TIME-FREQUENCY ANALYSES OF DISTURBANCES IN POWER DISTRIBUTION SYSTEMS

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Abstract:

Future smart distribution grids, apart from a large number of measurement instruments, communication infrastructure, intelligent software etc., will also require the appropriate techniques for the analysis of available signals. Various disturbances of different intensities constantly occur in real distribution systems. Many of them are just temporary ones, while others cause the tripping of protection devices and the suspension of electricity supply. For distribution network operators, timely identification and an adequate analysis of disturbances represent a very important segment of operation of power distribution networks. In this paper, the disturbance measured in the real distribution system of Bosnia and Herzegovina is analysed using four different time-frequency analysis techniques (Short-Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT), Wigner-Ville Distribution (WVD) and Hilbert-Huang Transform (HHT)). The results show that all the applied techniques have successfully identified the disturbance which is reflected in changes in frequency during the observed time period. These techniques could be suitable to be applied in power quality monitoring systems, which provide the required measurement signals. The utilization of these techniques can provide distribution system operators with very important additional information about the distribution system.

1 Introduction

Power quality is a very important segment for both electricity suppliers and distribution system operators. It is regulated not only by international standards (IEC, IEEE, EN), but also by national standards and legislation [1]. In recent years special attention has been given to power quality monitoring systems. Nowadays, there are many equipment manufacturers who provide high-quality measurement instruments and power quality monitoring systems. A significant number of

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electric power companies are actively testing or deploying such systems in their distribution networks [2]. Power quality monitoring instruments have very high sampling rate (up to 1024 samples per period, i.e. 50 kHz) and can provide a large number of measurement signals to the competent staff. These instruments are a part of power quality monitoring systems, which are also comprised of adequate communication infrastructure, servers with databases and software programs for the analysis of data and signals. An analysis of available signals with adequate techniques can provide additional information about power quality disturbances in distribution networks and enable better visualisation of the events.

In this paper, the analysis of signals/disturbances that occurred in the real distribution system in Bosnia and Herzegovina (B&H) is done using four different time-frequency techniques. The results of the analysis show that all the used approaches enable the successful identification of disturbances reflected in the changes of frequency during the observed time period. Generally speaking, Short-Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT), Wigner-Ville Distribution (WVD) and Hilbert-Huang Transform (HHT) are techniques that are often used for disturbance identification, power quality analysis, localisation of disturbances in distribution networks etc. [3-8]. Also, comparative analyses applying the techniques used in this paper for analysing different phenomena can be found in [8-13]. The calculations and visualisations used in this paper are performed with widely available code and software tools according to [14-17]. This paper, however, does not deal with some important aspects of using these techniques as a part of power quality monitoring systems such as computational complexity, signal processing time etc. Therefore, the rest of this paper is organised as follows. Section 2 briefly presents the analysed signals and gives a short overview of the applied time-frequency techniques. Section 3 presents and discusses the results. The conclusions are given in Section 4.

2 The data and applied time-frequency techniques

2.1 The signals from real power distribution system

Signals analysed in this paper are measurements from the real electricity distribution system of B&H. The measurements were conducted as a part of the pilot project for testing power quality monitoring system, implemented during the first three months of 2012. The measurements were performed using ELSPEC G4500 power quality analyser which was installed in the middle voltage power distribution system in the wider area of the city of Mostar. The disturbances analysed in this paper are shown in Fig. 1. They occurred in the monitored electricity distribution system on February 7, in 2012. Fig. 1 shows that the monitored disturbances are temporary earth-faults of very short duration in phase L3.

For the practical analysis, the signal sampling rate of 1600 Hz was selected, while the base frequency of the power system is 50 Hz. The first disturbance starts at 0.06 s and lasts until 0.1 s of the analysed time period. The second disturbance starts at 0.18 s and lasts until 0.23 s (Fig. 1). During the measured disturbance, the amplitude of L3 voltage drops to zero, while the amplitudes of the other two phase voltages increase by the factor of $\sqrt{3}$, which represents a classic earth-fault.

