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Simulation and Experimental study of brushless cascaded doubly fed machine as a BDFM

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Abstract: The Brushless Doubly-Fed Machine (BDFM) is a new-type of electrical machine. It combine the favorable characteristic of the asynchronous motor and synchronous generator. This type of machine solve the structural problems of brushless.

This paper presents the principle, structure and operation mode of BDFM, it is devoted to not only the simulation, but also the experimentation of BDFM. This study used three cascaded machine to successfully emulate a proper BDFM, therefore, a study were held on the speed-torque and current relationship , with one fixed constant at a time. Last but not least, this paper illustrates the open-loop control of the said BDFM.

Keywords: Brushless doubly-fed machine, steady-state operating, asynchronous mode, synchronous mode, open-loop.

I. INTRODUCTION

The Asynchronous brushless doubly fed induction machine (will be referred to as BDFM in this article) consists of two independent three-phase windings in the stator with different number of pair of poles, and a special squirrel-cage rotor with three windings that have a number of turns that equals the sum of the number of pair of poles of the two mentioned stator windings [2].

It's composed by two statoric windings magnetically unlinked and a special rotoric winding. One of the stator's windings is called Power Windings (SP), the other is called Command Windings (SC).

Although the BDFM concept was studied for a long time, it is not yet industrialized because of manufacturing constraints. The main constraints to respect in the design of the machine with one stator are:

- Avoid, wherever possible, direct electromagnetic coupling between the two stator windings.
- Maximize the electromagnetic coupling between the rotor and each of the stator windings.
- Ensure a precise ratio between the number of poles of both SP and SC stator windings and the number of turns of the rotor to ensure cross coupling.

The number of prototype of this machine that has been made and/or described in the published literature to date does not exceed ten. The main purpose of this prototype is not only to show the feasibility of the concept, but also to help move forward in the research for appropriate model and control structures.

In addition to the patented prototypes developed during the last years as René Spee (and others) of the Oregon State University (USA), the cascade structure (Fig. 1) of two asynchronous machines with coiled rotor can be considered the first working execution of a rotating, brushless machine with double stator. It is noted that this form of self-cascaded machine was patented by Lydall in 1903 [16] and the following improvements were done by Hunt [13], which resulted to BDFM being alternatively known as the self-cascaded machine.

In this article, we will examine, experimentally and by simulation, the different BDFM's operating modes and steady state's characteristic in order to validate the model and to deduce adequate control.

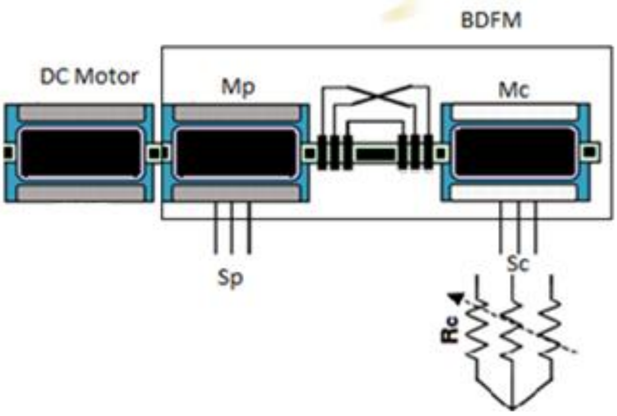


Fig1. Structure of cascaded double stator asynchronous machines

II. DIFFERENT OPERATING MODES OF THE BDFM

The BDFM have two operating modes:

- Asynchronous-Mode: in this mode, the machine behaves as an asynchronous machine that has p_p poles and the control windings BC has no effect on its behavior.
- Synchronous- mode: This mode is more interesting.

Due to its typical connection, the power winding (Bp) is directly connected to the grid while the control winding (SC) can be powered by a bi-directional converter to ensure control of the electromagnetic state of the machine, the BDFM can be operated at variable speed.

To ensure the proper operating of the BDFM in synchronous- mode and to be able to control the SP winding current, one must choose an exact SC windings power frequency to ensure adequate frequency coupling between the two stator windings.

In fact, using an improper power-supply frequency will produce two rotor fluxes with a different rotating slip frequencies. These two rotating flows will create an attracting force which will accelerate or brake the rotor.

However, if the difference between the two slip frequencies is not very big, it is possible to reach a balanced situation in which the rotor currents have an even slip frequency, thereby obtaining a proper coupling frequency (synchronous operating mode). Once operating in synchronous mode, even if the supply-power frequency of any stator winding changes, the rotor' speed will vary in order to maintain the rotor slipping.

In the synchronous operation mode, the rotor' speed imposes the frequency of the control winding's power-supply.

The frequency of the control winding is determined by the relationship:

$$fc = (pp+pc)fr - fp \qquad (1)$$

Where:

f_c et f_p are respectively the power windings and the control windings frequencies of the rotor.

p_p, p_c are respectively the power windings and the control windings' number of pole pairs of the rotor.

