Application of Parameter Estimation Methods to the Assessment of DFIG's Currents

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***Abstract*—Proliferation of nonlinear loads and development of renewable energy resources introduces new challenges in power quality monitoring due to the increased level of harmonic distortion of voltage and current signals. In this paper, the quality of harmonic distortion of currents recorded on a laboratory Double Fed Induction Generator drive is investigated. An efficient nonlinear estimation method is applied to evaluate the effects of interharmonic distortion in the estimation process. The results obtained are compared with those provided by the application of the Fast Fourier Technique (FFT).**

***Index Terms*-- Signal estimation, doubly fed induction generator, harmonic distortion.**

I. Introduction

MONITORING and control of power systems require fast and efficient measurement of basic electrical quantities (voltage or current phasors and spectra, local system frequency, etc.) as well as the calculation of other parameters that are derived from the basic quantities (active and reactive power, total harmonic distortion factor, etc.). The significance of measurement algorithms increases with the proliferation of nonlinear loads. These are a common source of harmonic distortion of voltages and currents, and are known to introduce various power quality related issues. An illustration of these effects is given in [1], where the increased number of renewable energy resources (e.g. off-shore wind farms) introduced the challenge of determining the level of harmonic distortion that originates from modern wind generators and application of power electronic elements.

A traditional tool for frequency analysis in power system engineering is the Fast Fourier Transform (FFT), a method that is both straightforward for implementation and efficient. However, there are drawbacks to using this technique, as it suffers from limited flexibility. This is particularly evident when processing signals that do not contain just harmonics, i.e. multiples of the fundamental frequency, but are also distorted, for example, by randomly distributed interharmonics, decaying DC component, etc. Recently, a number of algorithms have been proposed for power system measurement applications. In [2], the Newton Type Algorithm (NTA) is proposed for frequency and spectra estimation. An efficient application for power components measurement and power quality indices evaluation is presented in [3]-[4].

This paper evaluates the nature of interharmonic distortion in DFIGs. The NTA is applied for assessment of harmonic distortions in generator output current and the results obtained are compared with those achieved through application of the FFT. The results are also compared with the current signal recorded on a DFIG test rig.

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II. The Doubly Fed Induction Generator

Doubly fed induction generators (DFIGs) are widely used in modern variable speed wind turbines. A major benefit gained from employing DFIGs in wind power generation comes from the fact that these machines are capable of providing constant frequency output during transient operation. In addition, the development of decoupled active and reactive power flow control has made these even more attractive, as it minimizes the need for reactive power compensation.

A typical DFIG topology used in contemporary wind power applications is shown in Fig. 1. It comprises of a wound rotor induction machine whose rotor circuit is excited at slip frequency from a back-to-back PWM converter; the stator circuit is connected directly to the grid and generates power at supply frequency.

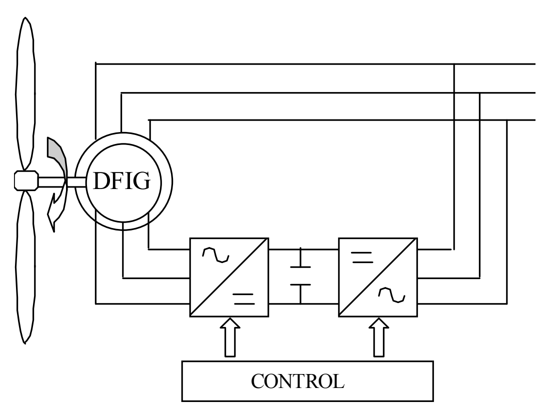

Fig. 1. Doubly Fed Induction Generator – DFIG.

The rotor circuit converter typically consists of two converter units coupled by a dc link. Here the rotor side converter regulates the voltage applied to the generator secondary circuit and enables the application of torque and speed vector control algorithms, and consequently makes it possible to independently manipulate active and reactive power flow between the generator and the grid. The grid side converter however employs a control system that enables the dc link voltage to be kept at a constant value and also provides a unity power factor connection to the grid [5]-[6].

