The Analysis of the Deforming Regime Generated by AC-DC Converters using Discrete Wavelet Transform

VIOREL APETREI[1], CONSTANTIN FILOTE[1,2], ADRIAN GRAUR[1]
[1]Electrical Engineering and Computer Science Faculty
Stefan cel Mare University of Suceava
University Street no. 13, 720029, Suceava, Romania
[2]S.C. Germaro Electronics S.R.L., Suceava, Romania
viorela@eed.usv.ro, filote@eed.usv.ro and adrian.graur@usv.ro

Abstract: - The emergence of deforming regimes is related to the proliferation of nonlinear electrical receivers. The higher harmonics of drawn currents from power systems can be evaluated using Discrete Wavelet Transform (DWT). Unlike Fast Fourier Transform (FFT), which provides only amplitude-frequency information but looses time information, DWT analyses the signal in a time-frequency domain using windows of variable sizes, relative to the frequency band; therefore reducing the computational effort and minimizing the spectral leakage. The operating mode of a static power converter as classic three-phase rectifier with diodes (TPRD) is compared with the modern rectifier with near sinusoidal input currents (RNSIC).

Key-Words: - Discrete Wavelet Transform (DWT), data acquisition system, AC-DC Converters, three-phase rectifier with diodes (TPRD), rectifier with near sinusoidal currents (RNSIC)

1 Introduction

Electric power quality is a topic of great interest that concerns both the compatibility of the electric power parameters with the operating characteristics of the customers, and the analysis of electromagnetic disturbances in the supply systems [1-2].

Considerable use of receivers with nonlinear characteristics generates the presence of intensive harmonic currents in power systems, which degrades the electric power product, and affects the other customers. The IEEE 519/1992 standard contains practical recommendations regarding harmonics control and reactive power compensation [3].

The 61000-3-2/2005 standard [4], which establishes the upper limits of the harmonics injected in the power systems by static power converters, is applicable in the case of electric and electronic devices intended for connection with low-voltage public distribution power systems having an input current value smaller than or equal to 16A on each phase, while the IEC 61000-3-4/2006 standard [5] concerns the current harmonics inlaid by nonlinear loads (including rectifiers) with phase current higher than 16A.

The common instruments employed in defining the main electric quantities are based on Fast Fourier Transform (FFT). Although it is a regular analysis tool, FFT is difficult to use with applications that require knowing the spectral composition of the signal at a certain point of time. As an alternative, Discrete Wavelet Transform (DWT) analyses the signal in a time-frequency domain, and minimizes the computational effort [6-8].

Even if the majority of the power systems are three-phase, weak attempts were made to define the electric power components for unbalanced three-phase systems under non-sinusoidal conditions, in wavelet domain.

The emergence of new technologies and novel generation of devices and equipments in domestic and industrial areas has determined important change in loads state. The main electromagnetic pollution sources are represented by three-phase rectifiers with thyristors, rectifiers with capacitive filter, arc furnaces, and variators.

Electronic power developments allow fighting pollution, either by producing non-polluting converters, which absorb the sinusoidal currents, or by using an active filter upstream of the pollutant.

The deforming regime produced by converters represents a generalized problem of the power system, which has to be avoided and minimized since design stage of production and spread of the higher harmonics.

The decrease of higher current harmonics generated by AC-DC converters can be achieved by using the pulse width modulation rectifiers (PWM). Although these loads allow obtaining practically sinusoidal input currents, they present different disadvantages comparing with the uncontrolled three-phase rectifiers as: larger switching losses, electromagnetic interference problems, high cost, and reduced operation security [9-23].

This paper proposes a harmonic analysis of the deforming regime generated by AC-DC converters based on Discrete Wavelet Transform (DWT) using the classical three-phase rectifier with diodes (TPRD), and the modern rectifier with near sinusoidal input currents (RNSIC). The generated waveforms are captured with a data acquisition system containing Hall voltage and current transducers.

2 Wavelet Theory

A precisely detection and analysis of power quality information can be obtained applying the wavelet theory.

The necessity of simultaneous localization and representation of time and frequency for non-stationary signals led to the development of DWT starting from the conventional FFT.