- The BP Frequency f_n is the same as the power grid.
- The BC frequency f_c (variable can be changed)

We define the winding slipping Sp and Scas: $s_p = \dfrac{\omega_p - p_p\Omega}{\omega_p}$ and $s_c = \dfrac{\omega_c - p_c\Omega}{\omega_c}$

Wealsodefinetheangularspeed ω_n as:(for ω_C=0): $\omega_n = \dfrac{\omega_p}{p_c + p_p}$

Thus, in synchronous-mode: $\dfrac{s_c}{s_p} = -\dfrac{\omega_p}{\omega_c}$

A synchronism procedure must be followed in case of a double power-supply

In fact, the synchronous speed is calculated by adding the two stator frequencies:

If we power the machine following (1), it will momentarily re-align its magnetic flux, thus, creating an auto-synchronization transition.

If the rotor speed was not kept constant, it would become extremely hard to synchronize the machine because the relation (1) wasn't followed for enough time for such synchronization to take place.

One way to solve this problem, would be to synchronize the machine at a null speed, and then, use the BC frequency to control the rotor speed. This method may be hard to apply because of the need to keep the rotor at a null speed.

III. DYNAMIC MODEL OF THE BDFM

There are not that many (mainly three) methods for modeling electrical machines, which are (sorted by difficulty)

· Park's transformation

·Permeance networks modeling

·The finite element method (FEM)

Park's transformation is obtained basing on the DBFM's electrical equations. In order to simplify this model, we put together some hypothesis:

In this modeling, we will not include the saturation of the magnetic circuit, the iron losses and the space harmonics.

Also, the induction filed in the air gap is supposedly sinusoidal.

The equations of the stator and rotor windings in the dq coordinate system referring to the stator winding [2], [4] can be written as:

$$\begin{cases} V_{dp} = R_p i_{dp} + \dfrac{d\varphi_{dp}}{dt} - \omega_p \varphi_{qp} \\ V_{qp} = R_p i_{qp} + \dfrac{d\varphi_{qp}}{dt} + \omega_p \varphi_{dp} \\ V_{dc} = R_c i_{dc} + \dfrac{d\varphi_{dc}}{dt} - \left(\omega_p - (p_p + p_c)\Omega\right)\varphi_{qc} \\ V_{qc} = R_c i_{qc} + \dfrac{d\varphi_{qc}}{dt} + \left(\omega_p - (p_p + p_c)\Omega\right)\varphi_{dc} \\ V_{dr} = R_r i_{dr} + \dfrac{d\varphi_{dr}}{dt} - \left(\omega_p - p_p\Omega\right)\varphi_{qr} \\ V_{qr} = R_r i_{qr} + \dfrac{d\varphi_{qr}}{dt} + \left(\omega_p - p_p\Omega\right)\varphi_{dr} \end{cases}$$

V_d,$V_q$tensions dq coordinate system

i_d,i_qCurrents in the dq coordinate system

□$_d$,□$_q$flux in the dq coordinate system

p_p, p_cNumber of pole pairs of the power and control windings respectively

ω_p,$\omega_c$pulsation of the power and control circuits respectively

P_p,$Q_p$active and reactive power of the power winding

Ωrotor angular pulsation

R_p, R_cPower and control windings resistors respectively

$R_r$rotor's resistor

L_p,L_cInductance per phase in the power and control windings in the dq coordinate system

L_rRotor inductance in the dq coordinate system.

M_p, M_c mutual inductance between the stators and the rotor windings.

Equations: Statorpower windings flux: $\begin{cases} \varphi_{dp} = L_p i_{dp} + M_p i_{dr} \\ \varphi_{qp} = L_p i_{qp} + M_p i_{qr} \end{cases}$

Equations: Stator control windings flux: $\begin{cases} \varphi_{dc} = L_c i_{dc} + M_c i_{dc} \\ \varphi_{qc} = L_c i_{qc} + M_c i_{qc} \end{cases}$

Equations: Stator control windings flux: $\begin{cases} \varphi_{dr} = L_r i_{dr} + M_p i_{dp} + M_c i_{dc} \\ \varphi_{qr} = L_r i_{qr} + M_c i_{qc} + M_p i_{qp} \end{cases}$

Using these equations, we can clearly observe that the variables that presents the two stators windings through the rotor current. The model equations can be expressed in vector form as follows:

$$\begin{cases} \vec{V}_p = R_p\vec{i}_p + \dfrac{d\vec{\varphi}_p}{dt} + j\omega_p\vec{\varphi}_p \\ \vec{\varphi}_p = L_p\vec{i}_p + M_p\vec{i}_r \\ \vec{V}_c = R_c\vec{i}_c + \dfrac{d\vec{\varphi}_c}{dt} + j\left(\omega_p - (p_p + p_c)\Omega\right)\vec{\varphi}_c \\ \vec{\varphi}_c = L_c\vec{i}_c + M_c\vec{i}_r \\ \vec{V}_r = R_r\vec{i}_r + \dfrac{d\vec{\varphi}_r}{dt} + j\left(\omega_p - p_p\Omega\right)\vec{\varphi}_r \\ \vec{\varphi}_r = L_r\vec{i}_r + M_p\vec{i}_p + M_c\vec{i}_c \end{cases}$$

This model is similar to the vector model of the induction machine in presence of two stator winding. The expressions related to stator power winding are the same as that of the induction machine. In rotor flux equation, the influence of the two stator currents is well represented.

