Variable Structure Direct Direct Torque Control of Brushless Doubly Fed Induction Generator for Wind Turbine Applications

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Abstract— **In this paper a variable structure direct torque control based on sliding mode approach, linear PI and space vector modulation (SVM) is proposed for a brushless doubly fed induction generator. The DTC transient merits and robustness are preserved and the steady state behavior is improved by reducing the torque and flux pulsations. The presented method also guarantees maximum power point tracking (MPPT) with a desirable operation. The simulation results verify an accurate, quick and robust operation of the brushless doubly fed induction generator for wind turbine applications.**

Keywords-Brushless doubly fed induction generator (BDFIG); Direct torque contol (DTC); Sliding mode control (SMC); Linear control; Wind turbine

I. INTRODUCTION

Brushless doubly fed induction generator (BDFIG) is a single frame and brushless machine which has two 3-phase windings that are set on the stator. One of them is power winding (PW) that is directly connected to the grid. Most of power is exchanged between the BDFIG and grid through this winding. The other winding connected to the grid through a back-to-back converter with less capacity than the generator, is called control winding (CW) [1]. The converter at generator side has the duty of speed control and also controlling the reactive power of generator but the converter at grid side, controls the voltage of DC link and regulates the terminal voltage by absorbing or supplying reactive power [2]. It must be mentioned that the control winding capacity is depended on the desired speed range and reactive power requirements [3].

Because of some advantages like elimination of brushes (high reliability and low maintenance) and the use of a fractionally-rated frequency converter, BDFIG have been paid attention to use in some industrial operations like wind – power generation [1].

Robustness and fast dynamic response are two important features of a controller which is applied for wind-power applications. In particular, the ability of tracking the fast changes in torque, due to wind gusts is important. Since the BDFIG is not stable over the whole operating speed range, a controller is required to stabilize the machine while achieving satisfactory dynamic performance in controlling the speed and torque [1]. Nowadays, different types of control methods such as direct torque control have been proposed for this machine [4]. In addition to simplicity of implementation of DTC, reaching to a desirable torque in steady state and transient conditions are other features of this control method.

However, classic DTC method because of using the hysteresis controller has some known drawbacks like complexity of flux and torque control at very low speeds, high torque and flux ripples, variable switching frequency, high disturbance in low speeds, impossibility to direct control of current and creation of acoustic noise. Besides, this method needs a high and variable sampling frequency for attaining to a good torque control and limiting the flux and torque errors in a special band and also estimation of them [5].

In recent years, widespread researches have been achieved to solve the mentioned problems. The use of improved switching tables [6], developing better switching patterns [7], improving the comparators with and without two and three level hysteresis bands [8], applying the fuzzy and neural–fuzzy approaches [9], using the flux modified estimators for improving the operation of DTC in low speeds [10] and finally, applying the methods based on SVM and PWM [11] and predictive control for fixing the sampling frequency [12].

In this paper, a new DTC method based on SMC, linear control (PI) and SVM is proposed to drive the BDFIG in wind turbine systems. The proposed method with accurate, quick and robust tracking of wind turbine mechanical torque, improves the operation of control system in gaining the maximum torque from wind and hence increases the efficiency of wind turbine.

II. INTRODUCTION TO BDFIG

A. BDFIG Operation

The stator of this generator has two windings which have different number of pole pairs to prevent direct coupling between them. Also, in order to reduce the electromagnetic forces on the rotor, the difference of pole pairs must be greater than one [13]:

$$|P_1 - P_2| > 1 \tag{1}$$

The rotor of this generator is designed with a special manner. The most conventional structure used in the rotor of this generator is nested-loop. The number of nests which is the number of rotor poles is equal to the sum of PW and CW pole pairs so as to cause indirect coupling between CW and PW [2].

Owing to special structure of rotor, there will be different modes of operation for this machine. But the best operation of BDFIG is achieved in synchronous mode. In this mode, the frequency of induced voltage in PW, because of indirect coupling with CW, is equal to grid frequency. This situation leads to generation of two fields that turn at rotor speed. Also, according to the number of rotor poles, in order to establish the indirect coupling between PW and CW, that is fundamental of torque generation in this machine, the direction of rotation of PW magneto-motive force (mmf) respect to the rotor, will be in opposite direction of CW mmf. In this condition [13]:

$$\omega_1 - P_1\omega_g = -(\omega_2 - P_2\omega_g) \tag{2}$$

So, the synchronous rotor speed is determined as follow [1]:

$$\omega_g = \frac{\omega_1 + \omega_2}{P_1 + P_2} \tag{3}$$

Where ω_1 and P_1 are PW angular speed and pole pairs and also ω_2 and P_2 are CW angular speed and pole pairs.

