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Improving Power Quality of Wind Energy Conversion System with Harmonic Filters

Gidwani Lata and H.P. Tiwari

Abstract—**The increasing interest to utilize wind energy as a power source prompted more researches to be dedicated to the efficient integration of this power source into the current grid. In this paper, one avenue to achieve this efficient utilization, through the use of integrated wind energy conversion system (WECS) using doubly fed induction generator (DFIG) is presented. Wind grid integration brings the problems of voltage fluctuation and harmonic distortion. This paper presents an efficient power electronic interface with harmonic filters to reduce the total harmonic distortion (THD) and enhance power quality during disturbances. A phase to phase fault is simulated on 132 kV bus and the measured results obtained from grid connection of the wind generation system are presented. The results have demonstrated the ability of power interface harmonic filters to reduce THD. The proposed system increases the effectiveness of the utilization of wind energy.**

Index Terms—**Doubly Fed Induction Generator, Efficient Power Electronic Interface, Power Quality, Total Harmonic distortion**

I. INTRODUCTION

THE increasing demand of energy from the growing modern society has created a concern in the last few decades. This is made worse by the fact that most of the current energy sources are exhaustible and depleting rapidly. Moreover, the combustion process of most of the current energy sources such as coal and fuel produces a high level or air pollution that causes global warming, which is a currently emerging problem. These issues have prompted the rapid development of many renewable energy sources over recent years, particularly the clean and pollution free wind energy that has an eligible rate of depletion. Thus, many efforts are dedicated to efficiently integrate wind energy into the grid network [1]-[2]. However, electric utility grid systems cannot readily accept connection of new generation plant without power electronic interface. Recent developments have made the trade-off benefits exceed the cost premium of machine in the power ranges up to several hundred kW. Considering these trends, one of the best topologies for wind power conversion system is the full size AC-DC-AC converter [3]-[4].

Power quality has also been a growing concern in recent years with many researches done in this area [5-6]. Harmonic emissions are recognized as a power quality problem for modern variable-speed wind turbines (WTs). For this reason, relevant standards require the measurement of harmonics [7]10] and their inclusion in the power quality certificates of WTs, and grid interconnection assessment procedures always comprise provisions for their control [11], [12]. In this paper, the WECS with harmonic filters capable of reducing THD noticeably during disturbances [13] is proposed. It has a pitchangled controlled wind turbine model, a DFIG model, a power system model with harmonic filters and EPEI having controlled converters. Simulations have been conducted with MATLAB/Simulink software to validate the model and the control schemes. This wind energy conversion system has many advantages, such as low total harmonic distortion, long distance between generator and converter possible, able to stand wide transients of grid voltage and current, and thus increase power quality. This paper is organized as follows. Section II presents modeling of wind turbine with DFIG. AC power grid model is present in Section III. Results and discussion are presented in Section IV. Finally important conclusions are summarized in Section V.

II. MODELING OF WIND TURBINE WITH DFIG

Half of the world‘s leading wind turbine manufacturers use the DFIG systems. This is due to the fact that the power electronic converter only has to handle a fraction (20% – 30%) of the total power, i.e., the slip power. This means that if the speed is in the range ±30% around the synchronous speed, the converter has a rating of 30% of the rated turbine power, reducing the losses in the power electronic converter, compared to a system where the converter has to handle the total power. In addition, the cost of the converter becomes lower. The WECS considered for analysis consist of a DFIG driven by a wind turbine, rotor side converter, DC to DC intermediate circuit and grid side converter. Fig. 1 shows a schematic diagram of WECS having DFIG and EPEI that will be discussed in this paper. The mechanical power available from a wind turbine

$$P_w = 0.5\,\rho\pi\,R^2\,V_w{}^3\,C_p(\lambda,\beta) \qquad (1)$$

$$C_p = \frac{1}{2}*(\lambda - 0.022*\beta^2 - 5.6)*e^{-0.17\lambda} \qquad (2)$$