In stator control winding, the factor $\lfloor \omega_p - (p_p + p_c)\Omega \rfloor$ characterizes the relative angular velocity between the reference frames.

IV. EQUIVALENT CIRCUIT OF THE BDFM

Equivalent circuit for the Brushless Doubly FedMachine (BDFM) is represented as below (fig 2).

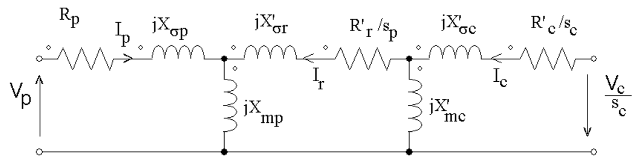


Fig 2:Equivalent circuit of BDFM

The terms of the different parameters of the equivalent scheme are detailed in [2] and [3].
The steady state operating characteristics of the BDFM are often determined using a per-phase equivalent circuit as shown in figure 2.
Expressions insteadystate can be written such as:

$$\begin{cases} \vec{V}_p = R_p\vec{i}_p + j\omega_p L_p\vec{i}_p + j\omega_p M_p\vec{i}_r \\ \vec{V}_c = R_c\vec{i}_c + j\omega_c L_c\vec{i}_c + j\omega_c M_c\vec{i}_r \\ 0 = R_r\vec{i}_{dr} + j\omega_r L_r\vec{i}_r + j\omega_r M_p\vec{i}_p + j\omega_c M_c\vec{i}_c \end{cases}$$

Where: $\omega_c = \omega_p - (p_p + p_c)\Omega$ and $\omega_r = \omega_p - p_p\Omega = s_p\omega_p$

The nominal apparent power is expressed as following:

$$\vec{S}_a = \vec{V}_p.\vec{i}_p^* + \vec{V}_c\vec{i}_c^* + \vec{V}_r.\vec{i}_r^* = P_a + jQ_a$$

The expression ofthe powers absorbed byPW, CW and the rotor isgiven by,

$$P_a = R_e\{\vec{V}_p.\vec{i}_p^*\} + R_e\{\vec{V}_c\vec{i}_c^*\} + R_e\{\vec{V}_r.\vec{i}_r^*\}$$

$$Q_a = I_m\{\vec{V}_p.\vec{i}_p^*\} + I_m\{\vec{V}_c\vec{i}_c^*\} + I_m\{\vec{V}_r.\vec{i}_r^*\}$$

The electromagnetic torque: $T_{em} = p_p M_p I_m \{\vec{i}_p\ \vec{i}_r^{\,*}\} + p_c M_c I_m \{\vec{i}_r\ \vec{i}_c^{\,*}\}$

V. SIMULATIONS RESULTS

To test the BDFM, the model has been implemented using MATLAB/SIMULINK.

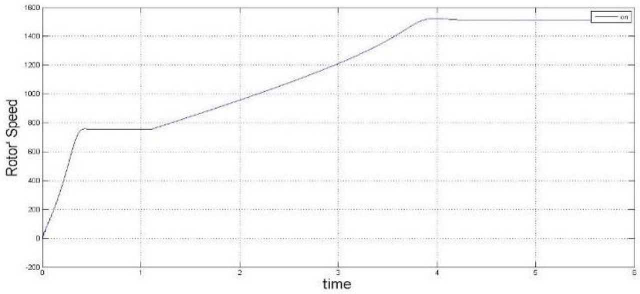


Fig3 : Speed profile

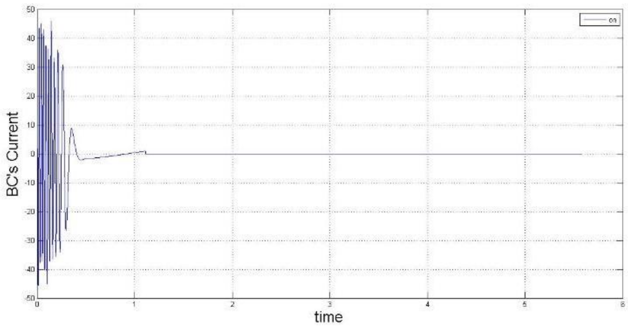


Fig4 : stator current (phase Ca)

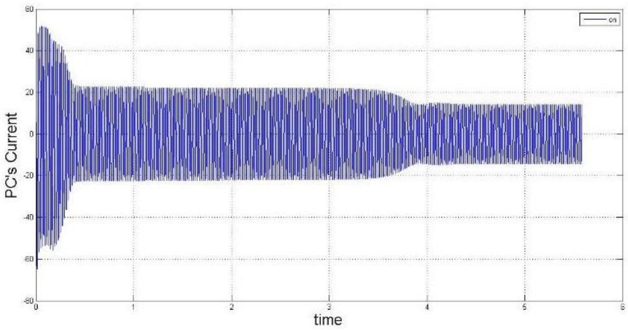


Fig5 : stator current (phase Pa)