If the CW current is dc, the natural speed will be achieved as [13]:

$$\omega_n = \frac{\omega_1}{P_1 + P_2} \tag{4}$$

The angular speeds ω_1 and ω_2 can be positive or negative depending on PW and CW the phase sequences. Due to PW phase sequence is often positive, there are two operation cases according to the CW phase sequence: the subsynchronous operation where ω_2 gets negative values, and the super-synchronous where ω_2 gets positive values [12].

B. BDFIG Model

Machine model in PW flux frame is expressed by the following [1]:

$$\vec{V}_1 = R_1\vec{I}_1 + \frac{d\vec{\psi}_1}{dt} + j\omega_1\vec{\psi}_1 \tag{5}$$

$$\vec{\psi}_1 = L_1\vec{I}_1 + L_{1r}\vec{I}_r \tag{6}$$

$$\vec{V}_2 = R_2\vec{I}_2 + \frac{d\vec{\psi}_2}{dt} + j(\omega_1 - (P_1 + P_2)\omega_g)\vec{\psi}_2 \tag{7}$$

$$\vec{\psi}_2 = L_2\vec{I}_2 + L_{2r}\vec{I}_r \tag{8}$$

$$\vec{V}_r = R_r\vec{I}_r + \frac{d\vec{\psi}_r}{dt} + j(\omega_1 - P_1\omega_g)\vec{\psi}_r \tag{9}$$

$$\vec{\psi}_r = L_r\vec{I}_r + L_{1r}\vec{I}_1 + L_{2r}\vec{I}_2 \tag{10}$$

In the above equations, the subscripts 1,2,r show PW, CW and rotor, respectively.

The electromagnetic torque is given by:

$$T_e = \frac{3}{2}P_1\,\mathrm{Im}\left[\vec{\psi}_1^*\vec{I}_1\right] + \frac{3}{2}P_2\,\mathrm{Im}\left[\vec{\psi}_2\vec{I}_2^*\right] \tag{11}$$

Also, the mechanical equation of machine is:

$$T_L - T_e = B\omega_g + J\frac{d\omega_g}{dt} \tag{12}$$

Where J is the moment of inertia, B is the friction coefficient and T_L is the torque produced by wind turbine.

The parameters and variables used in (5) - (11) are introduced in table 1:

TABLE1:BDFIG PARAMETERS AND VARIABLES

$\vec{V}, \vec{I}, \vec{\psi}, \omega_g$	Voltage, current, flux vectors and generator speed
R_1, R_2, R_r	Resistances of PW, CW and rotor
L_1, L_2, L_r	Self-inductances of stator windings and rotor
L_{1r}, L_{2r}	Coupling inductances between stator windings and rotor

III. VARIABLE STRUCTURE CONTROL

Due to nonlinear nature of electrical machines, if the reference voltage of CW winding is generated by a nonlinear controller, a better operation of electrical drive will be achieved. In this regard, the sliding mode controller because of robustness to uncertainties and variations in system parameters, fast dynamic response and also compensation of disturbance effects, have been paid attention by electrical drive researchers. However, robustness of this controller is only in its sliding phase and the reaching phase is designed so that the mechanical mode paths of system reach to sliding phase as quick as possible. In other words, the dynamic of system is not perfectly robust all the time. So, it is possible that the conventional SMC can not retain its stability against the uncertainties and disturbances .Also the other drawback of this controller is chattering effect, which might be harmful for the system.

To improve the stability of system to the uncertainties and also elimination of chattering in control system, in this paper a control method which is a combination of linear controller (PI) and SMC, introduced as Variable Structure Control (VSC), is proposed. This method, while having the simplicity of implementation, has the greatest features of linear controller (i.e. smooth and without chattering operation) and the feature of SMC (i.e. robustness to the uncertainties). Another advantage of this method is independence to system parameters.

The overall block diagram of direct torque and flux control of BDFIG based on variable structure is shown in Fig.1.

