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

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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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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].

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

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].

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

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 ($f_s$).

$$f_s = f_r \pm f_{injected} \tag{3}$$

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).

$$f_{hstator} = f_r \mp f_{6k-1} \tag{4}$$

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).

$$f_{hstator} = f_r \pm f_{6k-1} \tag{5}$$

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

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

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 exponential model to estimate frequencies and magnitude of harmonics in the signal.

Eq. (6) can be expressed as

$$y(n)=\sum_{k=1}^{K}A_k e^{j2n\pi f_k}+\sum_{k=1}^{K}A_k e^{-j2n\pi f_k}+w(n) \tag{7}$$

where $A_k$ is the complex amplitude and can be related to $a_k$ as

$$A_k=a_k/2 \tag{8}$$

Correlation matrix $R_y$ of M × M, obtained from available data samples of $y(n)$ of length $L = N + M - 1$ is given by Eq. (9).

$$R_y=\frac{1}{N}Y^HY \tag{9}$$

where $(.)^H$ is Hermitian operator

$Y$ is data matrix of size N × M and is described as

$$Y=\begin{pmatrix} y(0) & y(1) & \cdots & y(M-1)\\ y(1) & y(2) & \cdots & y(M)\\ \vdots & \vdots & \ddots & \vdots\\ y(N-1) & y(N) & \cdots & y(N+M-2)\end{pmatrix} \tag{10}$$

This cross correlation matrix is divided into two orthogonal subspaces (signal subspace and noise subspace) by determining eigen value and eigen vector of cross correlation matrix $R_y$.

To determine signal subspace and noise subspace from the eigen vector matrix ($\Upsilon$), eigen values are arranged in decreasing order and corresponding eigen vectors are also arranged as eigen values. First 2K eigenvectors of eigen vector matrix ($\Upsilon$) are belongs to the signal space matrix ($\Upsilon_{ys}$) and remaining $M-2K$ eigenvectors belongs to noise subspace matrix ($\Upsilon_{yn}$). Noise subspace matrix is used to compute pseudo spectrum in Eq. (11) [2]. Peaks of pseudo spectrum correspond to the dominant frequency components of signal.

$$P_{MUSIC}(e^{j\omega})=\frac{1}{\sum_{i=2K+1}^{M}|\Upsilon_{ys}^H\Upsilon_{yn}|^2}=\frac{1}{\sum_{i=2K+1}^{M}|Q_i(e^{j\omega})|^2} \tag{11}$$

where $\Upsilon_{ys}^H$ represents complex conjugate transpose of signal eigenvector.

$Z$ transform is applied on denominator of Eq. (11) to determine the roots of polynomial $\sum_{i=2K+1}^{M}|Q_i(e^{j\omega})|^2$. Order of this polynomial is $(2M-1)$ and it has $M-1$ pairs of roots. $M-1$ roots lies inside the unit circle rest $M-1$ roots lies outside the unit circle.

$$P_{MUSIC}(z)=\sum_{i=2K+1}^{M}Q_i(z)Q_i^*\left(\frac{1}{z^*}\right) \tag{12}$$

$2K$ roots ($R_k$) closest to unit circle correspond to complex sinusoid present in the signal. The angle of these roots is the estimate of frequency of complex sinusoids of the signal and it is estimated by using Eq. (13).

$$f_k=\frac{\angle R_k}{2\pi} \tag{13}$$

Amplitude of harmonics component is obtained by solving Eq. (12) [17,20].

$$A=(V^HV)^{-1}V^HY \tag{14}$$

where $V$ is defined as

$$\begin{pmatrix} 1 & 1 & \cdots & 1\\ e^{j2\pi f_1} & e^{j2\pi f_2} & \vdots & e^{j2\pi f_{2K}}\\ e^{j2*2\pi f_1} & e^{j2*2\pi f_2} & \vdots & e^{j2*2\pi f_{2K}}\\ \vdots & \vdots & \ddots & \vdots\\ e^{j(L-1)*2\pi f_1} & e^{j(L-1)*2\pi f_2} & \cdots & e^{j(L-1)*2\pi f_{2K}}\end{pmatrix} \tag{15}$$

And $Y$ is defined as

$$Y=[y(0)\ y(1)\ y(2)\ \cdots\ y(L-1)]^T \tag{16}$$

where $y(0), y(1), y(2)\cdots y(L-1)$ are samples of the signal at different instance.

## Estimation of signal parameters via rotational invariance technique (ESPRIT)

ESPRIT [1,13] is subspace based parametric technique. It also employs complex exponential model to estimate the signal parameters. However, it uses signal subspace for parameters calculation rather than the noise subspace. This employs rotational property between staggered subspaces to determine the frequency parameter. Once the frequency is estimated, magnitude is estimated by using Eq. (12).

Basic ESPRIT algorithm also utilizes complex exponential model as given in Eq. (7) to estimate frequencies and magnitude of harmonics in signal. ESPRIT follows same procedure from Eqs. (8)–(10) as in Root MUSIC to determine cross correlation matrix and also adopts similar procedure as in Root MUSIC to decompose correlation matrix into subspace matrix. Subsequently it uses signal subspace and determines the two shifted matrix from signal subspace matrix. The basic ESPRIT employs following steps to estimate harmonics/inter harmonics.

Similar procedure is adopted from Eqs. (6)–(10) to determine signal subspace matrix as explained in Section 'Root multiple signal classification (Root MUSIC)'.

Subsequently it uses two selection matrixes $V_1$ and $V_2$ to determine two shifted matrix $\Upsilon_1$ and $\Upsilon_2$ from $\Upsilon_{ys}$ using Eq. (18) for $i = 1, 2$.

