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DATA COMPRESSION USING PRONY'S METHOD AND WAVELET TRANSFORM IN POWER QUALITY MONITORING SYSTEMS*

The paper presents a new method for data compression that can be used in power quality monitoring systems. Described algorithm offers high compression ratio and keeps good accuracy of the reconstructed signals. The algorithm uses a modified Prony's method for initial power waveform modeling (basic parameters of estimation) as well as wavelet transform for additional reduction of compression artifacts present in the Prony model of the analysed signal. The combination of the Prony's method and wavelet transform enables obtaining effective compression of real signals observed in monitoring systems. It also gives information about harmonics and transient oscillatory components of power waveforms that can be used for the power quality analysis. Examples of real signals recorded in power monitoring systems are presented in the paper as well as discussion of compression efficiency for different sets of compression artefacts level.

Keywords: signal compression, Prony's method, wavelet transforms, power quality

1. INTRODUCTION

Recently, due to the considerable increase in the number of power receivers as well as gradual liberalization of the power market, more attention has been paid to its quality. Knowledge of the performance of the power system and the quality of the power signal sent, enables modernization and installation of additional protection for often expensive electric and electronic devices. Nowadays, there are a lot of different devices for the analysis and monitoring of the power quality. Price depending, they have the following parameters:

- measurement resolution: 12, 16 bits
- measurement frequency: 4 kHz, 6.4 kHz, 8 kHz, 12.8 kHz and more
- number of inputs: 6, 7, 8
- data memory: from 128 kB to 512 MB

These parameters indirectly determinate the maximum time of the possible storage of the parameters and signals from the power network.

While recording power signals at the frequency of 12.8 kHz, resolution of 16 bits and 8 analyzed inputs, the time of continuous recording for the memory of 512 MB, is about 44 minutes.

Hence, the compression of data is used [1,2].

The most often used method of data compression is the recording of some parts of the signal only (with some surrounding), which exceed the parameters determined by the person operating the device, for example: instantaneous voltage, content of harmonics, frequency deviation of a basic harmonic and alike. This method, however, often results in the loss of important information about the signal, mainly due to misfit of adjustment to a definite power network. The advantage of this method is its high compression ratio. There also exist methods of lossless compression, which are used in the power signal bases. These are the algorithms related to the commonly used data compression methods, for example ZIP or ARJ archives

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applying the algorithm LZ77 [3,4] also used in the signal archive files of the PQDIF type [5]. Their disadvantage, however, is a low compression ratio, limiting its application.

In the article, a new method of loss compression of the power waveform, enabling obtaining a high, compression ratio, maintaining at the same time information included in the signal, has been presented.

2. METHOD DESCRIPTION

A general principle of compression is presented in Fig. 1 [6]. The original data (in this case the data from the monitoring system) are compressed, and a new data format is obtained which occupies fewer number of bits in comparison with the original data.

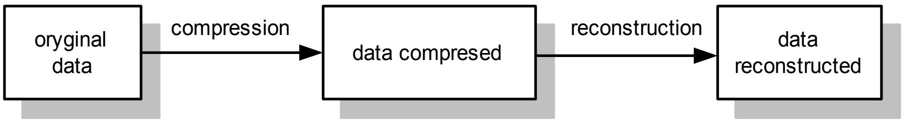

Fig. 1. The principle of data compression.

Such a representation of signal, so called compressed signal is archived or sent to a receiver, where it is further reconstructed (decompressed), to obtain a reconstructed signal. The ratio between the number of bits of original signal and the compressed one is called the compression ratio.

Presented algorithm belongs to lossy compression methods. It means that the decompressed data may be different from the original data. The differences between the original data and the reconstructed ones is called compression artifacts. In this paper compression artifacts (reconstruction errors) are represented by the following equation:

$$d(x, y) = |x - y|, \tag{1}$$

where: $\{x_n\}$ – original signal, $\{y_n\}$ – signal reconstructed.

A general concept of the proposed algorithm for the power waveform compression is presented in Fig. 2 [7,8].

