BRUSHLESS DOUBLY-FED INDUCTION MACHINE : OPERATING CHARACTERISTICS AND APPLICATIONS

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***Resumo* – O objetivo deste artigo é apresentar as principais características da máquina de indução duplamente alimentada sem escovas (" brushless doubly-fed machine"). Procura-se apresentar o seu princípio de funcionamento e indicar algumas possíveis aplicações. Ao final do artigo é apresentada uma bibliografia estendida visando permitir ao leitor um maior aprofudamento nas suas potencialidades.**

Abstract – **This paper presents the main characteristics of the brushless doubly-fed machine. Its principle of operation is described and some of its possible applications are indicated. An extend bibliography is provided in order to allow for a better understanding of its potentialities.**

I. INTRODUCTION

The development of power electronics providing more reliable and cheaper power converter units, along with the necessity for energy conservation , has promoted an increase in the use of adjustable speed drives and variable speed generators. However, more widespread use of such systems has been hampered by the cost of the power converter which is still high. Therefore there is a great interest in a system which reduces the converter rating requirements.

A system with this characteristic has been presented by Wallace, Spée and Lauw [1] and has been titled `brushless doubly-fed machine (BDFM) system'. The BDFM has been proposed as an option for an adjustable speed drive or a variable speed generator. In both cases the machine is part of a system which is represented schematically in figure 1. It is claimed that the BDFM system will provide the following features and advantages:

- reduced cost, compared to a conventional drive using a cage induction motor;
- precise synchronous operation over a wide speed range;
- possibility of working as a normal induction motor in case of power converter failure.

The aim of this paper is to present the main features of the BDFM system and provide the reader with a bibliography which will allow for a deeper understanding of its potentialities. Firstly a brief presentation of the machine operation is made. Then some characteristics of the system are presented and some possible applications are listed.
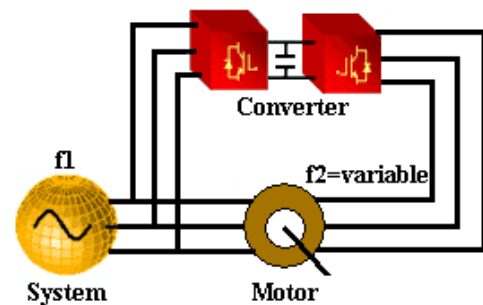

Fig. 1 Brushless Doubly Fed Machine System

II. BRUSHLESS DOUBLY FED MACHINE

The machine evolved from the self-cascaded machine proposed by Hunt [2]. At the beginning of the 20th century Hunt presented a self-cascaded machine, which incorporated the effect of two cascaded induction motors into one single frame. He showed that this could be accomplished by furnishing the stator with two three-phase windings of differing pole numbers, chosen so that no transformer coupling between them would occur. Being $2p_1$ and $2p_2$ the pole-numbers of the stator windings, the self-cascaded machine would be able to operate as an induction motor with ($p_1 + p_2$) poles. This required the rotor to be of a special design. The simplest rotor configuration consisted of furnishing the rotor slots with two three-phase windings of $2p_1$ and $2p_2$ poles. Those windings would be connected in series. Therefore current induced in the $2p_1$-pole rotor winding will also flow in the $2p_2$-pole rotor winding, producing a $2p_2$-pole field which will interact with the $2p_2$-pole stator winding. The reverse is also true. Hunt also showed that better performance could be achieved by using only one stator winding with terminals for operation as a $2p_1$- and $2p_2$-pole winding. He also presented how a single rotor winding could be used to couple with both stator fields.

Hunt's machine was later re-examined by Creedy [3] who presented an elegant 2/6 poles stator winding system. This winding configuration was used in several self-cascaded machines and in early BDFMs. Creedy also presented a simplified rotor winding.

Smith [4,5] presented a `twin stator induction machine' where the stator windings were magnetically independent but could share a common rotor. Later he indicated that both stator windings could share the same magnetic circuit and suggested that a converter of a rating lower than the machine could be connected to one of the stator windings to extract slip power from the rotor by induction [6]

Undeniably, a significant step was taken by Broadway and Burbridge [7] when they identified that cross-coupling of the stator fields would occur with a cage rotor with N_r bars where $N^r = p_1 + p_2$. That would render a more robust and manufacturable rotor. They also showed that, with the machine running near the cascade speed, supplying the other winding with direct current would make the machine pull into step and run synchronously.