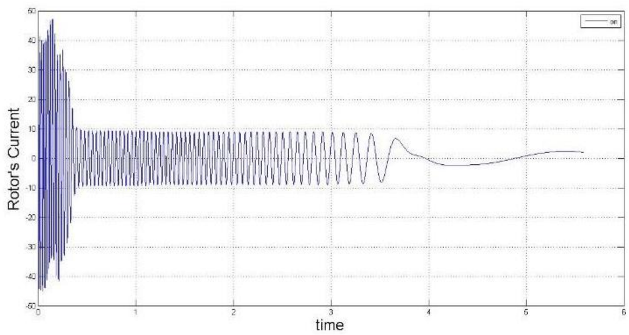


Fig 6: rotor current (phase Ra)

Figures 3-6 show the variations of different electrical and electromagnetic quantities during a transition from the synchronous mode to the asynchronous mode of the BDFM

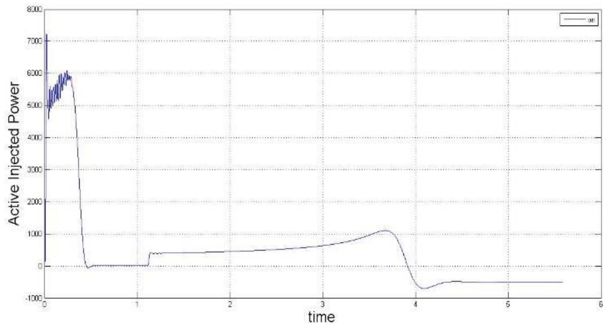


Fig 7: stator active power

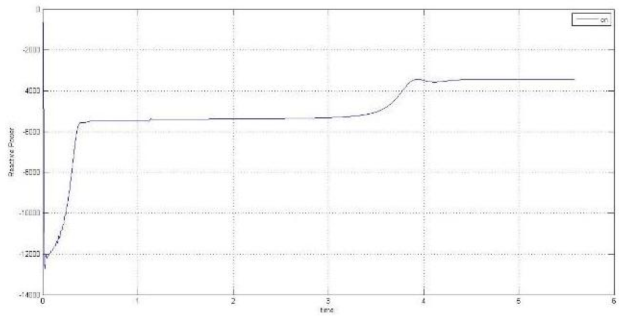


Fig 8: stator reactive power

Figure 8 shows that the reactive power in synchronous mode is greater than in the asynchronous mode, hence the need to act correctly on the excitation current to compensate the reactive power absorbed by the machine. The BDFM has a low power factor grid wise, which will drastically limit its usage in an open-loop. Such machine will have to be associated to a back-to-back converter that will control the power factor.

VI. EXPERIMENTAL RESULTS.

VI.1 EXPERIMENTATION RIG

The physical structure of the test platform is mainlycomposed of a DC motor driving two bipolar asynchronous machines with a wound rotor (IM1 and IM2) cascaded (BCDFM). IM1 with a 1.5KW power is grid connected via its stator S_p, IM2 in the other hand, with 370W power is connected to a variable load via its stator Sc.

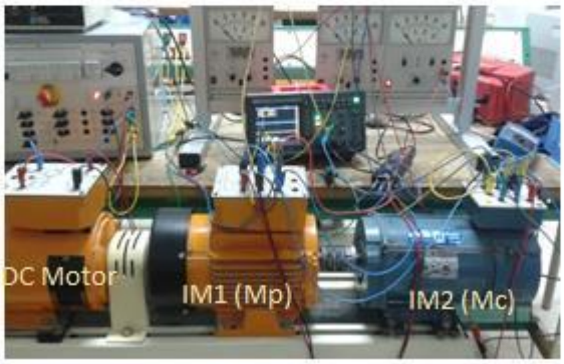


Fig 9: Photo of the experimental platform

The identification of the parameters of the power machine IM1 and IM2 the control machine gave the following results:

IM1 :Rp=4.6 Ω ; Rr=1.128Ω ; Lp=20mH ; Lr=20mH ; Mp= 370mH ;
IM2; Rc=9.54 Ω ;Lc=20m H ; Mc= 630.6 mH ; Rr=2.54Ω
J=0. 15 kg.m² ; f=0,004 N.m.s-1

VI.2 EXPERIMENTAL WAVEFORMS

CH1 2V/DIV CH2 50mv/div 50ms/div

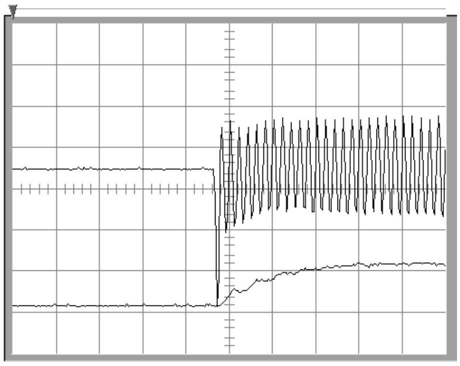


Fig 10: Stator current and angular speed during the start phase in synchronous mode

