AN IMPROVED THREE-LEVEL DIRECT TORQUE CONTROL METHOD OF BRUSHLESS DOUBLY-FED MACHINE BASED ON THE FIXED SYNTHESIZING VECTOR

Y. Liu – X. Wang – Y. Xing

School of Information Science & Engineering, North East University, Shenyang 110819, Liaoning, China

ARTICLE INFO

***Article history*:**
Received: 11. 09. 2013.
Received in revised form: 17.10.2013.
Accepted: 17.10.2013.

Keywords:
Brushless doubly-fed machine
Direct Torque Control
Fixed Synthesizing Vector
Three level inverter
Torque ripples
Flux linkage ripples

Abstract:

With the rapid growth of an AC adjusted speed system application, it is necessary to control and reduce harmonic pollution since the problem brought about by the device of power electronics not only blocks the development of power electronics technology, but also causes severe harm in an electric power system. In this paper an improved three-level direct torque algorithm for brushless doubly-fed machines has been developed for reducing the torque and flux ripples in a brushless doubly-fed machine. This method based on 48 fixed synthesizing vectors is implemented in the brushless doubly-fed machine. Compared with the traditional two-level direct torque control algorithm, this new method broadens the selection range on voltage vectors. It also effectively reduces the torque ripples and improves the properties of the magnetic chain track. In addition, this algorithm improves the dynamic performance and robustness of both the brushless doubly-fed machine and its control system. To validate the proposed method, some mathematic simulations have been done so that the simulation results have shown the effectiveness of the proposed method. Moreover, this proposed method has been implemented in the brushless doubly-fed machine system showing an enhancement in the motor performance.

1 Introduction

The brushless doubly-fed machine (BDFM) is a new type of machine which is evolved from the Cascade motor. It consists of two three-phase windings in the stator sides, which are called control winding and power winding [1, 2]. The rotor current induced by the power winding can be controlled by modifying the voltage of the control winding. BDFM has the advantage of being simple in its structure and reliable in operation. It has a high power factor and the cost of frequency converter is relatively low compared to Cascade motors. However, the existence of multiple reference frame, which are related to the two-stator windings and rotor, makes it difficult to exploit the well-known standard induction machine control strategies.

The development of dynamic models and steady state models of BDFM has attracted/aroused considerable research interests since the 18th Century. Wallace et al. developed a dynamic vector model, which referred to the rotor shaft position [3]. In this model, two different synchronous reference frames were used which were related to each pole-pair distribution. Designing the control method of BDFM can be facilitated by the implementation of a dynamic unified reference frame model for the pole-pair distributions.

Currently, two different strategies are employed in the field of BDFM research [4, 5], one of which is to optimize the system design of BDFM itself, whilst another is focused on developing high performance control units. At present, significant research efforts are being devoted to the development of a competitive drive for a BDFM which has the potential to replace the use of wound rotor machine in some particular industrial applications. However, it is a challenge to apply the standard control strategy to the BDFM as its dynamic behavior is far more complicated than the one of most other electrical machines. Nevertheless, thanks to the efforts made by BDFM researchers, several different control strategies have been developed, which include feedback linearization control, CW phase angle control, field oriented control (FOC) and direct torque control (DTC).

The DTC algorithm was first introduced by Takahashi in 1986 and since then it has been widely adopted in AC machine control due to its high dynamic performance. Unlike FOC, DTC does not require much coordinate transformation, pulse-width modulation (PWM) or a lot of excessive position sensors to achieve a decoupled control of the flux and torque. The flowing current in the machine is adjusted directly by controlling the torque and flux. In addition, the DTC is not over-sensitive to parameter detuning in comparison with the FOC. Furthermore, it permits a good torque control in steady-state and transient operating conditions. Recently, DTC has also been implemented in BDFM and has achieved a good dynamic and steady-state performance for different supplied topologies of the machine.

The traditional two-level direct torque control method has the advantages of being simple in its structure and of developing quite a mature branch from the control theory. .However, the selection of the voltage vector structure associated with this method is limited and the control accuracy of the stator flux linkage is relatively poor. Furthermore, the torque and flux ripples are quite high. These problems can be well solved in the three-level DTC structure. This paper proposes an improved three-level DTC method which can effectively reduce the motor stator flux linkage and torque ripples. The problem of neutral point unbalance and switching losses is resolved. Simulation and experimental results prove the feasibility and advantages of the proposed strategy.