Investigation of the operation of the self-cascaded machine connected to a power electronic converter has been carried out by Cook and Smith [8,9,10], Kusko and Somuah [11], Perera and Smith [12] and Shibata and Taka [13]. Although these works investigated different aspects of the machine operation, they had in common the fact that they used models derived directly from the cascade connection of two induction motors.

The brushless doubly-fed machine system, as presented in figure 1 was proposed by Lauw [14] for use as a variable speed generator. Shortly after, Wallace, Spée and Lauw presented the BDFM as a candidate for an adjustable speed drive [1,15].

The stator is furnished with two three-phase windings of different pole numbers, $2p_1$ and $2p_2$. As both windings share the same magnetic circuit, special care has to be taken when choosing the number of poles of each winding in order to avoid direct (transformer) coupling between them. Also, in order to avoid unbalanced magnetic pull, the difference between the number of poles must be greater than 2. The cylindrical rotor carries $(p_1 + p_2)$ sets of concentric loops, as will be discussed below. Generally, one stator winding is connected directly to the supply and the other is supplied from a power electronic converter. Full use of the machine's capabilities is achieved if a bi-directional, variable-frequency, variable-voltage converter is used. However, for some applications the requirements for the converter may be simplified. The key feature for the BDFM operation is the coupling between both stator windings via the rotor. This imposes certain restraints on the rotor design and that is investigated below.

A. Principle of operation

The torque production in cylindrical rotating electrical machines requires the fields produced by the stator and rotor to have the same number of poles and to be stationary with respect to each other. These requirements can be used to control the speed of the machine. Generally, if the rotor currents produce a field which rotates at angular velocity f' with respect to itself, that field will be seen by an observer stationary with respect to the stator as having an angular velocity f, in revolutions/second, given by $f = f_r + f'$, where f_r is the rotor angular velocity. In order to produce steady torque, f must equal the angular velocity of the stator field f_s.

For instance, suppose a wound rotor induction motor, with $2p_1$ poles and supplied at frequency f_1. If the rotor is also wound for $2p_1$ poles and the current flowing in it has a frequency f_2, the field produced by this current will rotate with respect to the rotor with a mechanical angular velocity

$$f' = \pm \frac{f_2}{p_1}, \qquad (1)$$

where the + or - signs depend on the sense in which the rotor field rotates. If both stator and rotor fields rotate in say the clockwise direction with respect to their corresponding members, the sign is positive, as it is if both rotate anti-clockwise. If one is clockwise and the other anti-clockwise, however, then the sign is negative. The required mechanical rotor speed may now be calculated using

$$f_r = \frac{f_1 \pm f_2}{p_1}. \qquad (2)$$

Therefore, if the frequency of the rotor current can be controlled by external means, so can the rotor speed. This speed is referred to as the *synchronous speed* and the machine is said to be operating synchronously. If a power electronics converter is used, this arrangement has the advantage in that only the slip power must be processed by the converter, thus reducing the cost of the system. It has however the disadvantage in that it requires the use of slip rings, which increase the cost and reduce the robustness and reliability of the system. The possibility of controlling the frequency of the rotor currents without the need of slip rings is quite attractive and that is the idea behind the brushless doubly fed machine.

It has already been pointed out that some restrictions are imposed on the rotor in order to obtain synchronous operation. These restrictions may now be identified [16]. Assume, in the first instance that the rotor carries a standard cage design, with N_r bars, equally spaced. The two stator windings are assumed to be ideal (i.e. no stator space mmf harmonics) and carry pure sinusoidal currents. These windings will set up airgap fields, which can be expressed in the stator reference frame by

$$b_1(\theta,t) = \hat{B}_1 cos(\omega_1 t - p_1\theta + \alpha_1), \text{ and}$$

