

# Improved Direct Power Control for Brushless Doubly-Fed Wind Power Generator Under Unbalanced Grid Voltage Conditions

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**Abstract** — The paper presents the complete modeling and control strategy of variable speed wind turbine system (WTS) driven brushless doubly fed induction generators (BDFIG). A back-to-back converter is employed for the power conversion exchanged between BDFIG and grid. The wind turbine is operated on the maximum power point tracking (MPPT) mode its maximum efficiency. Direct power control (DPC) based on selecting of the appropriate CW stator voltage vectors and the errors of the active and reactive power, the control strategy of CW stator side converter (MSC) combines the technique of MPPT and direct power control. In the control system of the grid side converter (GSC) the direct power control based an improved switching table (IST-DPC) with notch filter has been used to maintain a constant DC-Link voltage and the reactive power is set to zero and better current quality compared with the conventional switching table .in addition, the behaviors of BDFIG under unbalanced grid voltage conditions are studied and a power compensation scheme is developed to improve the power quality. Simulations results using MATLAB/SIMULINK are presented and discussed on a 7.5 KW BDFIG wind generation system demonstrate the effectiveness of the proposed control.

**Keywords** — Back-To-Back Converter, BDFIG, Direct Power Control, Unbalanced Grid, Wind Power Generation.

## I. INTRODUCTION

Wind power has become increasingly popular because of the increasing difficulty of the pollution of the Environment. Enormous efforts have been put in the advancement of WECS, to reduce costs, increase the efficiency and the reliability [1, 2], with the sustained and rapid growth of world economy, the energy demand is increasing day by day, but a large amount of fossil fuel is used to lead to the environmental pollution aggravation. The wind energy as a clean and renewable energy accords with the future energy development [3]. The permanent magnet synchronous generator and the doubly fed induction generator based of WECS (PMSG WECS, DFIG-WECS) has become the most popular configuration for wind energy applications on one hand, The DFIG has several advantages including the maximum power capture over a wide speed range and decoupled active and reactive power control. It also allows the use of a partially rated converter which reduces the system cost [2, 4]. The use of brushes and slip rings associated with the rotors of DFIG decreases the robustness of system and increases the maintenance cost [2, 5, 6].

The cost of maintenance for traditional DFIG based wind generators increased the pressure to seek other alternative

generator systems. Brushless doubly-fed machines are the evolution of the cascaded induction machine and can be widely used for medium and large wind turbines with limited speed ranges [2], [5].

The (BDFIG), also known as a self-cascaded generator, is composed of two stator of different pole numbers called stator of power winding (PW) and stator of control winding (CW) and a special rotor winding. The converters capacity in the CW stator are of almost 25% of the machines rated power, which can operate in a wide speed range including super-synchronous, synchronous and sub-synchronous [4], [7]-[11], a medium speed machine, enabling the use of a simplified one or two stage gearbox, excluding the third high-speed stage, known to be the highest failure rate part of the gearbox, hence reducing the weight of the overall drive train and further improving reliability, reduced capital and maintenance costs and has significantly greater LVRT capability [9], [10]. The (BDFIG-WECS) retains all the advantages of (DFIG-WECS) and improves reliability by removing brushes and slip rings. Therefore, the (BDFIG-WECS) shows great potential in future wind power generation, especially the large wind turbines and offshore wind farm where maintenance costs are high. [11], [12].

BDFIG modeling is much more complex, which makes quite difficult control system design. Various strategies of control have been used to control of machine side converter (MSC) (the scalar current control, direct torque control, fuzzy power control, sliding mode power control, and flux oriented control based on rotor flux or stator flux/voltage orientation [12]. At present, the vector control is mainly adopted to implement the power decoupling control of BDFG [7], [11], [14]. But the vector control requires the complicated control algorithm and high performance processor, and greatly depends on the BDFG parameters, which leads to the poor robustness of the system [4]. The direct torque control (DTC) with the simpler control algorithm, faster dynamic response and better robustness than the vector control has been attempted to apply for the variable-speed constant-frequency BDFG control system [4]-[6]. But the flux observer of DTC is sensitive to the generator parameter variation and inaccurate identification, which leads to the bad real-time of control system. Alternatively, the direct power control (DPC), derived from DTC, can directly decouple and independently control the active and reactive powers to implement the power tracking. DPC has a simpler algorithm and less calculation than DTC, and does not need to observe the flux amplitude, which can well solve the problem of the bad real-time of control

system caused by the flux observer being sensitive to generator parameter variations. Therefore, DPC of (MSC) has been applied to the (BDFIG) control system [3], [5], [11], the three strategies are based on the same principle with the only difference existing in flux estimation algorithm. DPC strategies developed in [11], high reliability with the elimination of rotor current/position sensor and rotating coordinate transformation, and less parameter independent with the control machine stator resistance