Standard DWT achieves a signal analysis in time-frequency domain by dividing the frequency spectrum into straps or levels, using windows of variable size, depending on the frequency band: for high frequencies, analysis windows of short length are used, while for low frequencies, windows of long length are used. It provides the possibility of representing the functions that have irregularities or/and edged peaks, by decomposing the signal into a sum of damped over time signals, thus performing a local analysis.

Since wavelet coefficients calculation, for each scale and position, requires a large amount of operations; to reduce the computational task, the coefficients are determined only in frequency bands of uniform width.

In DWT, the initial waveform S is first decomposed in approximation and detail, and then successive decompositions are carried out only in approximation, thus obtaining multi-resolution analysis (MRA), as shown in Fig. 1 [24-25].

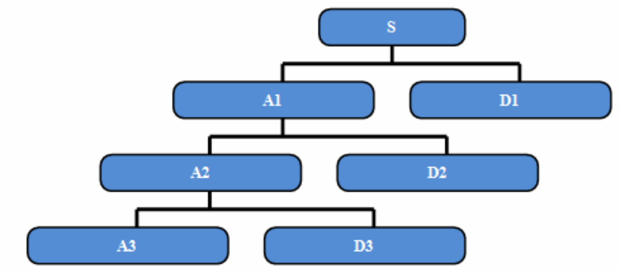


Fig.1. DWT decomposition tree on three levels

2.1 The Power Quality Indices (PQIs) definitions based on DWT in three-phase systems case

The calculation of voltage and current RMS values using DWT can be extended to three-phase systems in non-sinusoidal situations by considering any phase of the three-phase R, S or T, as follows [26]:

$$V_x = \sqrt{\frac{1}{T}\int_0^T v_x^2(t)dt} = \sqrt{\frac{1}{T}\sum_k c_{j_0,k,x}^{2} + \frac{1}{T}\sum_{j\geq j_0}\sum_k d_{j_0,x}^{2}} = \sqrt{V_{j_0,x}^2 + \sum_{j\geq j_0} V_{j,x}^2} \quad (1)$$

$$I_x = \sqrt{\frac{1}{T}\int_0^T i_x^2(t)dt} = \sqrt{\frac{1}{T}\sum_k c_{j_0,k,x}^{2} + \frac{1}{T}\sum_{j\geq j_0}\sum_k d_{j_0,x}^{2}} = \sqrt{I_{j_0,x}^2 + \sum_{j\geq j_0} I_{j,x}^2}. \quad (2)$$

The $V_{j_0,x}, I_{j_0,x}$ are voltage and current RMS values of the lowest frequency band j_0 also called approximated voltage (V_{xapp}) and approximated current (I_{xapp}) for any x phase. $\{V_{j,x}\}$, $\{I_{j,x}\}$ are the sets of voltage and current RMS values of each frequency band or wavelet-level higher than or equal to the scaling level j_0 being called detailed voltage (V_{xdet}) and detailed current (I_{xdet}) for any x phase.

The "approximation" effective values for three-phase voltages and currents can be formulated as [27]:

$$V_{eapp} = \sqrt{\frac{V_{RSapp}^2 + V_{STapp}^2 + V_{TRapp}^2}{9}} \quad (3)$$

$$I_{eapp} = \sqrt{\frac{I_{Rapp}^2 + I_{Sapp}^2 + I_{Tapp}^2}{3}}. \quad (4)$$

The "details" effective values for three-phase voltages and currents are:

$$V_{e\det} = \sqrt{\frac{V_{RS\det}^2 + V_{ST\det}^2 + V_{TR\det}^2}{9}} \quad (5)$$

$$I_{e\det} = \sqrt{\frac{I_{R\det}^2 + I_{S\det}^2 + I_{T\det}^2}{3}}. \quad (6)$$

Then the effective values of voltage and current are [26]:

$$V_e = \sqrt{V_{eapp}^2 + V_{e\det}^2}, \qquad I_e = \sqrt{I_{eapp}^2 + I_{e\det}^2}. \quad (7)$$

Based on the effective voltage and current, the total harmonic distortion can be calculated as follows:

$$THD_{eV} = \frac{V_{eH}}{V_{e1}} \quad (8)$$

where $V_{eH} = \sqrt{\dfrac{V_{RSH}^2 + V_{STH}^2 + V_{TRH}^2}{9}}$ and

$$V_{e1} = \sqrt{\frac{V_{RS1}^2 + V_{ST1}^2 + V_{TR1}^2}{9}}. \tag{9}$$

The V_{RS}, V_{ST} and V_{TR} are the line-to-line voltages for phases *R*, *S* and *T*, while the subscripts *1* and *H* represent the fundamental and the non-fundamental harmonic components.

