source of energy of the energetic system.

2. Modelling of Interactions. Simplifying Hypotheses. Analysis of Topological Structures

Phase 1

In the first phase, the modelling has been done for simple mini-systems, respectively transformers, secondary winding of which feed a static uncontrolled converter (an uncontrolled bridge diode rectifier). The feeding transformer has been chosen with linear ferromagnetic core only to highlight the effect of nonlinearity of load in secondary. Also, it has been done a comparative analysis of two three-phase transformers with the same type of connections (star-star), respectively different type connections (star-triangle) for primary and secondary windings.

The topological structures analysed are shown in Figs. 1 and 2.

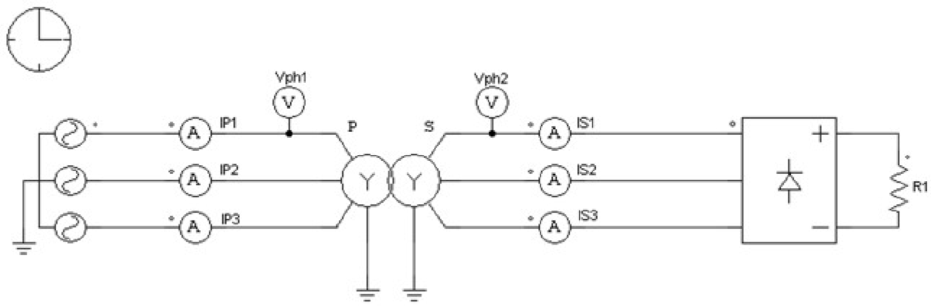


Fig. 1 – Three-phase transformer with connection star-star feeding an uncontrolled bridge rectifier.

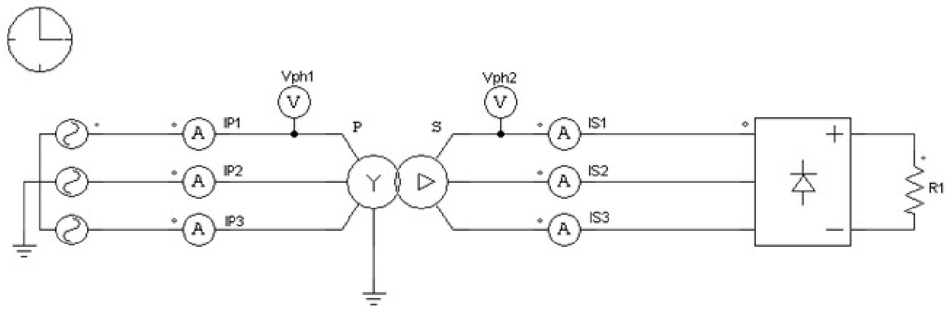


Fig. 2 – Three-phase transformer with connection star-triangle feeding an uncontrolled bridge rectifier.

It has been performed a double analysis for the signals: 1) Fourier analysis (frequency analysis); 2) fractal analysis. Fourier analysis shows occurrence of harmonics in the signals, while fractal analysis shows the distortion degree of curves.

It is worth mentioning the following:

a) to see the distortion degree of curves it has been calculated the fractal dimension of these curves using box counting method (Voncilă *et al*., 2016, 2017);

b) a fractal dimension close to 1 (a straight line) points to a signal curve a highly distorted (and high content of superior harmonics);

c) a fractal dimension close to 2 (a surface) points to a signal curve little distorted (and low content of harmonics).

Phase 2

In the next phase it has been performed the analysis of behaviour of the two types of three-phase transformers, with connections star-star, respectively star-triangle, in the case of supplying complex nonlinear loads:

A. The case of feeding a DC motor, load running, using an uncontrolled rectifier (bridge, with 6-pulses) (Fig. 3*a*, *b*). Fig. 4*a*, *b* shows the parameters of the two types of transformers, respectively of the DC motor used;

B. The case of feeding an asynchronous three-phase motor with short-circuit rotor, operating under load, using a frequency converter (Fig. 5*a*, *b*). Fig. 6 shows the parameters of the asynchronous motor with short-circuit rotor used.

