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DWT ANALYSIS OF SELECTED TRANSIENT AND NOTCHING DISTURBANCES

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Abstract – This paper is focused on the problem of transient and notching analysis occurring in electric power system. The aim of the research was to improve DWT algorithm especially for transient detection, in order to increase performance of a multi-parameter DSP system. The method described in the paper proposes rejecting insignificant wavelet decomposition stages and takes only these stages for reconstruction transient or notching, in which predominant energies were detected. The criterion of rejecting stages is that the frequency band of disturbances reconstructed in this way should be sufficient for further evaluation. The proposal is similar to idea of data compression by DWT. All analyses are based on the real voltage samples, registered in the real isolated electric power system, namely ships' systems. Finally, the results of the research are presented and commented on.

Keywords: power quality, transients, wavelet transform, digital signal processors

1. INTRODUCTION

The IEEE 1159-1995 standard [1] defines various power quality disturbances, including transient and notching.

Table1. Categories and typical characteristics of transients [1].

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	<50 ns	
1.1.2 Microsecond	1 μs rise	50 ns – 1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3 – 50 ms	0 – 4 pu
1.2.2 Medium frequency	5 – 500 kHz	20 μs	0 – 8 pu
1.2.3 High frequency	0.5 – 5 MHz	5 μs	0 – 4 pu

According to the standard transient are divided into two groups: impulsive and oscillatory. The former term means "a sudden non-power frequency change in steady-state conditions of voltage, current or both, that is unidirectional in polarity" [1]. An impulsive transient is unidirectional in polarity (primarily either positive or negative), but an oscillatory transient includes both positive and negative polarity value. Each transient is categorized into three subclasses defined in Table 1, according to typical spectral content and duration.

As it is presented in Table 1, these disturbances usually contain frequencies from a few hundred hertz up to a few MHz and their duration varies from below 50 ns up to a few dozens ms. Impulsive transient are normally characterised by their amplitude rise and decay times, whereas oscillatory transients are described by their spectral content, duration and magnitude.

Similar kind of disturbance is notching. This is "a periodic voltage disturbance" caused by power electronic devices operation [1]. Frequency components characterising notching are quite high like in the case of transients. Therefore, this disturbance is called "a periodic transient" [2]. According to IEEE 519-1992 standard, notching should be described by "the notch depth, the total harmonic distortion factor (THD), and the notch area of the line-to-line voltage at PCC" [2].

Transient are due to lighting strokes, self-clearing faults and switching actions. An important property of transient is their high-frequency contents and their broad frequency bandwidth from a few hundred hertz to the megahertz range [3]. The examples shown in this paper are limited to medium frequency ranges. The main reason for it is the limited range of the measurement instrumentation used. Most power quality analyzers do not use sampling frequency higher than 200 kHz [4]. Usually, the sampling frequencies are much lower e.g. 38.4 kHz [5]. Therefore, these sampling frequencies are insufficient for covering all transients defined in IEEE standard. Fortunately, the sampling frequencies are sufficient for common transients and notchings occurring in electric power system.

2. TRANSIENT AND NOTCHING DETECTION METHODS

As we known from previous section of the paper the main disadvantage of transients' detection is that they continuously require computational effort and high sampling frequencies. Therefore simple methods have to be applied to detect transient in order to save resources of measuring device. The transients can be evaluated with or without the fundamental frequency component. "When characterizing the transient, it is important to indicate the magnitude with and without the fundamental component" [1]. Most power quality monitors are using triggering method which bases on comparison the absolute value of the actual voltage waveform with a threshold. This method also can be used for a simple characterizing a transient by detecting its highest absolute peak value and for defining the duration. The disadvantage of the method is that it misses a large number of significant transients with long durations and large energies, but relatively small amplitudes [3]. If we need to detect this type of transients, other methods have to be used. The methods usually are based on the extracted transient component from a measured waveform. Therefore, some kind of high-pass filtration is required for transient and notching extraction and description. For example, in the case of measurement instrument described in Ref. [6], 6th order IIR filter was applied, with cut-off frequency 100 Hz. Next, mathematical morphology was used for signal processing. The tool was also discussed in Ref. [7].