The equivalent total harmonic distortion in the current case is defined as [27]:

$$THD_{e1} = \frac{I_{eH}}{I_{e1}} \tag{10}$$

where $I_{eH} = \sqrt{\dfrac{I_{RH}^2 + I_{SH}^2 + I_{TH}^2}{3}}$ and

$$I_{e1} = \sqrt{\frac{I_{R1}^2 + I_{S1}^2 + I_{T1}^2}{3}}. \tag{11}$$

The I_R, I_S and I_T are the line currents for phases *R*, *S* and *T*.

2.2 The AC-DC converters

The electromagnetic compatibility between supplier and customer is obtained using static power converters (rectifiers with active or passive filters, alternative voltage variators, independent inverters, choppers), which modifies the parameters of the energy provided by the source to meet the receiver requirements [28].

In many power electronics applications for three-phase systems with AC 50/60 Hz power supplies, the alternative sinusoidal voltage must be converted in a DC voltage. These applications are represented by the uninterruptible power supply (UPS systems), electrical drives with AC motors, static frequency convertors, which are using three-phase uncontrolled diode rectifiers.

Three-Phase Rectifier with Diodes (TPRD) is the most common rectifier used for the conversion of alternative current/ voltage in continuous current/ voltage. Due to the unidirectional conduction of diodes, the rectifier provides unipolar current and fix voltage with the same polarity. The three-phase six-pulse diode rectifier brings up to 10÷15 % of contribution in the AC to DC electric power conversion. Fig.2 shows the rectifier configuration with two possible versions.

The first version is represented by three-phase rectifier with constant DC current and practically zero value for AC inductance (L_S), while the second one is represented by three-phase rectifier with supplementary AC feature inductances L_S and with no DC inductance L_f [29-33].

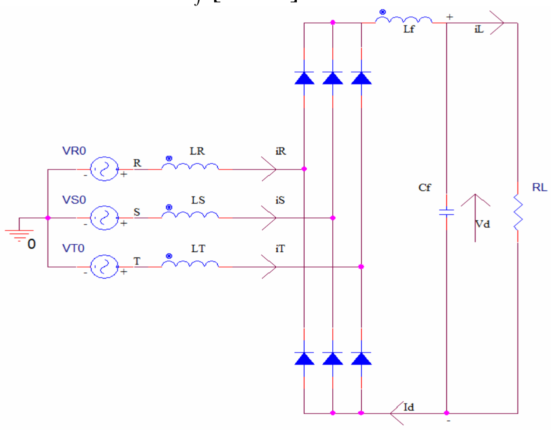


Fig.2. Three-Phase Rectifier with Diodes configuration [29]

Three-phase rectifiers with thyristors are controlled such as to modify the output continuous voltage, and to reduce the current harmonics rate. Currently, they are frequently replaced by the IGBT Rectifier (Insulated-Gate Bipolar Transistor), which is less polluting than those with diodes.

The higher order harmonics suppression of the drawn current can be obtained not only by using filtering systems (active or passive) or the PWM rectifiers, but also with a AC-DC converter, which has practically sinusoidal input current, also known as RNSIC (Rectifier with Near Sinusoidal Input Currents) - see Fig.3 [34-38].

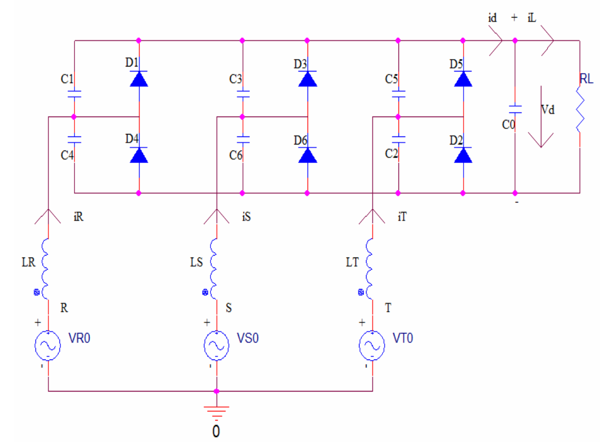


Fig.3. Rectifier with Near Sinusoidal Input Currents configuration [29]

This rectifier is a classic type of a three-phase bridge rectifier with parallel diode capacitors and serial inductors attached, characterized by high dynamic performance, whose functioning is not affected by the change of the power system resonance frequency.

