Active Filtering of Wind Energy Conversion System with DFIG for Nonlinear or Unbalanced Load

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***Abstract*— This paper presents a control for a doubly fed induction generator (DFIG) based on wind energy conversion system (WECS) for nonlinear or unbalanced load to intend harmonic currents mitigation. First, the model of the DFIG is derived with a stator field oriented. Then the control strategy is obtained based on rotor side converter (RSC) control and grid side converter (GSC) control. The RSC controls the active and reactive power injected to the grid by the stator of the DFIG. The specified control of the GSC ensures simultaneously the dc link voltage regulation and harmonic currents mitigation which are delivered by non linear load. Finally, some simulation results using MATLAB/Simulink are given to validate the proposed system.**

***Keywords*— Active filtering, doubly fed induction generator, grid side converter, wind energy conversion system.**

I. INTRODUCTION

The great interest to the electrical power quality in the industry encourages many researchers to propose a specific control system to improve the grid power quality. For instance, Barbosa *et al.* [1] proposed a control strategy for grid connected dc-ac converters with power factor correction. Mariusz *et al.* [2] presented simultaneously the active filtering function and PWM rectifier capability. Macken *et al.* studied the compensation of distorted currents through multiple converter-interfaced renewable generation units [3], [4]. Gaillard *et al.* [4] suggested a modified rotor side converter (RSC) control in WECS which uses the stator of the DFIG for harmonic currents elimination. He succeeds to reduce the total harmonic distortion (THD) of the grid currents but the high frequency of the harmonics injected in the stator and rotor sides of generator are the main scheme drawback. The active filter and the GSC power circuits of the WECS are basically the same. Moreover, they can be operated in the same conditions [5]. For these reasons, we propose a hybrid control of the GSC of the WECS to ensure the dc link voltage control with active filtering function at the same time. This control strategy is based on the decoupled d-q current control to regulate the dc link voltage to the desired value, and to set the power factor to the unity [6]. In addition, this strategy uses the instantaneous power theory to identify and then eliminate the harmonic currents injected by non linear load, which are connected to the grid.

The present paper is organized as follows: First, the modeling and control of the WECS have been presented. Second, the harmonic currents identification using instantaneous power method has been detailed, and the GSC control is explained. Finally, the simulation results are given and commented to prove the proposed control strategy performances.

II. WIND ENERGY CONVERSION SYSTEM MODEL

Fig. 1 shows the simplified diagram of the power system based on wind power generation. It consists of a wind turbine, a gearbox, a DFIG, a back-to-back converter and a non linear load.

A. Modeling of the DFIG

A classical modeling of the DFIG in the Park reference frame is used. The voltages and flux equations of the DFIG are [6]:

$$\begin{cases} V_{sd} = R_s i_{sd} + \dfrac{d\varphi_{sd}}{dt} - w_s \varphi_{sq} \\ V_{sq} = R_s i_{sq} + \dfrac{d\varphi_{sq}}{dt} + w_s \varphi_{sd} \\ V_{rd} = R_r i_{rd} + \dfrac{d\varphi_{rd}}{dt} - w_r \varphi_{rq} \\ V_{rq} = R_s i_{sq} + \dfrac{d\varphi_{sq}}{dt} + w_r \varphi_{sd} \end{cases} \tag{1}$$

with

$$\begin{cases} \varphi_{sd} = L_s i_{sd} + M\, i_{rd} \\ \varphi_{sq} = L_s i_{sq} + M\, i_{rq} \\ \varphi_{rd} = L_r i_{rd} + M\, i_{sd} \\ \varphi_{rq} = L_r i_{rq} + M\, i_{sq} \end{cases} \tag{2}$$

