Analyzing Signals from a Primary Winding of a Locomotive Transformer with Three Types of Wavelet-Based Transforms

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Abstract **– The paper is concerned with the analysis of instantaneous values and evaluation of certain power quality indices corresponding to phase currents and voltages acquired from the primary winding of a locomotive transformer. Representative data sets acquired during all operating regimes (acceleration, constant speed, normal and respectively regenerative braking) were analyzed. Firstly the background noise was estimated by using a wavelet thrashing tree considering a wavelet mother with a short filter. Specific computational aspects related to the use of the Stationary Wavelet Transform were presented and it was used to evaluate the instantaneous values of the fundamental harmonic, respectively the distorting residue. Discrete Wavelet Transform was used for 3 situations to deal with time-frequency localization of deviations from stationarity. A nodal analysis was also made with an original implementation of the Wavelet Packet Transform in a special situation, when the deviation from stationarity nearby the right edge prevents the use of DWT. Excepting the thrashing tree, the wavelet mother used in all transformations relied on a filter of length 40 due to the good properties of selectivity relative to the harmonics' energies. All methods were used to evaluate the 3 major root mean square values (for fundamental frequency, for distorting residue and total). The results yielded by different methods were compared. A good convergence of methods was noticed. Explanations for the small differences are suggested.**

Cuvinte cheie: *calcule specifice ingineriei energetice, calitatea energiei, transformata discretă Wavelet, transformata de tip Wavelet Packet Transform, transformata stationară Wavelet.*

Keywords: *power engineering computing, power quality, Discrete Wavelet transform, Wavelet Packet Transform, Stationary Wavelet Transform.*

I. INTRODUCTION

The voltages and currents from the primary winding of an electric locomotive's transformer are characterized by non-sinusoidal waveforms, due to the complex electronic equipment and electromagnetic interferences.

Moreover, the operating regime affects their harmonic spectra. Different methods for the analysis of power quality (PQ) were conceived along time. Among them, most popular and versatile are the Fast Fourier Transform (FFT) and the Wavelet based transforms (Discrete Wavelet Transform – DWT, Wavelet Packet Transform – WPT and Stationary Wavelet Transform – SWT) [1]…[4]. They were used for this study, because: (a) FFT is faster and yields more accurate harmonic spectra in a full (magnitude – phase difference) characterization, providing that the sampling frequency is high enough and the analyzed signal has symmetric semi-periods; (b) DWT, which is characterized by the decimation phenomenon and therefore is faster than SWT, being able to provide time-frequency information considering adjacent frequency ranges; (c) WPT, which is able to provide harmonic spectra with some limits and allows the revealing of deviations from the steady state in a time-frequency manner for particular harmonic orders; (d) SWT, which simultaneously with the counteracting of the decimation phenomenon, allows the extraction of instantaneous values oscillating at the fundamental frequency and respectively of instantaneous values corresponding to the distorting residue.

This paper is dedicated to studies completing and extending those presented in [1]. The new aspects introduced now are: (a) brief information on wavelet trees usability and implementation; (b) evaluation of noise by using a wavelet thrashing tree such as to make sure that the PQ analysis provides accurate data; (c) using SWT in an original implementation; (d) using the results yielded by SWT to detect 3 situations where deviations from stationarity are noticed and evaluating the harmonic range/order causing the deviation while addressing the "edge-effect" and dealing with it with DWT when possible or with WPT (implemented in an original mode , by analyzing the energies computed in the terminal nodes); (d) completing the comparative studies (FFT vs. WPT/DWT) concerned with the Root Mean Square (RMS) indices while considering the new results provided by SWT and adding a table considering as reference data the total RMS computed with Riemann sums; (e) evaluating the Total Harmonic Distortion (THD) while considering new data, yielded by SWT; (f) new discussions on the differences between the values of PQ indices provided with different methods.

II. OPERATIONAL CONTEXT

Single phase currents and voltages were acquired at a sampling frequency of 4100 Hz from the primary winding of a locomotive's transformer. This frequency corresponds to the data acquisition system used by the locomotive manufacturers during their first tests with this locomotive. All operating regimes were considered: acceleration, running at constant power, normal braking and regenerative braking respectively (Figs. 1 and 2) [1].

6 data sets with the length of 3 periods were considered

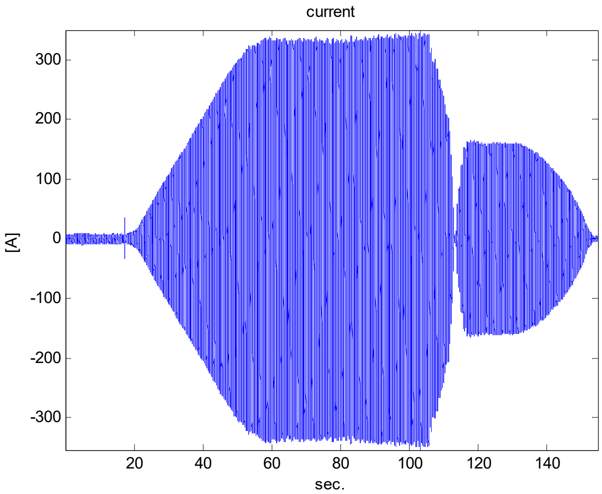


Fig. 1. Acquired current.

