

DFIG Based Wind Turbines Behavior Improvement during Wind Variations using Fractional Order Control Systems

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Abstract: This paper is concerned with behavior analysis and improvement of wind turbines with Doubly Fed Induction Generator (DFIG) when using a new fractional-order control strategy during wind variations. A doubly fed induction generator, two types of variable frequency power electronic converters and two input wind waveforms are considered. A fractional-order control strategy is proposed for the wind turbine control unit. Output parameters of the wind turbine are drawn by simulations using MATLAB/Simulink for both fractional-order and integer-order (classic) control systems and a complete comparison between these two strategies has been presented. Results show a better operation when using fractional-order control system.

Keywords: Control Strategy, DFIG, Fractional-Order, Integer-Order, Wind Turbine.

1 Introduction

Wind energy is rising rapidly and will become an important source of electricity in the future years because wind is available and often abundant in many regions of the world. Significant resources of wind energy are found on every continent and country. Exploiting maximum energy from only the worlds windiest locations can provide 13 times more electricity than all the electricity produced worldwide [1].

The overall performance of the electrical grid is increasingly affected by the characteristics of wind turbines as the wind energy share grows in power generation. Two major concerns related to wind turbines are the impact on power quality and power system stability [2]. Power quality of the wind power plants must be in proper and standard range. Thus, the Total Harmonic Distortion (THD) must be kept as low as possible [3]. Also, the power injected to the grid and the PCC voltage must remain steady and with little variations during disturbances.

The Doubly Fed Induction Generator (DFIG) is the most popular generator in the wind power industry [4]. It has the ability of controlling the active and reactive power independently with adjusting the rotor current. So power factor control is achieved in this system [5]. The study of output behavior of renewable energy technologies including power quality is vital in order to analyze their influence on the power systems [6].

A recent article published in [7] has labeled fractional-order continuous-time systems as the “21st century control systems”. Fractional calculus can be defined as the generalization of integer-order calculus to arbitrary chosen orders [8]. A fractional-order control system is more complex than the integer-order but it can improve the behavior of the origin system which in this paper is output parameters of a wind turbine.

This paper focuses on analyzing the output behavior of wind turbines with DFIG when using fractional-order control system and improves the power quality and power and voltage stability in comparison with using classic control system during wind variations, considering two types of ac/dc/ac power electronic converters. Also, modeling, control and simulation of wind turbine with PMSG using fractional-order control system can be found in [9]. The simulation results are shown in the last sections by using MATLAB/Simulink. A better operation can be seen when utilizing fractional-order control strategy.

This paper is organized as follows: Section 1 gave an introduction about the subject. Section 2 presents the components of the wind turbine with DFIG. Section 3 introduces fractional-order control systems and brings forward the detailed block diagrams of control unit used for simulations. Section 4 shows the simulation results and analyzes them. Finally conclusions are given in section 5.

2 Components of Wind Turbine with DFIG

The use of power-electronic converters makes variable-speed operation of the wind turbines possible and so enhancing the power extraction. It has been

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shown in recent studies that variable speed concepts with power electronics will dominate and be very promising technologies for wind farms for now and the future [10].

The main components of the variable speed wind turbines with DFIG are: turbine, gearbox, holding brake, generator, converter, transformer, control unit, protection system, mechanical supports, nacelle housing, and wind sensors. The block diagram of wind turbine with DFIG is shown in Fig. 1. The related control unit block diagram of this type of wind turbine has also been illustrated in Fig. 2. Two important components including DFIG and the converter are described in this section.

2.1 DFIG

The DFIG based wind turbine is widely utilized in today's wind energy industry and is the dominant technology [11]. The DFIG is a wound rotor induction generator that can handle variable-speed operation by using external devices in rotor circuit for controlling the rotor voltage and frequency. As Fig. 1 shows, the stator of the generator is directly connected to the grid through a transformer, but the rotor connection to the grid must be done through a back to back power converter and the transformer [12].

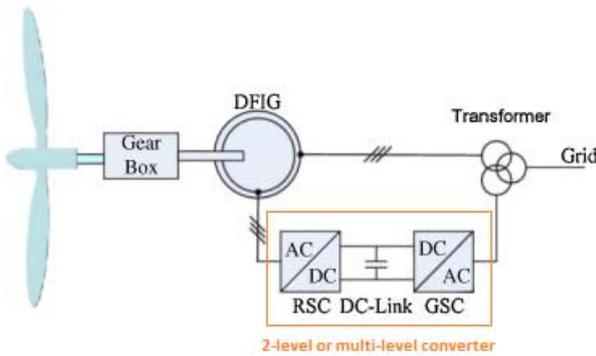


Fig. 1 Block diagram of wind turbine with DFIG.

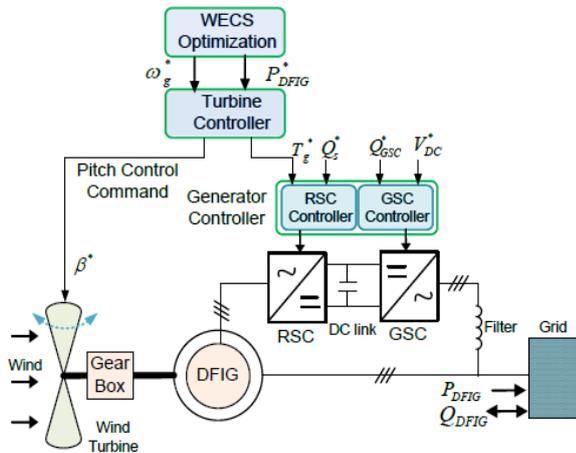


Fig. 2 Control unit block diagram [4].