2 The structure and dynamic model of BDFM

As *Fig1*, the BDFM is composed of two three-phase windings with a different pole number on the stator sides. The one is the power winding connected to the power grid, and the other is control winding (CW) connected to the inverter [6, 7].

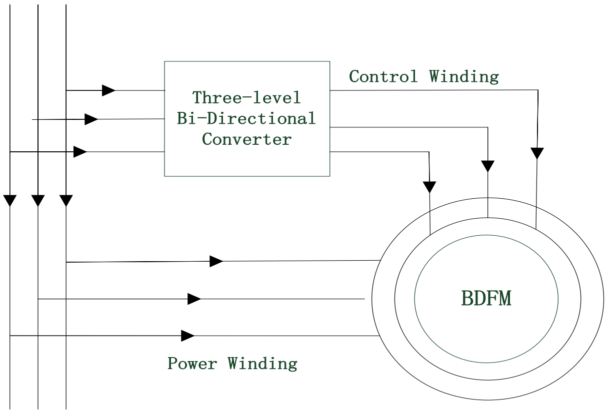


Figure 1. The structure of Brushless Doubly-fed Machine.

The rotor speed can be given as:

$$n_r = \frac{60\left(f_p \pm f_c\right)}{P_p + P_c} \tag{1}$$

In Equation 1, P_p and P_c are the number of pole pairs of the power winding and control winding. f_p and f_c are the frequency of the control winding. When the symbol before f_c is “+”, the three-phase power sequence of the power winding and control winding is the same, and, this state is called “positive modulation”. Otherwise, when the three-phase power sequences of the power winding and control winding are opposite, this state is called “negative modulation”. When $f_c = 0$, the speed of the motor is called natural synchronous speed. The frequency of the power winding is a constant value because it is supplied by the power grid. Thus, the variety of running status of BDFM can be controlled through the change of the frequency of the control winding.

The mathematic model of a BDFM can be described by the following equations:

$$v_p = R_{sp} i_p + \frac{d\psi_p}{dt} + j\omega_p \psi_p \tag{2}$$

$$\psi_p = L_{sp} i_p + L_{hp} i_r \tag{3}$$

$$v_c = R_{sc} i_c + \frac{d\psi_c}{dt} + j(\omega_p - (p_p + p_c)\omega_r)\psi_c \tag{4}$$

$$\psi_c = L_{sc} i_c + L_{hc} i_r \tag{5}$$

$$v_r = R_r i_r + \frac{d\psi_r}{dt} + j(\omega_p - p_p \omega_r)\psi_r \tag{6}$$

$$\psi_r = L_r i_r + L_{hc} i_c + L_{hp} i_p \tag{7}$$

$$T_{em} = \frac{3}{2} p_p \operatorname{Im}\left[\psi_p{}^* i_p\right] + \frac{3}{2} p_c \operatorname{Im}\left[\psi_c{}^* i_c\right] \tag{8}$$

Where, $v_p = v_{p\alpha} + jv_{p\beta}$ is the PW voltage vector, $v_c = v_{c\alpha} + jv_{c\beta}$ is the CW voltage vector and $v_r = v_{r\alpha} + jv_{r\beta}$ is the rotor voltage vector that is manipulated by the control winding of the BDFM.

The electromagnetic torque of BDFM can be expressed by a function composed of three fluxes of the machine: power windings, control windings and the rotor:

$$\begin{aligned} T_{em} &= \frac{3}{2} p_c \frac{L_p L_{hc}}{\sigma}\left(-\psi_{c\alpha}\psi_{r\beta} + \psi_{c\beta}\psi_{r\alpha}\right) \\ &+ \frac{3}{2} p_p \frac{L_c L_{hp}}{\sigma}\left(-\psi_{p\alpha}\psi_{r\beta} + \psi_{p\beta}\psi_{r\alpha}\right) \\ &+ \frac{3}{2}\left(p_p + p_c\right)\frac{L_{hp} L_{hc}}{\sigma}\left(-\psi_{p\alpha}\psi_{c\beta} + \psi_{p\beta}\psi_{c\alpha}\right) \end{aligned} \tag{9}$$