$$V_1=[I_{M-1}\ 0_d] \tag{17a}$$

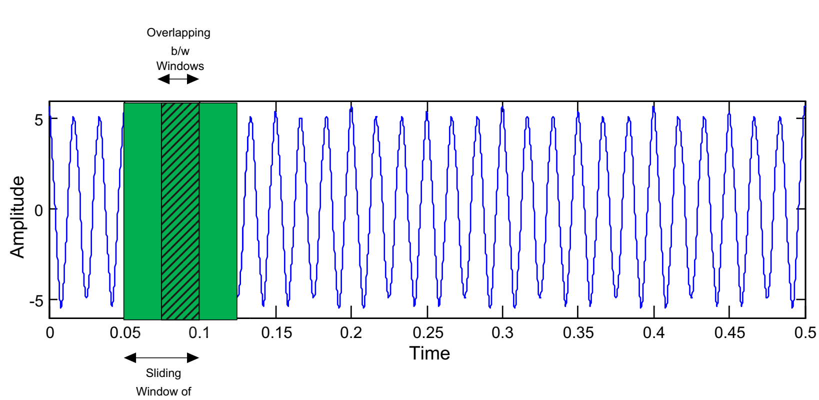


**Fig. 1.** Sliding window methodology.

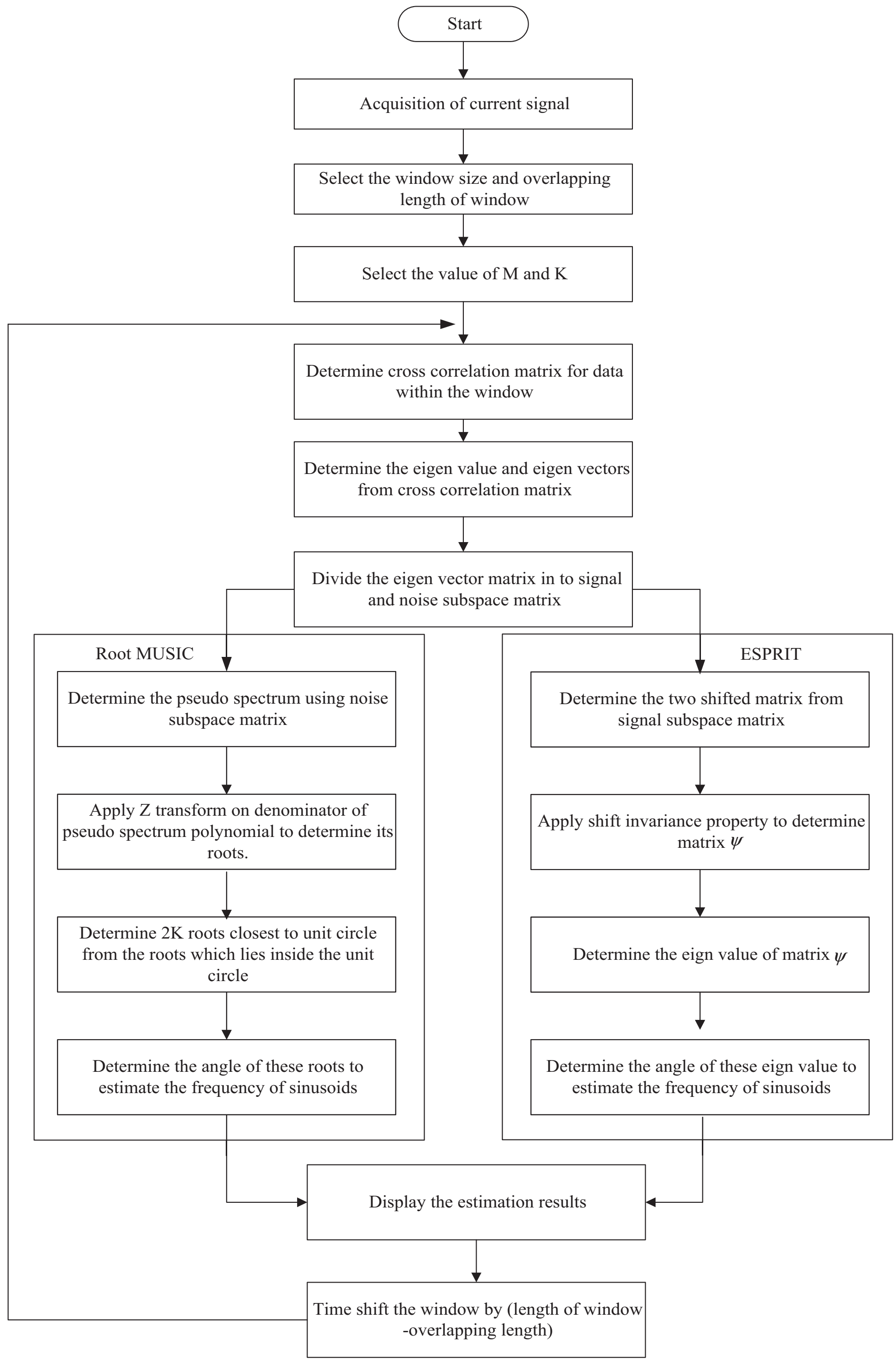


**Fig. 2.** Flow chart of sliding window Root MUSIC and sliding window ESPRIT.

$$V_2 = [0_d \; I_{M-1}] \tag{17b}$$

$$\Upsilon_i = V_i * \Upsilon_{ys} \tag{18}$$

where $I_{M-1}$ is an identity matrix of order $M-1$ and $d$ is the distance between two sub matrices.

Applying shift invariance property, $\Upsilon_1$ and $\Upsilon_2$ can be related using a matrix $\psi$, whose eigen values represents exponential terms $e^{j2\pi f_k}$ where k varies 1, 2, 3... $2K$.

$$\psi = (\Upsilon_1^H \Upsilon_1)^{-1} \Upsilon_1^H \Upsilon_2 \tag{19}$$

The frequency components are obtained from the eigen values of $\psi$ by using Eq. (20)

$$f_k = \frac{\angle \lambda_{\psi k}}{2\pi} \tag{20}$$

## Sliding window ESPRIT and sliding window Root MUSIC

Both the ESPRIT and Root MUSIC are able to estimate the accurate frequency when the signal is under steady state which means

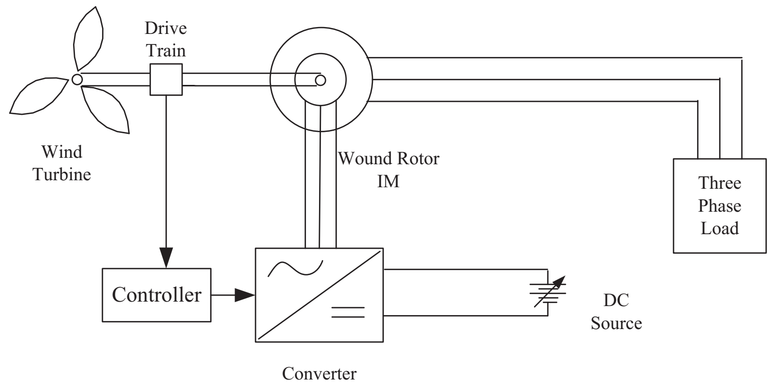


**Fig. 3.** Standalone DFIG wind power plant.

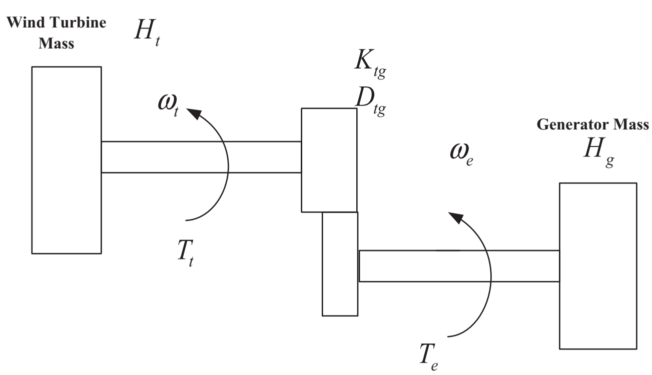


**Fig. 4.** Two mass drive train model.

**Table 1**
Machine parameter of 5 HP DFIG.

| S. No. | Parameters | Values |
|---|---|---|
| 1 | $R_s$ (Ω) | 0.32 |
| 2 | $L_{ls}$ (mH) | 1.19 |
| 3 | $M$ (mH) | 39.46 |
| 4 | $L_{lr}$ (mH) | 1.34 |
| 5 | $r_r$ (Ω) | 0.36 |
| 6 | Turn ratio a | 1.38 |
| 7 | Resistive load (Ω) | 11 |

**Table 2**
Description of synthetic signal.

| S. No. | Frequency (Hz) | Magnitude |
|---|---|---|
| 1 | 300 | 1 |
| 2 | 200 | 2 |
| 3 | 180 | 1.5 |
| 4 | 150 | 0.5 |
| 5 | 80 | 1 |
| 6 | 70 | 1 |
| 7 | 60 | 50 |

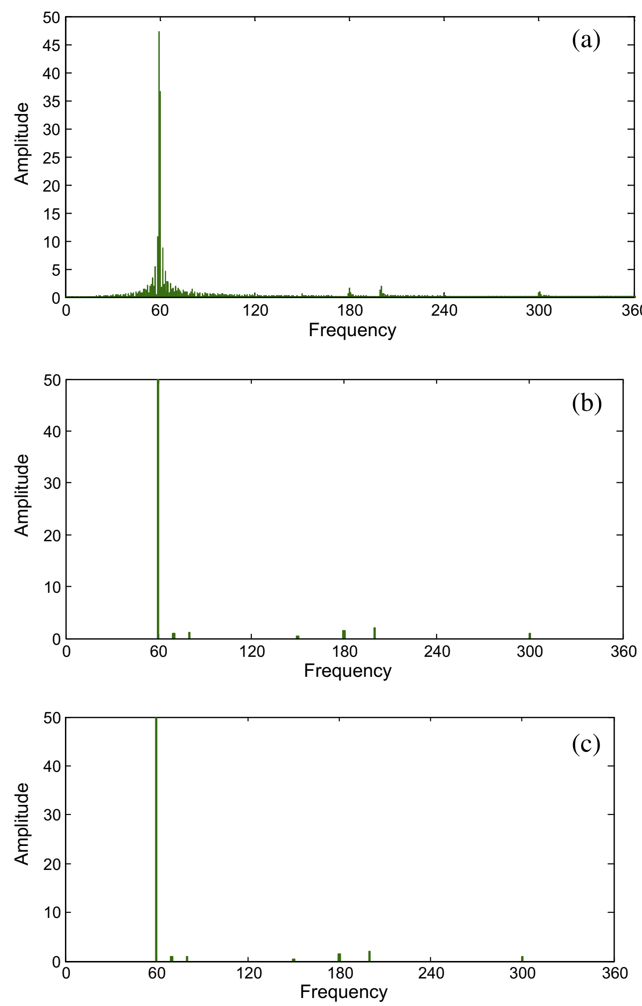


**Fig. 5.** Frequency and amplitude estimation of synthetic signal (a) FFT, (b) Root MUSIC and (c) ESPRIT.

the signal parameter like frequency and magnitude of harmonics components are not time varying in nature. It is clear from Section 'Harmonics generation in stator of DFIG' that harmonics magnitude and frequency introduced by DFIG is not constant and dependent upon the rotor speed. In sliding window ESPRIT and Root MUSIC [1], algorithm is applied within a small window which moves over the time with overlapping between successive window as shown in Fig. 1 to estimate instantaneous change in frequency and magnitude of harmonics/inter harmonics. Overlapping is provided to estimate sudden changes in signal. By using this sliding window concept both the methods are able to estimate frequency and magnitude of a time varying signal. With the implementation of sliding window concept it is assumed that signal is stationary within the chosen data window.

