A Novel Strategy for Applying Vector Control Methods in Motoring Mode

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Abstract: *In this paper, a novel strategy for applying vector control methods for BDFM is investigated. It is always intended in vector control methods to calculate torque and flux of the machine by transforming the machine equations into a proper system. The main idea is taken from the control method for direct current motors. It is notable that this method has more complexity than scalar control methods, and it is used in applications requiring accurate and fast response. Furthermore, there is no mutual inductance between two windings of stator. To achieve this, the winding of each phase is formed by a number of coils in series. The arrangement of these coils is in a way that the resultant of induced voltages in the winding of each phase due to the field of other winding is zero.*

Keywords: Supply machine, brush, rotor, pole, torque, BDFM

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1. Introduction

Undoubtedly the main idea of making BDFM comes from 1966 when Smith presented his machine structure which was not much different from the design of other scientists, and investigated the machine operation in synchronous mode. In 1970, Berdoy and Borberij proposed their design which is surely the origin of today's BDFM [7]. Proposing a new structure, they could make notable changes in the operation of the machine invented by hunt. U.S. department of energy found interest in research and application of BDFM in 1980 and then, research on this machine began widely in the university of Oregon. Valas and Rene from Oregon university presented many papers on creating a dynamic model for this machine[8],[9]. Different methods have been proposed for vector control of BDFM in both motoring and generating modes. The dependence of control scheme to parameters of both windings and high calculation complexity are the main disadvantages of the proposed methods[2],[5],[6]. Also, though scalar control methods [3] and feedback linearization methods [1],[4] maintain the stability of machine at a good level, they do not have enough speed and accuracy. DTC methods proposed for BDFM have high complexity in derivation of switching tables, and the stability of the proposed methods in literature has been tested with a 1Nm step increase which is not an acceptable criterion**2.**

2. Presenting the new form of torque formulation

The containing flux and torque equations in integrated reference system are as below

$$\begin{bmatrix} \Psi_{s1d} \\ \Psi_{s1q} \end{bmatrix} = M_{s1}^{dq} \begin{bmatrix} I_{s1d} \\ I_{s1q} \end{bmatrix} + M_{s1r}^{dq} \begin{bmatrix} -I_{rd} \\ I_{rq} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \Psi_{s2d} \\ \Psi_{s2q} \end{bmatrix} = M_{s2}^{dq} \begin{bmatrix} I_{s2d} \\ I_{s2q} \end{bmatrix} - M_{s2r}^{dq} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} = M_{s1r}^{dq} \begin{bmatrix} -I_{s1d} \\ I_{s1q} \end{bmatrix} - M_{s2r}^{dq} \begin{bmatrix} -I_{s2d} \\ I_{s2q} \end{bmatrix} + M_{r}^{dq} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} \quad (3)$$

$$T = \frac{dM_{s1r}^{dq}}{d\theta_r} [I_{s1q} \quad I_{s1d}] \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} + \frac{dM_{s2r}^{dq}}{d\theta_r} [I_{s2q} \quad I_{s2d}] \begin{bmatrix} I_{rd} \\ -I_{rq} \end{bmatrix} \quad (4)$$

where I_{s1d}, I_{s1q}, I_{s2d}, I_{s2q} are vector components of first stator(power) and second stator(control) currents,

Respectively Also Ψ_{s1d}, Ψ_{s1q}, Ψ_{s2d}, Ψ_{s2q} are vector components of first stator (power) and second stator currents, respectively. M_{s1}^{dq}, M_{s2}^{dq}, M_{s1r}^{dq}, M_{s2r}^{dq} are self-inductance of the first winding, self-inductance of the second winding, mutual inductance of the first winding and rotor, and mutual inductance of the second winding and rotor respectively. Note that the equations have been

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written with the assumption that rotor has only one loop. I_{rd} and I_{rq} are obtained from (2).