Such an active filter is placed in the power system node and serves multiple loads. This case does not absolutely exclude the emergence of some resonances, due to both the presence of some capacitors bank and the current harmonics. For the small nonlinear loads, one can use as many RNSIC convertors as to match the number of the loads. Therefore, it is avoided the presence of current harmonics in different parts of the power system.

3 Electric quantities acquisition

For the electric quantities acquisition and the analysis of their parameters, it was used a data acquisition system with Hall transducers, shown in Fig.4, which captures the current and voltage waveforms into 0 ÷ 200kHz frequency band, 10 ÷ 500V_{ef} voltages range, 0 ÷ 70A currents range. It includes the following components: a module with voltage and current transducers, an axing-amplifying module, a data acquisition module Technosoft International MSK28335, and a switching voltage source.

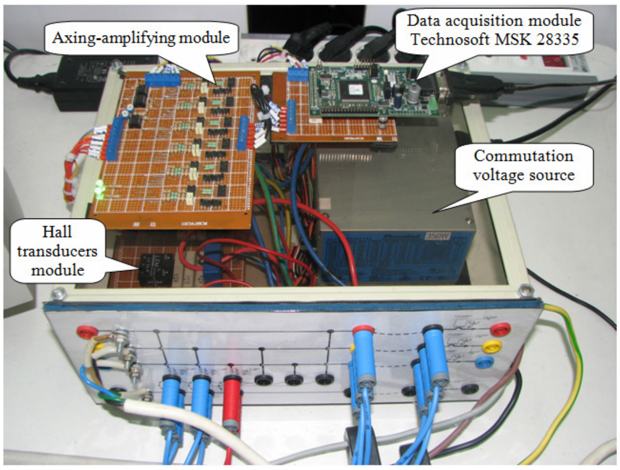


Fig.4. Data acquisition system

For the voltage and current measurement within the data acquisition system, three voltage transducers LEM LV-25P and three current transducers LEM LA-55P were adopted.

The axing-amplifying module is able to center and amplify the waveforms obtained from transducer module on 1,5V voltage, between 0 ÷ 3V.

The evaluation of A/D conversion possibilities is obtained using the Analogue to Digital Converter (ADC) Module presented in Fig.5, having sixteen multiplexed analogue inputs and a fast conversion time of 60ns. When the conversion is performed, the analogue multiplexer can select any of the 16 input channels, but it is also possible that the same channel be sampled multiple times (over-sampling), therefore obtaining a higher signal resolution.

The voltage and current waveforms of three-phase systems are obtained using the Capture Units Application of the MSK28335 kit (see Fig.6).

This application illustrates the detection of different external signal transitions using the capturing modules. The generation of the capture events depends on the presence of external connections to the capture input pins. When the application starts, the transition to the related input pin makes the timer counter value to be memorized into the appropriate Capture Register (CAP1…4). The status bits from ECFLG register are controlled, and the application view gives back the new status of the captures (1 capture or 2 captures = OVeRflow). The new counter value is saved into the Capture Register (CAP1…4).