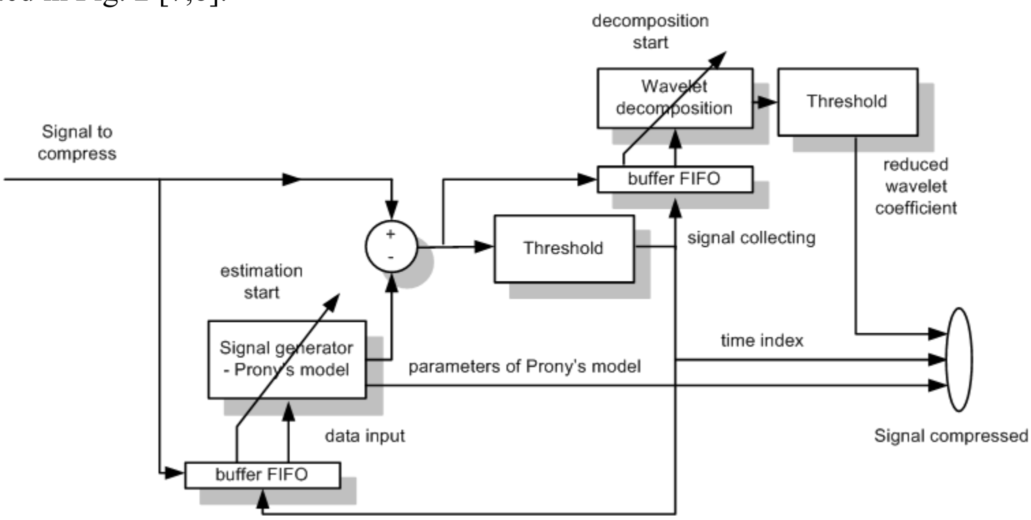

Fig. 2. Power waveform compression – general algorithm.

A signal from a measuring system is compared with the signal that is generated from Prony's model. If the difference between the original signal and the signal from the model exceeds threshold errors then sample signals are collected for a new Prony's model estimation, which will be presented further on. At the same time samples of the difference between the original signal and signal from Prony's model are collected for the wavelet decomposition. If the signal buffers are full, new wavelet and Prony's model estimation is started and next step buffers are cleaned. If new wavelet decomposition is finished it gives new decomposition coefficients that must be compressed, too.

Subsequent smallest wavelet decomposition coefficients are nullified (hard threshold elimination) [9,10] until the assumed reconstruction error is obtained. The position of wavelet coefficient non-zero blocs is registered.

Information about their location together with non-zero coefficients is the part of the compression frame (Fig. 3). The remaining parts are the parameters determined from the Prony's model as well as the time index for the event which resulted in the new estimation.

This algorithm of the signal analysis enables efficient compression of the power signal due to the modeling of oscillating, harmonic and interharmonic phenomena by means of the Prony's method as well as the compression of impulse signals by wavelet compression.

Combination of these methods allow for the compression of all power waveform described by the norms [11,12], for instance: transient oscillatory, notching, harmonics, transient impulsive, sags, swells etc.

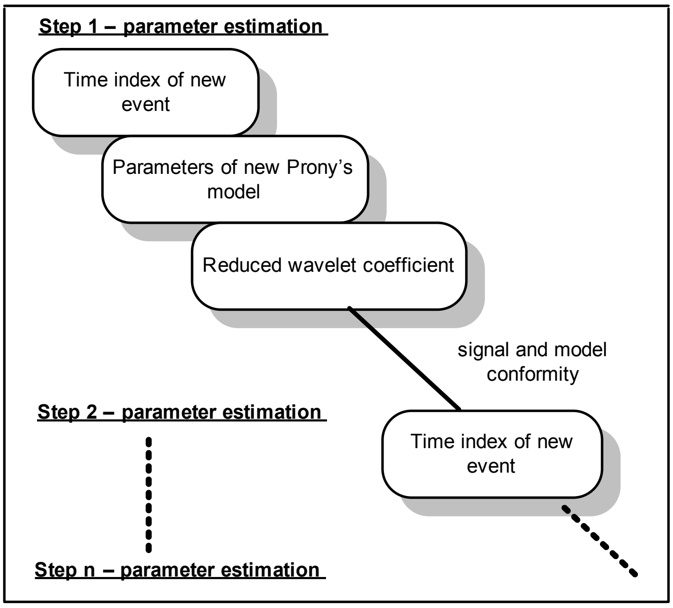

Fig. 3. Signal compressed frame – general model.

The signal compressed in this way can be reconstructed later for events visualization and power quality analysis. It is shown in Fig. 4.

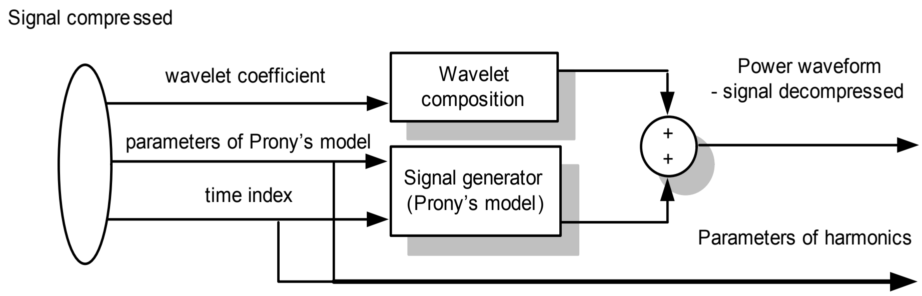

Fig. 4. Power waveform decompression – general algorithm.

