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Power Distortion Issues in Wind Turbine Power Systems Under Transient States

Tadeusz LOBOS, Jacek REZMER, Tomasz SIKORSKI, Zbigniew WACLAWEK
Wroclaw University of Technology, Department of Electrical Engineering,
Wybrzeze Wyspianskiego 27, 50-370 Wroclaw-POLAND
e-mails: tadeusz.lobos@pwr.wroc.pl • jacek.rezmer@pwr.wroc.pl
e-mails: tomasz.sikorski@pwr.wroc.pl • zbigniew.waclawek@pwr.wroc.pl

Abstract

In this paper time-frequency methods have been investigated for complex investigations of transient states in wind power plants. Application of parallel processing in time and frequency domain brought new findings in description of wind power plants working under transient conditions. Proposed algorithms represents standard Short-Time Fourier Transform (STFT) as well as alternative methods associated with Cohen's class: Choi-Williams Distribution (CWD) and Zhao-Atlas-Marks Distribution (ZAMD). In order to explore advantages and disadvantages of the method several experiments were performed using model of squirrel-cage induction machine connected directly to the grid. Investigated phenomena concerned power distortion caused by switching-on capacitor banks and faults as well as influence of wind speed on instantaneous character of the transient states.

Key Words: *Power quality, power system harmonics, time-frequency analysis, wind power plants.*

1. Introduction

In the era of technological development power quality issues have more and more crucial meaning. In spite of achieved experience in specification of distortions, including IEC norms, some cases and accompanying phenomena require individual approach. In author's opinion there is still significant need to extend power quality specification, e.g. by applying advanced signal processing methods. As examples can use wide researches on influence of dispersed energy sources on power quality, especially including wind power plants.

Wind turbines become nowadays regular element of power systems with all its desirable as well as undesirable influences. Behind the undisputed significance of wind power plants for searching the renewable energy sources there are some aspects which have impact on power quality. One of them is natural result of variable weather conditions. Another comes from mechanical construction of power plant and power electronic equipment. Recognizing sources and symptoms of mentioned impacts it can be detailed [1, 2, 3]: influence of stochastic wind variation on output torque, power, voltage and current fluctuation, periodical drop of output torque when the mill blade passes the tower (shadow effect), complex, nonlinear oscillation of the tower and wind turbine which can be transferred to turbine shaft (the frequency of generated oscillation can attain value from tenth to few Hz), and finally wide spectrum of harmonics in current and voltage caused by present of power converters.

Mentioned above mechanical oscillations as well as present of power converters manifest itself in influence on grid. The main symptom concerns deterioration of power quality. Recognized phenomena include voltage sags and flickers, main voltage drops caused by reactive power consumption, power oscillation in electrical transmission line, wide spectrum of harmonics.

The most significant meaning have the oscillations of generated power. This problem accompanies wind power plant both under normal and transient conditions. However, under transient conditions, such us faults, the range of oscillations is prominent. It must be emphasised that the range of power oscillations depends on construction of applied generator and load conditions. Wind power plant, working under load conditions below nominal value, are characterized by considerably higher level of power oscillations than in case of nominal-load operation. Furthermore, wind power plant fitted using asynchronous slip-ring generator (with controlled resistance in rotor circuit or double-fed) and synchronous generator connected to grid by power converters, minimize power oscillations in comparison with asynchronous squirrel-cage induction machines [1, 3].

Selection of proper method for analysis of power distortion in wind turbine system is still actual and crucial. In [4] we can find an idea which apply classical Fourier spectrum in order to investigate and classify power distortion. In this paper the authors propose to apply two-dimensional time-frequency analysis in order to obtain comprehensive analysis of power distortion. The main known applications of time-frequency analysis consist speech processing, seismic, economic and biomedical data analysis [5, 6, 7]. Recently some efforts was also made to introduce time-frequency analysis in electrical engineering area [6 - 10]. The authors perceive a crucial need for better estimation of distorted electrical signal that can be achieved by applying the time-frequency analysis [11 - 13].

One of the contributions of this paper is developing a new qualitative method for analysis of transient phenomena in wind turbine systems. The originality of the paper includes new findings concerning transient components of power distortion. Application of proposed methods allowed to compare instantaneous character of power distortion components, especially appearing under transient conditions with regard for wind speed. Thanks to proposed approach we can reveal difference in power distortions in point of its duration time or contribution of particular frequency components.

