A SIMPLE CONTROL STRATEGY FOR DOUBLY-FED INDUCTION GENERATOR TO REDUCE TORQUE RIPPLE DUE UNBALANCED GRID VOLTAGE

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Abstract – **This article develops a new control scheme for a Doubly-fed Induction Generator (DFIG) to reduce the torque ripple due to unbalance grid voltages. A dynamic model of DFIG including the proposed controller has been derived to show the impact of different controllers implementations on the impedance that is seen from the grid side. The main contribution of this paper is to demonstrate that a simple resonant controller included in the rotor current loop can reduce significantly the torque ripple due to voltage unbalance without any hardware modification. In order to validate the analysis carried out, experimental results using a DSP controlled 5kW DFIG prototype are presented.**

Keywords – **Control DFIG, Torque Pulsation, Voltage Unbalance, Wind Turbine (WT).**

I. INTRODUCTION

This paper presents the analysis and implementation of a vector control applied to wind turbine equipped with Doubly-Fed Induction Generators under unbalanced grid voltages. The DFIG is nowadays the most widely used concept for grid connected wind turbine, especially for rated power above 1 MVA [1-5]. The main reason is the low rotor PWM power converter rating (30-50%) [6].

Frequently, the WT with DFIG are connected in rural areas where just weak grids are available. To make the matter worse in some cases the wind turbine is connect at the end of long transmission or distributions lines where unbalanced are not corrected for many months [7-8]. Note that voltage unbalance problems also can be present in urban area where there is a large spread demand of single phase loads. Other cause for voltage unbalance can be unsymmetrical transforms, loads unbalanced in transmission and distribution systems among other factors [9-10].

Wind turbine connected at PCC for long times under voltage unbalance conditions can cause serious damage to the WT and DFIG, including overheating and stress on the mechanical components mainly from torque pulsations. The torque periodic pulsations can result in acoustic noise at low levels and at high levels can destroy the rotor shaft, gearbox and blade assembly. Therefore, beyond a certain amount of unbalance, for example 2% in Brazil [11], 1% in England, 2% in Scotland [12] and 1.3% in Ireland [13], induction wind generators can be switched out from the network. Nowadays, the amount of wind power in the Brazilian generation matrix is smaller if it compared with other countries such as Germany, Spain and Denmark. However, the wind power is increasing due to the governmental programs such as PROINFA. Therefore, it is important to develop control techniques that extend the range of grid conditions where the wind turbine can be kept connected to the grid. This brings benefits for both the wind turbine owner as well as to the distribution and transmission operator.

This article develops a new simple control scheme for a DFIG to reduce the torque ripple due to unbalance grid voltages. The main contribution of this paper is to demonstrate that a simple resonant controller added in the rotor current loop can reduce the voltage unbalance impact on the torque ripple without hardware modification. In order to validate the analysis carried out, experimental results are presented in the section VI of this paper using a DSP controlled 5kW DFIG set-up.

II. DFIG UNDER UNBALANCED GRID VOLTAGES

Figure 1 illustrates the connection diagram of DFIG driven by a wind turbine at the end of a weak power system or a long distribution line. Unbalanced loads can be represented by many single-phase loads, which are commonly found in rural and residential area. Unbalanced loading at the point of common coupling (PCC) can cause voltage unbalance drop across the distribution line, which will result in voltages unbalance at PCC.