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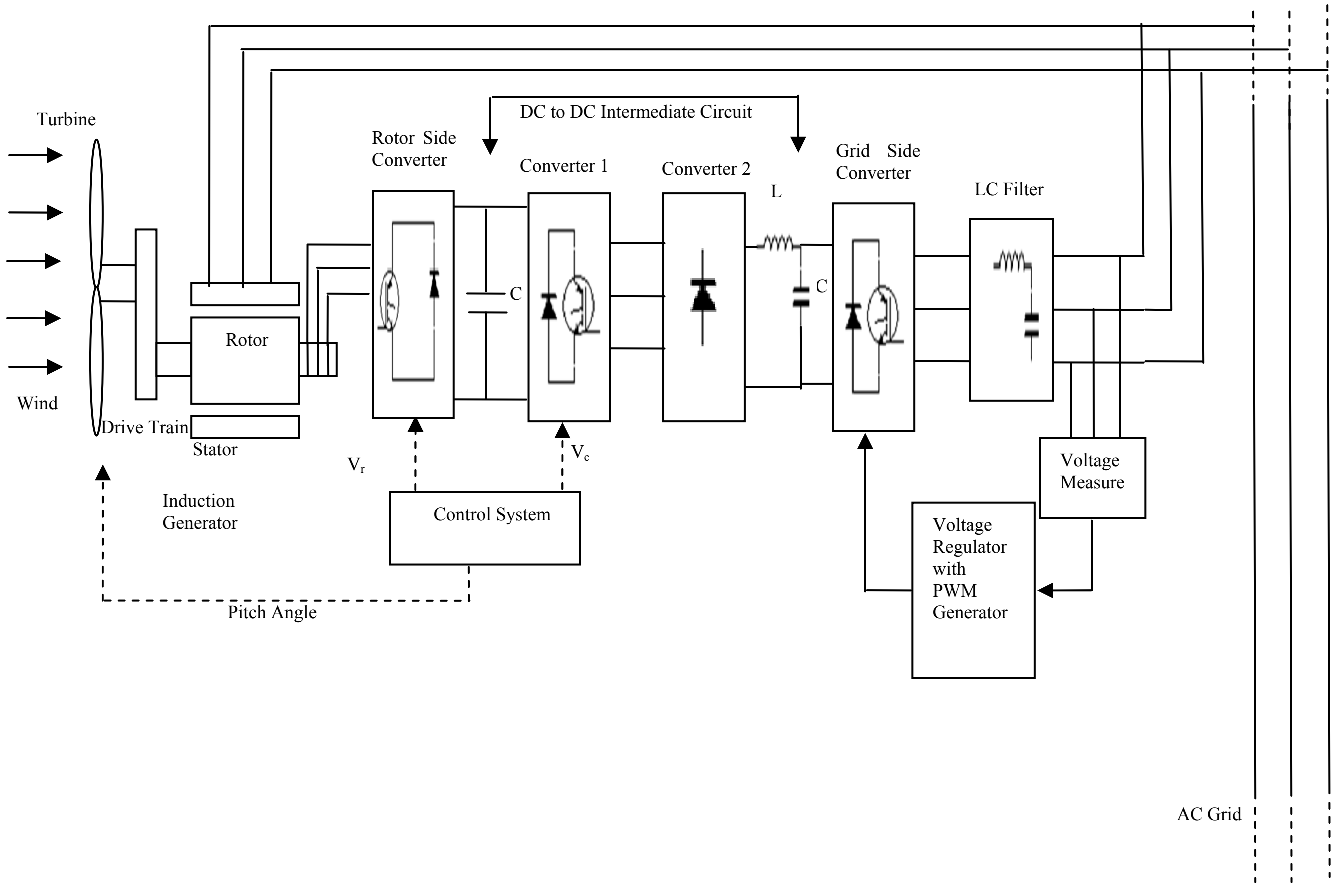

Fig.1: Proposed Wind Energy Conversion System with DFIG and Controlled Efficient Power Electronic Interface

$$\lambda = \frac{V_w}{\omega_B} \qquad (3)$$

where P_w is the extracted power from the wind, ρ is the air density, R is the blade radius and V_ω is the wind speed. C_p is called the 'power coefficient' and is given as a nonlinear function of the parameters tip speed ratio λ and blade pitch angle β. The calculation of the performance coefficient requires the use of blade element theory [197]. ω_B is the rotational speed of turbine. Usually C_p is approximated as [14-15],

$$C_p = \alpha\lambda + \beta\lambda^2 + \gamma\lambda^3 \qquad (4)$$

where α, β and γ are constructive parameters for a given turbine. The torque developed by the windmill is