III. The Newton-Type Algorithm

This section focuses on the presentation of the Newton Type Algorithm used in the processing of the DFIG stator current signal recorded on the DFIG laboratory test rig. The Newton Type Algorithm is a very efficient numerical algorithm aimed for simultaneous estimation of power spectrum and signal frequency. As a nonlinear parameter estimation method, it assumes the following observation model of the input signal:

$$s(t) = h(\mathbf{x}, t) + \xi(t) \tag{1}$$

where $s(t)$ is an instantaneous signal at time t, $\xi(t)$ is a random noise and h is a nonlinear function expressed in the most general way as follows:

$$h(\mathbf{x}, t) = S_0 e^{-\delta t} + \sum_{k=1}^{M} S_k \sin(k\omega t + \varphi_k) \tag{2}$$

and $\mathbf{x}$ is a suitable parameter vector of unknown parameters given by:

$$\mathbf{x} = [S_0, \delta, \omega, S_1, \ldots, S_M, \varphi_1, \ldots, \varphi_M]^T \tag{3}$$

where S_0 is the magnitude of the decaying dc component at t=0, δ=(1/T), T is the time constant, M is the highest order of the harmonics presented in the signal, ω is the fundamental angular velocity equal to $2\pi f$, with f being the signal frequency, and S_k and φ_k are the magnitude and the phase angle of the kth harmonic, respectively.

If the input signal is uniformly sampled with the sampling frequency f_s, then the value of t at a discrete time is given by $t_m = mT_s$, being T_s the sampling period ($T_s = 1/f_s$), and the following discrete representation of the signal model should be used:

$$s_m = h(\mathbf{x}_m, t_m) + \xi_m, \qquad m = 1,2,3,\ldots \tag{4}$$

$$h(\mathbf{x}_m, t_m) = S_{0m} e^{-\delta mt} + \sum_{k=1}^{M} S_{km} \sin(k\omega_m t_m + \varphi_{km}) \tag{5}$$

The number of unknowns is equal to $n=2M+3$. The selection of a simplified model for the input model (i.e., to consider only the fundamental component) reduces the number the unknowns and so the order of the model. The vector of unknown parameters, $\mathbf{x}$ (see equation (3)), is estimated by applying the following formula:

$$\hat{\mathbf{x}}_{i+1} = \hat{\mathbf{x}}_i + \left(\mathbf{J}_i^T \mathbf{J}_i\right)^{-1} \mathbf{J}_i^T \left(\mathbf{s} - \mathbf{h}(\hat{\mathbf{x}}_i, t)\right) \tag{6}$$

where i is an iteration index, $\mathbf{J}$ is a Jacobian matrix, $\mathbf{s}$ is a measurement vector and $\mathbf{h}$ is the vector of nonlinear functions defined by (2).

The elements of the Jacobian matrix $\mathbf{J}$ are the partial derivatives of the signal (2). Let us denote with $\mathbf{j}$ an arbitrary row of the Jacobian

$$\mathbf{j} = [j_1, j_2, j_3, \ldots, j_{3+2M}] \tag{7}$$

$$j_1 = \frac{\partial h(\mathbf{x})}{\partial S_0} = e^{-\delta t} \tag{8}$$

$$j_2 = \frac{\partial h(\mathbf{x})}{\partial \delta} = -S_0 e^{-\delta t} \tag{9}$$

$$j_3 = \frac{\partial h(\mathbf{x})}{\partial \omega} = \sum_{k=1}^{M} S_k kt \cos(k\omega t + \varphi_k) \tag{10}$$

$$j_{3+k} = \frac{\partial h(\mathbf{x})}{\partial S_k} = \sin(k\omega t + \varphi_k) \tag{11}$$

$$j_{3+M+k} = \frac{\partial h(\mathbf{x})}{\partial \varphi_k} = S_k \cos(k\omega t + \varphi_k) \tag{12}$$

where k=1,…,M.

The elements of the Jacobian are calculated from the estimates obtained in the previous step, where the data belonging to the preceding data window were processed.

The application of this algorithm requires the selection of the sampling frequency and the length of the data window T_{dw}. An initial guess for the unknown parameters $\mathbf{x}_0$ must be also provided, and it can be obtained by using FFT.

A more detailed discussion on the NTA algorithm may be found in [2]-[4].