In order to explore the effects, grid connected wind turbine system was modelled using Matlab SimPowerSystemToolbox [14]. Selected wind generator structure is squirrel-cage induction machine, connected directly to the grid. Many of the wind power plants installed today have such configuration. This type of the generator can not perform voltage control and it absorbs reactive power from the grid. Phase compensating capacitors are usually directly connected. That type of wind turbine is cheap and robust and therefore popular, but from the system analysis point of view it has some drawbacks [2, 3, 15].

2. Two-Dimensional Algorithms

The standard method for study time-varying signals is the short-time Fourier transform (STFT), based on the assumption that, for a short period of time, basis signal can be considered stationary. The spectrogram utilizes a short-time window $\mathrm{h}(\tau)$, whose length is chosen so that over the length of the window, the signal is stationary. The Fourier transform of this windowed signal is calculated to obtain the energy distribution along the frequency direction at the time corresponding to the centre of the window [7]:

$$\mathrm{STFT}_x\left(t,\omega\right)=\int\limits_{-\infty}^{+\infty}x\left(\tau\right)h\left(\tau-t\right)e^{-j\omega\tau}\mathrm{d}\tau, \tag{1}$$

where t denotes time, ω is angular frequency, τ denotes time lag.

The crucial drawback of this method is that the length of the window is related to the frequency resolution. Increasing the window length leads to improving frequency resolution but it means that the nonstationaries occurring during this interval will be smeared in time and frequency [7, 16]. This inherent relationship between time and frequency resolution becomes more important when one is dealing with signals whose frequency content is changing rapidly. A time-frequency characterization that would overcome above drawback became a major goal for alternative development based on non-parametric, bilinear transformations.

The first suggestions for designing non-parametric, bilinear transformations were introduced by Wigner, Ville and Moyal at the beginning of nineteen-forties in the context of quantum mechanics area. Next two decades beard fruit of significant works by Page, Rihaczek, Levin, Mark, Choi and Williams [17], Born and Jordan, who provided unique ideas for time-frequency representations, especially reintroduced to signal analysis [18, 19]. Then in the 1980s, Leon Cohen employed the concept of kernel function and operator theory to derive a general class of joint time-frequency representation. It can be shown that many bilinear representations can be written in one general form that is traditionally named Cohen's class [20].

Cohen defined a general class of bilinear transformation (TFC) introducing kernel function, $\phi_{\omega t}\left(\theta,\tau\right)$ [18 - 20]:

$$\mathrm{TFC}_x\left(t,\omega\right)=\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty}\mathrm{x}\left(u+\frac{\tau}{2}\right)\mathrm{x}^*\left(u-\frac{\tau}{2}\right)\cdot\phi_{\omega t}\left(\theta,\tau\right)\mathrm{e}^{j\theta t}\mathrm{e}^{-j\omega\tau}\mathrm{e}^{-j\theta u}\mathrm{d}u\mathrm{d}\tau\mathrm{d}\theta \tag{2}$$

where: t denotes time, ω is angular frequency, τ is time lag, θ is angular frequency lag, and u is an additional integral time variable.

Performing the transformations brings two dimensional planes which represent the changes of frequency component, here called auto-terms (a-t). Unfortunately, bilinear nature of discussed transformations manifests itself in existing of undesirable components, called cross-terms (c-t). Cross-terms are located between the auto-terms and have an oscillating nature. It reduces auto-components resolution, obscures the true signal features and make interpretation of the distribution difficult. One crucial matter of kernel function is smoothing effect of the cross-terms with preservation useful properties of designed distribution. Applying Gaussian kernel in general Cohen's equation (2) leads to Choi-Williams Distribution (CWD) which brings mentioned smoothing effect [17, 19]:

$$\mathrm{CWD}_x\left(t,\omega\right)=\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty}\sqrt{\frac{\sigma}{4\pi}\frac{1}{|\tau|}}e^{\left[-\frac{\sigma}{4}\left(\frac{t-u}{\tau}\right)^2\right]}\cdot x\left(u+\frac{\tau}{2}\right)x^*\left(u-\frac{\tau}{2}\right)e^{-j\omega\tau}\mathrm{d}u\mathrm{d}\tau \tag{3}$$