(3)

$$b_2(\theta,t) = \hat{B}_2 cos(\omega_2 t - p_2\theta + \alpha_2), \qquad (4)$$

where, ω_1 and ω_2 are the excitation angular velocities (rad/s) of winding 1 and 2 respectively. α_1 and α_2 are phase angles. B_1 and B_2 are the peak values of the magnetic flux densities. $b_1(\theta,t)$ and $b_2(\theta,t)$ are the instantaneous values of the magnetic flux densities at an instant of time t and at a position θ around the airgap. The fields described by (3) and (4) will induce currents in the rotor bars and these currents

will in turn produce airgap fields, which can be expressed in the rotor reference frame by

$$b_1 {}^{p_1 - q_1 N_r}(\theta', t) = \hat{B}_{r1} \cos\left((\omega_1 - p_1 \omega_r)t - (p_1 - q_1 N_r)\theta' + \alpha_{q1}\right) \quad (5)$$

and

$$b_2 {}^{p_2 - q_2 N_r}(\theta', t) = \hat{B}_{r2} \cos\left((\omega_2 - p_2 \omega_r)t - (p_2 - q_2 N_r)\theta' + \alpha_{q2}\right) \quad (6)$$

where ω_r is the rotor angular velocity (rad/s) and α_{q1} and α_{q2} are phase angles. q_1 and q_2 are integers. θ' is measured with respect to a reference frame, which is fixed to the rotor. Values of q_1 and q_2 other than zero are the rotor slot harmonics. Equation (5) shows that the current induced in the rotor by an airgap field of $2p_1$ poles will produce not only a flux of $2p_1$ poles but also fluxes of $2(p_1 - N_r)$, $2(p_1 + N_r)$, $2(p_1 - 2N_r)$, $2(p_1 + 2N_r)$ poles, etc. The second stator excitation similarly results in rotor slot-harmonic fields of $2(p_2 - N_r)$, $2(p_2 + N_r)$, $2(p_2 - 2N_r)$, $2(p_2 + 2N_r)$… poles.

The rotor fields given by (5) and (6) can be expressed in the stator reference frame, using the co-ordinate transformation $\theta = \omega_r t + \theta'$.

Steady torque will be produced if one of the slot-harmonic fields, arising from the second stator excitation (i.e. $q_2 \neq 0$), interacts with the fundamental field produced by the first ($q_1 = 0$). Equating frequencies and pole numbers, as required, yields

$$\omega_2 - q_2 N_r \omega_r = \omega_1 \quad \rightarrow \quad \omega_r = \frac{\omega_1 - \omega_2}{-q_2 N_r} \quad (7)$$

and

$$p_2 - q_2 N_r = p_1 \quad \rightarrow \quad -q_2 N_r = p_1 - p_2. \quad (8)$$

Substituting from (8) into (7) yields

$$\omega_r = \frac{\omega_1 - \omega_2}{p_1 - p_2} \quad \rightarrow \quad f_r = \frac{f_1 - f_2}{p_1 - p_2}. \quad (9)$$

The same analysis may be carried out on the assumption that a slot-harmonic field produced by the first excitation interacts with the fundamental field due to the second, and will give the same result as in (9). For practical values of p_1 and p_2, values of q_1 and q_2 other than unity will produce a rotor cage with a very small number of bars. Therefore (8) may be rewritten as $|p_1 - p_2| = N_r$, which gives the requirements for the number of rotor bars in order to have the BDFM operating synchronously. Equation (9) gives the associated synchronous speed and suggests that changing one of the stator frequencies can control the rotor speed. If ω_r, from (9), is substituted into (5) and (6), it can be shown that for synchronous operation the rotor fields and therefore the currents induced by both stators windings must have the same frequency.