2.2 A short review of time-frequency approaches applied to disturbance identification

The STFT, CWT, WVD and HHT are the time-frequency techniques often used in almost all the

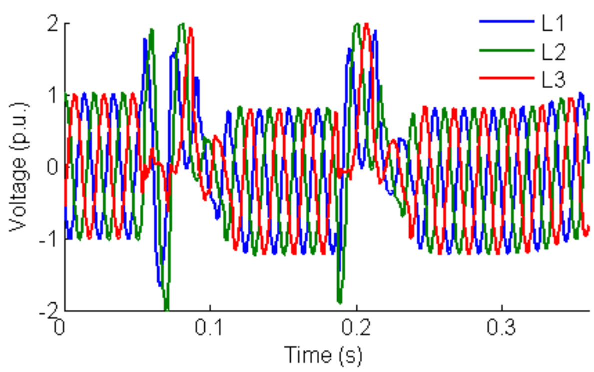

Figure 1. Voltage transients measured in real power distribution system.

area of science whereas in this section, based on [8-13, 17-18], only the basic information about these techniques is presented. Generally speaking, the Fourier transform gives a good insight into the frequency spectrum of stationary signals, but other techniques need to be used in the context of finding out which frequencies occur in certain time intervals in non-stationary signals. The drawback of the Fourier transform is partly solved by the use of STFT, i.e. by the multiplication of the signal with the small window moving in time, which enables the analysis of non-stationary signals. Mathematically, STFT can be defined as [17]:

$$STFT = (t, \nu; h) = \int_{-\infty}^{\infty} x(u) h^*(u - t) e^{-2j\pi\nu u} du \quad (1)$$

where: $x(u)$ is a signal, $h(t)$ is a short time analysis window and ν is the frequency.

On the other hand, CWT was developed partly in order to overcome the resolution problem of STFT. In comparison to STFT, the most important characteristic and key difference is in the width of the time window which adapts to the chosen frequency in a way that higher frequencies are identified with a narrower time window, while the lower frequencies are better identified with a wider time window. Mathematically, CWT is defined as:

$$CWT(t, a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(\tau) \psi^*\left(\frac{\tau - t}{a}\right) d\tau \quad (2)$$

where a is the scale and $\psi(t)$ is the mother wavelet [17]. On the other hand, following [17], WVD can be defined as:

$$WVD(t, \nu) = \int_{-\infty}^{\infty} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-2j\pi\nu\tau} d\tau \quad (3)$$

where: $x(t)$ is a signal, t is a chosen time instant and ν is the frequency variable. The WVD provides decomposition of the signal energy in the time-frequency plane [8]. Also, the aim of the WVD is to obtain a signal representation, whose form shows a sharp ridge describing the signals instantaneous frequency (IF) law of the signal over the time-frequency plane [9, 14]. The modification of WVD is pseudo WVD (PWVD), which for the reason of not knowing the product $x(t+\tau/2)x^*(t-\tau/2)$ in the interval from $-\infty$ to $+\infty$, replaces that product by its windowed version. By multiplying the expression $x(t+\tau/2)x^*(t-\tau/2)$ in Eq. (3) with the chosen time window $h(\tau)$, PWVD is defined [9].

Further on, HHT represents one of the commonly used techniques for the analysis of non-linear and non-stationary signals. HHT consists of two parts: empirical mode decomposition (EMD) and the Hilbert spectral analysis. By means of empirical signal decomposition, the signal is decomposed into intrinsic mode functions (IMF) which by definition have the following characteristics:

(i) On the whole length of the signal, the number of extremes and null points of the function must be equal to or differ by one;

(ii) In every point, the mean value of the envelope defined by the local maximums and minimums is equal to zero.

The functions defined in this way are suitable for further analysis by using the Hilbert transformation. Every IMF represents a simple harmonic function whose amplitude and frequency can also be the functions of time. The details on the whole algorithm can be found in [8, 10, 13, 16].

3 Results and discussion

In this section, the results of analysing signals in Fig.1 by using four selected time-frequency techniques for signal analyses (for all three phases) are shown in Fig. 2-5. Based on [17], for STFT and PWVD, we selected the Hamming window of N/4 samples length, where N is the length of signals. For the CWT approach, the Morlet wavelet function is selected for all the signals represented [17]. On the other hand, based on [18], we used the proposed procedure for the EMD and HHT time-frequency-energy representation. Signals are decomposed into three IMFs, where the first IMF usually represents a high frequency component of signals or time series. As noted in the previous section, the base frequency of the monitored power system is 50 Hz, and this frequency is identified as a base or dominant one by all the used techniques for all three phases. For all the time-frequency representations shown from Fig. 2-5, the occurrence of the disturbance is clearly identified in all three phases, i.e. for the time intervals 0.06 s up to 0.1 s and 0.18 s up to 0.23 s, there are evident changes in values of the frequency during these disturbances. In comparison to other approaches, clear identification of disturbances in time is generally one of the

