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POWER QUALITY ANALYSIS OF GRID-CONNECTED WIND TURBINE SYSTEM

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, called Choi-Williams Distribution (CWD). 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 concerns power distortion caused by faults in comparison with influence of the wind speed.**

Index Terms— **power system harmonics, signal analysis, time-frequency analysis, electric variables, estimation, wind turbine.**

1. INTRODUCTION

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 [4],[6],[14]: 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

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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 [4],[14].

Selection of proper method for analysis of power distortion in wind turbine system is still actual and crucial. In [20] 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 [3],[15],[16]. Recently some efforts was also made to introduce time-frequency analysis in electrical engineering area [1],[15],[17],[21]. The authors perceive a crucial need for better estimation of distorted electrical signal that can be achieved by applying the time-frequency analysis [2],[12],[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. 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 [19],[20]. 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 [6],[14].

2. PRESENT SIGNAL PROCESSING METHODS IN ELECTRICAL ENGINEERING

Present increase of computational power develops possibilities for application of different signal processing methods dedicated to analysis of transient states in electrical engineering. This section serves as review of classical and alternative algorithm associated with spectrum estimation and so called joint time-frequency analysis.

The most popular spectrum estimation method is well known Fourier algorithm. It represents classical non-parametric approach and already has very useful digital form but unfortunately reveals some drawbacks. The Fourier spectrum is very sensitive to noise or components of non-linear systems that can be observed as contamination in frequency domain. In order to reduce this inherent influence we can calculate the Fourier spectrum of autocorrelation function instead of the signal. Such additional step leads to power spectral density which in many cases is much clearer frequency representation, especially for the signal with noise. In signal processing area there is a few methods which serves as estimation of power spectral density. We can designate here periodogram, modified periodogram with smoothing window, Welsh method or Blackman-Tukey estimation. All mentioned proposition introduce improvements in frequency representation which enhance the resolution and reduce noise contamination. Regardless of chosen approach, all non-parametric methods have common feature which exhibits as strong tradeoff between number

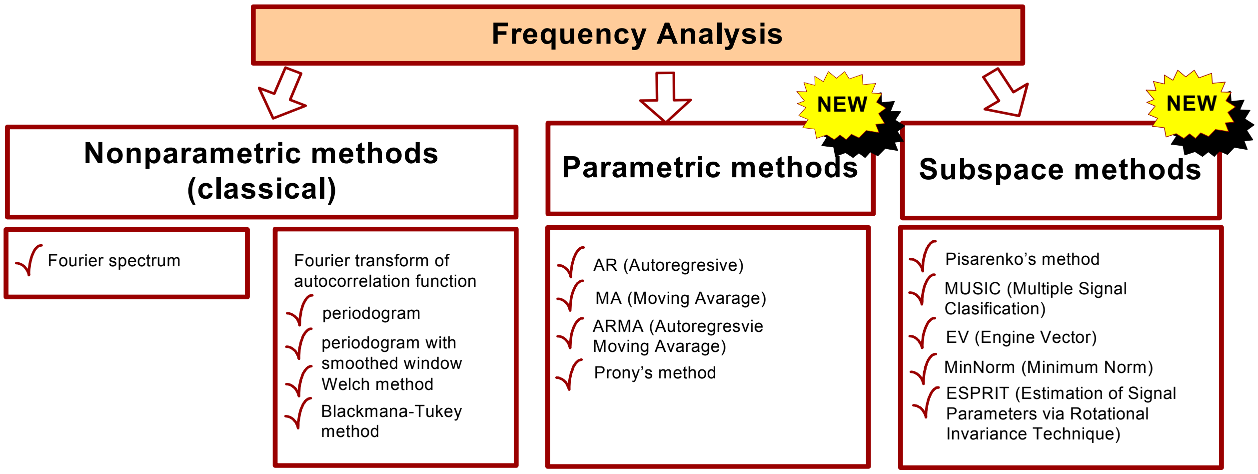


Fig. 1. Simplified division of spectrum estimation methods on account of executive equation

of samples taken into calculation and quality of obtained frequency representation. Alternative to classical approach are novel spectrum estimation methods, which can be grouped in two families: parametric and subspace methods.