$$T_t = 0.5\,\rho\left(\frac{C_p}{\lambda}\right)V_w{}^3\pi R^2 \qquad (5)$$

The equation of rotor motion is

$$\frac{d\omega_r}{dt} = \frac{2\,P_a}{J\,\omega_r} \qquad (6)$$

where J is the moment of inertia due to the rotating mass and P_a is the rotor accelerate mechanical power. The angular velocity of the rotor is considered in the region $0.7\omega \le \omega_r \le 1.3\omega$ for the case study presented in this paper. The DFIG equations can be written as [16],

$$\frac{d\lambda_{ds}}{dt} = u_{ds} - R_s i_{ds} + \omega\lambda_{qs} \qquad (7)$$

$$\frac{d\lambda_{qs}}{dt} = u_{qs} - R_s i_{qs} - \omega\lambda_{ds} \qquad (8)$$

$$\frac{d\lambda_{dr}}{dt} = u_{dr} - R_s i_{dr} + s\,\omega\lambda_{qr} \qquad (9)$$

$$\frac{d\lambda_{qr}}{dt} = u_{qr} - R_s i_{qr} - s\,\omega\lambda_{dr} \qquad (10)$$

The stator electric values are indicated by the subscript s and the rotor electric values are indicated by the subscript r. u is a voltage, R is a resistance, i is a current, λ is a flux linkage. ω is the stator electrical frequency and s is the rotor slip. The flux linkages are given by

$$\lambda_{ds} = L_s i_{ds} + M i_{dr} \qquad (11)$$

$$\lambda_{qs} = L_s i_{qs} + M i_{qr} \qquad (12)$$

$$\lambda_{dr} = L_s i_{dr} + M i_{ds} \qquad (13)$$

$$\lambda_{qr} = L_s i_{qr} + M i_{qs} \qquad (14)$$

L_s, L_r and M are respectively the stator and the rotor leakage

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inductance and the mutual inductance between the stator and the rotor.

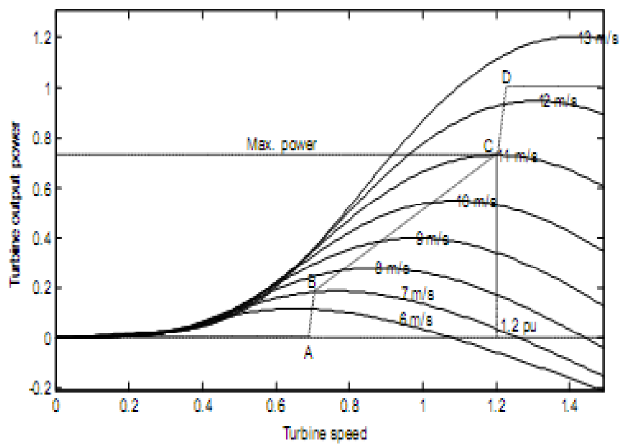

Fig. 2: Turbine Power Characteristics.

Fig. 2 shows turbine power characteristics for 0 degree pitch angle. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated in the Fig. 2 by the dotted ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The dashed line in Fig. 2 indicates maximum power at base wind speed (11 m/s) and pitch angle 0 degree.

Fig. 3 and Fig. 4 show the generator output characteristics. Rotor flux as d and q axis are presented in Fig. 3 and corresponding stator d and q axis flux are shown in Fig. 4.

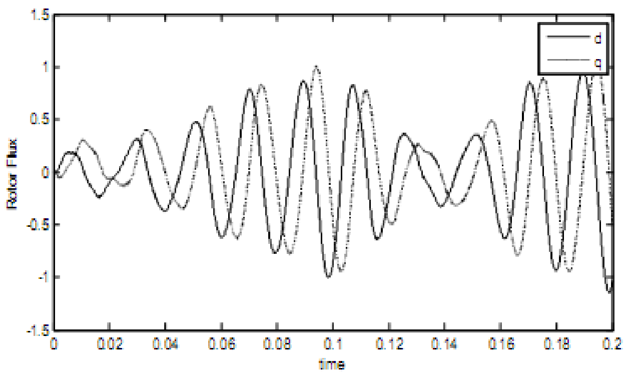

Fig. 3: Rotor Flux d and q Axis

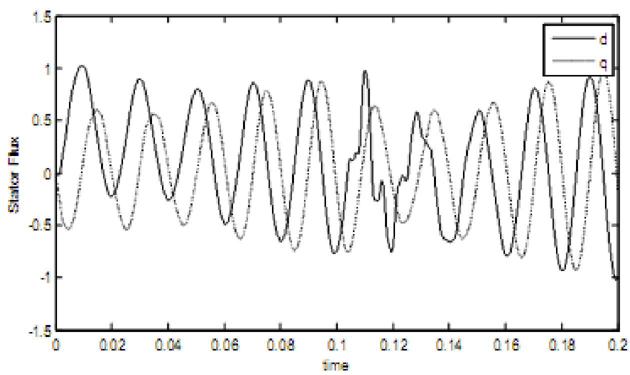

Fig. 4: Stator Flux d and q Axis.