Signal decompression consists in generating signal samples from the Prony's model and summing up their values and the samples obtained from the wavelet composition.

There is also the possibility to get valuable information from the Prony's model about oscillatory components of the analyzed signal like: amplitude of components, frequency, phase, and dumping factor.

The advantage of the presented method is also the ability to calculate amplitude and frequency of harmonics which precision is higher than for instance that of popular fast Fourier transformation [13].

Presented compression algorithm uses the Prony's method [14 - 17] (in fact modified last squares of it [18]) which is used for harmonics and transient oscillatory modelling. It consists in presenting a signal as a linear combination of exponential function with the assumed parameters [Eq. 2].

$$\hat{x}[n] = \sum_{k=1}^{p} A_k \exp[(\alpha_k + j2\pi f_k)(n-1)T + j\Theta_k], \tag{2}$$

for $1 \le n \le N$, where: N – is length of signal, p – is quantity of exponentials, T – is the sample interval in seconds, A_k – is the amplitude of the complex exponential, α_k – is the damping factor in seconds^{-1}, f_k – is sinusoidal frequency in Hz, and Θ_k – is the sinusoidal initial phase in radians.

Described compression method also includes wavelet transformation [19,20,21], which aim is to project impulse signals containing noise. Wavelet compression is based on the assumption that all signals can be represented with sufficient accuracy by a reduced number of decomposition coefficients.

A discrete wavelet db8 of Daubechies family with four decomposition levels and hard threshold coefficient elimination was used for the compression [10].

3. SIMULATIONS

Real signals of the resolution of 12 bits and sampling frequency of 4 kHz were used for the compression and reconstruction algorithm analysis. Ten different signals with the most diversified transient were chosen. The recordings show:

- Transient impulsive events: signal test_1
- Transient oscillatory events: signals test_4, test_8
- Harmonics distortion: signal test_2, test_5, test_7, test_10
- RMS Variations – Sags: signal test_4, test_8
- RMS Variations – Interruptions: signal test_3, test_9

They were released by the events occurring around the first second of the registered transients and lasted on average 5 s.

The amplitude of the investigated signals was normalized and equalled 100 for each transient. Then the signals were compressed and reconstructed with the defined maximal compression artifacts of the range <1; 5> % (where 100% is signal amplitude).

Table 1 shows compression ratios for defined maximal compression artifacts.

Table 1. Compression ratios for defined maximal compression artifacts.

signal	event \ errors	5.0%	4.5%	4.0%	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%
test_1	Impulse, Sags	116.1	78.2	63.8	66.5	39.9	33.0	29.0	27.5	11.4
test_2	Harmonics, Sags	72.5	73.0	63.6	62.0	59.1	51.0	48.9	25.7	10.1
test_3	Interruptions	32.9	30.9	27.9	24.4	22.7	19.2	16.2	13.8	10.3
test_4	Oscialltory, Sags	35.2	35.0	30.8	30.3	27.0	24.0	14.7	6.0	4.3
test_5	Harmonics	90.6	71.5	65.2	45.8	41.2	36.2	27.3	27.4	16.9
test_6	Oscialltory, Interruptions	30.5	27.7	25.3	19.9	18.1	16.6	14.9	11.6	7.7
test_7	Harmonics	86.5	95.1	80.0	70.5	62.6	50.7	33.8	29.1	14.7
test_8	Oscialltory, Sags	89.2	77.2	79.7	72.3	66.8	57.3	55.8	34.6	8.9
test_9	Oscialltory, Interruptions	30.5	27.7	25.3	23.1	18.1	16.6	14.9	11.6	7.7
test_10	Harmonics	90.6	71.5	65.2	45.8	41.2	36.2	26.8	24.0	16.9
	mean of compression ratio	67.5	58.8	52.7	46.1	39.7	34.1	28.2	21.1	10.9

Fig. 5 presents compression ratio dependence on the defined maximum compression artifacts for all tested signal (Table 1).