The grid side converter (GSC) control approaches can be classified, as cited in the literature as a vector oriented control (VOC) and direct power control (DPC) [13], the vector control (VC) can be either based on grid voltage [14-16] or virtual-flux [17] using proportional-integral (PI) controllers. However, it has some disadvantages, such as its dependence on the system parameters variation, that its performance largely depends on the tuning of the PI parameters [18]. In order to overcome complication due to the current control loops, an effective control, namely direct power control (DPC) has been developed [19], Direct power control (DPC) strategy has become one of the hot research topics in recent Years, because of its fast dynamic response, simple structure, and high power factor, and so on [20], [21]. This strategy is based on a hysteresis control of instantaneous active and reactive powers. A switching table addresses the optimal commutation states of the rectifier according to active and reactive power and to the position of the grid voltage. Big number of researchers offered different tables of commutation to reduce the complete harmonic distortion (THD) of the currents of line and the losses of commutation [22]-[26].

This paper is organized as follows: In Section 2, the mathematical model of BDFIG, Wind Turbine and three-phase grid side converter (GSC) is discussed. In Section 3, presents controls of different parts of the (WECS) chain, DPC method is used to control of machine side converter (MSC) of BDFIG, the maximum power point tracking (MPPT) method was implemented for optimal energy capture by the wind turbine, direct power control based improved switching table (IST-DPC) and notch filter of (GSC) converter to control the voltage of the DC Link is proposed for simplicity, robustness, and excellent performance. Section 4 presents Modified direct power control (MDPC) for MSC converter under unbalanced grid voltages condition. Section 5 presented some simulation results and discussion finally, the conclusion is provided in section 5.

## II. MODELING OF WECS COMPONENTS

A typical WECS configuration has been presented in Fig. 1. The considered topology consists of: Turbine via a gearbox connected to BDFIG, which the PW stator of BDFIG connected directly to the grid and the CW stator is connected to back-to-back converter, which includes MSC and GSC.

The Wind Turbine Aerodynamic Model is given by [27]-[30]

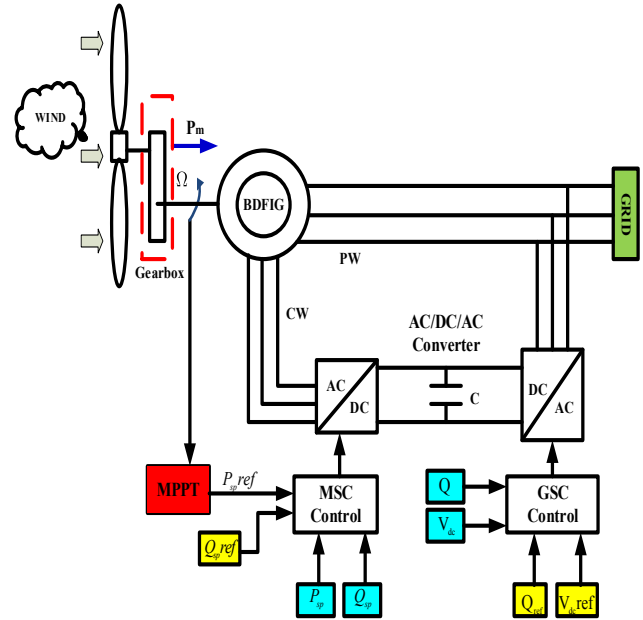


Fig. 1. The scheme of variable speed wind turbine system with BDFIG and back-to-back converter system

### A. Mathematical model of BDFIG

The model of the BDFIG in the PW flux frame is expressed as [12].

$$\begin{cases} v_{qsp} = R_{sp} i_{qsp} + \frac{d\psi_{sp}}{dt} + \omega_p \psi_{dsp} \\ v_{dsp} = R_{sp} i_{dsp} + \frac{d\psi_{dsp}}{dt} - (\omega_p - (P_p + P_c) \omega_r) \psi_{qsp} \\ v_{dsc} = R_{sc} i_{dsc} + \frac{d\psi_{dsc}}{dt} - (\omega_p - (P_p + P_c) \omega_r) \psi_{qsc} \\ v_{qsc} = R_{sc} i_{qsc} + \frac{d\psi_{qsc}}{dt} + (\omega_p - (P_p + P_c) \omega_r) \psi_{dsc} \\ 0 = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_p - P_p \omega_r) \Phi_{qr} \\ 0 = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_p - P_p \omega_r) \psi_{dr} \end{cases} \quad (1)$$