The flow chart of sliding window Root MUSIC and ESPRIT is shown in Fig. 2. This flow chart provides complete information about intermediate step estimating the frequency and amplitude of sinusoids present in signal.

**Table 3**
Comparison between Root MUSIC and ESPRIT for parameter estimation error of synthetic signal.

| Methods | | Root MUSIC | | ESPRIT | |
|---|---|---|---|---|---|
| True frequency | True magnitude | Frequency estimation error | Magnitude estimation error | Frequency estimation error | Magnitude estimation error |
| 420 | 5 | $2.5017 \times 10^{-5}$ | 0.00218 | $1.9571 \times 10^{-10}$ | $2.1967 \times 10^{-8}$ |
| 300 | 3 | 0.00131 | 0.00500 | $7.5866 \times 10^{-8}$ | $8.8362 \times 10^{-8}$ |
| 250 | 4 | 0.00367 | 0.00676 | $8.6023 \times 10^{-8}$ | $1.3285 \times 10^{-7}$ |
| 200 | 2.5 | 0.00293 | 0.00011 | $2.4257 \times 10^{-6}$ | $1.4586 \times 10^{-6}$ |
| 95 | 3.5 | 0.00097 | 0.06787 | 0.000105 | $6.2200 \times 10^{-6}$ |
| 70 | 6 | 0.00417 | 0.00020 | 0.000198 | $1.4160 \times 10^{-6}$ |
| 60 | 50 | 0.03317 | 0.01144 | $2.6350 \times 10^{-6}$ | $4.9917 \times 10^{-6}$ |
| Computation time (s) | | 0.5844 | | 0.0881 | |

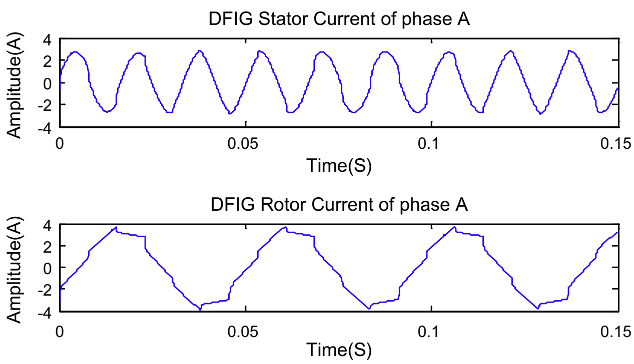


**Fig. 6.** DFIG stator and rotor current of phase A under 1140 RPM.

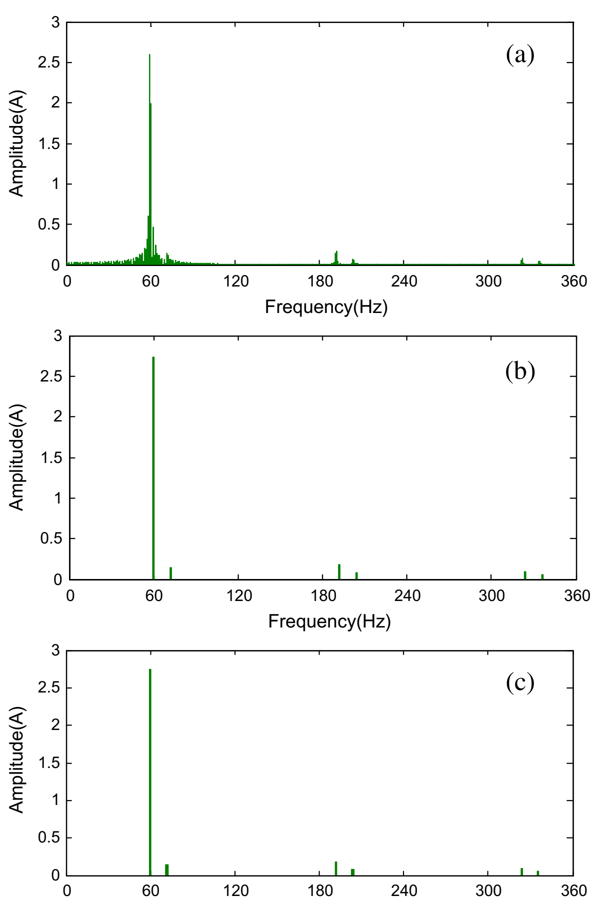


**Fig. 7.** Harmonics/inter harmonics component estimation of stator current under constant rotor speed (a) FFT, (b) Root MUSIC and (c) ESPRIT.

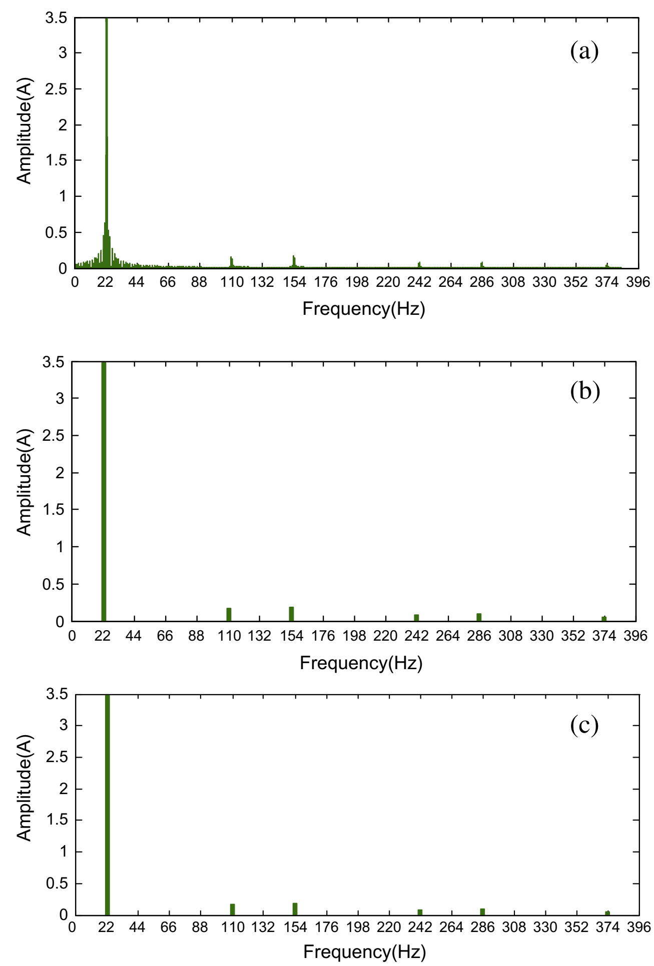


**Fig. 8.** Harmonics/inter harmonics component estimation of rotor current under constant rotor speed (a) FFT, (b) Root MUSIC and (c) ESPRIT.