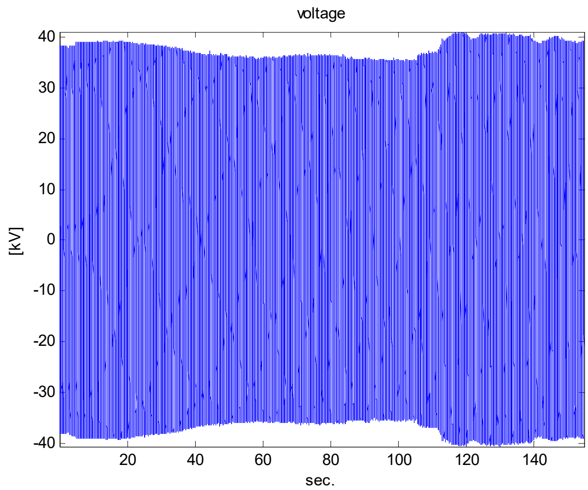


Fig.2. Acquired voltage.

as representative to this study and analyzed. A period consists of 82 samples and lasts 0.02 s, corresponding to the fundamental frequency of 50 Hz. The 1-st set belongs to the acceleration stage, the 2-nd one to the stage of running at constant speed, the 3-rd one for the normal braking and the remaining 3 for the stage of regenerative braking [1]. These selected sequences start from the following moments: 31.71 sec., 48.78 sec., 104.88 sec., 119.02 sec. 129.27 sec. and 146.34 sec. respectively. The representations of the associated waveforms are depicted in [1].

Fig. 3. depicts the electrical circuit to which the transformer is connected and the test point.

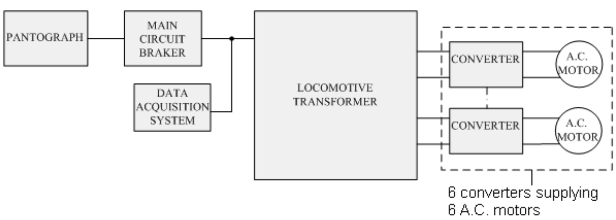
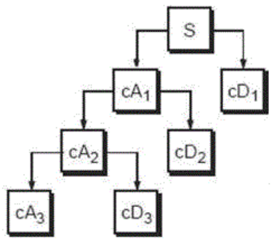


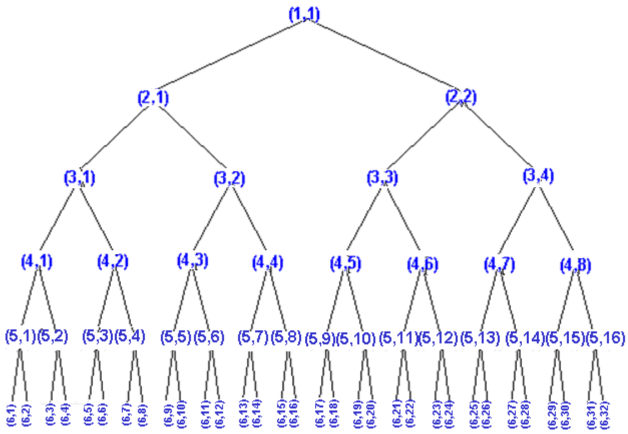
Fig.3. Electric circuit to which the transformer is connected and the test point.

III. Fundaments of Wavelet Based Analysis

Two different topologies are used by the wavelet based analysis approached in this paper (Fig. 4) [3], [5]. DWT and SWT use unbalanced trees whilst WPT and the denoising technique presented in the following section use a balanced tree.



(a)



(b)

Fig. 4. Trees topologies used by wavelet analysis: (a) unbalanced tree; (b) balanced tree.

For any of these trees, the vector (denoted by *S*) hosted by the parent node from the upper level is decomposed in two vectors (denoted by *CA* and *CD* respectively). *CA* includes the components of low frequencies whilst *CD* includes those of high frequencies. Considering a certain wavelet mother (WM) characterized by a low-pass filter *H* and a high-pass filter *L*, both of length *h*, the components of *CA* and *CD* are computed in an iterative manner, with:

$$CA_i = \sum_{j=1}^{h} S(i+j-1)\,x\,H(j)\ ;\ CD_i = \sum_{j=1}^{h} S(i+j-1)\,x\,L(j). \quad (1)$$

The index i is increased by 2 at each new iteration in the same level. Special assumptions are used when evaluating the "rightmost" indices of *CA* and *CD*. This leads to the so called "decimation phenomenon" and affects the time-resolution on bottom decomposition levels at DWT and WPT. On the other hand, SWT and the denoising technique relying on wavelet trees are using interpolation techniques to recover the number of samples on each level (technique known as "up-sampling").

All trees used in this paper (except for the thrashing tree) have 6 levels, host in the root node a signal consisting 256 samples per period (obtained after spline interpolations of the acquired periods of 82 samples) and employs a WM from the Daubechy family, denoted in Matlab by 'db20'.

IV. Evaluating the Level of Background Noise

The possibility to face background noise is high inside the locomotive owing to the complex electric/electronic equipment and high powers. A correct approach of a PQ analysis requires a preliminary evaluation of noise under the form of a parameter called „Signal to noise ratio" (SNR). SNR is defined as the ratio between the average power of the analyzed signal and the power of noise.

A modern technique, relying on wavelet thrashing trees, was employed. It relies on the MATLAB function "*wden*" which had to be carefully "tuned" due to the impressive number of parameters. The procedure used to deduce its parameters is complicated and it was described in [6] for another type of signals, where denoising was compulsory because small SNR-s were involved. A totally different thrashing tree was used in [6].

