Detection and Classification of Transients and Waveform Distortions Using an Algorithm Based on Sine-fitting

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Abstract-This paper describes a new method for detection of some power quality (PQ) disturbances, namely transients and waveform distortions. The proposed algorithm is based on a modified version of the four-parameter sine-fitting algorithm. The sine-fitting algorithm is used to estimate the parameters of the power system's voltage signal's fundamental and to extract the transient component of the voltage. The performance of the proposed method is compared with previously developed algorithm and with two commercial PQ analyzers.

I. Introduction

Transients and waveform distortions are one of the most common types of power quality disturbances. Although they do not represent such an inconvenience as interruptions and sags or the danger of swells, they can represent a serious problem as the magnitude during the transients can reach up to 4 pu and the high frequency components of transients and waveform distortions can affect the operation of equipment connected to the power network.

Methods for detection of transients and waveform distortions use algorithms to separate the fundamental of the voltage signal and the transient component that contains the information about the disturbance. The used methods include: calculating the cycle-by-cycle difference (comparing a cycle of the voltage signal with a previous cycle); comparing the measured voltage waveform with an average fundamental waveform and using high-pass or notch filters [1]. Algorithms such as the wavelet transform are also frequently used for transient detection [2].

In this paper, a method based on a modified four-parameter sine-fitting algorithm is presented. The performance of the proposed method is compared with the solution earlier published by the authors based on a digital high-pass filter [3] and with two commercial power quality analyzers.

II. Detection and Classification of Transients and Waveform Distortions

The proposed algorithm uses sine-fitting algorithm and mathematical morphology operation closing to extract, detect and classify disturbances present in the voltage signal. The block diagram of the algorithm is shown in Fig. 1.
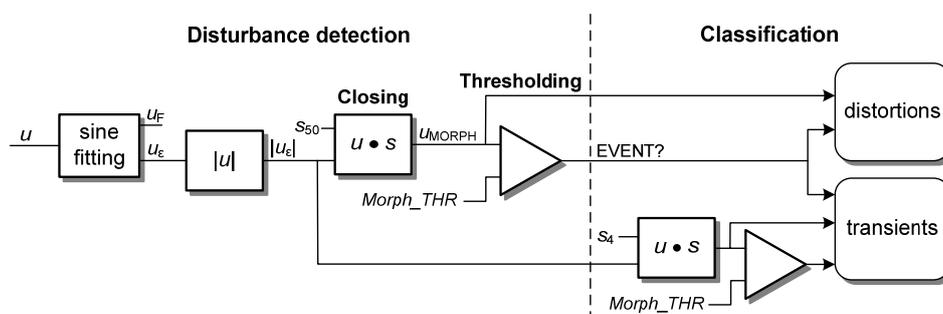

Figure 1. Block diagram of the detection and classification method.

First, the algorithm uses the four-parameter sine-fitting to separate the voltage's fundamental u_F and the transient component containing potential disturbances u_ε. To simplify the detection process, the signal u_ε is processed using mathematical morphology operation called closing. After the thresholding, the algorithm proceeds to the classification stage where the type of disturbance (transient or waveform distortion) together with the disturbance's parameters (magnitude, duration) is determined.

The main steps of the proposed algorithm (*i.e.*, sine-fitting, closing operation and classification) are described in the following subsections.

A. Extraction of the disturbance using four-parameter sine-fitting algorithm

Any component of the measured voltage other than the fundamental component represents a potential disturbance and has to be analyzed. Therefore an algorithm for detection and classification of power quality disturbances has to separate the fundamental component u_F and the component containing possible disturbances u_ε

$$u = u_F + u_\varepsilon .$$ (1)

The algorithm of PQ disturbance's detection described in this paper is based on sine-fitting algorithm. The sine-fitting algorithm estimates the parameters (amplitude, phase and frequency) of the fundamental u_F. The signal u_ε is then calculated as the difference between the estimated fundamental and the actual measured signal.

The proposed algorithm uses the modified four parameter sine-fitting algorithm. This modified algorithm improves the convergence of the known four-parameter algorithm [4]. The four-parameter sine-fitting algorithm estimates the fundamental's in-phase (A) and quadrature (B) components, the DC component (C) and signal's frequency ω

$$u_F = A\cos(\omega t) + B\sin(\omega t) + C .$$ (2)

The initial frequency estimate $\omega^{(0)}$ is obtained using the interpolated DFT algorithm [5]. The initial estimate of the rest of the parameters (A, B, C) is obtained using the three-parameter sine-fitting algorithm [4].

