A Few Remarks About Notching Analysis - Case Study

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Abstract-This paper has been focused on the problem of analysis of notching occurring in electric power systems. Especially a choice of appropriate sampling frequency and its consequence for results of the analysis have been considered. Moreover, the problem of wavelet filter length and, in some respect, wavelet family has been analyzed as well. All analyses have been based on the real voltage samples, registered in the real isolated electric power system, namely ship's system, during two different electric power plant configurations. Finally, results of the research have been commented on with respect of its impact on a whole device for power quality analysis.

1. Introduction

Nowadays, the term "electric power quality" is usually applied to description of different unwanted electromagnetic phenomena occurred in electric power systems. These phenomena, or in another words disturbances, can cause malfunction or failure of electric devices operating in the electromagnetic environment. One of the foremost tasks in dealing with electric power quality is proper evaluation of the quality. Fortunately, a constant progress in the field of the measurements of appropriate factors for the aim has been observed. Especially development in signal processing has been advancing, including both hardware and software. The digital signal processor technique and new algorithms of power quality estimation enable the estimation of the still increasing number of power quality factors in on-line mode.

But a few obstacles still exist. One of the notorious problems is waveform recognition of electric signals. According to IEEE 1159:1995 standard there are five types of steady-state waveform distortions: DC offset, harmonics, interharmonics, noise and notching [1]. This paper has been focused on the last phenomenon.

The notching is one of periodic voltage waveform disturbances [1]. The phenomenon could be described as periodic transient occurring within each cycle [2]. It is caused by commutation process in power converters. Since it is of periodic character, the disturbance could be described by harmonic and interharmonic content [1], [2]. However, the notching usually contains high frequency contents, considerably above 6 kHz. Moreover, its sharp edges and high level of voltage rise could cause a malfunction or damage of electronic equipment [2]. So, voltage notching is special case that falls between transients and harmonic distortions [1]. Then, dealing with notching needs the similar approach like dealing with transients.

2. Notching parameters

The best description of notching is to apply some typical transient indices, like: maximum voltage during disturbance, peak-to-peak voltage of disturbance, energy and time of occurrence [3]. The p-p amplitude of singular disturbance can be defined as a difference between maximum V_{imax} and minimum V_{imin} values of impulse voltage:

$$V_{p-p} = V_{i\,max} - V_{i\,min} \tag{1}$$

Energy of each impulse can be defined as bellow [4]:

$$E_t = \int_{t_1}^{t_2} u_t^2(t)dt \tag{2}$$

where: $u_t(t)$ - impulse signal,

t_1 - start of impulse,

t_2 - end of impulse.

The energy of impulse can be understood as the disturbance energy dissipated on one-ohm resistor [4].

Since the phenomena have periodic character, it seems advisable to calculate the aggregated energy and time of all such disturbances in the measurement window. The choice of width of measurement windows depends of chosen requirement. According to IEC:2000,61000-4-30 standard, measurement intervals of voltage magnitude, harmonics, interharmonics and unbalance shall be over 10-cycle time window for 50 Hz power system and 12-cycle for 60 Hz system, respectively [3]. For this paper purpose, that requirement has been observed when calculating aggregated energy and time of notching as well.

3. Signals under research

In this paper the two cases of voltage with notching have been chosen and carefully considered. These cases have been presented in Fig. 1. Shown examples are part of authors original power quality research carried out in ship’s (chemical tanker) electric power system and could be considered typical in isolated systems with power converters. The first example (Fig. 1a) has been registered during shaft and two diesel generators working in parallel (SG and 2xDG). The second example depicts the voltage during shaft generator working alone (SG). The shaft generator has been working on bus burs of main switchboard via power converter in both cases. The rated voltage in the system has been 440 V with frequency equal to 60 Hz.