Another example is the cone shaped kernel. This approach is associated with Zhao-Atlas-Marks Distribution (ZAMD) and also brings desirable smoothing effect of the cross-terms. Chosen function $\mathrm{h}\left(\tau\right)$ serves as the base of two-dimensional cone shaped kernel [18, 19]:

$$\mathrm{ZAMD}_x(t,\omega) = \int_{-\infty}^{+\infty} \mathrm{h}(\tau) \int_{t-\frac{|\tau|}{2}}^{t+\frac{|\tau|}{2}} x\left(u+\frac{\tau}{2}\right) x^*\left(u-\frac{\tau}{2}\right) e^{-j\omega\tau} \mathrm{d}u\mathrm{d}\tau \tag{4}$$

3. System Model

A wind turbine generates power and accordingly a mechanical torque on the rotating shaft, while the electrical machine produces an opposing electromagnetic torque [2]. In steady state operation, the mechanical torque is converted to real electrical power and delivered to the grid. The power P and torque T generated by the wind turbine are [2, 3, 15]:

$$P = \frac{1}{2}\rho A C_p V^3 \tag{5}$$

$$T = \frac{P}{\omega_s}, \tag{6}$$

where: ρ is density of air, A is swept area of the blade, C_p is performance coefficient, V is wind speed, T is mechanical torque, P is output power of the turbine, and ω_s is rotor speed of the turbine.

At the constant wind speed, coefficient C_p depends on the rotor speed ω_s and pitch angle. The pitch control dynamic can be neglected in power system transient analysis [15].

The turbine characteristic used in simulation is shown in Figure 1. Figure 2 presents the diagram of the simulated wind generator system. Simulation was done in Matlab using the SimPowerSystem Toolbox [14]. Simulated generator is a squirrel-cage induction machine rated at 150 kW, 400 V, 1487 rpm. It is connected to the grid through a Dyg 25/0.4 kV distribution transformer which nominal power equals 1 MVA. Point of common coupling is connected with the system via typical 5 km overhead line, represented by positive, negative and zero-sequence of impedance. The system was simulated by equivalent source with short circuit capacity of 100 MVA and X/R ratio of 7. Capacitor banks provides compensation of absorbed reactive power and are directly connected.

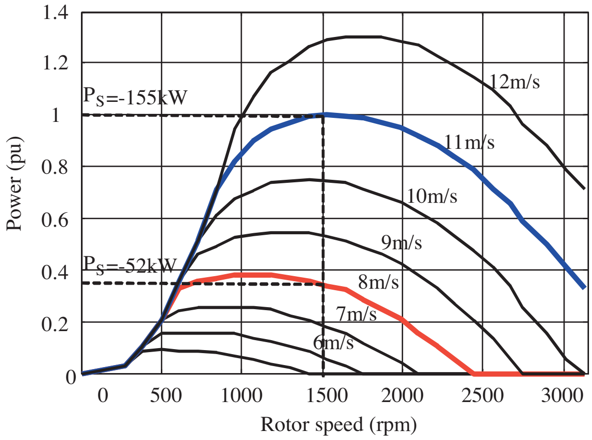

Figure 1. Characteristic of simulated wind turbine.

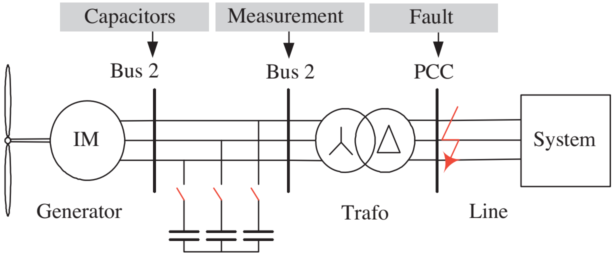

Figure 2. Diagram of simulated grid-connected wind turbine system.

4. Investigations

The purpose of investigation was to study the distortion of power generated by wind turbine under transient states introduced by switching-on capacitor banks and faults. In case of switching-on capacitor banks, the concern is with phenomena that includes transition from uncompensated to full-compensated state, for fixed, nominal wind speed of 11 m/s. Fault conditions are modelled as 1-phase fault with common coupling ground point. Simulations of the fault were carried out twice, corresponding to two different wind speeds: low-speed at 8 m/s, and nominal speed at 11 m/s. The wind turbine, presented in Figure 1, is designed to have non-nominal power ratings P_S = -52 kW, and nominal P_S = -155 kW, value of generated power. Additionally, we have assumed that fault appears in steady state with full compensation. Table 1 provides details about power conditions of investigated wind turbine in steady state as well as values of capacitors, according to selected wind speed.