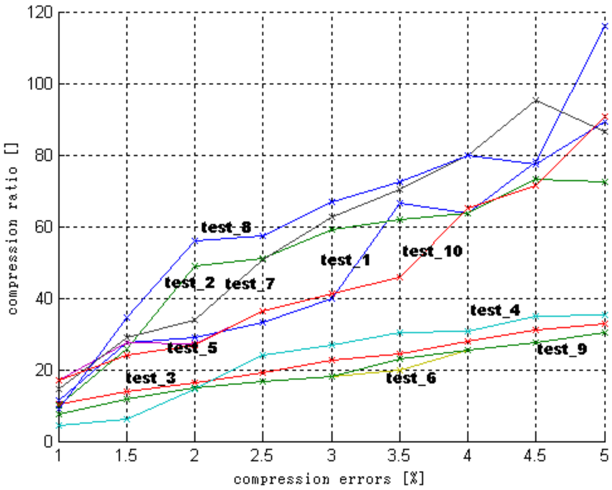

Fig. 5. The compression ratio depends on compression artifacts for all tested signal.

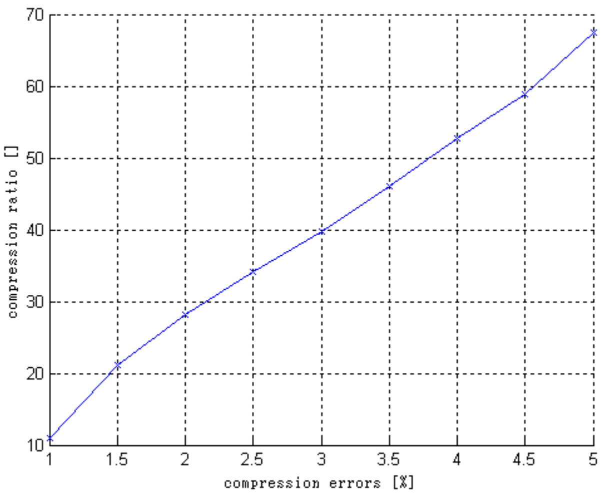

Fig. 6. The compression ratio depends on compression artifacts.

Figure 6 presents the distributions of mean values of the compression ratio for all tested signals. For higher accuracy of the signal projection, the compression ratio rapidly decreases giving the values comparable to the classical compression methods and the only benefit of the method is the information about harmonics of the signal.

Increasing maximum compression artifact level to 2.5 %, gives much better compression ratio with still high accuracy of harmonics and transient oscillatory estimation, but the algorithm is less sensitive to new power quality events.

4. RESULTS

The distribution of errors which occurred after the reconstruction of the original signal in the time domain, is presented in Figs. 7 to 11. Grey rectangles show the parts of signals by means of which the Prony's model was created and wavelet decomposition was calculated to find out the difference between the Prony's model and the original signal. The number of estimations determines indirectly the compression ratio and accuracy of the signal projection.

Figure 7 shows compression artifacts in the time domain with 1% maximum reconstruction error assumed. The number of generated models is in this case high (26 models for a 5 second signal).

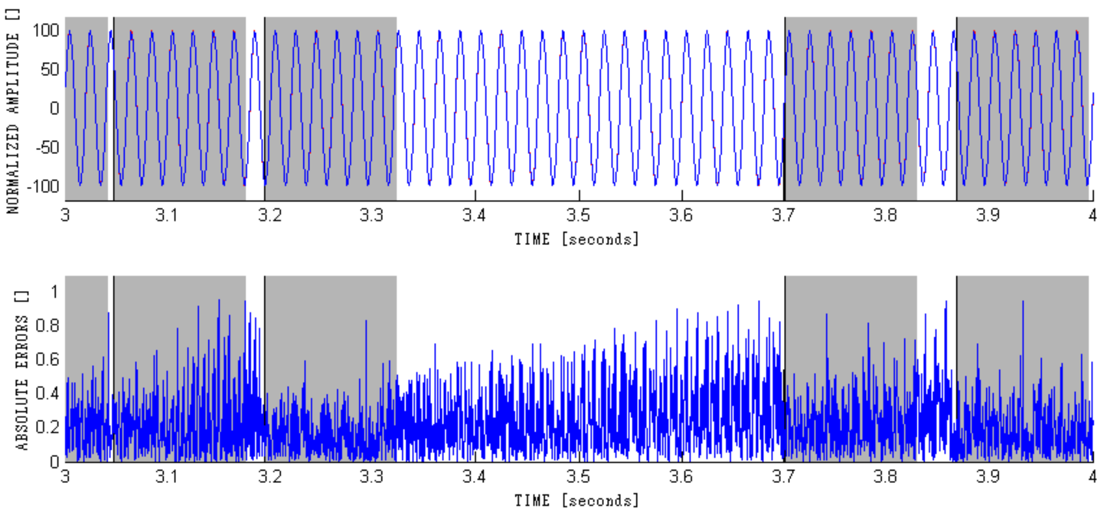

Fig. 7. Signal: test_7 - Decompression results. Reconstructed signal (top) and total compression artifacts (bottom). The maximum compression artifact level is set to 1 %.