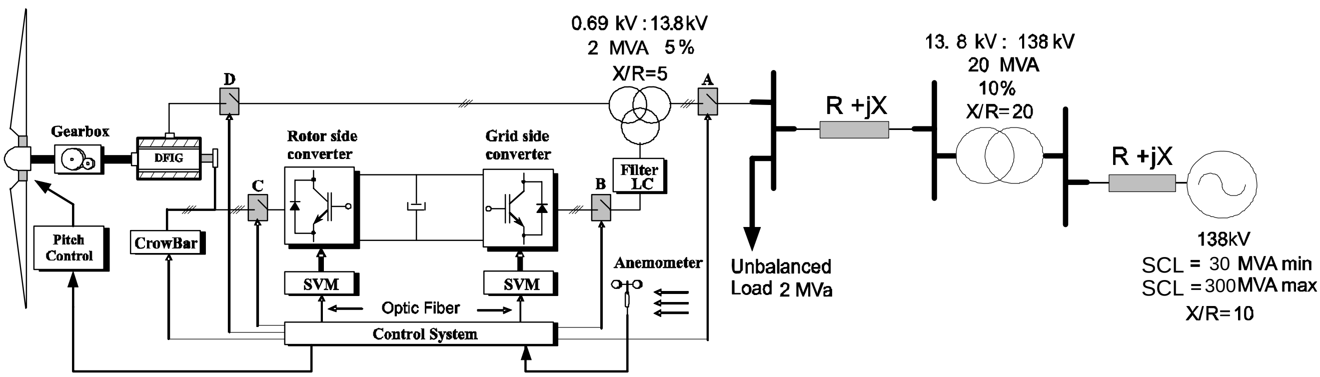

Fig. 1. Wind Turbine configuration equipped with 2 MVA doubly-fed induction generator under voltage unbalance.

The performance and control strategies of DFIG for WT applications with voltage unbalance have been studied [14-17]. However, the focus of study in [14] and [15] was on controlling the grid-side converter. In [16], one equation was expressed in synchronous reference frame for compensating torque pulsation. For this compensation to work correctly, the bandwidth of the controllers must be much higher than the frequency of the disturbance. However, it is well known that the increase the rotor current loops bandwidth cause adverse impacts on the low damped modes associated with the DFIG. The approach adopted in [17] used the observed torque pulsation as the input to a lead-lag controller to directly generate the rotor compensating voltage. In [19], a DFIG system model in the positive and negative synchronous reference frames is presented, although the result is promising, its complexity impairs its applicability. For all the approaches reported, the impact of unbalanced stator voltage on the stator and rotor currents has not been fully defined. In addition, the relationship between the disturbance voltage and the impedance of DFIG has not been established. Next section stator voltages oscillations in synchronous reference frame oriented in the stator voltage vector are presented.

A. Disturbance Voltage in Synchronous Reference Frame

There are several different ways to define a three phase unbalance. In this article, the voltage unbalance is given as the ratio of negative sequence voltage component to the positive sequence voltage components. Then, the percentage unbalance factor (VUF), is given by:

$$\%\text{VUF} = \left(V_-/V_+\right)\cdot 100\% \tag{1}$$

Using symmetrical components theory, a stator voltage unbalance can be seen as the addition of a negative sequence to stator voltage. The negative sequence rotates 60 Hz in the opposite direction of the positive sequence. The $\alpha\beta$ and Park transformation are used in this paper for obtain the stator voltage in synchronous reference frame oriented in the stator voltage vector. Then, the grid voltages components in synchronous form are given by:

$$v_q = V_+ + V_- \cos\left(2\omega_s t\right) \quad \text{and} \quad v_d = 0 \tag{2}$$

The equation (2) demonstrates that the stator voltage in synchronous reference frame will have a second harmonic in addition to the dc value. Therefore, all *qd* frame variables will have second harmonic. This 120 Hz component will cause torque pulsations, as well as active power and reactive power ripple. In order to better understand this phenomenon, a dynamic model of the DFIG in the synchronous reference frame is presented in the next section.

III. DFIG MODEL IN STATOR VOLTAGE VECTOR REFERENCE FRAME

In this section, the DFIG model presented in synchronous reference frame aligned with the stator voltage vector as show in Figure 2.

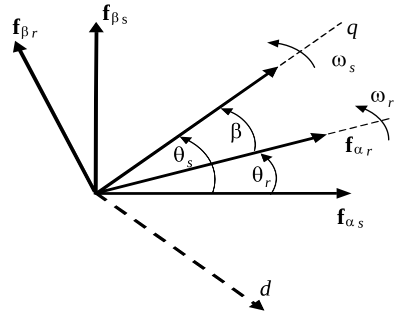

Fig. 2. Vector diagram for stator voltage-oriented control.

The *qd* equivalent circuit of DFIG is show in Figure 3.

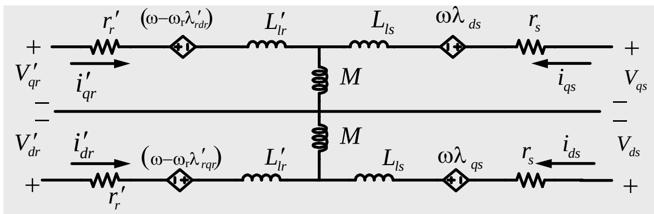

Fig. 3. Equivalent circuit of DFIG in synchronous reference frame.