Table 1. Power conditions of the wind turbine in steady state according to wind speed.

Wind	Generated active power	Capacitor
8 m/s	-52 kW	67.2 kVar
11 m/s	-155 kW	80.4 kVar

4.1. Switching-on the capacitor banks

One of the investigated phenomena concerns switching-on the capacitor banks, for compensation of reactive power. Figure 3 shows currents as well as active and reactive power under transition from uncompensated to compensated state. Analysis of power distortion P were performed using Short Time Fourier Transform, Choi-Williams Distribution and Zhao-Atlas-Marks Distribution. Observing Figures 4 and 5, we can see two transient components at 535 Hz and 430 Hz, which affect generated power for about 0.04 s. Additionally, some advantages of Cohen's class of distributions can be underline in point of sharp localization of transient components. In Figure 4 we can observe smearing effect, characteristic for sliding window in STFT method. Figure 5 confirms sharp detection of transient states when CWD or ZAMD was applied but also indicate problem of separation for components localized in near time-frequency regions or modulated by peak value.

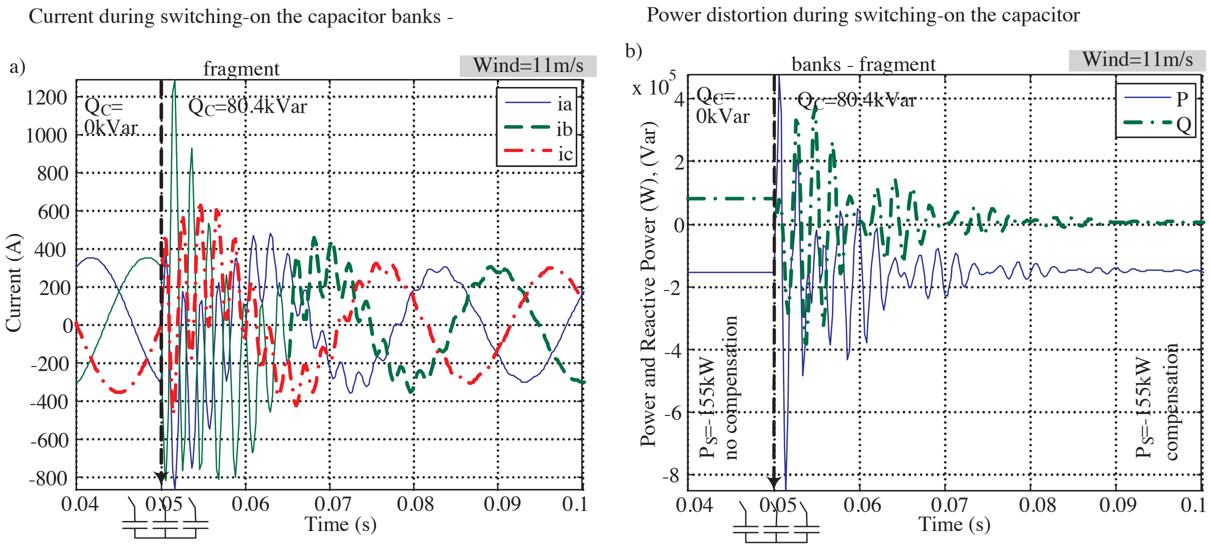

Figure 3. Switching-on the capacitor banks for compensation of reactive power, nominal wind speed equals 11m/sn: (a) currents (b) power distortion; fragments contained transient states.