The dynamics of the DFIG is represented by a fourth-order state space model using the dq-frame as given in Eq. (1) to Eq. (4) [4]:

$$V_{qs} = r_s I_{qs} + \omega_e \lambda_{ds} + \frac{d}{dt} \lambda_{qs} \quad (1)$$

$$V_{ds} = r_s I_{ds} - \omega_e \lambda_{qs} + \frac{d}{dt} \lambda_{ds} \quad (2)$$

$$V_{qr} = r_r I_{qr} + (\omega_e - \omega_r) \lambda_{dr} + \frac{d}{dt} \lambda_{qr} \quad (3)$$

$$V_{dr} = r_r I_{dr} + (\omega_e - \omega_r) \lambda_{qr} + \frac{d}{dt} \lambda_{dr} \quad (4)$$

where V_{ds} , V_{qs} , V_{dr} , V_{qr} , are the d and q axis stator and rotor voltages, I_{ds} , I_{qs} , I_{dr} , I_{qr} , are the d and q axis stator and rotor currents, λ_{ds} , λ_{qs} , λ_{dr} , λ_{qr} , are the d and q axis stator and rotor fluxes, respectively. ω_r and ω_e are the angular velocity and the synchronous angular velocity. r_s and r_r are the stator and rotor resistances, respectively.

Assuming negligible losses in stator and rotor windings, the active and reactive power from stator and rotor are given as [4]:

$$P_s = -1.5[V_{qs} I_{qs} + V_{ds} I_{ds}] \quad (5)$$

$$Q_s = -1.5[V_{qs} I_{ds} - V_{ds} I_{qs}] \quad (6)$$

$$P_r = -1.5[V_{qr} I_{qr} + V_{dr} I_{dr}] \quad (7)$$

$$Q_r = -1.5[V_{qr} I_{dr} - V_{dr} I_{qr}] \quad (8)$$

And T_e which is the electromagnetic torque of the generator can be written as follows:

$$T_e = \frac{3}{2}[\lambda_{qs} I_{ds} - \lambda_{ds} I_{qs}] \quad (9)$$

2.2 Power Converter

Adjusting the amplitude, phase and frequency of the rotor voltage makes generator torque, active and reactive power through the stator and rotor and the dc-link voltage controllable [13].

The power converter is made up of a back to back ac/dc/ac converter connecting the rotor circuit to the grid. The converters are typically made up of voltage source inverters equipped with IGBTs provided with freewheeling diodes, which enable a bi-directional power flow [4]. In this paper two types of converter is used for more analysis of the behavior. A 2-level converter is an ac/dc/ac converter, consisting of 6 IGBTs as a rectifier and 6 IGBTs as an inverter. The configuration of a 2-level converter is shown in Fig. 3.

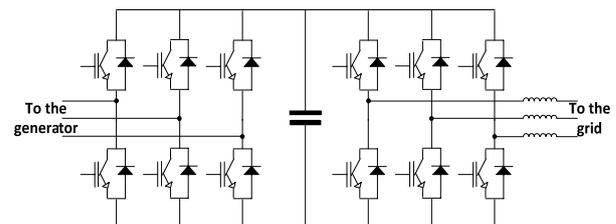


Fig. 3 2-level Power converter.

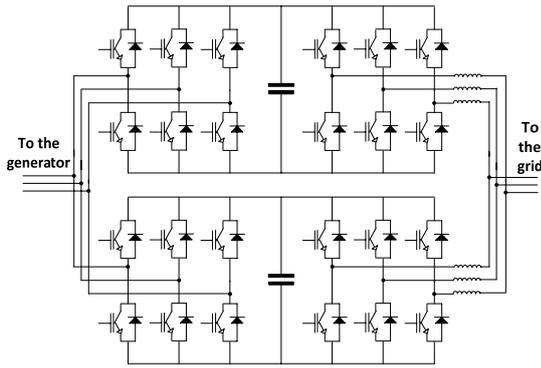


Fig. 4 multi-level Power converter.

A multi-level converter is also an ac/dc/ac converter, consisting of 12 IGBTs as a rectifier and 12 IGBTs as an inverter. The configuration of a multi-level converter is shown in Fig. 4.

As mentioned before, control of the DFIG is achieved by controlling rotor voltage and frequency with the converter, which includes control of the Rotor Side Converter (RSC) and control of the Grid Side Converter (GSC). The aim of the RSC control is to allow the DFIG wind turbine to control active and reactive power independently. This feature makes the wind turbine very flexible which enables maximum power capture from the wind on the one hand and on the other hand controlling the reactive power injected to the grid and so the power factor at the Point of Common Coupling (PCC). The objective of the GSC is to keep the dc-link voltage at proper and constant value [4].

Power electronic converters have harmonic injection into the grid. These harmonics lead to power quality distortion. The THD that shows the harmonic behavior of a signal is defined as follows [14]:

$$\text{THD}(\%) = 100 \frac{\sqrt{\sum_{H=2} X_H^2}}{X_F} \quad (10)$$

where X_H is the RMS value of the non-fundamental H harmonic component, and X_F is the RMS value of the fundamental component harmonic.

