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Research on a power quality monitoring technique for individual wind turbines

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ABSTRACT

The extensive deployment of megawatt-scale wind turbines is bringing more challenges to the safety and stability of electric grid than ever before. This is not only because of the unstable wind over time but the increased risk of power quality pollution by defective wind turbines particularly when the turbines today are still experiencing various reliability issues. To prevent the power quality pollution by defective turbines, a new power quality monitoring technique dedicated for individual wind turbines is developed in this paper, so that the quality of the power generated by an individual turbine can be monitored by the wind turbine condition monitoring system. Through simulated and physical experiments on a specially designed test rig, some encouraging results have been achieved. It has been shown that the proposed technique is not only valid for monitoring the power quality of an individual wind turbine, but helpful in detecting the mechanical and electrical faults occurring in the wind turbines.

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1. Introduction

Despite the current economic recession, the wind industry continues growing worldwide. According to the recent survey made by the Global Wind Energy Council (GWEC), the total global installed wind capacity has reached 318 GW at the end of 2013 versus 283 GW at the end of 2012 and 238 GW at the end of 2011 [1]. This means that a massive number of wind turbines (WTs) are being newly deployed, which will challenge the safety and stability of the electric grid more than ever before for the following reasons:

- wind is unstable over time, which will lead to the instability of the grid;
- the increased capacity of individual WTs lowers the unit installation cost, while requests stronger grids to accommodate them. Many of existing grids do not have this capability before upgrading;
- the WTs today are still suffering various reliability issues. The more operational WTs, the more difficult the grid management will tend to be. For example, the poor quality power generated by defective WTs is harmful not only to the grid itself but to the grid-connected facilities (e.g. equipment at substation) and can even damage them in worse case.

Accordingly, how to assure the WTs to produce premium quality power and minimize the risk of power quality pollution by defective WTs shares the equal importance as WT condition monitoring (CM) [2–6]. Today, various WT condition monitoring systems (CMSs) are available in commercial market [7], however none of them is applicable to WT power quality monitoring. This is because the previous interest of WT CM is primarily concentrated on detecting fault early and prolonging the residual life of defective components [8–11]. They were not designed to check whether the power quality generated by the WT is good enough to match the grid code.

Power quality monitoring has attracted increasing interest over the past years due to the increased use of equipment that is sensitive to power system disturbances and the widespread application of non-linearly behaving power electronic converters. Nowadays, the extensive application of WTs further highlights its importance due to the usual poor quality of wind power. In accordance with the standard IEC 61400-21 [12], the power quality of a grid-connected WT should be tested when certificating the WT. In practice, a double check of power quality will often be conducted when commissioning the turbine. However, this cannot guarantee that the WT can always produce premium quality power in the whole service time. For the sake of safety, in practice power quality will be checked regularly at wind farm substation. Such a measure is helpful however cannot completely prevent the power quality pollution by individual defective WTs. A potential solution is to monitor the power quality at individual

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WT and disconnect the turbine from the grid once it is found generating poor quality power. To reach such a purpose, every WT in the wind farm should be equipped with a power quality monitoring system. However, this is too expensive to the operator. Hence, to integrate power quality monitoring into the existing WT CMS might be a more cost-effective solution. In recent years, lots of researches have been done in the field of power quality monitoring. For example, a hidden Markov model was developed to classify power quality disturbances in Ref. [13]; a specific filter-based power quality characterization technique was researched in Ref. [14]; wavelet transform-based power quality monitoring techniques were developed in Refs. [15,16]; the S-transform based monitoring techniques were investigated in Refs. [17,18]; the independent component analysis based technique was considered in Ref. [19]; Support Vector Machine (SVM)-based and genetic algorithm-based techniques were studied respectively in Refs. [20,21], and so on. More comprehensive overview of relevant achievements are given in Refs. [22,23]. However, none of these techniques can be integrated into the online WT CMS due to their complex calculations. In addition, these techniques were designed purely for the purpose of power quality monitoring. They are not designed for executing WT CM tasks. Thus, how to promote the existing WT CM technology and enable them to conduct power quality monitoring has become one of the urgent issues need to resolve today, particularly at the eve of the massive deployment of WTs in the following years. The research reported in this paper is just in order to meet such a requirement.