Comparing one cycle of waveform with the waveform one cycle earlier in time is a commonly used method by monitor manufactures [8] and it is well described in Ref. [3,9]. This cycle-by-cycle difference could also be used for characterization purposes [3]. It requires a certain amount of computational time and longer a circular buffer for storing at least two adjacent cycles. This method allows for a low threshold setting and thus for a very sensitive detection of transients. One of disadvantages of the method is that it doesn't work when the same transient appears in two adjacent cycles of analyzed signal. In such situation the second cycle has to be compared with the last cycle before appearing transient (i.e. with two cycles back in time) and thus the algorithm for detecting transient became much more complicated.

Instead of comparing the measured waveform with the value one cycle back in time, the waveform can be compared with average fundamental waveform. This is easier to implement as there is no need for interpolation. When the extraction of the transient takes place in the monitor, a phase-locked loop may be used to generate the reference signal with which the waveform is compared [3].

However, it seems that the most popular tool for transients and notching analysis is discrete wavelet transform DWT [3,10-14]. Application of DWT does not require high-pass filtering. But the number of implemented decomposition stages has to be determined. In some respect, it can be treated as proper choice of the cut-off frequency of high-pass filter. The exact detection of transient beginning and ending can be carried out by various methods. They involves a comparison of respective original signal samples or extracted transient with user defined thresholds as well as comparison of waveform of two adjacent cycles of analyzed signal (comparison with the prevent steady-state waveform) [3,15].

It is very hard to find the best method for transient detection. As we can see above, each presented method has advantages as wall as disadvantages.

For this paper purpose, the DWT method was selected. Results presented in this paper have been analysed after wavelet decomposition, which is equivalent to band-pass filtering.

3. WHY DWT?

Although there are a few methods which give same results and they are much faster in computation, the DWT has been chosen for the paper. As distinct from most methods, the DWT gives us some advantages, if we additionally want to assess other power quality parameters, not transients only. Using the wavelet transform can significantly improve overall performance of a multi-parameter DSP system. Apart from transient analysis, the wavelet coefficients can be used for data compressions, which reduce RAM memory needed for data storing and/or transmitting outside, and also for others calculations, such as: harmonics measurement, signal rms value calculation, using coefficients as a prefiltered signal for fundamental frequency estimation based on zero crossover detection (multiple zero crossovers elimination), and so on [16-17].

In shorthand, wavelet coefficients are decimated after each decomposition stage, so using only the coefficients representing lower frequencies instead of original signal samples in calculation of low frequency disturbances significantly reduces computational burden and requirement for RAM memory. The method has been implemented in new instrumentation described in [16,18-19], and the RAM memory needed for data storage was reduced as many as five times It should be mentioned as well that the DWT is the most popular tool for transient analysis.

4. RESEARCH RESULTS

4.1. Signal under research

It is commonly know, how it is hard to detect and register a real impulsive transient in electric power networks. A short-duration impulse is usually missed by typical measurement devices for power quality monitoring. That's way, the amount of papers which present this phenomena are limited. These presented examples of transients and notching are from a research of power quality carried out in ship networks. They were registered by means of DAQ PCI 703-16A Eagle Technology with sampling frequency equal to 150375 Hz. The measurement device was equipped with insulation amplifiers and antialiasing filter. The maximum bandwidth of these components was equal to 50 kHz [19].

measurement device should be improved. The idea is similar to data compression algorithm based on DWT, where only high-magnitude wavelet coefficients are recorded.

For the paper purpose, the analysis has been carried out by signal decomposition into eight frequency bands and energy of each decomposition band is estimated. It should be added that the maximum considered frequency band is limited by antialiasing filter with cut-off frequency equal to 50 kHz. The evaluations of energy of wavelet decomposition for three different disturbances are presented in Table 2. The grey colour of the background in the tables' cells points at the insignificant wavelet decomposition frequency bands, which can be rejected before reconstruction signal.

