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Research Article

Sliding-Mode-based Improved Direct Active and Reactive Power Control of Doubly Fed Induction Generator under Unbalanced Grid Voltage Condition

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ABSTRACT

This paper proposes an improved direct active and reactive power control (DPC) strategy for a grid-connected doubly fed induction generator (DFIG) based wind-turbine system under unbalanced grid voltage condition. The method produces required rotor voltage references based on the sliding mode control (SMC) approach in stationary reference frame, without the requirement of synchronous coordinate transformation, and therefore causes a simpler design for power control system. Under unbalanced grid voltage condition two control targets, removing the stator active and reactive power oscillations, can be obtained simultaneously. Moreover this control method reduces the THD of the stator current. Also it is shown that not only the proposed control method has a high-speed dynamic response but it also is stable during wind speed and system parameters variations. Simulation results for a 2kw DFIG confirm prominence of the proposed control strategy.

1. INTRODUCTION

Recently due to the increasing concern about environmental pollution resulting fromcombustion offossil fuels, the use of renewable energy systems for generating electric power has made remarkable progress, especially wind energy generation for its lacking of greenhouse gas emissions, profitabilityandlowmaintenance costs [1]. Doubly fed induction generator (DFIG) has been widely used in large-scale wind power generation systems due to its many advantages, such as variable speed operation, reduced converter rating, which is typically 30% of the generator rating, lower cost and power loss , and independent control of active and reactive powers [2]. With DFIG, generation can be accomplished in variable speed ranging from sub-synchronous speed to super-synchronous speed, However since the stator of DFIG is directly connected to grid and the power rating of its excitation converter is limited, the DFIG system is quite sensitive to grid disturbances. The stator current of DFIG can become highly unbalanced even with small unbalanced stator voltage , which will cause unequal heating in stator windings and oscillation in stator power and torque with double grid frequency [3-7] ,which are harmful to the stability of connected power grid and damage the mechanical system of wind turbine. Disconnecting the generator from the power system during unbalanced grid voltage reduces the utilization of the wind power. Thus, it is desirable to keep the generator connected to the grid as long as possible and to eliminate or reduce the effect of the unbalanced condition of grid voltage [8-9]. Therefore finding strategies to improve system performance under unbalanced network condition is an important issue.

Power control schemes for DFIG based wind turbines can be divided into two general categories: vector control (VC) and direct power control (DPC). Classic control strategies have accurate response under balanced voltage grid. The main drawback of VC strategies is that their performance is highly dependent on tuning of the PI parameters and machine parameters [10]. DPC strategies don't have the complexity of VC methods and they have the minimal dependence to machine parameters, however they have variable switching frequency [11]. In order to achieve a constant switching frequency, space vector modulation schemes (DPC-SVM) [12] and predictive control (PDPC) [13] have been proposed. But because of frequent occurrence of unbalanced faults in the network, recently several improved VC and DPC schemes for power control

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of DFIG under unbalanced grid voltage condition have been proposed. The unbalanced VC schemes which are based on the symmetrical component theory [14] regulate the positive and negative components of rotor current in separate loops [15, 16]. In [15] two separate PI controller were used, one for controlling the positive component of rotor current and another for controlling the negative component. This methodhas an acceptable steady state response, but dynamic response and system stability are influenced. In [16] a proportional-integral-resonance (PIR) a controller is used to improve dynamic response, however it needs transformation to synchronous reference frame and make the calculation more complicated. Moreover some improved DPC methods have been proposed for DFIGs under unbalanced grid voltage condition [17, 20]. In [17] the required rotor voltage references have made by a PIR controller. Two resonance controllers are tuned to have a high enough gain in 50 and 100 Hz frequency. Compensation power components then calculated to provide selective control targets. This method can regulate the oscillation of active and reactive power and stator current according to different control targets, moreover it's independent of parameter deviations caused by unbalanced heating or over current. But it has a need for transformation of parameters to synchronous reference frame and decomposition of stator voltage and current to positive and negative sequence components that causes a slower dynamic response and complex calculation. In [18], the negative sequence component of the rotor current, which is extracted by band pass filters, is used to reduce the active and reactive power ripples individually. This algorithm has a good dynamic performance and ability to reduce the effect of the wind speed variation on the generator toque and speed, but cannot eliminate active and reactive power ripples at the same time. A control strategy which is called DPC+ is represented in [19]. This method is capable to control decoupled active and reactive power of DFIG under unbalanced grid voltage conditions. It is defined k parameter which is varied between -1 to 1 in order to provide different control targets. In [20], a power compensation method based on sliding mode control approach has been proposed which regulate stator power in stationary reference frame without a need for coordinate transformation. The active and reactive power compensation components are calculated and three selective control targets achieved respectively. The main drawback of these control strategies is the fact that selective control targets cannot obtain simultaneously and only one control target is achieved at the time.

Directly regulation of the instantaneous active and reactive powers of DFIG in the stationary stator reference frame based on model-predictive direct power control strategy is proposed in [21, 22]. A power compensation scheme in [22] is used to select the appropriate voltage vector according to an optimization cost function, hence the instantaneous active and reactive powers are regulated directly in the stator stationary reference frame without the requirement of coordinate transformation, PI regulators, switching table, or PWM modulators. The voltage vector selection method based on model predictive is a time consuming method and requires the exact model of the DFIG system.