After calculating the initial estimates, the algorithm proceeds to the iterative part of the four-parameter sine-fitting. First, the reconstructed estimate $\hat{\mathbf{u}}_F^{(0)}$ of the signal u_F is calculated using (2). In each iteration step, the algorithm builds a matrix $\mathbf{D}^{(i)}$ [4, p. 22] and uses this matrix to calculate the vector $\Delta\hat{\mathbf{x}}^{(i)}$ of changes of the parameters being estimated

$$\Delta\hat{\mathbf{x}}^{(i)} = \begin{bmatrix} \Delta\hat{A}^{(i)} & \Delta\hat{B}^{(i)} & \Delta\hat{C}^{(i)} & \Delta\hat{\omega}^{(i)} \end{bmatrix}^T = \left(\mathbf{D}^T\mathbf{D}\right)^{-1}\mathbf{D}^T\left(\mathbf{u} - \hat{\mathbf{u}}_F^{(i-1)}\right) .$$ (3)

The vector $\Delta\hat{\mathbf{x}}^{(i)}$ is then used to calculate a new vector of estimated parameters $\hat{\mathbf{x}}^{(i)}$

$$\hat{\mathbf{x}}^{(i)} = \begin{bmatrix} \hat{A}^{(i)} & \hat{B}^{(i)} & \hat{C}^{(i)} & \hat{\omega}^{(i)} \end{bmatrix}^T = \hat{\mathbf{x}}^{(i-1)} + \Delta\hat{\mathbf{x}}^{(i)} .$$ (4)

Using the newly estimated parameters, the estimate of the signal $\hat{\mathbf{u}}_F^{(i)}$ is calculated. The root-mean-square error of estimation is then calculated

$$\varepsilon_{RMS}^{(i)} = \sqrt{\frac{1}{M}\sum_{m=0}^{M-1}\left(u_m - \hat{u}_{F,m}^{(i)}\right)^2} .$$ (5)

If the change of the RMS error since the last iteration step is smaller than a certain level or if the maximum number of allowed iterations is exceeded, the algorithm is stopped and the signal $\mathbf{u}_\varepsilon$ is calculated

$$\mathbf{u}_\varepsilon = \mathbf{u} - \hat{\mathbf{u}}_F$$ (6)

B. Processing using morphology operation closing and disturbance detection and classification

The signal u_ε can be already used for disturbance detection using thresholding. However, since many of the disturbances that occur in power systems have an oscillatory character (*e.g.*, oscillatory transients caused by capacitor switching [1]) there are often more crossings of the threshold level that belong to the same disturbance. In order to simplify the task, the signal is pre-processed before thresholding.

First, the absolute value of the signal u_ε is calculated. The mathematical morphology operation closing [3][6] is then applied to the signal $|u_\varepsilon|$. Mathematical morphology operations are frequently used in image processing to process signals based on their shape. These operations apply to the processed signal a function called structuring element to highlight certain signal's features. The proposed method uses the closing operation to obtain the envelope of the signal $|u_\varepsilon|$ thus removing the multiple crossings of the threshold level that belong to one disturbance

$$u_{\text{MORPH}} = |u_\varepsilon| \bullet s_{50} \tag{7}$$

where s_{50} is the structuring element. The structuring element s_{50} is a binary vector (vector of ones) with the length of 50 ms.

A disturbance is detected when the signal after the closing operation u_{MORPH} exceeds the threshold level *Morph_THR*. The classification of the detected disturbance is based on typical parameters of power quality events [7].

III. Simulation Results

The proposed algorithm was implemented in Matlab and its performance was compared with the previously published method which uses a digital high-pass filter instead of sine-fitting [3]. To compare the two algorithms, a signal with a simulated transient was used. The signal is similar to the one used in [1] for testing of transient detection algorithms. The test signal is

$$u(t) = u_F(t) + u_{tr}(t) \tag{8}$$

where u_F is the fundamental with frequency 50 Hz and RMS value equal to 1 pu. The test signal is 10 cycles long. The transient, given by the component u_{tr}, is 2 cycles long and starts in the beginning of the 5th cycle

$$u_{tr}(t) = 0.1\sqrt{2}\cos(2\pi 370 t) - 0.0522\sqrt{2}\cos(2\pi 410 t) . \tag{9}$$