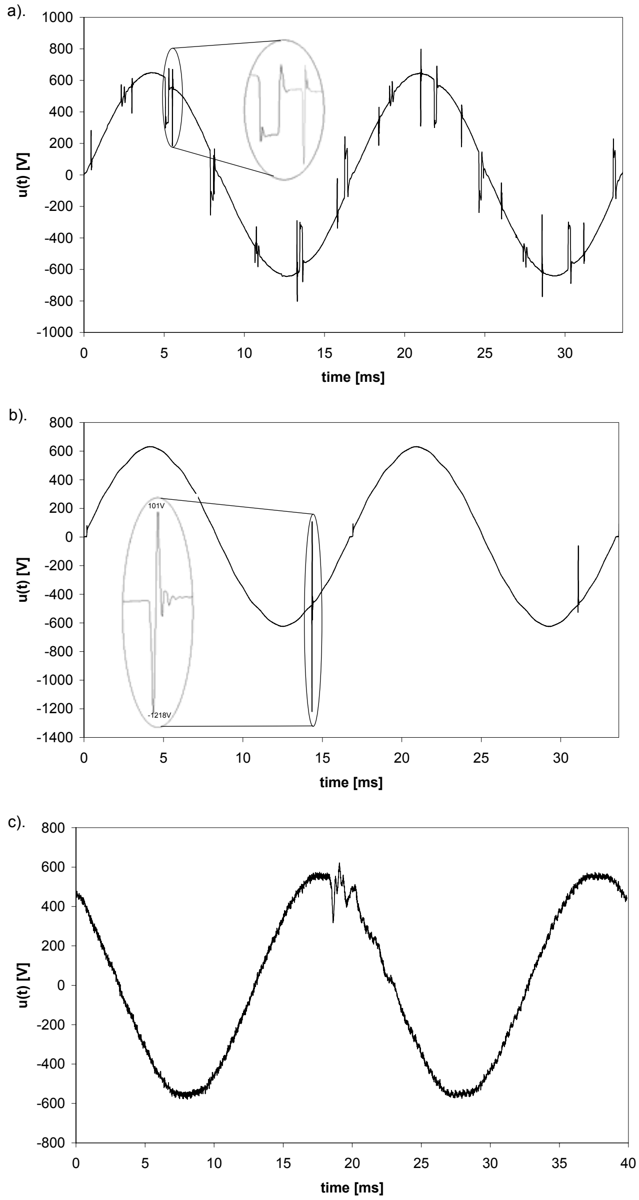

Fig. 1. Examples of transient and notching registered in ship networks: a) notching , b) impulsive transient and c) oscillatory transient [19].

It should be mentioned that the example presented in Fig. 2b was designated as impulsive transient, although it was bidirectional in polarity. It was for simplifying reasons, since in practical terms the transient is single triangle impulse.

4.2. Results of wavelet decomposition

The main goal of the paper is to improve measured algorithm especially for transient detection, in order to increase performance of a multi-parameter DSP system. Therefore, author proposed rejecting insignificant wavelet decomposition frequency bands and takes only these sub-bands for reconstruction transient or notching, in which predominant energies were detected. Whereas, the algorithm should stop the execution of wavelet reconstruction in case of lack of disturbances. So, the overall performance of

Table 2. Energy of wavelet decomposition divided into eight frequency sub-bands

Stage no.	Frequency sub-bands [kHz]	Energy [%]		
		Impulsive transient	Oscillatory transient	Notching
1	37.6 - 50	49.6	2.1	0.1
2	18.8 - 37.6	38.8	2.2	0.6
3	9.4 - 18.8	3.7	0.5	6.7
4	4.7 -9.4	6.0	1.6	7.2
5	2.3 - 4.7	0.8	15.1	30.8
6	1.2 - 2.3	0.8	26.0	10.9
7	0.6 - 1.2	0.4	37.6	12.2
8	0.3 - 0.6	0	15.0	31.7

The results presented in Table 2 confirm our expectations that the investigated impulsive transient (see Fig. 1b) contains high frequencies. In practical terms, only the wavelet detail coefficients from first to forth decomposition stage are required for the case rough assessment. It is equivalent to frequency range from 4.7 to 50 kHz. The opposite is true for the oscillatory transient (see Fig.1c) and the notching (see Fig.1a). Their rough assessments require the last four stages of wavelet decomposition (the maximum sufficient frequency is equal to 4.7 kHz) [19]. The remaining (the marked) decomposition stages can be passed over during reconstruction and they don't have a significant influence on disturbances' descriptions.