In [23], feedback compensators using resonant regulators are employed to control the rotor side converter.

The RSC is controlled to achieve four different control targets, including balanced stator current, sinusoidal rotor current, smooth stator active and reactive powers, and constant DFIG electromagnetic torque.

The proposed resonant controller coefficients are dependent on DFIG parameters and the rotor speed.

In [24], a model and a control strategy for DFIG wind energy system in an unbalanced micro-grid based on instantaneous power theory is proposed. Using the instantaneous real/reactive power components as the system state variables the torque and reactive power pulsations is mitigated.

This paper offers a new power control strategy for grid connected DFIG based wind turbines, which is able to provide two control targets i.e., removing stator active and reactive power oscillations, at the same time by a simple method based on sliding mode control approach. Moreover this method reduces the THD of stator current. Also it is shown that the proposed control method not only has a high-speed dynamic response but it also is stable during wind speed and system parameters variations.

1. DYNAMIC BEHAVIOR Of DFIG IN STATIONARY REFERENCE FRAM

Fig. 1 shows the schematic diagram of a DFIG based wind energy generation system. Stator of DFIG via a star-delta transformer and rotor by means of power electronic converters are connected to the grid.

Fig. 2 shows the equivalent circuit of DFIG in the stator stationary reference frame: stator and rotor voltages can be obtained as (1):

$$\begin{aligned} V_{s\alpha\beta} &= R_s I_{s\alpha\beta} + \frac{d\lambda_{s\alpha\beta}}{dt} \\ V_{r\alpha\beta} &= R_r I_{r\alpha\beta} + \frac{d\lambda_{r\alpha\beta}}{dt} - j\omega_r \lambda_{r\alpha\beta} \end{aligned} \tag{1}$$

$$\begin{cases} \lambda_{s\alpha\beta} = L_s I_{s\alpha\beta} + L_m I_{r\alpha\beta} \\ \lambda_{r\alpha\beta} = L_r I_{r\alpha\beta} + L_m I_{s\alpha\beta} \end{cases} \tag{2}$$

Where $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$. All of the parameters in (1) and (2) are referred to the stator side of DFIG.

Since $\lambda = \frac{\psi}{\omega_b}$, equation (1) can be modified as:

$$\begin{cases} V_{s\alpha\beta} = R_s I_{s\alpha\beta} + \frac{1}{\omega_b}\frac{d\psi_{s\alpha\beta}}{dt} \\ V_{r\alpha\beta} = R_r I_{r\alpha\beta} + \frac{1}{\omega_b}\frac{d\psi_{r\alpha\beta}}{dt} - j\frac{\omega_r}{\omega_b}\psi_{r\alpha\beta} \end{cases} \tag{3}$$

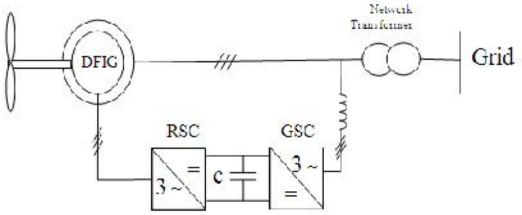


Figure 1.Schematic diagram of DFIG based wind generation system reference frame

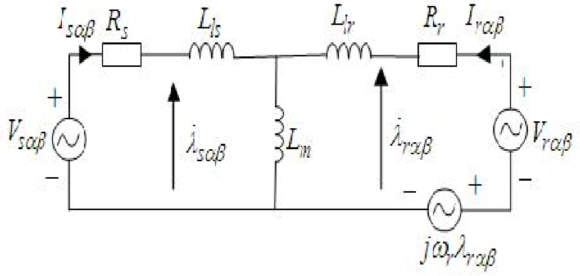


Figure 2. shows the equivalent circuit of DFIG in the stator stationary reference frame

Based on (2) and (3) stator current can be expressed in terms of stator and rotor linkage fluxes in stator stationary reference frame:

$$I_{s\alpha\beta} = \frac{1}{\sigma L_m \omega_b}(\psi_{r\alpha\beta} - \frac{L_r}{L_m}\psi_{s\alpha\beta}) \quad)$$

By substituting from (3) variation of stator current is obtained as (5):

$$\begin{aligned} \frac{dI_{s\alpha\beta}}{dt} &= \frac{1}{\sigma L_m \omega_b}(\dot{\psi}_{r\alpha\beta} - \frac{L_r}{L_m}\dot{\psi}_{s\alpha\beta}) \\ &= \frac{1}{\sigma L_m}\left[V_{r\alpha\beta} - R_r I_{r\alpha\beta} + \frac{L_r}{L_m}(V_{s\alpha\beta} - R_s I_{s\alpha\beta})\right] \\ &+ j\frac{\omega_r}{\omega_b}\frac{1}{\sigma L_m}\left[\frac{L_r}{L_m}\psi_{s\alpha\beta} + \sigma L_m \omega_b I_{s\alpha\beta}\right] \end{aligned} \tag{5}$$

The instantaneous stator active and reactive power outputs in stator stationary reference frame expressed as:

$$\begin{cases} P_s = -\frac{3}{2}(v_{\alpha s} i_{\alpha s} + v_{\beta s} i_{\beta s}) \\ Q_s = \frac{3}{2}(v_{\beta s} i_{\alpha s} - v_{\alpha s} i_{\beta s}) \end{cases} \tag{6}$$

