Combined Vector Control and Direct Power Control Methods for DFIG under Normal and Unbalanced and Distorted Grid Voltage Conditions

Mohammad Ebrahim Zarei
School of ECE, College of Engineering
University of Tehran
Tehran, Iran
m.e.zarei@ut.ac.ir

Behzad Asaei
School of ECE, College of Engineering
University of Tehran,
Tehran, Iran
basaei@ut.ac.ir

Abstract — **In this paper, a new control method for rotor side converter (RSC) and grid side converter (GSC) of doubly fed induction generator (DFIG) is proposed. Using the main principle of vector control (VC) and direct power control (DPC) results in a new control strategy for the RSC. Instead of using DPC strategy for the GSC, a direct current control is applied. Under the unbalanced and distorted grid voltage conditions, the new control strategy injects a pure sinusoidal and balanced stator and GSC currents without any need of extracting the negative sequence and 5th and 7th voltage harmonics. Only a modified phase locked loop (PLL) to extract the positive sequence of the fundamental phase angle, is added to this situation. The accuracy of the proposed control strategy for 2 MW DFIG under normal and unbalanced and distorted voltage conditions is evaluated in MATLAB/SIMULINK environment and results are compared with DPC strategy.**

Keywords—doubly fed induction genarator (DFIG); direct power control (DPC); vector control (VC); unbalanced and distorted grid voltage conditions

I. INTRODUCTION

One of the most popular wind turbines because of the preference to other wind turbines is doubly fed induction generators [1], [2]. Since the stator winding of the generator is directly connected to the grid any turbulence affects the generators, so controlling the DFIG in this situation is necessary. Controlling the DFIG under normal conditions and distorted and unbalanced grid voltage is a very interesting topic [1], [3]. A DFIG based wind energy generation system is shown in Fig. 1.

Two main power control strategies for DFIG are vector control [4], [5] and direct power control [5], [6]. Under normal Situation, these two power control work properly, but when the grid voltage is unbalanced and non-sinusoidal, without any additional controller, the electromagnetic torque, rotor and stator currents will have dc term and oscillation terms [7], [8].

In [7], an improved vector control for DFIG under unbalanced grid voltage was proposed, two notch filters have been used to extract the positive and negative sequence of grid voltage. So according to specified target like balanced stator currents, these components were applied to generate the reference rotor currents. In [8] a new algorithm for generating the power reference for direct power control was presented. It was shown that the oscillation term of electromagnetic torque can be eliminated without any sequence extraction.

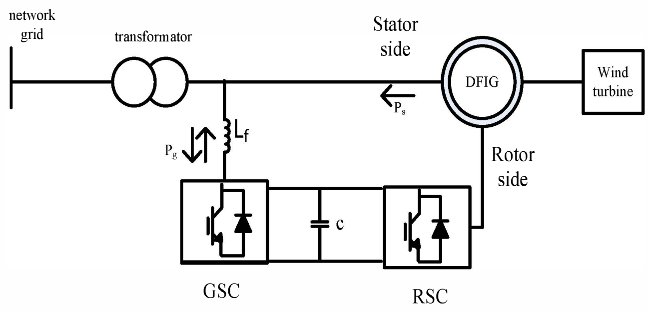

Figure 1. Configuration of a DFIG

In [9], a vector control and direct torque control for an induction motor drive was investigated. The authors discussed the similarity of these two control methods then proposed a combined vector control and direct torque control for the induction motor to have fast dynamics in controlling the motor.

This paper proposes a new control method for RSC and direct currents control for GSC to inject balanced and sinusoidal currents into the grid under normal and disturbance supply voltage without extracting the negative sequence and 5th and 7th voltage harmonics. The performance of this new control method is investigated and is compared with the DPC method.

The main idea is to take the stator voltage orientation (SVO) from VC method into DPC method. Variations of powers suggest a new method that directly controls the stator currents. This paper is organized as follows: Section II describes VC, DPC and proposed a new control method for RSC, section III presents DPC and direct current control for GSC, section IV investigates proposed control method under unbalanced and distorted supply voltage conditions. The simulation results are shown in section V, and finally conclusions are drawn in section VI.