Where, $\sigma = L_c L_r L_p - L^2{}_{hc} L_p - L_c L^2{}_{hp}$

From Equation (9), the electromagnetic torque is composed of two parts: The one produced by the cross coupling is called synchronous torque, and the other produced by the interaction of the control windings and power windings on the stator side of the BDFM with the rotor is called asynchronous torque. The asynchronous torque still exists though the status one of the stator windings has been short circuited.

The dynamic model of the BDFM is modeled using Equations (2)-(9) and implemented in the Matlab/Simulink.

3 The Three-level Control Structure

The main circuit structure of the inverter connected to the control winding of the BDFM adopts three-level neutral point hybrid clamped. *Fig.2* shows the main circuit of the three-level NPC inverter. As shown in *Fig.2*, each phase of the inverter contains two neutral clamping diodes, four power circuits and four freewheeling diodes. The switching states of the three-level inverter are shown in the Table.1. Moreover, taking the first phase as an example, three kinds of voltage level can achieve an output corresponding to the three kinds of switching states, where P, O, N are listed in Table 1.

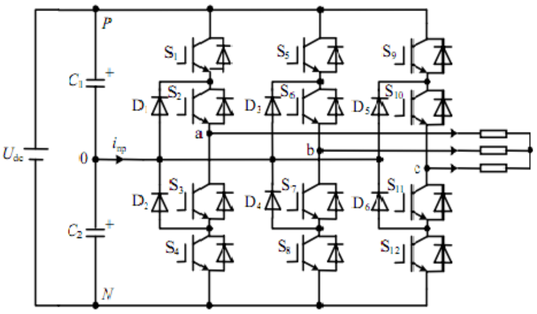


Figure 2. The main circuit of three-level inverter.

It can be seen from Table.1 that when the S1 and S2 are on and S3 and S4 are off, the status of switch is P. When the S2 and S3 are on and the S1 and S4 are off, the status of switch is O. When the S3 and S4 are on and the S1 and S2 are off, the status of switch is N. Since three kinds of switching states exist in each phase, the three-level inverter will have 27 possible switching states.

Table1. Three- level Inverter switching states

S1	S2	S3	S4	Switching states
ON	ON	OFF	OFF	p
OFF	ON	ON	OFF	O
OFF	OFF	ON	ON	N

Fig.3 shows a space vector diagram for the three-level NPC inverter. The 27 switching states define 19 space vectors, classified as zero, small, medium, and large vectors. The positive small vectors and the negative small ones have the reverse impacts on the neutral point balance. The large vectors do not affect the neutral point voltage.

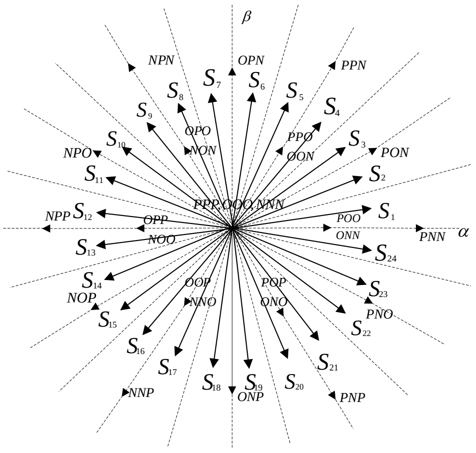


Figure 3. Space vector method diagram.

4 The Improved Three-Level Direct Torque Control method

4.1 The Improved Three-level Control Method

The traditional two-level direct torque control method has the advantage of being simple in its structure and of having rather mature theories developed from the modern control theory. However, the selection of the voltage vector structure associated with this method is limited and the control accuracy of the stator flux linkage is relatively poor. Furthermore, the torque and flux ripples are quite high. These problems can be well solved in the three-level structure. Three-level inverters are thus becoming increasingly popular and they can be used in high-voltage and high-power applications.