$$\begin{cases} \psi_{dsp} = L_{sp} i_{dsp} + M_{spr} i_{dr} \\ \psi_{qsp} = L_{sp} i_{qsp} + M_{spr} i_{qr} \\ \psi_{dsc} = L_{sc} i_{dsc} + M_{scr} i_{dr} \\ \psi_{qsc} = L_{sc} i_{qsc} + M_{scr} i_{qr} \\ \psi_{dr} = L_r i_{dr} + M_{scr} i_{dsc} + M_{spr} i_{dsp} \\ \psi_{qr} = L_r i_{qr} + M_{scr} i_{qsc} + M_{spr} i_{qsp} \end{cases} \quad (2)$$

The aerodynamic torque is given by:

$$C_{em} = (i_{qsp} i_{dr} - i_{dsp} i_{qr}) + p_c M_{scr} (i_{dsc} i_{qr} - i_{qsc} i_{dr}) \quad (3)$$

According to the instantaneous power theory, the active and reactive powers of the (PW) are defined as:

$$P_{sp} = \frac{3}{2} (V_{sdp} I_{sdp} + V_{sqp} I_{sqp}) \quad (4)$$

$$Q_{sp} = \frac{3}{2} (V_{sqp} I_{sdp} - V_{sdp} I_{sqp}) \quad (5)$$

### B. Model of three-phase PWM converter (GSC & MSC)

The main objective of grid side converter (GSC) is to keep the dc-link voltage constant. It is controlled using a VF-DPC based new switching table [23].

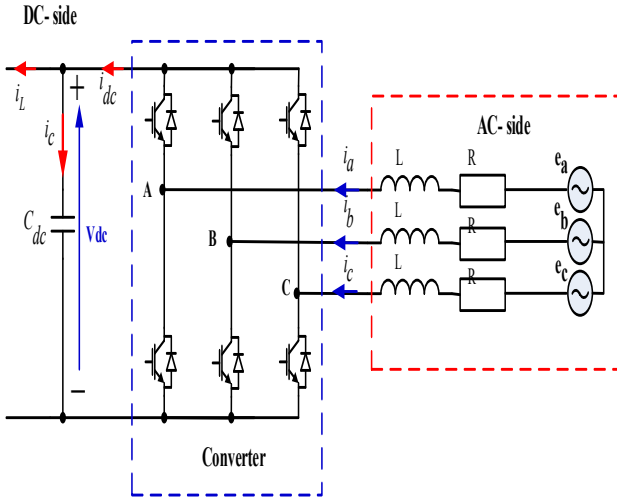


Fig. 2. Block diagram for three-phase PWM rectifier

The converter can be expressed, in a-b-c reference frame with following equations [20]:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (6)$$

Where:  $L$  and  $R$  are the inductance and resistance of the chokes, respectively.  $e_a, e_b, e_c, i_a, i_b$  and  $i_c$  are the electrical grid voltage and current,  $V_A, V_B, V_C$  are the AC side voltages of the converter.

$$\begin{cases} V_A = \frac{V_{dc}}{3} (2S_a - S_b - S_c) \\ V_B = \frac{V_{dc}}{3} (-S_a + 2S_b - S_c) \\ V_C = \frac{V_{dc}}{3} (-S_a - S_b + 2S_c) \end{cases} \quad (7)$$

$S_a, S_b$  and  $S_c$  are the switching states of the rectifier show Fig.5.

The relationship between the AC side rectifier currents  $i_a, i_b$  and  $i_c$  and the DC bus voltage  $V_{dc}$  can be written as:

$$C_{dc} \frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_L \quad (8)$$

### III. CONTROL STRATEGIES OF WECS

The control strategy used in this paper includes the MPPT algorithm developed in [29], to maximize the power extracted from the Wind, the DPC for MSC by controlling the stator active and reactive powers and the DPC for GSC by controlling the DC-Link voltage and active and reactive powers exchanged with grid.

### A. Direct Power Control DPC OF BDFIG with PW Stator side Converter

The control idea of DPC is derived from DTC. The DPC principle diagram of the BDFIG is shown as Fig. 3, which is similar to DTC, the reference active power  $P_{sp}^*$  is set by maximum power tracking strategy according to wind speed. Reference reactive power  $Q_{sp}^*$  is set zero for kept unity power factor, and  $dP, dQ$  are respectively the errors of the active and reactive power.