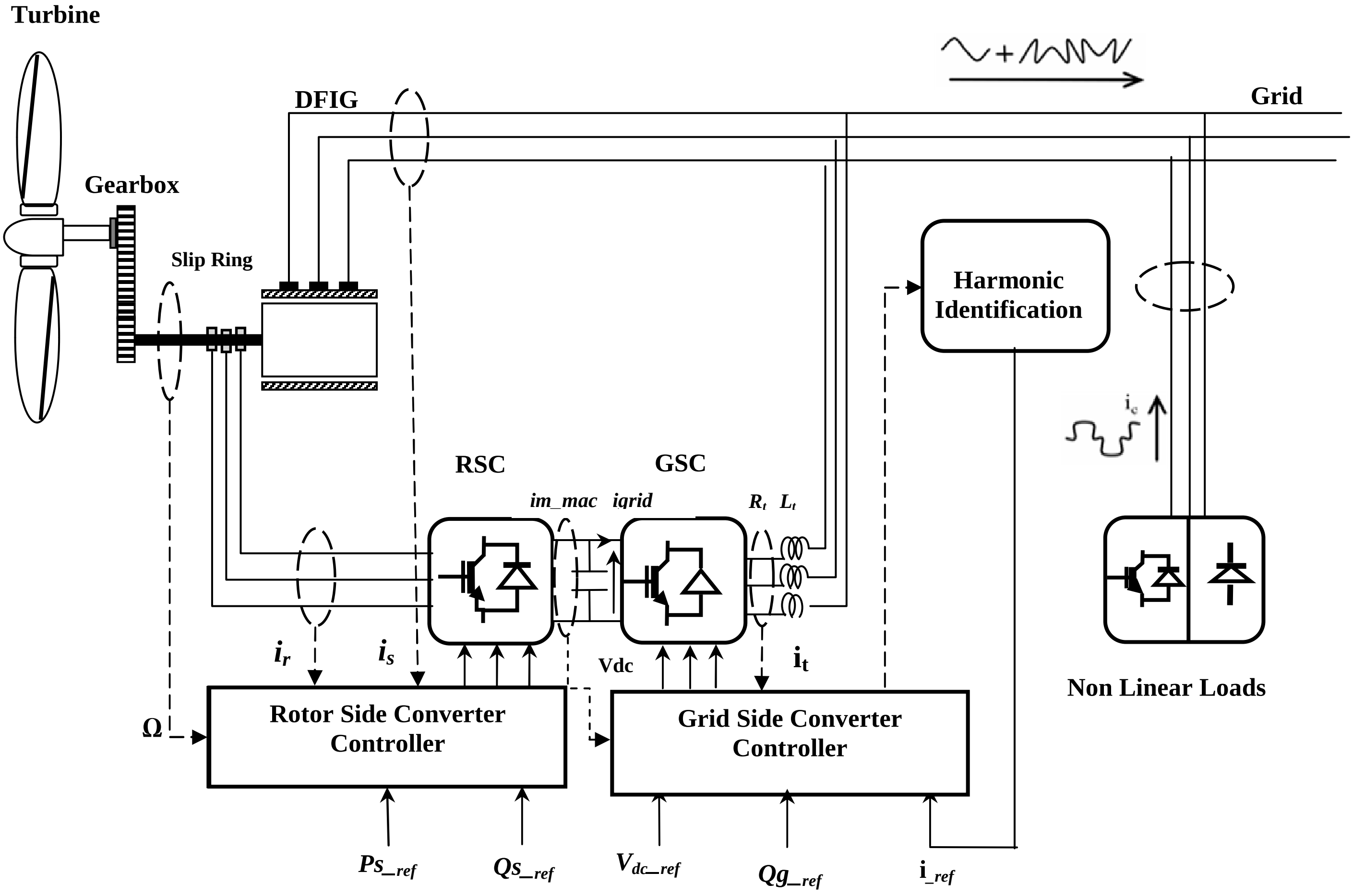

Fig. 1 Control principle of the WECS with active filtering function.

The active and reactive powers at the stator side and rotor side are defined as:

$$\begin{cases} P_s = V_{sd}\, i_{sd} + V_{sq}\, i_{sq} \\ Q_s = V_{sq}\, i_{sd} - V_{sd}\, i_{sq} \end{cases} \tag{3}$$

$$\begin{cases} P_r = V_{rd}\, i_{rd} + V_{rq}\, i_{rq} \\ Q_r = V_{rq}\, i_{rd} - V_{rd}\, i_{rq} \end{cases} \tag{4}$$

The electromagnetic torque is expressed by:

$$T_{em} = p(i_{sq}\varphi_{sd} - i_{sd}\varphi_{sq}) \tag{5}$$

Where p is the number of pole pairs, and the electro-mechanical equation is:

$$T_{em} = T_r + f\,\Omega + J\,\frac{d\Omega}{dt} \tag{6}$$

The main variables of the DFIG are: Rs, Rr, Ls and Lr. They are respectively the resistances and the inductances of the stator and the rotor windings, M is the mutual inductance.

V_{sd}, V_{sq}, V_{rd}, V_{rq}, i_{sd}, i_{rd}, $i_{rq,}\varphi_{sd}$, φ_{sq}, $\varphi_{rd,}\varphi_{rq}$ are the d and q components of the stator and rotor voltages, currents and flux. P_s ,Q_s and P_r ,Q_r are the active and reactive power at the stator and rotor of the DFIG.