In spite of their superiority, there are some problems that need to be avoided in the three-level structure. The first one is that three-level inverter neutral-point voltage unbalance should be suppressed. The second one is that the voltage variation and its impact on inverter output and inverter and motor insulation must be limited. Another problem is to decrease the switching losses of switching devices. To solve these problems, an improved control method using the synthesizing fixed vector was proposed in reference. The switching losses of *s* device, high d_v / d_t of out voltage and neutral point voltage unbalance can be restrained effectively. The high flux linkage and torque ripples still exist in this strategy. According to the control analysis of the flux and torque, the flux linkage and torque ripples are determined by the voltage vector supplied by the inverter connected to the control winding.

There are mainly two approaches to the solution of the torque and flux ripples. The former is to reduce the voltage on the DC-link side or the modulation index. It is worth noting that although the flux linkage and torque ripples could be reduced effectively, they might lead to the bad performance of the torque fast response. The latter method is used to increase synthesizing fixed vectors and to divide the coordinate plane into more sectors [8]. So, there are a lot more synthesizing fixed vectors in every sector that can reduce the flux linkage and torque ripples in a small scope of the whole coordinate system.

This paper employs the second method and proposes a three-level DTC method based on 48 fixed synthesizing vectors for the BDFM. In this method, the ripples of the flux linkage and torque are significantly reduced. Furthermore, considerable benefits of the former schemes have been preserved and plenty of experimental results given to show the effectiveness of the proposed method.

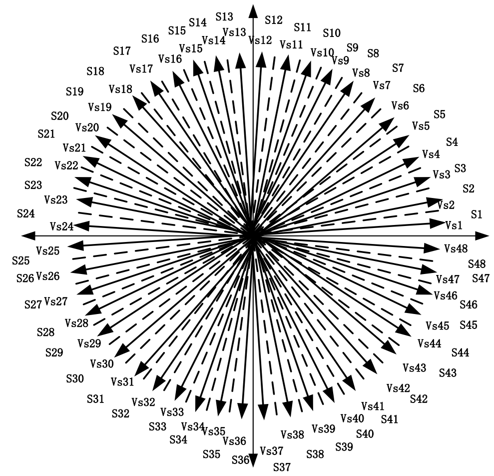


Figure 4. Space Vector graph of fixed synthesizing vectors.

Fig.4 shows the vector graph of the fixed synthesizing vectors. The whole space is divided into 48 sectors S1-S48. As part of the sector S1 shown in *Fig. 4*, the vector V_{S1} is located in the position of 7.5° of the space vector coordinate plane. According to the principle of Space Vector PWM (SVPWM) method, by adjusting the duty cycle of each switching state in synthesizing sequence, it can make synthesizing vector be located in the position of 3.25° and 10.75° of the coordinate plane with the same modulation index. The vector V_{S1} is thus divided into two vectors. And other 47 fixed synthesizing vectors in the *Fig.4* are operated in the same way. Consequently, all the 48 vectors have fixed synthesizing vectors in the space so that the vector graph can be acquired. As shown in *Fig. 4*, the whole coordinate plane is divided into 48 sectors by the method of angular bisectors of adjacent vectors and therefore the width of each sector is 7,5°.

With this method, the amount of the fixed synthesizing vectors increases, and the sectors of the space vector coordinate plane are to be further subdivided. As a result, the dv/dt of the output voltage is reduced, and the problem of controlling and balancing of a neutral point and reducing of switching losses can be resolved. Consequently, the performance of flux linkage and torque control is further improved.

4.2 The Structure of Direct Control Torque of BDFM

Unlike the normal AC induction motor, the electromagnetic field of the rotor in the Brushless doubly-fed machine was generated by the uncontrolled power windings and controlled control windings. Thus the traditional direct torque method for the AC induction motor cannot be applied to the BDFM. When the BDFM operates in the stator state, the operating status of the BDFM is similar to an AC induction motor, whose pole pairs are $2(p_p + p_c)$. The power windings and the control windings are respectively equivalent to the stator and the rotor of an AC induction motor. And the electromagnetic torque can be expressed by the flux of stator windings [9-11].

$$T_{em} = \frac{3(p_p + p_c)L_{sp}}{2(L_{sp}L_{sc} - M_c)} |\psi_p||\psi_c| \sin\delta \quad (10)$$

where p_p and p_c denote the pole pairs of the power winding and the control winding respectively. ψ_p and ψ_c represent the flux linkage of the power winding and control winding respectively. δ is the angle between the flux ψ_p and ψ_c.