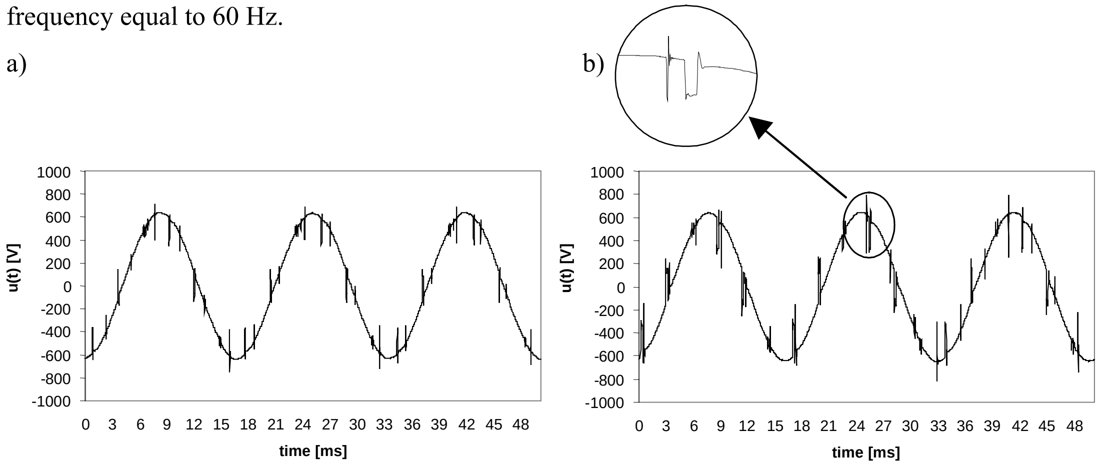

Fig. 1. Exemplary voltage in isolated electric power system: a) shaft generator and two diesel generators working in parallel, b) shaft generator working alone

The above presented examples have been registered by means of Data Acquisition Board DAQ with two significantly different sampling frequencies: 10504 Hz and 150375 Hz for both signals. The cut-off frequency of antialiasing filter has been equal to 3.5 kHz in the case of lower sampling frequency and 50 kHz in the case of higher sampling frequency. In this paper mostly the case depicted in Fig. 1b has been considered due to limited length of the paper but some comparison with the other case (Fig. 1a) will be presented as well.

4. Results of notching analysis

The notching analysis has been carried out by means of digital wavelet transform DWT. It is widely used tool for such phenomena analysis as transient and notching. In this paper the Daubechies family of wavelets has been applied due to its common use in the area [5]. However, some results for other wavelet families will be presented as well.

The analysis have been carried out by signal decomposition into eight frequency bands when using 150375 Hz sampling frequency and further synthesis the frequency band of 587 Hz to five different frequencies (maximum 50 kHz which involves analysis for all higher frequency bands). It should be added that signal have been decomposed into four frequency bands when 10504 Hz sampling frequency has been used.

The first task in notching (and transient) analysis is to detect each singular impulse, especially to determine start and end point of the impulse. For detection the start and end points of notching disturbances the following formula has been applied [6]:

$$(|s_k - s_{k-1}| > p1) \vee (|s_k| > p2) \tag{3}$$

where: s_k - k-sample of disturbance signal (high frequency components of the original signal),
$p1, p2$ - threshold values

If condition (3) has logical value equal to "true", it means the occurrence of impulse. The above mentioned method is not sufficient for all kind of considered disturbances. The small-amplitude impulses without high frequency components can not be detected. Nevertheless, it seems insignificant because of their relatively little importance for electrical power systems. Moreover, the simplicity of the formula (3) allows easy implementation for fast transient and notching detection with minimum computational power requirement of measurement device. However, the threshold values p1 and p2 have to be chosen carefully. For the considered signals the p1 value equal to 100 V and p2 value equal to 30 V have been experimentally selected.

A. Tale of two impulses and …

The above-described analysis has been carried out for impulses of two different kind i1 and i2, previously presented in zoomed area in Fig. 1. The graphical example of such analysis has been depicted in Fig. 2.

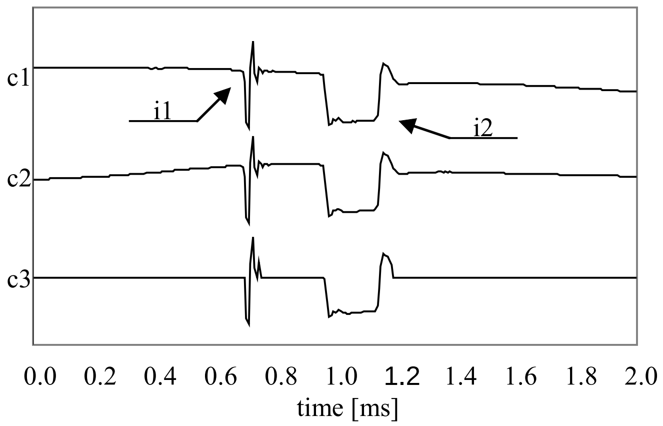

Fig. 2. Example of notching analysis; curve c1 – original voltage samples, curve c2 – voltage components of 587 – 50000 Hz frequency band, curve c3 – filtered two impulses 12 and i2 by means of formula (3)