Fig. 8 presents decompression results where the maximum reconstruction errors are set to 2.5%. In this case for the same test signal (test_7) compression algorithm gives less number of generated signal models. This fact causes compression ratio to increase from 14.7 to 50.7. The accuracy of each signal model is the same as in the case when 1% reconstruction error was set, which is shown in Fig. 6 and Fig. 7 (bottom part of figures – grey rectangles). In the described case however, another phenomenon is visible.

The error between subsequent estimations gradually increases. It is well visible between 2 and 3.5 second for Fig. 8 and while assuming even bigger error. In Fig. 9 simulation for 5 % error has been shown. The described phenomenon might be caused by an original signal that probably changes gradually or, more likely, by some inaccuracy of reconstructed samples estimation.

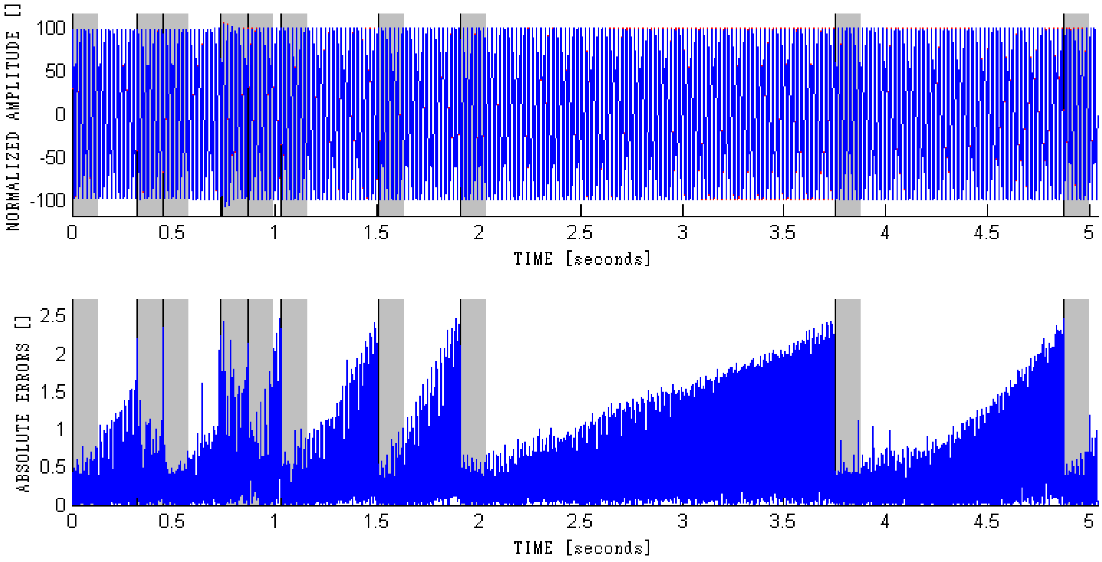

Fig. 8. Signal: test_7 – Decompression results. Reconstructed signal (top) and total compression artifacts (bottom). The maximum compression artifact level is set to 2.5 %.

With 5 % maximum reconstruction error, compressing signal: test_7 gives only 8 models (Fig. 9) and automatically the compression factor increases and equals 86.5.