3 Fractional-Order Control System

A fractional-order control system means a system with controllers using fractional-order differential and integral calculus. In fractional-order calculus, the order of system can be arbitrary (non-integer). Fractional calculus can be defined as the generalization of integer-order calculus. Though the concepts of fractional-order calculus are new, the first idea took place in a famous letter from Leibniz to Hopital in 1695 [8]. For understanding the meaning of fractional-order dimensions, Fig. 5 can be helping [15].

Application of fractional-order control systems has considerably grown in practical control and engineering fields.

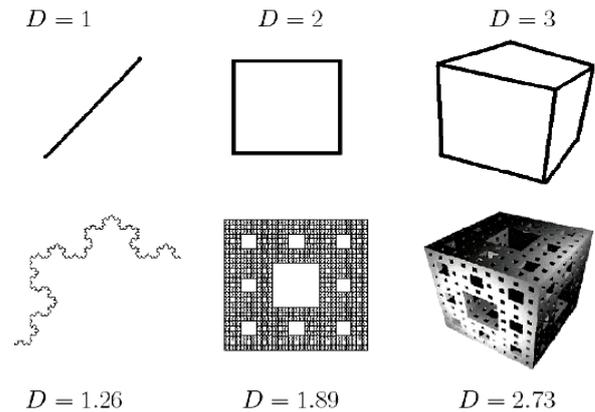


Fig. 5 Integer and fractional-order dimensions [15].

Designing a control system based on fractional-order controllers is more complex than classic control systems but it will make the control system capable of improving the behavior of the origin system. Obviously, arbitrary-order controllers have a better flexibility than integer-order controllers for adjusting their characteristics. So fractional-order controller is a powerful and flexible tool in designing of control system parameters [15]. One particular and important feature of fractional-order operator that is concluded from Riemann–Liouville and Grunwald–Letnikov’s definitions is that fractional-order derivative and integral are made up of series with infinite number of terms whereas putting integer order in these definitions makes the terms number finite. This feature means the integer-order operator is a local operator while the fractional-order operator acts global and has an infinite memory so that affects all the input signals from the beginning to make the next output signal [16].

The fractional derivative and integral operator can be shown as ${}_a D_t^\mu$ so:

$$\begin{aligned} \text{for } \Re(\mu) > 0: \quad & {}_a D_t^\mu = \frac{d^\mu}{dt^\mu} \\ \text{for } \Re(\mu) = 0: \quad & {}_a D_t^\mu = 1 \\ \text{for } \Re(\mu) < 0: \quad & {}_a D_t^\mu = \int_a^t (d\tau)^{-\mu} \end{aligned} \quad (11)$$

where μ is the order of derivative or integral and $\Re(\mu)$ is the real part of μ [17].

The definition of Riemann–Liouville fractional-order integral is as follows [8]:

$$D_c^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_c^t (t-\tau)^{\alpha-1} f(\tau) d\tau, \quad t \geq c, \quad \alpha \in \mathbb{R}^+ \quad (12)$$

Also, the definition of Riemann–Liouville fractional-order derivative has the following form [8]:

$${}_R D^\alpha f(t) = D^m D^{-(m-\alpha)} f(t) = \frac{d^m}{dt^m} \left[\frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f(\tau)}{(t-\tau)^{\alpha-m+1}} d\tau \right] \quad (13)$$

where $m-1 < \alpha < m$ and $m \in \mathbb{N}$.

The equation for a fractional-order continuous-time dynamic system can be written as follows:

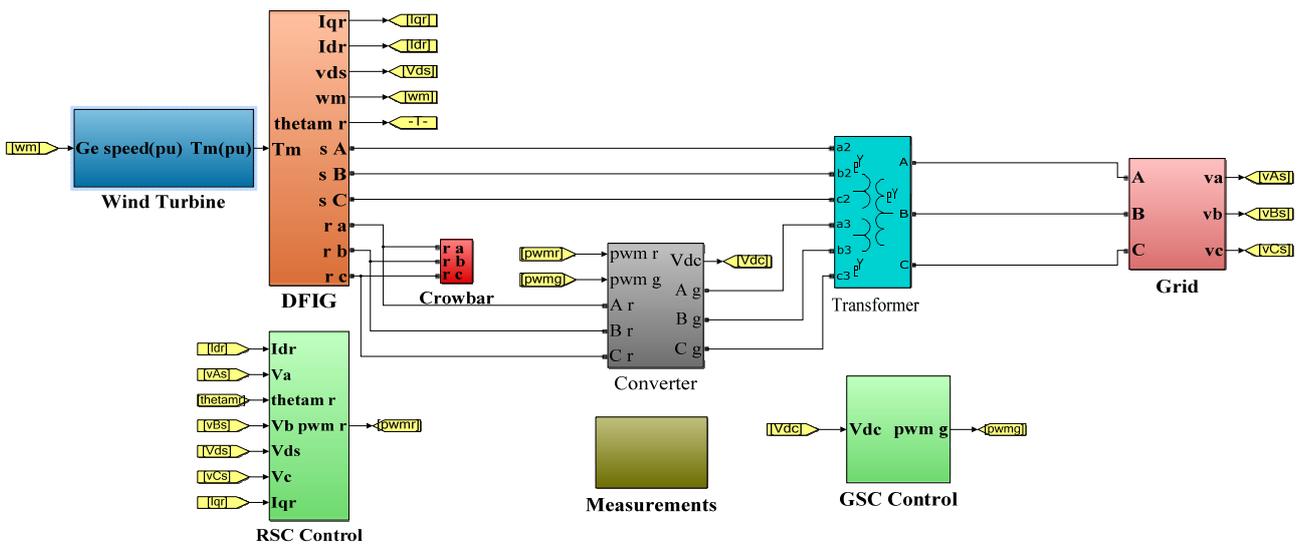


Fig. 8 Block diagram of wind turbine with DFIG in MATLAB.