The flux amplitude  $\psi_{sp}$  of the PW stator is approximately constant due to the PW stator is directly connected to the power grid see Fig. 3, so the active power  $P_{sp}$  can be controlled by changing the rotational speed and direction of the control winding flux  $\psi_{sc}$ , referring to the DTC method, the reactive power  $Q_{sp}$  can be controlled by changing the flux amplitude  $\psi_{sc}$  of the CW stator [3].

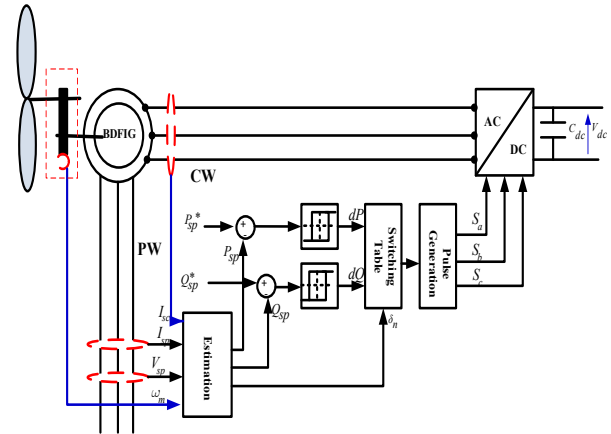
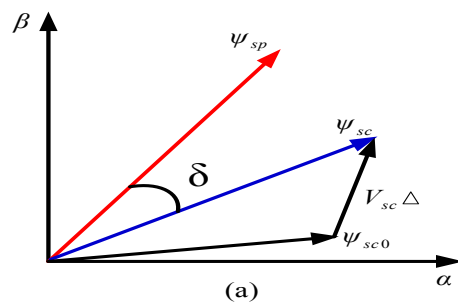


Fig. 3. Block diagram of DPC controller for BDFIG

For MSC three-phase two-level inverters, there are eight possible voltage vectors (six active vectors and two null vectors), and the  $\alpha$ - $\beta$  plane is divided into six sectors, as shown in Fig. 4(b).

The actual output powers  $P_{sp}$  and  $Q_{sp}$  are first estimated, and then compared with the references  $P_{ref}$  and  $Q_{ref}$ . The errors are sent to two fixed band hysteresis comparators to produce digitized signals  $dP$  and  $dQ$ . Finally, the voltage vector is selected from Table 1 according to  $dP, dQ$ , and the position of  $\psi_{sc}$ .

Relationship of CW stator voltage and flux vector is shown in Fig. 4(a) [30].



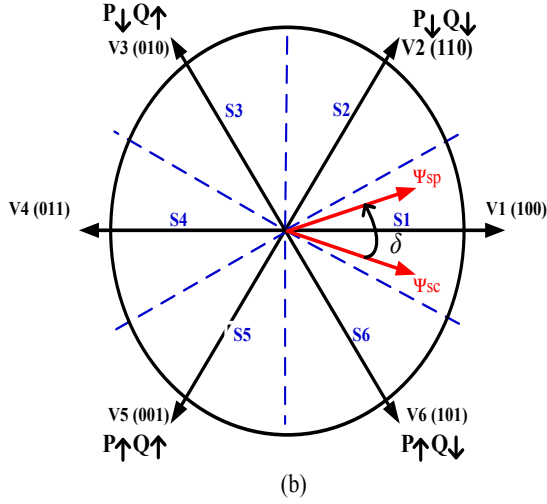


Fig. 4. (a) relationship between voltage vector and flux vector (b) Voltage vectors generated by the inverter and sector division.

Tab. 1: The voltage vector control selection table [3], [30]

Error		Section					
$dP$	$dQ$	$\delta_1$	$\delta_2$	$\delta_3$	$\delta_4$	$\delta_5$	$\delta_6$
0	0	V <sub>6</sub>	V <sub>1</sub>	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>
1	0	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>1</sub>
0	1	V <sub>5</sub>	V <sub>6</sub>	V <sub>1</sub>	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>
1	1	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>1</sub>	V <sub>2</sub>

In this paper, we have used the same flux estimation principle used in [5]. The PW and CW stator fluxes are estimated in PW stator reference. Then the estimated CW stator flux is transformed to the CW stator reference frame to execute the sector detection algorithm [5].

The (PW) stator flux and (CW) stator flux are estimated by (9), (10) [5].

$$\psi_{sp} = \int (V_{sp} + R_{sp} i_{sp}) dt \quad (9)$$

$$\psi_{sc} = R_{sc} i_{sc} - \frac{L_{scm}}{L_{spm}} (\psi_{sp} - L_{sp} i_{sp}) \quad (10)$$

#### B. Direct power control of grid side converter

The basic principle of the DPC was proposed by Noguchi [19] and is based on the well know Direct Torque Control (DTC) for induction machines. Fig. 5 shows the configuration of the direct instantaneous active and reactive power controller.