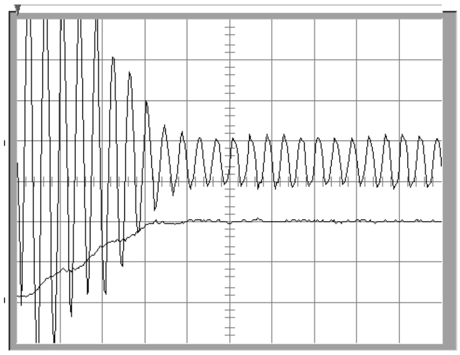


Fig 11: Stator current and angular speed during the start phase in asynchronous mode

CH1 100mvV/DIV CH2 2v/div 200ms/div

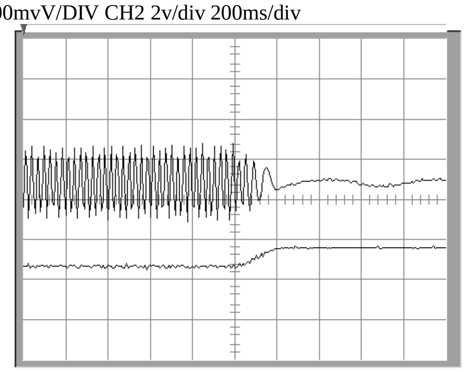


Fig 12: Rotor current and angular speed during the Transition from synchronous mode to asynchronous mode

Figure 10-11 show the waveforms of the current and angular speed during the start phase angular respectively in the case of Control winding (BC) open and shorted.

In the case where BC is open, the machine absorbs a fixed level of reactive power corresponding to the asynchronous operation (2.15A, 1455 rpm).

While in the case where the Control winding (BC) is shorted, the machine absorbs a higher level of reactive power corresponding to the synchronous operation (4.5A, 750 rpm).

It is observed that once the I_C current value is less than a synchronous mode minimum, the machine no longer works in the synchronous mode and speed cup to 1455rpm corresponding to the asynchronous mode. The frequency of the rotor current becomes quite small (f_{rc}=0.92Hz);

Fig. 12 shows the temporal values of the currents of the rotor.

CH1 100mv/div CH2 2v/div 5000ms/div

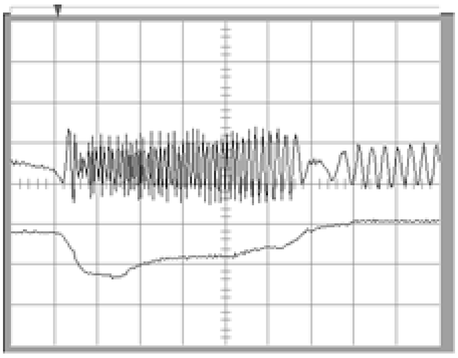


Fig13: Transition back to synchronous mode when theI_c current is null

CH1 100mv/div CH2 2v/div 5000ms/div

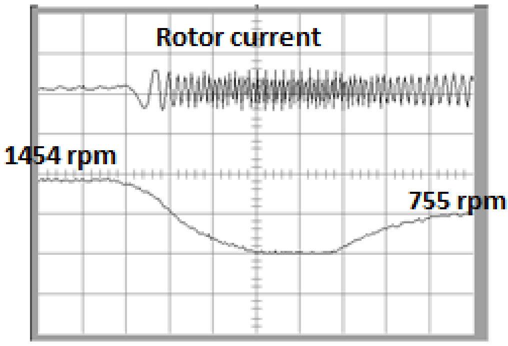


Fig 14:Transition from BDFM generator mode into synchronous mode

CH1 100mv/div CH2 2v/div 200ms/div

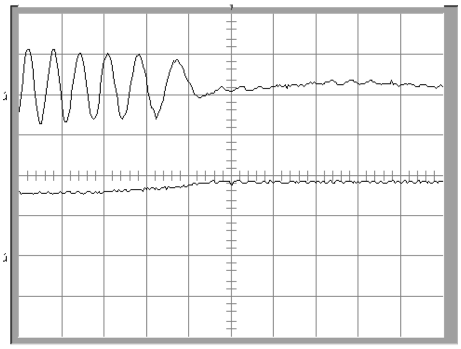


Fig 15: Transition from BDFM generator mode into an asynchronous motor mode

It is observed that once the I_C current value is less than a synchronous mode minimum, the machine no longer works in the synchronous mode and speed cup to 1455rpm corresponding to the asynchronous mode. The frequency of the rotor current becomes quite small (f_{rc}=0.92Hz).

CH1 100mvv/div CH2 2v/div 1s/div

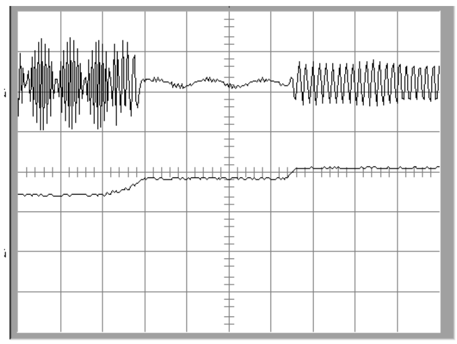


Fig 16:Winding control stator current and angular Speed duringtransition for different mode