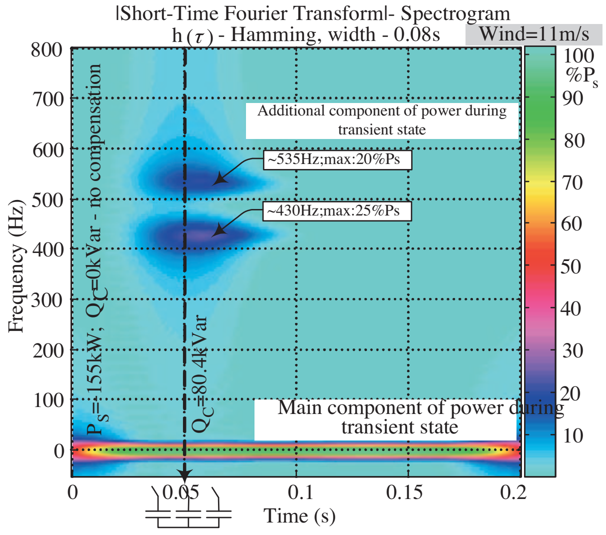

Figure 4. Time-frequency plane of power distortion (P from Figure 3(b)) during switching-on the capacitor banks obtained using STFT: nominal wind speed, 11 m/s.

4.2. 1-Phase fault

Next investigated case concerns 1-phase fault in point of common coupling. The fault duration is 100 ms. Figure 6 shows an example of transient current and power at low wind speed, 8 m/s. Simultaneous simulations was carried out for nominal wind speed of 11 m/s. Then, obtained 3-phase power distortion P in both cases were investigated using time-frequency methods. In Figure 7 we can observe the effects of analysis when Short-Time Fourier Transform were applied. Comparing Figure 7a, corresponding to low-speed wind, with figure 7b, showing nominal wind turbine work, we can see some influence of wind speed on transient states. Time-frequency analysis shows visible drift in the frequency of transient components towards lower frequencies, for wind turbine function under nominal conditions. For wind speed of 8 m/s, in figure 7a we can observe main as well as transient components: 100 Hz, which exist during the fault, and 480 Hz, 582 Hz which accompany the operation of switching of the fault. The same fault occurring for wind speed equals 11 m/s, shown in figure 7b, generates transient components which frequency concentration shifted to 430 Hz and 540 Hz, respectively. Moreover, the percentage power contribution of the transient components also decrease. For better perception of discovered relations between character of appearing transient components and wind speed we have also group the parameters of detected component in Table 2.

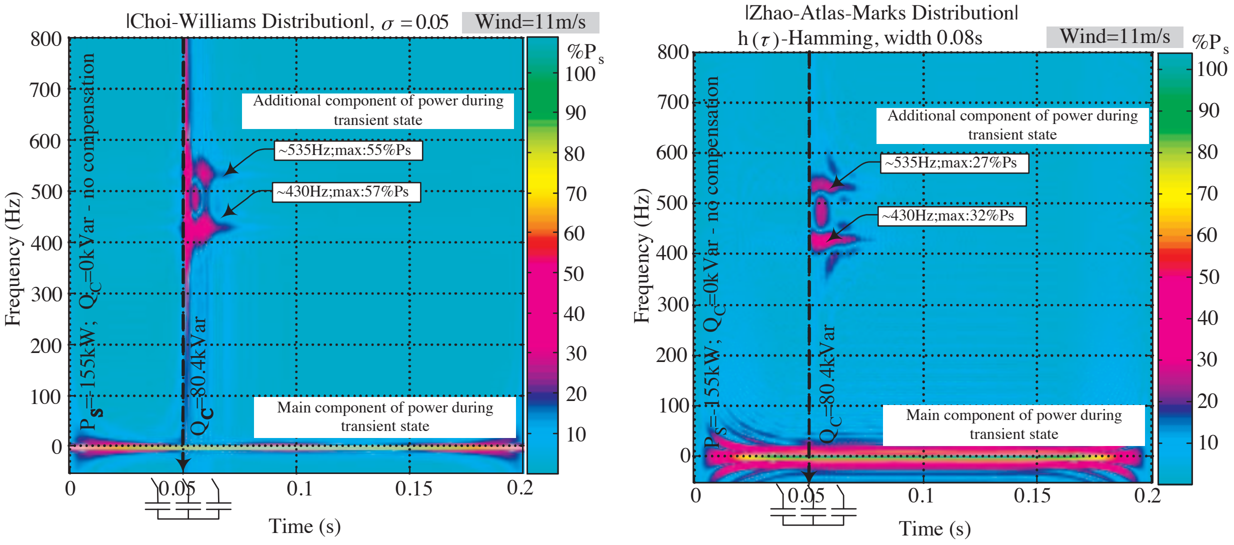

Figure 5. Time-frequency plane of power distortion (P from Figure 3(b)) during switching-on the capacitor banks obtained using CWD: nominal wind speed, 11 m/s.

