Detection of power system transients disturbances in distributed generation systems using Hilbert transform and signal decomposition

Tomasz Sikorski, Pawel Kostyla
Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
tomasz.sikorski@pwr.wroc.pl, pawel.kostyla@pwr.wroc.pl

Abstract – An idea of empirical mode decomposition (EMD) with Hilbert Transform (HT) as well as cross-section of smoothed pseudo Wigner-Ville distribution (SPWVD) and instantaneous distortion index (IDIN) are investigated in point of detection of high frequency inrush power quality disturbances. Application and assessment of mentioned techniques are performed using disturbances recorded by wide area power quality monitoring system installed in the three substations connected to the same medium voltage line i.e. two substations of small hydro power plants (SHP) and one urban substation. Dynamic aspect of SHP integration with power systems are tracked using mentioned techniques in point of local and area mutual influence.

Keywords – power system transients, distributed generations, signal processing, decomposition techniques

I. INTRODUCTION

Dynamic aspect of integration of distributed generation (DG) with power systems corresponds to several issues concerning sustained interruptions, voltage regulation and voltage events including under voltage fault right through condition, frequency disturbances, harmonics contribution, as well as operating conflicts for utility fault-clearing requirements, reclosing, interference with relaying, and finally islanding issues. Any variation in magnitude and/or frequency of the voltage or current waveform is the matter of interest of power quality disturbances (PQD). General discussion around power quality issue affected by distributed generation (DG) has been developed for last decades. Last works of or Baggini [2] and Bollen [5] and Dugan et al [10]-[13] underline crucial need for investigations and determine suitable techniques for detection and identification of power quality disturbances.

The signal decomposition methods (SDM) have been applied in a wide variety of research areas, depending on kind of measured signals and aims of investigations. There are several different signal decomposition methods including [23]:

- multiresolution signal decomposition
- subspace decomposition method
- polynomial decomposition method
- adaptive decomposition and wavelet transforms
- empirical mode decomposition with Hilbert transform
- state space signal decomposition method
- data adaptive linear decomposition transform

The mathematical model for the computation and interpretation of the concept of a multiresolution representation is described by Mallat in [19]. Author explained how to extract the difference of information between successive resolutions and thus define a new complete representation called the wavelet representation. This representation is computed by decomposing the original signal using a wavelet orthonormal base, and can be interpreted as a decomposition using a set of independent frequency channels having a spatial orientation and Gaussian white noise is analyzed. A method of subspace decomposition is proposed for the purpose of suppressing noise interference and increasing the ability of recognizing target and multiple signal classification, an algorithm of harmonic retrieval, was introduced to extract harmonic frequencies. Then the frequency of harmonics is estimated by setting threshold in MUSIC power spectrum curve.

Demitras et al. in [8] proposed to use polynomial decomposition method (PDM) for signal processing application. Polynomials are ubiquitous in signal processing in the form of z-transforms. Efficiencies in using exact decomposition techniques and a new approximate polynomial decomposition technique based on the use of Structured Total Least Norm (STLN) formulation is proposed.

Adaptive decomposition and wavelet transform are proposed by Sushama et al. for detection and classification of power quality disturbance [30]. The work presents the wavelet multiresolution analysis as a new tool for extracting the distortion features. For different types of voltage sag conditions, the classification has been done with the help feature extraction
using multi resolution analysis (MRA) and feed forward back propagation neural network (FFBPNN) training algorithm.

The statespace signal decomposition is presented by Zivanovic for power system disturbance analysis [32]. The proposed method estimates the parameters of a signal model expressed as a sum of damped complex exponentials from a noisy waveform samples recorded during some power system disturbances. The method is based on the Singular Value Decomposition of the Hankel data matrix.

In recent years, the new point of view on signal processing of nonlinear and nonstationary phenomena has been proposed by Huang et al. [16],[17] named as Empirical Mode Decomposition (EMD). It is an empirical approach to decompose a signal into a set of oscillatory modes known as intrinsic mode functions (IMFs). Based on an empirical energy model of IMFs, the statistically significant information content is established and combined. The magnitude plot IMFs is proposed to detect the disturbance. Application of this technique has been applied in mechanical [7],[26] and electrical engineering [20],[21],[25].

Nonstationary phenomena can be represented in complex form using joint time-frequency analysis (JTFA) [15],[27].

Additional motivation for this work is permanent development in definition of new power quality indices dedicated to transient disturbances. First suggestion was introduced by Heydt et al. in [14],[18] where application of windowed FFT algorithm (short-time Fourier transform) for definition of short-term harmonic distortion (STHD) was introduced. Further works concerned time-frequency analysis and provided unified or novel definitions of transient version of power quality indices. In works [28],[29] an unified definition of normalized instantaneous distortion ratio (NIDE) - which is a transient version of distortion index DIN, instantaneous frequency (IF) - as a first frequency moment of time-frequency distribution, or instantaneous K-factor (IK), were introduced.