**Table 4**
Comparison between Root MUSIC and ESPRIT for parameter estimation of stator current signal under constant rotor speed.

| S. No. | Theoretical Frequency (Hz) | Root MUSIC Frequency (Hz) | ESPRIT Frequency (Hz) |
|---|---|---|---|
| 1 | $f_{hstator} = f_r - f_{17} = 336$ | 335.890469 | 335.898335 |
| 2 | $f_{hstator} = f_r + f_{13} = 324$ | 323.979852 | 323.990997 |
| 3 | $f_{hstator} = f_r - f_{11} = 204$ | 203.905074 | 203.938431 |
| 4 | $f_{hstator} = f_r + f_7 = 192$ | 191.9865699 | 191.981898 |
| 5 | $f_{hstator} = f_r - f_5 = 72$ | 71.8064935 | 71.979629 |
| 6 | $f_s = f_r + f_{injected} = 60$ | 59.9878801 | 60.000097 |
| Computation time (s) | | 0.5386 | 0.0837 |

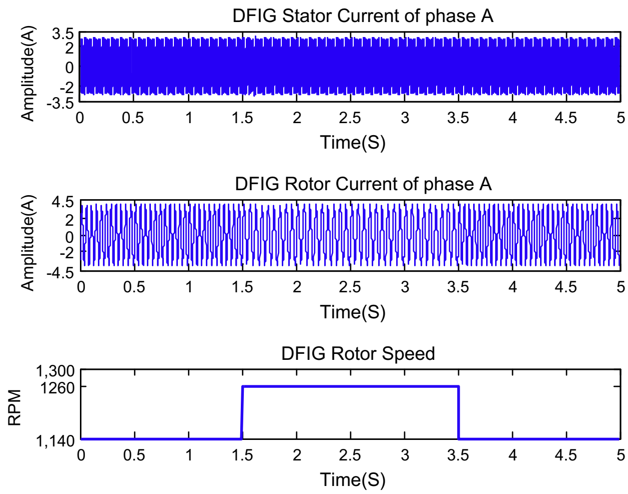


**Fig. 9.** Stator and rotor current of phase A and rotor speed in RPM.

## Model of standalone DFIG

Model of Standalone DFIG is shown in Fig. 3 [18] in which DFIG is connected to three phase star connected load. In rotor circuit, voltage is injected by using DC/AC converter. When Rotor speed is below the synchronous speed, it acts like inverter and supplies power to rotor circuit. It acts as rectifier when rotor speed is above the synchronous speed and stores power into battery. Different switching techniques are implemented for DC/AC converter like space vector pulse width modulation (SVPWM), pulse width modulation (PWM) and six pulse switching etc. Out of these techniques six pulse switching technique have simple control circuitry and less switching losses.

In present study, six pulse switching technique is used to inject rotor voltage. In six pulse switching techniques, triplen harmonics never appears in the output voltage and only $6k \pm 1$ order harmonics present in output voltage. Due to these harmonics injected rotor voltage waveform of is quasi-sine wave.

To study the variation of gear mesh stiffness two mass model of drive train is considered in the present standalone DFIG power

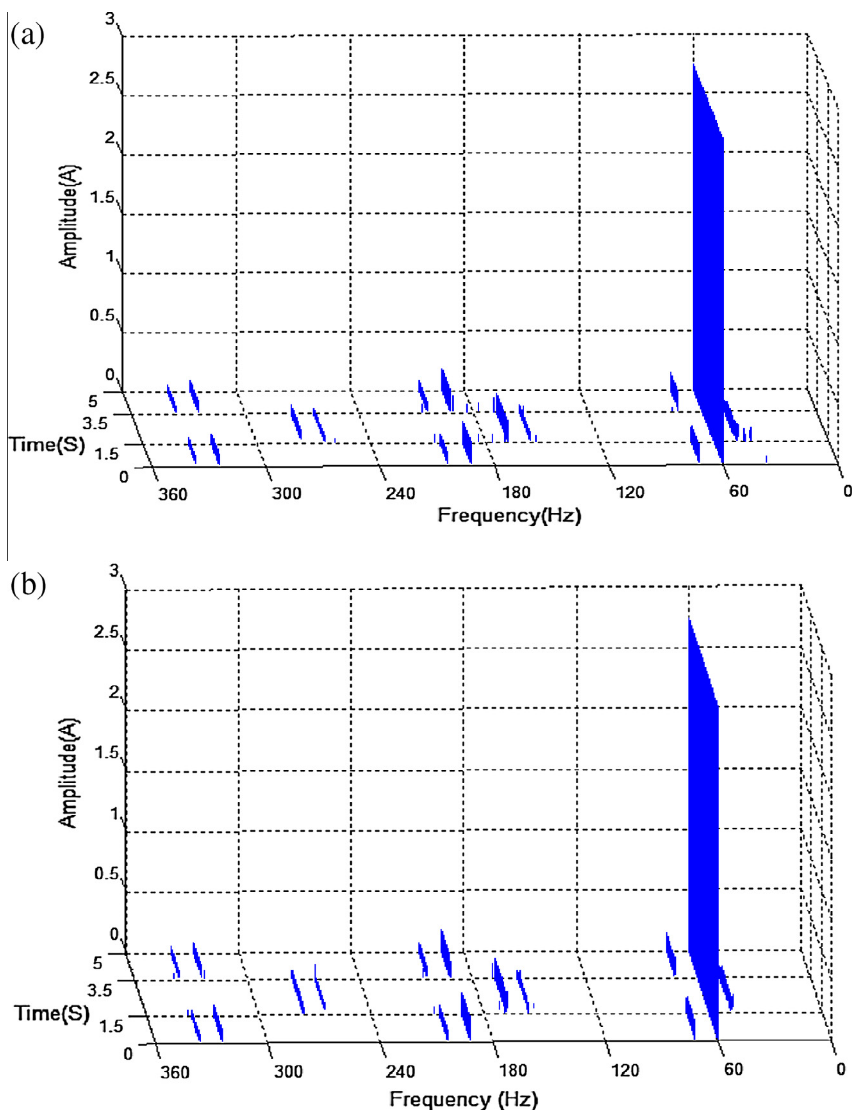


**Fig. 10.** Harmonics/inter harmonics component estimation of stator current of phase A under variable rotor speed (a) Sliding window Root MUSIC and (b) sliding window ESPRIT.

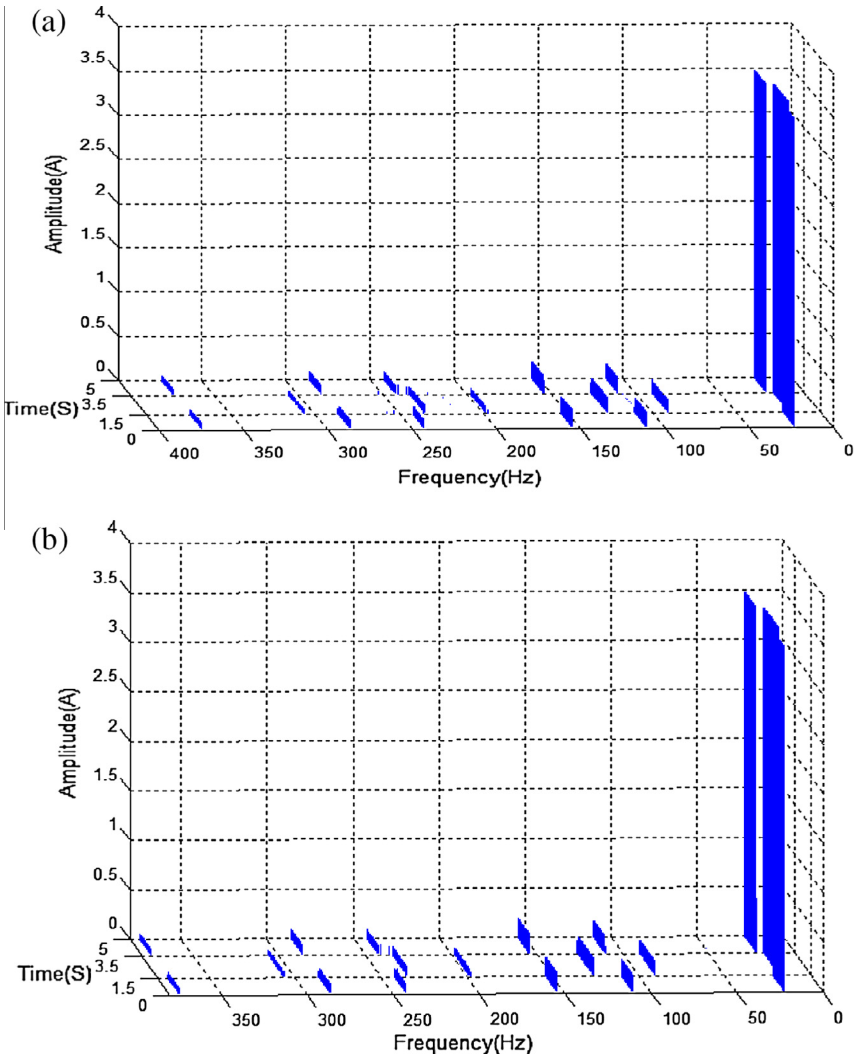


**Fig. 11.** Harmonics/inter harmonics component estimation of rotor current of phase A under variable rotor speed (a) sliding window Root MUSIC and (b) sliding window ESPRIT.