Parametric approach is aimed at definition of transfer function of the linear system that would allow to extract from white noise only components approximating investigated signal. Practically, the process of estimation utilizes digital filter with coefficient responsible for selection of desirable components. The estimation criterion is based on minimum squared error between original signal and signal obtained after designed filter. On account of possible structure or searched transmittance we can distinguish three possible approach to model of the system: autoregressive (AR), moving average (MA) and combined autoregressive-moving-average (ARMA) parameter estimation. It is worth emphasizing that selection of above models should be associated with approximated signal. Thus, autoregressive method is dedicated to signals of wide but clearly harmonic spectrum. Continuous spectrum is appropriately represents by moving average process. And finally spectra characterized by continuous component with additional harmonics can be represent by ARMA model. Here reveals itself the crucial difficulties of the parametric methods which is associated with proper selection of the model and its order that have prominent influence on the accuracy of the estimation. In the literature we can find some additional optimization algorithms which serve the selection of minimum order of designed filter. The parametric group of spectrum estimation methods is closed by Prony method, which is aimed at construction of impulse response of the system that would represent investigated signal.

Next group of alternative spectrum estimation method utilizes matrix analysis tools, especially engine value decomposition (EVD) and singular value decomposition (SVD). Generally, mathematical background of the methods is based on relations between calculated engine vectors and subspace of noise and subspace of signal. Mentioned mathematical operation is carried out on special construction of signal or autocorrelation matrixes and leads to selection of characteristic vectors associated with desirable spectrum. Usually these vectors contains minimum or maximum values of engine or singular values. The family of subspace methods is represented by few algorithm: Pisarenko method, multiple signal classification method (MUSIC), engine value (EV), minimum norm (MinNorm) as well as estimation of the signal via rotational invariance technique (ESPRIT).

Mentioned methods have already complex description among others in [11],[18],[22] and can be generally divided in three groups on account of executive equation, Fig. 1.