B. Modeling of the DFIG with a Stator Field

Simplified expression of the electromagnetic torque is obtained by setting the following conditions:

$$\varphi_{sq} = \frac{d\varphi_{sq}}{dt} = 0 \tag{7}$$

$$\varphi_{sd} = \varphi_s \tag{8}$$

Hence, it yields

$$T_{em} = p I_{sq}\varphi_{sd} \tag{9}$$

In consequence, the Park frame has to be synchronized with the stator flux is shown in Fig. 2.

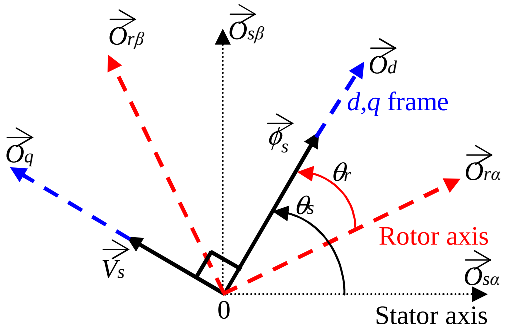

Fig. 2. Orientation of the *d, q* frame.

Assuming that the resistance of the stator winding R_s is neglected, the voltage equations and the flux equations of the stator windings can be simplified in steady state as:

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = w_s \varphi_{sd} \end{cases} \tag{10}$$

$$\begin{cases} \varphi_s = L_s i_{sd} + M i_{rd} \\ 0 = L_s i_{sq} + M i_{rq} \end{cases} \tag{11}$$

Since the stator voltage frequency is set by the grid, the rotor speed is deduced from:

$$w_r = w_s - p\Omega \tag{12}$$

Where w_r and w_s are respectively the rotor speed and the grid speed in rad/s. The angle θ_r is obtained by integrating the preceding equation:

$$\theta_r = \int_0^t w_r \, dt + \theta_{r0} \tag{13}$$

From (11), the equations linking the stator currents to the rotor currents are deduced below:

$$\begin{cases} i_{sd} = \dfrac{\varphi_s}{L_s} - \dfrac{M}{L_s} i_{rd} \\ i_{sq} = -\dfrac{M}{L_s} i_{rq} \end{cases} \tag{14}$$

Tacking into consideration the chosen reference frame, the active and reactive powers at the stator side can be written as follows:

$$\begin{cases} P_s = V_s i_{sq} \\ Q_s = V_s i_{sd} \end{cases} \tag{15}$$

The electromagnetic torque is as follows:

$$T_{em} = p \frac{M}{L_r} i_{rq} \tag{16}$$

Replacing the stator currents by their expressions given in (14), the equations below are expressed:

$$\begin{cases} P_s = V_s \dfrac{M}{L_s} i_{rq} \\ Q_s = \dfrac{V_s Q_s}{L_s} - \dfrac{V_s M}{L_s} i_{rd} \end{cases} \tag{17}$$

III. PROPOSED WIND CONVERSION SYSTEM WITH ACTIVE FILTER FUNCTION

With the proliferation of nonlinear loads as power electronics equipment, the disadvantage of harmonics is more and more, which influence quality of power grid and endanger the normal work of electrical equipment. Conventionally, passive LC filters have been used to eliminate line current harmonics and to improve the power factor. They were robust and easy to install and the efficiency was high with passive filters. But the passive filters have many disadvantages, such as fixed solve above compensation, large size and resonance problems. To mentioned problems, active power filters were introduced [7], [8].

In recent years, various active power filter configurations with their respective control strategies have been proposed, and have gradually been recognized as a viable solution to the problems created by high-power nonlinear loads. One of the most popular active power filters is the shunt active power filter [9].

Hence, the WECS shown in Fig. 1 can simultaneously, controls electrical power to the grid and compensate the grid harmonic currents. In fact, the GSC in this case regulates the dc link voltage and sets the power factor to the unity. So, it cancels harmonic currents generated by non linear load.

A. Harmonic Identification

In order to generate the reference signals being used for the control of the active filter, we chose the method of the instantaneous powers [7], [10]. This method is based on the measure of the three-phase instantaneous variables of the grid voltages.