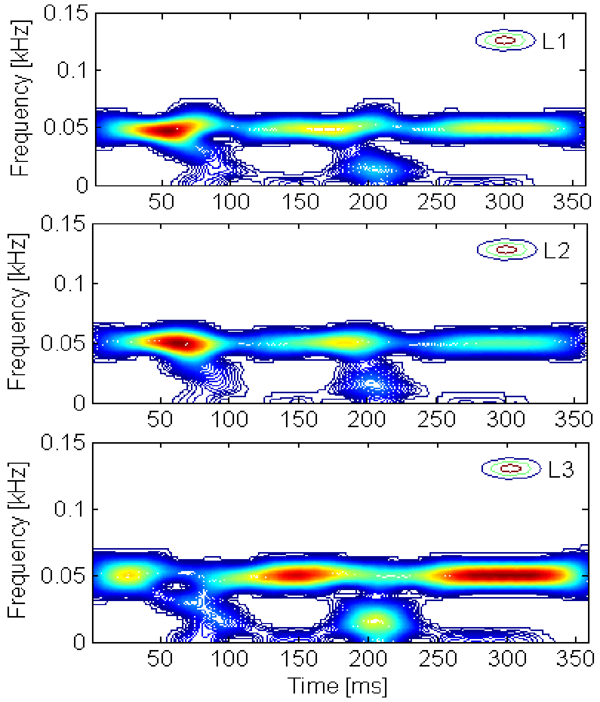

Figure 2. *The time-frequency representation of signals (L1, L2, L3) from Fig. 1 using STFT.*

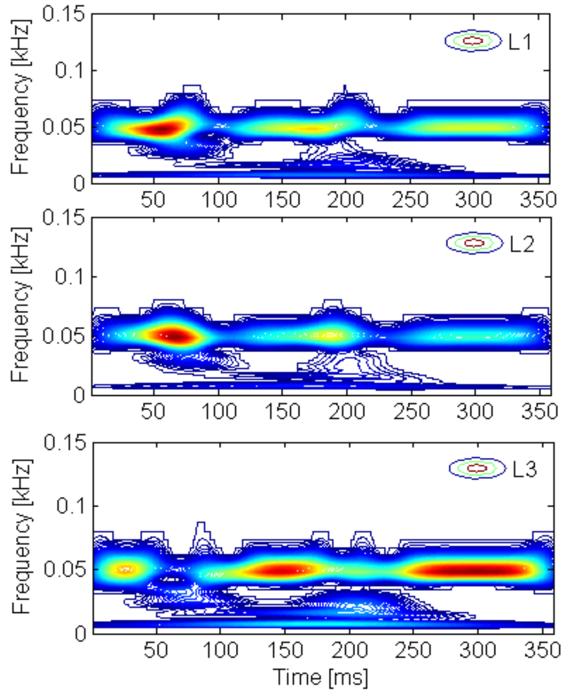

Figure 3. *The time-frequency representation of signals (L1, L2, L3) from Fig. 1 using CWT.*

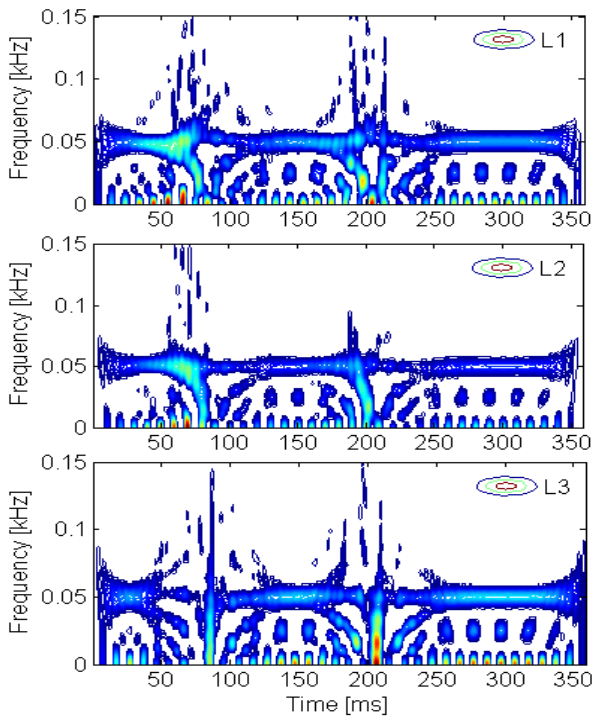

Figure 4. *The time-frequency representation of signals (L1, L2, L3) from Fig. 1 using PWVD.*