IV. Laboratory Test

Experimental results for stator line current obtained from the DFIG laboratory test rig are presented in this section. The rig consists of a wound rotor induction machine that is mechanically coupled to a DC motor. The motor drives the generator thus making it possible to experimentally achieve a range of sub- and super-synchronous operating points. The induction machine rotor circuit is excited from an industrial back-to-back converter, shown in Fig 2.

Fig. 2. Rotor circuit back-to-back converter

The rig is designed to enable DFIG operation at a selected operating point, characterized by a constant sub- or super-synchronous speed. Steady state operation is thus established through running the generator at a pre-chosen constant speed, setting the power converter to provide adequate rotor circuit excitation and loading the DFIG.

For the purpose of this work the DFIG operating speed was set at 1680 rpm in the tests. The rotor circuit excitation frequency f_R is defined by the corresponding slip frequency formula:

$$f_R = \frac{p\omega_R}{2\pi} - f_S \tag{13}$$

where p is the number of pair poles, f_S is the supply frequency (50Hz), and ω_R is the rotor speed (rad/s).

A DFIG steady state stator line current trace was recorded in the test with a sampling frequency of 2kHz. The total observation time was 5 s. A zoomed in section of the registered signal is shown in time domain in Fig. 3.

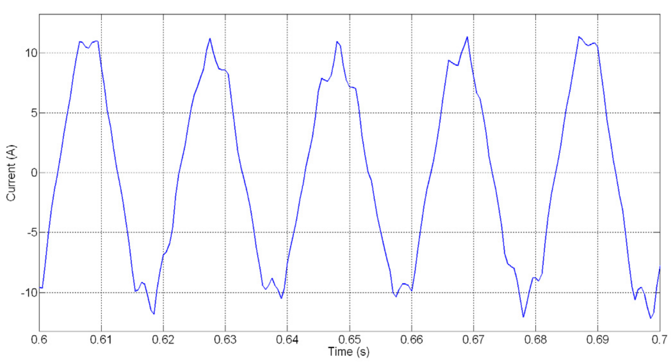

Fig. 3. Current signal provided by the DFIG

The current signal exhibits a considerable harmonic distortion, as is shown in the harmonic spectrum shown in Fig. 4. Even though higher harmonic frequencies caused by the converter were not detected with the sampling frequency considered, lower harmonic components caused by the generator itself were registered.

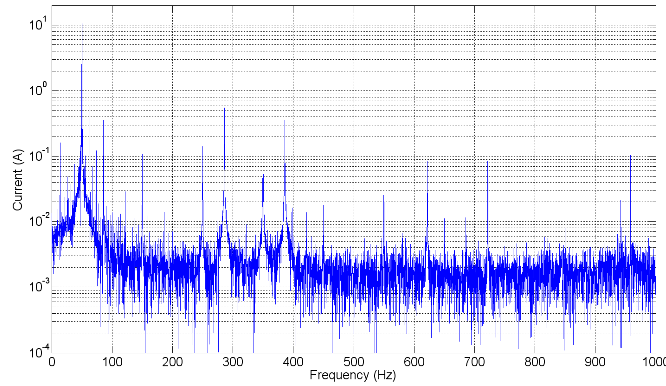

Fig. 4. Harmonic spectra of the current signal provided by the DFIG

Harmonic components at 150Hz, 250Hz, 350Hz, etc are obvious in the spectra. These are mostly introduced from the power supply, but can also arise from magnetic saturation in the machine. In addition, other harmonics are also noticeable in the spectrum, most noticeably at 286 Hz, 386 Hz, 622 Hz, 722 Hz and 958 Hz. The frequencies of these components are slip dependant and the electromagnetic phenomena leading to their generation is explained in detail in [7].

V. Estimation Results

In this section, the results obtained when estimating the current signal from the measured samples are presented. Both the FFT and the previously described Newton-type algorithm have been applied to estimate the unknown signal parameters. Given that the FFT allows only the estimation of the magnitude of the DC component, no time constant was included in the signal model to represent the evolution of this component. All the simulation tests were carried out for the sampling frequency f_s of 2 kHz and the selected data window size was $T_{dw} = 4T_0$ ($T_0 = 0.02$ s).