Similar to [6], previous estimation of the noise were done considering 4 WM-s, denoted in MATLAB by 'db2', 'db3','db4' and 'sym4'. An average noise signal was used to get estimated noise powers. For each acquired signal, sets of 10 Gaussian noises with powers identical to the above mentioned estimations were randomly generated and used to determine in an original (statistical) way the best WM [6]. The configuration deduced for the denoising tree is as follows: noise of type "Gaussian white noise", tree with a single level, "soft denoising" (the alternative being "hard denoising" which proved to be too aggressive), and WM of type'db3'. Figs. 5 and 6 represent

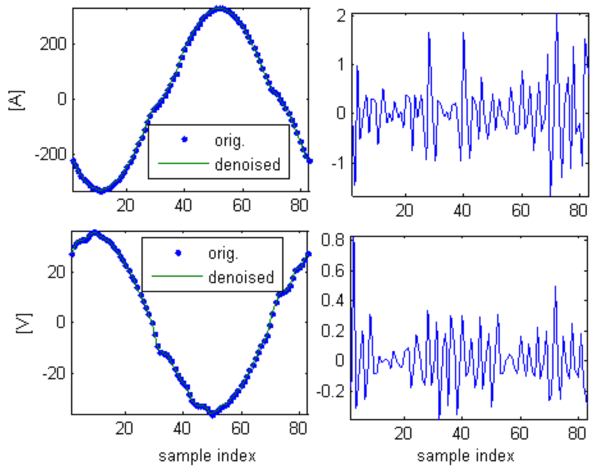


Fig. 5. Signals and noises for the 1-st period from the 1-st data set.

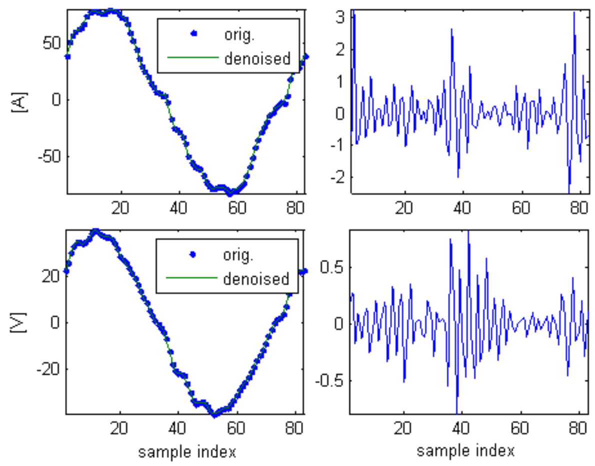


Fig. 6. Signals and noises for the 1-st period from the 6-th data set.

the signals before and after denoising and respectively the estimated noise for the 1-st and 6-th datasets. The noise was evaluated as the difference (acquired signal - denoised signal). In both figures, we represented at left the waveforms before and after denoising (currents at top and voltages at the bottom), In the right side the estimated noises were represented: at currents – top and at voltages – down. Fig. 7 depicts a zoom corresponding to Fig. 6 when considering signals associated to the acquired and denoised current. It reveals the correctness of the denoising procedure and the low level of the background noise.

Fig. 8 represents the high values of SNR for all analyzed waveforms, proving that the Gaussian background noise had reduced values and therefore no special measures had to be taken.

V. Computing Instantaneous Values with the Stationary Wavelet Transform

A. Computational aspects

SWT is a very useful tool because it is able to provide instantaneous values of the fundamental harmonic and respectively of the distorting residue in a "non-decimated" manner. The MATLAB function conceived to perform this is called 'swt'.

When applying it to the analyzed datasets, problems were identified relative to both scale factors and phase difference between the real instantaneous values of the fundamental harmonic and those yielded by MATLAB, as exemplified by Figs. 9 and 10.

Therefore tests were made on synthetic data in order to diminish the errors produced by the above mentioned issues. The deduced scale factor (0.125), was found to be insensitive to the magnitude and phase difference of the

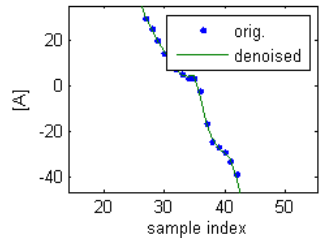


Fig. 7. Zoom corresponding to the acquired and denoised current represented in Fig. 6.

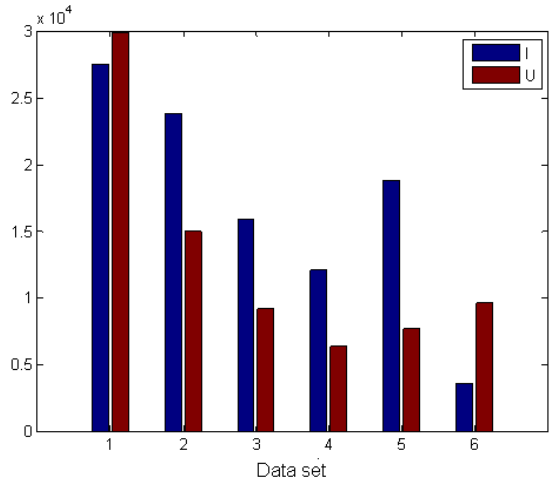


Fig. 8. Signal to noise ratios for the analyzed data sets.

analyzed signals and respectively to the nature/length of the WM whilst the phase difference was found to be variable with the WM and therefore had to be computed for each tested WM.

Therefore the components of *CA* from the last level of the tree (these ones being those to provide the instantaneous value for the fundamental harmonic) had to be processed with the original formula:

$$CA_{6,i_m} = 0.125 \bullet CA_{6,i+pd}, \tag{2}$$

where $CA_{6,i}$ is the *i*-th component from the vector *CA* of the 6-th level, as yielded by ‘swt’ and $CA_{6,im}$ represents the associated component from the vector corrected by our algorithm, considering the phase difference *pd*, calculated by us to be 168 for this tree configuration.