Based on (6) the variation of stator active and reactive powers can be given as:

$$\begin{cases} \frac{dP_s}{dt} = -\frac{3}{2}(i_{\alpha s}\frac{dv_{\alpha s}}{dt} + i_{\beta s}\frac{dv_{\beta s}}{dt} + v_{\alpha s}\frac{di_{\alpha s}}{dt} + v_{\beta s}\frac{di_{\beta s}}{dt}) \\ \frac{dQ_s}{dt} = \frac{3}{2}(i_{\alpha s}\frac{dv_{\beta s}}{dt} + v_{\beta s}\frac{di_{\alpha s}}{dt} - i_{\beta s}\frac{dv_{\alpha s}}{dt} - v_{\alpha s}\frac{di_{\beta s}}{dt}) \end{cases} \tag{7}$$

As can be seen, for calculating power variations, the stator voltage and current variations in the stationary reference frame are required. When the network voltage is balanced, we have:

$$\begin{cases} v_{\alpha s} = V_m \cos(\omega_s t) \\ v_{\beta s} = V_m \sin(\omega_s t) \end{cases} \tag{8}$$

Therefore the voltage variations can be obtained as:

$$\begin{cases} \frac{d}{dt}v_{\alpha s} = -\omega_s V_m \sin(\omega_s t) = -\omega_s v_{\beta s} \\ \frac{d}{dt}v_{\beta s} = \omega_s V_m \cos(\omega_s t) = \omega_s v_{\alpha s} \end{cases} \tag{9}$$

Moreover based on (5) the variation of α and β components of stator current can be expressed as:

$$\begin{aligned} \frac{d}{dt}i_{\alpha s} &= \frac{1}{\sigma L_m}\left[v_{\alpha r} - R_r i_{\alpha r} - \frac{L_m}{L_r}(v_{\alpha s} - R_s i_{\alpha s})\right] \\ &+ \frac{\omega_r}{\omega_b}\frac{1}{\sigma L_m}\left[\frac{L_r}{L_m}\psi_{\beta s} + \sigma L_m \omega_b i_{\beta s}\right] \\ \frac{d}{dt}i_{\beta s} &= \frac{1}{\sigma L_m}\left[v_{\beta r} - R_r i_{\beta r} - \frac{L_m}{L_r}(v_{\beta s} - R_s i_{\beta s})\right] \\ &- \frac{\omega_r}{\omega_b}\frac{1}{\sigma L_m}\left[\frac{L_r}{L_m}\psi_{\alpha s} + \sigma L_m \omega_b i_{\alpha s}\right] \end{aligned} \tag{10}$$

By substituting (9) and (10) in (7) and arranging them in a matrix form yields:

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} P_s \\ Q_s \end{bmatrix} &= -\frac{3}{2}\frac{1}{\sigma L_m}\begin{bmatrix} v_{\alpha s} & v_{\beta s} \\ -v_{\beta s} & v_{\alpha s} \end{bmatrix}\begin{bmatrix} v_{\alpha r} \\ v_{\beta r} \end{bmatrix} \\ &- \frac{3}{2}\frac{R_r}{\sigma L_m}\begin{bmatrix} -v_{\alpha s} & -v_{\beta s} \\ v_{\beta s} & -v_{\alpha s} \end{bmatrix}\begin{bmatrix} i_{\alpha r} \\ i_{\beta r} \end{bmatrix} - \frac{3}{2}\frac{L_r}{\sigma L_m^2}\begin{bmatrix} -v_{\alpha s}^2 - v_{\beta s}^2 \\ 0 \end{bmatrix} \\ &- \frac{3}{2}\frac{\omega_r}{\omega_b}\frac{L_r}{\sigma L_m^2}\begin{bmatrix} -v_{\beta s} & v_{\alpha s} \\ -v_{\alpha s} & -v_{\beta s} \end{bmatrix}\begin{bmatrix} \psi_{\alpha s} \\ \psi_{\beta s} \end{bmatrix} \\ &- \begin{bmatrix} \frac{-L_r R_s}{\sigma L_m^2} & -(\omega_r + \omega_s) \\ (\omega_r + \omega_s) & \frac{-L_r R_s}{\sigma L_m^2} \end{bmatrix}\begin{bmatrix} P_s \\ Q_s \end{bmatrix} \end{aligned} \tag{11}$$

2. SLIDING MODE CONTROL METHOD

In this method the control objective for DFIG system is tracking or sliding along the predefined active and reactive power trajectories. The sliding surfaces are defined as:

$$\begin{cases} S_1 = e_P(t) + k_P \int_0^t e_P(t) \\ S_2 = e_Q(t) + k_Q \int_0^t e_Q(t) \end{cases} \tag{12}$$

Where $e_P = P_s^* - P_s$ and $e_Q = Q_s^* - Q_s$. k_P and k_Q are controller positive gains.