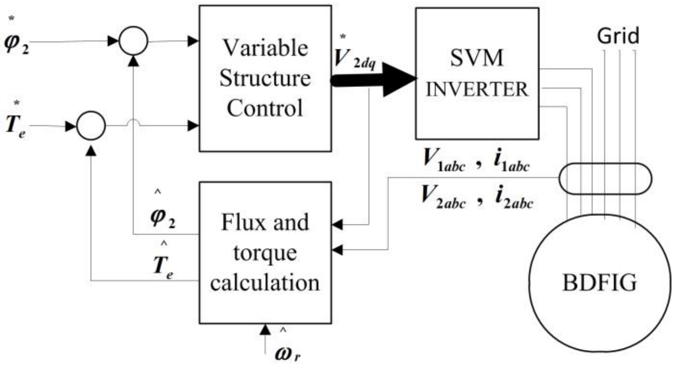


Figure1. Direct torque and flux control of BDFIG based on variable structure

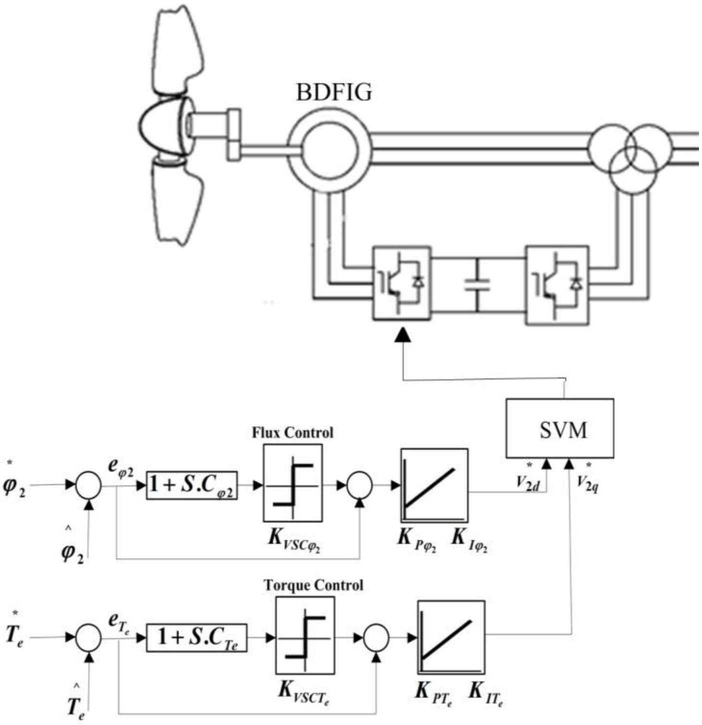


Figure2. Variable structure controller of torque and flux in wind turbine application

The control parameters are CW flux amplitude and generator torque. The main task of variable structure controller that is shown in Fig.2, is fast and reliable access to control of torque and CW flux. This control method is a flexible DTC which has advantages like smooth operation and stability against disturbances.

A SVM unit generates switching signals (S_a, S_b, S_c). The sliding surface is defined as below:

$$S_{\varphi_2} = e_{\varphi_2} + c_{\varphi_2} \cdot \frac{de_{\varphi_2}}{dt} \tag{13}$$

$$S_{T_e} = e_{T_e} + c_{T_e} \cdot \frac{de_{T_e}}{dt} \tag{14}$$

Where $e_{\varphi_2} = \overset{*}{\varphi}_2 - \hat{\varphi}_2$ and $e_{T_e} = \overset{*}{T}_e - \hat{T}_e$ are the CW flux and torque errors, respectively. Superscript "^" shows measured values and "*" shows reference values. Design constants c_{φ_2} and c_{T_e} are selected so as to impose the desired dynamics in the sliding mode. CW reference voltage, $\overset{*}{V}_2 = \overset{*}{V}_{2d} + j\overset{*}{V}_{2q}$ is gained at the output of variable structure controller that $\overset{*}{V}_{2d}$ is obtained by the control law of CW flux and $\overset{*}{V}_{2q}$ is obtained by torque control law. Sign function, $Sgn(.)$, is used in control law.

$$\overset{*}{V}_{2d} = (K_{P\varphi 2} + \frac{K_{I\varphi 2}}{s}).(e_{\varphi_2} + K_{VSC\varphi_2}.Sgn(S_{\varphi 2})) \tag{15}$$

$$\overset{*}{V}_{2q} = (K_{PTe} + \frac{K_{ITe}}{s}).(e_{Te} + K_{VSCTe}.Sgn(S_{Te})) \tag{16}$$

In the above equations, s is Laplace operator, $K_{P\varphi 2}$, $K_{I\varphi 2}$, K_{PTe}, K_{ITe} are PI controller gains and $K_{VSC\varphi 2}$, K_{VSCTe} are variable structure control gains.

With selection of proper coefficients for linear controller and SMC, the best response from the aspect of system robustness and the best time response without chattering effect is attainable. It must be paid attention that in transient condition, linear controller is more dominant and PI coefficients must be set so as to obtain the desired dynamic response. In steady state, SMC is more dominant and the best steady state response can be achieved by optimally setting the $K_{VSC\varphi 2}$ and K_{VSCTe}. It can be proved that large enough values for K_{VSC} fulfill the reaching and stability condition $S.\dot{S} < 0$ [14].

IV. WIND TURBINE AND MPPT

A. Aerodynamic Model

wind turbine extracts the energy of its blades and transmits this energy to the generator. The power absorbed from wind turbine is given below [15]:

$$P_{mech} = \frac{1}{2}\pi.C_p(\beta,\lambda).\rho.R^2.v^3 \tag{17}$$

Where ρ is air density, R is turbine radius, v is wind speed and C_p is the turbine power coefficient which its maximum value is 0.59. In wind turbine, this coefficient is usually between 0.25 and 0.45. This quantity is depended on tip speed ratio (λ) and the blade pitch angle (β). λ is obtained by the following:

$$\lambda = \frac{R\omega}{v} \qquad (18)$$

Where ω is the speed of turbine rotor .