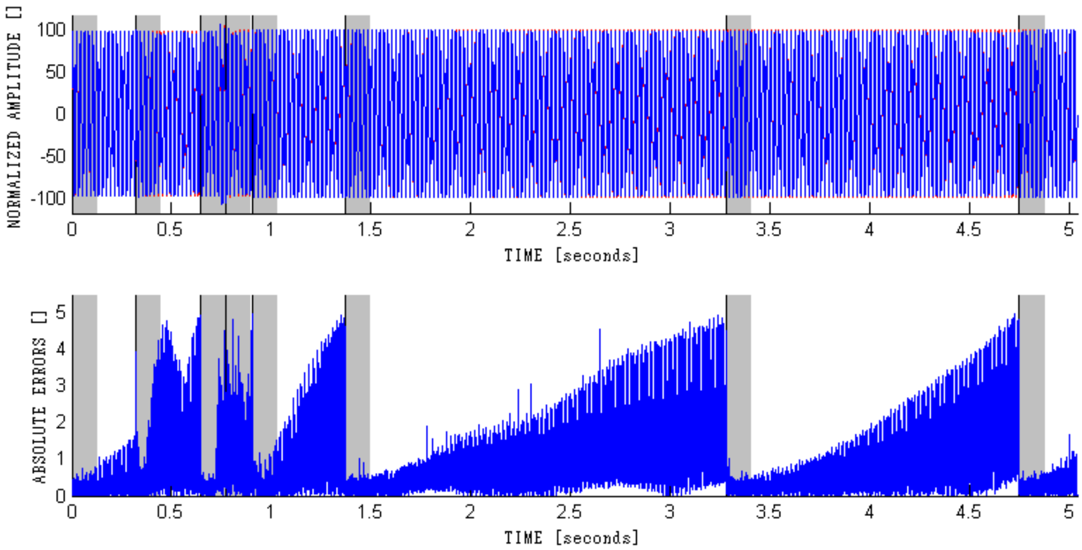

Fig. 9. Signal: test_7 – Decompression results. Reconstructed signal (top) and total compression artifacts (bottom). The maximum compression artifact level is set to 5 %.

New model estimation is caused not only by gradual change of original signal parameters or inaccuracy in samples computations, but also by sudden signal change like impulsive transient. The moment the change appears is beginning of the part of the signal which undergoes Prony's analysis due to which parameters estimation for events like oscillatory transient (including the damping factor), can be done more accurately.

Described procedure is important and results from some disadvantages of the Prony's model. It does not position estimated parts in time and does not average those occurring with some offset in the analysed part of the signal.

Impulsive transient events that might happen in the original signal (Fig. 10 – about 2.2 seconds), are not analyzed well by the Prony's model and their compression is possible due to the wavelet decomposition of the part of signal undergoing Prony's modelling. Similarly, in the case of many oscillatory transcient events with different offset, the Prony's model may not give a full model of the signal, so wavelet compression is recommended. Described phenomenon is shown in Figures 10 and 11.

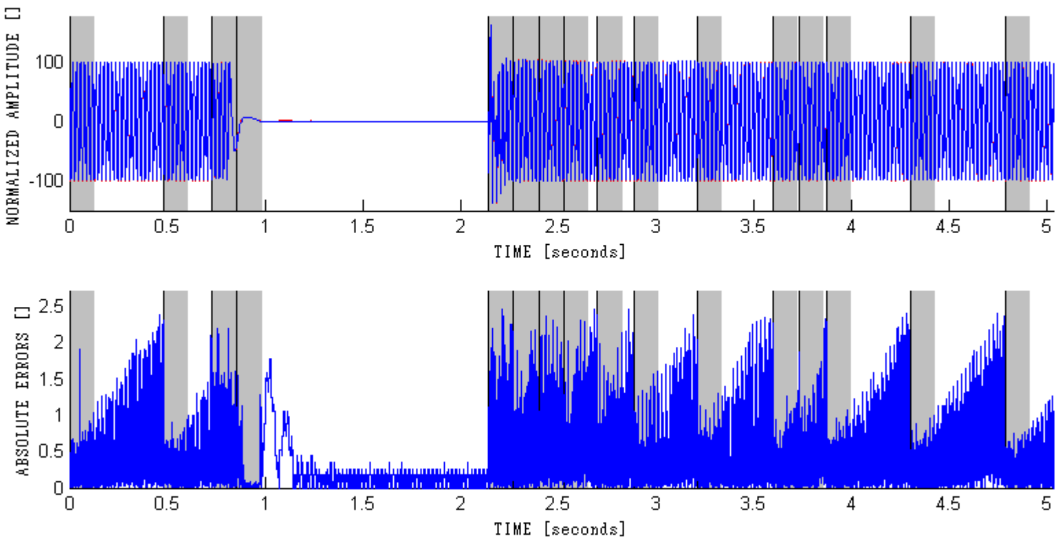

Fig. 10. Signal: test_9 – Decompression results. Reconstructed signal (top) and total compression artifacts (bottom). The maximum compression artifact level is set to 2.5 %.