This work is concentrated on assessment of contribution of distributed generation in transitions in power systems. Proposed engines for detection of the disturbances are based on three methods: instantaneous magnitude of intrinsic mode functions, cross section of joint time-frequency analysis and tracking of instantaneous power quality indices. The member functions, cross section of joint time-frequency analysis and tracking of instantaneous power quality indices. The member functions, cross section of joint time-frequency analysis and tracking of instantaneous power quality indices. The member functions, cross section of joint time-frequency analysis and tracking of instantaneous power quality indices.

Hilbert transform is defined as instantaneous frequency [1],[3],[4],[6].

The Hilbert transform of given real signal x(t) allows to obtain its orthogonal form y(t) as follows:

$$y(t) = H\{x(t)\} = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau$$

$$x(t) = H^{-1}\{y(t)\} = -\frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{y(\tau)}{t-\tau} d\tau$$

Having a pair of orthogonal components we can defined complex analytic signal z(t) as:

$$z(t) = x(t) + jy(t) = |z(t)| e^{j\psi(t)}$$

Here reveals definition of instantaneous amplitude (IA) recognized as:

$$IA(t) = |z(t)| = \sqrt{(x(t))^2 + (y(t))^2}$$

Simultaneously, we can distinguish instantaneous phase (IP) as phase of analytic signal or as imaginary part of natural logarithm of complex analytic function:

$$IP(t) = \psi(t) = \arg\{z(t)\}$$

$$IF(t) = f(t) = \frac{1}{2\pi} \omega(t) = \frac{1}{2\pi} \frac{d\psi(t)}{dt}$$

Successful application of Hilbert transform is possible only for narrow range of signals. The meaningful results are achieved in case of monocomponents signals. Thus, in practical cases, the HT is applied not strictly for investigated signal, but for single components, obtained using selected signal decomposition method. There are several signal decomposition methods as mentioned in the introduction. Last work of Huang brought new idea of signal expansion into the set of so called intrinsic mode functions (IMFs), which represents the oscillatory mode embedded in the signal. The IMF functions should satisfy two main conditions: the number of extremes and the number of zero crossings must either equal or differ at most by one, and, at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The algorithm, which serves the idea of representation of the signal by the set of IMFs, is called empirical mode
decomposition (EMD) and was derived by Huang et al. [16],[17],[24]:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n$$  \hspace{1cm} (6)

The basis of the decomposition is derived from the data using systematic way designates as sifting process. Finally, signal can be reconstructed using the IMF components ($c_i$), starting from longest to shortest periods. The residue of the expansion ($r_n$) is not the IMF however has useful, physical meaning, indicated as running mean.

Obtained elements of expansion can be putted through an examination by Hilbert transform in order to track instantaneous amplitude and instantaneous frequency of particular components of the expansion. Described approach is known as Hilbert Huang Transform (HHT) [16],[17],[24]. In this work instantaneous amplitude of first intrinsic mode function ($c_1$) is proposed as the detector of the transients.

Advantage of empirical mode decomposition is that the method does not use predefined set of basic functions as it is in case of classical fixed decomposition represented by Fourier expansion or scaled technique to obtain family of basic functions as in case of Wavelets. In case of EMD elements of the expansion are obtained by using time sample algorithm directly based on investigated signal and do not use predefined basic functions. As the results of calculation a set of intrinsic mode functions are obtained that are frequency components as in case of classical fixed decomposition represented by Fourier, wavelet and are free of problems of selection of proper mother wavelet. Frequency range of particular intrinsic mode functions can be revealed using instantaneous frequency function.

B. Cross-section of time-frequency representations

One of the member of wide time-frequency family is Wigner-Ville distribution [15],[27]:

$$WVD(t,\omega) = \int_{-\infty}^{\infty} x_d\left(t + \frac{\tau}{2}\right)x_d^*\left(t - \frac{\tau}{2}\right)e^{j\omega\tau}\,d\tau$$  \hspace{1cm} (7)

Practical application requires adaptation of additional smoothing operation realized by smoothing windows: smoothing function $h(t)$ is multiplied with signal and brings smoothing effect along frequency axis, other one, $g(t)$, is convoluted with obtained representation after $h(t)$ and exhibits itself in smoothing effect along time axis. It leads to so called smoothed pseudo Wigner-Ville distribution (SPWVD).

$$SPWVD(t,\omega) = \int_{-\infty}^{\infty} h(\tau)\int_{-\infty}^{\infty} g(t-u)\cdot\cdot\cdot x_d\left(u + \frac{\tau}{2}\right)x_d^*\left(u - \frac{\tau}{2}\right)\,du\,e^{-j\omega\tau}\,d\tau$$  \hspace{1cm} (8)

Obtained time-frequency representation represents full time varying nature of frequency components. However in case of detection of the transients only selected items of full time-frequency plane is proposed to use. Applied in this work technique of transient detection is based on cross-section of time-frequency plane in relation to high frequency components.