The flux vector of the power windings is:

$$\psi_p = \int (u_p - R_p i_p) dt \quad (11)$$

The power winding is supplied by the power grid. So the voltage amplitude of the power winding is a constant. At the same time, the voltage drop of the resistance in the power winding can be ignored [12, 13]. Equation 11 shows that the flux linkage ψ_p of the power winding is a constant. If the amplitude of control winding flux linkage is kept constant, the rotation speed of ψ_c can be controlled by the space voltage vector u_c, and the electromagnetic torque T_{em} can be then controlled by changing the value of δ.

The flux vector of the control windings is:

$$\psi_c = \int (u_c - R_c i_c) dt \quad (12)$$

The approximate relation between voltage and flux of the stator winding is:

$$U_c \approx \frac{d\psi_c}{dt} \quad (13)$$

The formula for control winding flux vector is:

$$\psi_c = \psi_{mc} e^{j\omega_c t} \quad (14)$$

Thus

$$U_c = \omega_c \psi_{mc} e^{j\left(\omega_c t + \frac{\pi}{2}\right)} \quad (15)$$

As shown in Equation 15, the value of U_c is proportional to ω_c when the amplitude of flux ψ_{mc} is constant. The direction of the vector U_c is orthogonal to the flux vector. So the trajectory of the space voltage vector is similar to the flux of control winding. From the above analysis, the electromagnetic torque of the BDFM can be controlled by adjusting the voltage of the control winding.

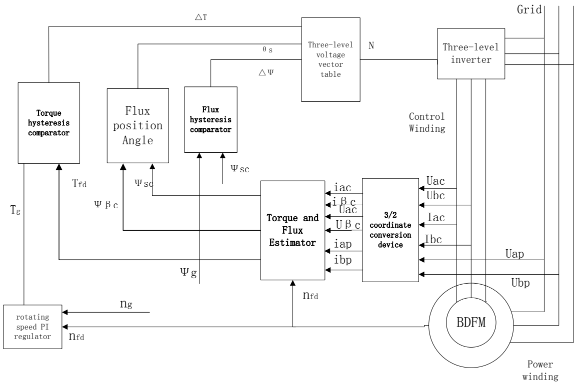


Figure 5. The structure of Three-level Direct torque Control method of BDFM.

Fig.5 shows the three-level direct Torque control system structure. The whole control structure is composed of two closed loops in the control structure of the proposed direct torque control strategy, a torque loop and flux loop. The given value of the electromagnetic torque is obtained from the speed regulator. The important part of direct torque control algorithm is the observation of the torque and the flux linkage. The three-phase voltage and three-phase current of the control winding and power winding in the $\alpha - \beta$ coordinate plane is obtained through the use of coordinate transformations Hysteresis comparators are adopted in the two closed loops. The difference between the output of the torque and flux estimator and the given value are the input of the hysteresis comparator of the torque and flux linkage. And then the switch pulse is obtained from the voltage vector table. The motor speed can be adjusted through the whole progress.

5 Experimental results and discussion Simulation results

In order to verify the proposed three-level DTC algorithm, a simulation model of the algorithm was established in software package matlab/simulink. In the model, the power winding is supplied by the power grid (380V). And the control winding is supplied by a three-level back to back control unit. The power of the power winding is set to be 1,5 kW. The number of pole pairs of the motor is 6, and the power of the control winding is 0,5kW, i.e., extremely logarithmic. The modulation index is 0,8. The given number of flux linkage of the BDFM is 1,9W. The connection method of the windings is 3Y-

3Y. *Fig.6- Fig.7* shows the wave of the phase voltage and the line voltage of the control windings.