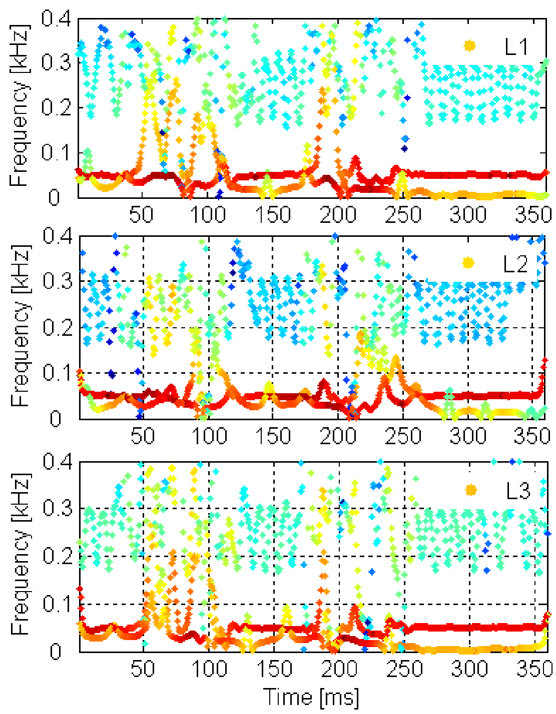

Figure 5. *The time-frequency representation of signals (L1, L2, L3) from Fig. 1 using HHT.*

advantages of the applied time-frequency techniques for signal analyses.

Apart from the changes in the base frequency, when using the STFT, PWVD and CWT approaches, other components were not identified and Fig. 2, Fig. 3, and Fig. 4 are thus zoomed up to 0.15 kHz or 150 Hz. Changes in the window characteristics will lead to the changes in the resolutions and consequently, the shorter duration of time window gives better time resolution and poorer frequency resolution, while the longer duration of windows gives better frequency resolution and poorer time resolution. By changing the characteristics of windows for the STFT and PWVD approaches, only the changes in the resolution were identified whereas other higher frequency components were not identified. Because of a large number of pictures resulting from these analyses, not all the results are presented. On the other hand, using the HHT approach, high-frequency components are identified in the frequency range around 250 Hz (5^{th} harmonic component). An insight into the properties of IMFs clearly shows that the first IMFs for all three cases have significantly lower amplitudes in comparison to the other IMF components. This is also evident from the presentation shown in Fig. 5. Also, it is worth noting that for analysed phenomenon, the HHT approach clearly identifies the changes in the basic frequency (Fig. 5). Generally, all the applied approaches provide information on time and duration of the disturbance. This information is very important in the context of smart distribution grids

4 Conclusion

Future smart distribution grids will require systems and techniques which will provide distribution system operators with the useful information needed for operation and maintenance. Among others, information on disturbances in power distribution systems can help in making timely decisions. In this paper, four different time-frequency techniques for signal analyses are used to analyse disturbances measured in the real power system of B&H. Analysed signals were measured during the project of testing the power quality monitoring system in distribution networks, which was conducted during the first three months of 2012. The results show that applied techniques have successfully identified the time and duration of the disturbances in power distribution system, indicating that the application of these techniques in the analysis of available signals could provide useful information to the competent staff.

References

[1] Music, M., Bosovic, A., Hasanspahic, N., Avdakovic, S., Becirovic, E.: *Integrated power quality monitoring systems in smart distribution grids*, IEEE Energycon, Florence, 2012, 501-506.

[2] Music, M., Bosovic, A., Hasanspahic, N., Avdakovic, S., Becirovic, E.: *Integrated power quality monitoring system and the benefits of integrating smart meters*, IEEE CPE, Ljubljana, 2013, 86-91.