C. Instantaneous power quality indices

For given recorded set of samples the instantaneous characteristics utilizes shifting executive window. Every points of the characteristic represents local values, calculated on the basis of predefined number of samples $N$, designated by the window, many times for particular location. In high quality mode the window is shifted sample by sample. In monitoring mode we can consider rough time resolution with time step equals window or another time interval. Practically, most of power quality analyzers available on the market apply one-cycle calculation. Classical example is one-cycle calculation of rms value or ten-cycle calculation of harmonics.

Mentioned approach can be adapted to track changes in spectrum, and is represented by well known windowed Fourier transform. For every local set of $N$ samples, designated by the window, we can calculate instantaneous linear spectrum. Then, particular harmonics can be distinguished, even and odd harmonics, interharmonics, subharmonics, harmonic, interharmonics groups. For every time epoch, containing $N$ samples of the local data, we can calculate M samples of the local spectrum. Local or instantaneous means related to window position along the time axis. If no zero-padding process is involved in discrete Fourier transform calculation, the number of spectrum samples is equal the number of data samples ($M=N$). For given sampling rate $f_s$, the fundamental component $f_0$ the Fourier resolution is $df = f_s/N$. Maximum order of harmonics can be calculated as $H = (1/2) f_s/ f_0$.

The local value of distortion index, according to the number of harmonics $H$, can be calculated as [14],[18]:

$$DIN = \frac{\sum_{h=1}^{H} \frac{v_h^2}{\bar{v}_h^2}}{\sqrt{\sum_{h=1}^{H} \frac{v_h^2}{\bar{v}_h^2}}} * 100\%$$  \hspace{1cm} (9)

Definition of DIN has advantageous aspect over the total harmonic distortion (THD) where the absence of the fundamental component fails the evaluation of the index. Application of above equations for every set of $N$ data with respect to actual window position characterizes instantaneous values of DIN, and allows to create time-varying characteristic of instantaneous IDIN. Practical application of IDIN idea requires initial assessment of numerical time and frequency resolution. From the time point of view we expect dynamic representation of IDIN, which can be achieved by using short window. Unfortunately, in opposite to the short window stays frequency resolution, which is bounded by sampling rate and number of data samples.
III. CASE STUDY

In order to reveal and evaluate property of proposed techniques for application in transient detection in distributed generation systems several investigations were performed using real measurements in fragment of radial distribution network consisting of two small hydro power plants (SHP1 and SHP2) and one urban substation (SUB) connected to the same medium voltage line via transformers MV/LV 20/0.4 kV. Synchronized measurement were made using class A power quality recorders. Distance from the main point of supply HV/MW 110/20 kV is 3.4 km, 3.9 km and 4.5 km respectively for SHP1, SHP2, SUB. Localization of discussed disturbances in network scheme is depicted in Fig. 1. Considered hydro power plants represent the group of configuration with canal derivation. Power is produced by two independent asynchronous generators 200kW/0.4kV. In SHP1 generators are droved by Kaplan and Francis turbines in vertical configuration. SHP2 uses two Kaplan turbines in vertical configuration. Out of ordinary is link between turbines and generators via transmission belt. The control systems of the power plants are completely automated and provide, among other things, service of reactive power control, switching off generators in case of voltage drop in the system and automatic switching on generators after voltage restoration. Measurements are made in the low voltage main power circuit.

The aim of the installation was to observe area mutual influence of the hydro power plants. Presented example shows influences of switching-on capacitor banks in SHP1 on detected disturbances in SHP2 and SUB. Transient phenomena, expressed by inrush current with prominent contribution of harmonics in point of LV of SHP1, is also recognized as inrush current with harmonics in SHP2, Fig. 2. No significant influence was detected in urban substation. Detailed profile of power quality disturbances corresponded to switching on the capacitor banks in SHP1 in relation to SHP2 and SUB are presented in Table 1. Recognized disturbances is the inrush current with prominent contribution of odd harmonics in point of LV of SHP1. Additionally, voltage is deteriorated by fast transient event including higher harmonics. Phenomena Phase Duration Magnitude

Table 1. Profile of recorded dynamic disturbances corresponded to switching on the capacitor banks in SHP1