I. III. AC Power Grid with Harmonic Filters

A. *AC Power Grid*

The WECS having EPEI is connected to a 33 kV distribution system exports power to a 220 kV grid as shown in Fig. 5. A-B fault at t=0.104 s for a duration of 3 ms is simulated at B3. The wind speed is maintained constant at 10 m/s. The control system shown in section III is used to maintain the speed at 1.09 pu and to regulate reactive power produced by the wind turbine at 0 MVAR.

Harmonic filters are included in power system model at bus B1 with a circuit breaker with transition time between 0.0667 and 0.1667 secs, breaker resistance of 1×10 Ω, snubber resistance of 1×10^6 Ω and snubber capacitance of infinite value.

B. *Three Phase Harmonic Filters*

Due to the significant amount of capacitance in a typical wind power plant, there is a high potential for resonance problems to occur [8], [9], [17]. That can result in unacceptable levels of harmonic current distortion at the substation capacitor banks, high voltage distortion at the MV bus of the plant main substation, and unacceptable harmonic current injected from

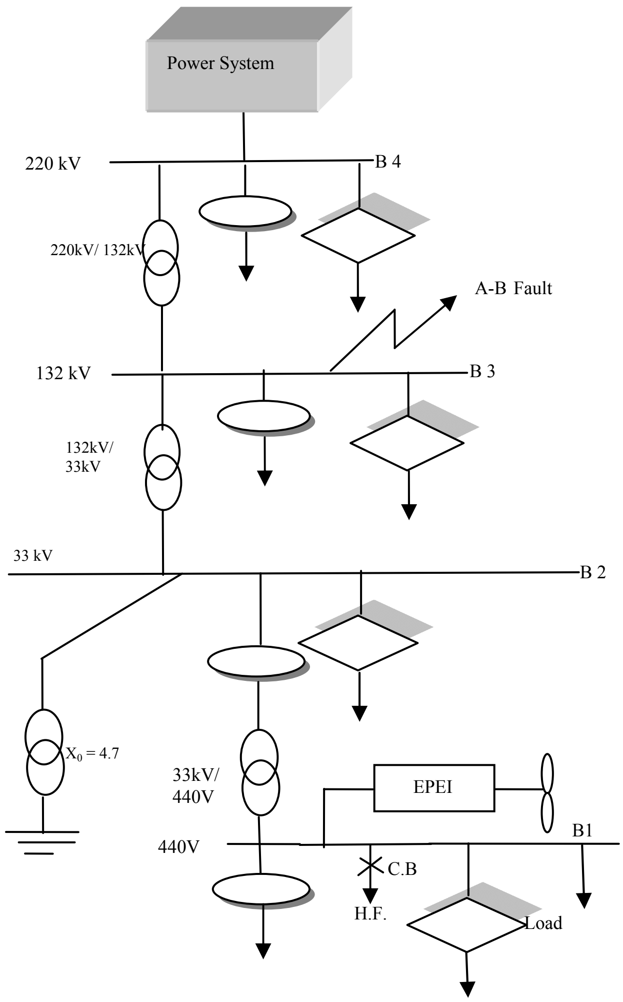

Fig. 5: Power System Model used in Paper.

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the plant at the PCC. In order to reduce distortion, several banks of filters of different types are usually connected in parallel. The filter set, used in paper, is made of the following four components:

- One capacitor bank of 100 kVAR
- Three filters

(1) One C-type high-pass filter tuned to the 3rd harmonic (100 kVAR)

(2) One double-tuned filter 11/13th harmonic (100 kVAR).