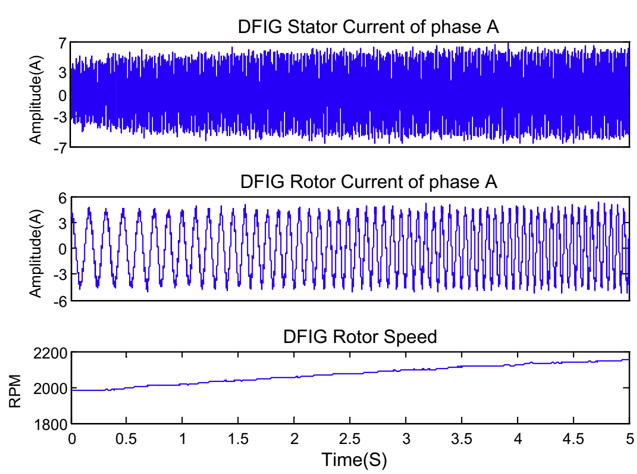


**Fig. 12.** Stator and rotor current of phase A for sweep rotor speed.

system [22]. Details of two mass model is shown in Fig. 4. It realised by using following equation of motion

$$T_e - D_{tg}(\omega_e - \omega_t) + K_{tg}(\theta_e - \theta_t) = 2H_g\dot{\omega}_e \tag{21}$$

$$D_{tg}(\omega_e - \omega_t) + K_{tg}(\theta_e - \theta_t) - T_t = 2H_t\dot{\omega}_t \tag{22}$$

where

$\omega_e$, $\omega_t$ are the generator and turbine speed respectively.
$\theta_e - \theta_t$ is shaft twist angle.
$K_{tg}$, $D_{tg}$ are shaft stiffness and damping coefficients respectively.
$T_e$, $T_t$ are turbine torque and electromagnetic torque.
$H_g$, $H_t$ are the generator and turbine inertia respectively.

5 HP 4 pole slip ring induction motor is used to model DFIG. Parameters of motor is taken from the [18,19] given in Table 1. The model of standalone DFIG comprising of wind turbine two mass drive train is simulated in the MATLAB/SIMULINK environment. As per the discussion in Section 'Harmonics generation in stator of DFIG', it is clear that harmonics produced in the stator due to rotor voltage harmonics is dependent upon the rotor speed.

## Simulation results and discussions

This section contains four parts. In the first part, performance of the parametric techniques described in Sections 'Root multiple signal classification (Root MUSIC)' and 'Estimation of signal parameters via rotational invariance technique (ESPRIT)' are tested in the synthetic signal and compared with FFT. In the second part, harmonics estimation of standalone DFIG under constant rotor speed is performed by using FFT, Root MUSIC, and ESPRIT. In third part, harmonics emission by standalone DFIG under variable rotor speed is estimated by techniques described in Section 'Sliding window esprit and sliding window Root MUSIC'. In the last part, Harmonics estimation of standalone DFIG system under constant rotor speed but under variable load condition is determined by sliding window Root MUSIC and Sliding window ESPRIT.

*Parameter estimation of synthetic signal*

In this section, performances of parametric techniques are judged for low amplitude harmonics estimation for a synthetic signal and compared with FFT. Synthetic signal has seven frequency components having different magnitude. It is sampled with sampling frequency 10 kHz. Descriptions of synthetic signal are provided in Table 2. First, FFT is performed on this signal and frequency spectrum obtained is shown in Fig. 5(a). After that 1500 samples of synthetic signal are used to determine harmonics parameters of signal by Root MUSIC and ESPRIT. Estimation of frequency and amplitude of sinusoids present in the signal are obtained by parametric techniques and results are shown in Fig. 5(b) and (c) respectively. Result shows that FFT suffers from spectral leakage and cannot able to achieve the accurate frequency estimation as well as magnitude. In comparison to FFT, results obtained by parametric techniques are more promising and near to actual value. From the results shown in Fig. 5(b) and (c), it is difficult to analyze in which parametric technique has better accuracy in harmonics estimation. To further analyze, estimation error are calculated to judge performance of these parametric techniques. From the estimation error shown in Table 3, it is clear that signal parameter estimation by ESPRIT is much better than Root MUSIC. Computation time taken by ESPRIT is much less as compared to Root MUSIC. This feature of ESPRIT makes it more powerful than the Root MUSIC for estimation objective.

*Harmonics estimation of standalone DFIG under constant rotor speed*

Standalone DFIG model described in Section 'Model of standalone DFIG' is used for estimation of harmonics and inter-harmonics in stator and rotor current under constant rotor speed. Stator and rotor current are extracted under situation when rotor rotates with rotational frequency of 38 Hz which means rotor rotates at 1140 RPM.RSC injects a voltage of 22 Hz to maintain

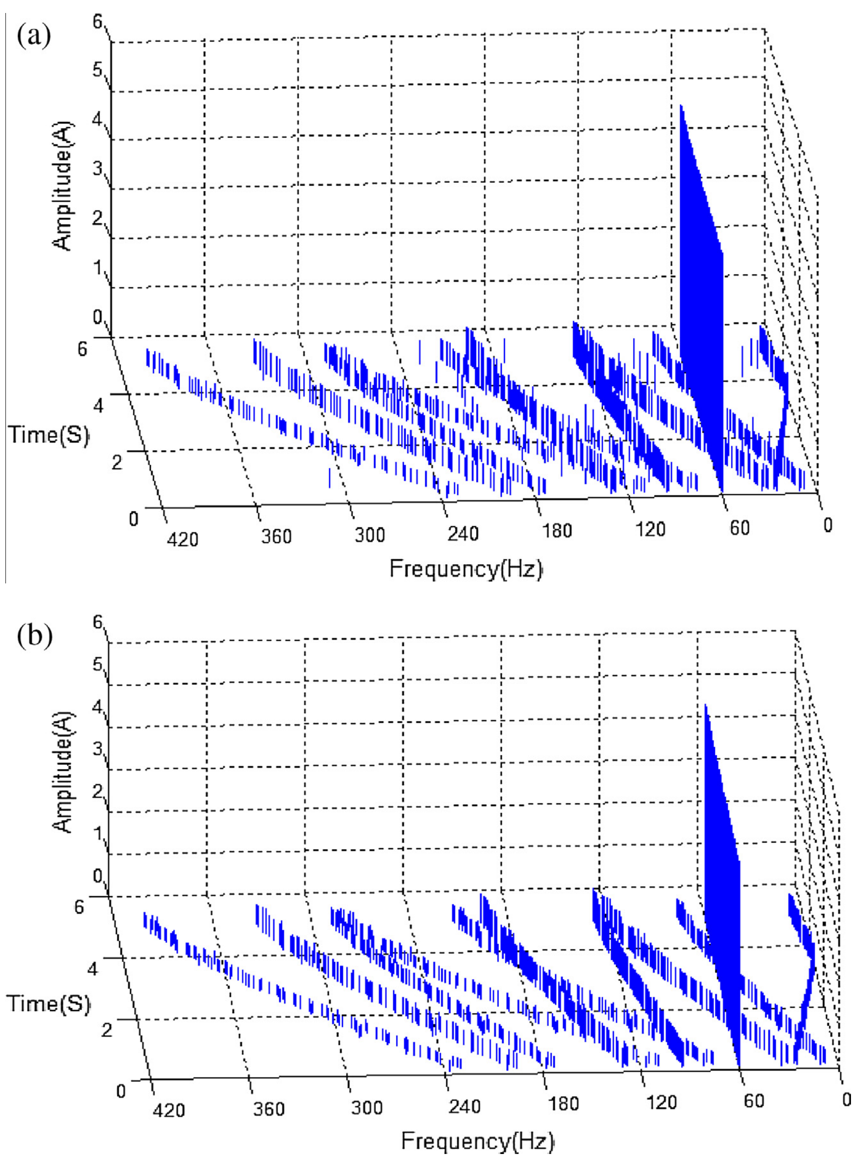


**Fig. 13.** Harmonics/inter harmonics component estimation of stator current of phase A sweep rotor speed (a) sliding window Root MUSIC and (b) sliding window ESPRIT.