The symbol ′ denotes that the variable is referred for stator circuit. Considering i'_{qr}, i'_{dr}, λ_{qs} e λ_{ds} as states variables the DFIG, ω_s is the supply voltage angular frequency. So, the DFIG model in stator voltage vector reference frame is given by (6):

When equation (6) is used to represent a model high power generator connected to the grid, it is reasonable to consider that $r_s \ll 1$, as a result:

$$\frac{d}{dt}\lambda_{qs} = v_{qs} - \omega_s\lambda_{ds} \quad \text{and} \quad \frac{d}{dt}\lambda_{ds} = v_{ds} + \omega_s\lambda_{qs} \tag{3}$$

The equilibrium point of (3) is given by:

$$\lambda_{ds} \cong \frac{v_{qs}}{\omega_s} \quad \text{and} \quad \lambda_{qs} = 0 \tag{4}$$

and through the linear system (3), it is found the following eigenvalues:

$$\lambda_1 = -j\omega_s \text{ and } \lambda_2 = +j\omega_s \tag{5}$$

$$\begin{aligned}
\frac{d}{dt}i'_{qr} &= \frac{1}{L_{eq}}\left[L_{eq}i'_{dr}\left(\omega_r-\omega_s\right)+\left(-\frac{M^2}{\left(L_{ls}+M\right)^2}r_s-r'_r\right)i'_{qr}-\frac{M}{\left(L_{ls}+M\right)}v_{qs}+\frac{M}{\left(L_{ls}+M\right)^2}r_s\lambda_{qs}+\omega_r\frac{M}{\left(L_{ls}+M\right)}\lambda_{ds}+v'_{qr}\right]\\
\frac{d}{dt}i'_{dr} &= \frac{1}{L_{eq}}\left[L_{eq}i'_{qr}\left(\omega_s-\omega_r\right)+\left(-\frac{M^2}{\left(L_{ls}+M\right)^2}r_s-r'_r\right)i'_{dr}-\frac{M}{\left(L_{ls}+M\right)}v_{ds}+\frac{M}{\left(L_{ls}+M\right)^2}r_s\lambda_{ds}-\omega_r\frac{M}{\left(L_{ls}+M\right)}\lambda_{qs}+v'_{dr}\right]\\
\frac{d}{dt}\lambda_{qs} &= -\omega_s\lambda_{ds}+r_s\frac{M}{\left(L_{ls}+M\right)}i'_{qr}+v_{qs}-r_s\frac{\lambda_{qs}}{\left(L_{ls}+M\right)}\\
\frac{d}{dt}\lambda_{ds} &= \omega_s\lambda_{qs}+r_s\frac{M}{\left(L_{ls}+M\right)}i'_{dr}+v_{ds}-r_s\frac{\lambda_{ds}}{\left(L_{ls}+M\right)} \qquad \text{where} \qquad L_{eq}=\frac{\left(L_{ls}+M\right)}{\left(L'_{lr}L_{ls}+L'_{lr}M+L_{ls}M\right)}
\end{aligned} \tag{6}$$

Therefore, from (5) is possible to conclude that DFIG have two oscillatory eigenvalues, resultant of the variation on the stator flux, near to the supply frequency. In addition, it can also be concluded that if $r_s \cong 0$ the stator flux oscillation can not be controlled from the rotor side, since they do not depend of the rotor currents i'_{qr} and i'_{dr}. Another important consideration is that as r_s became significant this eigenvalues became more damped. It can be observed through the λ_{qs} equation in (6), where the variables λ_{qs}, and i'_{qr} can create an additional stator flux damping.

The electromechanical torque equation can be written as:

$$T_e = \frac{3}{2}\frac{n_p}{2} M \left(i_{qs} i'_{dr} - i_{ds} i'_{qr} \right) \tag{7}$$

where, n_p is the machine poles number.

The active and reactive power at the machine terminal of the stator winding, can be expressed as:

$$P_s = v_{qs}\, i_{qs} + v_{ds}\, i_{ds} \quad ; \quad Q_s = v_{qs}\, i_{ds} - v_{ds}\, i_{qs} \tag{8}$$

Since the stator voltage vector $v_{ds} = 0$, the equation (8) becomes:

$$P_s \approx \frac{3}{2}\frac{\lambda_{qs} - M i'_{qr}}{\left(L_{ls} + M\right)} v_{qs} \;\; ; Q_s \approx \frac{3}{2}\frac{\lambda_{ds} - M\, i'_{dr}}{\left(L_{ls} + M\right)} v_{qs} \tag{9}$$

In addition from (4), it is possible to conclude, that since the supply voltage amplitude is approximately constant the λ_{qs} and λ_{ds} can also be considered approximately constant. Thereby, the active power can be controlled by i'_{dr} and the reactive power can be controlled by i'_{qr}. In order to do so, the i'_{qr} and i'_{dr} must be controlled in a close loop way.