[3] Borghetti, A., Bosetti, M., Di Silvestro, M., Nucci, C.A., Paolone, M., Peretto, L., Scala, E., Tinarelli, R.: *Assessment of Fault Location in Power Distribution Networks*, Electrical Power Quality and Utilization Journal, 13 (2007), 1, 33-41.

[4] Borghetti, A., Corsi, S., Nucci, C.A. Paolone, M., Peretto, L., Tinarelli, R.: *On the Use of Continuous-Wavelet Transform for Fault Location in Distribution Power Systems*, International Journal of Electrical Power & Energy Systems, 28 (2006), 9, 608-617.

[5] Borghetti, A., Bosetti, M., Nucci, C.A., Paolone, M.: *Integrated Use of Time-Frequency Wavelet Decompositions for Fault Location in Distribution Networks: Theory and Experimental Validation*, IEEE Transactions on Power Delivery, 25 (2010), 4, 3139-3146.

[6] Szmajda, M., Górecki, K., Mroczka, J.: *Gabor Transform, SPWVD, Gabor-Wigner Transform and Wavelet Transform - Tools for Power Quality Monitoring*, Metrology and Measurement Systems, 17 (2010), 3, 383-396.

[7] Yong-June Shin, Powers, E., Grady, M., Arapostathis, A.: *Power Quality Indices for Transient Disturbances*, IEEE Transactions on Power Delivery, 21 (2006), 1, 253-261.

[8] Bouchikhi, E.H., Choqueuse, V. Benbouzid, M.E.H., Charpentier, J.F., Barakat, G.: *A comparative study of time-frequency representations for fault detection in wind*

turbine, IEEE IECON, Melbourne, 2011, 3584-3589.

[9] Saulig, N., Sučić, V., Stojković, N.: *Signal Representation Quality Enhancement by Applying Mathematical Operations to Time-Frequency Distributions*, Engineering Review, 29 (2009), 2, 21-32.

[10] Rosero, J.A., Romeral, L., Ortega, J.A., Rosero, E.: *Short-Circuit Detection by Means of Empirical Mode Decomposition and Wigner–Ville Distribution for PMSM Running Under Dynamic Condition*, IEEE Transactions on Industrial Electronics, 56 (2009), 11, 4534-4547.

[11] Xiang, L., Hu, A.: *Comparison of Methods for Different Time-frequency Analysis of Vibration Signal*, Journal of Software, 7 (2012), 1, 68-74.

[12] Dash, S., Shelley, K.H., Silverman, D.G., Chon, K.H.: *Estimation of Respiratory Rate from ECG, Photoplethysmogram, and Piezoelectric Pulse Transducer Signals: A Comparative Study of Time–Frequency Methods*, IEEE Transactions on Biomedical Engineering, 57 (2010), 5, 1099-1107.

[13] Li, M., Gu, X.K., Yang, S.S.: *Hilbert-Huang Transform Based Time-Frequency Distribution and Comparisons with Other Three*, International Journal Of Circuits, Systems And Signal Processing, 2 (2007), 1, 155-160.

[14] Orini, M., Bailón, R., Mainardi, L.T., Laguna, P., Flandrin, P.: *Characterization of the Dynamic Interactions Between Cardiovascular Signals by Time-Frequency Coherence*, IEEE Trans. Biomed. Eng., 59 (2012), 663-673.

[15] Grinsted, A., Moore, J.C., and Jevrejeva, S.: *Application of the Cross Wavelet Transform and Wavelet Coherence to Geophysical Time Series*, Nonlinear Processes in Geophysics, 11 (2004), 561-566.

[16] Huang, N.E., Shen, Z., Long, S., Wu, M.C., Shih, H.H., Zheng, Q., Yen, N.-C., Tung, C.C., Liu, H.H.: *The Empirical Mode Decomposition and Hilbert Spectrum for Nonlinear and Non-Stationary Time Series Analysis*. Proceedings of Royal Society London A, 454 (1998), 903-995.

[17] Auger, F., Flandrin, P., Goncalves, P. Lemoine, O.: *Time-frequency toolbox, for use with matlab*. NRS, GDR ISIS, Tech. Rep., 1997.

[18] Flandrin, P., Rilling, G. Goncalves, P.: *Empirical Mode Decomposition as a Filter Bank.* IEEE Signal Process. Lett., 11(2004), 112–114.