B. *Evaluting Instantaneous values of the fundamental harmonic and distorting residue computed with SWT*

Once finished the calibration of the decomposition tree, the evaluations of instantaneous values of fundamental harmonic and distorting residue became possible. Fig. 11 depicts the current and voltage from the 1-st data set, overlapped with the computed instantaneous values of the fundamental harmonic

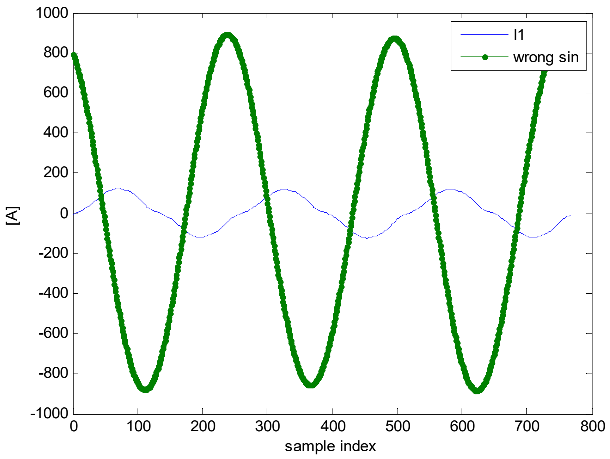


Fig. 9. 1-st data set (current) overlapped with the wrong waveform (displaced and badly scaled) yielded as sinusoid corresponding to the fundamental harmonic by the function ‘swt’ from MATLAB.

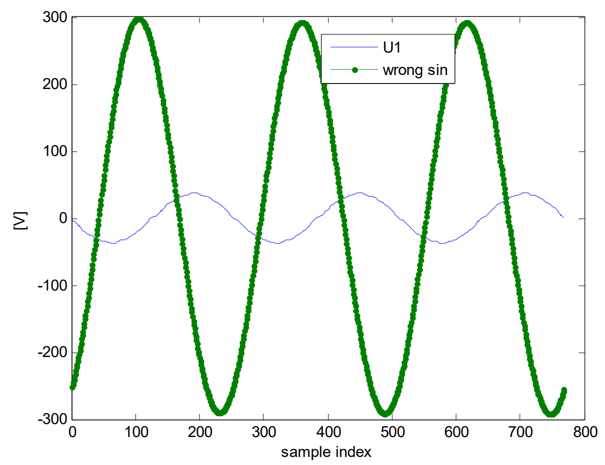


Fig. 10. 1-st data set (voltage) overlapped with the wrong waveform (displaced and badly scaled) yielded as sinusoid corresponding to the fundamental harmonic by the function ‘swt’ from MATLAB.

The values of the distorting residues (R_i) were computed with:

$$R_i = S_i - CA_{6,i_m} \tag{3}$$

Figs. 12-14 represent the residues revealing deviations from stationarity inside their associated analyzed datasets.

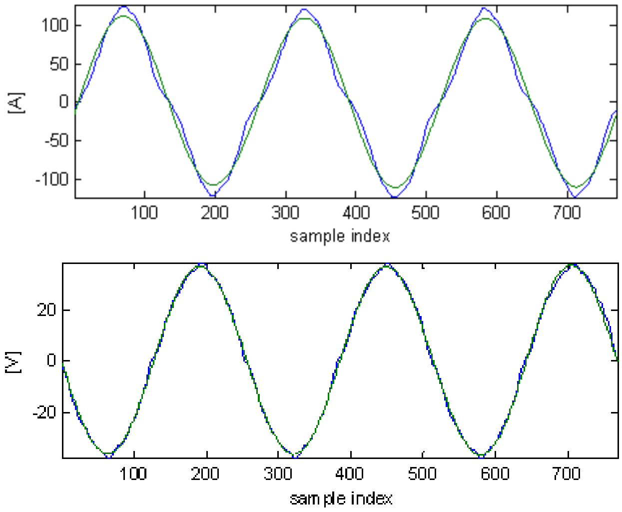


Fig. 11. Current (top) and voltage (down) from the 1-st data set, overlapped with the instantaneous values of the fundamental harmonic.

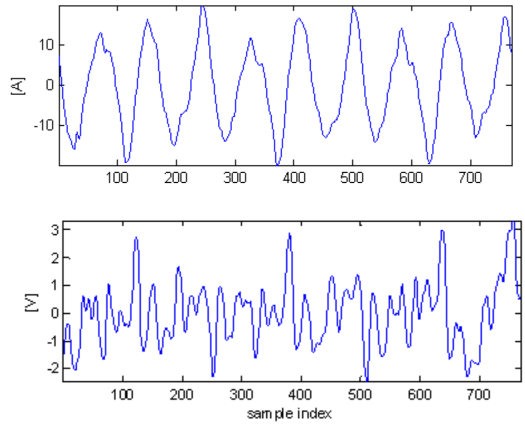


Fig. 12. Distorting residue for the 1-st data set. Current – top and voltage – bottom.

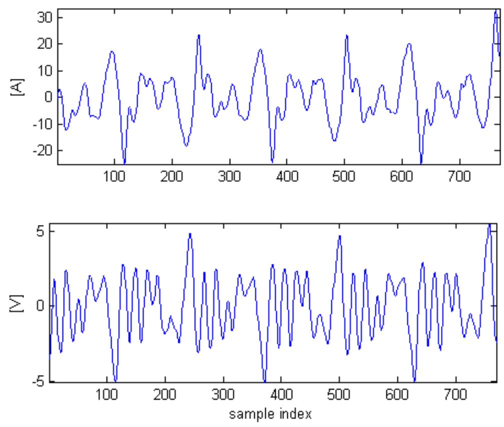


Fig. 13. Distorting residue for the 5-th data set. Current – top and voltage – bottom.