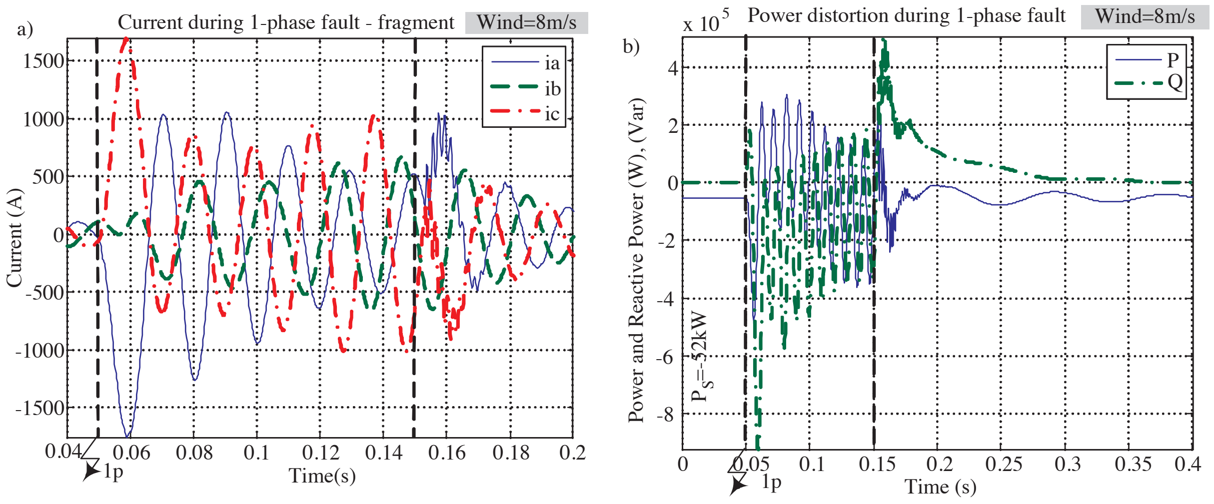

Figure 6. 1-phase fault in phase A for low wind speed. (a) Currents: fragment contained the fault; (b) power distortion.

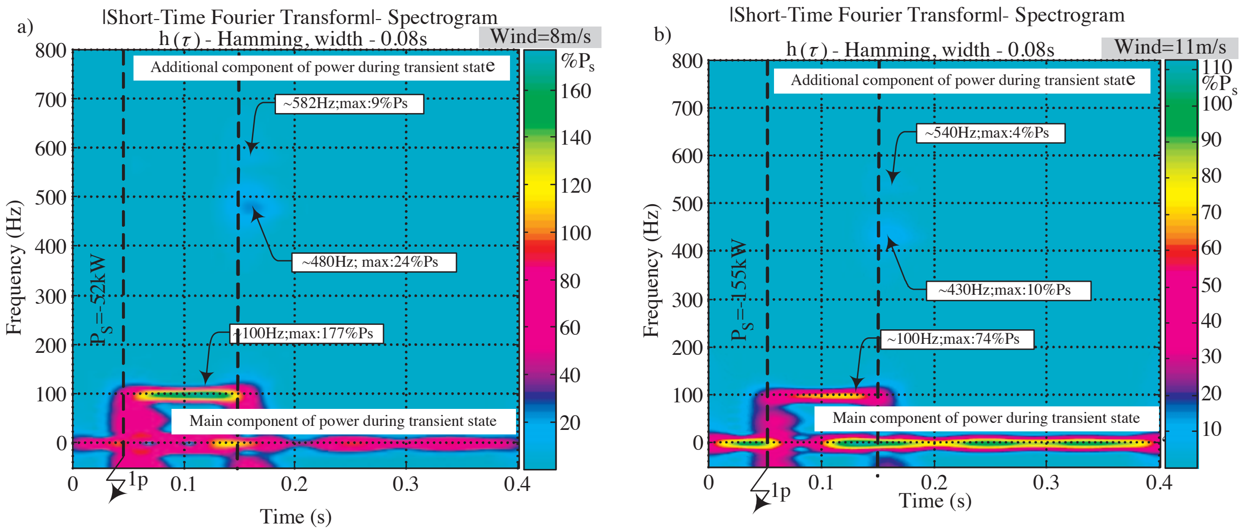

Figure 7. Time-frequency plane of power distortion (P from Figure 6(b)) during 1-phase fault in phase A obtained using STFT: (a) low-speed wind 8 m/s, (b) nominal wind speed 11 m/s.