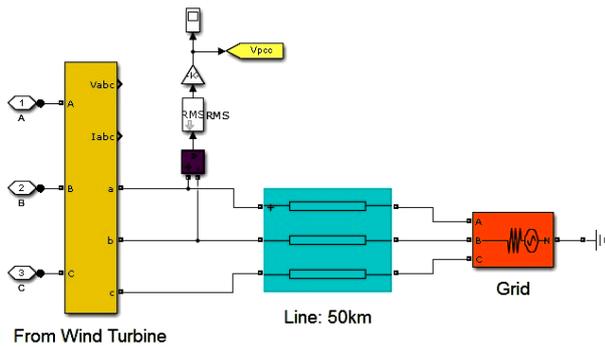


Fig. 9 Block diagram of the transmission line and the grid.

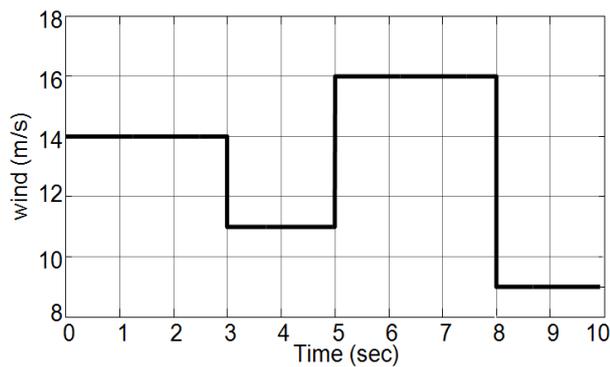


Fig. 10 step wind waveform.

4.2 Case 2: Wind with Random Variations

Fig. 23 shows a random wind waveform during 10 seconds. Figs. 24 to 29 show a comparison between total output reactive power, total output current, voltage at the point of common coupling, the THD of total

output current, THD of output stator current and THD of voltage at the PCC when using integer-order and fractional-order (with $\mu=0.5$) controllers, using a 2-level converter. Figs. 30 to 35 show the similar items using a multi-level converter.

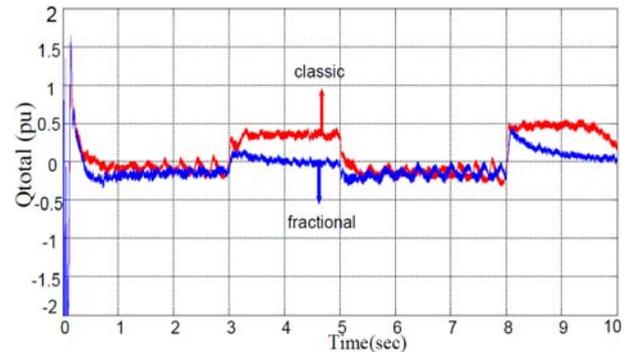


Fig. 11 Total output reactive power (2-level converter).

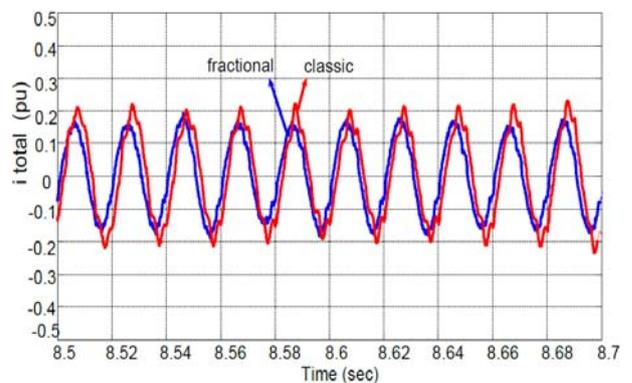


Fig. 12 Total output current (zoomed) (2-level converter).

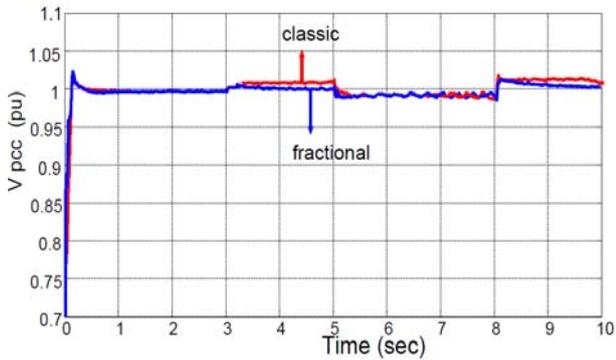


Fig. 13 Voltage at the PCC (2-level converter).