Aiming to mitigate the effect of the voltage unbalance, next section presents an analysis of DFIG using PI and resonant controllers under unbalanced conditions.

IV. SYSTEM CONTROL

A. DFIG with Conventional PI Controller

Normally, the DFIG is controlled in a synchronous rotating *qd* reference frame. A conventional PI controller in rotor current loop of DFIG is show in Figure 4.

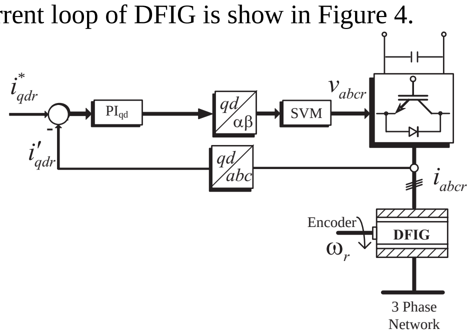

Fig. 4. Conventional PI controller in rotor current loop.

The gains of the PI controllers are obtained from (6), considering the following assumption: (i) $r_s \cong 0$; (ii) $\omega_r \cong \omega_s$; (iii) supply voltage is a disturbance. Under these assumptions, the relationship between the rotor side PWM converter voltage and the rotor current is given by:

$$G_q(s) = G_d(s) = \frac{1}{sL_{eq} + r'_r} \tag{10}$$

In order to simplify the *d* and *q* PI controller design, the controller parameters will be expressed as a function of the rotor current closed loop bandwidth B_ω, that is:

$$k_p = L_{eq} B_\omega \qquad , \qquad k_i = r'_r B_\omega \tag{11}$$

The trajectory of the system eigenvalues given in (6) has been investigated for different values of the current loop bandwidth ($100 \le B_\omega \le 800$). The root locus diagram have been used in Figure 5 for shows the trajectory of this eigenvalues for the operation point where the wind turbines supply only active power to the grid.

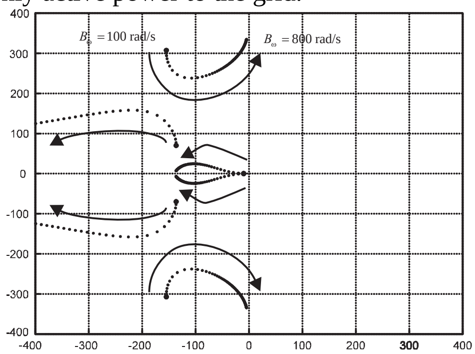

Fig 5 - Root locus for a variation of B_ω from 100 to 800 rad/s.

It is possible to see from Figure 5 that when *qd* PI controller bandwidth increases the poorly damped eigenvalues move toward the instability. Considering a 2MVA DFIG which the parameters are given in Table I, the maximal bandwidth considered is around 200 rad/s.

Unfortunately, the DFIG negative impedance is similar to conventional induction generators. If voltage unbalance is not taken into account by the control system, the stator current could be highly unbalanced even with a small unbalanced stator voltage. The relationship between stator voltage and current can be obtained from dynamic model of DFIG (6).

The Figure 6 shows this relationship that result in equivalent to induction generator.

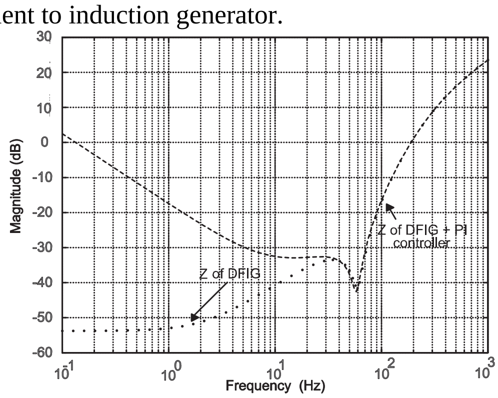

Fig. 6. Impedance Z of DFIG with PI controller seen from grid-side.