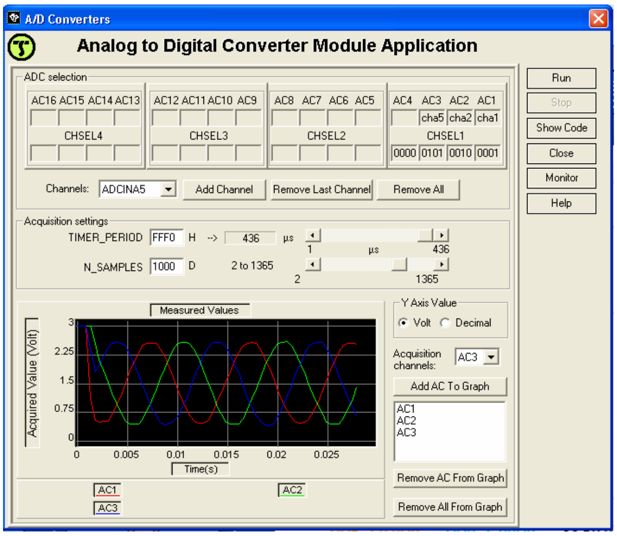


Fig.5. Analog to Digital Converter Module Application

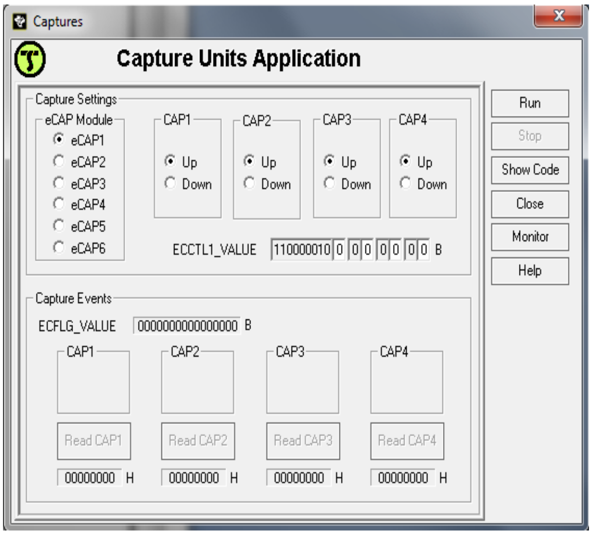


Fig.6. Capture Units Application

4 Results and analysis

The PQ indices calculation is presented in this section through a comparative analysis of the deforming regime generated by AC-DC converters based on DWT, using a three-phase rectifier with diodes, and a rectifier with near sinusoidal input currents. In TPRD case, the experimental tests use the filtering capacitor C_0 of 4700μF, the inductances L1-L3 equal to 16mH, the CS411299 rectifier bridge with D_1-D_6 diodes and the resistive load R_L = 3.2kΩ. The AC input voltage magnitude V_{m1} is equal to 311V, and the frequency is 50Hz. Unlike TPRD, the RNSIC converter configuration contains also the C_1-C_6 capacitors, with 60μF value, connected in parallel with the diodes (See Fig.7).