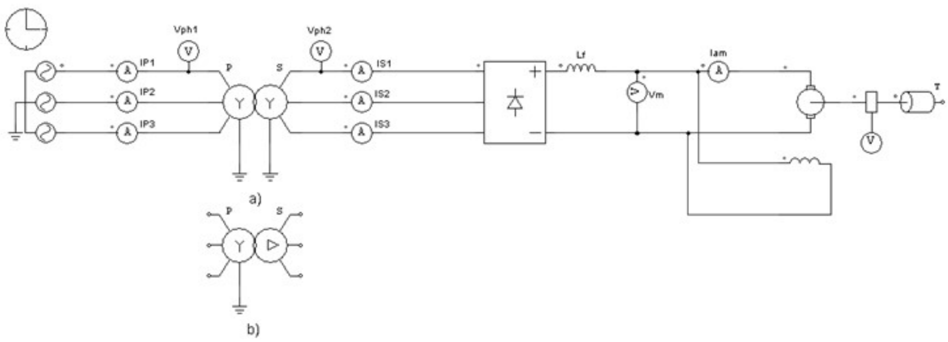
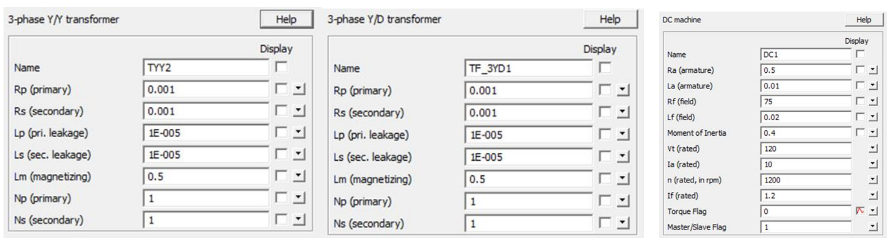


Fig. 3 – Feeding a DC motor using an uncontrolled rectifier:
a – with three-phase transformer with connection star-star;
b – with three-phase transformer with connection star-triangle.



a *b*

Fig. 4 – Parameters of the force electromagnetic systems:
a – of electric transformers; *b* – of DC motor.

For each of the cases studied, both in phase 1 and 2 there have been shown the signals of interest (the currents of primary and secondary windings of the feeding transformer) as time variables. Then, it has been performed the double analysis specified above: a) frequential analysis, respectively b) fractal analysis. The results obtained are presented below.

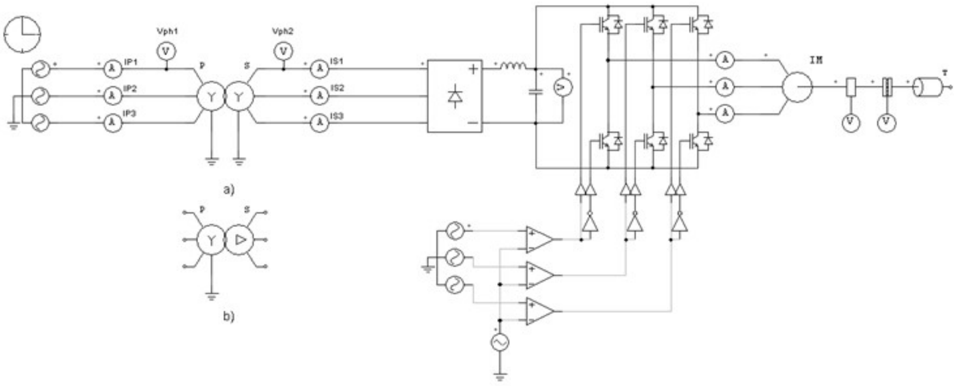


Fig. 5 – Feeding an asynchronous three-phase motor with short-circuit rotor, using a frequency converter: *a* – with three-phase transformer with connection star-star; *b* – with three-phase transformer with connection star-triangle.