The controller control of the active and reactive power with the aid of the use of hysteresis comparators and an improved switching table (IST-DPC) used in [23]. The new switching schedule improves the quality of line current and results in better dynamic performances as compared with the conventional switching table (ST-DPC) used in [19].

In this configuration, the dc-bus voltage is regulated by Controlling the active power, and the unity power factor Operation is achieved by controlling the reactive power to be zero.

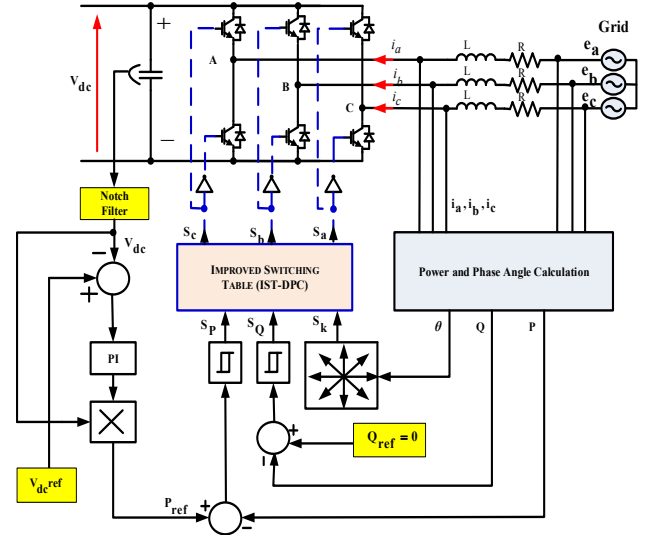


Fig. 5. Block diagram of the conventional DPC

The notch filter on the DC link voltage is there in order to remove 100 Hz oscillations that arise during unbalanced conditions. Therefore, these filters ameliorate technique of conventional (DPC). A filter that removes the 100 Hz oscillations can also be made by using a SOGI tuned to 100 Hz, instead of 50 Hz. One can subtract the input signal with the filtered signal from the SOGI [31]-[33]. The digitized variables  $S_p, S_q$  and the line voltage vector position  $\theta = \tan^{-1}(e_a/e_b)$  form a digital word, which by accessing the address of lookup table selects the appropriate voltage vector according to the switching table [23]. For this purpose, the stationary coordinates are divided into 12 sectors [19-26] :

The instantaneous input active and reactive powers of three phase rectifier and voltage vector position are generally defined as:

$$P = e_a i_a + e_b i_b + e_c i_c \quad (11)$$

$$q = \frac{1}{\sqrt{3}} [(e_a - e_c) i_a + (e_c - e_a) i_b + (e_a - e_b) i_c] \quad (12)$$

#### IV. MODIFIED DIRECT POWER CONTROL (MDPC) FOR MSC CONVERTER

When the grid is unbalanced, according to symmetric decomposition theory, an unbalanced three-phase system can be decomposed in three balanced symmetric three phase system, the zero sequence (0), the positive sequence (+), and the negative sequence (-), in this analysis assume a three-wire connection system) [5], as a result, the zero of the currents will be zero.

In stationary reference frames, the voltage and current of PW stator are expressed in (13), (14) :

$$V_s = V_{s\alpha} + jV_{s\beta} = (V_{s\alpha}^+ + V_{s\alpha}^-) + j(V_{s\beta}^+ + V_{s\beta}^-) \quad (13)$$

$$I_s = I_{s\alpha} + jI_{s\beta} = (I_{s\alpha}^+ + I_{s\alpha}^-) + j(I_{s\beta}^+ + I_{s\beta}^-) \quad (14)$$

The apparent power is given by

$$S = P + jQ = \frac{3}{2} I_{sp}^* V_{sp} \quad (15)$$

After substituting the voltage and current by their values shown in (13) and (14), the active and reactive powers results can be regrouped in three terms:

$$P = \frac{3}{2} \left( \begin{aligned} &(V_{sp\alpha}^+ I_{sp\alpha}^+ + V_{sp\beta}^+ I_{sp\beta}^+ + V_{sp\alpha}^- I_{sp\alpha}^- + V_{sp\beta}^- I_{sp\beta}^-) \\ &+ (V_{sp\alpha}^+ I_{sp\alpha}^- + V_{sp\beta}^+ I_{sp\beta}^-) + (V_{sp\alpha}^- I_{sp\alpha}^+ + V_{sp\beta}^- I_{sp\beta}^+) \end{aligned} \right) \quad (16)$$

$$Q = \frac{3}{2} \left( \begin{aligned} &(V_{sp\beta}^+ I_{sp\alpha}^+ + V_{sp\beta}^- I_{sp\alpha}^- - V_{sp\alpha}^+ I_{sp\beta}^+ - V_{sp\alpha}^- I_{sp\beta}^-) \\ &+ (V_{sp\beta}^+ I_{sp\alpha}^- - V_{sp\beta}^- I_{sp\alpha}^+) + (V_{sp\beta}^- I_{sp\alpha}^+ - V_{sp\beta}^+ I_{sp\alpha}^-) \end{aligned} \right) \quad (17)$$