Table 2. Additional component of power distortion and its contribution in 1-phase fault referring to wind speed

Wind (Power)	Frequency component (instantaneous max. power corresponding to PS)			
8 m/s (PS=-52kW)	f1=100Hz (177%PS)	f2=480Hz (24%PS)	f3=581Hz (9%PS)	⇩
11 m/s (PS=-155kW)	f1=100Hz (74%PS)	f2=430Hz (10%PS)	f3=540Hz (4%PS)	

Additionally, some efforts to apply alternative representations were done in the case of Choi-Williams and Zhao-Atlas-Marks Distributions. Figure 8 shows sharp localization of time-varying components in comparison with STFT. Simultaneously, smoothing effect of applied kernels can be revealed.

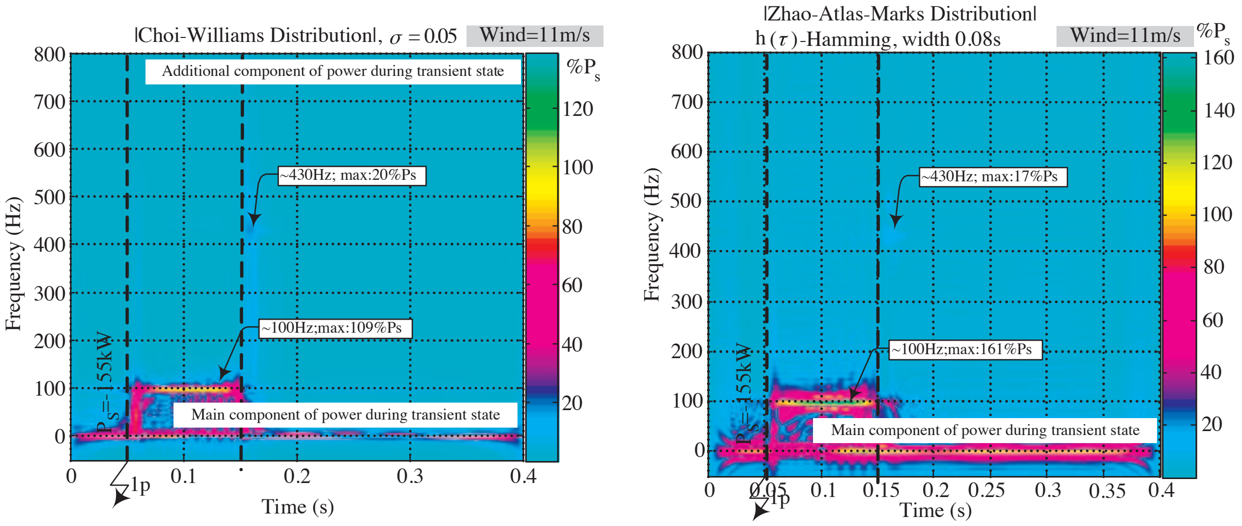

Figure 8. Time-frequency plane of power distortion (P from Figure 6(b)) during 1-phase fault in phase A obtained using CWD and ZAMD: nominal wind speed 11 m/s.

5. Conclusion

Delivered by time-frequency representations two-dimensional view, analyzed transient phenomena brings new possibilities in analysis of power distortion in wind power plants. The present investigation uncovered complex nature of power distortions which occur during transient conditions.

Merged time and local spectrum allows one to find some relations between transient components of power distortion during fault and wind speed. For low-speed, wind transient components are concentrated around higher frequency regions. Moreover, its percentage contribution in power distortion, comparing to generated power in steady state, is higher. Reaction of wind turbine working in nominal conditions to faults occurring on medium voltage level are characterized by transient components which are localized in lower frequency regions. The contribution of transient components in power distortion decreases.

The above investigation indicates time-frequency representations as a appropriate method in analysis of wind turbine work conditions. The work reveals distortion in power transient components when time-frequency analysis was applied. Advantages of the proposed approach is examination of the influence of different kind of faults, wind speed or kind of applied generator on the range of power destabilization.

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