The PI controller in rotor current loop has an impact on the impedance of DFIG, mainly at low frequency, as showed in Figure 6. In addiction, the impedance increases with PI bandwidth B_ω. However, the bandwidth variation of the PI controller can lead the instability of the DFIG, as showed in Figure 5. Due the limitation of bandwidth PI controller, all *qd* frame variables will have second harmonic that is the causes of torque pulsations.

The next section, present the simple alternative for increases the impedance of system that is seen from the grid side.

B. Design of Disturbance Rejection Controller Resonant

The alternative for increase the impedance seen from the grid side without compromiser stability and without hardware modification is connect in parallel with PI controller a resonant controller at the twice line frequency, as showed in Figure 7.

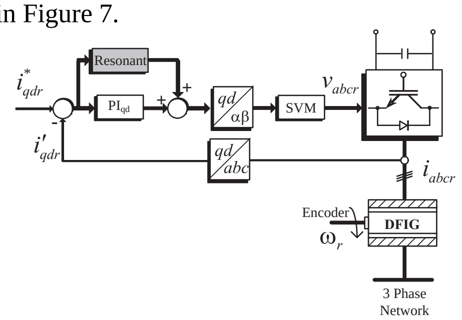

Fig. 7. Proposed Resonant controller added in the rotor current loop structure.

The PI plus resonant controller is represented in Figure 8.

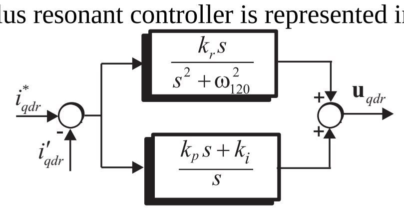

Fig. 8. Structure of PI plus Resonant controller.

The impact of the inclusion resonant controller in rotor current loop increases the impedance of DFIG around 120Hz, as showed in Figure 9.

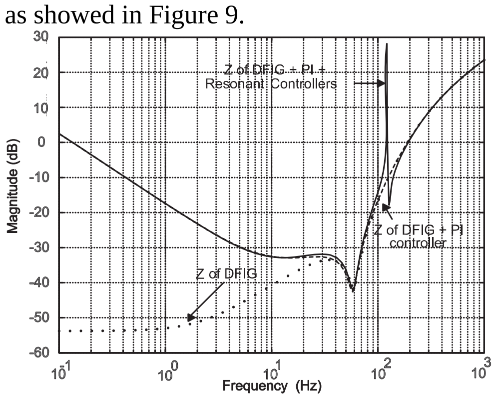

Fig. 9. Impact of the inclusion resonant controller in rotor current loop under impedance of DFIG.

Therefore, the inclusion of resonant controller in rotor current loop increases the impedance of DFIG as showed in Figure 9. With this simple modification, the torque pulsation can be reduce significantly without hardware modification, as will be demonstrated later

In the next section, simulations results are presented to demonstrate the advantages this simple modification on the rotor current controller.

V. SIMULATIONS STUDIES

A doubly-fed induction generation model has been constructed in MATLAB/Simulink [20]. The simulation results shown below are for a 2MW generator which parameters given in Table I. A VUF = 6% has been applied to the stator terminals. The generator starts at 0 seconds without the resonant controller. At 1.39 seconds, the line voltage becomes unbalanced. At 1.62 seconds the resonant controller is turned on. The torque pulsations are decreased by a factor of 10.

It is possible to see in Figure 10 the grid voltages, stator and rotor currents, torque and stator active and reactive powers.