The $C_p - \lambda$ characteristic is shown in Fig.3. In this paper, β is supposed to be zero and so C_p is only depended to λ .

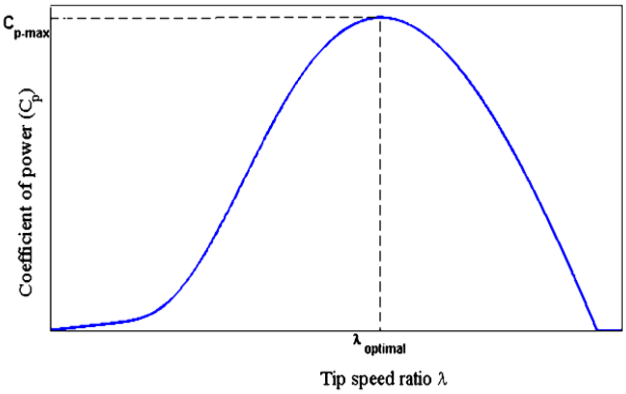


Figure3. The characteristic of the power coefficient as a function of tip speed ratio [16]

According to Fig. 3, there is only one optimum value for λ , which at this point, C_p has its maximum value. The continuous operation of wind turbine at λ_{opt} guaranties that the maximum available torque will be extracted from wind.

This statement is the fundamental of an issue named maximum power point tracking (MPPT). It can be demonstrated that in a wind turbine the maximum available power is [16]:

$$P_{wind-opt} = \frac{0.5\pi\rho\, C_{p\max}\, R^5}{\lambda^3_{opt}}\omega^3 = K_{opt}\omega^3 \qquad (19)$$

In order to absorb the maximum power, λ must be set in its optimum value.

B. *MPPT Algorithm*

The extracted power from wind turbine is depended on the accuracy of the algorithm of MPPT that ensures maximum energy yielding. The strategies can be classified into two groups [17]: the look-up table based strategies; and the strategies that are independence of aerodynamic characteristics. Some of the control algorithms that require the aerodynamic information are tip speed ratio (TSR) control, power signal feedback (PSF) control and optimum torque (OT) control.

The MPPT techniques which do not need aerodynamic characteristics are often known as HCS methods. The two significant control strategies of this category includes perturbation and observation (P&O) method and fuzzy logic control (FLC) method.

In this paper, regarding to BDFIG torque control, the best method to achieve MPPT, is the optimum torque control method. This method is superior to others because of its simplicity and accuracy. The other advantage of this method is that there is no need to speed controller and wind speed sensor.

In this technique the reference value for torque can be obtained using rotor speed and also the optimum torque versus generator speed curve. In (20), the optimum torque is expressed as a function of generator speed [16].

$$T_{opt}(\omega_g) = K_{opt}\omega_g{}^2 \qquad (20)$$

With controlling the generator torque in T_{opt} , maximum power can be extracted from wind turbine. T_{opt} is used as the reference torque in DTC.

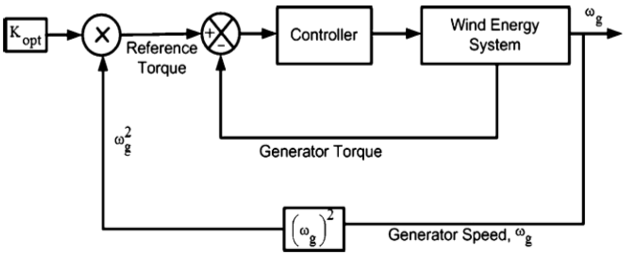


Figure4: The block diagram of MPPT method based on optimal torque control [16]

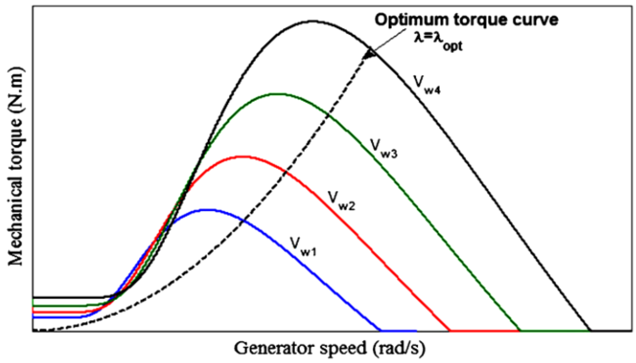


Figure5: The torque–speed characteristic curve for a series of wind speeds [16]

V. Simulation Results

In this part, the simulation results are presented to confirm the desirable operation of proposed control method. Table 2 shows the wind turbine and generator parameters.