CH1 1V/DIV CH2 100mv/div 20ms/div

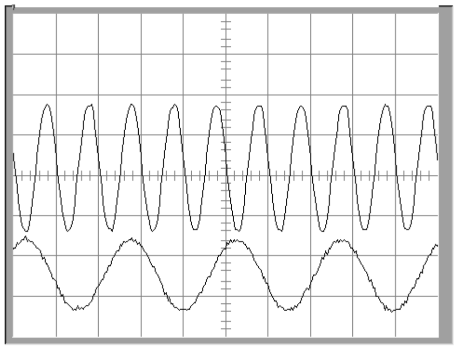
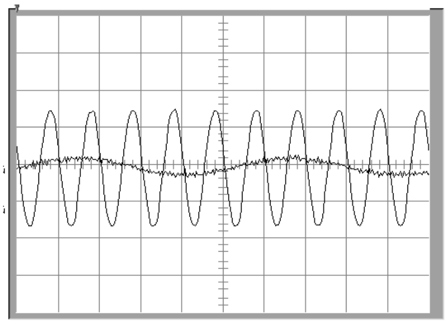
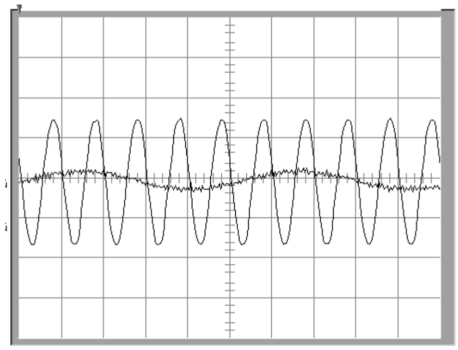


Fig 17: Close-up of both the rotor and the stator current in synchrounous mode



CH1 1V/DIV CH2 20mv/div 20ms/div

Fig 18: Zoom of stator and rotor current and following a drop of synchronous mode



CH1 1V/DIV CH2 20mv/div 20ms/div

Fig 19. Zoom of stators current in synchronous mode

CH1 1V/DIV CH2 100mv/div 20ms/div

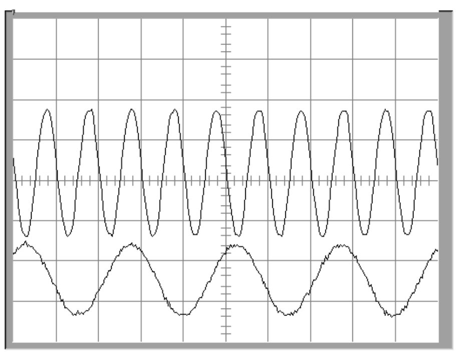


Fig 20: Zoom of winding power stator current $I_{sp}$and rotor current I_r in synchronous mode

Fig 19 shows the temporal values of the phase currents for both of the stator windings.

Fig.16. shows that once the synchronous speed is reached, the frequency of the BC corresponding to the synchronous mode of operation gets quite small (f_c =8.2Hz).

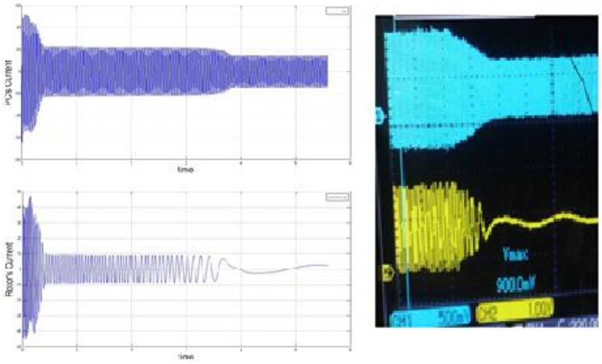


Fig 21:The Simulated and experimental stator and rotor current .

According to the figure 21, we can clearly see a complete concordance between practical results and the simulation results of the dynamic model.
From this point, if one increases the load torque there are no a stable operating point and the machine loses synchronism.
Thus , we can say that the BC current can be considered as an 'excitation current' and the synchronous operation mode is guaranteed if the BC is powered with the minimum I_c module necessary for torque of maximum load application.

VI.3ALLURES OF VARIOUS ELECTRICAL AND ELECTROMAGNETIC CHARACTERISTIC

VI.3.1 -Operate at a constant Excitation Current (I_c=0.6A)

