Modeling and Simulation Study for Dynamic Model of Brushless Doubly Fed Reluctance Machine using Matlab Simulink

William K Song
School of Electrical Engineering
University of Technology, Sydney
Sydney, NSW, Australia
William.K.Song@student.uts.edu.au

David G. Dorrell
School of Electrical Engineering
University of Technology, Sydney
Sydney, NSW, Australia
d.g.dorrell@gmail.com

Abstract— The Brushless Doubly Fed Reluctance Machine (BDFRM) is a type variable speed machine with two sets of windings. One set is fed from a variable frequency inverter while the second set is fed at constant frequency. Comparing with the traditional induction machine, BDFRM has simple structure and higher efficiency, higher power density, smaller size and lower maintenance cost. So, it is important to build an accurate dynamic model of BDFRM for many control method studies. This paper presents mathematical model for a dynamic model of BDFRM using d-q reference coordination system and the simulation model be designed on Matlab/Simulink®.

Keywords-BDFRM, Dynamic Modeling, Simulation

I. INTRODUCTION

The induction machine is a widely used because it has a simple brushless structure, so they are low cost in terms of their manufacture and maintenance. They can operate as variable speed machines through the use of variable frequency power electronic inverters, and control theories, such as flux orientated control, have been developed. But there are also some disadvantages, the speed control is complex because it has non-linear characteristics with mutual interference among the machine parameters. This means the machine speed cannot be easily controlled compared to, for example, the DC machine. So it will make the controller cost is higher compared to the DC machine. Another disadvantage of the machine is its high starting current if is started direct on-line. It may be five to eight times higher than the full load current. This can be reduced by use of a variable frequency inverter. The machine also has the lower lagging power factor when the machine is lightly loaded. It will make the inverter system is larger due to the higher required currents; the machine has large kVA rating. If the inverter can be reduced in size then this would be advantageous.

In recent years, the Brushless Doubly Fed Reluctance Machine (BDFRM) has come under investigation. The BDFRM is one of a family of slip energy recovery machines suitable for a wide range of applications [1]. It can operate in several different modes but one is as a slip energy machine similar to the doubly-fed induction machine (DFIM), which is now very common in wind turbines. However, the BDFRM is operates at higher frequency for given pole numbers compared to the induction motor. Higher frequency operation means that the machine has higher efficiency, higher power density, smaller size and lower cost as illustrated in [2]. The BDFRM also has a brushless structure which is an advantage over the DFIM. This combination creates the prospect of a robust, controllable, and low maintenance machine.

The BDFRM has two sets of 3-phase windings in the stator. One is connected directly to the grid which is called the primary winding or power winding and the other is connected to grid via a bi-directional inverter which is called the secondary winding or control winding. The machine is controlled through controlling the bi-directional inverter. Because the BDFRM only requires a partially rated converter it is possible to reduce the cost of the drive system; and the brushless nature of the machine increases its reliability. This is especially beneficial in large power applications such as wind turbines and large pumps. Hence, various control methods for the BDFRM have been investigated [3-4].

Computer simulation analysis is one of best testing methods to probe and show the performance of a new proposed theory before experimental prototyping. Using a computer simulation tool, the performance can be compared to existing controls and any potential performance improvement assessed. To obtain accurate simulation results for proposed control methods for the BDFRM, it is very important to use an accurate machine simulation model. There are numerous computer simulation tools available, but the most popular computer simulation tool is Matlab/Simulink®. In this paper, a dynamic simulation of a BDFRM model is developed using Matlab/Simulink®. This dynamic simulation model is then available for use in further simulation studies of the BDFRM.

II. MATHMETICAL MODEL OF BDFRM

The basic mathematical equations of the BDFRM make are necessary in order to analysis and simulate the control algorithms of the BDFRM. This section will explain the mathematical model of the BDFRM. In basic form, the BDFRM stator model is similar to the induction machine, but it has two sets of three phase windings, and these have different pole numbers. The magnetic coupling between the two sets of windings is due to the rotor reluctance and the pole number selection is critical. The number of salient poles on the rotor should equal the average of the two stator windings. For instance, for a 2/6 stator pole machine it would have 4 pole and for a 4/8 stator pole machine it would have 6

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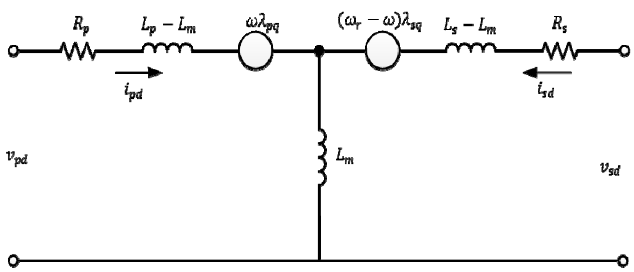
poles. The machine should not have a stator pole pair different by one (i.e., 4/6 stator poles) because this will generator unbalanced magnet pull [9]. More detailed numerical assumptions and analysis are given in previous research papers [4-6].