TABLE2: GENERATOR AND WIND TURBINE PARAMETERS

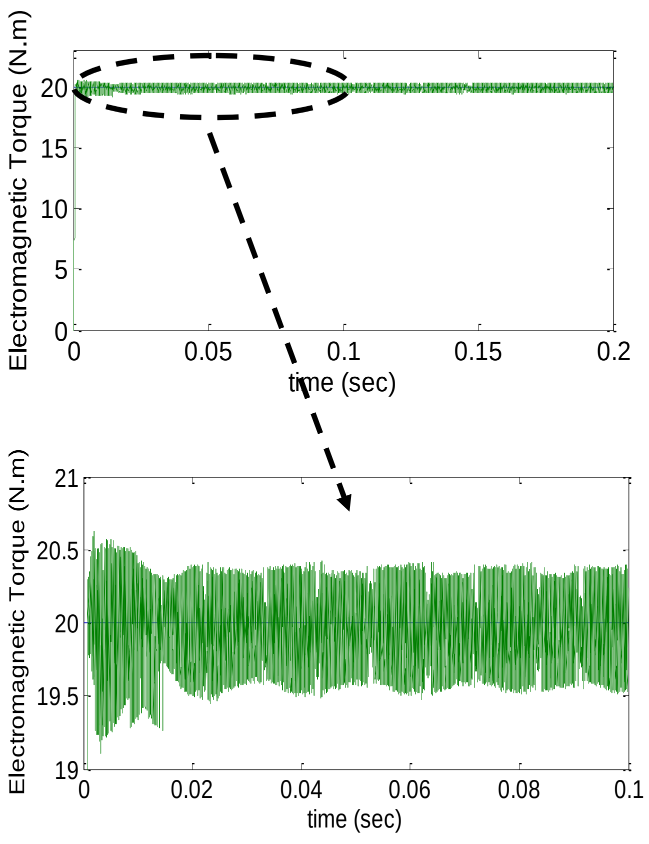
Brushless Doubly Fed Induction Generator			
Parameter	**Value**	**Parameter**	**Value**
PW Pole-Pair	2	L_1 (mH)	349.8
CW Pole-Pair	4	L_2 (mH)	363.7
Natural speed (rpm)	500	L_{1r} (mH)	3.1
PW rated voltage (V)	380	L_{2r} (mH)	2.2
CW rated voltage (V)	380	L_r (mH)	0.044
Rated torque (N.m)	27	R_1 (Ω)	2.3
J (Kg.m^2)	0.53	R_2 (Ω)	4.4
B (N.m.s)	0.036	R_r (Ω)	0.00013
Wind Turbine			
Blade radius (m)	3.3	$C_{p\max}$	0.436
Gear ratio	3.8	Rated wind speed (m/s)	6
Air density (Kg/m^3)	1.25	λ_{opt}	8

According to simulation results, in steady state condition, torque and CW flux follow the reference values ($\hat{T}_e = 20\,N.m$ and $\hat{\varphi}_2 = 0.8\,W.b$) with minimum ripple (Fig. 6(a,b)).

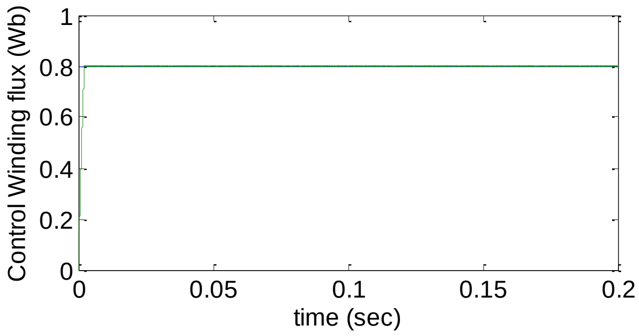
The currents of PW and CW are shown in Fig. 6(c,d). The PW current oscillates with grid frequency (50 Hz). However, with controlling the speed of generator at 600 rpm and using (1), the frequency of CW current will be 10 Hz that can be observed in Fig. 6(d).

In Fig. 7, the sliding surfaces of torque and CW flux are shown.

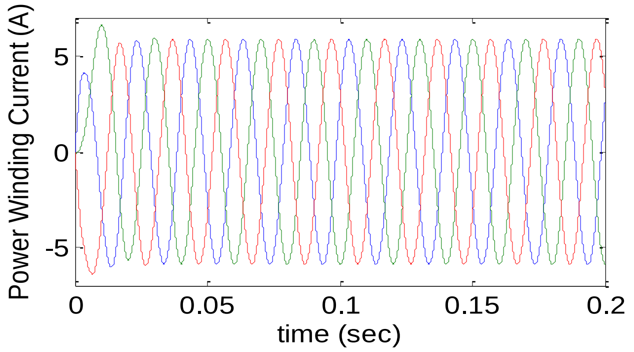
The machine response to a step change of torque from -20 (N.m) to 20 (N.m), is depicted in Fig. 8(a). As shown, the torque response to variations is very fast. In this condition, CW flux has also followed the reference value ($\hat{\varphi}_2 = 0.8\,Wb$) except for the moments that the torque has changed.