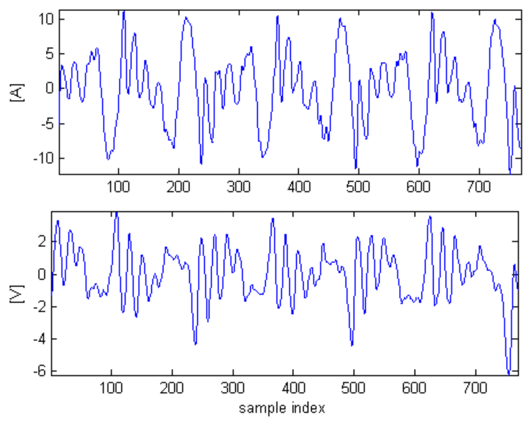


Fig. 14. Distorting residue for the 6-th data set. Current – top and voltage – bottom.

VI. Study of Methods Convergence when Evaluating Root Mean Square Indices

All types of RMS indices presenting interest for a PQ analysis were evaluated with the FFT, WPT and DWT [1], relying on [7, 8]. New results are now available, yielded by the SWT, considering the theoretical support from [9]. Tables I and II gather the values evaluated with FFT for RMS of the fundamental frequency (RMS_F) and respectively for the distortions (RMS_D) and the percent relative differences (PRD) computed relative to the counterpart values, yielded by the wavelet-based methods.

An analysis of Table I reveal that, with only 3 exceptions (where the differences measured in PRD (DWT/WPT vs. SWT) are at most 0.02%), identical values are yielded by all wavelet-based methods for the RMS_F. Very small PRD (wavelet vs. FFT) were obtained as well, within the range [0.12, 1.07]% at currents and respectively [-0.04, 0.29]% at voltages. As expected the smallest differences were obtained for the 2-nd data set, when the locomotive ran at constant speed, both fundamental components of current and voltage being identical along the entire dataset.

Extremely close values were also provided by (DWT/WPT) and respectively by SWT for RMS_D. The differences between them are highly acceptable and fall into the ranges [-0.1, 0.21]% for currents and [0.04, 1.23]% for voltages. More probably they are due to the up-sampling performed at each decomposition level by SWT in order to counteract the decimation phenomenon.

The highest PRD "FFT vs. wavelet - based" were encountered for RMS_D. They fall into the range [-2.89, 3.95] % at currents and [0, 6.2]% for voltages. Considering the absolute value of this PQ index, they are practically acceptable because are translated into insignificantly small absolute differences. Moreover, previous studies performed on synthetic data ([4, 10, 11]) proved that the accuracy in evaluating this PQ index is limited for any numerical method, the percent relative errors falling into the ranges: [- 2, 1.46]% at FFT, [-1.68, 2.44]% at DWT/WPT and [2.08, 2.22]% at SWT. One should also consider that at voltages the harmonic content is less significant, being dominated by low harmonic orders (Fig. 15 [1]). As long as the highest numerical errors are associated to low harmonic orders of small weights ([4, 10, 11]), this might be an explanation for higher differences noticed at voltages in all datasets.

TABLE I.
Root Mean Square Values for the Fundamental Frequency Computed with FFT and Percent Relative Differences Relative to Them when Using Wavelet Analysis

Set ID	RMS_F I [A]	PRD relative to WPT/DWT [%]	PRD relative to SWT [%]	RMS_F U [V]	PRD relative to WPT/DWT [%]	PRD relative to SWT [%]
1	78.27	1.06	1.07	25.95	0.23	0.23
2	224.58	0.12	0.12	24.44	-0.04	-0.04
3	228.53	0.43	0.43	24.28	0.25	0.29
4	112.86	0.12	0.12	27.01	0.22	0.22
5	112.12	0.37	0.37	26.93	0.07	0.07
6	55.75	0.14	0.16	26.72	0.11	0.11

TABLE II.
Root Mean Square Values for the Distorting Residue Computed with FFT and Percent Relative Differences Relative to Them when Using Wavelet Analysis

Set ID	RMS_D I [A]	Percent rel. diff. WPT/DWT [%]	Percent rel. diff. SWT [%]	RMS_D U [V]	Percent rel. diff. WPT/DWT [%]	Percent rel. diff. SWT [%]
1	10.05	-2.79	-2.89	1.02	1.71	2.94
2	16.82	3.20	3.27	1.42	1.37	1.41
3	17.25	4.14	4.35	1.36	6.20	5.88
4	9.61	3.81	3.95	2.12	0.18	0.00
5	9.40	0.85	0.74	2.04	2.46	2.94
6	5.48	3.02	3.10	1.62	2.89	3.09

Table III gathers the total RMS values (RMS_T) evaluated with Riemann sums [12] and the PRD associated to the same PQ index evaluated with FFT and wavelet-based methods respectively. The Riemann sums provide an accurate method for the evaluation of RMS_T.

For this study these sums were evaluated based on the analyzed dataset submitted to a spline interpolation which increased the number of samples per period from 82 to 256, required by the wavelet-based methods. Therefore it is natural to have "best estimations" provided by the wavelet-based analysis. A "perfect match" was provided by WPT for RMS_T. Very close PRD relative to the Riemann sums (within [0.001, 0.013]% at currents and respectively ranging from -0.264% to 0.041% at voltages) were provided by SWT as well. The effects of up-sampling are probably an explanation for this.