(3) One high-pass filter tuned to the 24th harmonic (100 kVAR)

The total MVAR rating of the filters set is 400 kVAR. The filter set is attached to 440 V bus. A three-phase circuit breaker, as shown in Fig. 5, is used to connect the filters set on the AC bus. Fig. 6 shows three phase harmonic filters connected to 440 V bus, which are used to improve power quality and reduce harmonic distortion.

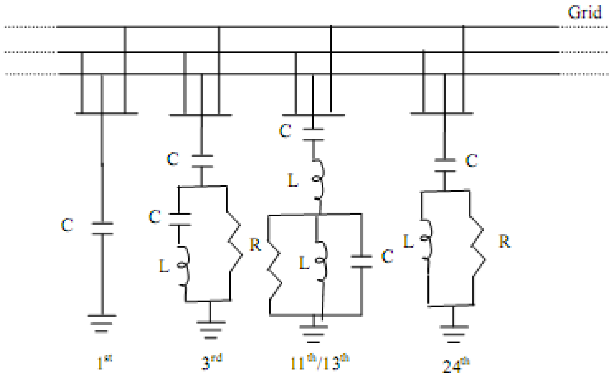

Fig. 6: Three Phase Harmonic Filters Connected to 440 V Bus.

IV. Results and Discussion

In this section the results obtained through simulations for the grid connection of the DFIG using the power electronic interface and control system described above are presented. Direct-axis and quadrature-axis components of stator voltage and rotor voltage in pu based on the generator rating are shown in Fig. 7 and Fig. 8 respectively. They are real and imaginary parts of the positive-sequence stator and rotor phasor voltage respectively. The wind turbine generator power is shown in Fig. 9. As shown in Fig. 10, the system currents oscillate due to phase to phase fault at t=0.104, but they return to their normal behavior quickly. During the disturbance, the control systems try to regulate power system and it recovers after sometime. The pitch angle is regulated at 0 deg.

Two different cases are considered now. One case (C1) is that wind energy generation system with rotor side converter and converter 1 of DC to DC intermediate circuit is connected to AC grid without harmonic filters. Another case (C2) is that wind generation system with rotor side converter, DC to DC intermediate circuit and grid side converter is connected to AC grid having harmonic filters on 440 V bus. The comparison of voltage V_{b0} and current I_{b0} at different locations in power system in both cases is presented in Figures 10 to 13. As clear from figures, transients in voltages and currents in C2 are much lower than C1.

THD comparison for both cases at buses B1 to B4 is presented in Figures 14 to 17, which clearly indicate that THD rises due to fault, but then lowers at a much quicker rate in C2 than C1 and system returns to normal behavior. The results have clearly demonstrated the ability of proposed system to reduce the transients and harmonic distortion in power system and thus enhance the power quality.

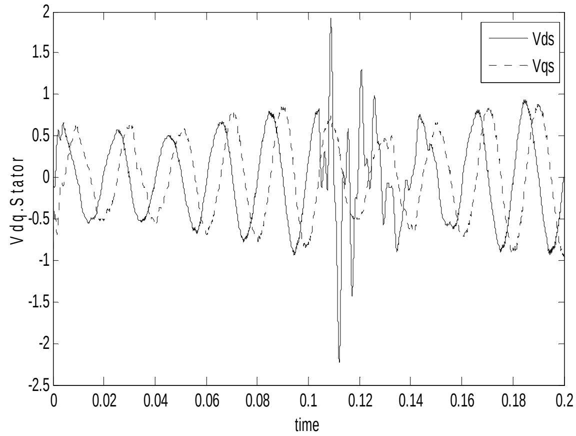

Fig. 7: d and q Axis Voltages at Stator.

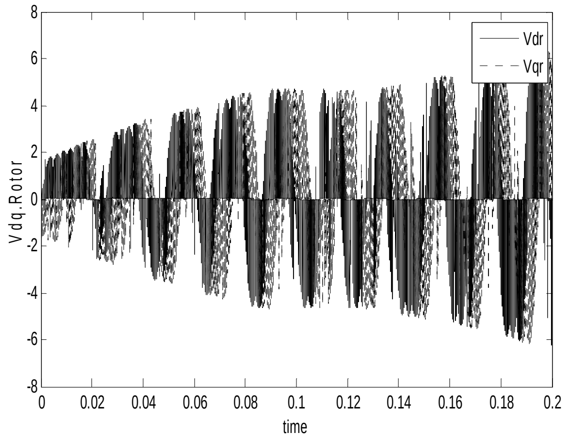

Fig. 8: d and q Axis Voltages at Rotor.