When system states reach the sliding surface and slide along it, we have

$$S_1 = S_2 = \frac{dS_1}{dt} = \frac{dS_2}{dt} = 0 \tag{13}$$

Substituting (12) in (13), give us the variation of sliding surface as:

$$\frac{d}{dt}\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = -\frac{d}{dt}\begin{bmatrix} P_s \\ Q_s \end{bmatrix} + \begin{bmatrix} k_P(P_s^* - P_s) \\ k_Q(Q_s^* - Q_s) \end{bmatrix} \tag{14}$$

It can be arranged as (15) by substituting power variations from (11)

$$\frac{dS}{dt} = F + D V_{r\alpha\beta} \tag{15}$$

Where F and D matrixes are:

$$\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \frac{3}{2}\frac{R_r}{\sigma L_m}\begin{bmatrix} -V_{\alpha s} & V_{\beta s} \\ V_{\beta s} & -V_{\alpha s} \end{bmatrix}\begin{bmatrix} i_{\alpha r} \\ i_{\beta r} \end{bmatrix} - \frac{3}{2}\frac{L_r}{\sigma L_m^2}\begin{bmatrix} V_{\alpha s}^2 + V_{\beta s}^2 \\ 0 \end{bmatrix}$$
$$+ \frac{3}{2}\frac{\omega_r}{\omega_b}\frac{L_r}{\sigma L_m^2}\begin{bmatrix} -V_{\beta s} & V_{\alpha s} \\ -V_{\alpha s} & -V_{\beta s} \end{bmatrix}\begin{bmatrix} \psi_{\alpha s} \\ \psi_{\beta s} \end{bmatrix} + \begin{bmatrix} -\frac{L_r R_s}{\sigma L_m^2} & -(\omega_r + \omega_s) \\ (\omega_r + \omega_s) & -\frac{L_r R_s}{\sigma L_m^2} \end{bmatrix}\begin{bmatrix} P_s \\ Q_s \end{bmatrix}$$
$$+ \begin{bmatrix} k_P(P_s^* - P_s) \\ k_Q(Q_s^* - Q_s) \end{bmatrix}$$

$$D = \frac{3}{2}\frac{1}{\sigma L_m}\begin{bmatrix} V_{\alpha s} & V_{\beta s} \\ -V_{\beta s} & V_{\alpha s} \end{bmatrix}$$
$$, V_{r\alpha\beta} = \begin{bmatrix} V_{\alpha r} \\ V_{\beta r} \end{bmatrix} \tag{16}$$

Now the control law can be expressed as:

$$\begin{bmatrix} V_{\alpha r} \\ V_{\beta r} \end{bmatrix} = -D^{-1}\left\{\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} + \begin{bmatrix} k_{P1} Sgn(S_1) \\ k_{Q1} Sgn(S_2) \end{bmatrix}\right\} \tag{17}$$

Where k_{P1} and k_{Q1} are positive control gains.

For reducing the chattering phenomena which is caused by fast variations of control law around the surfaces S=0 because of Sign (s_i) term, the function Sat (s_i) can be used as:

$$Sat(S_i) = \begin{cases} 1 & S_i \rangle \lambda_i \\ \frac{S_i}{\lambda_i} & |S_i| \le \lambda_i \\ -1 & S_i \langle \lambda_i \end{cases} \tag{18}$$

Where i =1, 2 and λ_i is the width of boundary layer.

I. DIFFERENT METHODS UNDER UNBALANCED GRID VOLTAGE CONDITION

When the network is unbalanced, stator voltage and current contain the positive and negative sequence components

$$\begin{cases} V_{s\alpha\beta} = V_{s\alpha\beta}^+ + V_{s\alpha\beta}^- = (v_{\alpha s}^+ + jv_{\beta s}^+) + (v_{\alpha s}^- + jv_{\beta s}^-) \\ I_{s\alpha\beta} = I_{s\alpha\beta}^+ + I_{s\alpha\beta}^- = (i_{\alpha s}^+ + ji_{\beta s}^+) + (i_{\alpha s}^- + ji_{\beta s}^-) \end{cases} \tag{19}$$

A) Unbalanced SMC/DPC method based on compensation power components [20]

Substituting (19) in (6) shows that under unbalanced grid voltage condition the active and reactive powers contain not only average components but oscillation components with double grid frequency Where

$$\begin{cases} P_s = P_{sav} + P_{s1} + P_{s2} \\ Q_s = Q_{sav} + Q_{s1} + Q_{s2} \end{cases} \tag{20}$$

$$\begin{bmatrix} P_{sav} \\ P_{s1} \\ P_{s2} \\ Q_{sav} \\ Q_{s1} \\ Q_{s2} \end{bmatrix} = -\frac{3}{2}\begin{bmatrix} V_{\alpha s}^+ & V_{\alpha s}^- & V_{\beta s}^+ & V_{\beta s}^- \\ 0 & V_{\alpha s}^+ & 0 & -V_{\beta s}^+ \\ V_{\alpha s}^- & 0 & -V_{\beta s}^- & 0 \\ -V_{\beta s}^+ & V_{\beta s}^- & V_{\alpha s}^+ & V_{\alpha s}^- \\ 0 & V_{\beta s}^+ & 0 & V_{\alpha s}^+ \\ -V_{\beta s}^- & 0 & -V_{\alpha s}^- & 0 \end{bmatrix}\begin{bmatrix} i_{\alpha s}^+ \\ i_{\alpha s}^- \\ i_{\beta s}^+ \\ i_{\beta s}^- \end{bmatrix} \tag{21}$$

Different control targets are suggested that only one of them can be obtained at the time.

These targets are (1) getting sinusoidal and symmetrical stator current (2) removing the stator active power oscillations (3) cancelling the stator reactive power ripple.

Power compensation components are calculated and added to the power references.