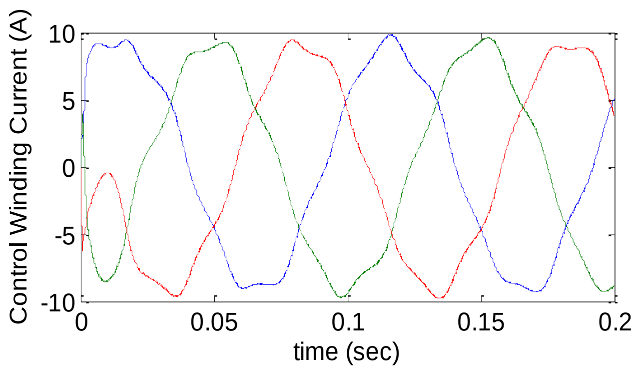
(a)



(b)

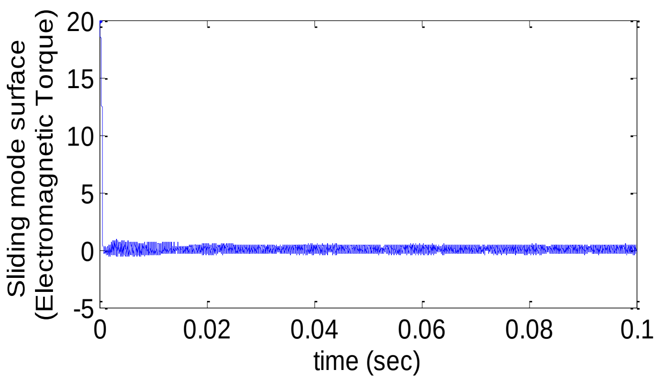


(c)

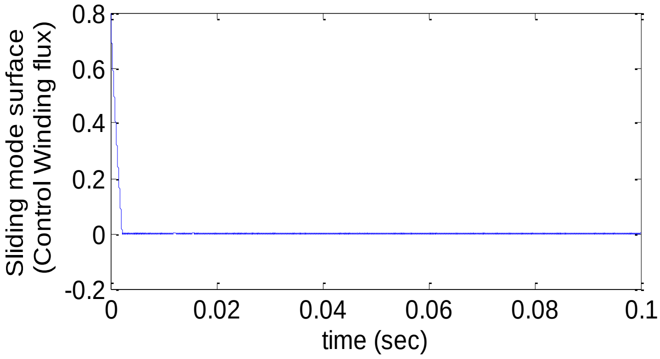


(d)

Figure6: Steady state response; (a) Torque, (b) CW flux, (c) PW current, (d) CW current

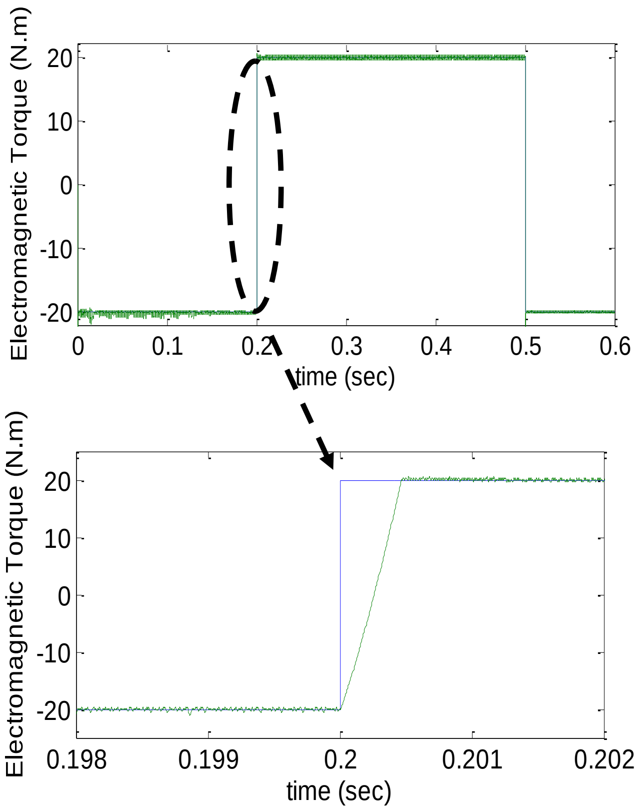


(a)