We pose:

$$P_2 = V_{sp\alpha}^- I_{sp\alpha}^+ + V_{sp\beta}^- I_{sp\beta}^+ \quad (18)$$

$$Q_2 = V_{sp\beta}^- I_{sp\alpha}^+ - V_{sp\alpha}^- I_{sp\beta}^+ \quad (19)$$

$P_2$ ,  $Q_2$ : represents the interaction between the negative and positive sequence of voltages and currents that generates an oscillation in the active and reactive power with a frequency that is (6w).

There are many control laws that can be applied in the proposed control, to obtain sinusoidal and balanced line currents; the negative sequence components must be eliminated ( $I_{sp\alpha}^- = I_{sp\beta}^- = 0$ ), and at the (16) and (17) can be written as (20) and (21).

$$P = \frac{3}{2} (V_{sp\alpha}^+ I_{sp\alpha}^+ + V_{sp\beta}^+ I_{sp\beta}^+) + \frac{3}{2} P_2 \quad (20)$$

$$Q = \frac{3}{2} (V_{sp\beta}^+ I_{sp\alpha}^+ - V_{sp\alpha}^+ I_{sp\beta}^+) + \frac{3}{2} Q_2 \quad (21)$$

Under the balanced and perfectly sinusoidal grid voltage supply, there only exists a positive sequence component, and the powers can be described as:

$$P = \frac{3}{2} (V_{sp\alpha}^+ I_{sp\alpha}^+ + V_{sp\beta}^+ I_{sp\beta}^+) \quad (22)$$

$$Q = \frac{3}{2} (V_{sp\beta}^+ I_{sp\alpha}^+ - V_{sp\alpha}^+ I_{sp\beta}^+) \quad (23)$$

It can be seen from (20) and (21) that we want to eliminate the effect of the negative component of the grid; the active and reactive power compensated components can be obtained as:

$$P_{comp} = \frac{3}{2} P_2 \quad (24)$$

$$Q_{comp} = \frac{3}{2} Q_2 \quad (25)$$

The modified DPC strategy is based on the idea of injecting the active power compensated components the original referenced power to achieve control objectives. Fig.6 shows the control diagram.

The new power references that can achieve sinusoidal and symmetric stator current as:

$$P_{ref} = P_{const} + P_{comp} \quad (26)$$

$$Q_{ref} = Q_{const} + Q_{comp} \quad (27)$$

Where  $P_{const}$  and  $Q_{const}$  are the original constant power reference under normal grid conditions.

In this section we illustrate the real-time extraction of positive, negative, sequences from of three phase voltages and current. To achieve that, several methods have been proposed in the literature. The Dual second order

generalized integrator (DSOGI-FLL) methods proposed in [32, 33] is used to separate the positive and negative sequences of voltage and current. When the proposed method is applied in the DC distribution system. Stable system operation is feasible by performing phase extraction of input voltage, positive sequence voltage extraction only using the SOGI-FLL. Moreover, proposed method reduces the harmonics, which is contained in the input voltage [32], [33].

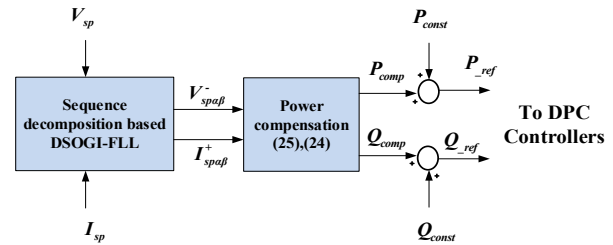


Fig. 6. Control strategy of BDFIG under unbalanced grid voltage conditions [5].

## V. SIMULATION RESULTS AND ANALYSIS

In order to verify and the validation of the proposed DPC strategy, the system has been modeled and built in MATLAB/SIMULINK software environment. The dc link voltage is set at 600 V. The control of (GSC) aims to maintain a constant dc-link voltage, and it is controlled using IST-DPC with integrating notch. The (MSC) is exploited to regulate the power flow via BDFIG stator to the grid using conventional DPC and modified DPC strategy. The specific generator parameters listed in [4]. The sampling frequency during simulation is 20 kHz and the bandwidth of hysteresis controller is set at zero for simplicity.