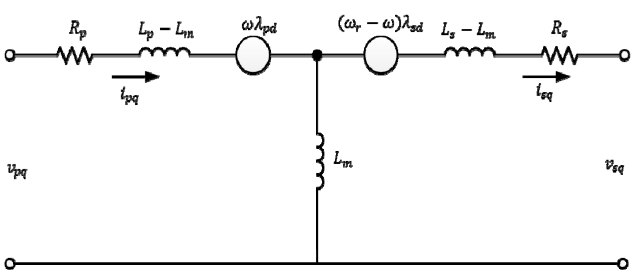
The main concept of the basic mathematical model is that it consists of two d-q reference frames. Using equivalent two-phase d-q models for the three-phase windings it is more straightforward to analyze and simulate the machine because the d-q models has less variables. This is standard practice in many control strategies. The d-q equations of the BDFRM model can be expressed as a set of voltage equations:

$$\begin{bmatrix} v_{pd} \\ v_{pq} \\ v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R_p + pL_p & -\omega L_p & pL_m & \omega L_m \\ \omega L_p & R_p + L_p p & \omega L_m & -pL_m \\ pL_m & (\omega_r - \omega)L_m & R_s + pL_s & (\omega_r - \omega)L_s \\ (\omega_r - \omega)L_m & -pL_m & (\omega_r - \omega)L_s & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{pd} \\ i_{pq} \\ i_{sd} \\ i_{sq} \end{bmatrix} \tag{1}$$

where v_{pd} and v_{pq} are the primary (power – fixed frequency) winding d and q voltages, v_{sd} and v_{sq} are the secondary (control – variable frequency) winding d and q voltages, i_{pd} and i_{pq} are the primary winding d and q currents, i_{sd} and i_{sq} are the secondary winding d and q current, ω is primary reference frame angular velocity, ω_r is the rotor speed of machine, p is a differential function, L_p, L_s and L_m are the primary, secondary and mutual inductances, and R_p and R_s are the primary and secondary winding resistances. There are four expressions: two equations for the primary winding which connect to power grid and two equations for the secondary winding which connect to controlled inverter.



a) d axis of BDFRM



b) q axis of BDFRM

Figure 1. d-q equivalent circuit of BDFRM

From the (1), the d-q equations can be further manipulated:

$$\begin{aligned} v_{pd} &= R_p i_{pd} + \frac{d}{dt}\left(L_p i_{pd} - L_m i_{pd}\right) + \frac{d}{dt}\left[L_m\left(i_{pd} + i_{sd}\right)\right] - \omega\lambda_{pq} \\ v_{sd} &= R_s i_{sd} + \frac{d}{dt}\left(L_s i_{sd} - L_m i_{sd}\right) + \frac{d}{dt}\left[L_m\left(i_{sd} + i_{pd}\right)\right] - (\omega_r - \omega)\lambda_{sq} \\ v_{pq} &= R_p i_{pq} + \frac{d}{dt}\left(L_p i_{pq} - L_m i_{pq}\right) + \frac{d}{dt}\left[L_m\left(i_{pq} - i_{sq}\right)\right] + \omega\lambda_{pd} \\ v_{sq} &= R_s i_{sq} + \frac{d}{dt}\left(L_s i_{sq} - L_m i_{sq}\right) + \frac{d}{dt}\left[L_m\left(i_{sq} - i_{pq}\right)\right] + (\omega_r - \omega)\lambda_{sd} \end{aligned} \tag{2}$$

where $\lambda_{pd} = L_p i_{pd} + L_m i_{sd}$, $\lambda_{sd} = L_s i_{sd} + L_m i_{pd}$, $\lambda_{pq} = L_p i_{pq} - L_m i_{sq}$ and $\lambda_{sq} = L_s i_{sq} - L_m i_{pq}$.

This leads to the development of the equivalent circuit for the BDFRM as shown in Fig. 1.