The existence of interharmonic components in the real signal makes the application of the FFT in the estimation process more difficult as it makes necessary the adoption of a convenient data window size so that interharmonic frequencies can be appropriately represented and a more precise estimation can be calculated. However, this approach to include interharmonic components in the estimation process leads also to increase in computation time, which is undesirable in real time applications.

The result obtained when applying FFT to estimate the DFIG current signal parameters is shown in Fig. 5. The data window size of $T_{dw} = 4T_0$, means that harmonic components at multiples of 12.5 Hz, in the range 0 – 1 kHz, were considered in the calculation process. A very good correlation between the real signal and its estimation is observed. The time evolution of the magnitude of both the fundamental component and the closest interharmonic components to those existing in the real signal is represented in Fig. 6, showing also a great similarity with the amplitudes provided by the harmonic spectra depicted in Fig. 4.

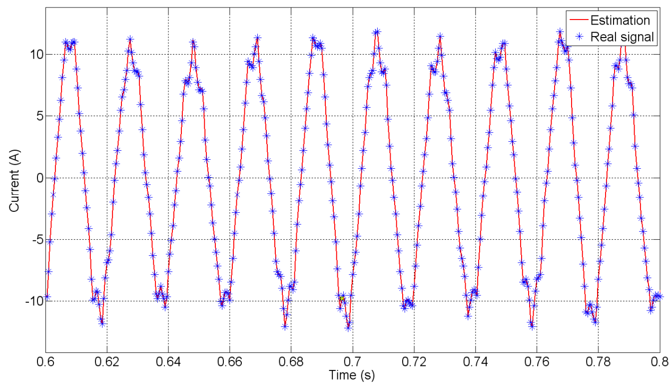

Fig. 5. DFIG current signal estimated by FFT (harmonics of frequency multiple of 12.5 Hz from 0 to 1 kHz)

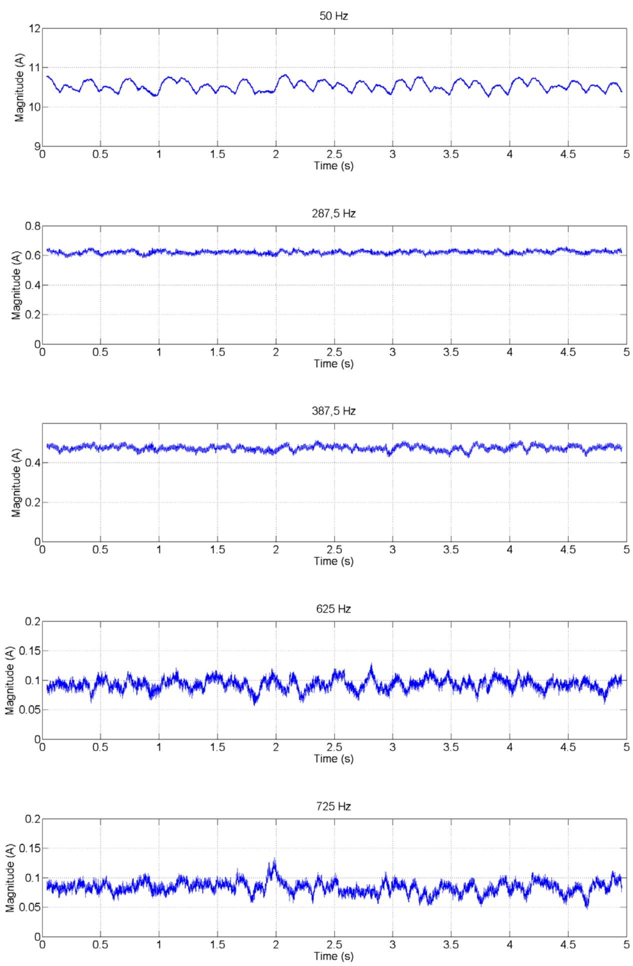

Fig. 6. Evolution of the amplitude of harmonic components estimated by FFT (harmonics of frequency multiple of 12.5 Hz from 0 to 1 kHz)

The results obtained when applying the NTA are presented in Figs. 7 and 8. In this first simulation a constant frequency of 50 Hz was assumed, as well as all harmonic components at frequencies multiple of 12.5 Hz, in the range of 0 – 1 kHz. Similarly to the results obtained when applying FFT, a very good correlation is achieved with the real signal and the predictions for corresponding harmonic component magnitudes exhibit consistent behaviour to that observed in Figs. 4 and 6. This result confirms the capability of NTA to work with highly distorted signals.