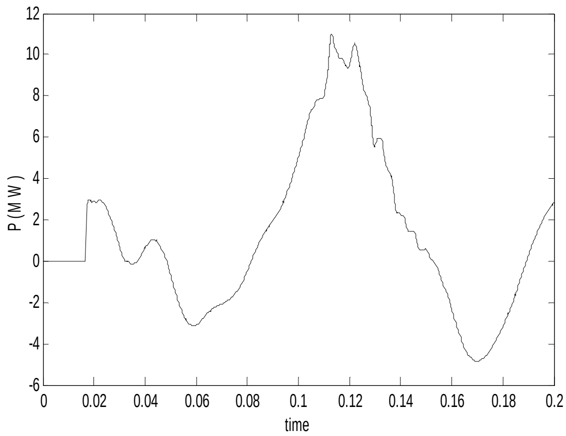

Fig. 9: WTDFIG Output Active Power.

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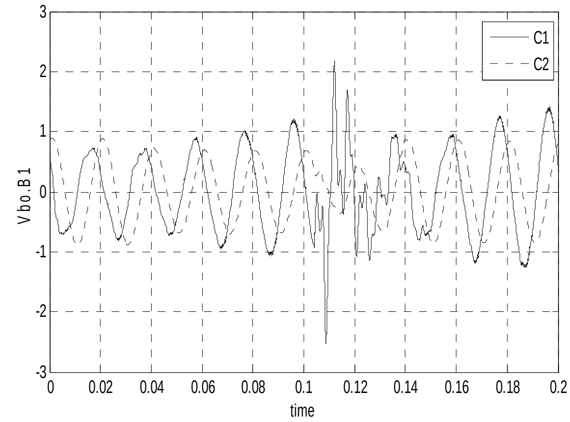

Fig. 10: Comparison of Voltage V_{b0} at B1 in both Cases.

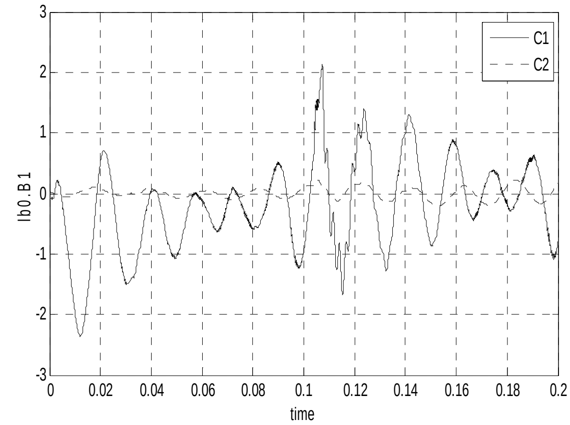

Fig. 11: Comparison of Current I_{b0} at B1 in both Cases.

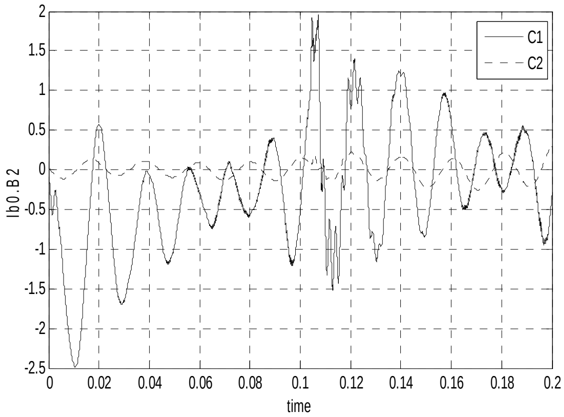

Fig. 12: Comparison of Current I_{b0} at B2 in both Cases.

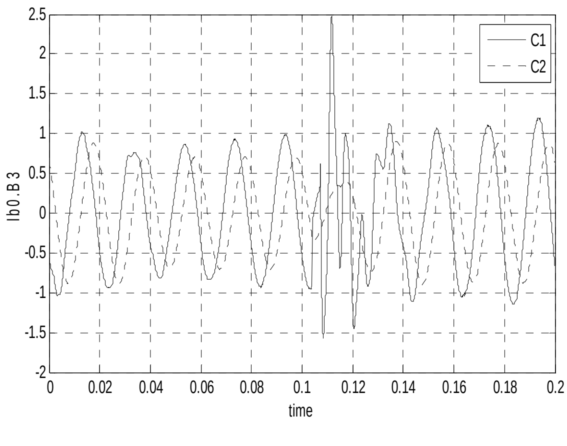

Fig. 12: Comparison of Current I_{b0} at B3 in both Cases.