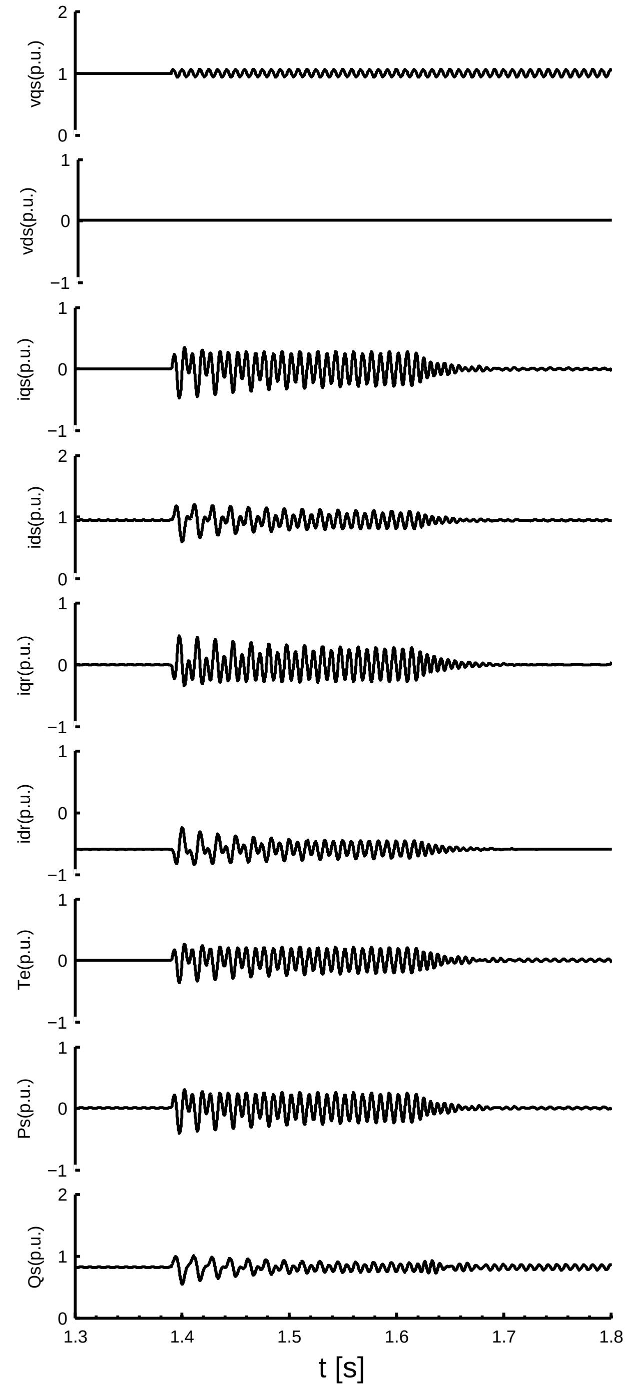

Fig. 10. Simulated results with VUF = 6%

Note in Figure 10 that the reduction torque pulsation is due to the increase of the system impedance at 120 Hz. For this reason, all variables have the 120 Hz component reduced.

TABLE I: Parameters of the 2 MVA DFIG

NOMINAL VALUES OF THE DFIG		
Rated power	P_n	2.27MVA
Rated voltage (Y)	$V_{rms,l-l}$	690V
Rated current	I_n	1900A
Rated frequency	f_n	60Hz
Number of pole pairs	n_p	2
BASE VALUES		
Base voltage (phase-phase)	$V_{rms,l-l}$	690V
Base current	I_n	1900A
Base impedance	f_n	60Hz
PARAMETERS OF THE INDUCTION MACHINE		
Stator resistance	r_s	0.0022 Ω ⇔ 0.01 p.u.
Rotor resistance	r_r'	0.0018 Ω ⇔ 0.009 p.u.
Stator leakage indutance	L_{ls}	0.12 mH ⇔ 0.18 p.u.
Rotor leakage indutance	L_{lr}'	0.05 mH ⇔ 0.07 p.u.
Magnetizing indutance	M	2.9 mH ⇔ 4.4 p.u.

VI. EXPERIMENTAL RESULTS

In order to validate the analysis carried out, experimental results are presented using a reduce scale laboratory prototype that is shown in Figure 12. It is basically composed by: one DFIG, two power converters connected in the rotor-side and in the grid-side, a line filter and the data acquisition. The resonant controller designed as well as the supervisory software was implemented in a DSP TMS320F2812. Both converters are commercial units and are vector controlled at a switching frequency of 4 kHz using appropriate interfaces and they are connected back-to-back, sharing the same DC bus as shown in Figure 1. One of them is supplied through a line filter from the power grid and the other one with the output of the generator's rotor. The stator of the generator is directly connected to the power grid. In addiction, the wind turbine (WT) is simulated by induction motor system sharing the same DFIG shaft. The voltage unbalance is generated using a 3ϕ transformer that supply only negative voltage sequence.

Figure 11 shows experimental results where the generator starts at 0 seconds without the resonant controller. At 0.39 seconds, a VUF = 6% has been applied to the stator terminals and at 0.62 seconds the resonant controller is turned on. Note that the torque pulsations are decreased by a factor of 8. This reduction torque pulsation is significant, in addition, all others variables also have the 120 Hz component reduced.