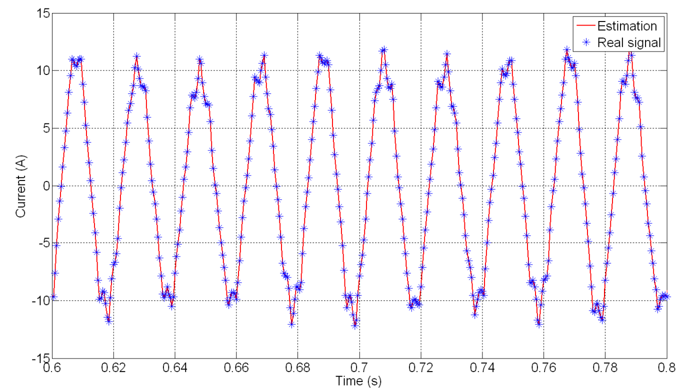

Fig. 7. DFIG current signal estimated by NTA (harmonics of frequency multiple of 12.5 Hz from 0 to 1 kHz)

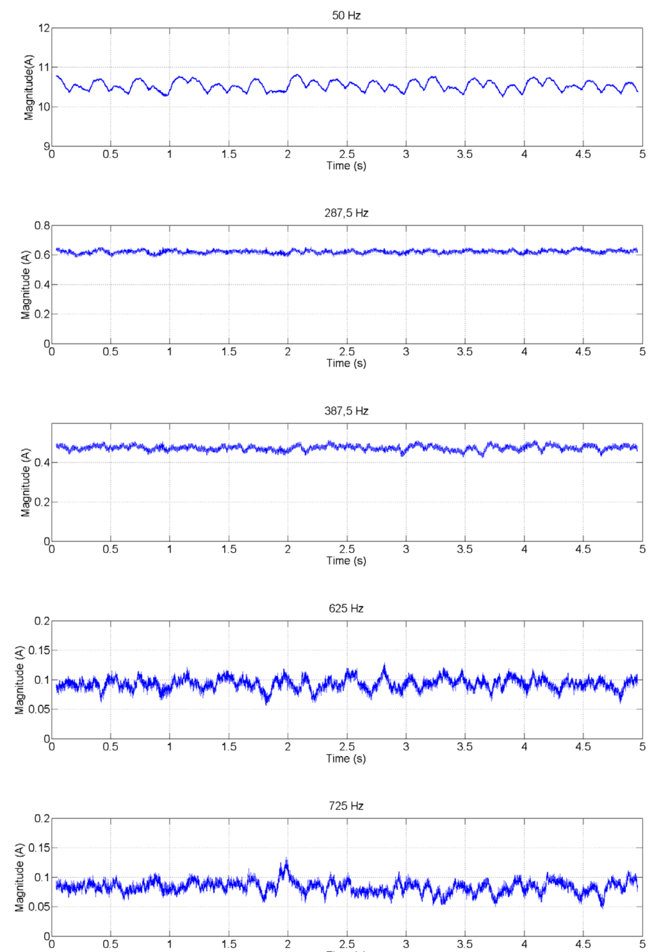

Fig. 8. Evolution of the amplitude of harmonic components estimated by NTA (harmonics of frequency multiple of 12.5 Hz from 0 to 1 kHz)

However, the NTA has an advantage in the possibility of selecting the particular harmonics that will be included in the signal model. This makes it possible to reduce the number of unknowns and consequently the calculation time, while on the other hand obtaining a good estimation of parameters of the real signal when a proper signal model has been defined. In order to evaluate the influence of considering the interharmonic distortion in the signal model two different tests were developed to estimate the DFIG current signal.