The system is analyzed during steady-state and conditions at two cases represent in the table 2,

Table 2. Case Simulation Study

Case	WIND SPEED	POWER SUPPLY	Duration	applied technique
1	9 m/s	balanced	0 to 0.5 s	DPC
	11 m/s	balanced	0.5 to 0.8s	
2	11 m/s	balanced	0 s to 0.5s	DPC
		balanced	0.5s to 0.6 s	DPC
		Unbalanced (15% supply voltages)	0.6 s to 0.8s	MDPC

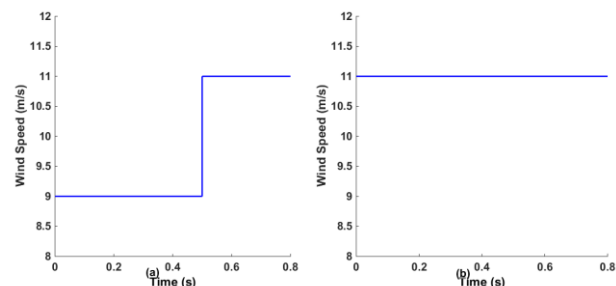


Fig. 7. Simulation results. (a) Wind speed of case 1.

(b) Wind speed of case 2.

#### A. Simulation result of case 1 :

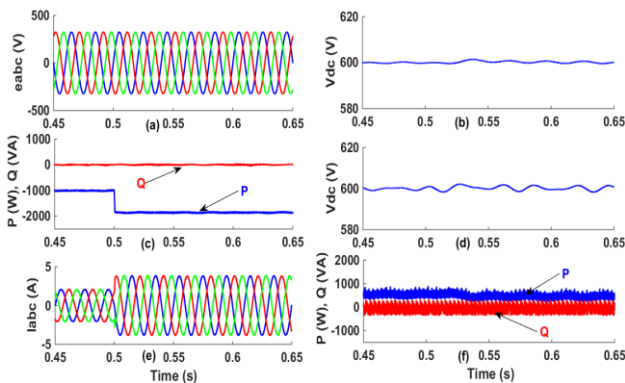


Fig. 8. Simulation results of (case1). (a) 3- phase voltages waveform of PW stator. (b) DC-link voltage with notch filter. (c) Active power and reactive power of PW stator. (d) DC-link voltage without notch filter. (e) 3- phase current waveform of PW stator. (f) Active power and reactive power of GSC

The accurate and smooth of (active and reactive power, DC- link voltage) control in the case1 can be observed from Fig. 8. At  $t = 0.5s$ , a wind speed steps from 9 m/s to 11 m/s as shown in Fig.7 (a). Fig. 8(c) and (f) shows the excellent dynamic and steady state response of (P) and (Q) of GSC and MSC. It is important to notice the inherently decoupled control of real and reactive power. The (PW) stator active power reference is obtained through the MPPT control algorithm, and the GSC power reference is obtained through measured and filtered DC-link voltage with notch filter. The integration of the notch filter in the control scheme, notably improved the waveform of the DC-linkvoltage show Fig. 8(b) and Fig. 8(d). The control strategy (DPC) of MSC provides balanced and sinusoidal PW stator currents see Fig. 8(a).

#### B. Simulation result of case 2:

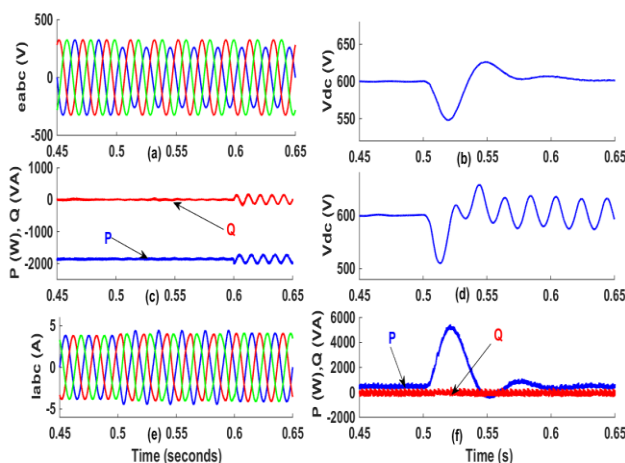


Fig. 9. Simulation results of (Case2). (a) 3- phase voltages waveform of PW stator. (b) DC-link voltage with notch filter. (c) Active power and reactive power of PW stator. (d) DC-link voltage without notch filter. (e) 3- phase