$$\begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} = \frac{M_{s2}^{dq}}{M_{s2r}^{dq}} \begin{bmatrix} I_{s2d} \\ I_{s2q} \end{bmatrix} - \frac{1}{M_{s2r}^{dq}} \begin{bmatrix} \Psi_{s2d} \\ \Psi_{s2q} \end{bmatrix} \qquad (5)$$

and I_{s1d} and I_{s1q} are obtained from (3)

$$\begin{bmatrix} -I_{s1d} \\ I_{s1q} \end{bmatrix} = \frac{M_{s2r}^{dq}}{M_{s1r}^{dq}} \begin{bmatrix} I_{s2d} \\ I_{s2q} \end{bmatrix} - \frac{M_{r}^{dq}}{M_{s1r}^{dq}} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} + \frac{1}{M_{s1r}^{dq}} \begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} \qquad (6)$$

By substituting (5) and (6) in (4), the torque equation is

$$T = (P_1 + P_2).(I_{s2q}.\Psi_{s2d} - I_{s2d}.\Psi_{s2q}) + P_1.(I_{rd}.\Psi_{rq} - I_{rq}.\Psi_{rd}) \qquad (7)$$

Also it can be proved that if the number of loops in the structure of rotor is increased(e.g. three loops), (7) will change into (8):

$$\begin{aligned} T &= (P_1 + P_2)(I_{s2q} \cdot \psi_{s2q} - I_{s2q} \cdot \psi_{s2q}) \\ &+ P_1[(I_{rd}^{in} \cdot \psi_{rd}^{in} - I_{rd}^{in} \cdot \psi_{rd}^{in}) \\ &+ (I_{rd}^{mi} \cdot \psi_{rd}^{mi} - I_{rd}^{mi} \cdot \psi_{rd}^{mi}) + \\ &(I_{rd}^{out} \cdot \psi_{rd}^{out} - I_{rd}^{out} \cdot \psi_{rd}^{out})] \end{aligned} \qquad (8)$$

Now if we investigate the second term of equation (7) in steady state, the following equa tion is obtained

$$T_d = \frac{P_1}{\omega_1} \frac{R_r}{s_1} |I_r|^2 \qquad (9)$$

Where s_1 is the slip of power winding which is calculated as below

$$s_1 = \frac{\omega_1 - P\omega_r}{\omega_1} \qquad (10)$$

As it can be proven form (9), T_d is a torque proportional to rotor resistance and square of its current. In other

Words, this torque is direct coupling and can be neglected in synchronous operating mode where main torque of machine is cross coupling. This idea was verified by simulations and the following results were obtained:

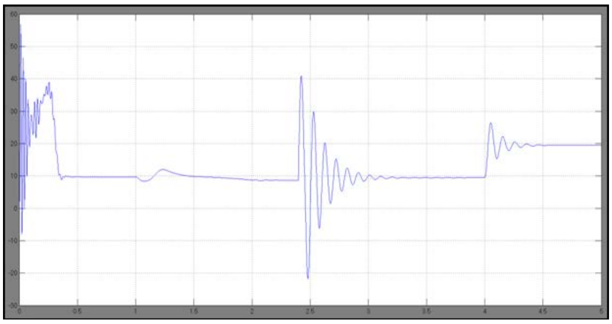


Fig. 1. The torque resulted by the first term of equation (8)

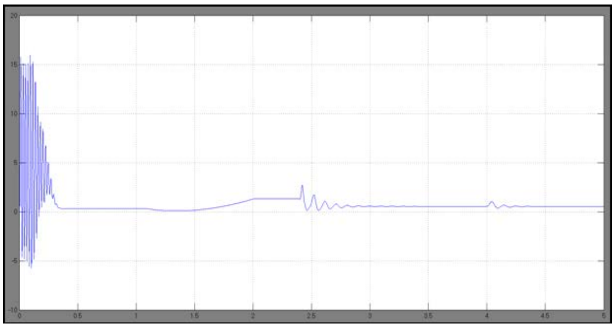


Fig. 2. The torque resulted by the second term of equation (8)