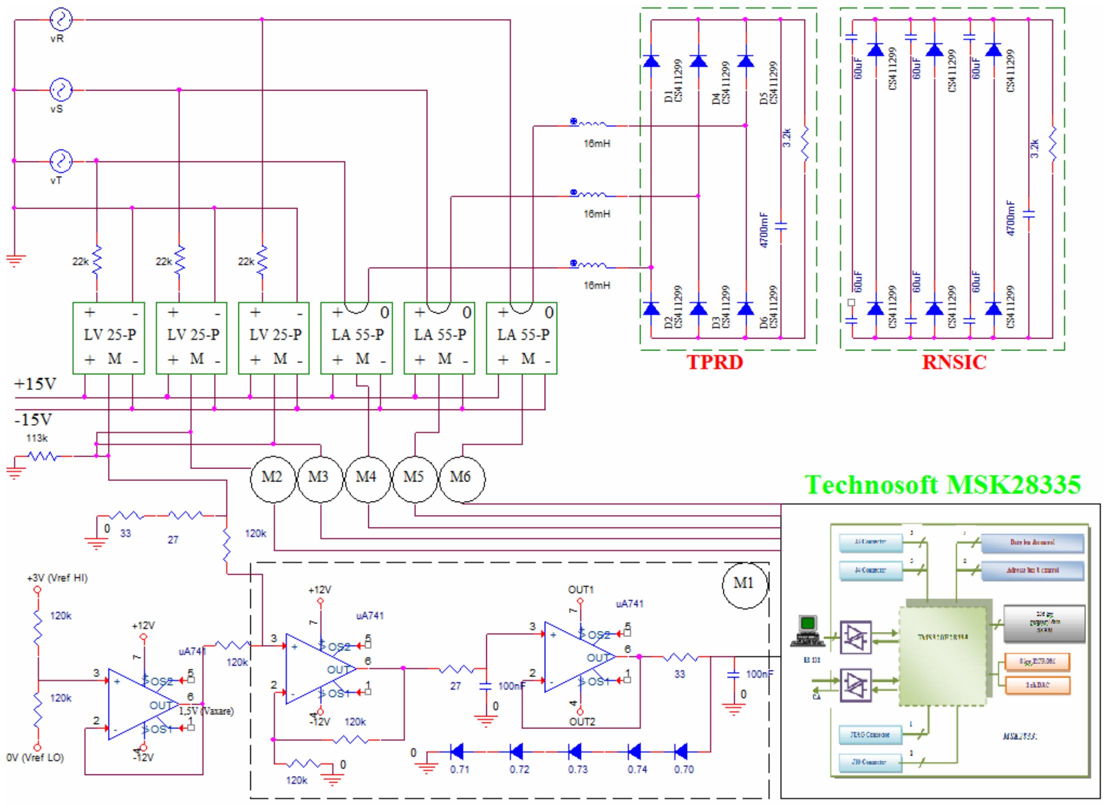


Fig.7. The electric scheme of data acquisition system with TPRD and RNSIC loads

Voltage and current waveforms was analysed using the oscilloscope as presented in Fig.8 (a)-(b). With the Math FFT module of the oscilloscope, which converts a signal from time domain in its frequency components, it was determined the effective values of voltage and current for a 50Hz frequency and 5ms period. In current case, a 200mA/div setup of the oscilloscope was made for TPRD, and 10A/div for RNSIC, while for the voltage case, the configuration was 100V/div, for both rectifiers.

When TPRD is used, for an effective value of the input current I_R of 289.5mA, the harmonic components represent 111% from the fundamental harmonic, which has a 130.1mA value (see Fig.8 (c)).

For the same configuration of the system, when RNSIC is used, the harmonic components decrease to 1.53% from the fundamental harmonic, and the current effective value increase up to 11.75A (see Fig.8 (d)).