current waveform of PW stator. (f) Active power and reactive power of GSC

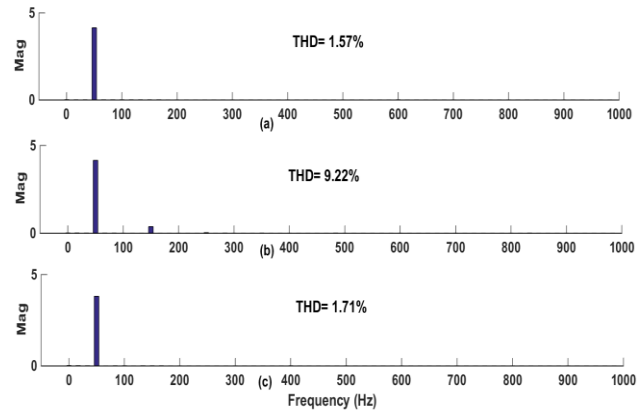


Fig. 10. Spectra of PW stator current (a) under balanced grid voltage condition using classical DPC. (b) Under unbalanced grid voltage condition using classical DPC. (c) Under unbalanced grid voltage, condition using MDPC.

The unbalanced grid voltage is generated at ( $t = 0.5 s$ ) with a 20 % voltage unbalance of phase (a) under fixed wind speed at 11 m/s, as shown in Fig. 9(a) and Fig.7(b). At ( $t = 0.5 s$  to  $0.6 s$ ), Fig. 9 shows the BDFIG behaviour using conventional DPC strategy under unbalanced grid voltage and (IST-DPC) with notch filter of GSC. It can be seen the active and reactive powers are smooth and constant due to the excellent control ability of the both proposed DPC method. However, the currents exchanged with the grid (i.e., the PW stator currents) get quite distorted with serious harmonic distortions see Fig.9 (e) and Fig.10 (b), which will pollute the power system. This is unacceptable for grid-connected distributed generations. The waveform of DC-link voltage (Fig.9 (b)) clearly indicate that the second-order harmonic component at 100 Hz presented in waveform of DC-link voltage (Fig.9 (d)) is eliminated by using the notch filter based SOGI technique under unbalanced voltage condition.

At ( $t = 6s$  to  $t = 0.65 s$ ), under unbalanced grid voltage with incorporating the proposed power compensation scheme (MDPC) for MSC, it can be seen that the active and reactive power of PW stator oscillate at twice the grid frequency around their rated values. While the power ripples resulting from an unbalanced part of the supply voltage that it still exists. As well we can see the PW stator currents become sinusoidal and symmetric; thus, power quality is improved significantly. The presence of an unbalance in voltage supply creates pulsation terms in output DC-link voltage without notch filter Fig. 9(d). The integration of notch filter in scheme control of GSC eliminate this drawback. As a result, the active and reactive powers of GSC DC-link voltage are smooth and constant. The PW stator current spectra in different scenarios are summarized in Fig. 10. The frequency spectra clearly show that the low-order harmonics can be reduced by employing the modified control strategy (MDPC) under unbalanced voltage supply. The total harmonic distortion (THD) of PW stator current under ideal supply is 1.57% and it is increased to 9.22% under unbalanced supply, and after applying the

MDPC strategy the THD is decreased to 1.71%, which meets the IEEE standard 519-1992.

## VI. CONCLUSION

In this paper, a robust direct power control approach applied for wind energy conversion system (WECS) based BDFIG machine has been investigated. Mathematical modeling of various parts of the system is introduced and explained. The control process is done in a coordinated manner between grid side and machine side. Whereas, conventional direct power control has been used for the CW stator side converter in order to adapt and capture the maximum power available by wind turbine to be fed via PW stator to the grid. The maximum power point is defined by an MPPT algorithm, which could provide the reference power signal, used in the DPC PW stator controller. Meanwhile, grid side control issue focus mainly to ensure constant DC link voltage during system operation, test of robustness was conducted using variable wind profile and results demonstrated a pretty good set-point tracking behavior. The proposed strategy is verified by simulation for tow cases, which are balanced voltage, unbalanced voltage. It proves its capability of yielding sinusoidal and balanced grid current with unity power factor under unbalanced voltage source. DPC approach of GSC in combination with a notch filter and improved switching table ensures that the dc link voltage is maintained constant (without oscillation) and the supply side power factor is kept close to unity under the unbalanced supply voltage operating conditions. Finally, the proposed IST-DPC with notch filter and MDPC based BDFIG system obtaining a very good power quality on the grid side with a satisfactory power factor and a low THD factor for the PW stator current within the standard limits whatever the power grid.

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