POWER DISTORTION ISSUES IN WIND TURBINE POWER SYSTEMS UNDER TRANSIENT STATES

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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. Two algorithms were proposed: Short-Time Fourier Transform (STFT) and 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 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.

I. 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 [3,5,16]: 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 [3,16].

Selection of proper method for analysis of power distortion in wind turbine system is still actual and crucial. In [15] 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. 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 [13,15]. 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 [5,16].

II. TWO-DIMENSIONAL ALGORITHMS

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 $\mathrm{h}(\tau)$, 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 [12]:

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

where: t – time, ω – angular frequency, τ – 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 nonstationarities occurring during this interval will be smeared in time and frequency [9,12]. 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 [4], Born and Jordan, who provided unique ideas for time-frequency representations, especially reintroduced to signal analysis [7,8]. 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 that is traditionally named Cohen's class [6,8].

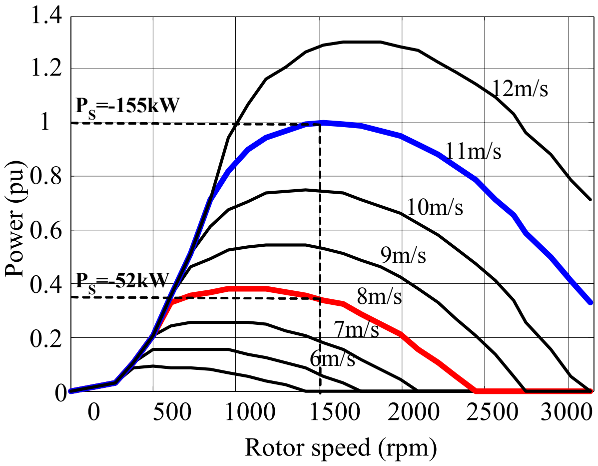

Fig. 1. Characteristic of simulated wind turbine

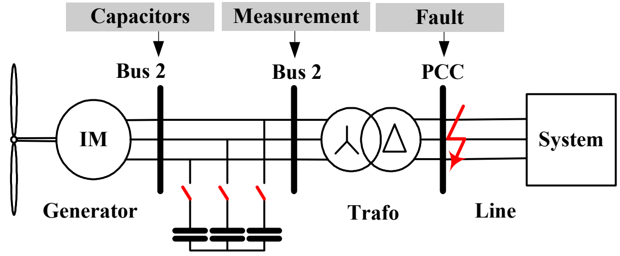

Fig. 2. Diagram of simulated grid-connected wind turbine system

TABLE I
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

Cohen defined a general class of bilinear transformation (TFC) introducing kernel function, $\phi_{\omega t}(\theta,\tau)$ [6,7,8],:

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

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

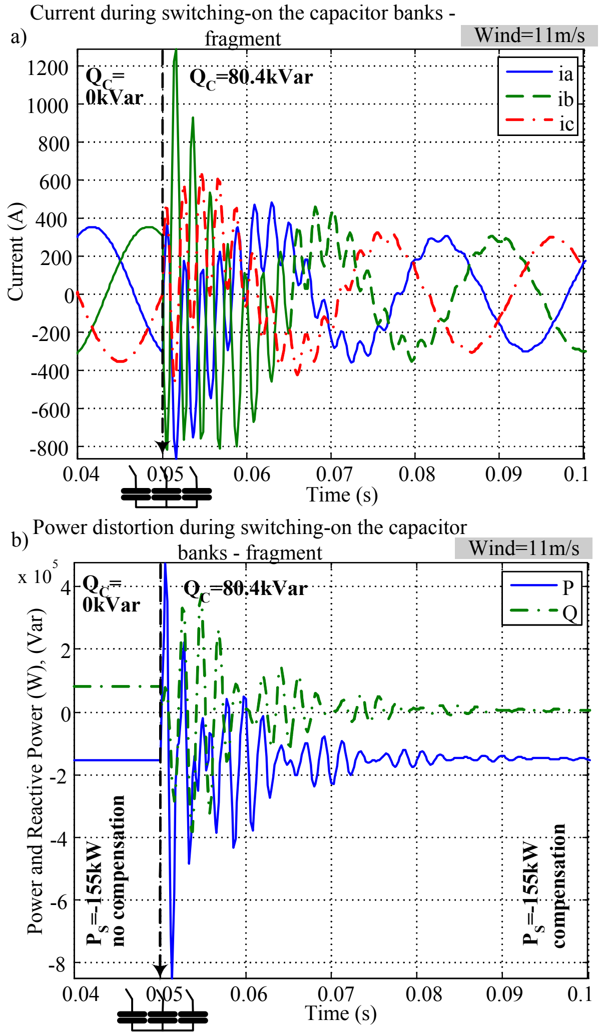

Fig. 3. Switching-on of the capacitor banks for compensation of reactive power, nominal wind speed equals 11m/s : (a) currents (b) power distortion; fragments contained transient states

Gaussian kernel in general Cohen's equation (2) leads to Choi-Williams Distribution (CWD) which brings mentioned smoothing effect [4,8]:

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

The main novel fields of application consist speech processing, seismic, economic and biomedical data analysis [2,11,12]. Recently some efforts was also made to introduce time-frequency analysis in electrical engineering area. The authors perceive a crucial need for better estimation of distorted electrical signal that can be achieved by applying the time-frequency analysis [1,2,11,10].

III. MODEL OF THE SYSTEM

A wind turbine generates power and accordingly a mechanical torque on the rotating shaft, while the electrical machine produce an opposing electromagnetic torque [5]. In steady state operation, the mechanical torque is converted to real electrical power and deliveredto the grid. The power P and torque T generated by the wind turbine is [5,13,16]:

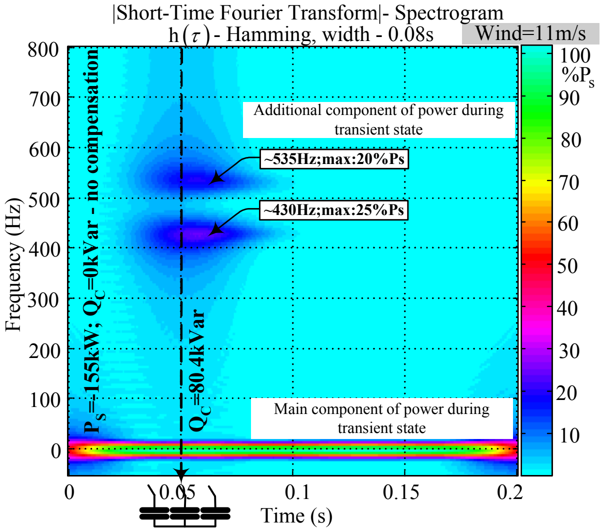

Fig. 4. Time-frequency plane of power distortion (P from Fig. 3b) during switching-on the capacitor banks obtained using STFT: nominal wind speed, 11m/s

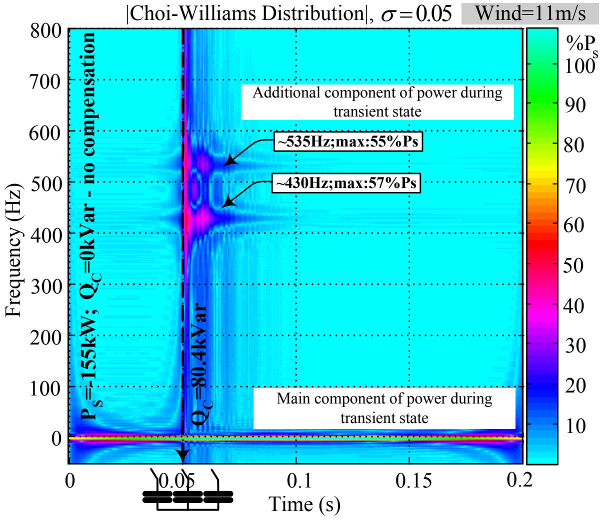

Fig. 5. Time-frequency plane of power distortion (P from Fig. 3b) during switching-on the capacitor banks obtained using CWD: nominal wind speed, 11m/s