The presented in Fig. 2 analysis has been done by means of Daubechies filters of length 12 (number of filter coefficients). In the analyses below the family will be designated simply as D with additional number representing filter length. So, in the presented case filters D12 has been applied.
After extraction of particular impulse, estimation of its parameters is relatively simple task. However, one has to remember that the extracted impulses presented in Fig. 2 have been reconstructed for relatively wide frequency band. Such, high frequency components required high sampling frequencies. Sampling frequency above 2.5-4 times greater than highest frequency component is usually recommended [7]. Because a high sampling frequency is inconvenient and can be enormous burden for measurement device, let us look at results of reconstruction the above-depicted impulses for narrower frequency bands and accordingly decimated samples. These results have been presented in Fig. 3 and have been shown after extracting impulses by means of formula (3).

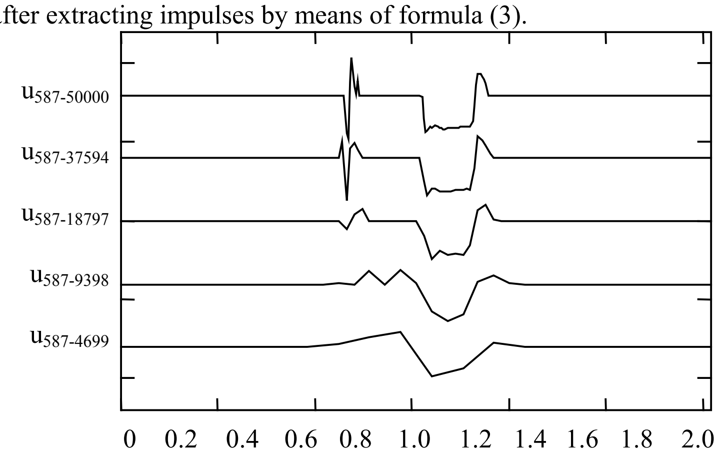

Fig. 3. Reconstructed higher frequency components for five different frequency bands (represented as subscripts in figure designations) and respectively decimated samples

The influence of chosen frequency band (at in the same chosen sampling frequency) for result of measurement is unavoidable and can not be omitted. The observed impulses have been virtually widened and flattened. The former is due to removing of high frequencies as well as decreasing number of samples (poor time resolution). In the case, there have been depicted 304 samples for 587-50000 Hz frequency band and only 19 samples for 587-4699 Hz frequency band. For better reasoning of the problem, the results of measurement of these impulses basic parameters, like peak-to-peak voltage of impulse and its energy for five different frequency bands, have been laid in Table 1.

Table 1. Results of peak-to-peak voltage V_{p-p} and energy En analysis for considered impulses i1 and i2

frequency band [Hz]	impulse i1		impulse i2	
	V_{p-p} [V]	En [J]	V_{p-p} [V]	En [J]
587 - 50000	515.0	1.401	370.2	7.760
587 - 37594	375.2	1.329	374.5	7.784
587 - 18797	130.1	0.279	339.0	7.372
587 - 9398	---	---	327.1	7.508
587 - 4699	---	---	282.0	7.141

It is easy to observe that the results of the impulses analysis have been affected differently by narrowing frequency band, depending on particular impulse character. The impulse i1 of relatively low energy, short duration but high magnitude is hardly noticed when analyzing with upper limit of frequency band below approximately 19 kHz whereas the impulse i2 evaluation deteriorates when upper limit of frequency band falls below approximately 5 kHz. Nevertheless, whole voltage quality estimation would be badly misleading by too low upper limit of frequency band (read insufficient sampling frequency). It is worth mentioning that the effect has been also noted when the voltage has been sampled with sampling frequency 10504 Hz and cut-off frequency of antialiasing filter equal to 3.5 kHz. In practical terms, impulses of i1impulse kind have been filtered out.

B. … twelve periods and …

After detailed analysis of two randomly chosen impulses, let us take broader look and take into account measurement for whole basic measurement window. This measurement has involved an estimation of such parameters as: maximum registered peak-to-peak voltage V_{p-p} of singular impulse and maximum registered energy En of singular impulse as well as aggregated energy and duration of all impulses detected in basic measurement window. The results of these parameters measurement for maximum upper limit of frequency band (50 kHz) and D12 filters have been laid in Table 2. The results in Table 2 consist of analysis of both voltages depicted in Fig. 1. The designations in the table means: ΣEn – aggregated notching energy during measurement window (12 periods due to voltage nominal frequency 60 Hz), time – aggregated time of notching during measurement window, V_{p-p} – maximum peak-to-peak voltage of singular disturbance during measurement window, maxEn – maximum energy of singular disturbance during measurement window.