Using the basic set of equations in (1), the basic mathematical equations can be rewritten for development of the ideal BDFRM model as Matlab/Simulink® block:

$$\begin{aligned} v_{pd} &= R_p i_{pd} + \frac{d}{dt} L_p i_{pd} + \frac{d}{dt} L_m i_{sd} - \omega\lambda_{pq} \\ v_{pq} &= R_p i_{pq} + \frac{d}{dt} L_p i_{pq} - \frac{d}{dt} L_m i_{sq} + \omega\lambda_{pd} \\ v_{sd} &= R_s i_{sd} + \frac{d}{dt} L_s i_{sd} + \frac{d}{dt} L_m i_{pd} - (\omega_r - \omega)\lambda_{pq} \\ v_{sq} &= R_s i_{sq} + \frac{d}{dt} L_s i_{sq} - \frac{d}{dt} L_m i_{pq} + (\omega_r - \omega)\lambda_{sd} \end{aligned} \tag{3}$$

The primary and secondary d-q current equations can be expressed in a manner suitable for use in a Matlab/Simulink® block:

$$\begin{aligned} i_{pd} &= \frac{1}{L_p}[\int \left(v_{pd} - R_p i_{pd} + \omega\lambda_{pq}\right) - L_m i_{sd} \\ i_{pq} &= \frac{1}{L_p}[\int \left(v_{pq} - R_p i_{pq} - \omega\lambda_{pd}\right) + L_m i_{sq}] \\ i_{sd} &= \frac{1}{L_s}[\int \left(v_{sd} - R_s i_{sd} + (\omega_r - \omega)\lambda_{sq}\right) - L_m i_{pd}] \\ i_{sq} &= \frac{1}{L_s}[\int \left(v_{sq} - R_s i_{sq} - (\omega_r - \omega)\lambda_{sd}\right) + L_m i_{pq}] \end{aligned} \tag{4}$$

The equivalent torque expressions are developed in previous studies [4][6 - 8], For the BDFRM:

$$T_e = \frac{3}{2}\, p_r \,\frac{L_m}{L_p}\, \lambda_p\, i_{sq} \tag{5}$$

where T_e is the electro-magnetic torque, p_r is the rotor pole number, L_p and L_{ps} are the primary and mutual inductances, λ_p is the primary flux, i_{sq} is the secondary stator current along the q-axis. $(L_{ps}/pL)\lambda_p$ is the primary flux coupling the secondary winding which is rotating at the same speed as the secondary mmf (ω_s), it represents as λ_{ps}. The primary flux, λ_p, is almost constant because the primary winding is connected to the power grid so that the machine is operating under fully fluxed conditions. This means that the variation of the inductance is sufficiently small so that it can be ignore. Therefore, the primary and mutual inductances, L_p and L_{ps}, can be considered as constant values. The secondary stator current along the q-axis can be replace with $i_{sq} = i_s \sin\alpha_p$ where the secondary current vector position is at angle α_p. Hence, (5) can be rewritten as

$$\frac{T_e}{i_s} = \frac{3}{2}\, p_r \,\frac{L_{ps}}{L_p}\, \lambda_p \sin\alpha_p \quad (6)$$

This is called torque per secondary inverter ampere (TPIA) and the maximum torque per secondary inverter ampere (MTPIA) is clearly achieved when $\alpha_p = \pi/2$. This MTPIA is important for selecting the inverter rating and improving the efficiency for a given torque. The (6) can be replaced by:

$$T_e = \frac{3}{2} p_r L_m \left(i_{sd} i_{pq} + i_{sq} i_{pd}\right) \quad (7)$$

using the current expressions in (2) for adding up the simulation blocks. The machine speed can be obtained from

$$J \frac{d}{dt}\omega_r + K_d \omega_r = T_e - T_L \quad (8)$$

And this can be re-arranged using ω_r in the simulation blocks:

$$\omega_r = \int \left[\frac{1}{J}\left(T_e - T_L - K_d \omega_r\right)\right] \quad (9)$$

Therefore, based on the mathematical model derived in (4), (7) and (9), the ideal dynamic simulation model of the BDFRM is illustrated in Fig. 5.

III. SIMULATIONS AND RESULTS

As previously discussed, the BDFRM needs two windings to supply power to the machine through the primary or power windings, and, for the additional role of controlling the machine, through the secondary or control windings. Fig. 2 shows the equivalent circuit used in the simulation block diagrams under no-load condition. The simulation parameters are as shown in the Table I.

The simulation is still under development. However, some results are given here. The machine requires speed feedback not only for the speed terms in impedance matrix (1) but also there are synchronization issues. The secondary can be short circuited to form an induction machine operating mode but to obtain true operation through the control winding then speed feedback is required to the inverter in order to set the correct frequency and phase. This is shown in Fig. 5. It can be seen in (7) that with no secondary current there should be no torque. Even with secondary current, if the winding currents and speed are not synchronized then the torque should simply oscillate.