The grid voltages and the load currents can be written in this reference frame as follows [10]:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{g1} \\ v_{g2} \\ v_{g3} \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} \tag{19}$$

The instantaneous real power p and the instantaneous reactive power q can be expressed by a two-phase system by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ -v_{s\beta} & v_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \tag{20}$$

The instantaneous real power and the instantaneous imaginary power can be expressed by:

$$p = p_c + p_h \qquad q = q_c + q_h \tag{21}$$

To eliminate the continue component, two low pass filters from order two are used.

The currents of references are calculated by the following expression:

$$\begin{bmatrix} i_{h\alpha\_ref} \\ i_{r\beta\_ref} \end{bmatrix} = \frac{1}{v^2{}_{s\alpha} + v^2{}_{s\beta}} \begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix} \begin{bmatrix} p_h \\ q_h \end{bmatrix} \tag{22}$$

The ($\alpha\beta$) harmonic currents of equation (22) are expressed in Park reference frame as follows:

$$\begin{bmatrix} i_{hd\_ref} \\ i_{hq\_ref} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{h\alpha\_ref} \\ i_{h\beta\_ref} \end{bmatrix} \tag{23}$$

B. GSC Control

Before realizing active filter operation, the (dq) currents references itd_ref and itq_ref must be transferred and then we need to add harmonic current references.

The new (dq) references can be calculated from the desired reference active and reactive powers.

IV. SIMULATION RESULTS

In order to verify the performance of the proposed wind energy conversion system with active filtering function, the simulation work has been done using Matlab/Simulink package. The parameters of the simulation studies are listed in the Appendix. Simulation study has been carried out in two cases: balanced load and unbalanced linear load. The DFIG speed is considered as constant 500 rpm. The switching frequency of RSC and GSC is fixed to 10 kHz.

A. Balanced Nonlinear Loads

The simulation results of the active and reactive powers control of the WECS based on DFIG are shown in Fig. 3. It is clearly noticed that the measured active and reactive powers of the DFIG follow respectively their references. Fig. 4 illustrates the load current, the GSC current and the grid current without and with active filtering function. It is clearly shown that before t =1.2 s (WECS without active filtering function), the grid current contains harmonics. The total harmonic distortion of nonlinear load current is 23.95 %. However, after t =1.2 s (WECS with active filtering function) the grid current became a near sinusoidal waveform and the harmonic currents are compensated. Fig. 5 displays the harmonic spectrum of grid current before and after compensation; in this case the THD of the grid current is reduced to 3.62 %. It is evidently shown from Fig. 6, which the measured dc voltage follows its reference for: with and without active filtering function.

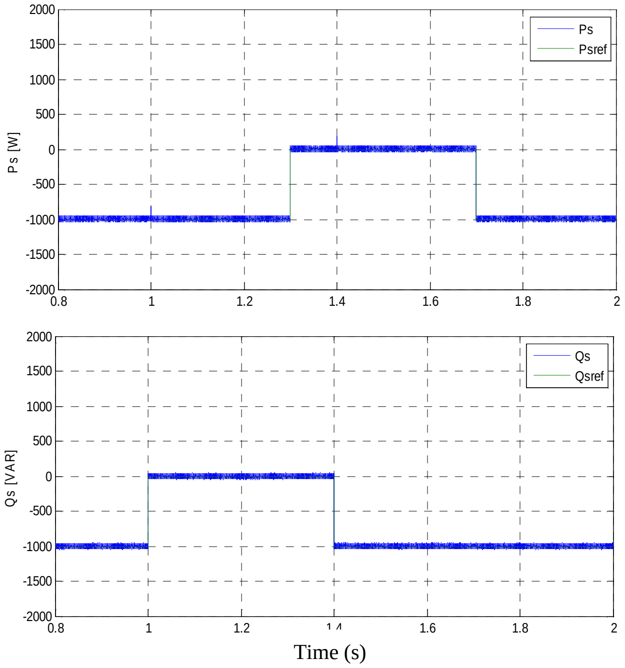

Fig. 3. Simulation waveforms of the active and reactive powers.