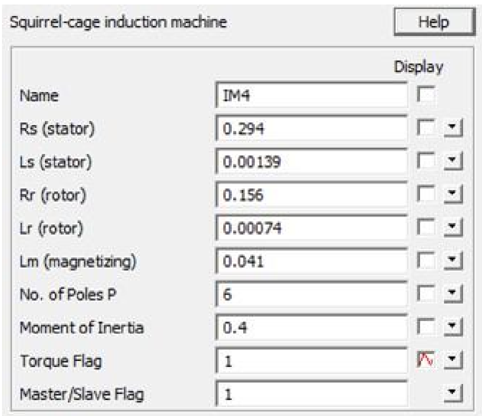


Fig. 6 – Parameters of asynchronous motor with short-circuit rotor.

3. The Results Obtained. Frequency Analysis

For the simple cases, analysed in phase 1, the time variations of primary and secondary currents, through a single phase of the transformers studied, are shown in Fig. 7 (transformer with star-star connection), respectively Fig. 8 (transformer with star-triangle connection). Figs. 9 and 10 show the results of frequency analysis (the harmonics content for the signals of Figs. 7 and 8).

It turns out that in these simple cases, both the shape of time variation of currents of primary and secondary windings of transformers supplying the same type of load and the harmonics spectrum are different, but differences are quite hard to measure. The results for the cases studied in phase 2 are shown in Figs. 11-14.

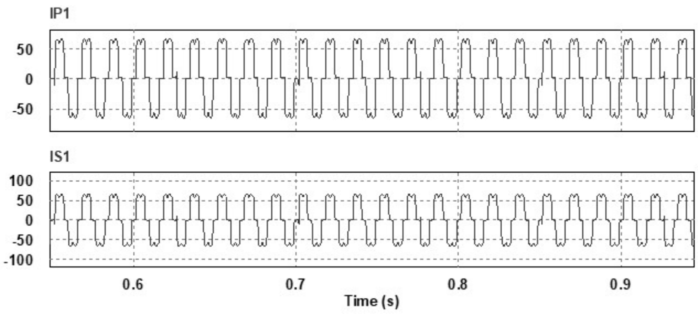


Fig. 7 – Phase current variation of primary (IP1) and secondary (IS1) windings of transformer with star-star connection, in the case of feeding an uncontrolled bridge rectifier (detail).

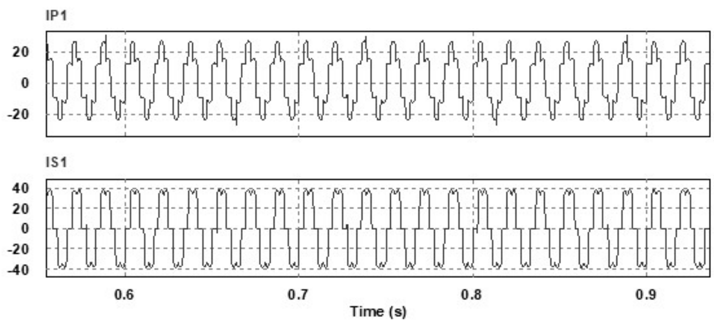


Fig. 8 –Phase current variation of primary (IP1) and secondary (IS1) windings of transformer with star-triangle, in case of feeding an uncontrolled bridge rectifier (detail).