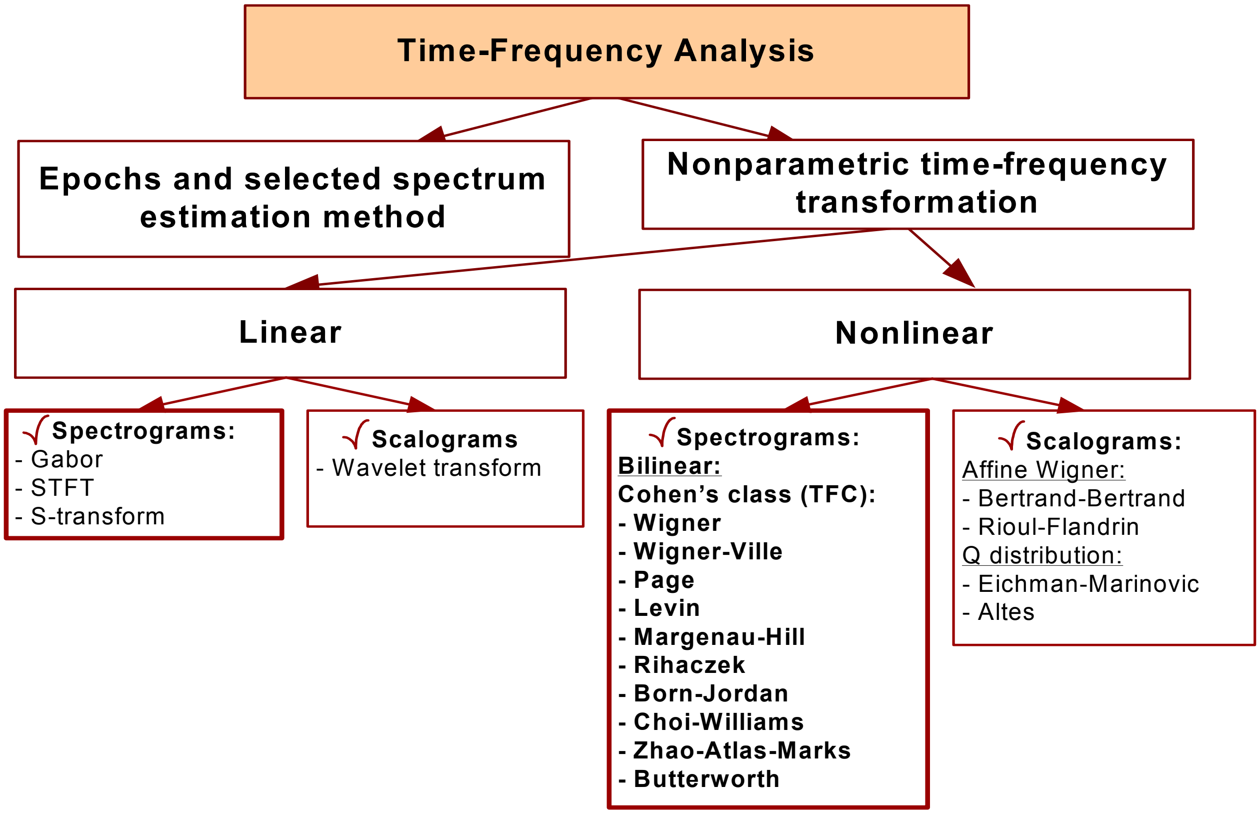


Fig. 2. Simplified division of time-frequency methods on account of main ideas and executive equations

Regardless of the difference between mentioned spectrum estimation methods they have common property – in point of time axis they are averaged representations. It means that transient character of the spectrum components are smeared in time. The crucial need for detection of appearing moment of the transients as well tracking its instantaneous frequencies during the investigated phenomena became major goal of time-frequency analysis. The standard method for study time-varying signals is the short-time Fourier transform (STFT) that is based on the assumption that for a short-time basis signal can be considered as stationary. The spectrogram utilizes a short-time window $h(\tau)$, whose length is chosen so that over the length of the window signal is stationary. Then, 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 [8],[16],[22]:

$$\mathrm{STFT}_x(t,\omega)=\int_{-\infty}^{+\infty} x(\tau)h(\tau-t)e^{-j\omega\tau}\mathrm{d}\tau \qquad (1)$$

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 nonstationarities occurring during this interval will be smeared in time and frequency [10],[15]. 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 [5], Born and Jordan, who provided unique ideas for time-frequency representations, especially reintroduced to signal analysis [8],[9]. Finally in nineteen-eighties Leon Cohen employed 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 introducing kernel function $\phi_{\omega t}(\theta,\tau)$ that is traditionally named Cohen's class [7],[8],[9]:

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

where: t – time, ω – angular frequency, τ – time lag, θ – angular frequency lag, u – additional integral time variable.

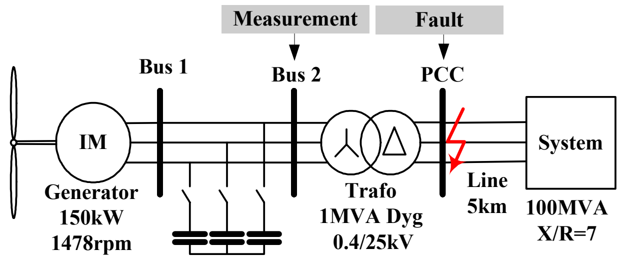
Performing the transformations brings two dimensional planes which represent the changes of frequency component, here called auto-terms (a-t). Unfortunately, bilinear nature of discussed transformations manifests itself in existing of undesirable components, called cross-terms (c-t). Cross-terms are 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 [5],[9]:

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

Beside described above ideas of nonparametric time-frequency analysis we can consider mechanism using sliding window and any spectrum estimation methods. This idea is based on short epochs of the investigated signal, overlapped or separated, and local spectrum associated with particular epoch, which indicate time axis. The mechanism of local spectrum estimation is free and can utilizes described earlier classical or alternative algorithms. Fig. 2 illustrates simplified division of time-frequency methods on account of main ideas and executive equations.

3. MODEL OF THE WIND TURBINE POWER SYSTEM

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 5km 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 realize compensation of absorbed reactive power and are 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 [6],[14],[17],[19]. The simulation was done in Matlab using the SimPowerSystem Toolbox. Fig. 3 illustrates diagram of simulated grid-connected wind turbine system, its characteristic and details in point of the wind condition.