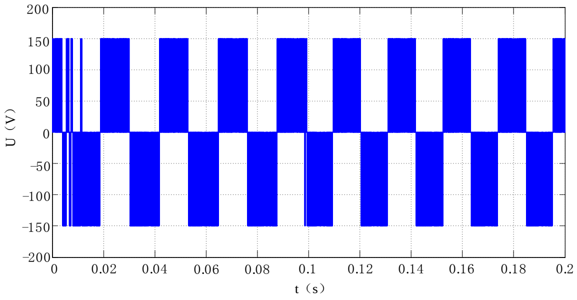


Figure 6. The wave of phase voltage.

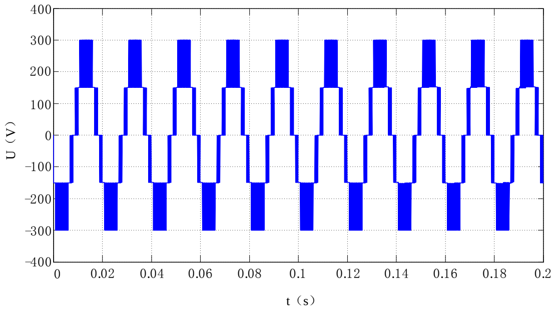


Figure 7. The wave of line voltage.

he flux linkage according to the traditional method and improved fixed synthesizing vector method is shown in the *Fig.8*. The diagram shows that the amplitude of the flux has increased and achieved the given value faster when using this improved method. A traditional estimation method using the waves of the electromagnetic torque of BDFM and an improved estimation method based on the fixed synthesizing vector have been compared in *Fig.9*. From the diagram the faster dynamic response of the torque can be observed. The wave torque is better than shown in *Fig.10*. The rotor speed of the improved method is much more stable than the one of the traditional method. The speed control is very effective with the traditional three-level method. It can be seen that, the performance of BDFM has been greatly improved with the method using fixed synthesizing vector. The experimental results as shown in the figures above certify the validity of the proposed improved three-level DTC method based on the fixed synthesizing vector of BDFM.

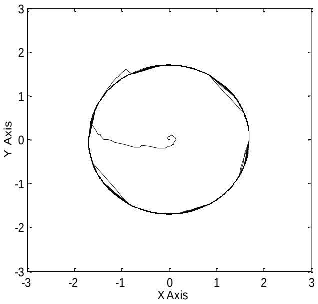
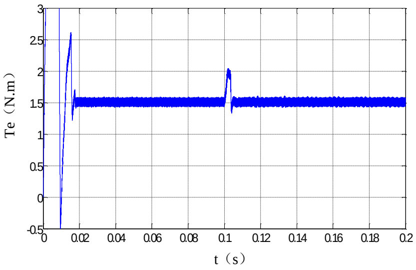
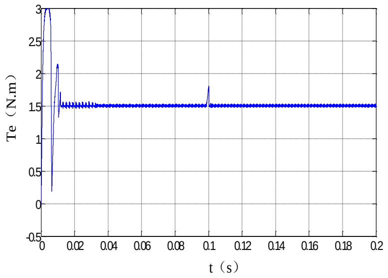


Figure 8. The flux linkage of BDFM.

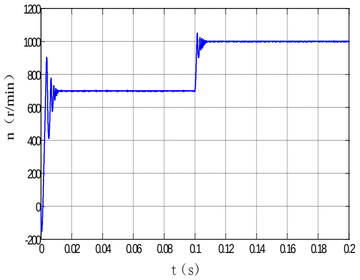


a the wave of torque of traditional method

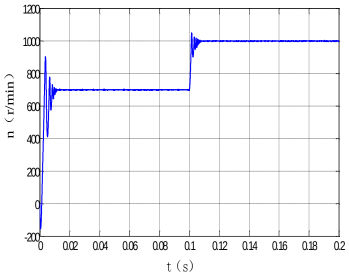


b the wave of the torque by an improved method

Figure 9. The wave of the torque of BDFM.



a The wave by a traditional rotor speed estimation method



b The waveby an improved rotor speed estimation method

Figure 10. The wave of rotor speed of BDFM.