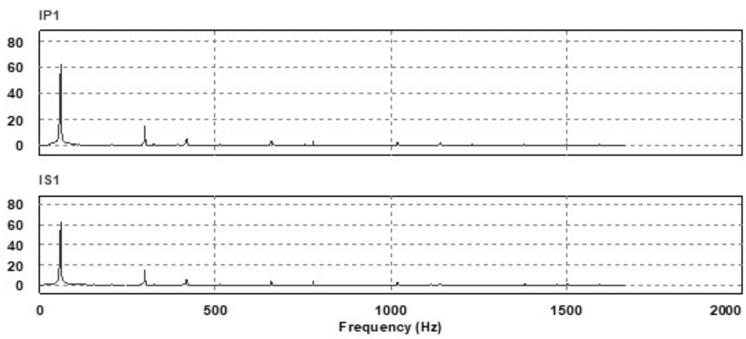


Fig. 9 – The harmonics spectrum of phase current of primary (IP1) and secondary (IS1) windings of transformer with star-star connection, in case of feeding an uncontrolled bridge rectifier.

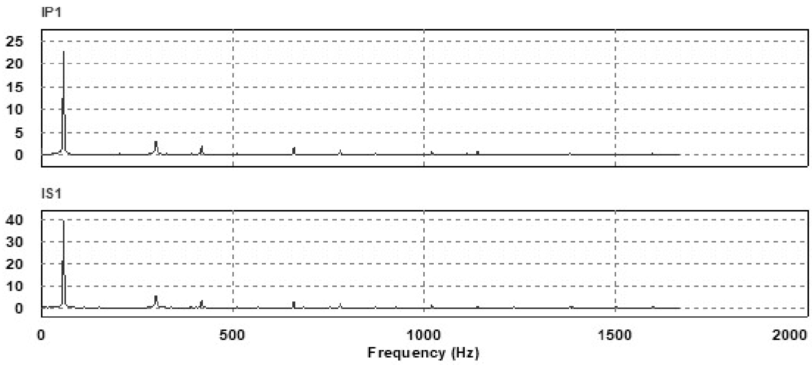


Fig. 10 – The harmonics spectrum of phase current of primary and secondary windings transformer with star-triangle connection, in case of feeding an uncontrolled bridge rectifier.

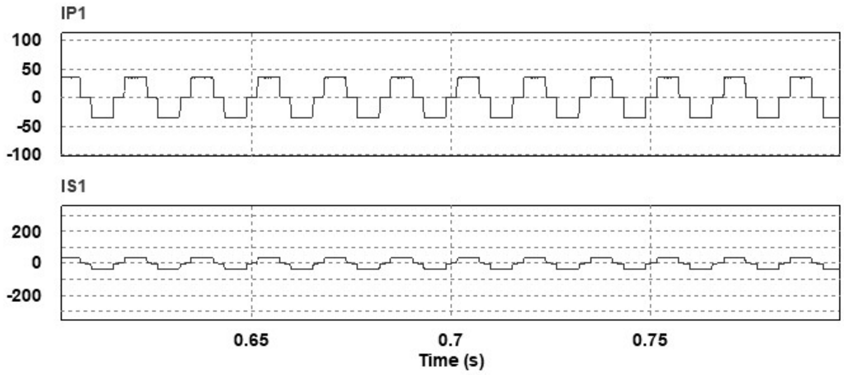


Fig. 11 – Phase current variation of primary (IP1) and secondary (IS1) windings of transformer with star-star connection, in case of feeding a DC motor using an uncontrolled rectifier (detail).

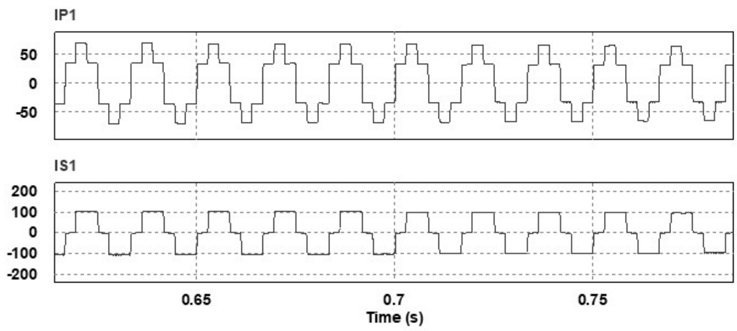


Fig. 12 – Phase current variation of primary (IP1) and secondary (IS1) windings of transformer with star-triangle connection, in case of feeding a DC motor using an uncontrolled rectifier (detail).