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Phase</th>
<th>Duration</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscilloscope-Wave</td>
<td>L1</td>
<td>36.32ms</td>
<td>711.6 V</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L3</td>
<td>37.95ms</td>
<td>-718.4 A</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L2</td>
<td>40.22ms</td>
<td>1208 A</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L3</td>
<td>199.96ms</td>
<td>0.5836 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L2</td>
<td>199.96ms</td>
<td>0.2063 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L1</td>
<td>199.96ms</td>
<td>1.339 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L3</td>
<td>199.96ms</td>
<td>1.204 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L2</td>
<td>199.96ms</td>
<td>1.401 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L1</td>
<td>199.96ms</td>
<td>0.5638 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L3</td>
<td>199.96ms</td>
<td>0.6343 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L2</td>
<td>199.96ms</td>
<td>0.6658 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L1</td>
<td>199.96ms</td>
<td>3.189 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L3</td>
<td>199.96ms</td>
<td>2.063 [%]</td>
</tr>
<tr>
<td>Oscilloscope-Wave</td>
<td>L2</td>
<td>199.96ms</td>
<td>1.339 [%]</td>
</tr>
</tbody>
</table>

SHP1

SHP2

SUB

No prominent influence on Substation
IV. INVESTIGATIONS

The aim of the investigations is to compare and evaluate properties of proposed techniques for detection of the transients. Fig. 3 and Fig. 4 shows the application of EMD and HT. At first decomposition of the one-phase current signal into a set of intrinsic mode functions using empirical mode decomposition is done. Then application of Hilbert transform leads to calculation of instantaneous amplitude IA of decomposition components. Instantaneous amplitude of first IMF function (c1) is proposed as the detector of the disturbances which is activated during existence of high frequency components. Proposed detector has indicated inrush current in the origin point SHP1 and its mutual influence on SHP2.

As the indicator of transients the instantaneous amplitude (IA) was selected depicted as modulus of Hilbert transform. Such detector of the transient is close to energy impact of the transient component. The instantaneous frequency (IF) which follows by instantaneous phase (IP) was not considered in the detection, however IP characteristic gives possibility to track phase angle jump disturbances. Selection of first IMF as transient indicator is dictated by typical contribution of higher components in electrical transient states and its fast dynamic character including indication as well as suppression. Sharpe detection of the beginning time as well as slope character of the characteristic allows to proposed idea of threshold and hysteresis for the detection of the transient. Additionally different maximum level of the characteristic during the event observed in different nodes of monitoring allows to determine direction of the disturbance including its source.

Full visualization and qualitative comparison of analyzed distortion can be made using time-frequency analysis. As an example Fig. 5 and Fig. 6 depicts harmonics of current in SHP1 and SHP2 and its time distribution during switching on capacitors in SHP1 SPWVD.
Third proposed technique follows by tracking of instantaneous distortion index as the representative of instantaneous power quality indices. Due to definition equation based on ratio of higher harmonics to all harmonic including fundamental component the inherent tradeoff between local instability of the index when first harmonic has a relatively small value is avoided. Fig. 7 represents IDIN characteristic as the detector of inrush current in SHP1 and SHP2. The beginning time of the disturbance is indicated properly. However end time of the disturbances is weighted by length of the window taken for the calculation. In calculation of IDIN characteristic sampling rate was synchronized with power frequency. Additionally, referring to balance between desirable sharp time identification of transients and frequency resolution a one-cycle window was applied.

In order to assess the dynamism of transients detection using investigated techniques in Fig. 8 normalized detectors were presented. Application of cross-section of smoothed time-frequency plane is characterized by most smeared identification. The beginning time of the transient is oriented correctly in case of instantaneous amplitude of IMF and IDIN applications. However sliding window and reference to wide range of harmonics cause that identification of the end of the transient using IDIN characteristic is delayed.
V. CONCLUSION

Dynamic aspects of integration of distributed generation with power systems is still actual and developed issue. This work compares three techniques of transients detection: empirical mode decomposition method joint with Hilbert transform, cross-section of time-frequency plane, instantaneous power quality indices. The methods are applied for identification of origin inrush current and its mutual area influence on power systems with small hydro power plants. Approach based on the decomposition technique supported by calculation of instantaneous amplitude using Hilbert approach, represents fast decomposition technique supported by calculation of inrush current and its mutual area influence on power systems indices. The methods are applied for identification of origin mode decomposition method joint with Hilbert transform, cross-section of time-frequency analysis requires time-consuming calculation and placed the technique in off-line analysis. Additionally weighted effect of the definition equation and smoothed functions exhibits itself in smeared nature of the cross-section. Idea of tracking instantaneous power quality index gives suitable results of the transient detection, however in case of distortion index requires local calculation of spectrum components. This rule may have influence on detection of the transients duration time. Described methods were implemented and assessed on the basis of real measurement signals recorded in distribution network caused by operations of two installed small hydro power plants. Investigated cases represent distributions systems and consider emitted by SHP disturbances. Presented methods were applied for transients detection not for long term diagnostic data. Thus at this moment of investigation it is not available answer if the method can be implemented in prevention of the possible events.

ACKNOWLEDGMENT

This work is supported by Polish National Science Center under grant DEC-2011/01/B/ST8/02515.

REFERENCES