6 Conclusion

In this paper an improved direct torque method was proposed for reducing the power pollution of the power grid in the brushless double-fed machine system based on the fixed synthesizing vectors. A number of benefits have been achieved through this new configuration. Firstly, further refining of the sector division has become feasible. Secondly, the selecting range of the voltage vector in the procession of sector conversion has been widened. Thirdly, the torque ripple could be effectively reduced and therefore the system control will be performed more accurately than before. Also, a novel direct torque control method for improving the three-level DTC structure based on 48 fixed synthesizing vectors is demonstrated in this paper. This control method successfully reduces the negative impact of the neutral-point and high voltage offsets on the control system In addition, since 48 fixed synthesizing vectors were used, the coordinate plane space can be divided into a lot more portions by the small sectors. This also broadens the choice of voltage vectors. Other benefits associated with the new design include smaller torque and flux ripples as well as better magnetic chain track. The harmonic pollution of the BDFM is also effectively restrained.

References

[1] Abad G., Rodríguez M. A., Poza J: *Two level VSC based predictive direct torque control of the doubly fed induc-tion machine with reduced torque and flux ripples at low constant switching frequency*. IEEE Trans Power Elec-tron, 23 (2008) 3, 1050-1061.

[2] Poza, J, Oyarbide E, Roye D, Rodriguez MA.: *Unified reference frame dq model of the brushless doubly-fed machine*. IEE Proceedings Electric Power Applications, 153(2006) 5, 726–734.

[3] Li, R., Wallace, A, Spee, R.: T*wo-axis model development of cage-rotor brushless doubly-fed machines*, IEEE Trans on Energy Conversion, 6 (1991), 453–460.

[4] Roberts, P. C, Flack T J, Maciejowski J M, McMahon R A.: *Two stabilising control strategies for the brushless doubly-fed machine (BDFM)*. In: International conference on power electronics, machines and drives (IEE Conf. Publ. No.487). Bath UK: IEE, 341–346, 2002.

[5] Poza, J, Oyarbide E, Roye D, Sarasola I.: *Stability analysis of a BDFM under open-loop voltage control*. The 11th European conference on power electronics and applications (EPE), Germany Dresden, 2005, 1–10.

[6] Poza, J, Oyarbide E, Roye D, Rodriguez MA.: *Unified reference frame dq model of the brushless doubly-fed machine*. IEE Proceedings Electric Power Applications, 153 (2006) 5, 726–734.

[7] Poza, J, Oyarbide E, Sarasola I, Rodriguez M.: *Vector control design and experimental evaluation for the brushless doubly-fed machine*. IET Electric Power Applications, 3 (2009) 4, 247–256.

[8] Lei L., Heqing Z., Jie Z., Yu D., Yun P. Z.: *A Three-level Induction Motors DTC Algorithm Based on Fixed Synthesizing Vectors with Reduced Flux and Torque Ripples*, Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on ,Wu Han China, 2008,1359 -1364.

[9] P.C. Roberts, R.A. Mchon, P.J Tavner, J.M.Maciejowski, T.J.Flack: *Equivalent circuit for the brushless doubly fed machine (BDFM) including parameter estimation and experimental verifiction*. IEE Proc Electr Power Appl , 152 (2005) 4 , 933–942.

[10] Sarasola I., Poza J., Oyarbide E., Rodriguez M.A.: *Stability analysis of a brushless doubly-fed machine under closed loop scalar current control*. IEEE Industrial Electronics, IECON 2006-32nd Annual Conference on, Paris France, 2006, 1527–1532

[11] Sarasola I., Poza J., Rodriguez M. A., Abad G.: *Direct torque control for brushless doubly fed induction machines*. International electric machines and drives conference (IEMDC), Antalya Turkey, 2007, 1496–1501, 2007.

[12] Sarasola I., Poza J., Rodriguez M. A., Abad D. G.: *Direct torque control for brushless doubly fed machine with reduced torque ripple at constant switching frequency*. Electric Machines & Drives Conference, 2007. IEMDC '07, Vigo Spain, 2007, 1074–1079.

[13] Sarasola I., Poza J., Rodriguez M. A., Abad, G.: *Direct torque control design and experimental evaluation for the brushless doubly fed machine,* Energy Conversion And Management, 52 (2011) 2, 1226-1234.