The PRD "FFT vs. Riemann sums" are a little bit higher but highly acceptable for practical application. Still one should recall that a different base of calculation points was used (around 20 intermediate points between any 2 adjacent samples were used in order to provide the harmonic spectrum with an acceptable accuracy).

TABLE III.
Total Root Mean Square Values Computed with Riemann Sums and Percent Relative Differences Relative to Them when Using FFT and Wavelet Analysis

Set ID	RMS_T I [A]	PRD to FFT [%]	PRD to WPT/ DWT [%]	PRD to SWT [%]	RMS_T U [V]	PRD to FFT [%]	PRD to WPT/ DWT [%]	PRD to SWT [%]
1	78.12	-1.01	0	0.003	25.91	-0.23	0	-0.227
2	224.91	-0.13	0	0.000	24.49	0.04	0	0.041
3	28.15	-0.45	0	0.001	24.25	-0.25	0	-0.263
4	113.1	-0.15	0	0.002	27.03	-0.22	0	-0.233
5	112.1	-0.37	0	0.001	26.98	-0.11	0	-0.084
6	55.92	-0.18	0	0.013	26.74	-0.11	0	-0.098

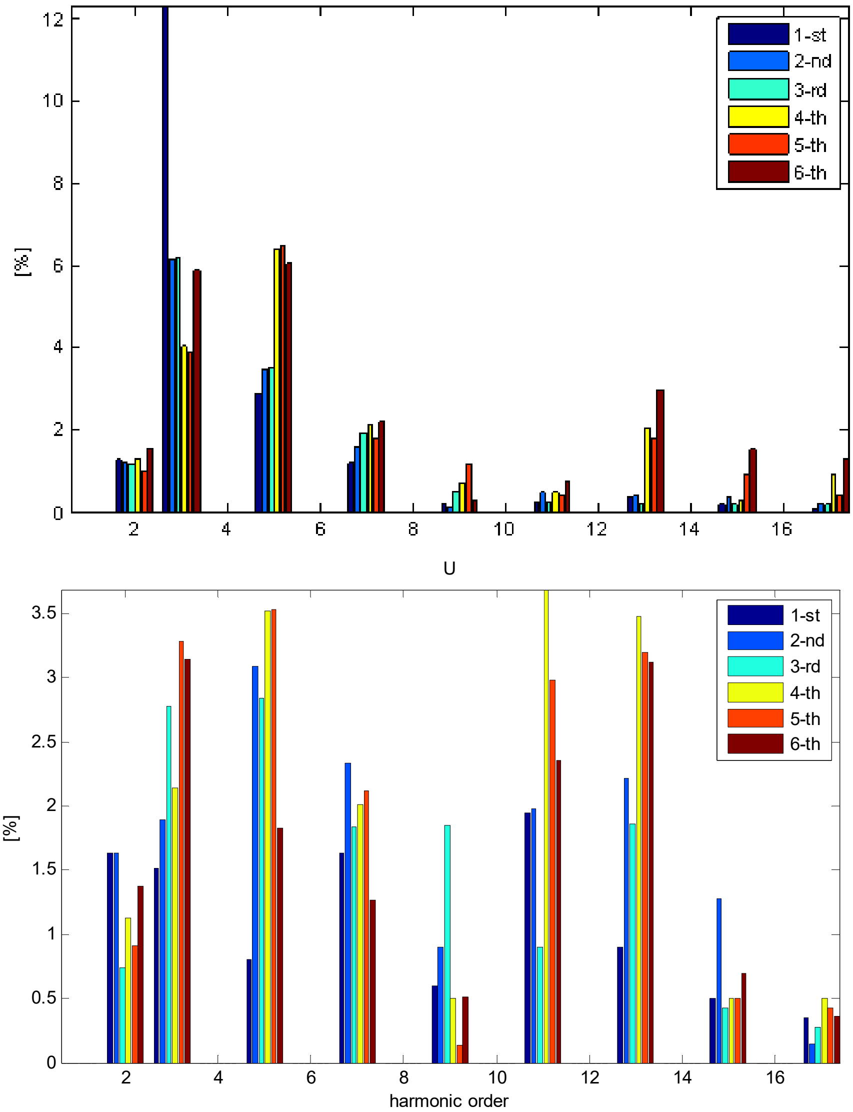


Fig. 15. Harmonic spectrum, computed with FFT. Up – currents. Down – voltages.

VII. Clear versus Questionable Deviations from Stationarity

A. *DWT analysis*

The DWT analysis allows for the detection of local deviations from stationarity in a "time-frequency" manner. In this paper the DWT tree was implemented by the function 'dwt' from MATLAB.

Two of the analyzed datasets exhibiting deviations from stationarity take advantage at this type of analysis. The 1-st one refers to the voltage for the 1-st dataset represented in the bottom at Fig. 12. A clear deviation from stationarity can be seen in the 3-rd period and it is better emphasized by Fig. 16, where the instantaneous values of the distorting residues from the 3-rd period (yielded by SWT) are overlapped over those from the 1-st period.

Fig. 17 depicts the vector of details for all levels yielded by DWT analysis, revealing that the deviation from stationarity was produced at low harmonic orders, in the low frequency range (level 7 corresponding to the 3-rd and 5-th harmonic order).

The 2-nd case with deviations corresponds to the current from the 5-th dataset (Fig. 13 – top), where the deviation occurs nearby the right margin of the 3-rd period. The vectors of details yielded by DWT are depicted by Fig. 18. Fig. 19 depicts the 1-st period overlapped with the 2-nd period and respectively the 1-st period overlapped with the 3-rd period for the 5-th level.