As mentioned in the IEC standard, the power quality assessment of a WT is accomplished through analysing the electrical signals (i.e. voltage and current) measured from the terminals of WT generator [12]. It is proved that these electrical signals are applicable to WT CM as well [24–27]. Thus, in principle an integrated power quality and WT health monitoring technique can be achieved based on the analysis of WT electrical signals. The work presented in this paper is to demonstrate the feasibility of such a proposal with the aid of some advanced signal processing techniques, such as Fast Individual Harmonic Extraction (FIHE) [28].

2. Theory

2.1. Favoured signals for both power quality and WT health monitoring

Before developing the desired technique, it is essential to identify the CM signals that are ideal for conducting both power quality monitoring and WT health monitoring tasks. In principle, they should be.

- readily accessible in all concepts of WTs, either geared or direct-drive; and
- applicable to both power quality monitoring and WT health monitoring.

Apparently, the electrical signals measured from the terminals of WT generator can meet better both requirements than the vibration and other non-destructive testing signals that are popularly adopted in WT CM. For facilitating understanding, a few WT concepts are depicted in Fig. 1, where SCIG means squirrel cage induction generator; WRIG wound rotor induction generator; PMSG permanent magnet synchronous generator; and WRSG wound rotor synchronous generator. Different concepts of WTs have different hardware configurations therefore different weights, costs, control strategies, and reliability properties [29,30]. But the electrical current, voltage and power signals of all of them are accessible. Moreover, it has been proved that:

- The mechanical faults occurring in the WT drive train are detectable via analysing the generator electrical signals [25,27,31];
- The WT electrical faults are also detectable through analysing the generator electrical signals [32];
- Electrical signals are the unique information used for power quality assessment [12].

Therefore, the electrical signals measured from the WT generator are the most ideal signals for realizing the integrated power quality monitoring and WT health monitoring technique.

2.2. Fast individual harmonic extraction

The FIHE is an individual harmonic extraction technique specially designed for analysing the harmonics in three-phase electrical signals. It has been proved that in contrast to the traditional harmonic extraction techniques in frequency domain, the FIHE has an excellent dynamic response and provides overshoot- and ripple-free characteristics [28]. Assume the line current signals measured at WT generator terminals are $I_1(t)$, $I_2(t)$ and $I_3(t)$, the FIHE is:

$$\boldsymbol{\Psi}(t) = \frac{2}{3}\boldsymbol{\Gamma}(t)\mathbf{I}(t) \tag{1}$$

where

$$\boldsymbol{\Psi}(t) = \begin{bmatrix} I_\mathrm{d}(t) \\ I_\mathrm{q}(t) \\ I_0(t) \end{bmatrix} \tag{2}$$

$$\mathbf{I}(t) = \begin{bmatrix} I_1(t) \\ I_2(t) \\ I_3(t) \end{bmatrix} \tag{3}$$

$$\boldsymbol{\Gamma}(t) = \begin{bmatrix} \sin(\omega t) & \sin\left(\omega t - \frac{2m\pi}{3}\right) & \sin\left(\omega t + \frac{2m\pi}{3}\right) \\ \cos(\omega t) & \cos\left(\omega t - \frac{2m\pi}{3}\right) & \cos\left(\omega t + \frac{2m\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4}$$

and

$$m = \frac{\omega}{\omega'} \tag{5}$$

where ω denotes the frequency of interest; ω' the fundamental frequency of the signal.

For those balanced line current signals.

$$\mathbf{I}(t) = \begin{bmatrix} I_1(t) \\ I_2(t) \\ I_3(t) \end{bmatrix} = \begin{bmatrix} A\sin(\omega' t) \\ A\sin\left(\omega' t - \frac{2}{3}\pi\right) \\ A\sin\left(\omega' t + \frac{2}{3}\pi\right) \end{bmatrix} \tag{6}$$

has

$$I_\mathrm{d}(t) = \frac{A}{3}\left\{\left[1 + 2\cos\left(\frac{2}{3}\left(m-1\right)\pi\right)\right]\cos((\omega' - \omega)t) - \left[1 + 2\cos\left(\frac{2}{3}\left(m+1\right)\pi\right)\right]\cos((\omega' + \omega)t)\right\} \tag{7}$$

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