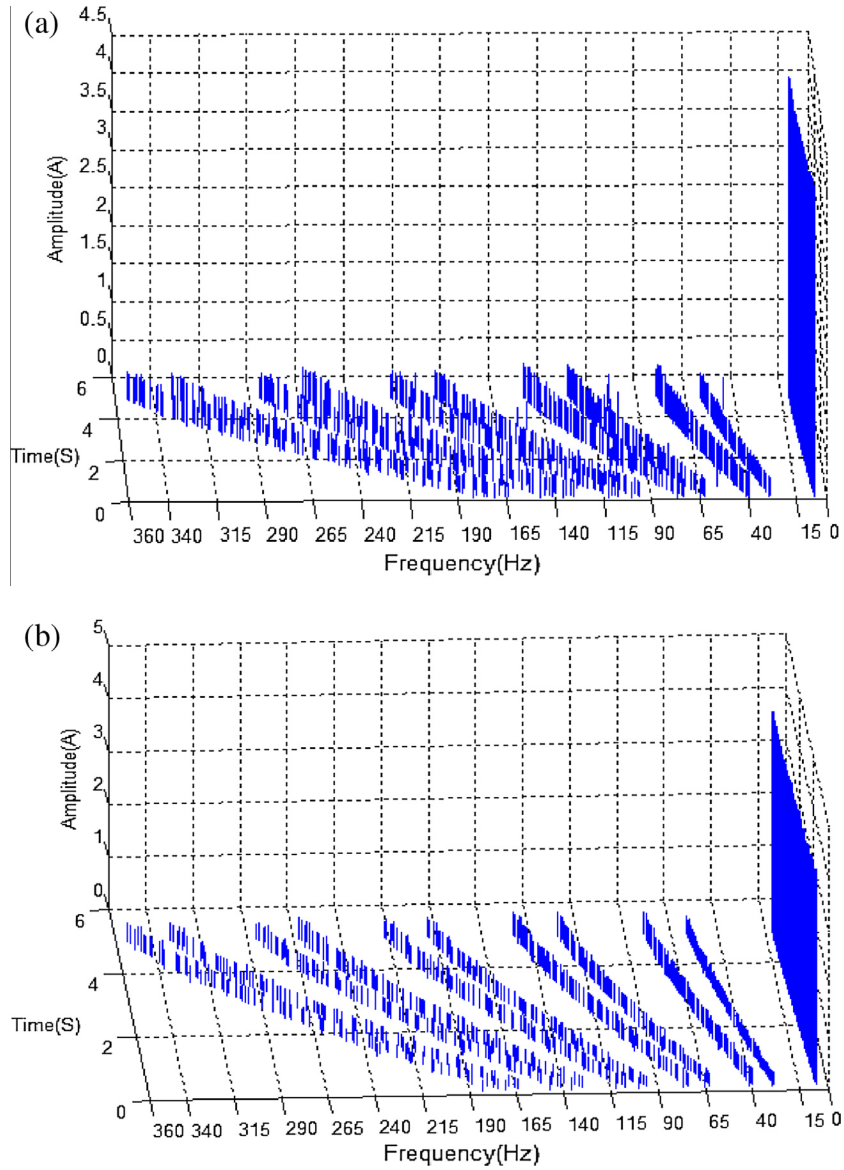


**Fig. 14.** Harmonics/inter harmonics component estimation of rotor current of phase A sweep rotor speed (a) sliding window Root MUSIC and (b) sliding window ESPRIT.

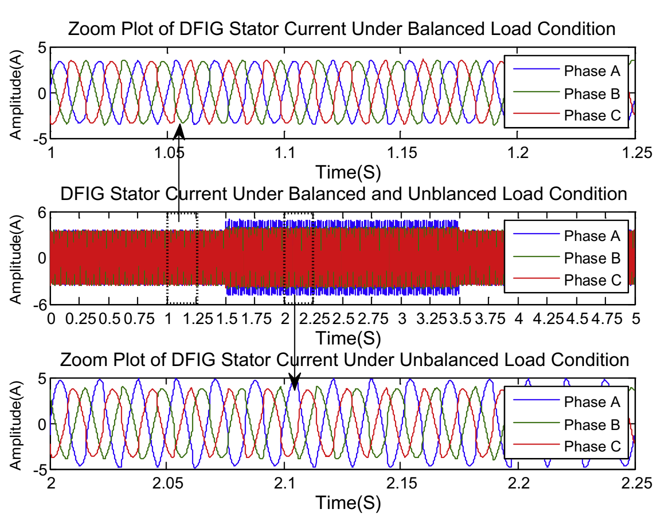


**Fig. 15.** Stator current during balanced and unbalanced load condition.

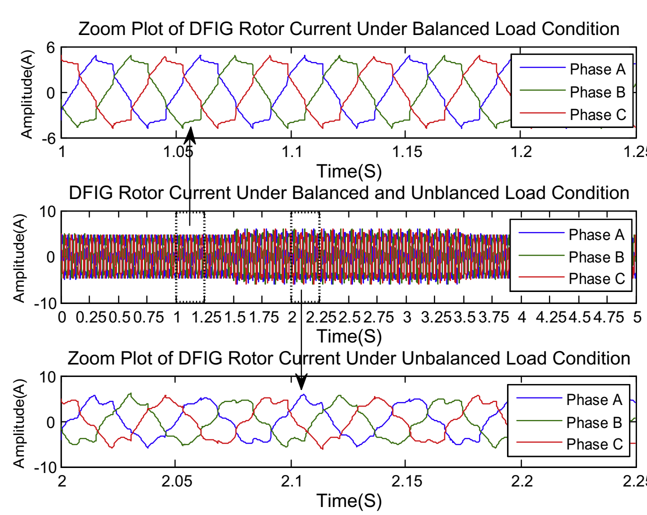


**Fig. 16.** Rotor current during balanced and unbalanced load condition.

the stator voltage and current at synchronous frequency $f_s = f_r + f_{injected} = 60$ Hz Extracted signals are sampled with sampling frequency 10 kHz. 1500 samples are taken to determine the frequency and magnitude of harmonics/inter harmonics by Root MUSIC and ESPRIT. These results are also compared by FFT. Stator and rotor current wave form are shown in Fig. 6. Estimated harmonics/inter harmonics component of stator current by FFT, Root MUSIC and ESPRIT are shown in Fig. 7(a)–(c) respectively. Estimated harmonics component of rotor current by FFT, Root MUSIC and ESPRIT are shown in Fig. 8(a)–(c) respectively.

Results show that harmonics component estimation by parametric techniques for both stator and rotor current are more accurate in comparison to FFT. From results shown in Fig. 7, it is clear that parametric techniques are better than the FFT. But in the same time it is difficult to distinguish which parametric technique has better estimation accuracy and less computational burden. Thus a qualitative analysis between these techniques for harmonics/inter harmonics frequency estimation of stator current is carried out which is presented in Table 4. This qualitative analysis shows that ESPRIT has better accuracy and less computational burden in comparison to Root MUSIC. Computation time taken by Root MUSIC is much higher in comparison to ESPRIT.

*Harmonics estimation of standalone DFIG under variable rotor speed*

As described in Section 'Harmonics generation in stator of DFIG', harmonics and inter harmonics component is dependent upon the rotor speed means harmonics components frequency varies as the rotor speed varies. Thus, conventional parametric techniques fail to determine accurate harmonics parameter under variable rotor speed. To tackle such situation sliding window concept with these parametric techniques are described in Section 'Sliding window esprit and sliding window Root MUSIC' is used to determine harmonics parameters under variable rotor speed condition. To analyze performances of methods described in Section 'Sliding window esprit and sliding window Root MUSIC', stator current and rotor current signal of 5 s duration is captured by simulating the model described in Section 'Model of standalone DFIG' in MATLAB platform and extracted signal is sampled with sampling frequency 10 kHz. In such time duration, rotor speed varied from 1140 RPM (38 Hz) to 1260 RPM (42 Hz) at the instant 1.5 s and rotor regains speed of 1140 RPM at the instant of 3.5 s. Stator and rotor current waveform of phase A and rotor speed variation is shown in Fig. 8. RSC injects a voltage of frequency 22 Hz and 18 Hz for the rotor speed 38 Hz and 42 Hz respectively to maintain