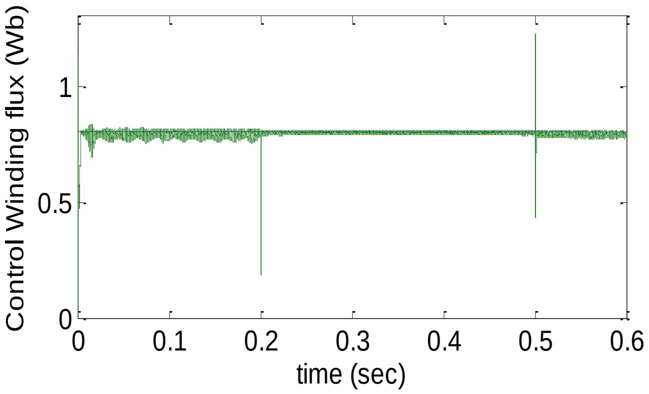


(b)

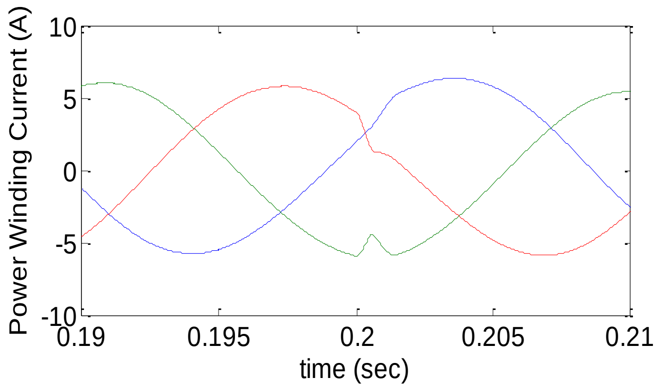
Figure7: Sliding surface; (a) Torque, (b) CW flux



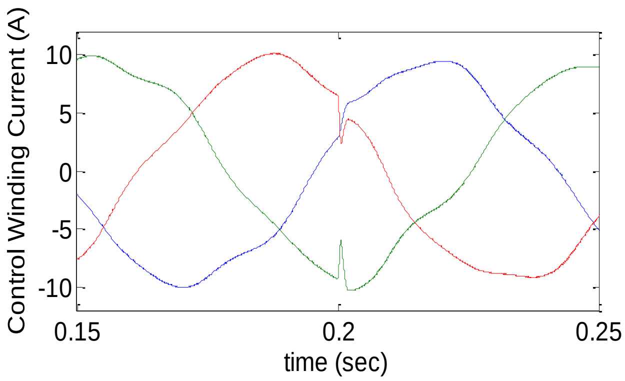
(a)



(b)



(c)



(d)

Figure8: Step response; (a) Torque, (b) CW flux, (c) PW current, (d) CW current

In this stage, the speed control loop will be removed and the reference torque will be made by MPPT algorithm .

The generator torque is tracking the reference value in variable wind speed correctly (Fig. 10). The wind speed pattern can be seen in Fig. 9.

The power coefficient of wind turbine has been shown in Fig. 11. It can be seen that this parameter is set truly in its maximum value using the proposed control system.

In order to test the realization of the presented MMPT algorithm, the desirable performance of the control system in tracking λ_{opt}, has been illustrated in Fig. 12. It tends to capture maximum power from wind turbines and proper implementation of the MPPT algorithm.