The 3-rd case is a special one, because the deviation occurs very close to the right edge of the voltage associated

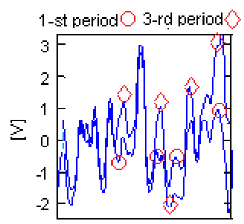


Fig. 16. Distortions corresponding to the voltage from the 1-st dataset, 1-st and 3-rd periods, overlapped.

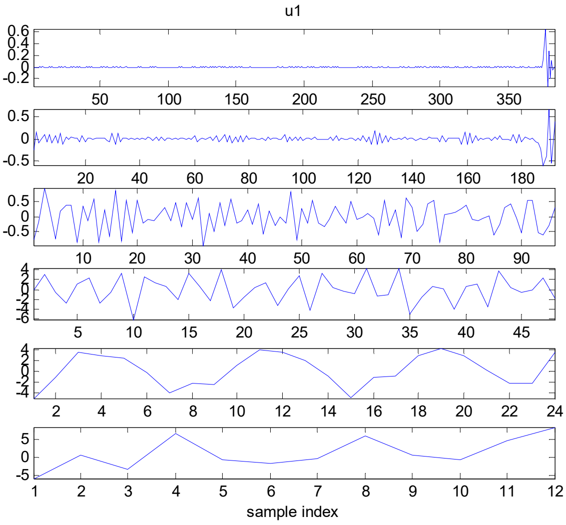


Fig. 17. Vectors of details computed with DWT for voltage, 1-st dataset. Decomposition levels increasing from top to down.

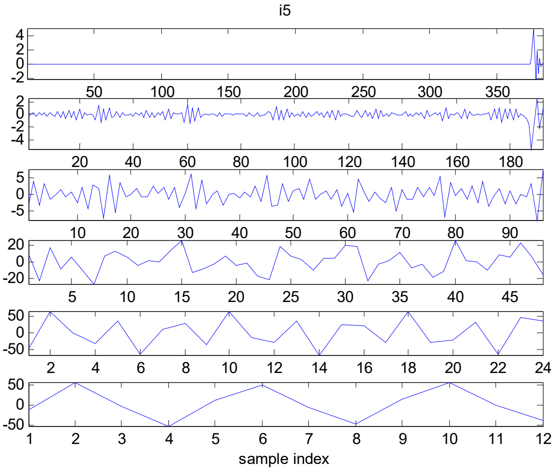


Fig. 18. Vectors of details computed with DWT for current, 5-th dataset. Decomposition levels increasing from top to down.

to the 6-th dataset. The vectors of details yielded by DWT are depicted by Fig. 20.

The very small difference recorded at the end of the 3-rd period for the 5-th level cannot represent a clear verdict relative to a changing in the distortions' composition. Due to the decimation phenomenon, too few points are available at the bottom levels. Moreover, the decomposition was made with the function 'dwt' from MATLAB considering that the components following after the right edge of the 3-rd period are identical to those from the beginning of the 1-st period (periodicity was assumed). The wavelet filter is long (40 components) and therefore it is hard to evaluate 38 components from only 2. Neither spline, nor mean-tangent based methods [1, 3] cannot be used and therefore an "edge-effect" is the price paid for this type of analysis. It is not harmful for the upper levels, corresponding to high harmonic orders with negligible weighs but it

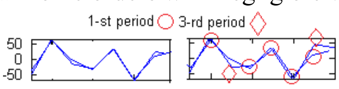


Fig. 19. Vector of details for the 5-th level , for the current from the 5-th dataset. Left: 1-st and and 2-nd period overlapped; Right: 1-st and 3-rd periods, overlapped.

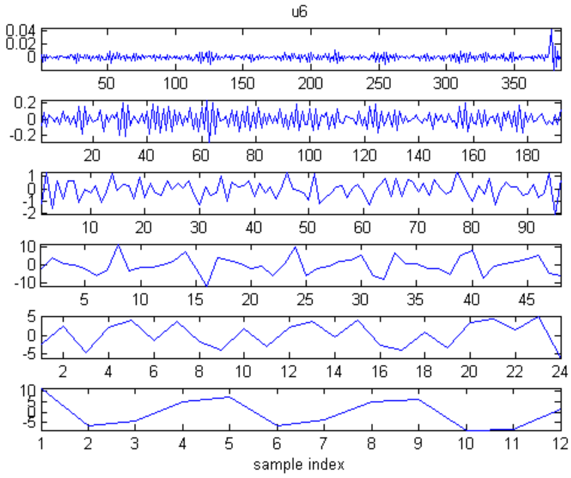


Fig. 20. Vectors of details computed with DWT for voltage, 6-th data-set. Decomposition levels increasing from top to down.

can require a compulsory additional analysis with WPT in situations like this.

B. Harmonics-Related Nodal Analysis Provided by WPT

In order to perform the WPT analysis, an original decomposition technique was implemented. The use of '*wpdec*' (provided by MATLAB for the WPT analysis) proved to be wasting runtime because it performed all decompositions, irrespective to the content of the decomposed vector. Therefore, in our algorithm, 'db20' was invoked in a iterative manner, individually for each node, in order to perform a new decomposition only if the signal to be decomposed was non-zero. This was especially useful for the nodes associated only to high order harmonic, which are not present in the harmonic spectra from Fig. 15. Significant runtime savings (up to 30%) were obtained.