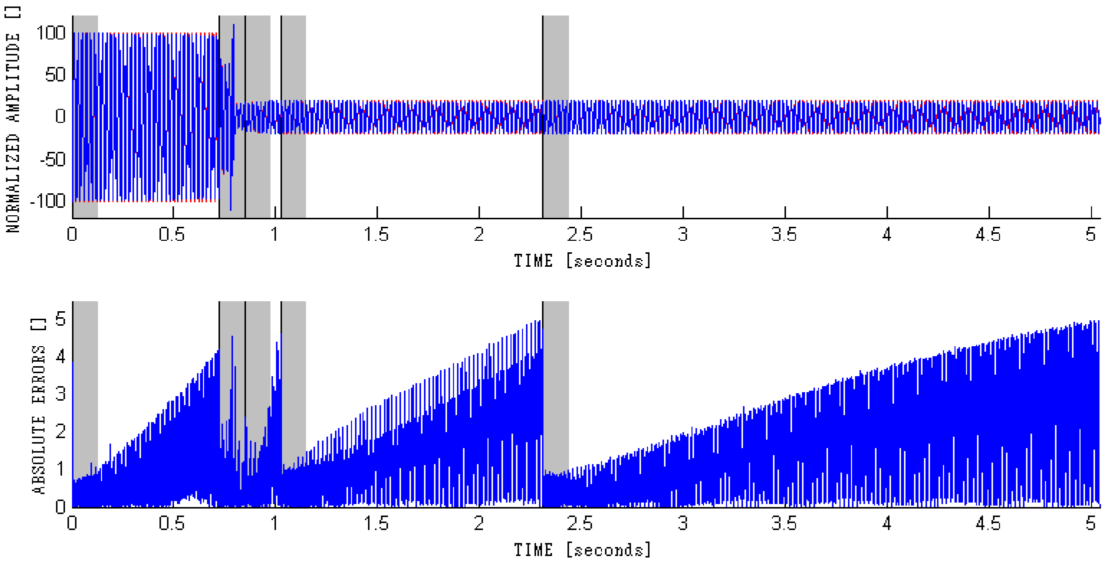

Fig. 11. Signal: test_8 – Decompression results. Reconstructed signal (top) and total compression artifacts (bottom). The maximum compression artifact level is set to 5 %.

Table 2 presents Prony's models for signal: test_7, where the maximum compression artifact level is set to 1 %. It shows that all parameters of models give high accuracy of the estimated harmonic components: amplitudes, frequencies, phase, and dumping factor. Parameters of the Prony's method are the part of the compressed power waveform and enable for power quality analysis.

Table 2. Estimation of parameters of the Prony's model for signal test_7. The maximum compression artifact level is set to 1 %.

no.	time	amplitude	frequency	phase	damping factor
	[ms]	[ ]	[Hz]	degree	[1/s]
1	0.00	96.23	49.99	-71.97	0.01
		1.54	250.06	60.78	-1.32
		0.85	350.26	-117.32	0.47
2	139.50	96.24	49.99	-81.57	0.00
		1.48	250.02	13.76	-0.30
		0.85	349.82	-179.99	0.71
3	321.00	96.40	49.98	-55.25	-0.02
		1.14	254.50	89.48	2.74
		0.93	352.40	-25.19	-0.77
4	449.00	96.18	49.99	88.07	0.02
		1.43	249.90	143.00	0.62
		0.89	349.60	-70.48	-0.11
5	638.25	96.30	49.99	-106.29	-0.02
		1.46	249.87	-109.08	-0.19
		0.95	350.01	4.98	-1.97
6	766.25	102.08	50.02	37.23	-1.57
		1.36	357.93	-156.48	-12.96
7	894.25	96.41	49.97	-178.20	0.03
		1.66	249.90	-113.23	-0.62
		0.88	349.85	-146.18	-0.24
8	1030.25	96.96	49.98	108.75	-0.03
		1.67	253.34	-155.56	-3.93
9	1159.25	97.03	49.98	-90.26	-0.02
		1.65	249.92	-31.14	-0.73
		0.84	349.91	110.00	0.15
10	1350.50	96.91	49.98	111.01	-0.01
		1.68	250.23	-108.22	-1.26
		0.89	350.62	73.27	-1.39

no.	time	amplitude	frequency	phase	damping factor
	[ms]	[ ]	[Hz]	degree	[1/s]
11	1486.00	96.78	49.99	29.26	0.00
		1.63	249.96	-154.73	-0.29
		0.77	350.02	-133.03	2.12
12	1756.75	96.74	49.99	-138.37	-0.01
		1.54	249.96	86.98	1.23
		0.82	350.65	127.62	0.60
13	1922.00	96.71	49.99	-44.52	0.00
		1.72	249.90	-162.52	-1.57
		0.82	350.44	67.73	0.92
14	2107.75	96.72	49.99	58.05	-0.02
		1.59	250.10	-13.12	0.26
		0.85	350.31	66.86	-0.71
15	2261.00	96.62	49.99	-64.21	0.00
		1.61	250.09	96.77	-0.23
		0.88	350.44	-69.72	-0.95
16	2406.50	96.59	49.99	34.14	-0.01
		1.57	249.88	-130.26	0.48
		0.81	349.72	-94.42	1.20
17	2642.75	96.52	49.99	-34.20	0.00
		1.61	250.00	-112.34	0.02
		0.85	349.89	145.88	-0.28
18	2909.50	96.51	49.99	86.20	0.01
		1.57	249.92	130.31	0.17
		0.84	350.08	-95.75	-0.03
19	3042.75	96.54	49.99	-35.96	0.00
		1.62	249.88	-119.73	-0.09
		0.82	348.92	142.95	-0.02