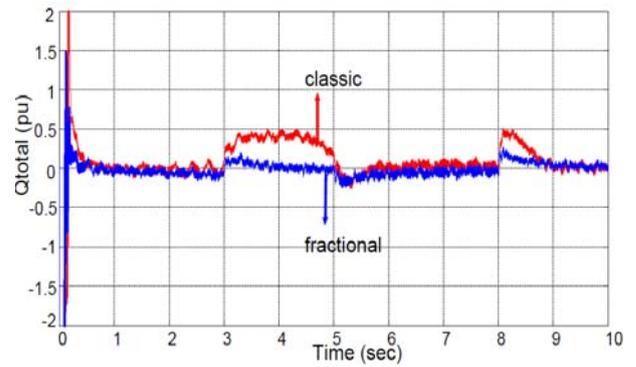


Fig. 17 Total output reactive power (multi-level converter).

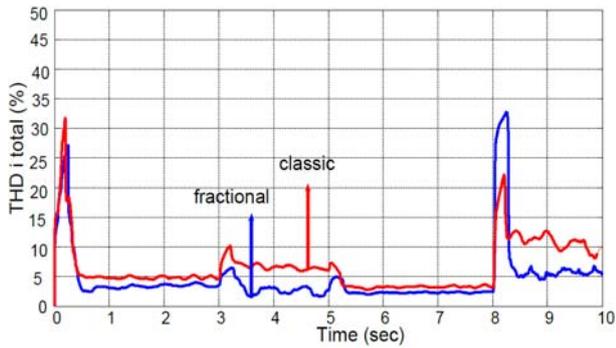


Fig. 14 THD of total output current (mean value) (2-level converter).

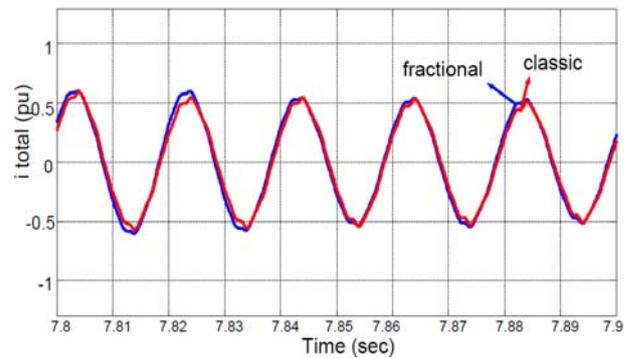


Fig. 18 Total output current (zoomed) (multi-level converter).

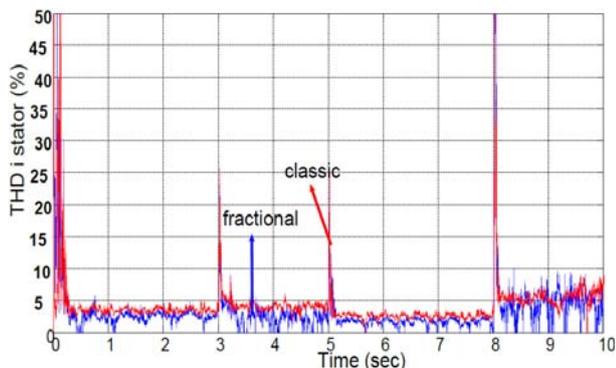


Fig. 15 THD of stator output current (2-level converter).

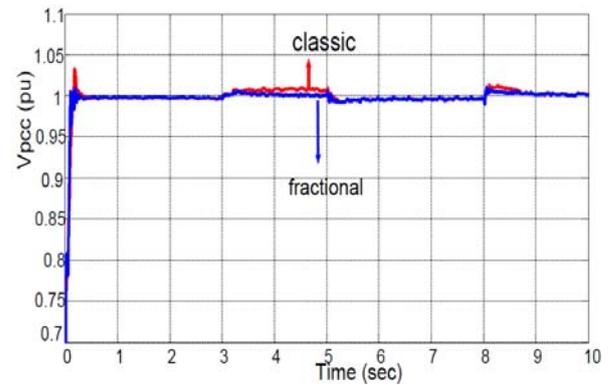


Fig. 19 Voltage at the PCC (multi-level converter).

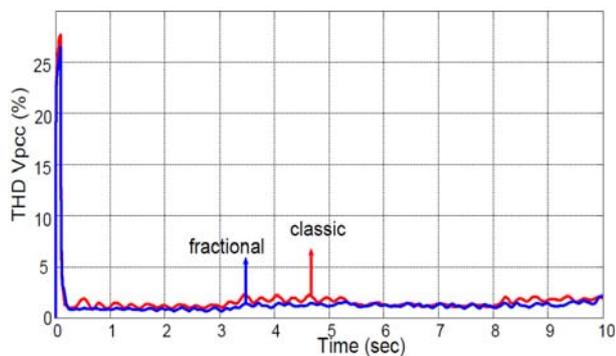


Fig. 16 THD of voltage at the PCC (2-level converter).

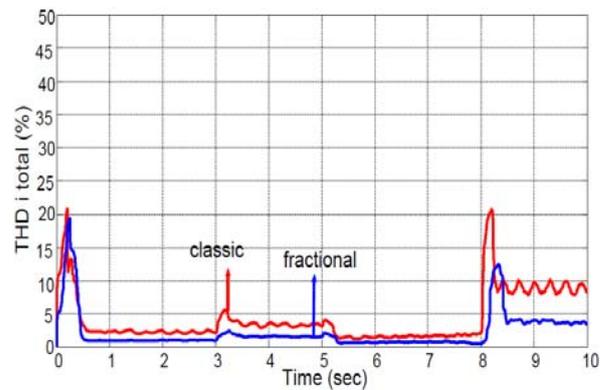


Fig. 20 THD of total output current (mean value) (multi-level converter).