Table 2.Results of some notching parameters measurement

Power plant configuration	ΣEn [J]	time [ms]	V_{p-p} [V]	maxEn [J]
SG and 2xDG	159.9	9.9	407.2	4.1
SG	435.6	14.9	592.3	10.6

It is easy discernible that power plant configuration affected the level of notching in the system. So, it is at least advisable to consider a problem of proper frequency band for the new case as well as its influence on the aggregated parameters (energy and duration) evaluation. Such analysis has been carried out for both cases and its results have been depicted in Fig. 4. The presented in Fig. 4 results are relative values (in relation to values laid in Table 2 for broadest applied frequency band 587 – 50000 Hz) of considered notching parameters for five aforementioned frequency bands. This way results of all considered notching parameters measurement for broadest frequency band are equal to 100%. The samples decimation has been applied for limited frequency bands respectively.

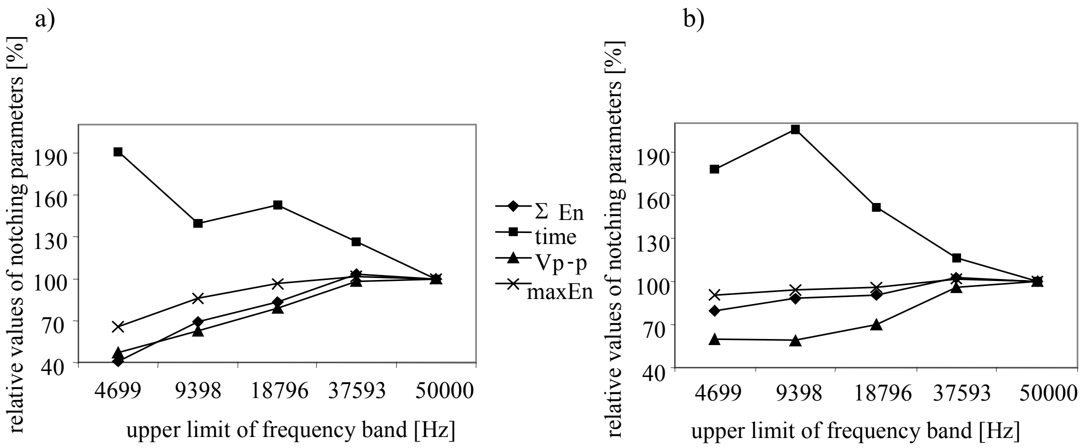

Fig. 4. Relative values of notching analysis for both cases: a) shaft generator and two diesel generators working in parallel, b) shaft generator working alone

So, it could be stated that limited frequency band affects similarly evaluation of both cases with only minor discernible differences. It should be mentioned, that the same analysis carried out without samples decimation have lead to similar conclusions. Only, estimation of aggregated time leads to different results (results fall below 100%) due to different time resolution.

After so many considerations, one question still linger. What about a number of filter coefficients and other wavelet families? After all, it is widely know that filter response and shape could affect the disturbances analysis [5]. Answering this important question requires additional calculations. These calculations have been carried out for Daubechies filter of length from 4 to 20 (D4 – D20) as well as other wavelet families used in the field of electric power analysis: Vaidyanathan (V8), Smith&Barnwell (S&B8) and symmlets (Daubechies Maximum Symmetry wavelet filters)(S8). In all different wavelets families' cases, filters of 8 coefficients have been applied. Obviously, the different filters have been applied for the same set of original signal samples. The results of related analysis have been graphically presented in Fig. 5. Once again, the relative values of previously defined parameters have been depicted, for comparison reason. But this time, these values have been in relation to mean values calculated for different filter length or wavelet family respectively.