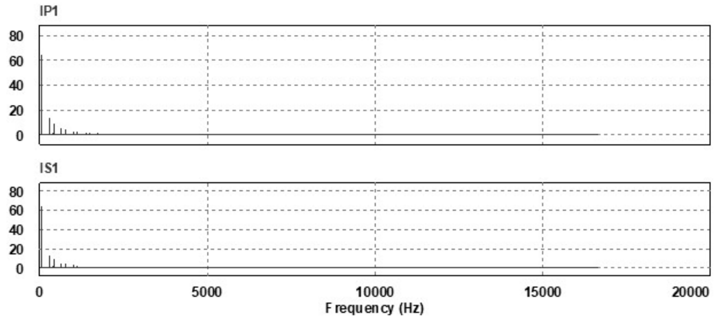


Fig. 13 – The harmonics spectrum of phase current of primary (IP1) and secondary (IS1) windings of transformer with star-star connection, in case of feeding a DC motor using an uncontrolled rectifier.

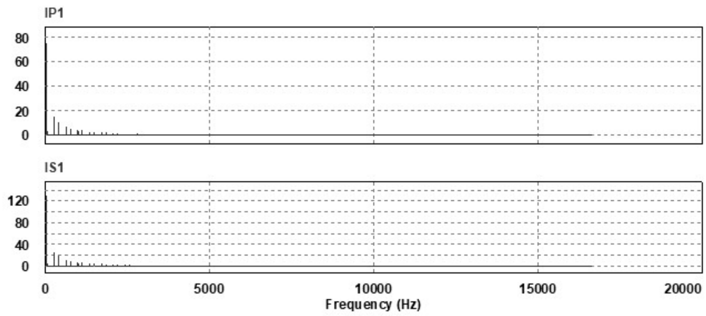


Fig. 14 – The harmonics spectrum of phase current of primary (IP1) and secondary (IS1) windings of transformer with star-triangle connection, in case of feeding a DC motor using an uncontrolled rectifier.

The analysis performed in this case (feeding a DC motor) has shown that the number of harmonics from the current curves of primary and secondary windings of transformer highly increase, leading to a doubling of detected harmonics compared to the case of the simple load in the first phase. The results of the frequential analysis in the case of feeding the asynchronous motor using a frequency converter are shown below. Thus, Fig. 15 shows current variations of primary and secondary windings of transformer with star-star connection, while Fig. 16 shows the same variations for the transformer with star-triangle connection.

Fig. 17 and Fig. 18 show the harmonics spectrum of current in the two cases above mentioned (respectively, for feeding a three-phase asynchronous motor with short-circuit rotor using a frequency converter).

In this case, the number of harmonics of the two circuits of three-phase transformer (for each of the two connections studied) is higher than for the case of feeding a DC motor using an uncontrolled rectifier. Moreover, it has been found out of the analysis of current variations in time of the two circuits of the

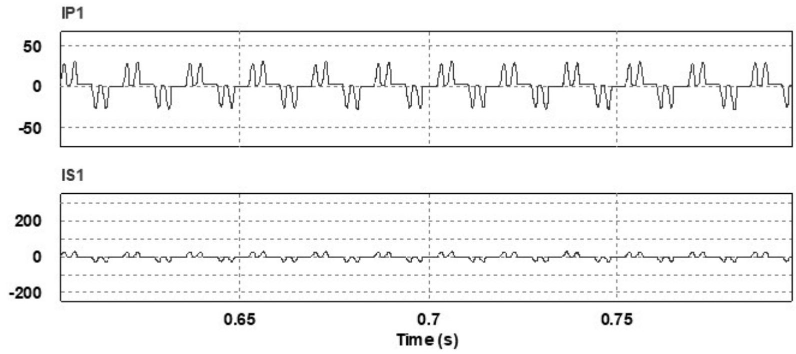


Fig. 15 – Phase current variation of primary (IP1) and secondary (IS1) windings of transformer with star-star connection, in case of feeding an asynchronous motor with short-circuit rotor using a frequency converter (detail).