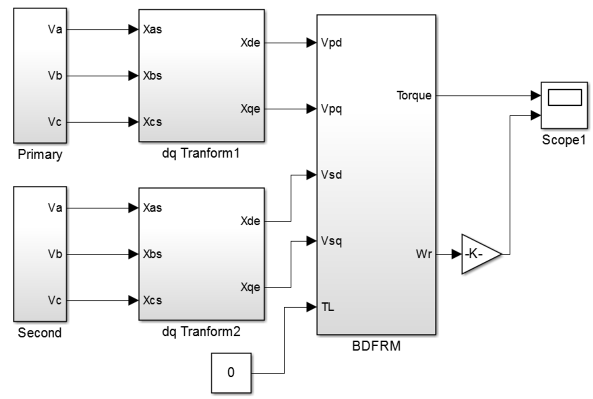


Figure 2. Simulation Blocks

TABLE I. SIMULATION PARAMETERS

Parameter	Values
Pole Contributions	$p_g = 8$, $p_s = 4$, $p_r = 6$
Primary Resistance	1.2 ohm
Primary Inductance	46 mH
Secondary Resistance	0.9 ohm
Secondary Inductance	87 mH
Mutual Inductance	62 mH
Grid Power	240 V / 50 Hz
Secondary Power	100 V / 50 Hz

To gain an insight into the frequency and speed relationship then taking the high pole winding to be the power winding, there is a synchronizing requirement for the inverter-fed (control) winding [9]:

$$f_c = P f_r \pm f_p \quad (1)$$

where f_c, f_r and f_p represent the control winding electrical frequency, rotor mechanical rotational frequency and grid (power winding) frequency. For the 4-8 stator pole machine, if the machine is in induction motor mode with the secondary shorted, then the speed with be close to 500 rpm. Fig. 3 shows the speed and control winding frequency relationship.

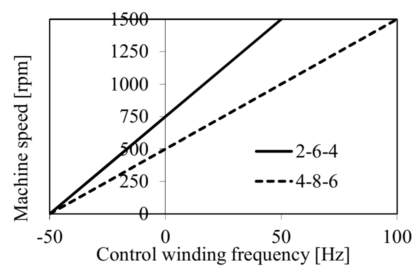
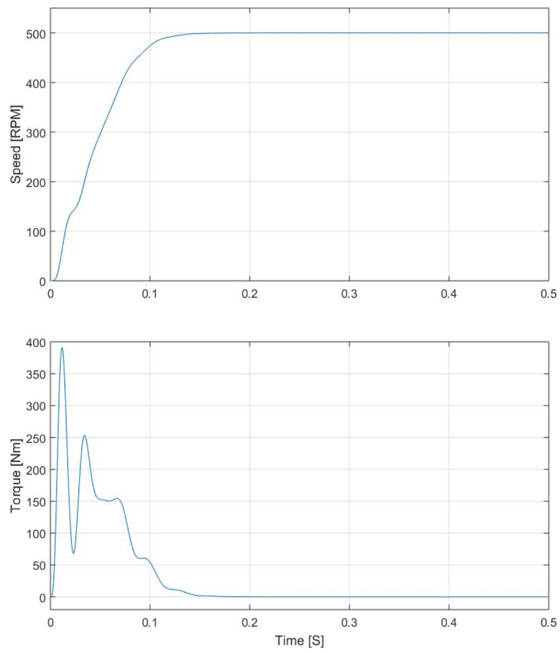
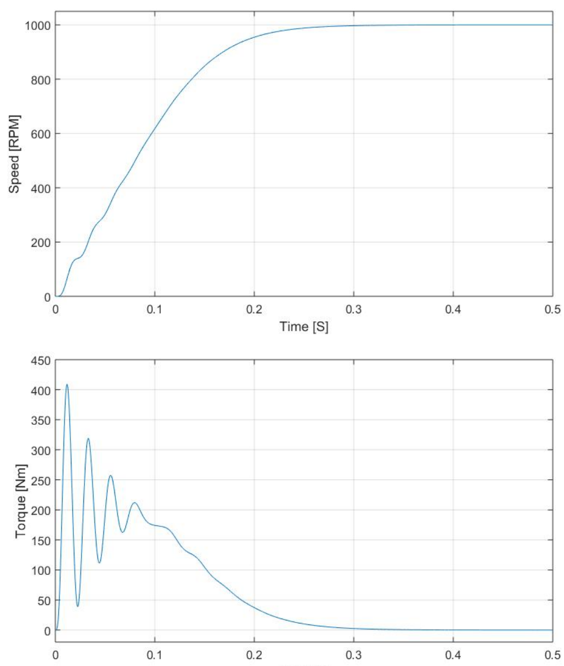


Figure 3. Variation of control winding frequency with speed when power winding connected to 50 Hz grid. Two machines (2-6-4, 4-8-6) are displayed.



