Electrical Power and Energy Systems 67 (2015) 52–65

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Harmonics and inter harmonics estimation of DFIG based standalone wind power system by parametric techniques

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ARTICLE INFO

Article history:
Received 3 February 2014
Received in revised form 13 October 2014
Accepted 15 November 2014
Available online 5 December 2014

Keywords:
Doubly fed induction generator (DFIG)
Harmonics
Inter-harmonics
Sliding window ESPRIT
Sliding window Root MUSIC

ABSTRACT

This paper presents application of parametric techniques (Estimation of signal parameter by rotational invariance techniques (ESPRIT), Root multiple signal classification (Root MUSIC)) for the estimation of harmonics/inter harmonics produced by wind generator under constant, variable rotor speed, load imbalance. Accuracy of estimation by parametric techniques is checked on synthetic signal as well as signal extracted from DFIG based standalone system with constant rotor speed and balanced load condition. Further sliding window concept is applied to parametric techniques to estimate the harmonics/inter harmonics under variable rotor speed and load unbalance. Series of simulation results demonstrate the advantages of the sliding window ESPRIT over sliding window Root MUSIC in the estimation of harmonics and inter harmonics under variable rotor speed as well as load unbalance condition.

Introduction

In DFIG based wind power system, rotor side converter injects the current of appropriate frequency to maintain the stator current frequency at fundamental frequency. Injected rotor current frequency depends upon the DFIG rotor speed. Rotor Side converter is based on semi-conductor power electronics devices thus it also injects harmonics into the stator. These injected harmonics are translated into the inter-harmonics and appear in the stator current which is closely spaced and difficult to estimate accurately. These inter-harmonics component frequencies vary with the rotor speed. As the matter of fact accurate estimation of inter harmonics is essential in order to avoid undesirable conditions like resonance, control malfunction, protection equipment failure of nearby equipment's etc.

Various techniques [1,2] are available for harmonics and inter-harmonics estimation. IEC Standard 61000-4-7 [3] has been developed using Fast Fourier Transform (FFT) and grouping methodology to estimate harmonics and inter-harmonics estimation of stationary signal. Short time Fourier Transform (STFT) [2] having the fixed narrow window is also employed for estimation of harmonics and inter harmonics. Discrete Wavelet Transform (DWT) [4] is a technique which gives spectrum in the terms of frequency bands has been also used for estimation of harmonics and inter-harmonics. Artificial intelligence [5,6], and Kalman filters [7,8] have been formulated for the harmonics estimation where the prior knowledge of harmonics frequency available. Prony [9] is used for estimation of power system harmonics [10,11].

These techniques have some short comings. FFT [3] suffers from many disadvantages like poor spectral resolution, highly sensitive to power system frequency variations, noise and require a minimum number of samples. Grouping methodology employed in [3] cannot estimate exact inter harmonic frequency component present in the signal. STFT also suffers from leakage and piketfence effect which leads poor frequency resolution. DWT requires additional tool for extracting frequency from these bands. It only suits for off line measurement and not suitable for instantaneous frequency estimation. Its accuracy is highly dependent upon the mother wavelet and resolution levels. Artificial intelligence accuracy is highly depends upon knowledge of harmonics and inter harmonics frequency. Kalman filter suffers from poor accuracy when an unknown frequency component appears in the signal and also improper choice of covariance matrix may lead to divergence of filter. Prony is parametric technique and have a high frequency resolution however its estimation accuracy of is highly dependent upon the noise content in the signal.

MUSIC [12], ESPRIT [13], are the some of the available parametric techniques which are capable of estimation of closely spaced frequency components its accuracy does not depend upon the number of samples and the knowledge of fundamental frequency but the application of these techniques are limited to estimation of the frequency of steady state signal which frequency and

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http://dx.doi.org/10.1016/j.ijepes.2014.11.014
0142-0615/

magnitude is constant. Leonowic [21] has applied ESPRIT for harmonics detection wind power plant in under steady state condition. In DFIG based power plant, inter harmonics are closely spaced and its frequency varies with rotor speed. Fundamental frequency DFIG is nearly constant but small changes is also resulted due to rotor speed variation. Above discussed techniques either suffers from poor spectral resolution or require pre knowledge of fundamental or inter-harmonics frequency thus these techniques are not suited for harmonics and inter-harmonics estimation. Sliding window ESPRIT [14] is used to estimate the inter harmonics of time varying signal which gives efficient results in harmonics and inter harmonics estimation of non-stationary signal but it needs filtering of fundamental component from the signal thus it cannot be used in real time estimation and require pre knowledge of fundamental frequency component.

The Motivation for this research is to exploit ESPRIT and Root MUSIC along with sliding window to estimate accurate instantaneous frequency of harmonics and inter harmonics along with fundamental frequency component of the DFIG based power plant under variable conditions like unbalance load, variable rotor speed and change in stiffness of drive train mechanism.