Daubechies filters with 10 coefficients were used for disturbance decomposition and reconstruction.

Finally the whole process of transient parameters estimation is shortened.

4.3. Results of wavelet reconstruction

In the next step of the research, wavelet reconstruction for eight different frequency bands was carried out. In this way, extracted disturbances were evaluated by means of basic parameters, like their energy *En*, duration *t* and peak-to-peak value V_{p-p}. The parameters are defined as fallow:

- Transient energy *En* is a measure of the amount of additional energy absorbed by equipment due to appearing transient.

$$En = \int_{t_1}^{t_2} v^2(t)dt$$

where: v(t) – transient waveform,
t_1 – time of the transient beginning,
t_2 – time of the transient end.

- Duration of transient *t* is defined as the amount of time during which the extracted transient is above a threshold.

$$t = t_2 - t_1$$

- Peak-to-peak value V_{p-p} is defined as difference of the highest v_{max} and the smallest v_{min} value of extracted transient.

$$V_{p-p} = v_{\max} - v_{\min}$$

The results are presented in Table 1 and Fig. 2.

Table1. Results of selected disturbances analysis after wavelet reconstruction with various decomposition stages; energy E_n, duration *t* and peak-to-peak value V_{p-p}

	Frequency sub-bands [kHz]	En		t		Vp-p	
		[V²s]	[%]	[μs]	[%]	[V]	[%]
Notching	0.3 - 50	11.298	100.0	285.95	100.0	424.77	100.0
	0.3 -37.6	11.291	99.9	285.95	100.0	422.18	99.4
	0.3 - 18.8	11.210	99.2	292.60	102.3	407.97	96.0
	0.3 - 9.4	10.406	92.1	372.40	130.2	337.59	79.1
	0.3 - 4.7	9.489	84.0	412.30	144.2	323.42	74.3
	0.3 - 2.3	5.533	49.0	638.40	223.3	202.72	26.7
	0.3 - 1.2	4.307	38.1	957.61	334.9	162.42	19.7
	0.3 - 0.6	2.778	24.6	1768.91	618.6	106.11	11.6
Oscillatory transient	0.3 - 50	10.304	100.0	5093.9	100.0	327.8	100.0
	0.3 -37.6	10.160	98.6	5093.9	100.0	323.0	98.5
	0.3 - 18.8	10.003	97.1	5093.9	100.0	309.3	94.3
	0.3 - 9.4	9.971	96.8	5100.6	100.1	305.5	93.2
	0.3 - 4.7	9.819	95.3	5047.4	99.1	310.4	94.7
	0.3 - 2.3	8.204	79.6	5040.7	99.0	210.2	64.1
	0.3 - 1.2	5.417	52.6	5346.6	105.0	127.9	39.0
	0.3 - 0.6	1.406	13.6	7228.6	141.9	54.5	16.6
Impulsive transient	0.3 - 50	6.90	100.0	119.7	100.0	1316.9	100.0
	0.6 - 50	6.90	100.0	119.7	100.0	1317.1	100.0
	1.2 - 50	6.89	99.9	119.7	100.0	1317.2	100.0
	2.3 - 50	6.82	98.9	119.7	100.0	1316.6	100.0
	4.7 - 50	6.71	97.2	119.7	100.0	1310.0	99.5
	9.4 - 50	6.38	92.5	232.8	194.4	1273.0	96.7
	18.8 - 50	6.12	88.8	192.9	161.1	1233.9	93.7
	37.6 - 50	3.44	49.8	153.0	127.8	826.0	62.7

It has been mentioned above that the analyses were carried out for wavelet reconstruction with various decomposition stages in the range from 0.3 to 50 kHz. The parameter values of impulse transient were measured with constant upper stage (no.1) of the wavelet decomposition and various lower stages, which were changed from eighth to second stage (0.3 – 37.6 kHz). Whereas, the parameter values of the oscillatory transient and the notching were measured with constant lower stage (no.8) of the wavelet decomposition and various upper stages which were changed from first to seventh stage (from 50 to 0.6 kHz). The results are presented in relation to respective values calculated for maximum considered band 0.3-50 kHz (for all reconstructed stages). It means that the value calculated for the whole frequency band is 100%.