(a) Speed and torque for shorted winding



(b) Speed and torque for run up to 50Hz on control winding

Figure 4. Results for shorted control winding and 50 Hz control.

Fig. 4(a) shows the torque and speed against time for the short circuit control winding scenario. If the machine has 50 Hz on both windings then the speed with be 1000 rpm and this is shown in Fig. 4(b). Since there is double the speed then the time to reach this speed is longer. To run dynamically up to this point then the control winding has to start at -50 Hz (i.e., backwards rotation) then then run up to this speed by varying the frequency. It appears to do this successfully.

IV. Conclusions

This paper presents at dynamic simulation model of BDFRM using Matlab/Simulink® as shown in Fig. 5. A set of equations are put forward to define the machine. Some initial results are put forward and further work will be to thoroughly test the model and validate experimentally.

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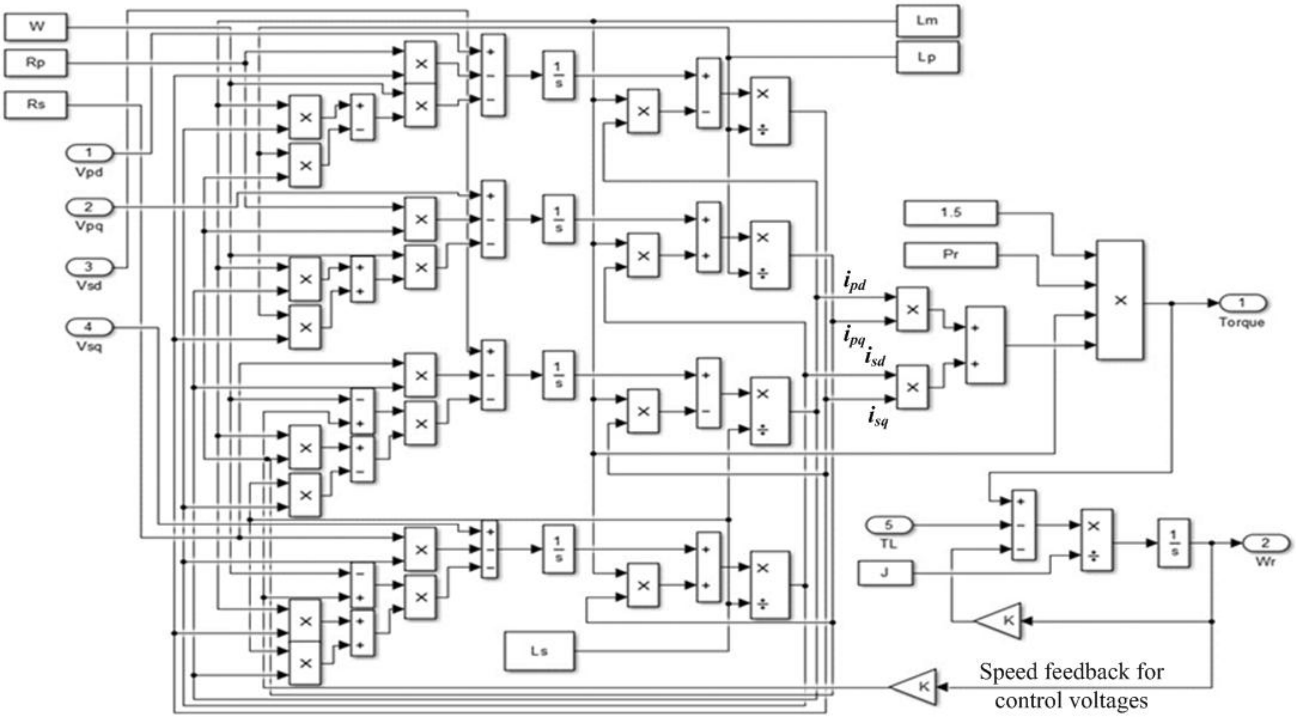

Figure 5. Ideal Dynamic Simulation Model of BDFRM for Matlab/Simulink®