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II. THE CONTROL METHODS FOR THE ROTOR SIDE CONVERTER OF DFIG

A. vector control (VC)

The dynamic stator, active and reactive power equations of a DFIG in a synchronously (ω_s) rotating d-q reference frame can be expressed by the following equations [4], [5]:

$$P_s = \frac{3}{2}(V_{ds}I_{ds} + V_{qs}I_{qs}) \quad (1)$$

$$Q_s = \frac{3}{2}(V_{qs}I_{ds} - V_{ds}I_{qs}) \quad (2)$$

In stator voltage orientation (SVO), the stator voltage vector is aligned with the d axis, therefore V_{qs} is equal to zero and $V_{ds}= V_s$, so the stator active and reactive power equation is simplified to:

$$P_s = \frac{3}{2}V_{ds}I_{ds} \quad (3)$$

$$Q_s = -\frac{3}{2}V_{ds}I_{qs} \quad (4)$$

B. Direct power control (DPC)

The equations of active and reactive power in DPC method can be expressed as follows [6]:

$$P_s = \frac{3}{2}\frac{L_m}{\sigma L_s L_r}\omega_s|\overrightarrow{\lambda_s}||\overrightarrow{\lambda_r}|\sin\delta \quad (5)$$

$$Q_s = \frac{3}{2}\frac{\omega_s}{\sigma L_s}|\overrightarrow{\lambda_s}|\left[\frac{L_m}{L_r}|\overrightarrow{\lambda_s}| - |\overrightarrow{\lambda_r}|\cos\delta\right] \quad (6)$$

$$\delta = \rho_s - \theta_r \quad (7)$$

Where L_s, L_r are the stator and rotor self inductance, L_m is the mutual inductance, σ is leakage coefficient, ω_s is the stator angular frequency, δ is the angle between the stator and rotor flux linkage space vector, ρ_s and θ_r are the angle between D axis (rotating at electrical angular speed of the rotor ω_m) and their flux linkage as shown in Fig. 2. λ_s and λ_r are the stator and rotor flux linkage.

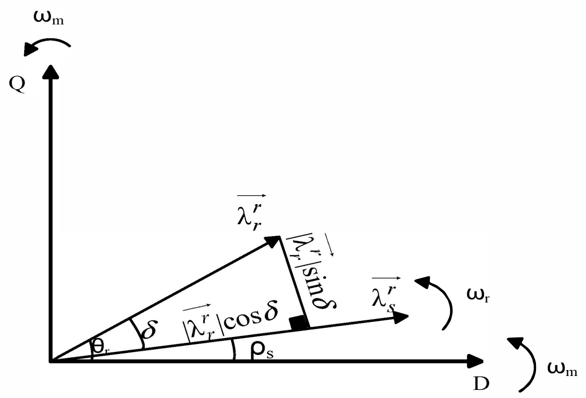

Figure 2. Flux space vector in rotor reference frame (DQ)

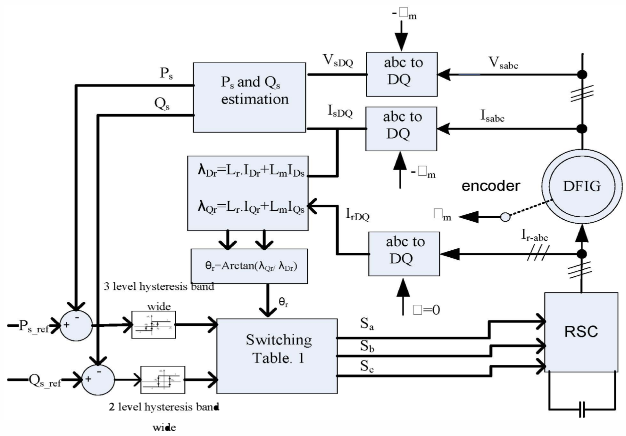

Figure 3. Block diagram of a DPC for DFIG

The stator windings of DFIG are directly connected to the grid. Therefore under normal conditions, the stator voltage is constant and by neglecting the stator resistance; the stator flux linkage is constant too, thus the stator active and reactive power can be written as:

$$P_s = A|\overrightarrow{\lambda_r}|\sin\delta \quad (8)$$

$$Q_s = B\left[C - |\overrightarrow{\lambda_r}|\cos\delta\right] \quad (9)$$

Where A, B and C are constant value. From the above equations, it can be seen stator active power is related to magnitude of rotor flux linkage and sinus of the angle between stator and rotor flux linkage, also stator reactive power is related to magnitude of rotor flux linkage and Cosine of the angle between stator and rotor flux linkage, as shown in Fig. 2.

In direct power control, the stator active and reactive power are directly controlled by comparing the reference power with estimated power. The power error is compared with a hysteresis band wide and flags of the hysteresis band wide are specified. The block diagram of this method is shown in Fig. 3. Optimal voltage vector can be selected by Knowing rotor flux sector, and the flags of hysteresis comparators. This optimal switching table is shown in Table. 1.

For example, if the rotor flux linkage vector located in sector 1 and $\overrightarrow{V_2}$ selected, this voltage vector makes active and reactive power to decrease (the active power will be more negative) and if $\overrightarrow{V_3}$ selected, makes the active power to decrease and reactive power to increase.

C. Proposed combined vector control and direct power control

According to vector control, a phase locked loop (PLL) for the stator voltage used, so the stator voltage space vector gets along the d axis that rotates at slip speed ($\omega_r=\omega_s-\omega_m$) in the DQ reference frame. Therefore, by neglecting the stator resistance, the stator flux linkage space vector lags the stator voltage space vector by 90 degrees. The location of stator voltage vector and d-q axis in the DQ reference frame is shown in Fig. 4.

It is supposed the rotor flux linkage vector in Small variation's time, rotates from $\lambda_{r,in}$ to the $\lambda_{r,fin}$ while the stator

TABLE I. SWITCHING TABLE FOR DPC METHOD

Reactive power	Active power	sector					
		1	2	3	4	5	6
Q+	P+	V_5	V_6	V_1	V_2	V_3	V_4
	P=	V_0	V_7	V_0	V_7	V_0	V_7
	P-	V_3	V_4	V_5	V_6	V_1	V_2
Q-	P+	V_6	V_1	V_2	V_3	V_4	V_5
	P=	V_0	V_7	V_0	V_7	V_0	V_7
	P-	V_2	V_3	V_4	V_5	V_6	V_1

flux linkage remains intact. According to the equations (8) and (9), the related variations of active power and reactive power are shown by red lines in Fig. 4. As shown in this figure, variation of active power is along the d axis, and the variation of reactive power is along the q axis. From equations (3) and (4) and Fig. 4, it is concluded:

$$\Delta P_s \propto \Delta I_{ds} \qquad \Delta Q_s \propto -\Delta I_{qs} \tag{10}$$

It means that the variation of active power is proportional to the variation of d axis stator current and variation of reactive power is proportional to negative variation of q axis stator current. Therefore, d-q axis stator currents can be directly controlled like DPC by a switching table. However, because of the negative relative of reactive power and q axis stator current, the switching table became as Table. 2.

Fig. 5 shows the block diagram of the proposed method which the d –q axis stator currents errors have been compared with a hysteresis band wide. The flags of this comparator and the sector of rotor flux select the voltage vector from Table. 2.

III. THE CONTROL MTHODS OF GRID SIDE CONVERTER OF DFIG

Direct power control of voltage source converters has been introduced in [10]. The injected or absorbed Active and reactive power of a voltage source converter directly control by this method. The main idea of this method is like DPC for rotor side converter. However, in GSC instead of rotor flux vector position, the stator voltage vector location defines the sector.