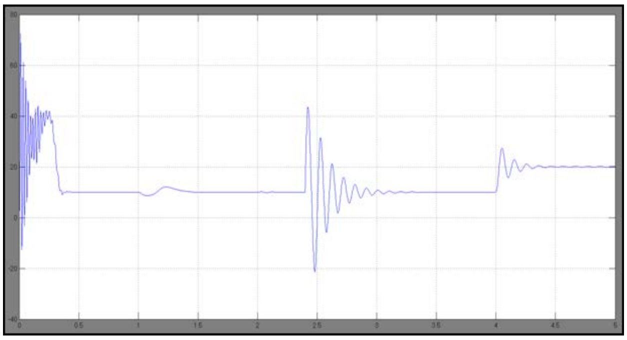


Fig. 3. The sum of two torques in Figs. (1) and (2)

Before investigating the above figures it should be noted that validity of equation (8) in dividing the equation into two direct coupling and cross coupling terms is correct only in synchronous mode. As it can be concluded from (1) and (2), the torque created by second term of (8) is quite negligible in comparison with the first term. Since the sum of these two curves in Fig. 3 is completely coinciding with main curve of machine torque, there is no doubt in validity of this relation. Therefore, the machine torque can be approximated as only cross coupling torque with a good accuracy.

$$T_c = (P_1 + P_2).(I_{s2q}.\Psi_{s2d} - I_{s2d}.\Psi_{s2q}) \qquad (11)$$

Induced in the winding of each phase due to field of other winding is zero.

3. Control Method

From (11) for machine torque, it can be concluded that the principles used in vector control of induction machine(FOC) can be applied to control BDFM. In the flux frame of control winding we have

$$\begin{cases} \Psi_{s2d} = 0 \\ \Psi_{s2q} = -|\Psi| \end{cases} \qquad (12)$$

So the torque equation is as follows

$$T = -(P_1 + P_2).(I_{s2d}.|\Psi|) \qquad (13)$$

According to (13), the torque of this machine is controllable with I_{s2d} by keeping the flux containing the control winding constant. To achieve this, two PI controllers are used for making I_{s2d} and I_{s2q} from torque and flux reference values. Then, voltage references are made by two other PI controllers from the difference between reference current and actual current of the machine. Switching commands are sent to inverter. Different stages of this control method are shown in Fig. 4.

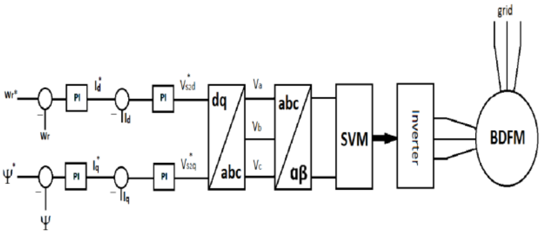


Fig. 4. Different stages of this control method

One of the main advantages of this control method is that it can be used for entering the machine into synchronous mode.

4. Machine startup

In order to start the machine, first, we make the control winding short-circuit and allow the machine to reach its steady state. In steady state operation, load torque is 15Nm and machine speed is 477rpm. One second after the start-up, the proposed control scheme is applied to the machine so that it enters synchronous mode. The simulation results of machine are as follow

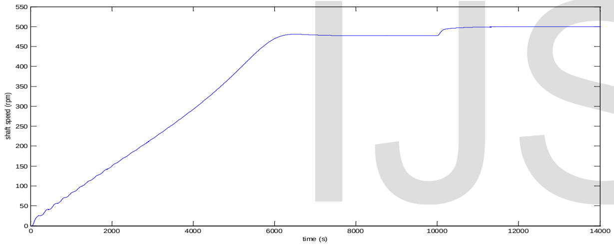


Fig. 5. The speed of machine rotor during acceleration and synchronization steps

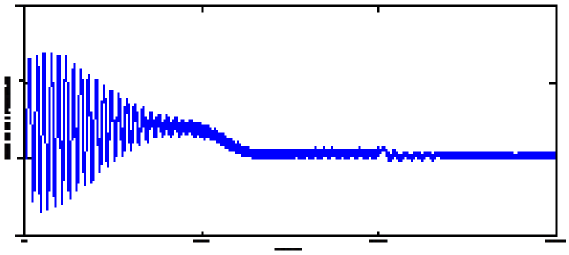


Fig. 6. The electric torque of machine during acceleration and synchronization steps