In Fig. 2, the transient components extracted using an IIR high-pass filter (Fig. 2b) and using the sine-fitting algorithm (Fig. 2c) are shown. The cut-off frequency of the filter was 100 Hz and its attenuation in the stop band is 80 dB (for more details see [3]). From Fig. 2 it can be seen that the sine-fitting algorithm extracts the transient component more accurately. In case of the signal u_ε extracted by the digital filter (Fig. 2b), there is a clearly visible distortion (especially at the beginning and at the end of the transient) caused by the filter's non-linear phase response. However, the sine-fitting algorithm (also due to its iterative nature) is slower than filtering (in Matlab, it is approximately 5 times slower).
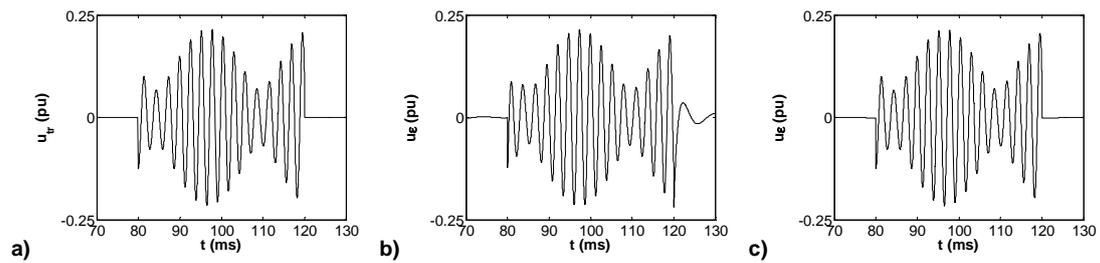

Figure 2. Original simulated transient component (a) and the component extracted from the signal using b) digital filtering and c) sine-fitting.

IV. Experimental Results

In order to gather real single-phase power quality disturbances from the power network, a PC-based measuring setup was assembled. The measuring setup contains a voltage transducer LEM CV 3-500 and data acquisition board (DAQ) NI USB-9215 (in Fig. 3 and 6 the transducer and the DAQ are included in the Sensor box). The nominal input RMS range of the transducer is 350 V and its frequency range is from DC up to 300 kHz. The sampling rate of the DAQ was set to 50 kS/s. The measured waveform was divided into data frames 10 cycles long to which the proposed algorithm was applied.

The performance of the proposed method and its implementation in the measuring setup was compared

with two commercial power quality analyzers: Fluke 434 and Chauvin Arnoux C.A 8334B. The Fluke 434 analyzer has an input range of 500 V, frequency bandwidth 100 kHz and sampling rate 200 kS/s per channel. The C.A 8334B has a voltage range of 480 V and sampling rate 12.8 kS/s per channel.

A. Measurement of disturbances in the power system

In the first measurement, the measuring setup with the proposed method and the two considered commercial power quality analyzers were connected to a single phase 230V/50Hz power system (see Fig. 3).
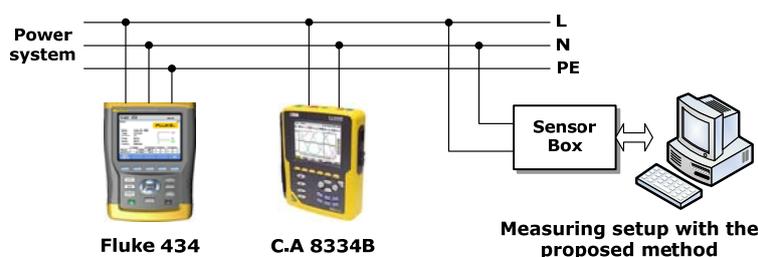

Figure 3. Measuring setup for measuring of power quality disturbances in the power system.

Figure 4 shows an example of one transient measured using the three considered instruments.
In Fig. 5, the processing of this transient using the proposed method is shown. One cycle of the voltage signal containing the transient together with the fundamental u_F estimated using the four-parameter sine-fitting algorithm are shown in Fig. 5a. In Fig. 5b the calculated transient component u_ε is shown. Figure 5c depicts the signals used to detect and classify the disturbance.
The magnitude of the disturbance measured by the proposed method was 0.59 pu and its duration was 1.9 ms. The magnitude measured by the C.A 8334B analyzer was 123.7 V (0.54 pu). The Fluke 434 analyzer does not extract any information (neither magnitude nor duration) about transients.
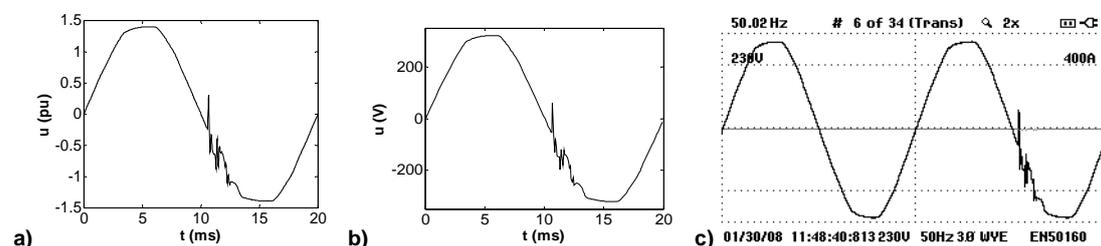