'db20' exhibited good properties of harmonic selectivity, which made possible the association between the energies from the terminal nodes of the WPT tree and the harmonic orders [5,13,14,15]. Our original technique, presented in [5] was used to associate the computed nodes' energies to the harmonic orders generating them. Fig. 21 depicts the vectors of details from the final nodes of the WPT tree associated to the voltage from the 6-th dataset. The most significant variation is noticed at the 6-th node, revealing that the deviation from stationarity is associated to the 3-rd period, to the 13-th harmonic.

VIII. TOTAL HARMONIC DISTORTIONS

Table IV gathers the THD-s for voltages and currents evaluated with all methods. The values yielded for this PQ index by different methods are very close to each other. Considering the standardized limits (8% for THD at currents and 5% for voltages), it was revealed that only for

TABLE IV.
TOTAL HARMONIC DISTORTIONS EVALUATED WITH ALL METHODS

Set ID	THDI [%]			THDU[%]		
	FFT	WPT/DWT	SWT	FFT	WPT/DWT	SWT
1	12.84	13.34	13.35	3.93	3.86	3.82
2	7.49	7.26	7.25	5.81	5.73	5.73
3	7.55	7.27	7.25	5.60	5.28	5.29
4	8.51	8.20	8.19	7.85	7.87	7.87
5	8.38	8.34	8.35	7.58	7.40	7.36
6	9.83	9.57	9.54	6.06	5.88	5.88

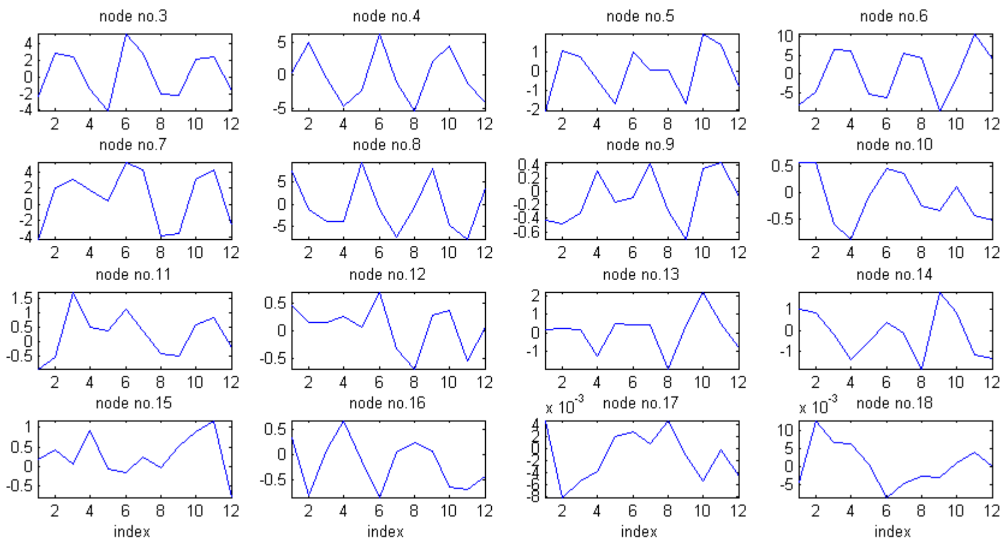


Fig. 21. Vectors of details from final nodes of the WPT tree corresponding to the voltage of the 6-th dataset.

the 2-nd and 3-rd datasets the limits for currents are obeyed (in extremis!) whilst the only case when the limit is obeyed at voltage is the 1-st case. Therefore corrective measures should be taken.

IX. Conclusions

Four methods of analysis (FFT, DWT, WPT and SWT) were used in order to evaluate the most significant PQ indices from all operating regimes of a Romanian electric locomotive and to perform time-frequency analysis.

SWT was used to provide instantaneous values for the fundamental harmonic and distorting residue. When SWT revealed deviations from stationarity, DWT was used to provide instantaneous variations of distortions considering frequency ranges, therefore representing a useful tool for time-frequency localization of faults. DWT presents limits relative to an acceptably small right-edge effect of fake faults when mismatching appears between the first samples after the right edge of the analyzed dataset and the 1-st ones, nearby the left edge. Neither spline interpolations nor the mean tangent method can be used to avoid this.

The presence of a deviation from stationarity nearby the right edge of the analyzed dataset sometime requires a WPT analysis, because WPT can provide with approximation the harmonic spectra. Its unique capabilities are related to the localization of the harmonic orders where faults or deviations occurred and was exemplified through a nodal analysis.

The values yielded by all methods for the studied PQ indices were very close to each other and possible explanations for the small noticed differences were provided. The convergence of methods demonstrates the reliability of the developed algorithms.

The total harmonic distortions were evaluated for each of the 6 data sets. Considering the standardized limits of 8% for THD at currents and 5% at voltages, all methods revealed that only for the 2-nd and 3-rd datasets the limit is obeyed for currents whilst the only case when the limit is obeyed at voltage is the 1-st case. Therefore corrective measures should be taken. This study is also useful because is drawing an alarm in this sense. A special attention should be paid for the increasing of THD for the datasets associated to the regenerative braking!

This study is an "overall" approach of possibilities to analyze different experimental data. It is a good example of identifying deviations from stationarity and using different appropriate wavelet-based tools for time-frequency analysis (DWT is faster and therefore WPT should be used only in special situations whilst SWT has unique characteristics).

The provided details relative to the trees implementation and other special computational aspects (proving that the MATLAB tools cannot always be used without errors or runtime-wasting) make this study a good "user-guide" for specialists in power quality for other applications as well.

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Contribution of authors:

First author – 40%

First coauthor – 30%

Second coauthor – 20%

Third coauthor – 10%

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