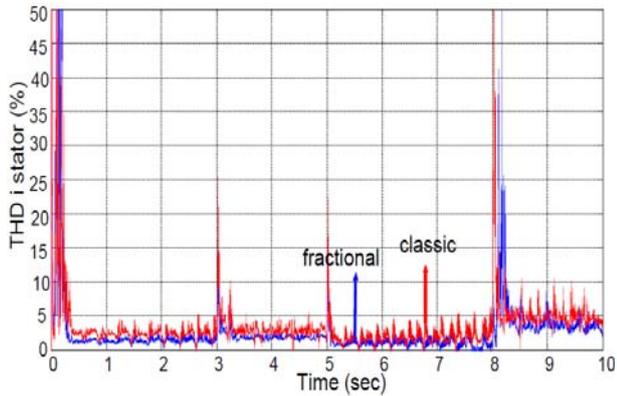


Fig. 21 THD of stator output current (multi-level converter).

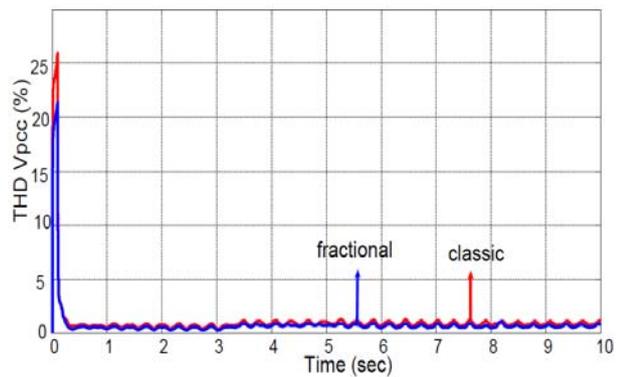


Fig. 22 THD of voltage at the PCC (multi-level converter).

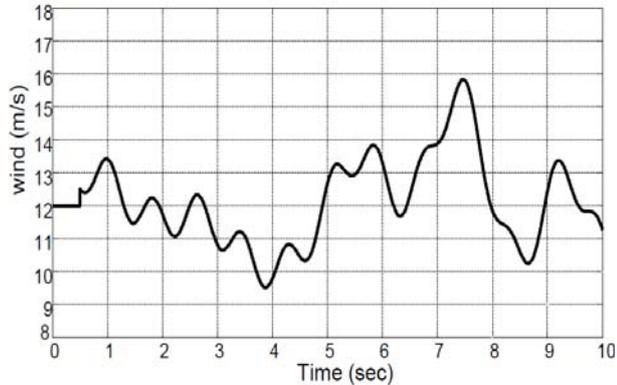


Fig. 23 Random wind waveform.

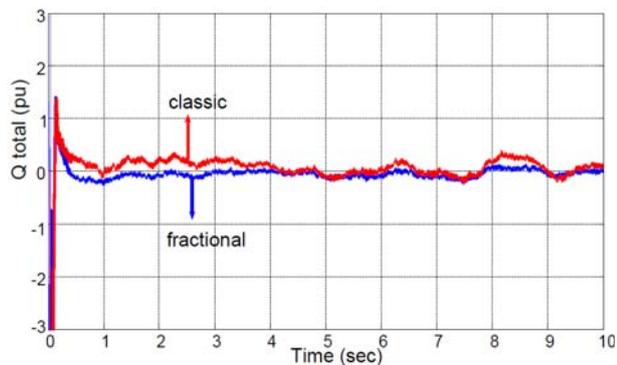


Fig. 24 Total output reactive power (2-level converter).

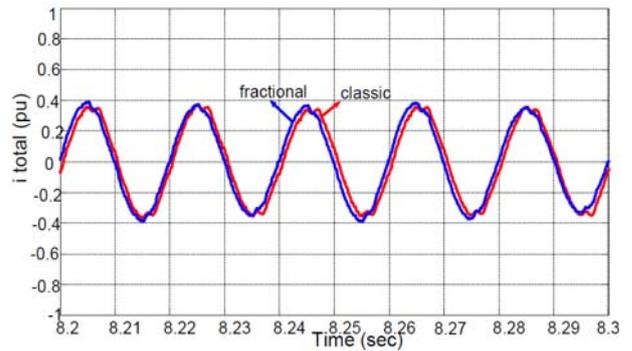


Fig. 25 Total output current (zoomed) (2-level converter).

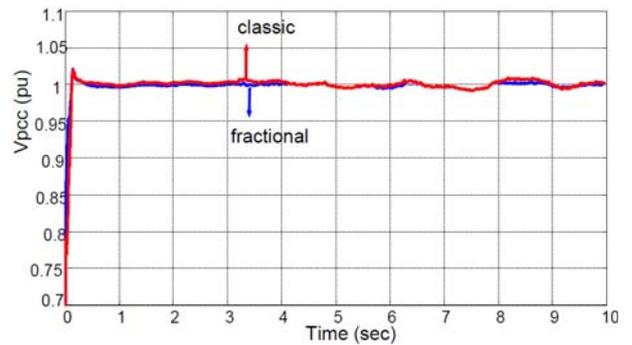


Fig. 26 Voltage at the PCC (2-level converter).

