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Probabilistic power quality indices for electric grids with increased penetration level of wind power generation

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ABSTRACT

In future electric grids it is expected that the share of power produced by renewable energy systems will increase to supply large deficits in power demand. Wind energy is one of the most important sources of renewable energy generation systems. With increased penetration level of wind energy conversion systems in modern electric grid, the quality of power will inevitably be affected. Power quality (PQ) indices are used to quantify the quality of the power. They serve as the basis for comparing negative impacts of different disturbances on power networks. Previous research of PQ indices with electric grids including wind energy sources was mainly based on fixed wind speed. Therefore, the PQ indices were calculated as instantaneous values that do not reflect the overall power quality impact of the grid connected wind energy systems. The main objective of this paper is to propose new probabilistic PQ indices for electric grids including wind energy systems. The proposed PQ indices combine both the probabilistic nature of wind speed using discrete Markov analysis and the electric grid behavior. The main PQ indices proposed are those concerning harmonics, flicker, and voltage sag. The developed indices are suitable for electric grids that include high penetration level of wind based power sources. The method used is general and can be applied to other power quality indices or power system performance indices.

Introduction

With the increased consumption of electricity, present fossil fuel based power stations are unable to supply the increased demand, which leads to increased electricity interruptions and possible blackouts. Therefore, the expected solution is to build new power stations to cover the deficit in the demand; however, due to lack of fossil fuel needed to run these stations, other alternative sources should be used based on renewable energy sources such as wind energy. Renewable energy based wind power generation systems are not fully controllable due to the stochastic nature of their prime source. This will introduce additional uncertainties into the daily operation and long-term planning of the electric system with increased penetration level of wind power generation systems [1]. Power and voltage generated by a wind turbine are more variable than that produced by conventional generators. Therefore, with the increased penetration level of wind energy systems in the electric grid, it is very important to determine the effect of voltage fluctuations caused by the connection of wind energy systems to the electric grid and other power quality aspects, using proper Power Quality (PQ) indices. With the introduction of the concept of "*Smart Grid*", PQ indices are used to quantify the quality of the power supply, serving as the basis for comparing negative impacts of different disturbances on smart electric power grids. This will enable the smart grid to achieve the desired performance with high reliability and power quality to host a wide range of wind energy systems [2].

In literature, there were many research papers that discussed the different PQ indices and their calculation methods in conventional electric grids, such as papers [3–5]. In [3], time–frequency based PQ indices are proposed for the non-stationary PQ disturbances. Those indices allow one to quantify the effects of transient disturbances with high-resolution and accuracy using wavelet analysis. In [4], new PQ indices was introduced, this indices described nonlinear harmonic loads which was directly related to the generation of distortion power. In [5], a new approach called "integrated approach" is introduced for PQ analysis that addressed several major problems, with the results showing that the proposed structure can yield an automatic online/offline monitoring of PQ with sparser structures and less computational execution time.

Other papers focused on the PQ indices calculations in case of wind energy presence in electric grids, such as papers [6,7]. In [6], the authors dealt with future standards and regulatory requirements for measuring and testing wind energy systems power quality effects. Special attention was given to harmonics and

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inter-harmonics, voltage dips and short supply interruptions, voltage unbalance, power frequency variations and voltage fluctuations or flicker calculations according to new recommendations for grid connected wind energy systems. In [7], different configurations of wind turbines were discussed with respect to power quality and the requirements regarding wind turbine modelling for power quality analysis. A model of a stall-regulated, fixed-speed and variable-speed wind turbine system were introduced and its power quality impact on the electric grid was evaluated. The previously discussed research papers [3–7] can be described as traditional approach to power quality studies which was based on deterministic analysis. A deterministic analysis does not provide a realistic evaluation of system steady-state performance. A more realistic evaluation can be achieved through a probabilistic analysis that takes into account the stochastic behavior of wind power generation and power quality analysis.

Probabilistic analysis of power quality was the focus of some research papers, such as [1,8]. In [1], the stochastic wind power model is introduced on the basis of an autoregressive integrated moving average (ARIMA) process. Such model is suitable for researchers who do not have access to wind power measurements. In [8], a probabilistic approach for harmonic analysis of a multi-convertor power system which could include converter based wind energy systems, was introduced using the Point Estimate Method (PEM) to account for the uncertainties affecting the steady state operating conditions.