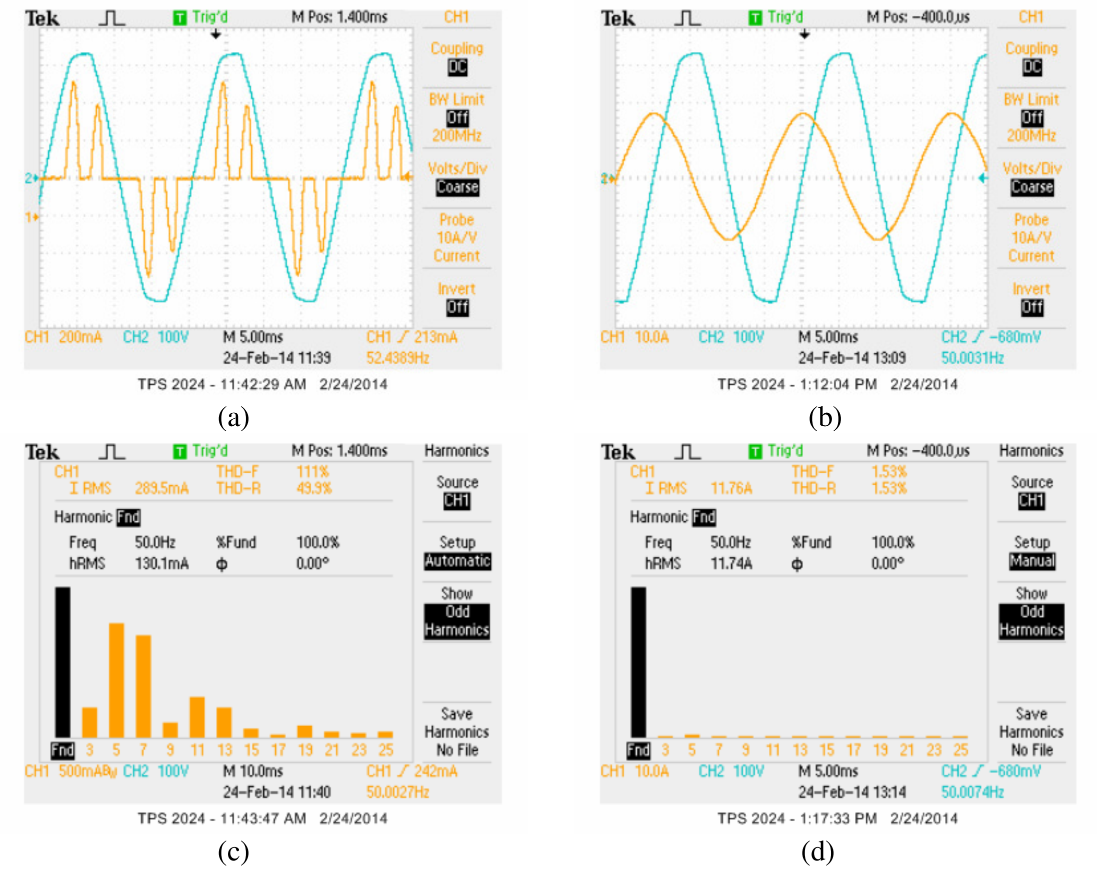


Fig.8. (a) The current (yellow) and voltage (green) waveforms of the *R* phase for TPRD; (b) The spectrum of I_R phase current for TPRD; (c) The current (yellow) and voltage (green) waveforms of the *R* phase for RNSIC; (d) The spectrum of I_R phase current for RNSIC

The waveforms captured with the data acquisition system were imported in Matlab, where it was made a time-frequency domain analysis using DWT (see Fig.9). In wavelet analysis, it was used the 'db10' (Daubechies), which is considered the most suitable mother wavelet, due to its capacity of giving the least deviation between the calculated percentage energy of the harmonics and the percentage energy of the coefficients for the wavelet levels [39].

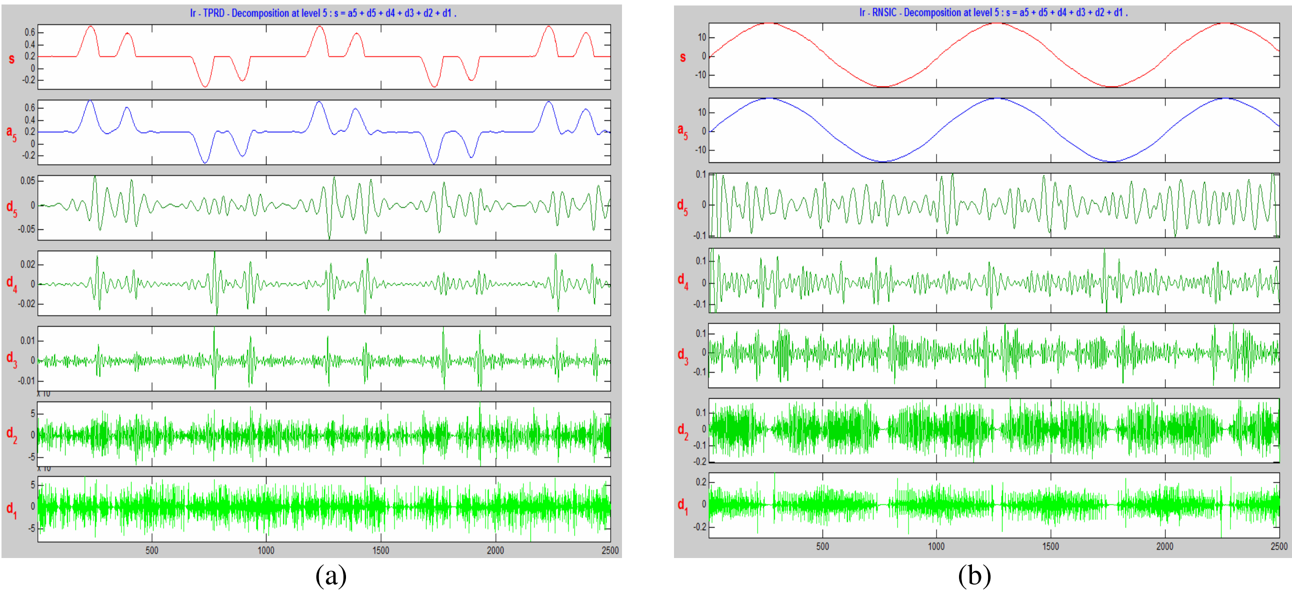
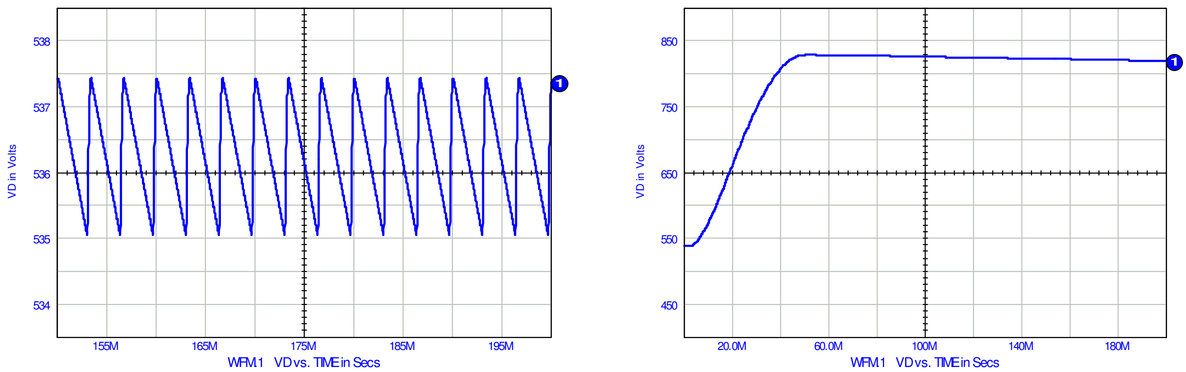