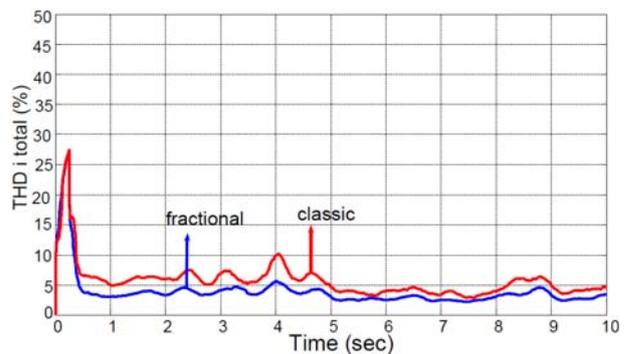


Fig. 27 THD of total output current (mean value) (2-level converter).

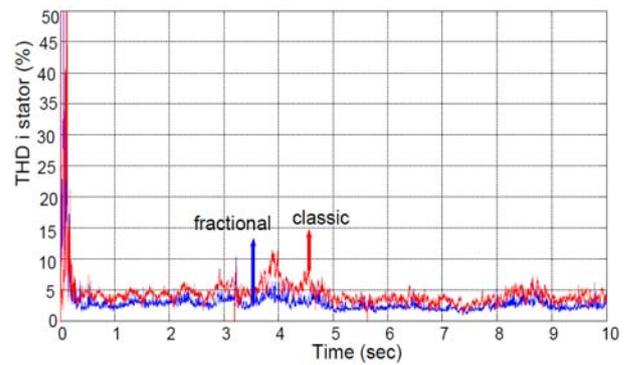


Fig. 28 THD of stator output current (2-level converter).

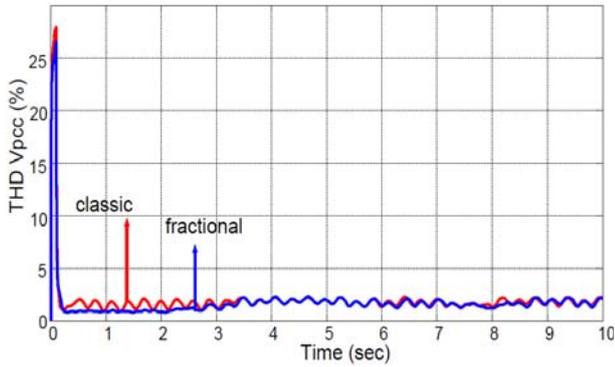


Fig. 29 THD of voltage at the PCC (2-level converter).

In Figs. 24 to 35 a random wind is considered, all these Figs. again confirm a better performance when using fractional-order control system comparing to classic control system and when using a multi-level power electronic converter comparing to a 2-level converter. For more analysis, according to figs. 14, 20, 27 and 33 the mean value of the THD of total output current can be calculated and compared in four conditions. This is shown in Fig. 36. Also using Figs. 11, 17, 24 and 30 the mean tolerance of the total output reactive power is shown in Fig. 37. It is obvious that a wind turbine with a fractional-order control unit and a multi-level converter has the best performance and improves the output behavior the most.

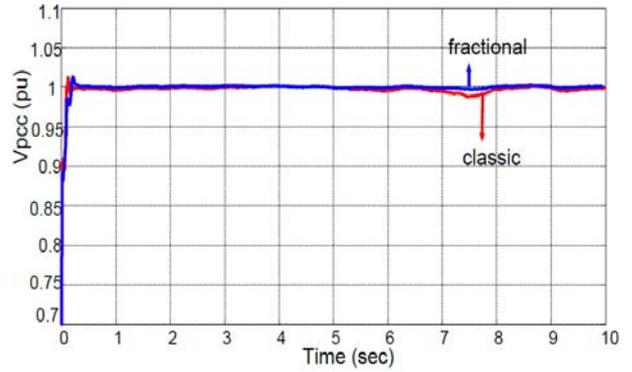


Fig. 32 Voltage at the PCC (multi-level converter).

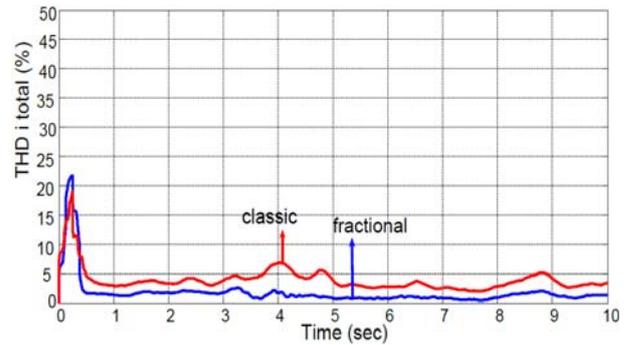


Fig. 33 THD of total output current (mean value) (multi-level converter).

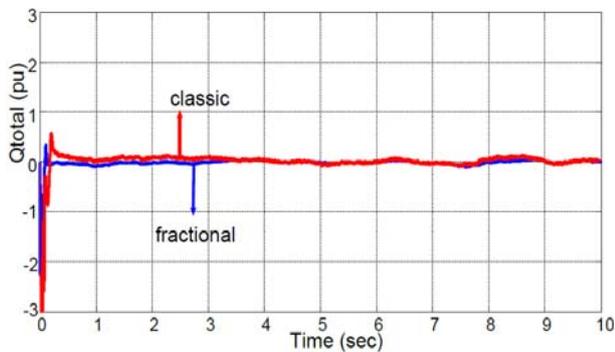


Fig. 30 Total output reactive power (multi-level converter).