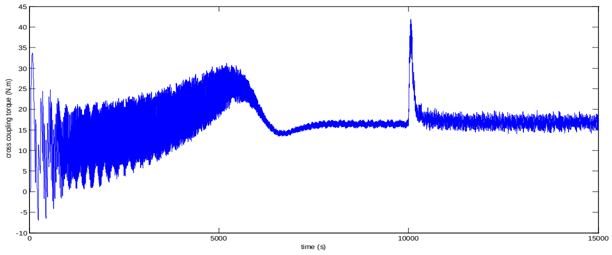
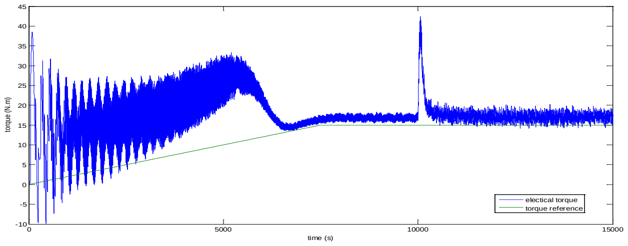


Fig. 7. The torque caused by cross coupling during acceleration and synchronization steps

Fig. 8. The direct coupling torque during acceleration and synchronization steps



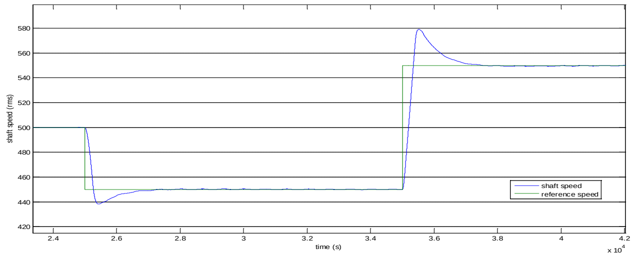


Fig. 9. The flux containing the control winding of machine during acceleration and synchronization steps in the reference frame of control winding flux

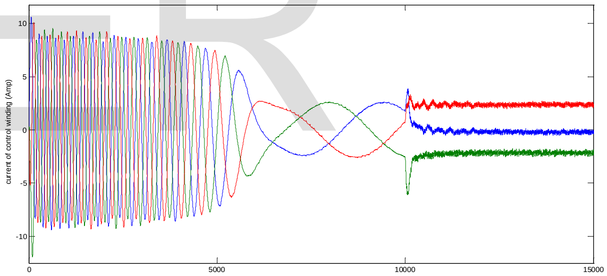


Fig. 10. The three phase currents of machine control winding during acceleration and synchronization steps

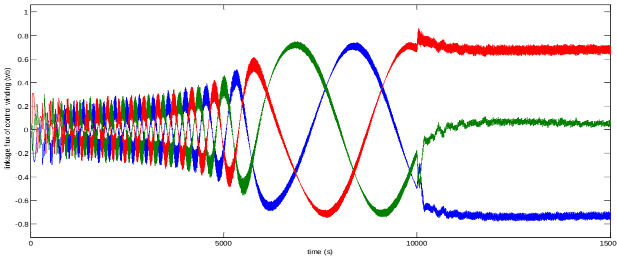


Fig. 11. The flux containing three phases of machine control winding during acceleration and synchronization steps

The machine reference speed and torque are changed after the start-up in order to investigate the performance of the proposed control method.

5. Changing speed reference during no-load operation

In the first step, we change the reference speed from 500rpm to 450rpm at t=2.5s and then change it from 450rpm to 550rpm after one second. The following figures show the machine behavior when applying these changes.