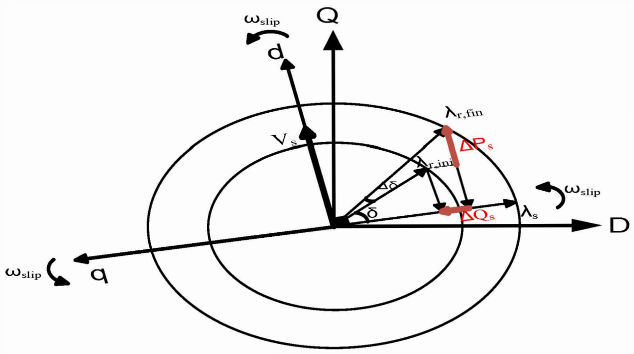

Figure 4. Stator voltage and flux in DQ reference frame and the relation of direct power to d-q axis currents

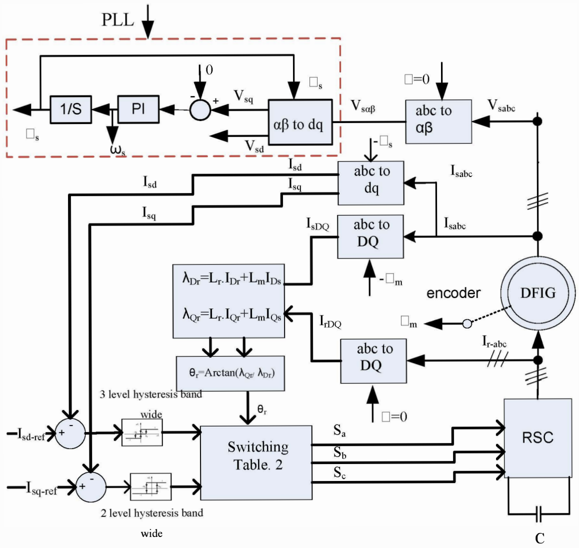

Figure 5. The block diagram of proposed method for RSC

The voltage of the GSC is the same as voltage of stator windings. By applying phase of the PLL that had been introduced in previous section the grid voltage vector is along the d-axis, thus active and reactive power of the GSC can be simplified as:

$$P_g = \frac{3}{2} V_{dg} I_{dg} \tag{11}$$

$$Q_g = -\frac{3}{2} V_{dg} I_{qg} \tag{12}$$

Variations of GSC active and reactive powers are related to:

$$\Delta P_g \propto \Delta I_{dg} \qquad \Delta Q_g \propto -\Delta I_{qg} \tag{13}$$

Therefore, the direct current control for GSC can be applied. The block diagram of this method for GSC is displayed in Fig. 6. The switching table introduced in [10] changes to Table. 3.

IV. UNBALBNCED AND DISTORTED GRID VOLTAGE CONDITION

Under simultaneously unbalanced and distorted stator voltage supply, with 5th and 7th harmonics voltage, the stator voltage in the d-q reference frame that rotate at ω_s can be

TABLE II. SWITCHIING TABLE OF PROPOSED METHOD FOR RSC

Stator q axis current	Stator d axis current	sector					
		1	2	3	4	5	6
I_{qs}+	I_{ds}+	V_6	V_1	V_2	V_3	V_4	V_5
	I_{ds}=	V_0	V_7	V_0	V_7	V_0	V_7
	I_{ds}-	V_2	V_3	V_4	V_5	V_6	V_1
I_{qs} -	I_{ds}+	V_5	V_6	V_1	V_2	V_3	V_4
	I_{ds}=	V_0	V_7	V_0	V_7	V_0	V_7
	I_{ds}-	V_3	V_4	V_5	V_6	V_1	V_2