Figure 4. An example of one transient measured using a) measuring setup with the proposed method; b) power quality analyzer Chauvin Arnoux C.A 8334B and c) power quality analyzer Fluke 434.
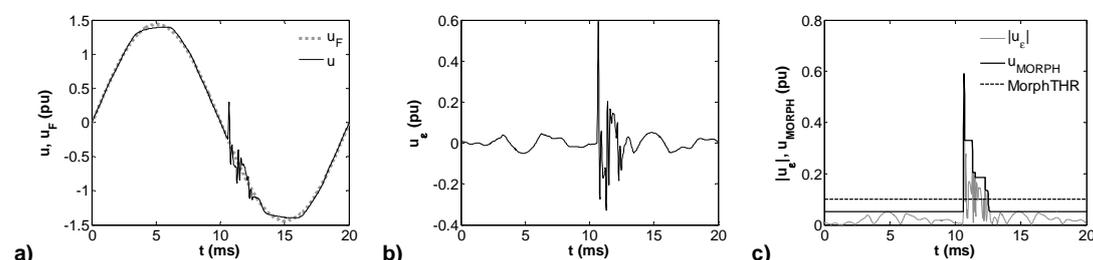

Figure 5. Example of a measured transient a) voltage waveform with the fundamental; b) the transient component extracted using sine-fitting; d) signals used in disturbance detection.

B. Measurement of disturbances generated by a power source

In order to compare the detection capabilities of the proposed method with the two commercial power quality analyzers, the measuring set-up depicted in Fig. 6 was assembled.
In this setup, the power signal was generated by the Agilent 6811B Power Source. The power signal contained in every 10th period one transient with specified parameters. Two types of transients were generated: i) impulsive transients (similar to the ones that originate from lightning strikes) and

ii) oscillatory transients (which are caused in power systems e.g. by capacitor switching).
The impulsive transients were generated using

$$u_{TR}(t) = V_0 \left(e^{-t/\tau_b} - e^{-t/\tau_a} \right) \tag{10}$$

from [1] where $\tau_a = 71$ μs and $\tau_b = 0.2$ μs. The value of V_0 was adjusted in order to obtain transients with the desired peak values.
The oscillatory transients were generated using

$$u_{TR}(t) = A_{TR} e^{-t/\tau} \cos(2\pi f_{TR} t) \tag{11}$$

from [1] where $\tau = 1$ ms, $f_{TR} = 920$ Hz. Due to the power source's limitations, it was not possible to generate transients with higher frequencies.
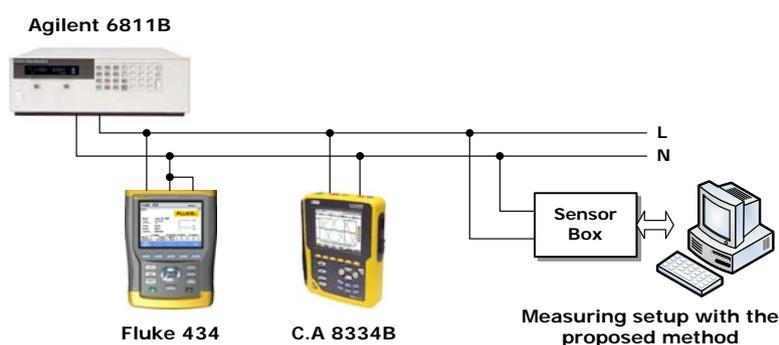

Figure 6. Measuring setup for measuring of power quality disturbances generated by the power source.