Wind condition	Power P_S	Current I_{as}	Capacitors Q_C
	Steady state before the fault		
weak **8m/s**	-52 kW	106,3A	67.2 kVar
nominal **11m/s**	-155 kW	309,7A	80.4 kVa

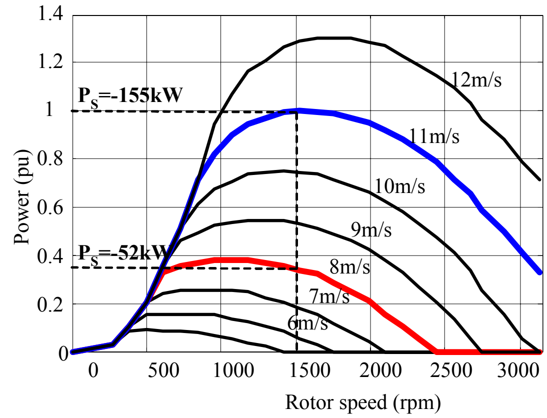


Fig. 3. Diagram of simulated grid-connected wind turbine system, its characteristic and details in point of the wind condition

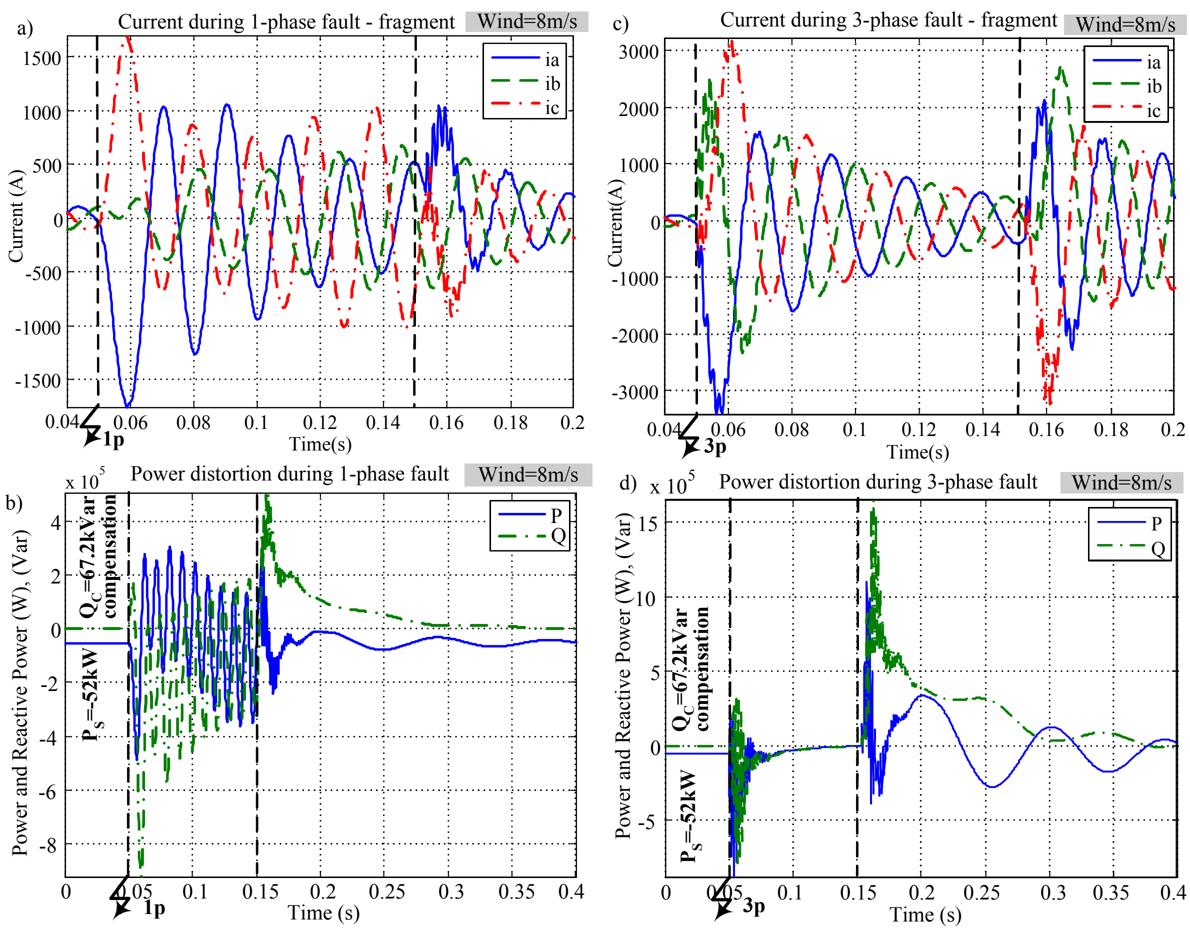


Fig. 4. Currents and power distortions during 1-phase (a),(b) and 3-phase (c),(d) faults for low-speed wind conditions 8m/s

4. SIMULATION AND INVESTIGATION OF THE TRANSIENT STATES

The aim of carried out investigations was to study the distortion of power generated by wind turbine under transient states caused by the faults in point of common coupling (PCC). Fault conditions were modeled as 1-phase and 3-phase faults with ground in point of common coupling with duration time equals 100ms. Simulations of the fault were carried out twice, corresponding to different wind speeds: low-speed 8m/s and nominal speed 11m/s. Coming back to characteristic of the wind turbine, it corresponds to the non-nominal, P_S=-52kW, and nominal, P_S=-155kW, value of generated power. Additionally, in carried out investigations we have assumed that fault appears in steady state with full compensation. Fig. 4 depicts currents and power distortions during 1-phase and 3-phase faults for low-speed wind conditions 8m/s.

In Fig. 5 we can observe time-frequency planes of power distortion caused by 1-phase fault when Short-Time Fourier Transform (STFT) and Choi-Williams distribution (CWD) were applied. Comparing Fig. 5a, corresponding to low-speed wind, with Fig. 5b, representing nominal condition of wind turbine work, we can reveal some influence of wind speed on character of transient components.