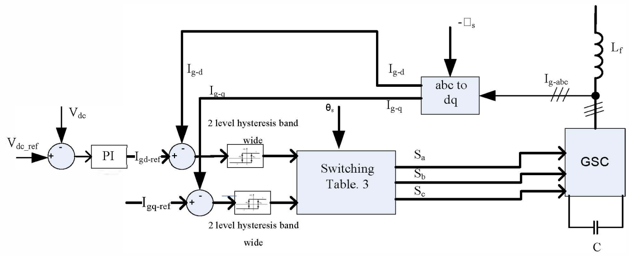

Figure 6. Direct current control for GSC

expressed as [11]:

$$V^{+}_{sdq} = V^{+}_{sdq+} + V^{+}_{sdq-} + V^{+}_{sdq5-} + V^{+}_{sdq7+} \tag{14}$$

And can be rewritten as:

$$V^{+}_{sdq} = V^{+}_{sdq+} + V^{-}_{sdq-} e^{-2j\omega_s t} + V^{5-}_{sdq5-} e^{-6j\omega_s t} + V^{7+}_{sdq7+} e^{+6j\omega_s t} \tag{15}$$

Where the superscripts show the reference frame and subscripts represent the sequence of the fundamental component and the harmonics [11]. For example V^{+}_{sdq7+} is the 7^{th} harmonic voltage in d-q reference frame that rotates at ω_s, and V^{7+}_{sdq7+} is the 7^{th} harmonic voltage in $7\omega_s$ rotating reference frame that is a dc term. In equation (15), V^{+}_{sdq+}, V^{-}_{sdq-}, V^{5-}_{sdq5-}, V^{7+}_{sdq7+} are dc terms, and illustrate that the stator voltage in positive d-q reference frame consist of a dc term and a term that oscillates with twice the synchronous speed ($2\omega_s$) and two terms that oscillates with the speed of $6\omega_s$.

According to the equation (15) the stator voltage in this condition is disturbed, thus the phase locked loop must be modified to lock to the positive fundamental sequence voltage (V^{+}_{sdq+}). The modified PLL is displayed in Fig. 7.

Under unbalanced and distorted grid voltage conditions various control targets can be selected like constant electromagnetic torque or balanced and sinusoidal rotor or stator currents and etc. In this paper the aim is to have balanced and sinusoidal stator and GSC currents. Heating of the stator windings will be balanced.

In [10], it is investigated to have balanced GSC currents under only unbalanced grid voltage. To achieve this goal the positive and negative sequence extractor is needed and then the reference powers of DPC have been modified. Reference powers have two terms, on term is dc and other term oscillates with twice the synchronous speed ($2\omega_s$).

The stator current can be expressed as [11], [12]:

$$I^{+}_{sdq} = \frac{\lambda^{+}_{sdq}}{L_s} - \frac{L_m}{L_s} I^{+}_{rdq} \tag{16}$$

TABLE III. SWITCHIING TABLE OF PROPOSED METHOD FOR GSC

GSC q axis current	GSC d axis current	sector					
		1	2	3	4	5	6
I_{qs} +	I_{ds} +	V_2	V_3	V_4	V_5	V_6	V_1
	I_{ds} -	V_3	V_4	V_5	V_6	V_1	V_2
I_{qs} -	I_{ds} +	V_1	V_2	V_3	V_4	V_5	V_6
	I_{ds} -	V_5	V_6	V_1	V_2	V_3	V_4

In these conditions, the stator flux also has negative sequence and 5^{th} and 7^{th} harmonics, so if no control strategy taken in VC and DPC methods the stator currents have negative sequence and 5^{th} and 7^{th} harmonics, as illustrated in below:

$$I^{+}_{sdq} = I^{+}_{sdq+} + I^{-}_{sdq-} e^{-2j\omega_s t} + I^{5-}_{sdq5-} e^{-6j\omega_s t} + I^{7+}_{sdq7+} e^{+6j\omega_s t} \tag{17}$$

Where I^{+}_{sdq+}, I^{-}_{sdq-}, I^{5-}_{sdq5-} and I^{7+}_{sdq7+} are dc terms. This means stator currents in positive d-q reference frame includes a dc term and oscillating terms.