BDFM characteristics taken and plotted using MicrosoftEXCEL

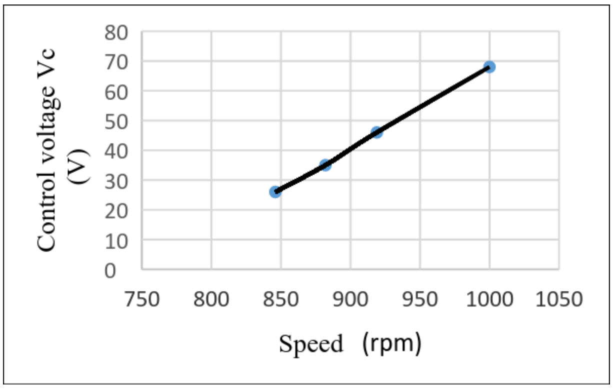


Fig 22: The control winding voltage changing with shaft speed

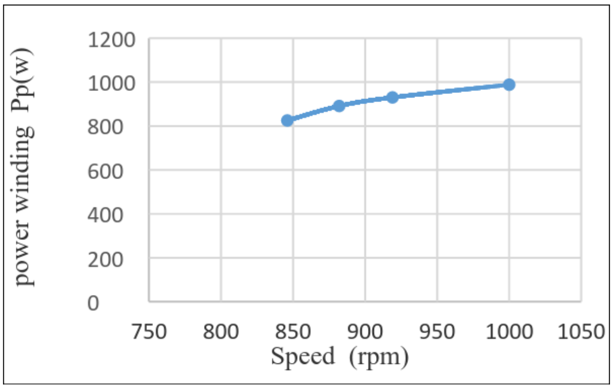


Fig 23: Active power of the stator winding changing S_p with shaft speed

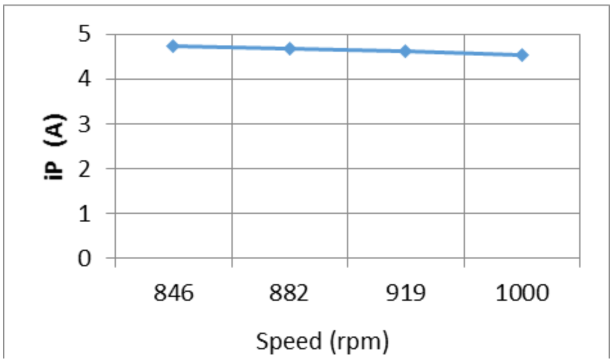


Fig 24: Thepower winding current changing with shaft speed

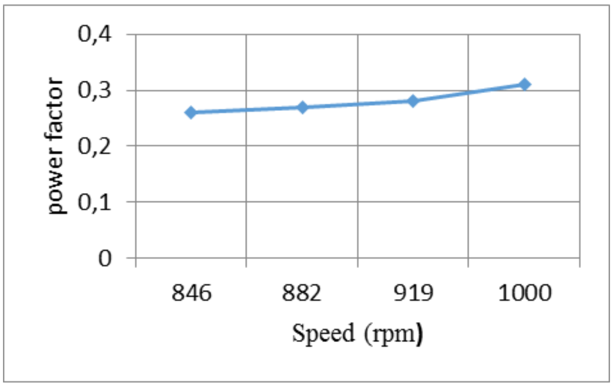


Fig 25: The power factor changing with shaft speed

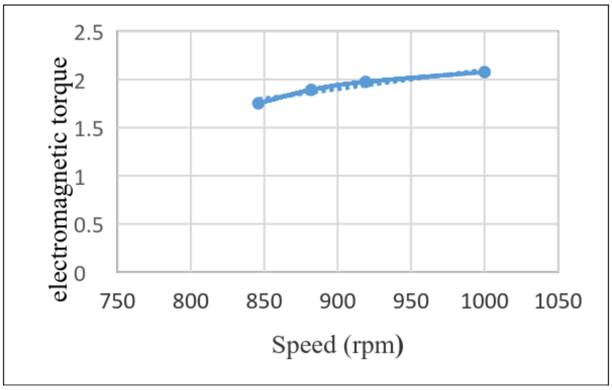


Fig 26: Generator torque

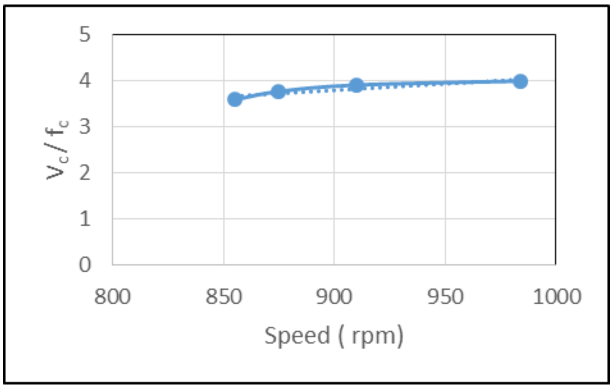


Fig 27:The ratioV_c/f changing with shaft speed

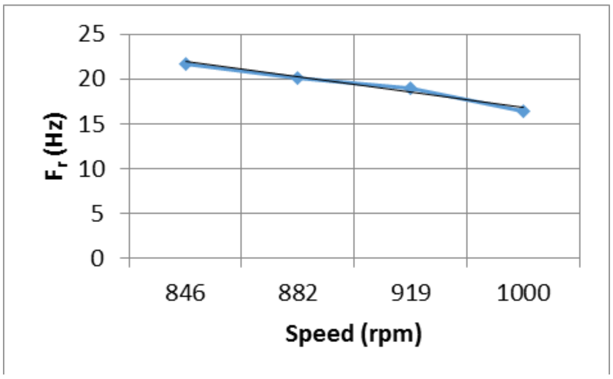


Fig 28: Variation of the rotor current frequency with the shaft speed

The fig.27-28 show that the control winding voltage grow linearly when the rotor speed repels of w_m (750 rpm) and the ratio V_c/f_c is held constant by the stated linear growth.