The detection thresholds of all instruments were set to approximately the same level. The threshold *Morph_THR* of the proposed method was set to 0.1 pu; the threshold of the Fluke 434 was set to 23 V and the detection threshold of the C.A 8334B was set to 10%. The analyzers Fluke 434 and C.A 8334B can only store 40 and 50 transients at a time, respectively, which limited the time of continuous measurement. All three instruments were set to approximately 8 second measurement. At the end of the measurement interval, the successfulness of detection of transients that occurred during this interval was evaluated.
Table 1 shows the number of impulsive transients (in percents) detected by individual instruments. Transients with peak values from $V_{PP} = 0.1$ up to 1.3 pu and in 3 different positions within the power signal's period ($\varphi = 0°$, 30° and 90°) were generated. Blank fields in the table represent configurations that the employed power source is not able to generate.

Table 1. Results of detection of impulsive transients using the considered power quality analyzers.

V_{PP} (pu)	$\varphi = 0°$			$\varphi = 30°$			$\varphi = 90°$		
	Proposed method	Fluke 434	C.A 8334B	Proposed method	Fluke 434	C.A 8334B	Proposed method	Fluke 434	C.A 8334B
0.1	100 %	12.5 %	0 %	100 %	0 %	0 %	100 %	0 %	0 %
0.2	100 %	100 %	83.3 %	100 %	100 %	81 %	100 %	67.5 %	81 %
0.3	100 %	100 %	81 %	100 %	100 %	81 %	100 %	100 %	81 %
0.4	100 %	100 %	81 %	100 %	100 %	83.3 %			
0.5	100 %	100 %	85.7 %	100 %	100 %	81 %			
0.75	100 %	100 %	83.3 %						
1.0	100 %	100 %	92.9 %						
1.3	100 %	100 %	81 %						

The proposed method was able to detect all transients. The Fluke 434 had problems detecting transients with the smallest magnitudes, however these problems may have been caused by the threshold setting (the disturbances were probably just below the threshold level). The C.A 8334B had more problems detecting disturbances. Some can be attributed to the narrow frequency band. However, this does not explain all missed transients (especially the ones with bigger magnitude).
Similar results were obtained in case of oscillatory transients as shown in Table 2. Again, the proposed method detected all transients, the Fluke 434 analyzer had problems with the smallest magnitudes and the C.A 8334B had a detection rate just over 80 % at the best.

Table 2. Results of detection of oscillatory transients using the considered power quality analyzers.

A_{TR} (pu)	$\varphi = 0°$			$\varphi = 90°$			$\varphi = 180°$		
	Proposed method	Fluke 434	C.A. 8334B	Proposed method	Fluke 434	C.A. 8334B	Proposed method	Fluke 434	C.A. 8334B
0.1	100 %	10 %	0 %	100 %	0 %	0 %	100 %	2.5 %	0 %
0.2	100 %	100 %	83.3 %	100 %	75 %	81 %	100 %	100 %	81 %
0.3	100 %	100 %	83.3 %	100 %	100 %	81 %	100 %	100 %	83.3 %
0.5	100 %	100 %	81 %				100 %	100 %	81 %
0.75	100 %	100 %	83.3 %				100 %	100 %	83.3 %
1.0	100 %	100 %	81 %				100 %	100 %	81 %
1.25	100 %	100 %	83.3 %						

IV. Conclusions

A new method for detection and classification of transients and waveform distortions is presented in this paper. The method uses a modified version of the four-parameter sine-fitting algorithm and the morphology operation closing to extract and process the transient component of the voltage in the power system.

The proposed method was compared with a previously developed method based on a digital high-pass filter. Compared to this method, the proposed method is slower however it is more accurate because it does not experience the problems with non-linear phase response characteristic for IIR filters. As a by product, the sine-fitting algorithm returns the estimates of the instantaneous frequency and amplitude of the voltage's fundamental which can be used in further analysis of the power quality.

The performance of the proposed method was compared with two commercial power quality analyzers: Fluke 434 (which complies with the IEC 61000-4-30 Class B specification) and C.A 8334B. All three instruments were used for monitoring of a single-phase power system. During the monitoring they were able to detect all disturbances that occurred during the monitoring. However, due to the limited memory of the commercial power quality analyzers, the monitoring period was limited to approximately 2 hours (given by the number of disturbances that occur in the monitored power system). For more detailed comparison of the performance, a power signal containing transients with different characteristics was generated using the Agilent 6811B Power Source. The performance of the proposed method was the same or better as the performance of the Fluke 434 analyzer.

Even though the presented measurements do not represent a full test of compliance with power quality standards they show that the proposed method is suitable for reliable and on-line detection of the considered power quality disturbances.

Acknowledgement

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