In the proposed combined vector control and direct power control in RSC, the stator currents in d-q synchronous speed frame (ω_s) directly compared with a dc term, so the voltage vector selected to have dc currents in d-q reference frame. This means I^{-}_{sdq-} and I^{5-}_{sdq5-} and I^{7+}_{sdq7+} will be equal to zero without any need of extracting the negative sequence and 5^{th} and 7^{th} harmonics of stator voltage.

For the proposed GSC control as the same of the RSC control, the currents directly controlled. in d-q synchronous speed frame the current only have dc terms that means the grid side current will be balanced and sinusoidal.

V. SIMULATION RESULTS

The accuracy of proposed controlling method for RSC and GSC of DFIG has been evaluated by MATLAB/SIMULINK. The DFIG parameters are listed in Table. 5.

First to evaluate the performance of the proposed method under the normal voltage conditions at t=2.6 s the d axis stator current changed from -2100 A to -1600 A and the q axis stator current changed from -400 A to 0 A, so the stator active power changed from -1.77 MW to the -1.35 MW (negative value means injected into the grid and positive value means absorbed from the grid) and stator reactive power changed from +0.34 MVAR (absorbing reactive power from the grid) to zero MVAR, as shown in Fig. 8.

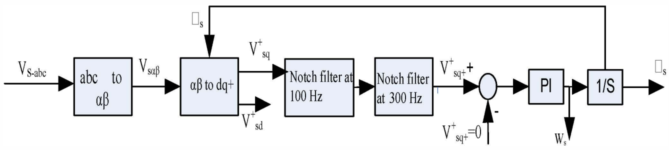

Figure 7. Modified PLL

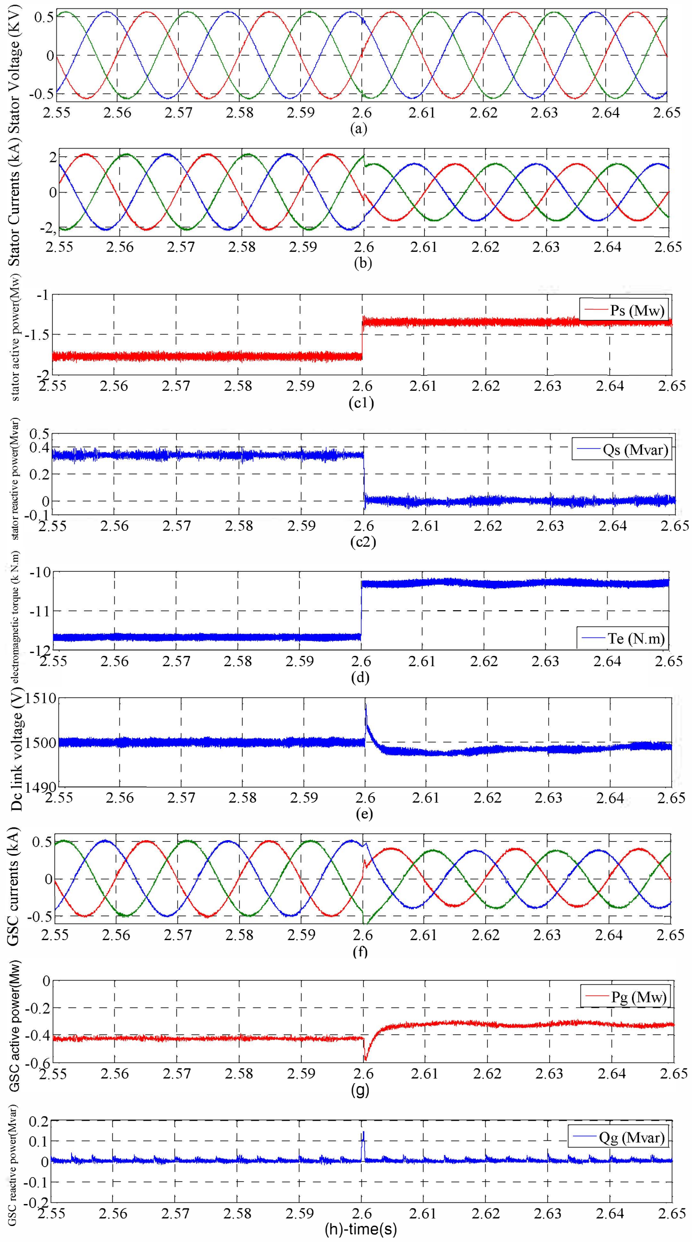