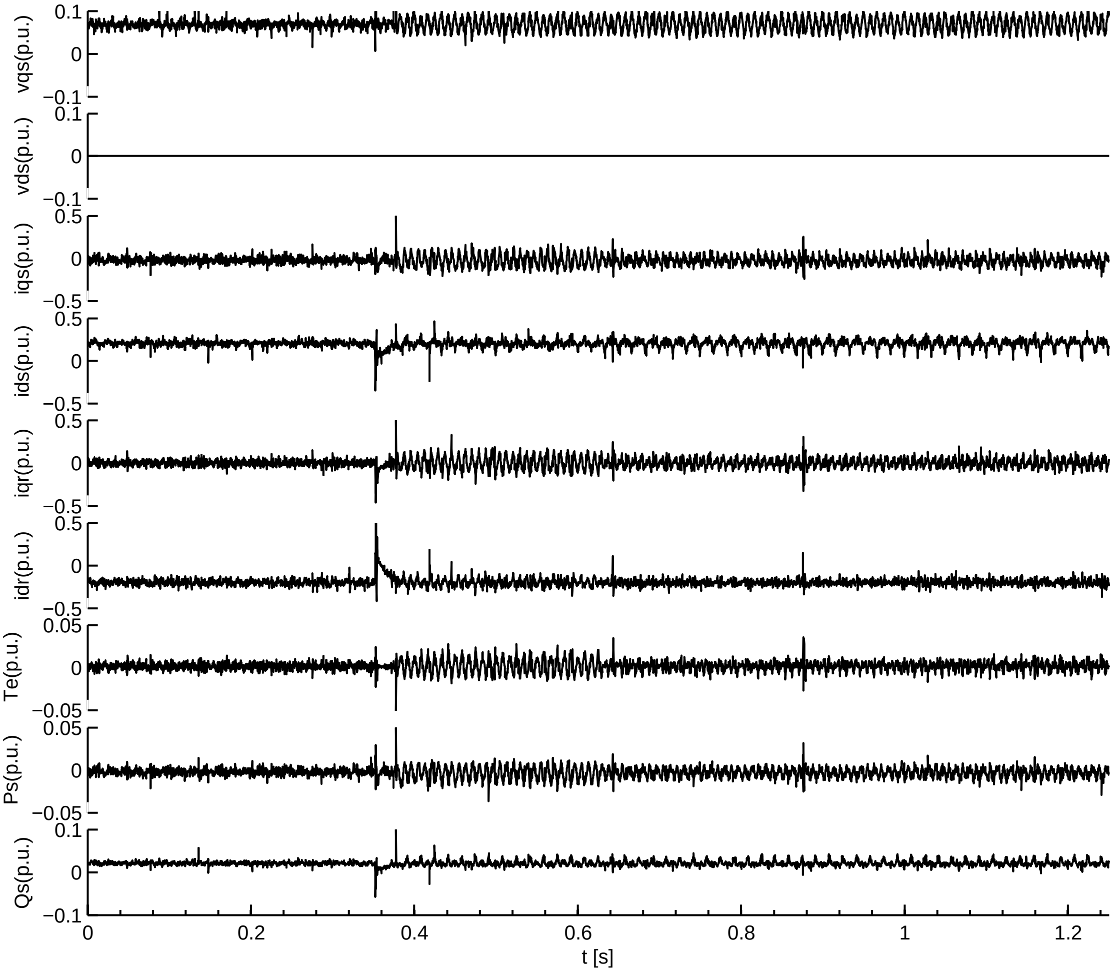

Fig. 11. Experimental results with VUF = 6%.

Fig. 12. The reduce scale laboratory prototype - 5kVA DFIG

VII. CONCLUSION

This paper proposes a new simple control schemes for a Doubly-fed Induction Generator to reduce the torque ripple due to unbalance grid voltages. In addiction, a dynamic model of the DIFG including the controllers is derived to show the impact of different controllers on impedance seen from the grid side. This paper demonstrates that the impedance of DFIG with a conventional PI controller is low at twice line frequency. In addition, it is concluded that through of the eigenvalues trajectory of system, it is impossible to increase impedance same the *qd* PI controller bandwidth increases because DFIG have the poorly damped eigenvalues move toward the instability.

Finally, it is conclude that with a simple resonant controller added in the rotor current loop it is possible to reduce the impact of voltage unbalance on the torque ripple without hardware modification. In addiction, is possible to increase the impedance what is seen from the grid side.

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