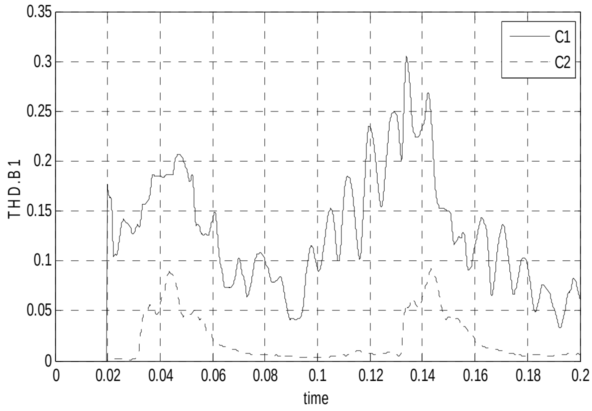

Fig. 14: Comparison of Voltage THD at Bus B1 in both Cases

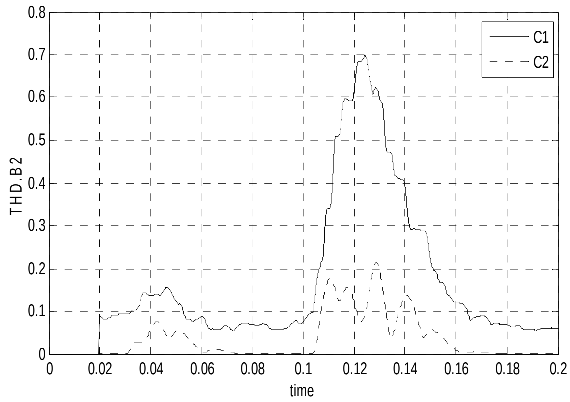

Fig. 15: Comparison of Voltage THD at Bus B2 in both Cases

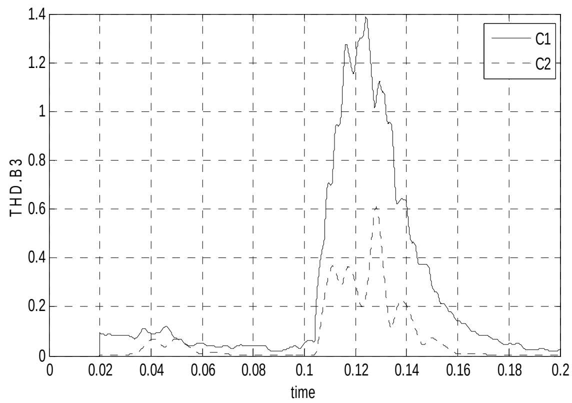

Fig. 16: Comparison of Voltage THD at Bus B3 in both Cases

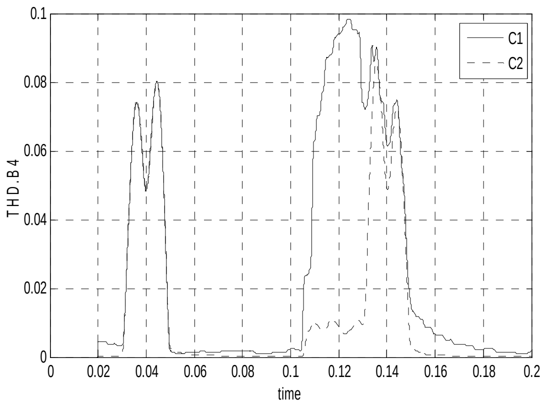

Fig. 17: Comparison of Voltage THD at Bus B4 in both Cases

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V. Conclusions

In this paper, the effect of adding harmonic filters to power interface is demonstrated. Two different cases are considered and results obtained are compared to demonstrate the ability of power electronic interface with harmonic filters in event of transient fault. The results obtained indicate that the variations in currents and voltages at different locations in power system model are much less in C2. They return to normal behavior after experiencing oscillations for much less time. As a whole, it can be concluded that the proposed wind energy conversion system with harmonic filters can enhance the power quality of system during a transient fault and also reduces THD at various locations in power system.

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