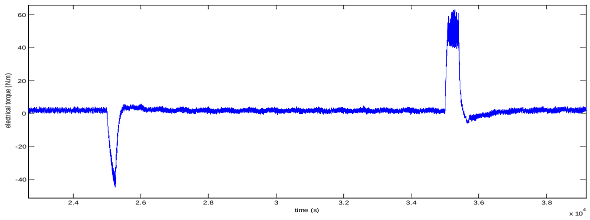


Fig. 12. The speed of machine rotor when changing the reference speed in no-load operation

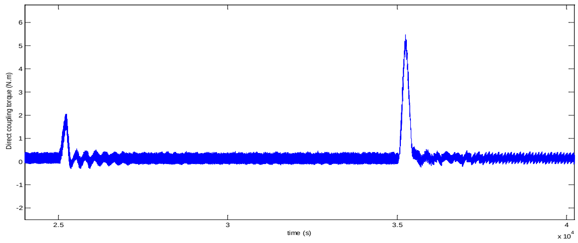


Fig. 13. The machine electric torque when changing the reference speed in no-load operation

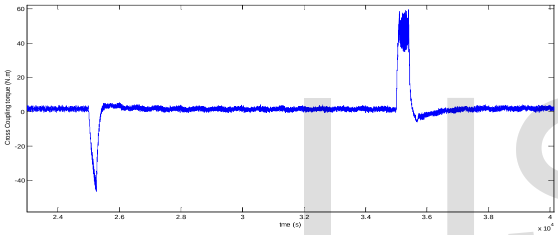


Fig. 14. The cross coupling torque when changing the reference speed in no-load operation

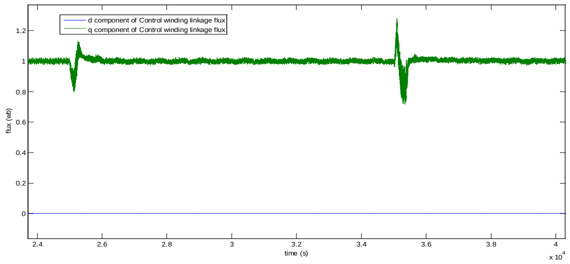


Fig. 15. The flux containing the control winding when changing the reference speed in no-load operation in the frame of control winding flux

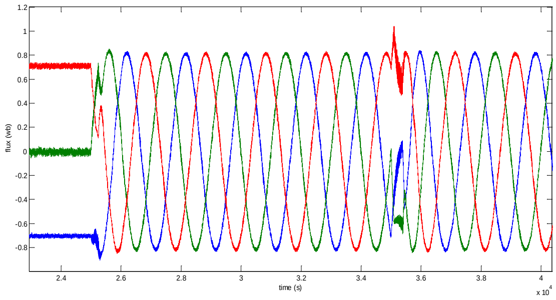


Fig. 16. The flux containing three phases of control winding when changing the reference speed in no-load operation

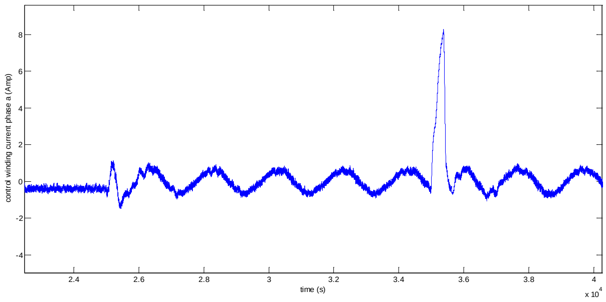


Fig. 17. Phase a current of control winding when changing the reference speed in no-load operation

6. Conclusion

As it was shown by simulations, using the proposed controller increased the machine synchronization speed significantly. Furthermore, it led to acceptable time response for speed change and also high stability in response to load torque change. It should be noted that unlike the previous methods in literature, there is no need for measuring the parameters at the power winding side. Finally, it is required to mention that the PI coefficients chosen for the controller may change according to different applications, and the coefficients used in the simulations are only for showing the validity of our proposed method.

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