$$P=\frac{1}{2}\rho A C_p V^3 \qquad (4)$$

$$T=\frac{P}{\omega_s} \qquad (5)$$

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

At the constant wind speed, the C_p coefficient depends

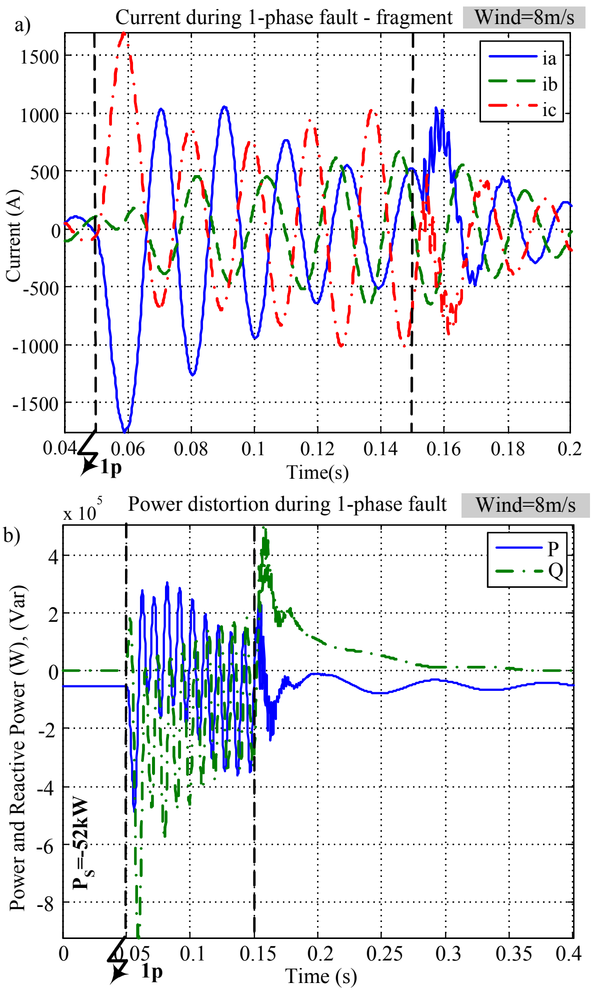

Fig. 6. 1-phase fault in phase A for low speed of wind: (a) currents – fragment contained the fault, (b) power distortion

on the rotor speed ω_s and pitch angle. The pitch control dynamic can be neglected in power system transient analysis [13].

The turbine characteristic used in simulation is shown in Fig. 1. Fig. 2. presents the diagram of simulated wind generator system. The 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 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 realizes compensation of absorbed reactive power and are directly connected.

IV. INVESTIGATIONS

The aim of carried out investigations is to study the distortion of power generated by wind turbine under transient states caused by switching-on capacitor banks and faults. In case of switching-on capacitor banks