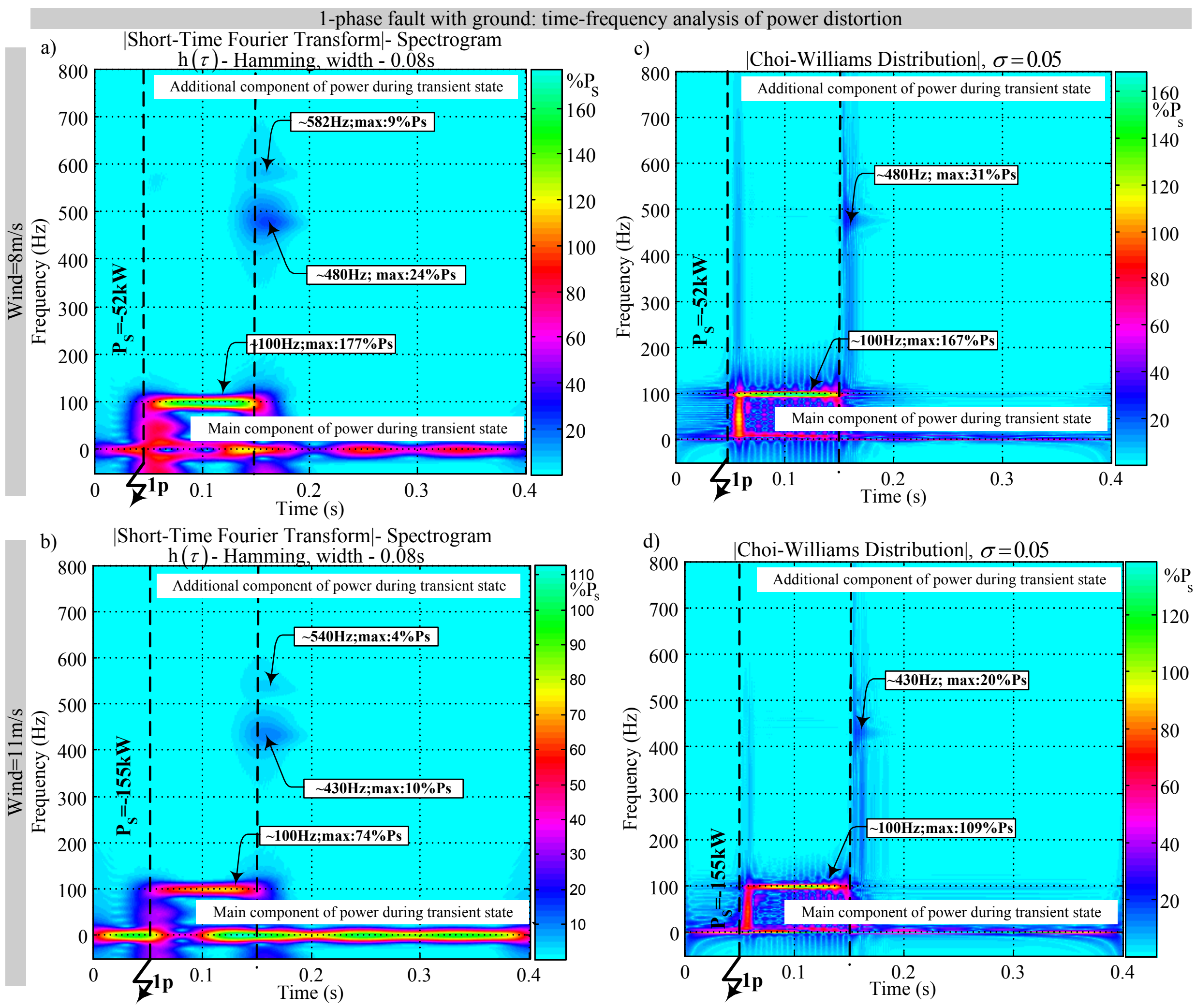


Fig. 5. Time-frequency planes of power distortion *P* during 1-phase fault with ground, for different wind conditions using Short-Time Fourier Transform (a), (b) and Choi-Williams Distribution (c), (d)

Visualization of the phenomena in time-frequency planes allowed to detect drift of the frequency of transient components in direction to smaller frequency value when the wind turbine works in nominal conditions. For wind speed equals 8m/s, Fig. 5a, we can observe main component as well as transient components: 100Hz, which exist during the fault, and higher transients 480Hz, 582Hz which accompany the operation of switching of the fault. For wind speed equals 11m/s, Fig. 5b, the frequency concentration of transient components are shifted to 430Hz and 540Hz, respectively. Moreover, the percentage power contribution of these components decrease. The same conclusions comes after observation of time-frequency planes obtained using CWD, Fig. 5c and 5d. Additionally, we can reveal sharper localization of the transient components when CWD is applied but also some problems of separation of terms localized in near time-frequency regions or contamination by modulated peak value are visible.

Fig. 6 depicts power distortion in case of 3-phase fault with association to week and nominal wind condition. Classical spectrogram STFT delivers the information about two group of transient components. The first one corresponds to beginning of the fault, the second - to switching-off the fault. In case of low-speed wind we can recognize: 502Hz and 590Hz as well as 478Hz, respectively, Fig. 6a.