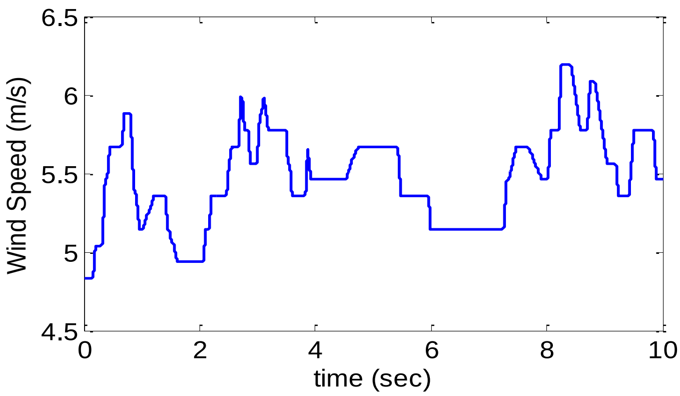


Figure9: Wind speed

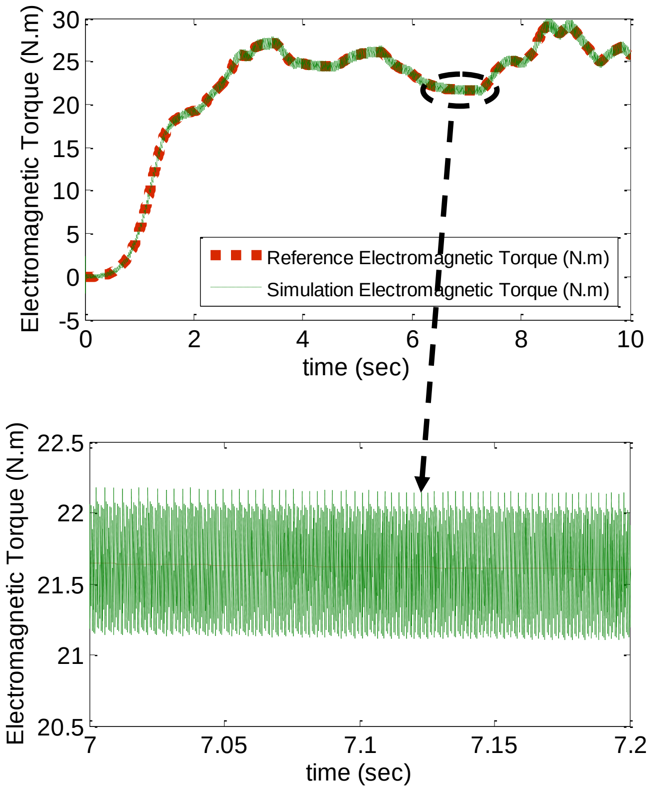


Figure10: Generator torque response to wind speed variations

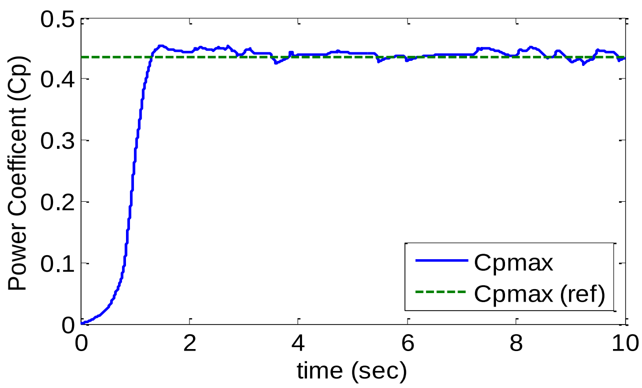


Figure11: Power coefficient variation

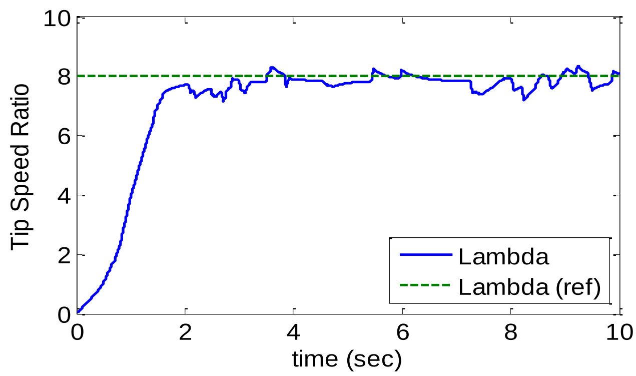


Figure12: Maximum power point tracking performance

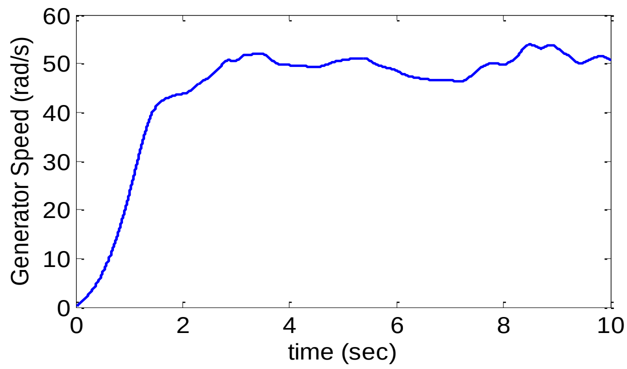


Figure13: Generator speed

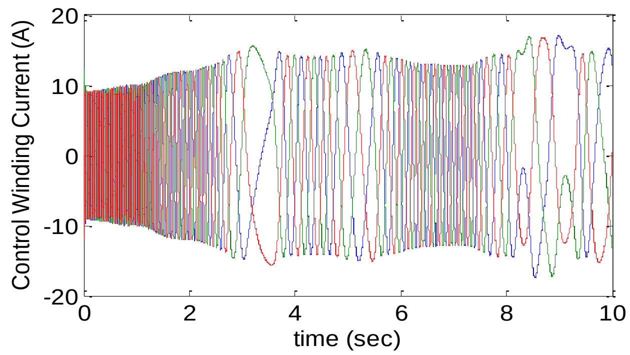


Figure14: CW current

VI. CONCLUSION

In this paper a variable structure direct torque control of BDFIG for wind turbine application is proposed and evaluated. The control strategy combines sliding mode controller and linear PI principles to achieve a simple and robust high performance drive. In particular, SMC has made the drive robust to disturbances and operating point variations, PI controller guaranties a smooth and without chattering operation, DTC makes the dynamic response quick and SVM improves the steady state responses of torque and flux with reducing the ripple. During transient operation the proposed approach verified good dynamic response and strong robustness to fluctuations of wind profile. This simple, quick, accurate and robust control strategy guaranties proper performance of MPPT algorithm and therefore best energy capturing from wind turbine.

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