The first test accounts for only the odd harmonics in the range 0 – 1 kHz. In the second test, the interharmonics at frequencies 286, 386, 622, 722 and 958 Hz registered in the real signal were also included. In Figs. 9 and 10, the real signal and the signal estimated in each test are represented. The results illustrate that when taking into account interharmonic distortion a better estimation of the measured signal is achieved.

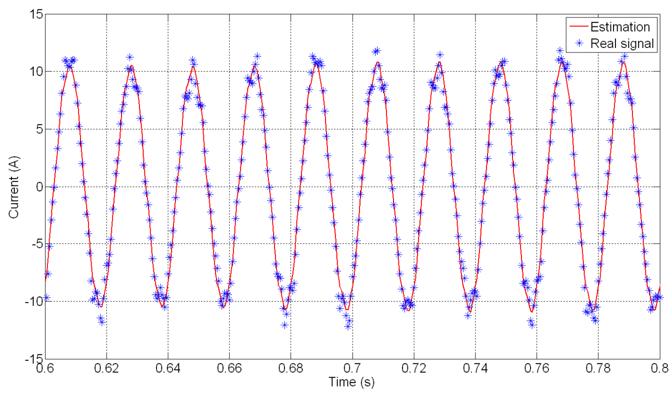

Fig. 9. DFIG current signal estimated by NTA (odd harmonics from 0 to 1 kHz)

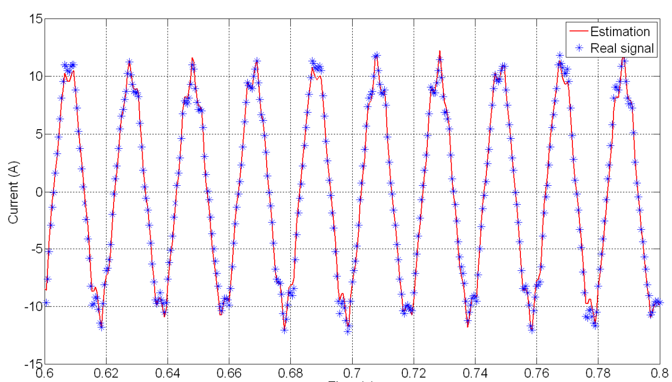

Fig. 10. DFIG current signal estimated by NTA (odd harmonics from 0 to 1kHz and interharmonics at 286, 386, 622, 722 and 958 Hz)

In this case, the magnitude of the harmonic components is consistent with the harmonic spectra shown in Fig. 4, and also similar to the results obtained when a more complete signal model was considered (Figs. 6 and 8), as it is represented in Fig. 11.

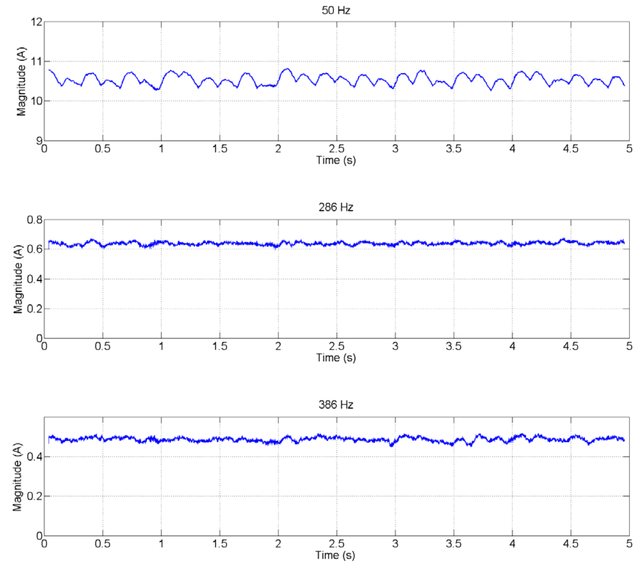

Fig. 11. Evolution of the amplitude of harmonic components estimated by NTA (odd harmonics from 0 to 1kHz and interharmonics at 286, 386, 622, 722 and 958 Hz)

Finally, another important feature of the NTA is the application for signal frequency estimation, as signal frequency may be considered not to be constant but variable in time, and so may also be considered to be an unknown signal parameter. This characteristic avoids the issue of FFT sensitivity to frequency variations and offers the possibility of applying the NTA in transient processes where frequency variations commonly occur. To evaluate the behaviour of the algorithm to perturbations in the signal frequency, an additional simulation was developed where, similarly to before, odd harmonics up to 1 kHz as well as interharmonic distortion were considered in the calculations and signal frequency was assumed to be unknown. As expected, no difference in the results for estimated signal (Fig. 12) or in the calculated magnitude of harmonic components can be noticed when compared to predictions where constant frequency was considered.