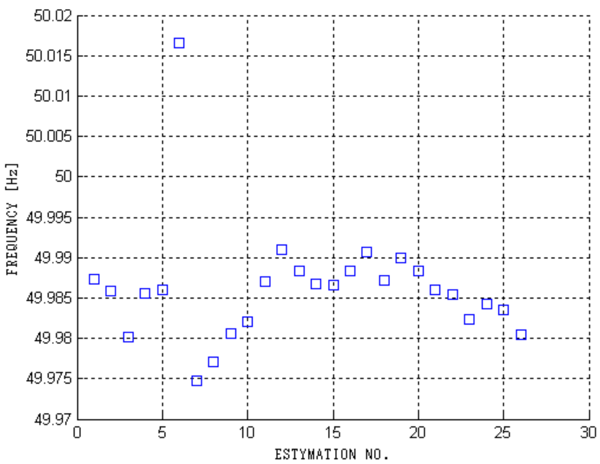

Fig. 12 Estimated basic harmonic frequency for subsequent signal model. Results for signal test_7, where the maximum compression artifact level is set to 1 %.

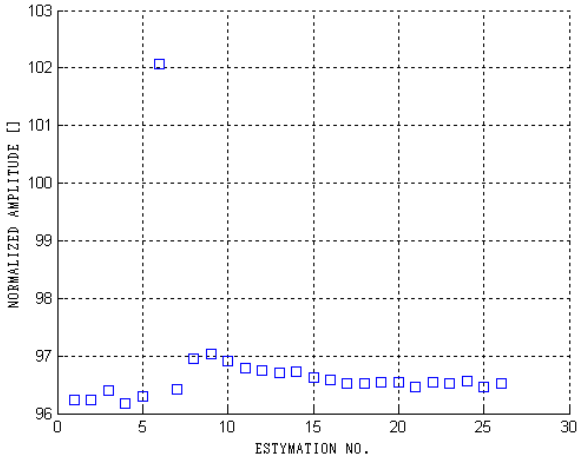

Fig. 13 Estimated basic harmonic amplitude for subsequent signal model. Results for signal test_7, where the maximum compression artifact level is set to 1 %.

Figure 12 presents dispersion of the estimated frequency parameter of the Prony's model for basic harmonics (50 Hz). Figure 13 presents dispersion of the basic harmonic amplitude. Accuracy of frequency estimation determines the increase of estimation frequency.

5. CONCLUSION

The described compression method enables obtaining high compression factor for power waveform with low compression artifact level. Compressed data can give valuable information about harmonics and other oscillatory parts of the signal, which can facilitate the analysis of the registered events.

Estimated basic signal parameters are computed with high accuracy in comparison to popular method of signal analysis like for instance fast Fourier transformation.

Presented method however requires fast computations which can limit applications in portable power quality monitoring systems. Yet the described algorithm may be used in power waveform bases to compress signals.

The method will be improved to decrease the time of compressed signal computations and to increase the compression factor as well.

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KOMPRESJA DANYCH Z ZASTOSOWANIEM METODY PRONY'EGO I TRANSFORMACJI FALKOWEJ W SYSTEMACH MONITOROWANIA JAKOŚCI SYSTEMÓW ENERGETYCZNYCH

Streszczenie

Artykuł opisuje metodę kompresji sygnału elektroenergetycznego rejestrowanego w celu analizy jakości energii. Opisany algorytm umożliwia uzyskanie wysokiego współczynnika kompresji sygnału przy zachowaniu dużej dokładności rekonstrukcji oryginału. Algorytm wykorzystuje zmodyfikowaną metodę Pronego analizy sygnałów w celu wyznaczenia podstawowego modelu sygnału oraz dodatkowo dla zmniejszenia błędów rekonstrukcji stosuje także dyskretną analizę falkową. Połączenie tych metod umożliwia efektywną kompresję rzeczywistych sygnałów z urządzeń pomiarowych oraz dodatkowo realizuje analizę składowych harmonicznych i zdarzeń o charakterze oscylacyjnym przebiegów, co może ułatwić późniejszą analizę zjawisk zachodzących w monitorowanych obiektach. Artykuł zawiera analizę przykładowych rzeczywistych sygnałów z systemu monitorującego, pokazuje analizę wydajności algorytmu dla różnych założonych błędów kompresji oraz opisuje błędy generowane przez metodę.