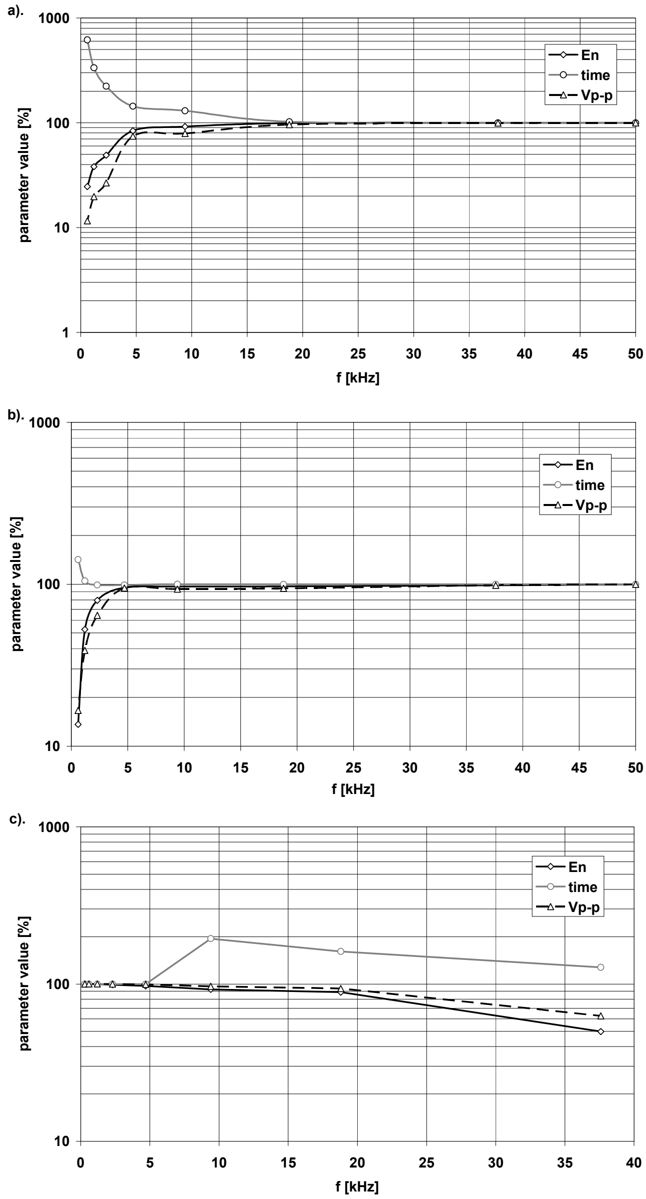

Fig. 2. Results of selected disturbances analysis after wavelet reconstruction with various decomposition stages: a) values of notching energy, duration and amplitude measured with constant lower stage of the wavelet decomposition and various upper stages,

b) values of oscillatory transient energy, duration and amplitude measured with constant lower stage of the wavelet decomposition and various upper stages and c). values of impulsive transient energy, duration and amplitude measured with constant upper stage of the wavelet decomposition and various lower stages.

The results presented in Fig. 2 fully agree with the results from previous Subsection 4.2. It seems that lower limit of the analyzed frequency band equal to 10 kHz should be sufficient for impulsive transient evaluation. In the case of other two examples a frequency band up to 5 kHz and 3-4 kHz are sufficient for proper evaluation of parameters of such disturbances like notching and low frequency oscillatory transient respectively. But quite low frequencies should be included in analysis of these disturbances parameters. These two categories of transients and notching are the most frequently encountered in ship networks and easily measured by majority of power quality analyzers.

4. CONCLUSIONS

Various transient and notching disturbances have different characteristic. The impulsive transients have significant energy in three upper stages of wavelet decomposition, but oscillatory transients and notching have the energy in four lower stages of wavelet decomposition. So, it is not necessary to use all stages for reconstruction to get correct assessment of detected disturbances. Elimination of insignificant wavelet decomposition frequency bands during reconstruction process can even more improve performance of measure algorithm and overall performance of a multi-parameter DSP system.

Next step of the research will be estimation of benefits of the method application in a real algorithm.

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