Then based on this control method required rotor voltages are produced and desirable control target is obtained.

For reaching sinusoidal and symmetrical stator current, the negative sequence components of it should be removed.

It means that $P_{s1} = Q_{s1} = 0$ because these terms are made of positive sequence voltage and negative sequence current products. Therefore the compensation power components can be expressed as:

$$\begin{cases} P_{com} = P_{s2} = -\frac{3}{2}[v_{\alpha s}^{-} i_{\alpha s}^{+} - v_{\beta s}^{-} i_{\beta s}^{+}] \\ Q_{com} = Q_{s2} = \frac{3}{2}[v_{\beta s}^{-} i_{\alpha s}^{+} + v_{\alpha s}^{-} i_{\beta s}^{+}] \end{cases} \tag{22}$$

If the aim is removing active power oscillation then $P_{s1} = P_{s2} = 0$. It leads to compensation reactive power component as:

$$\begin{cases} P_{com} = 0 \\ Q_{com} = \frac{3}{2}[-v_{\beta s}^{+} i_{\alpha s}^{-} - v_{\alpha s}^{+} i_{\beta s}^{-} + v_{\beta s}^{-} i_{\alpha s}^{+} + v_{\alpha s}^{-} i_{\beta s}^{+}] \\ \qquad \square\ 3[v_{\beta s}^{-} i_{\alpha s}^{+} + v_{\alpha s}^{-} i_{\beta s}^{+}] \end{cases} \tag{23}$$

For cancelling reactive power ripples, $Q_{s1} = Q_{s2} = 0$ and therefore compensation active power component is obtained as:

$$\begin{cases} P_{com} = -\frac{3}{2}[v_{\alpha s}^{+} i_{\alpha s}^{-} - v_{\beta s}^{+} i_{\beta s}^{-} + v_{\alpha s}^{-} i_{\alpha s}^{+} - v_{\beta s}^{-} i_{\beta s}^{+}] \\ \qquad \square\ -3[v_{\alpha s}^{-} i_{\alpha s}^{+} - v_{\beta s}^{-} i_{\beta s}^{+}] \\ Q_{com} = 0 \end{cases} \tag{24}$$

The schematic diagram of the DFIG system operating under unbalanced grid voltage condition based on compensation power components method is shown in Fig. 3.

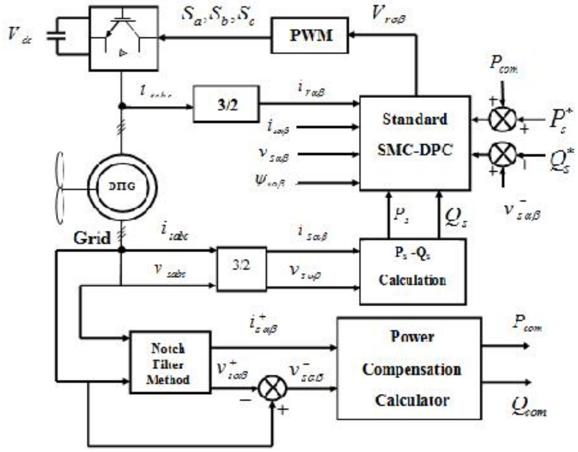


Figure 3. Schematic diagram of SMC/DPC based on compensation power components method [20]

As it can be seen, based on SMC approach, rotor voltage references produce directly in the stator stationary reference frame and then based on PWM technique the required signals for switching of inverter are made. A notch filter tuned at 100Hz is applied to extract the positive sequence of stator current and negative sequence of stator voltage in order to making compensation power components.

Since notch filter is out of control loop, inherent defects like slow dynamic response doesn't impact the system.

B) Improved Direct Power Control (DPC+) trategy [19]

In this method stator active and reactive power are defined as (25):

$$\begin{cases} P_s = P_s^{+} + P_s^{-} \\ Q_s = Q_s^{+} + Q_s^{-} \end{cases} \tag{25}$$

Where

$$\begin{cases} P_s^{+} = -\frac{3}{2}[(V_{\alpha s}^{+} i_{\alpha s}^{+} + V_{\beta s}^{+} i_{\beta s}^{+}) + (V_{\alpha s}^{+} i_{\alpha s}^{-} + V_{\beta s}^{+} i_{\beta s}^{-})] \\ P_s^{-} = -\frac{3}{2}[(V_{\alpha s}^{-} i_{\alpha s}^{+} + V_{\beta s}^{-} i_{\beta s}^{+}) + (V_{\alpha s}^{-} i_{\alpha s}^{-} + V_{\beta s}^{-} i_{\beta s}^{-})] \\ Q_s^{+} = \frac{3}{2}[(V_{\beta s}^{+} i_{\alpha s}^{+} - V_{\alpha s}^{+} i_{\beta s}^{+}) + (V_{\beta s}^{+} i_{\alpha s}^{-} - V_{\alpha s}^{+} i_{\beta s}^{-})] \\ Q_s^{-} = \frac{3}{2}[(V_{\beta s}^{-} i_{\alpha s}^{+} - V_{\alpha s}^{-} i_{\beta s}^{+}) + (V_{\beta s}^{-} i_{\alpha s}^{-} - V_{\alpha s}^{-} i_{\beta s}^{-})] \end{cases} \tag{26}$$

Also air gap power can be obtained from

$$P_{Te} = T_e.\omega_s = P_s^{+} - P_s^{-} \tag{27}$$

In order to provide different control targets, k parameter is defined as (28):

$$\begin{cases} P_s = P_s^{+} + k.P_s^{-} \\ Q_s = Q_s^{+} + k.Q_s^{-} \end{cases} \tag{28}$$

Where $-1 \leq k \leq 1$.