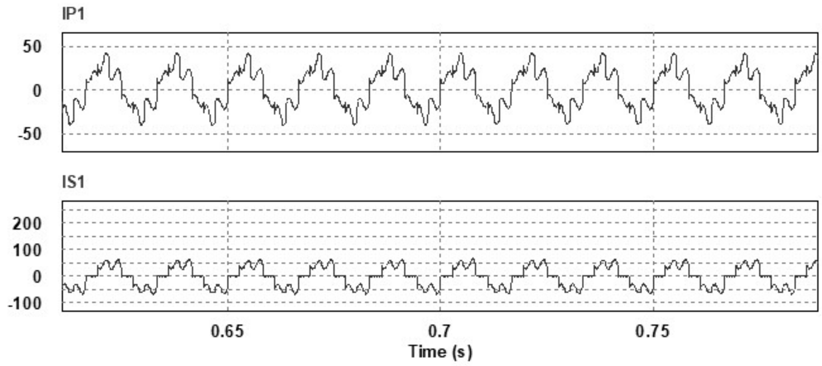


Fig. 16 – Phase current variation of primary (IP1) and secondary (IS1) windings of transformer with star-triangle connection, in case of feeding an asynchronous motor with short-circuit rotor using a frequency converter (detail).

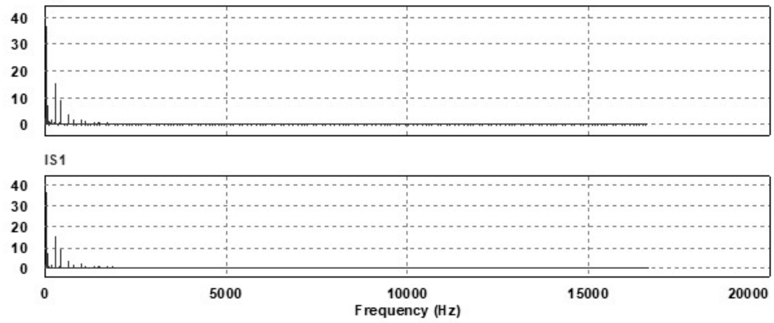


Fig. 17 – The harmonics spectrum of phase current of primary (IP1) and secondary (IS1) windings of transformer with star-star connection, in case of feeding an asynchronous motor with short-circuit rotor using a frequency converter.

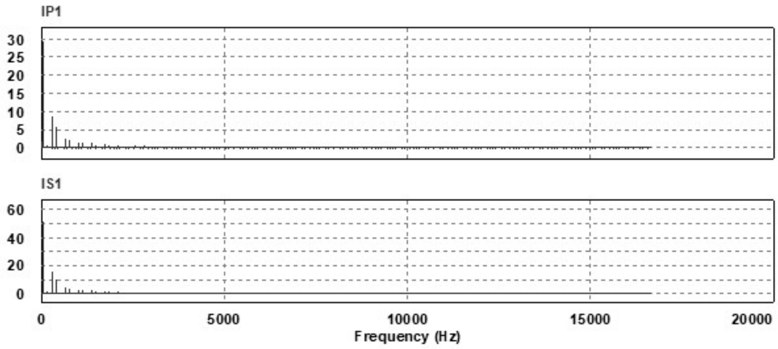


Fig. 18 – The harmonics spectrum of phase current of primary (IP1) and secondary (IS1) windings of transformer with star-triangle connection, in case of feeding an asynchronous motor with short-circuit rotor using a frequency converter.

transformers studied, that in the case of feeding a DC motor using a frequency converter, the distortion degree of current signals is higher than in the case of feeding a DC motor using an uncontrolled rectifier. Precisely this fact justifies a complementary analysis to the frequential analysis, respectively the fractal analysis so as to check the distortion degree of current curves for the transformers interconnected within the energetic system, in transition from the DC to AC drives.