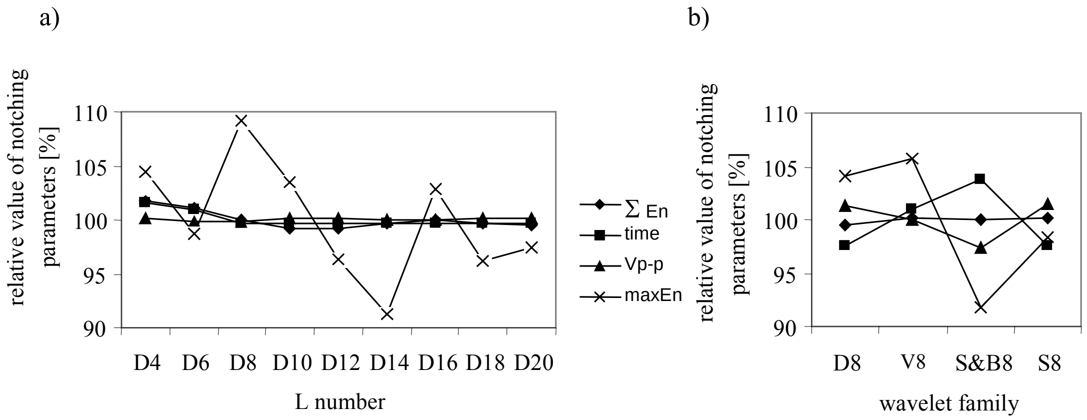

Fig. 5. Relative values of notching analysis; a) different filter lengths of Daubechies filters, b)different wavelets families

Taking into account results laid in Fig. 5, it could be stated that the filter length for Daubechies family as well as applying other chosen wavelet families have only minor influence on the analyzed parameters estimation, near to nothing when compared with sampling frequency influence. Only evaluation of maximum energy of singular impulse could vary ±10% of mean value. The presented in Fig. 5 results have been obtained when analyzing for maximum frequency band but similar results have been obtained for narrower frequency bands.

C. … two sampling frequencies at last.

As has been mentioned earlier, two sampling frequencies have been applied during registering the voltages depicted in Fig. 1 and accordingly two cut-off frequencies of antialising filters have been used. Now, it seems interesting to look on some statistical data concerning notching analysis with two such different sampling frequencies. The case of shaft generator working alone (SG) has been chosen for the purpose. The mean values EX and standard deviations DX of measurement results of singular impulse maximum peak-to-peak voltage and singular impulse maximum energy as well as aggregated energy and time of notching over twelve periods have been calculated for span of approximately 60 s (300 measurement windows). The values of mentioned parameters for both sampling frequencies and D12 filters have been laid in Table 3. Moreover, maximum observed values of the respective parameters have been added.

Table 3. Results of measurement of notching parameters for two sampling frequencies

Sampling frequency	ΣEn [J]			time [ms]			V_{p-p} [V]			maxEn [J]		
	EX	DX	max	EX	DX	max	EX	DX	max	EX	DX	max
f_s=150375 Hz	432.2	10.8	457.9	14.7	0.54	16.2	561.3	22.9	646.0	10.8	0.50	12.6
f_s=10504 Hz	281.7	13.6	316.1	29.3	0.56	30.8	316.6	7.05	342.2	8.4	0.42	10.3

In shorthand, the evaluation of results laid in Table 3 once again reveals importance of sampling frequency for notching analysis, like previously described analyses.

5. Final conclusions

The most obvious conclusion of the presented research is the requirement of high sampling frequencies in dealing with notching. For the presented cases the sampling frequency of above 75 kHz seems at least advisable. The Daubechies's filter length has minor influence on measurement of respective notching parameters. Only small differences have been observed for filters of 4 and 6 coefficients. Also, the impact of an applying other considered wavelet families seem to be of less importance.
However, the aforementioned requirement of high sampling frequency has utmost influence on algorithms of measurement of other power quality parameters due to large number of samples taken in measurement window. It is especially troubling when dealing with harmonic and interharmonic measurement. These phenomena analysis should typically cover frequency band up to 6 kHz [1]. So, significantly lower sampling frequencies are required than in the transient and notching cases. Then, some improvement for the methods of these phenomena measurement will be needed as well, like e.g. hybrid wavelet-Fourier method for harmonic and interharmonic measurement [8]. In shorthand, this method consists in the simple assumptions:

- wavelet coefficients for each decomposition layer contain relevant frequency information
- number of wavelet coefficients for each consecutive decomposition layer is divided by factor of 2

So, if one applies the discrete Fourier transform to appropriate wavelet coefficients, a significant reduction in a number of the required mathematical operation would be achieved due to decreasing of the input data [8]. In practical terms, the number of needed multiplication would be divided by factor 2^3 or more, depending on the measured signal character.

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