By regulating k parameter different control targets can be obtained as

1) For k=1 stator active and reactive powers are constant but stator current is not sinusoidal and symmetrical.

2)For k=0 stator current is sinusoidal and symmetrical, but active and reactive power have oscillation with double grid frequency.

3)For k=-1constant electromagnetic torque and reactive power are obtained simultaneously.

For making unbalanced voltage source, UF is introduced as:

$$UF = \frac{V_s^-}{V_s^+} \tag{29}$$

Where V_s^- and V_s^+ are the modulus of the positive and negative sequence components, respectively.

Schematic diagram of this method is shown in Fig. 4. As it can be seen it is made of four different modules which calculate) the stator voltage symmetrical components and their angle in real time, 2) the positive and negative active and reactive power, 3) the power (including the control strategy and feedback it), 4) the power error in order to feed the hysteresis regulators to obtain the optimal active rotor vector to be applied by the optimal switching table (see Table 1).

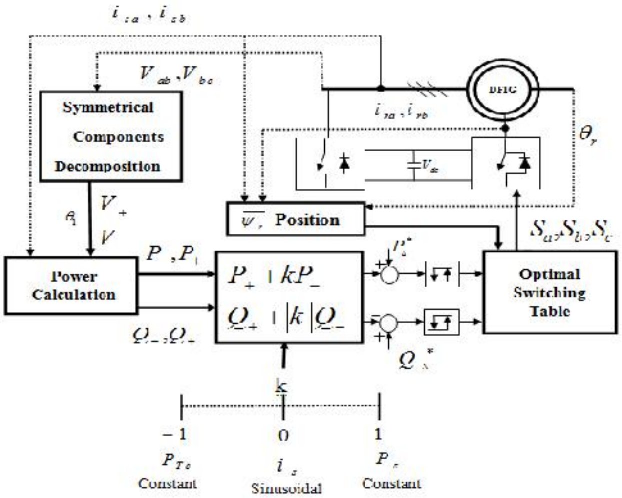


Figure 4. Control system diagram for direct power control DPC+ under an unbalanced network [19]

TABLE 1. Optimal switching table for DPC +[19]

		Sec 1	Sec2	Sec 3	Sec 4	Sec 5	Sec 6
$P_s \uparrow$	$Q_s \downarrow$	2	3	4	5	6	2
	$Q_s \uparrow$	3	4	5	6	1	2
$P_s \downarrow$	$Q_s \downarrow$	6	1	2	3	4	5
	$Q_s \uparrow$	5	6	1	2	3	4

C. Proposed control strategy

This section introduces proposed control strategy which is capable to provide constant stator, active and reactive powers, simultaneously. Also this method reduces the THD of stator current more than DPC+ strategy.

It is proven that in case of constant active and reactive powers, obtaining sinusoidal and symmetrical stator current is not possible.

Therefore in this paper the aim is removing the oscillations of stator active and reactive power and decreasing the THD of stator current.

Fig. 5 shows the schematic diagram of proposed control strategy. As it can be seen, this method is simpler than the two other mentioned methods, because there is no need for optimal switching table or decomposing stator voltage and current into positive and negative sequences in it.

This method at first measures stator voltage and current and calculates active and reactive power according to (6). Then makes the rotor voltage references by using SMC/DPC strategy. Switching signals are produced by PWM technique and injected to rotor side converter.

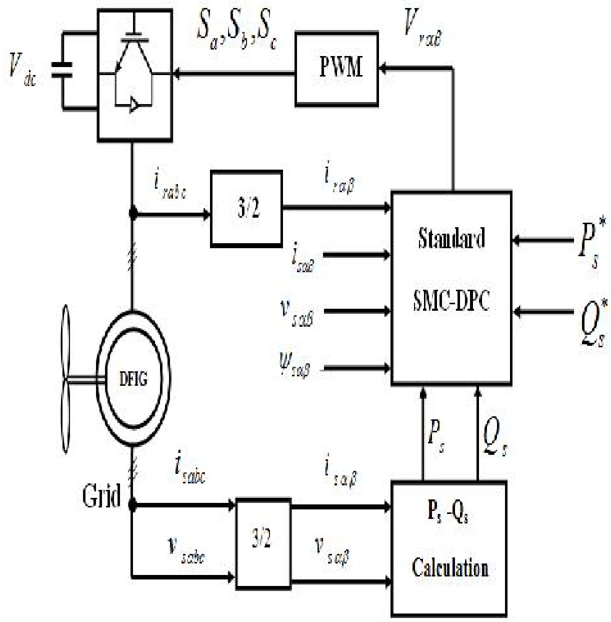


Figure 5. Schematic diagram of the proposed SMC/DPC method for grid connected DFIG

2-1. Simulation Results

Simulation of the proposed control strategy is carried out by MATLAB/Simulink.

Discrete model is used with a simulation time step of 5 **µs**. The DFIG which is used, has 2 kW rated power and its parameters are given in Table 2.