4. The Results Obtained. Fractal Analysis

The fractal analysis of current signals of primary and secondary windings of the three-phase feeding transformer (for the two connections and for the nonlinear loads of secondary winding studied) is based on determination of fractal dimension of these curves in steady-state conditions by using box counting method. The values of the fractal dimension for all the current curves seen are shown in Table 1.

Table 1

Fractal Dimensions of Current Curves of Primary and Secondary Windings of Feeding Transformer for the Nonlinear Loads Analysed

	Type of nonlinear load	Three-phase uncontrolled bridge rectifier		Uncontrolled rectifier and DC motor operating under load		Frequency converter and asynchronous motor with short-circuit rotor operating under load	
Type of connection of feeding transformer		Fractal dimension of current signals of primary and secondary windings of transformer					
		Primary	Secondary	Primary	Secondary	Primary	Secondary
Star-star		1.7098	1.7120	1.4771	1.4222	1.4447	1.3937
Star-triangle		1.7226	1.7760	1.6525	1.7050	1.6232	1.6193

Analysing the data in the Table 1 it is found that there is a wide range of variation in the fractal dimension, in case of supplying nonlinear loads from three-phase linear transformers (nonlinearity generated, first of all, by the existence of static converters/power electronics).

5. Conclusions

Consequent to the analysis performed in this paper, the following conclusions can be drawn:

a) as the harmonics content increases (in case of complex nonlinear loads) the cover of plane surface, given by the fractal dimension for the current signals of primary and secondary windings of transformer, considered as linear electromagnetic device, decreases (the distortion degree/unevenness increases);

b) this decrease is more pronounced in case of three-phase transformer with star-star connection, compared to the one with star-triangle connection;

c) the highest fractal dimensions are obtained in case of supplying a linear load (resistive) using a three-phase uncontrolled bridge rectifier;

d) the lowest fractal dimension of current curves is obtained for the signals in secondary winding of transformer for feeding a three-phase asynchronous motor with short-circuit rotor using a frequency converter.

Additional to the above, the following remarks are to be made:

i) in order to supply heavy nonlinear loads it is recommended the use of three-phase transformers, which have to have an adequate windings connection, so as to keep a fractal dimension close to sinusoidal signals (for which it was found the value 1.731);

ii) the increase of nonlinearity degree of load (nonlinearity generated by the ferromagnetic cores, etc.) leads to a decrease of fractal dimension, an increase of harmonics number, and as a consequence to a narrowing of steadiness range for long term operation of electric networks, altogether, and, specifically, of electric drives.

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COMPORTAREA TRANSFORMATORULUI ELECTRIC LA SARCINĂ NELINIARĂ ÎN SECUNDAR
Analiză fractală

(Rezumat)

În lucrare se realizează o analiză duală (frecvențială şi fractală) a semnalelor de curent ce apar în primarul şi secundarul transformatoarelor electrice ce alimentează sarcini puternic neliniare (neliniaritate generată atât de miezurile feromagnetice din structura diverselor dispozitive electromagnetice cât şi de utilizarea, pe scară largă, în acționările electrice moderne, a electronicii de putere). Analiza s-a realizat în două medii de programare PSIM (analiza frecvențială), respectiv, MATLAB (analiza fractală). Scopul declarat al lucrării este de a pune în evidență, pe lângă popularea, din ce în ce mai puternică, a rețelelor electrice, cu armonici (analiza frecvențială, uzuală) şi creşterea gradului de deformare al curbelor de curent (analiza fractală).