The present paper is organized as follows. In Section 'Harmonics generation in stator of DFIG', origin of harmonics and inter harmonics component in DFIG is explained. Basic principle of harmonics estimation by ESPRIT and Root MUSIC with mathematical formulation is explained in Sections 'Root multiple signal classification (Root MUSIC)' and 'Estimation of signal parameters via rotational invariance technique (ESPRIT)' respectively. Sliding window Root MUSIC and sliding window ESPRIT concept explained in Section 'Sliding window esprit and sliding window ROOT' MUSIC. Section 'Model of standalone DFIG' gives the description about the DFIG and two mass of drive train model taken for signal generation. Simulation results and discussion on the performance of estimation methods are presented in Section 'Simulation results and discussions'. Finally conclusions are drawn in Section 'Conclusion'.

Harmonics generation in stator of DFIG

In standalone DFIG, harmonics and inter harmonics are generated in stator due to mechanical design of induction machine and rotor side converter (RSC). MMF space harmonics and slot harmonics are generated due to the mechanical design of stator, rotor windings and slots. Harmonics of injected rotor voltage is also appears in the stator in modulated form. Harmonics/inter harmonics frequency of these harmonics are dependent upon the rotor speed. Rotor is driven by the wind turbines thus as the wind speed changes rotor speed also changes. These harmonics/inter harmonics generation and its dependability on rotor speed are explained in subsequent sections.

MMF space harmonics

Due to the machine design limitation, mechanical distribution of rotor and stator winding creates air gap flux which is not perfectly sinusoidal in nature. Harmonics produced by such flux is referred to as MMF space harmonics. Inter harmonic frequencies due to this flux are given by the following equation [15].

$$f^k_{space} = |6k(1-s) \pm 1| f_s \quad (1)$$

where $k = 0, 1, 2, 3 \ldots$

f_s is synchronous or stator frequency,

s is the actual slip of the induction generator.

As stated in [16], Eq. (1) is applicable if both stator and rotor supplies are balanced. If this condition is not fulfilled, many other frequency components are also produced.

From Eq. (1) it is clear that these frequencies are dependent upon the slip. Value is dependent upon the rotor speed. Thus, space harmonics frequency is changed as rotor speed changes.

Slot harmonics

These harmonics generated by variations in reluctance due to the slots. Slot harmonics are given by following equation [15].

$$f_{slot} = f_s\left(\frac{2S}{P}(1-s) \pm 1\right) \quad (2)$$

where S is the number of slots

From Eq. (2), it is clear that slot harmonics frequency also depends upon rotor speed.

Harmonics and inter harmonics produced by RSC

In DFIG, rotor side converter (RSC) injects voltage of variable magnitude and frequency in rotor circuit. Frequency and magnitude of the injected voltage depends upon the rotor speed. When rotor speed is below synchronous speed, MMF produced by injected rotor voltage rotates in the same direction as the rotor. When rotor speed is above the synchronous speed, it rotates in opposite direction to the rotor. This is an inherent property of DFIG to make net flux linkage and stator current/voltage frequency at synchronous frequency (f_s).

$$f_s = f_r \pm f_{injected} \quad (3)$$

where, $f_{injected}$ is the injected rotor voltage frequency.

f_r is the rotor rotational frequency.

In Eq. (3) +ve sign is used when rotor speed is below the synchronous speed and −ve sign is used when rotor speed is above the synchronous speed.

$6k-1$ harmonics components of rotor injected voltage have different phase difference (0,240,120) from fundamental rotor injected voltage. These rotor harmonics cause harmonics in stator voltage and current are given by Eq. (4).

$$f_{hstator} = f_r \mp f_{6k-1} \quad (4)$$

In Eq. (4) −ve sign is used when rotor speed is below the synchronous speed and +ve sign is used when rotor speed is above the synchronous speed.

$6k+1$ harmonics components have same phase difference as the fundamental rotor injected voltage. These rotor harmonics cause harmonics in stator voltage and current are given by Eq. (5).

$$f_{hstator} = f_r \pm f_{6k-1} \quad (5)$$

In Eq. (5) +ve sign is used when rotor speed is below the synchronous speed and −ve sign is used when rotor speed is above the synchronous speed.

Root multiple signal classification (Root MUSIC)

MUSIC [1,2,12] is subspace based parametric technique. It is based on the eigenvalue decomposition of the correlation matrix and its partitioning into signal and noise subspaces. It utilizes noise subspace for frequency estimation.

Harmonics polluted power system signal is expressed as

$$y(n) = \sum_{k=1}^{K} a_k \cos(2n\pi f_k) + w(n) \quad (6)$$

where a_k is amplitude, f_k is harmonics frequency, K is the number harmonics frequency components present in the signal and $w(n)$ is white noise with zero mean. MUSIC employs complex exponen-