The dc voltage link is set in 300v and switching frequency of converter is 5 kHz. Control parameters are given in Table 3.

In order to verify the prominence of the proposed SMC/DPC strategy, this section compares simulation results of this method with SMC method which is based on producing compensation power components [20] and improved direct power control (DPC+) strategy [19].

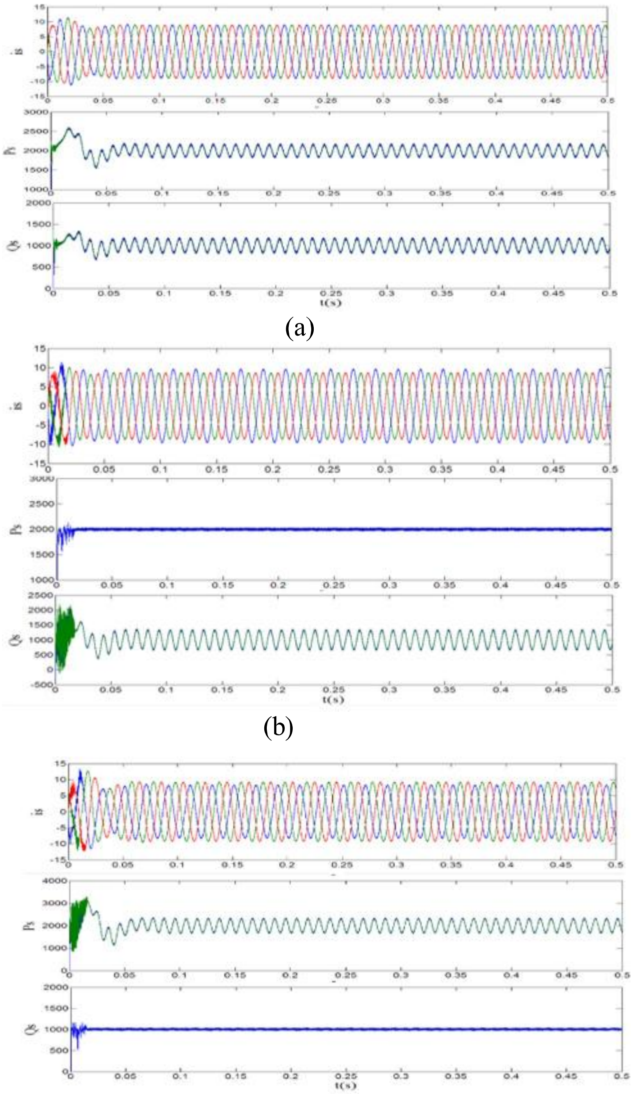
TABLE 2 . DFIG parameters

2kW	P_{rated}
220V	$V_{L-L}(rms)$
0.5132	n_s / n_r
1.19188Ω	R_S
2.5712Ω	R_r
0.00744H	L_{ls}
0.00744H	L_m
2	P

TABLE 3. Controller parameters

K_P	35000	K_{P_1}	10	λ_1	50
K_Q	35000	K_{Q_1}	10	λ_2	50

Fig. 6(a)-(c) show the simulation results of SMC/DPC strategy based on [20]. Asit can be seen, control targets were obtained respectively by producing different compensation power components which are mentioned in section IV-A. The active and reactive powers were set in 2Kw and 1Kvar respectively. In Fig. 6(a) the first control target was obtained i.e., sinusoidal and symmetrical stator current, but active and reactive powers are contained 100 Hz disturb oscillations. In Fig. 6(b), (c) it's obvious that by removing oscillations of active or reactive powers, the stator current become a symmetrical.



(a)

(b)

(c)

Figure 6. Simulation results of unbalanced SMC/DPC method based on compensation power components under 80% single-phase grid voltage dip. (a) Target 1 (b) Target 2 (c) Target 3**.** [20]

Fig. 7 shows the simulation results of DPC+ strategy [19]. It can be seen that under unbalanced grid voltage condition with unbalanced factor UF=20%, by varying k parameter between - 1 and 1 different control targets obtain. By setting k=-1, air gap power and stator reactive power are constant but active power has 100Hz oscillations with large amplitude. When k is set on zero, stator current is sinusoidal and symmetrical but there are oscillation on active and reactive powers and electromagnetic torque. By setting k=1, constant active and reactive powers are obtained, and the THD of stator current in this case is 20%.

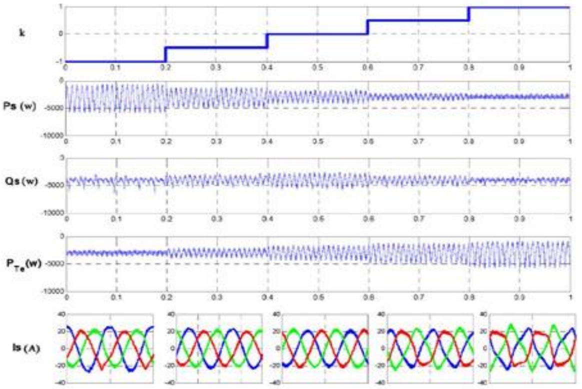


Figure 7. Simulation results of DPC+ strategy under unbalanced factor UF=20% . [19]

The simulation results of proposed control strategy under 80% single-phase grid voltage dip are shown in Fig. 8. In this method by using sliding mode control approach, rotor voltage references are produced and then switching signals are produced by PWM technique and injected to rotor side converter.