Fig.9. The five level wavelet decomposition (Daubechies 10) of input current I_R: *s* – input current (original signal); a_5 – five level approximation; d_5 – five level details; d_4 – four level details; d_3 – third level details; d_2 – two level details; d_1 – first level details for (a) TPRD and (b) RNSIC

Since in the electric system waveforms, the third and fifth component are those that prevail, the analysis involves signal decomposition on five wavelet levels. The approximation level a_5 includes the fundamental component, while the detail level d_5 and d_4 contain the third and fifth components. Reducing the number of levels will lead to the combination of the fundamental with the third component in a single level or in a single band, while the enhancement of the level number determines the decomposition of the fundamental in several bands [39].

The wavelet analysis shows that, for TPRD case, the current waveform deviates from the original sinusoidal form, while for RNSIC case, the input current fundamental increases, the waveforms being practically sinusoidal.

Fig.10 illustrates the output voltage values obtained for the two rectifier topologies, as follows: for the classic three-phase rectifier, this is 537V, while for the modern rectifier, it is 795V. The rectified voltage value is in direct ratio with the values of the inductors connected in series on each supply phase of the power system.



(a) (b)

Fig.10. The waveforms of continue voltage V_d for (a) TPRD and (b) RNSIC

Table 1 presents the PQIs values obtained in harmonic analysis of the deforming regime generated by AC-DC converters, based on DWT. Therefore, using TPRD and RNSIC allows calculating the current effective values (RMS), current harmonic distortion factor (THD), the ratio between the fifth and the fundamental harmonic, and the ratio between the seventh harmonic and the fundamental one for each phase.

Table1. PQIs values for each phase of the power system using TPRD and RNSIC

		I_1 RMS (A)	THD-F (%)	I_5 RMS (A)	I_7 RMS (A)	I_5/I_1 (%)	I_7/I_1 (%)
Phase R	**TPRD**	0.13	111	0.11	0.09	76.92	69.23
	RNSIC	16.56	3.83	0.32	0.16	1.93	0.97
Phase S	**TPRD**	0.17	106	0.13	0.11	76.47	64.71
	RNSIC	17.11	2.48	0.24	0.18	1.40	1.05
Phase T	**TPRD**	0.15	117	0.13	0.09	86.67	59.33
	RNSIC	16.71	2.94	0.34	0.13	2.04	0.78

5 Conclusion

This paper has proposed a harmonic analysis of the deforming regime generated by AC-DC converters based on DWT, using a three-phase rectifier with diodes and a rectifier with near sinusoidal input currents.

The use of capacitors on RNSIC input, together with AC side inductances lead to the decrease of the I_5/I_1 and I_7/I_1 harmonics rate below the 4% limit provided by IEEE 519/ 1992 standard and IEC 61000-3-2/ 2005 standard; decrease of THD value below the 5 % limit provided by the same standards; increase of DC intermediate voltage with 10% to 15%; correction of the power factor for an extensive range of the load current.

The fifth and seventh harmonic level and the total harmonic distortion value obtained with TPRD are higher than in the RNSIC case, where the results are situated within the international standard limits.

The DC voltage V_d measured for the modern RNSIC output is higher with 15% to 25% than the DC voltage obtained in the case of the classical TPRD.

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