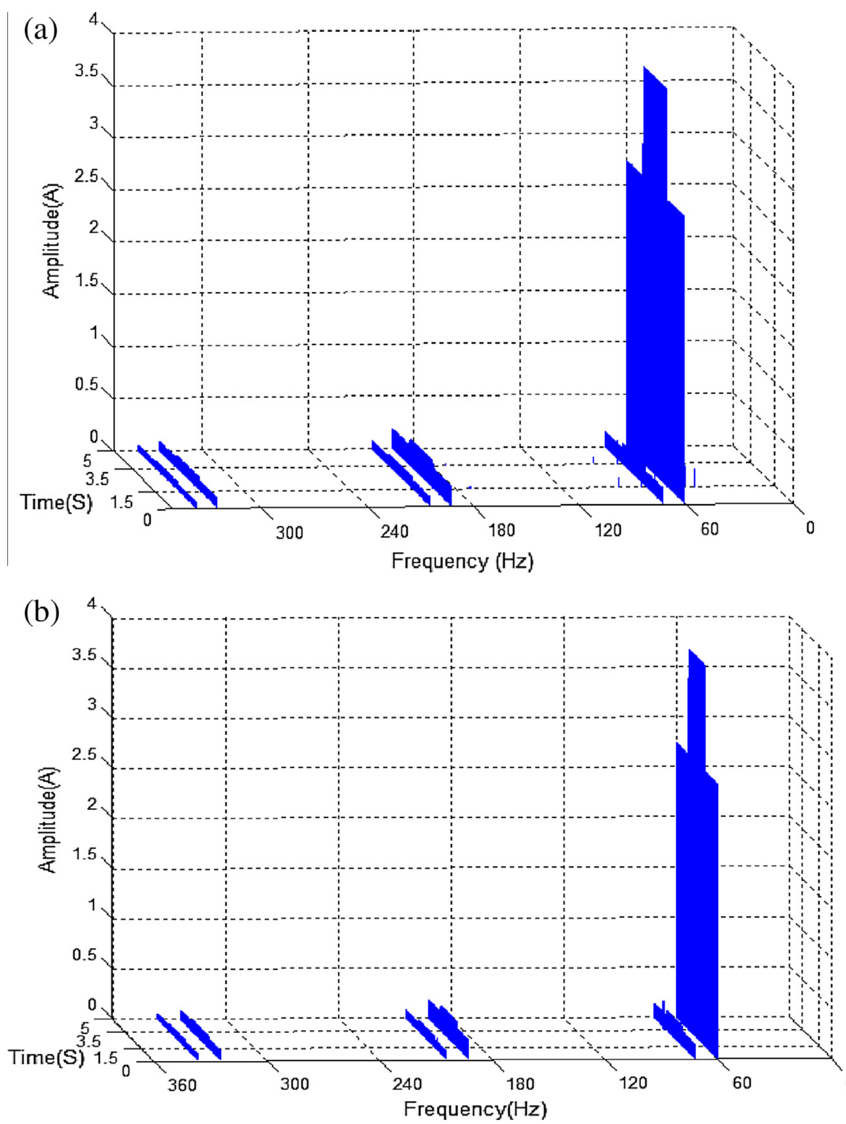


**Fig. 17.** Harmonics/inter harmonics component estimation of stator current of phase A under variable load condition (a) sliding window Root MUSIC and (b) sliding window ESPRIT.

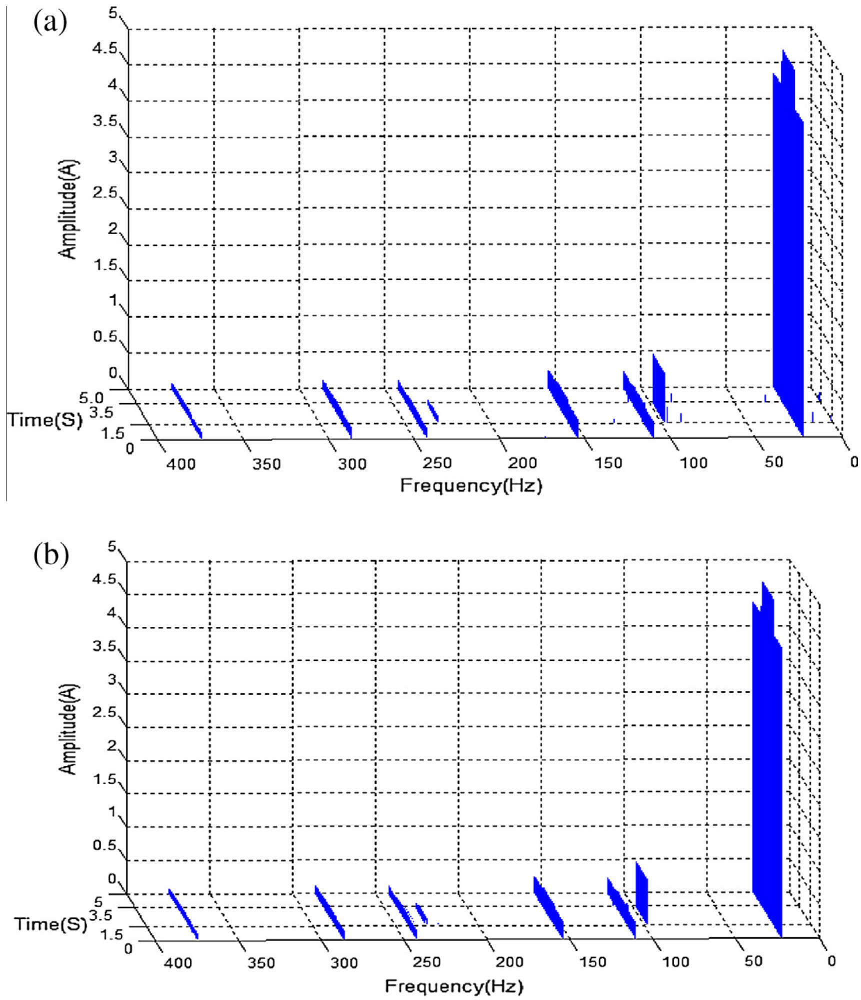


**Fig. 18.** Harmonics/inter harmonics component estimation of rotor current of phase A under variable load condition (a) sliding window Root MUSIC and (b) sliding window ESPRIT.

the stator voltage at synchronous frequency $f_s = f_r + f_{injected}$ = 60 Hz. Injected rotor voltage harmonics also causes harmonics in stator voltage and current and it depends upon injected rotor voltage frequency and rotor speed as described in Section 'Harmonics generation in stator of DFIG'. It clearly seen from Fig. 9 magnitude of stator and rotor current almost remains unchanged under rotor speed variation because power supplied by dc source is also adjusted with rotor speed variation. Thus it is very difficult to judge where the harmonics frequencies are varied or not. For estimating the frequency and magnitude of harmonics/inter harmonics, a fixed data window of length 0.15 s with 66.6% overlapping between successive window is taken by sliding window Root MUSIC and ESPRIT. Estimated harmonics/inter harmonics component of stator current by sliding window Root MUSIC and sliding window ESPRIT are shown in Fig. 10(a) and (b) respectively. Estimated harmonics/inter harmonics component of rotor current by sliding window Root MUSIC and sliding window ESPRIT are shown in Fig. 11(a) and (b) respectively. The Average computational time taken by sliding window Root MUSIC and sliding window ESPRIT is 0.5342 and 0.0912 s respectively.

From these results it is clear that both methods are capable of estimating harmonics/inter harmonics components of stator and rotor current precisely but sliding window Root MUSIC takes more computational time in comparison to sliding window ESPRIT.

For sweep rotor speed, harmonics and inter harmonics is also estimated. Stator and rotor current along with rotor speed is shown in Fig. 12. In this rotor speed varies from 1978 RPM to 2152 RPM. Harmonics and inter harmonics estimation by sliding window Root MUSIC and sliding window ESPRIT for stator and rotor current are shown in Figs. 13(a), 14(a) and Figs. 13(b),

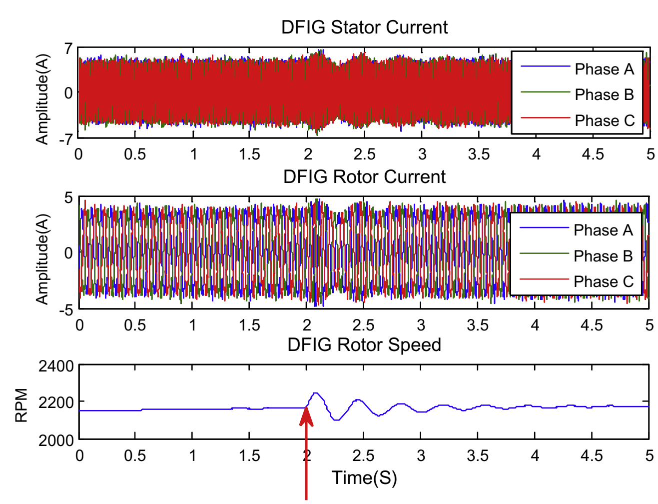


**Fig. 19.** Stator and rotor current along with rotor speed for change in stiffness of drive train.

14(b) respectively. It is clear from the result that ESPRIT has better efficiency than the Root MUSIC.