VI.3.2 Operating at constant rotor speed (1000 rpm)

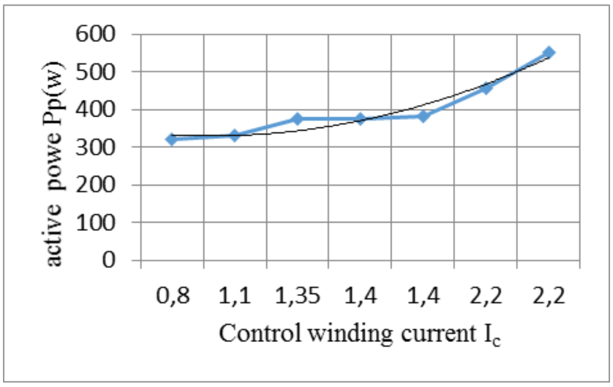


Fig 29 : The active power winding changing with Control winding current Ic

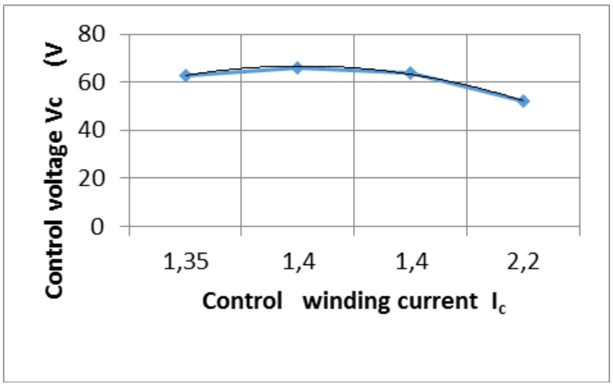


Fig 30 : The winding Control voltage V_c changing with Control winding current I_c with capacitive load

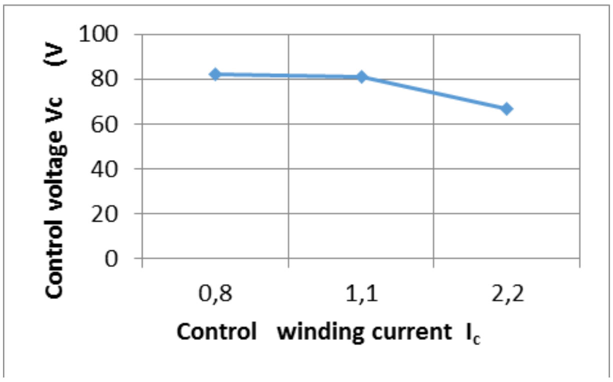


Fig 31: The winding Control voltage V_c changing with Control winding current I_c with resistive load

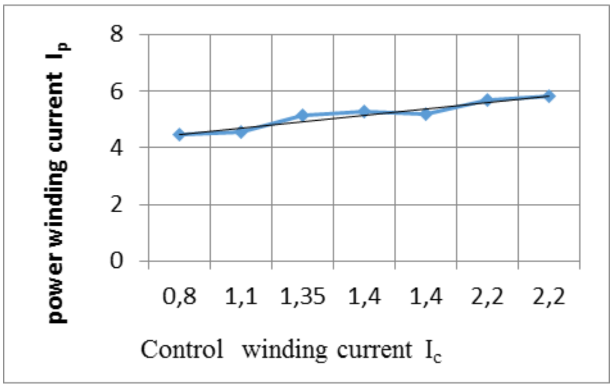


Fig32: the power winding current according with control winding current Ic

Figure 32 shows that**,** for a constant speed, the current of the power winding varies linearly with the excitation current ic.

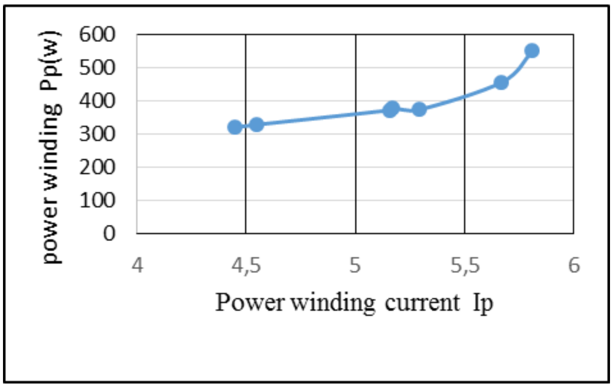


Fig. 33: Active power winding changing with power winding current Ip.

CONCLUSION

This article detailed the steady state characteristics of BDFM basing on experimental surveys. The BDFM was tested and controlled in open loop. As expected, the speed and power of BDFM can be controlled by adjusting the voltage applied to the CW.

The graphs obtained basing on the rotor speed confirm that the operation of the BDFM in synchronous mode is similar to that of the synchronous machine. The relations between currents allow us to establish an operating mode for vector control of high performance, in which BP would regulate the current by varying the BC current.

The tests described above is a necessary part for understanding the behavior of the machine and provide the basis for the development of robust control strategies for BDFM in closed loop.

Due to its reliability and robustness, BDFM is an interesting solution for applications of wind energy, it can and would be a very successful candidate to replace the wound-rotor induction machine [DFIG] due to its advantages and mainly the absence of a brush-collector system. It is a remarkable alternative to the slip ring induction motor for application in wind systems conversions which eliminates the need for brush- gear.

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