Figure 8. The performance of proposed method under normal stator voltage condition. (a) stator voltage (phase to ground) ; (b) stator currents; (c1) stator active power; (c2) stator reactive power; (d) electromagnetic torque; (e) dc link voltage; (f) GSC currents; (g) GSC active power; (h) GSC reactive power

Since the slip speed of the generator is -0.24 the GSC first injected 0.43 MW active power to the grid and at t= 2.6 injected active power changed to 0.33 MW, and the reactive power was set to zero before and after this time. The electromagnetic torque and dc link voltage and stator currents and GSC currents for this case is shown in Fig. 8.

To examine the performance of the proposed method under disturbance conditions at t=3 s the stator voltage changes from nominal value to $V_{sa}=V_{sc}=$ 398 V (phase to ground rms voltage) and have 7%, 5th and 5%, 7th voltage harmonics, V_{sb} =343 V and have 7%, 5th and 5%, 7th voltage harmonics.

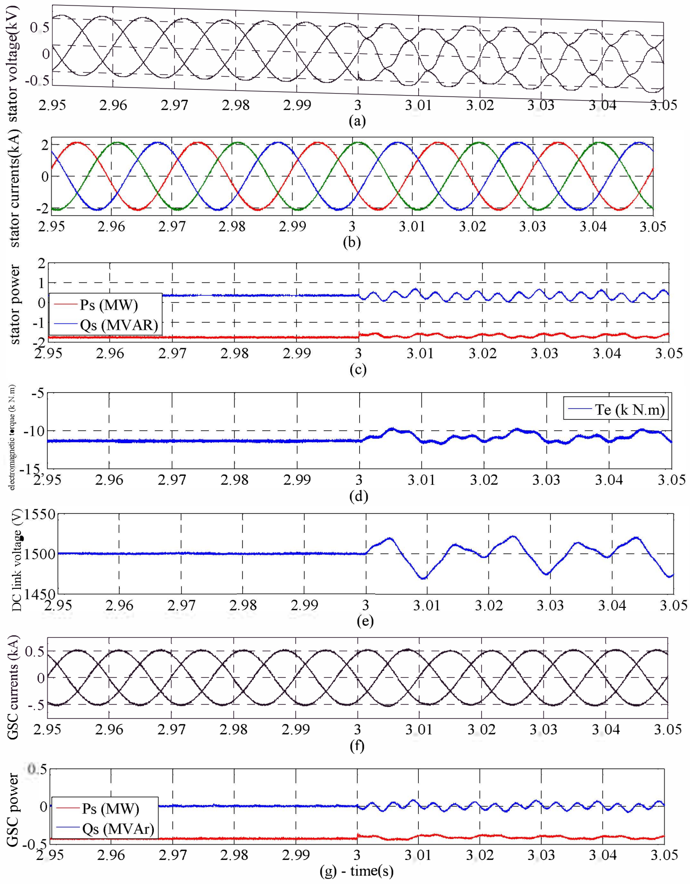

Figure 9. The performance of proposed method under unbalanced and distorted stator voltage condition. (a) stator voltage; (b) stator currents; (c) stator active and reactive power; (d) electromagnetic torque; (e) dc link voltage; (f) GSC currents; (g)GSC active and reactive power

As shown in Fig. 9 the stator and GSC under this condition still injects pure sinusoidal and balanced currents to the grid. However, the stator active and reactive power and GSC active and reactive power and electromagnetic torque have a dc term and oscillating terms (oscillating with $2\omega_s$, $4\omega_s$, $6\omega_s$, $8\omega_s$, $12\omega_s$) as displayed in Fig. 9.