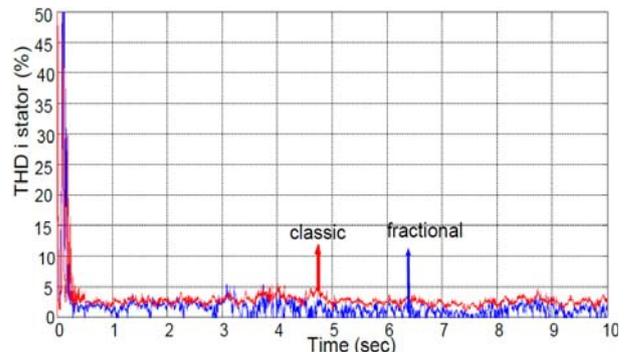


Fig. 34 THD of stator output current (multi-level converter).

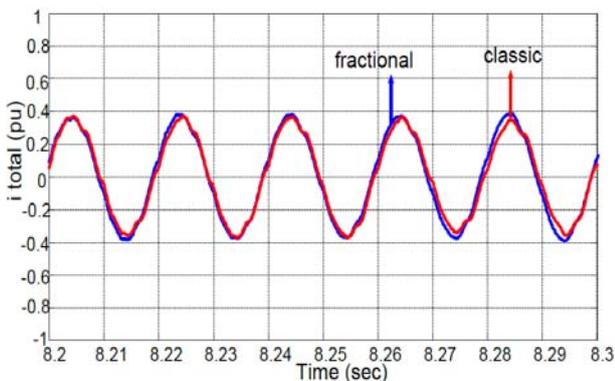


Fig. 31 Total output current (zoomed) (multi-level converter).

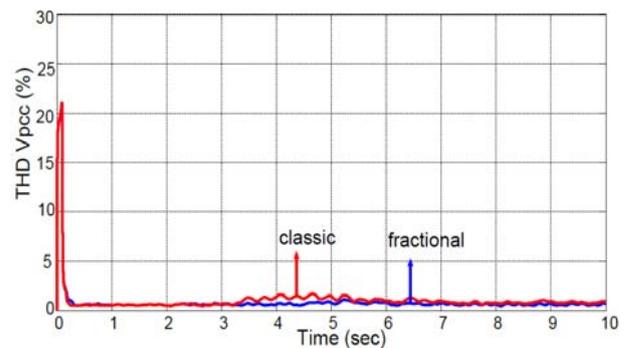


Fig. 35 THD of voltage at the PCC (multi-level converter).

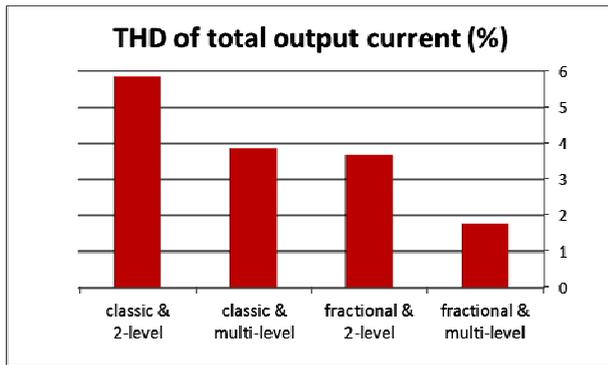


Fig. 36 The mean value of THD of the total output current (%).

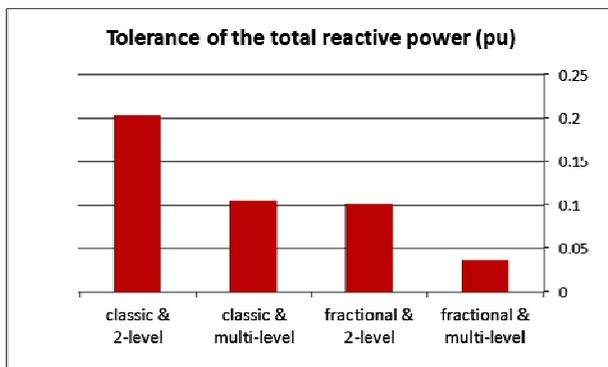


Fig. 37 The mean value of tolerance of the total Q (pu).

5 Conclusion

Among the renewable energy technologies, wind power is the world's fastest growing source. The overall performance of the electrical grid is increasingly affected by the characteristics of wind turbines as the wind energy share grows in power generation. This paper discussed employment of a new fractional-order control strategy in wind turbines with DFIG and gave a complete comparison of output parameters of the wind turbine considering classic and fractional-order control systems, with 2-level and multi-level converters. For two types of wind waveform, the wind power system was simulated with MATLAB/Simulink using fractional-order and integer-order controllers. Results show that utilizing fractional-order control system improves the stability of reactive power and voltage at the PCC and more importantly, it decreases the THD of total output current injected to the grid and the THD of stator current and also the THD of voltage at the PCC. It is concluded that fractional-order control strategy is more complex but improves the output behavior of the wind turbine with DFIG. As the last Figs. showed, changing the controllers from classic to fractional order improves the output behavior more than changing the converter from 2-level to multi-level and so with less costs a better performance can be achieved. After all, the wind turbine with a multi-level converter and a fractional order control unit has the best results.

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energies, wind turbines, Distributed Generation (DGs), and distribution systems.



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