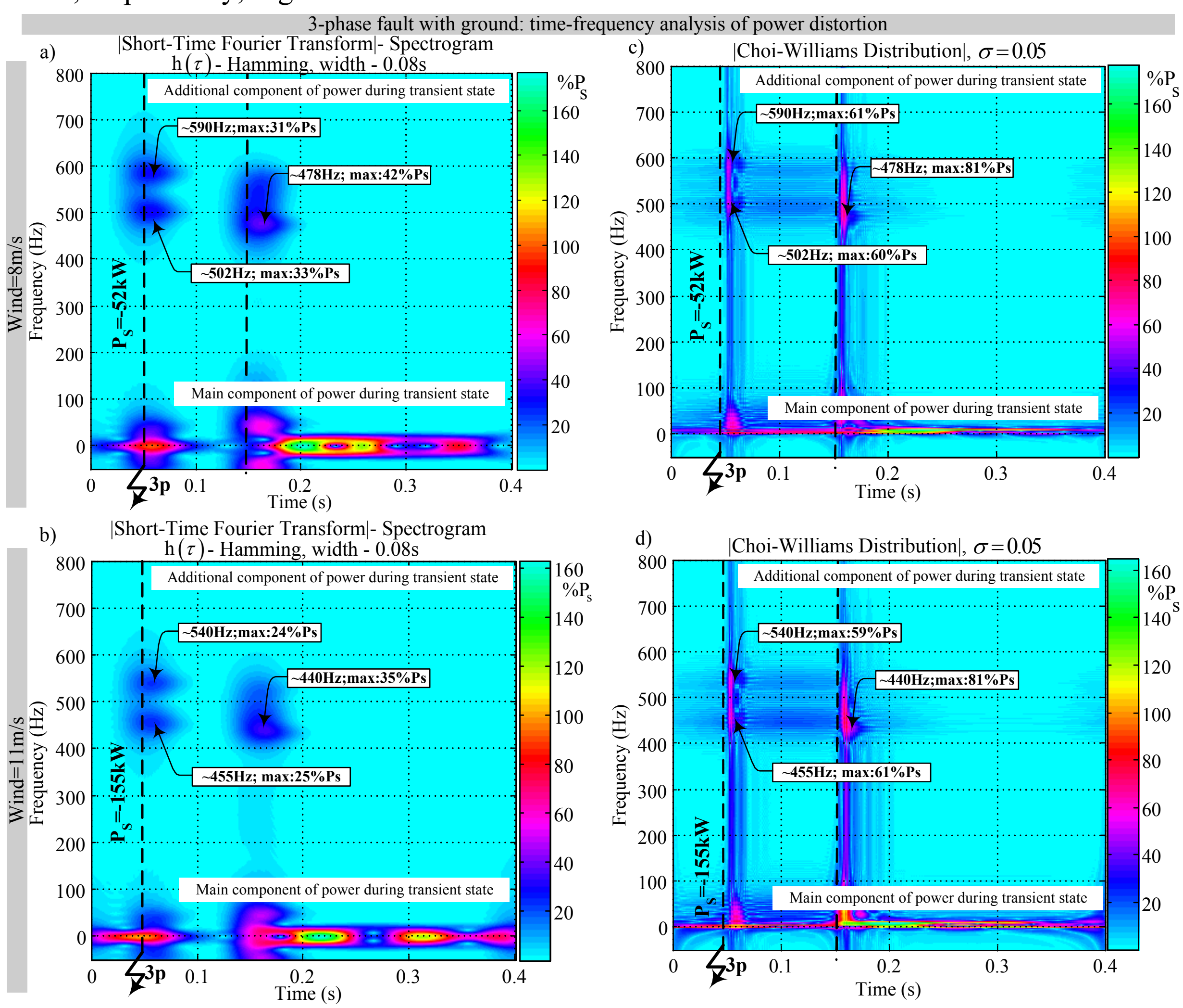


Fig. 6. Time-frequency planes of power distortion *P* during 3-phase fault with ground, for different wind conditions using Short-Time Fourier Transform (a), (b) and Choi-Williams Distribution (c), (d)

All have a transient character and decay very fast on the pattern of overpower peak. For nominal wind speed equals 11 m/s, the character of transient components is preserved but drift effect of frequency localization of transient components and decrees of its percentage contribution in power distortion is visible again. Observing Fig. 6b we can reveal transient components which are localized in 455Hz and 540 as well as 440Hz, respectively. Described drift effect of frequency localization of transient components and decrees of its percentage contribution in power distortion is confirmed by CWD. Again we can reveal sharper localization of the transient components when CWD is applied but also some contamination by modulated peak value are visible.

5. CONCLUSIONS

Carried out investigations using time-frequency methods allowed to uncover complicated nature of power distortions in wind power system which occur during transient states. Joint time-frequency domain delivers comprehensive information about relations between transient components of power distortion 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 are characterized by transient components which are localized in lower frequency regions. The contribution of these components in power distortion decreases.

This paper introduce also some comparison between classical spectrogram and Choi-Williams Distribution with Gaussian kernel. Short-Time Fourier Transform, which is naturally weighted by sliding window, is characterized by smeared localization of instantaneous components. Choi-Williams Distribution represents high-resolution group of transformation. Obtained results confirm sharp detection of transient states but also indicate problem of separation for components localized in near time-frequency regions or modulated by peak value.

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