Since the rotor and GSC active power have oscillating terms, therefore, the dc link voltage would have these oscillating terms, too.

Simulation of DPC for RSC and GSC under same unbalanced and distorted stator voltage condition is shown in Fig.10. Since the active and reactive power directly controlled the stator and GSC active and reactive powers are constant and have only a dc term, in return the stator and GSC inject unbalanced and non-sinusoidal currents to the grid. The electromagnetic torque is shown in this Fig. 10. The electromagnetic torque in this method approximately is greater than the proposed method. The total harmonic distortion (THD) of stator and GSC currents for these two strategies are summarized in Table .4.

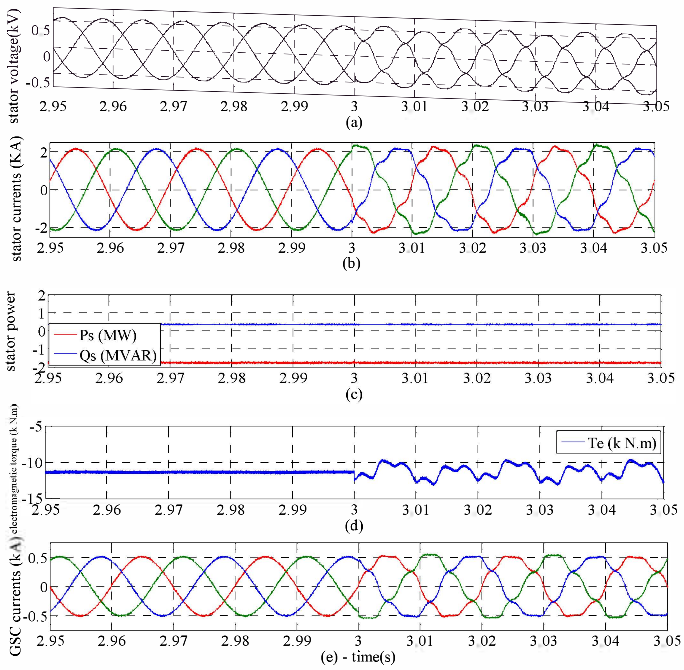

Figure 10. The performance of DPC method under unbalanced and distorted stator voltage condition. (a) stator voltage; (b) stator currents; (c) stator active and reactive power; (d) electromagnetic torque; (e) GSC currents

This Table demonstrates the effectiveness of the proposed method in decreasing the disturbances of stator and GSC currents.

TABLE IV. TOTAL HARMONIC DISTORTION OF DPC AND PROPOSED METHOD

Control strategy	Proposed method THD	DPC method THD
Stator currents I_s	0.8%	10%
GSC currents I_g	1.1%	10.5%

VI. CONCLUSION

This paper has presented new control strategies for RSC and GSC of DFIG under usual and unusual grid voltage conditions. A combined vector control and direct power control for RSC and direct current control for GSC have been introduced. The RSC directly controls the stator d-q axis currents (rotating at synchronous speed ω_s) by applying an optimal voltage vector from a switching table. The GSC directly controls the d-q axis currents by a switching table too. Under the unbalanced and distorted grid voltage the PLL has been modified to extract the positive fundamental sequence phase and therefore, the proposed method for GSC and RSC injects balanced and sinusoidal currents to the grid without the need of any additional controller or extracting negative sequence and harmonics voltage. The simulation results for DPC for RSC and GSC illustrate that under this unmoral conditions, stator and GSC currents are unbalance and non-sinusoidal.

Appendix

TABLE V. PARAMETERS OF THE SIMULATED DFIG

Rated power	2MW	Rotor inductance L_r	3.1 mH
Rated voltage (phase to phase)	690 v	Mutual inductance L_m	3mH
Stator resistance R_s	1.162 mΩ	Number of pole P	4
Rotor resistance R_r	1.3072 mΩ	DC link capacitor C_f	16000µF
Stator inductance L_s	3.1 mH	Grid frequency	50 Hz

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