*Harmonics estimation of standalone DFIG under unbalanced load condition*

Unbalanced load also affects harmonics parameters present in stator and rotor current. Under unbalanced load condition, inter harmonics components may appear in the rotor current. Sometimes, these inter harmonics components are dominant enough to affect the performances of RSC like switching and excessive heating of ICs etc. Apart from this stator current harmonics as well as fundamental component magnitude in all the three phases of stator are not same. From the above discussion it is clear that harmonics/inter harmonics components does not remain constant from balanced to unbalanced load condition even rotor speed is constant. To check the accuracy and performances of methods described in 'Sliding window ESPRIT and sliding window Root MUSIC'. Stator and rotor current of 5 s duration with sampling frequency 10 kHz of model shown in Section 'Model of standalone DFIG' is captured under unbalanced load by simulating the model in MATLAB. In such duration of time, load resistance of phase A is varied from 11 ohm to 6 ohm at the instant 1.5 s and further becomes equal to 11 ohm at the instant of 3.5 s. Rotor speed is constant and equal to 1140 Hz. Stator current waveform and its zoom plot during balanced and unbalanced condition are shown in Fig. 15. Form Fig. 15, it is clear that magnitude of all the three phase are same under balanced condition but during the unbalanced condition magnitude of current in all the three phase is not same. Rotor current waveform and its zoom plot during balanced and unbalanced condition are shown in Fig. 16. From Fig. 16, it is clear that waveform of rotor current is more distorted

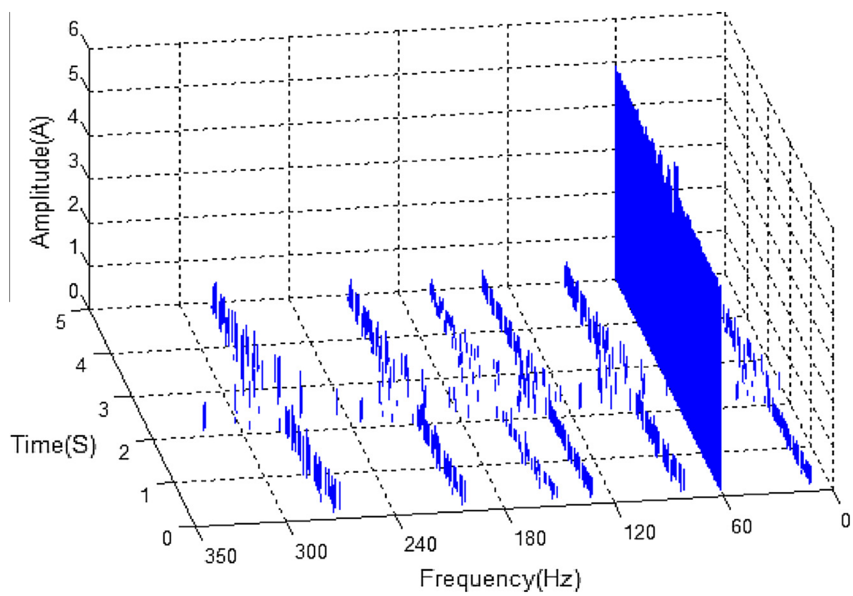


**Fig. 20.** Harmonics/inter harmonics component estimation of stator current of phase A by sliding window ESPRIT for change in stiffness of drive train.

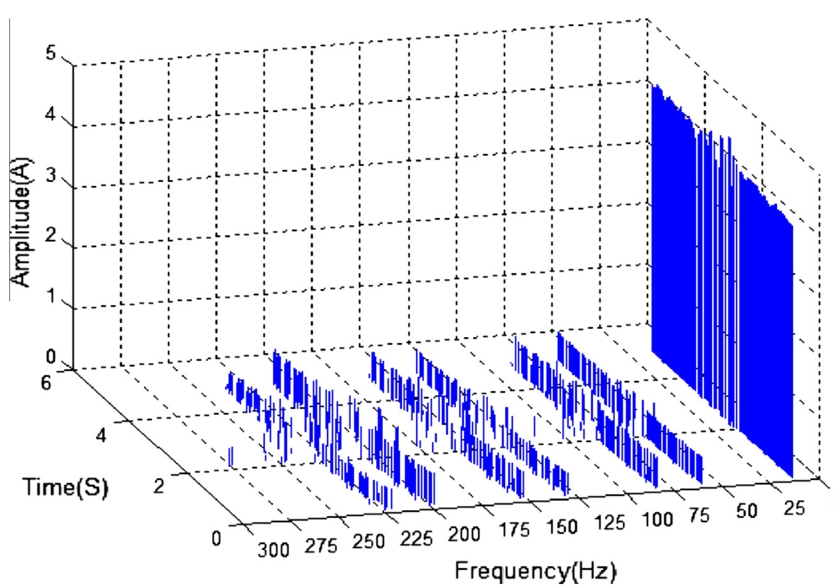


**Fig. 21.** Harmonics/inter harmonics component estimation of rotor current of phase A sliding window ESPRIT for change in stiffness of drive train.

during unbalanced situation in comparison to balanced situation means extra harmonics component may be present in the rotor current during unbalance.

For estimating the Frequency and magnitude of harmonics/inter harmonics of stator and rotor current of phase A under unbalanced condition, a fixed data window of length 0.15 s with 66.6% overlapping between successive window is taken by sliding window Root MUSIC and ESPRIT. Estimated harmonics/inter harmonics component of stator current by sliding window Root MUSIC and sliding window ESPRIT are shown in Fig. 17(a) and (b) respectively.

From these result it is clear that in stator current only magnitude of harmonics/inter harmonics are changed and no extra harmonic/inter harmonics component appears during unbalance. Both the methods are capable of detecting frequency and magnitude precisely under unbalanced load condition. Estimated harmonics/inter harmonics component of rotor current by sliding window Root MUSIC and sliding window ESPRIT are shown in Fig. 18(a) and (b) respectively. The average computational time taken by Sliding window Root MUSIC and sliding window ESPRIT is 0.5412 and 0.0907 s respectively.

From these result it is clear that in stator current only magnitude of harmonics/inter harmonics are changed and extra inter harmonics component of 98 Hz and 236 Hz appears during unbalance. These inter harmonic components are accurately estimated by these methods. From these results it is clear that both methods are capable of detecting frequency and magnitude precisely under unbalanced load condition but sliding window Root MUSIC takes more computational time than the sliding window ESPRIT.

To analyze the effect of variation of gear mesh stiffness, two mass model of drive train is considered in this paper. Variation in the gear mesh stiffness causes oscillations in the rotor [23] which in turn causes variations in rotor current and stator current as shown in Fig. 19. In the present study gear mess stiffness increased to 2 times of the nominal value at the time instant of two second. It is clear from Fig. 19, stator and rotor current also oscillates. ESPRIT is used to estimate the harmonics and inter harmonics frequencies. Results are shown in Figs. 20 and 21 respectively. Results obtained indicate that the harmonics and inter-harmonics frequencies also vary until the effect of change in stiffness is diminished.

## Conclusion

The works in this paper has introduced a study on the estimation of harmonics and inter harmonics in DFIG using ESPRIT and Root MUSIC under constant speed and balanced load condition. It is clear from the results that both the techniques give accurate result in comparison to FFT. However, ESPRIT has better accuracy in comparison to Root MUSIC and also takes very less computational time. Further dynamical changes in frequency and magnitude of harmonics under variable rotor speed conditions, load unbalance condition and stiffness variation are estimated by sliding window ESPRIT and sliding window Root MUSIC. From the series of simulation results, it is concluded that sliding window ESPRIT is more accurate and computationally efficient than the sliding window Root MUSIC for the estimation of harmonics/inter harmonics.

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