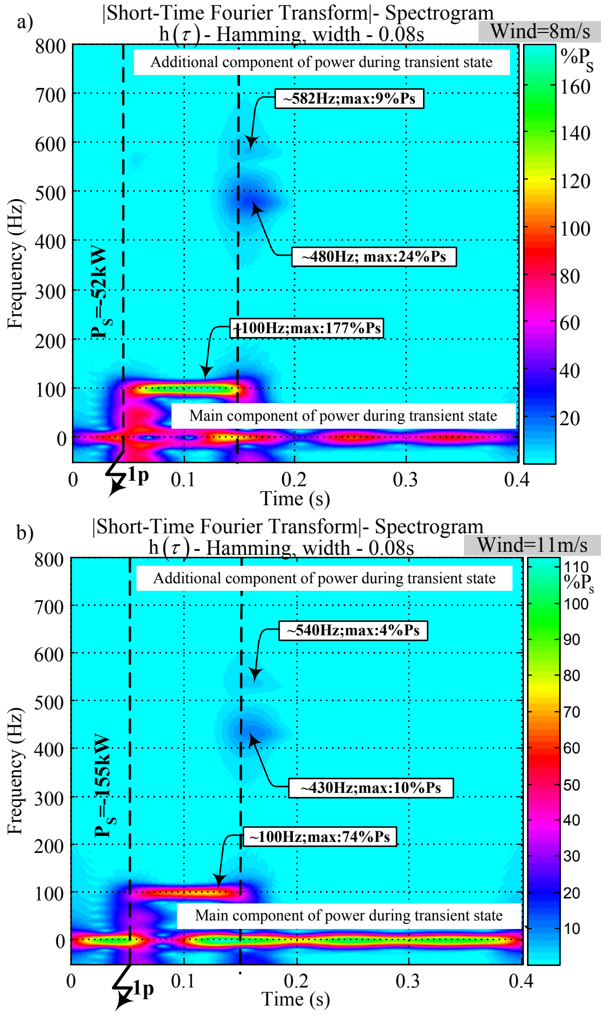

Fig. 7. Time-frequency plane of power distortion (P from Fig. 6b)during 1-phase fault in phase A obtained using STFT: (a) low-speed wind 8m/s, (b) nominal wind speed 11m/s

we have concerned phenomena includes transition from not compensated to full-compensated state of work for fixed, nominal wind speed, equals 11m/s. Fault conditions was modeled as 1-phase fault with ground point of common coupling. Simulations of the fault were carried out twice, corresponding to two different wind speeds: low-speed 8m/s and nominal speed 11m/s. Coming back to characteristic of the wind turbine, presented in Fig. 1, 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. Table I provides details about power conditions of investigated wind turbine in steady state as well as values of capacitors, according to selected wind speed.

SWITCHING-ON THE CAPACITOR BANKS

One of the investigated phenomena concerns switching-on the capacitor banks for compensation of reactive power. Fig. 3. presents currents as well as active and reactive power under transition from not-compensated to compensated state. Analysis of power distortion using

Short Time Fourier Transform and Choi-Williams Distribution delivered information about components of power distortion as well about its duration time. Observing Figs. 4 and 5 we can reveal two transient components 535H and 430Hz, which affects generated power for about 0.04s. Additionally, some advantages of Choi-Williams distribution can be underline in point of sharp localization of transient components. In Fig. 4 we can observe smearing effect, characteristic for sliding window in STFT method. Fig. 5, confirms sharp detection of transient states when CWD was applied but also indicate problem of separation for components localized in near time-frequency regions or modulated by peak value.

1-PHASE FAULT

Second of the investigated cases concerns 1-phase fault in point of common coupling. The duration time of the fault was 100ms. Fig. 6. presents an example of current as well as power behavior under transient condition for low speed of the wind equals 8m/s. Simultaneous simulations was carried out for nominal wind speed equals 11m/s. Then, obtained 3-phase power distortion P in both cases were investigated using time-frequency methods. In Fig. 7 we can observe the effects of analysis when Short-Time Fourier Transform were applied. Comparing Fig. 7a, corresponded to low-speed wind, with Fig. 7b, represented nominal condition of wind turbine work, we can reveal some influence of wind speed on character of transient states. Carried out time-frequency analysis allowed to detect visible drift of the frequency of transient components in direction of smaller frequency value, when the wind turbine works in nominal conditions. For wind speed equals 8m/s, Fig. 7a, we can observe main component as well as transient components: 100Hz, which exist during the fault, and 480Hz, 582Hz which accompany the operation of switching of the fault. The same fault occurring for wind speed equals 11m/s, Fig. 7b, generates transient components which frequency concentration is shifted to 430Hz and 540Hz, respectively. Moreover, the percentage power contribution of the transient components also decrease.

V. CONCLUSION

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

Merged time and local spectrum in one allowed to find out some relations between transient components of power distortion occurring 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.

Carried out investigations indicate time-frequency representations as a appropriate method in analysis of wind turbine work conditions. The contribution of the paper includes new findings in reviling transient components of power distortion when time-frequency analysis were applied. Advantages of proposed approach manifests itself when the influence of different kind of faults, wind speed or kind of applied generator on range of power destabilization would be explored.

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