Active and reactive power references are set on 2kWand 1kvar and DC link voltage is 300V. Rotor speed is 1200rpm and the switching frequency of converter is 1 kHz. It can be seen that by using proposed control strategy not only the oscillations of active and reactive powers are removed simultaneously but also the THD of stator current is reduced to 6.82% which is more acceptable than the THD of stator current in DPC+ strategy.

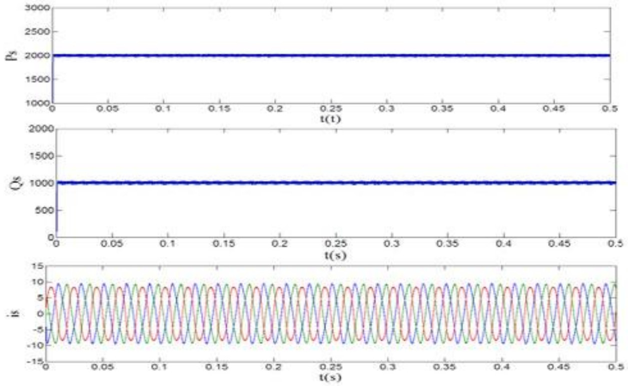


Figure 8. Simulation results of the proposed SMC/DPC method under 80% single-phase grid voltage dip

Also this method has a high speed dynamic response and its time response is 1µs during active and reactive variations as shown in Fig. 9.

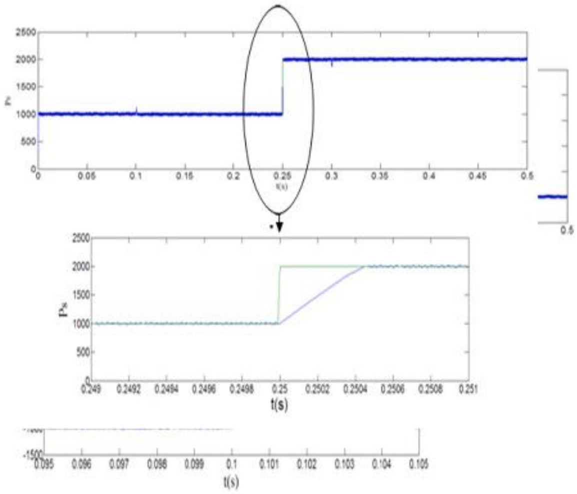


Figure 9. Dynamic response of proposed control strategy under 80% single-phase grid voltage dip Active power variations Reactive power variations

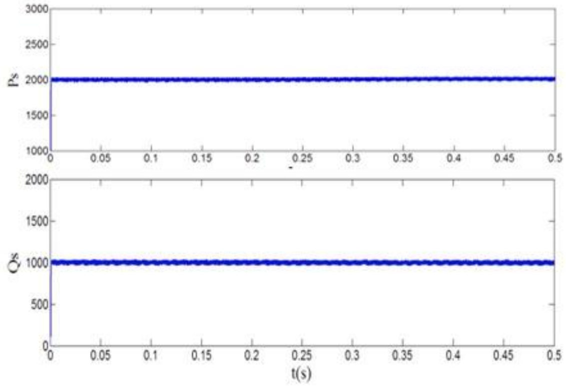


Figure 10. Simulation results of proposed control strategy under 80% single-phase grid voltage dip during wind speed variations

The comparison of the proposed method with DPC+ [19] and DPC/SMC with compensation terms [20] is summarized in Table 4.

The superiority of the proposed method in comparison with the recent research works [19, 20] can be summarized as: 1) In the proposed method, the main control object is simultaneously active and reactive power control while in [20] only one of three control targets can be achieved in each time instant, for example if the active power control is done, the reactive power has oscillation with double grid frequency and also the stator current will not be symmetrical, 2) The proposed method is done in the stationary reference frame while the method in [19 , 20] needs to notch filter to compute the positive and negative sequence of the stator voltage and currents and is a time consuming method, 3) the stator current in the proposed method has less THD as well as the generated ripple in the active and reactive is less than the previous works as summarized in Table 4. The proposed method is tested in variable speed range of the wind, 5) the proposed method is robust to the machine parameters variation because of robust structure of the sliding mode technique (this is not shown in this paper because of the paper page restriction).

TABELE 4. Comparison of the proposed method with DPC+ [19] and DPC/SMC with compensation terms [20]

	THD of stator current	**Active power ripple%**	**Reactive power ripple%**	**Note**
DPC^+ [19]	20%	20%	20%	By setting k=1, constant active and reactive powers
SMC/DPC based on compensation power components	1% (when the stator current compensation is the control object)	33%	16.6%	Only one of three control targets can be achieved
SMC/DPC (proposed method)	6.825	2%	2.5%	The active and reactive power control is the main target and THD reduction is not the main target

3.CONCLUIONS

In this paper active and reactive power control strategy for grid-connected DFIG based-wind turbine system under unbalanced grid voltage condition has been proposed. This method doesn't required transformations to synchronous reference frame and all calculations were carried out in stator stationary reference frame which causes less calculation volume. This method has remarkable prominence because it is capable to provide two control targets simultaneously i.e. removing active and reactive power oscillations by a simple method and with a high speed dynamic response. Also it reduces THD of the stator current and is robust against the wind speed variations.

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