To study the stochastic behavior of wind, it is important to specify the types of probabilistic analysis. In literature, there are two main types of wind speed/wind power models developed, namely ARMA models presented in papers such as [9], and [10], and Markov models presented in papers such as [11–13]. In [9], an autoregressive (AR) model was applied to a transformed wind speed time series; while in [10], an autoregressive integrated moving average (ARMA) model was directly applied. The discrete Markov model is mainly based on a transition matrix as described in [11,13]. The birth-and-death Markov model developed in [12] was a simplified Markov model, as it considered only transition rates among two adjacent states. Although an ARMA model usually requires fewer parameters than the Markov model, an ARMA model cannot guarantee a good fit in probability distribution [13].

In this paper, a discrete Markov approach is used to model the intermittent wind speed. In the proposed model, the wind speed time variability is taken into account by means of wind speed classification in a discrete reduced number of contiguous classes, each corresponding to an opportune range of values, starting from field measurement data. The main contribution of this paper is introducing probabilistic power quality indices that are based on probabilistic factors calculated from discrete Markov analysis, and power quality analysis.

Problem formulation

This section has two subsections, first section represents the power quality analysis, and second section represents the mathematical formulation of Markov analysis.

A. Power quality

Perfect power quality means that the voltage is continuous and sinusoidal having a constant amplitude and frequency. Power quality can be expressed in terms of physical characteristics and properties of electricity. It is most often described in terms of voltage, frequency and interruption. The quality of the voltage must fulfill requirements stipulated in national and international standards. In these standards, voltage disturbances are subdivided into voltage variations, flicker, transients and harmonics' disturbances [14].

Harmonics

Harmonics have always been presented in power systems. Recently, the wide spread use of power electronic components resulting in an increase in harmonic magnitude, it becomes a key issue in installations. The fluctuating nature of the wind energy conversion system (WECS) is expected to inject both voltage and current harmonics into power systems. This harmonic injection is obvious to increase by increasing the wind penetration in the system. However, the grid has to make sure that the injected harmonics doesn't exceed the permitted level [6,15].

The distorted waveform may be expressed as a sum of sinusoids with various frequencies and amplitudes, by application of the Fourier transform. The sinusoids with frequencies equal to an integer multiple of the fundamental frequency are denoted harmonics, whereas the others are denoted inter harmonics [16,17].

Harmonic voltages, U_h, where h denotes the harmonic order (i.e. an integer multiple of 50 Hz) can be evaluated individually by their relative amplitude as shown:

$$U_h = \frac{V_h}{V_n} \tag{1}$$

While harmonic current, I_h can be evaluated individually by their relative amplitude as shown:

$$I_h = \frac{I_h}{I_n} \tag{2}$$

Further, the total harmonic distortion (THD) of the voltage, is calculated according to Eq. (3), has to be less or equal 8%:

$$THD_v = \left[\sum_{h=2}^{40} (U_h)^2\right]^{1/2} \tag{3}$$

However, the current total harmonic distortion is calculated according to Eq. (4), has to be less or equal 6%:

$$THD_i = \left[\sum_{h=2}^{40} (I_h)^2\right]^{1/2} \tag{4}$$

The connection of electric equipment does change the harmonic impedance of the network; for example, capacitor banks, which are often installed as part of wind farms consisting of fixed-speed wind turbines, may shift the resonance frequency of the harmonic impedance. Hence, possible harmonic sources already present in the network may, then, given unfortunate conditions, cause unacceptable harmonic voltages. Consequently, for networks with significant harmonic sources, the connection of new appliances such as wind farms with capacitor banks should be carefully designed in order to avoid an ill conditioned modification of the harmonic impedance.

Voltage sag

The monitoring of sags is critical to ensuring optimal performance of power systems. Monitoring can be used as a vital diagnostic tool, identifying problem conditions on a power system before they can cause disturbances or interruptions. A successful power quality monitoring program requires flexibility, powerful data processing, value adding reports, and easy access to information [18].

For sags, indices of interest include:

- Sag Score
- Sag Energy

Typically, once sag is detected, the RMS method is used to determine the sag magnitude and duration. For advanced