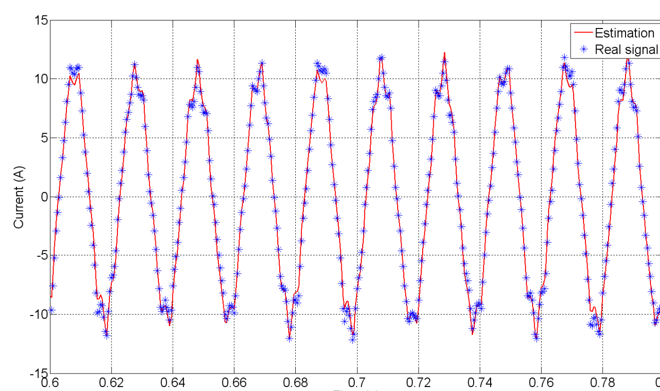

Fig. 12. DFIG current signal estimated by NTA considering variable frequency (odd harmonics from 0 to 1 kHz and interharmonics at $5.72f_s$, $7.72f_s$, $12.44f_s$, $14.44f_s$ y $19.16f_s$)

VI. CONCLUSION

The ability of NTA to estimate highly distorted signals has been confirmed. This technique has been successfully applied in the processing of the DFIG current signal obtained from the laboratory tests. The ultimate objective of the processing has been to analyze the effect of interharmonic distortion on the estimation process. The presented analysis quantifies the influence of interharmonics on the frequency and spectrum estimation and demonstrates that failing to account for interharmonic distortion may lead to greater errors in the estimation process.

In addition, the results achieved when applying the NTA have been compared with those provided by the FFT, observing a high similarity between them. However, the higher flexibility of the NTA in building the signal model and the possibility of considering the signal frequency as an unknown parameter makes it a highly versatile tool for use in real time applications and in transient processes with off-nominal frequency conditions.

VII. REFERENCES

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VIII. BIOGRAPHIES

Esther Torres received her M.Sc. and Ph.D. degrees in Electrical Engineering from the University of the Basque Country, Spain, in 1998 and 2008. At present, she is Assistant Professor at the Department of Electrical Engineering of the University of the Basque Country. Her research interests are currently in the area of power distribution systems, power quality and distributed generation.

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Vladimir Terzija (M'95, SM'2000) is the EPSRC Chair Professor in Power System Engineering in the School of Electrical and Electronic Engineering, The University of Manchester, where he has been since 2006. From 1997 to 1999, he was an Assistant Professor at the University of Belgrade. In 1999, he was awarded a prestigious Humboldt Research Fellowship. From 2000 to 2006, he was with ABB AG, Germany, working as an expert for switchgear and distribution automation. His main research interests are application of intelligent methods to power system monitoring, control, and protection, switchgear and fast transient processes, as well as DSP applications in power systems.

Steve Williamson (M'81, SM'88, F'95) received the first degree and Ph.D. in electrical engineering from Imperial College, London, U.K. He first took up a lectureship at Aberdeen University. Leaving Aberdeen in 1981, he moved back to Imperial College. In 1989, he became a Professor in the Department of Engineering at Cambridge University, Cambridge, U.K., and shortly afterwards a Fellow at St. Johns College. In 1997, he left the university system to take up the post of Group Technical director for Brook Hansen. Afterwards, he moved back to the academe, this time at the University of Manchester, Manchester, U.K, where he was Head of the School of Electrical and Electronic Engineering. He is currently the deputy vice-chancellor for research and innovation at the University of Surrey, Guilford, U.K. Dr. Williamson is a Fellow of the Royal Academy of Engineering.