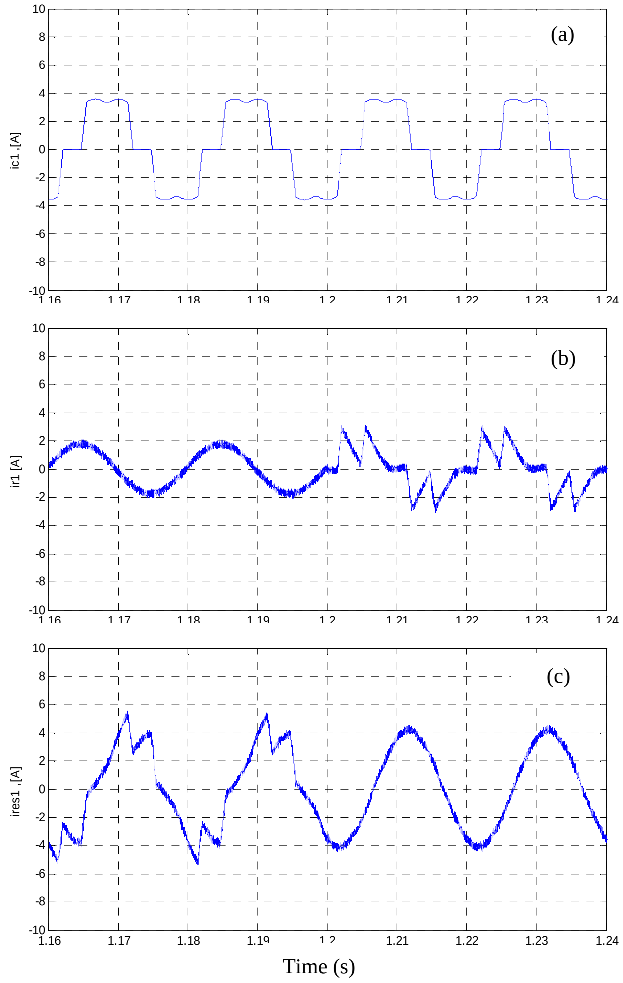

Fig. 4. Simulation results of WECS for balanced load: (a) load current, (b) GSC current and (c) grid current.

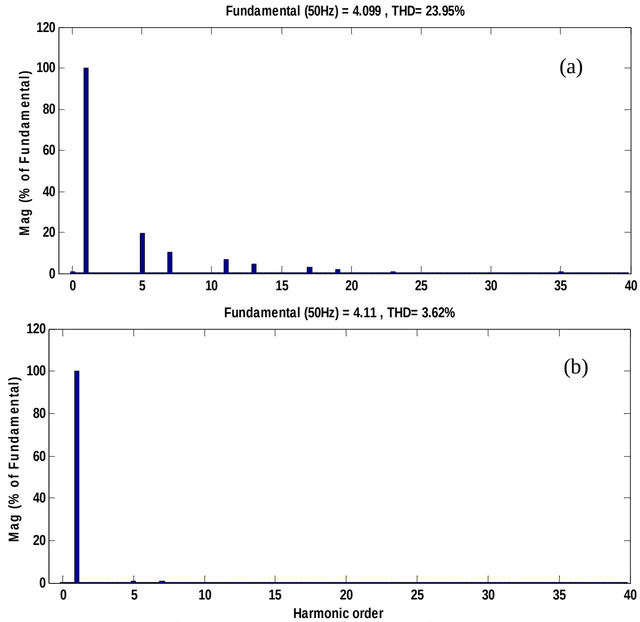

Fig. 5. Spectrum of grid current (a) before and after (b) compensation.

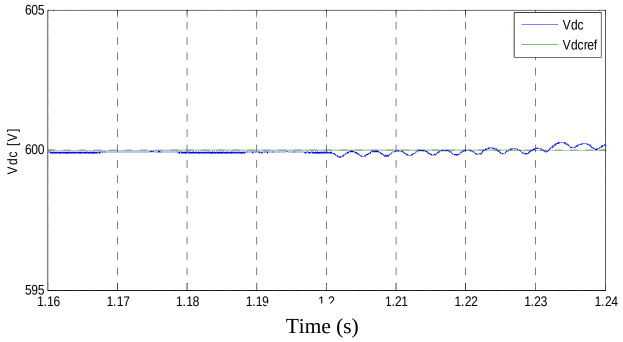

Fig. 6. dc link voltage regulation.

B. *Unbalanced Linear Loads*

Fig. 7 and Fig. 8 give the simulated results of the adopted system for the case of unbalanced loads (R_1 = 20Ω & L_1 =0.9 mH, R_2 =50 Ω & L_2 = 0.9 mH, R_3 =100 Ω & L_3 =0.9 mH). Three-phase linear load currents are shown in Fig. 7. Fig. 8(c) gives grid voltage and grid current. Notice that the grid current after compensation are balanced and in phase with the grid voltage. Fig. 8(d) shows the dc bus voltage, it can be seen that the voltage v_{dc} is stable and regulated around its reference.

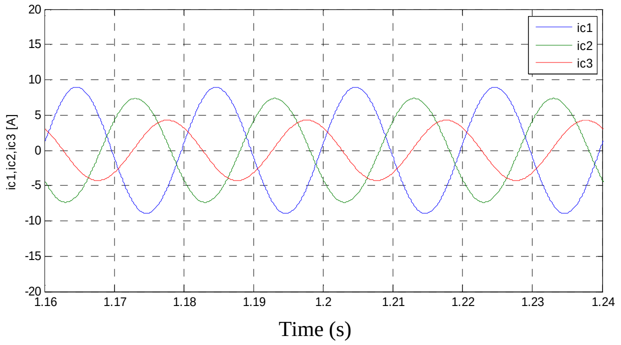

Fig. 7. Waveforms of the linear load currents.

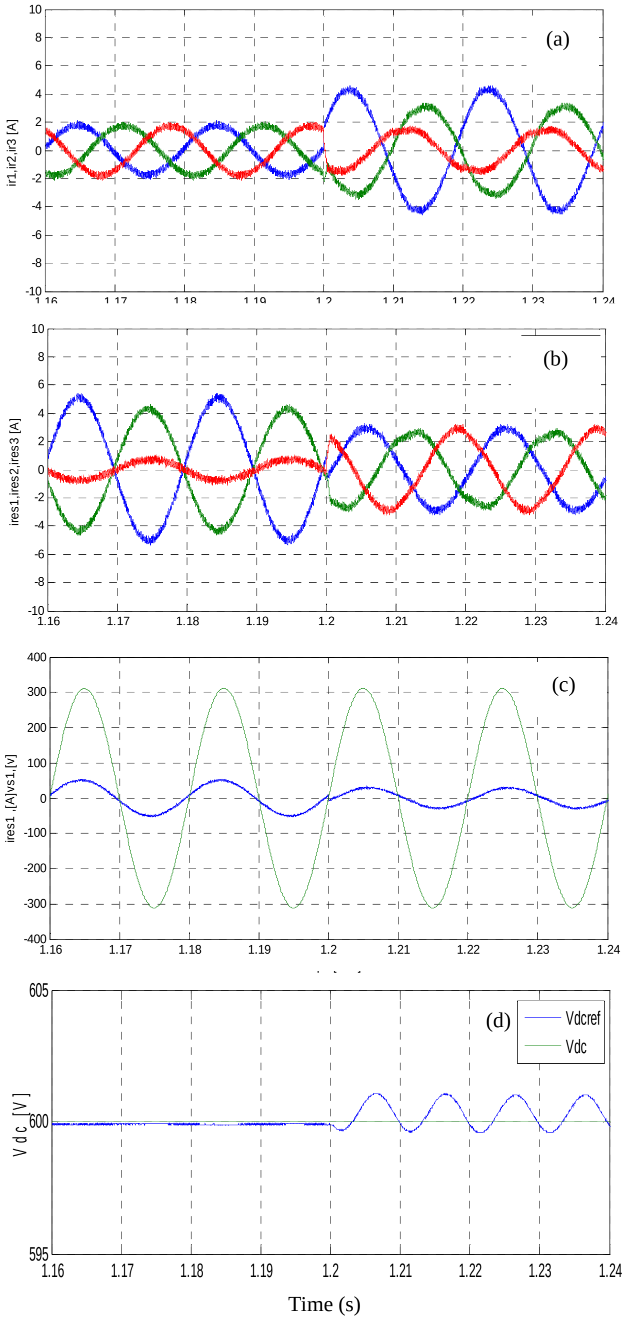

Fig. 8. Simulation results of WECS for unbalanced load.

V. CONCLUSIONS

A doubly fed induction generator based on wind energy conversion system was proposed to perform harmonics elimination, reactive power compensation and dc voltage regulation. The adopted DFIG system can be operated with nonlinear or unbalanced load. Simulation results have shown the feasibility of the proposed control method. When, the grid currents are become balanced and sinusoidal with nearly unity power factor for the nonlinear or unbalanced load.

APPENDIX

DFIG parameters	$P_{DFIG} = 7.5\,\mathrm{kW}$ $R_s = 0.455\,\Omega$ $R_r = 0.455\,\Omega$ $L_s = 84\,\mathrm{mH}$ $L_r = 81\,\mathrm{mH}$ $M = 78\,\mathrm{mH}$ $p = 2$ $f = 0.00673\,\mathrm{Nm/s}$ $\sigma = 0.0106$ $J = 0.3125\,\mathrm{Kg.m}^2$

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