Another condition for the synchronous operation arises if it is noted that (6) may also be written as using cosθ=cos-θ. Equating the frequency and displacement terms and carrying out the same analysis as before, yields a new set of rotor requirements and synchronous speed. Therefore, for a given pair of stator frequencies there are two rotor configurations that allow for the machine to run synchronously. Each one of these configurations requires a different rotor speed

- Condition 1

$$N_r = |p_1 - p_2| \quad and \quad \omega_r = \frac{\omega_1 - \omega_2}{p_1 - p_2}, \quad (10)$$

- Condition 2

$$N_r = |p_1 + p_2| \quad and \quad \omega_r = \frac{\omega_1 + \omega_2}{p_1 + p_2} \quad (11)$$

For practical values of p_1 and p_2 it is more convenient to choose N_r as given by Condition 2 because it results in a cage with higher number of bars. However by choosing the number of bars according to one of the conditions above will not render the other condition redundant. Assume that, in (3) and (4), ω_1, ω_2 and p_1 can only have positive values and allow p_2 to have positive or negative values. Then (3) and (4) indicate that for positive values of p_2 both stator fields rotate in the same direction in the stator reference frame. For negative values of p_2 those fields rotate in opposite directions. Indeed a negative value of p_2 indicates that winding 2 is being excited in reverse sequence to that of winding 1.

If the machine has a cage with the number of rotor bars equal to the sum of the number of pole-pairs of the stator windings, then when both stator fields are rotating in the same direction ($p_2 > 0$), $p_1 + p_2 = N_r$ and Condition 2 applies. If the phase sequence of winding 2 is reversed ($p_2 < 0$) then $p_1 - p_2 = N_r$ and now Condition 1 applies. Therefore the rotor speed for synchronous operation can be calculated by

$$\omega_r = \frac{\omega_1 \pm \omega_2}{N_r}. \quad (12)$$

The positive sign arises when both stator fields rotate in the same direction in the stator reference frame. On the other hand, the negative sign arises when they rotate in opposite directions. It may be noted that if winding 2 is excited with direct current ($f_2 = 0$), (12) gives the synchronous speed of the cascade connection of two induction motors. However, the main purpose of the BDFM is to change the synchronous speed by varying the frequency f_2. Therefore in this work the term *synchronous speed* refers to the rotor speed which is given by (12). The speed obtained when $f_2 = 0$ is referred to as the *natural speed* [17]. Then, if the stator fields rotate in the same direction with respect to the stator, the machine will operate above the natural speed and if the fields counter-rotate the machine will operate below the natural speed. The same analysis can be carried out for the case where the number of rotor bars is calculated from the difference of the number of poles.

B. Rotor configurations

Whatever the way N_r is chosen, for any realistic combination of pole-pair numbers p_1 and p_2 it will result in a cage rotor with a low number of bars, yielding a very high referred rotor leakage reactance [7]. As pointed out by

Broadway, the referred rotor leakage reactance decreases as the number of rotor slots is increased from a low value. Therefore steps must be taken in order to increase the number of rotor slots while still complying with the requirements of the effective number of rotor bars. Fig. 2, Fig. 3 and Fig. 4 present three typical BDFM rotor configurations in which this is achieved. In Fig. 2 the rotor bars are connected to produce a set of nests, each formed of a number of individual concentric loops. In Fig. 3 all the loops are connected at one end to a common end-ring. In Fig. 4 the outermost loops of each nest form a cage with N_r bars. The other loops are connected to one common end-ring.
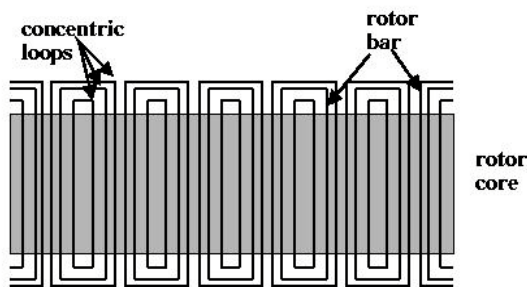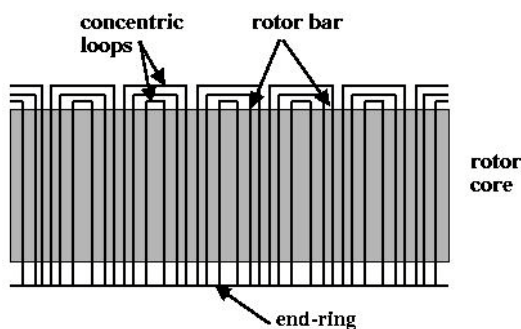

Fig. 2. BDFM rotor configuration 1

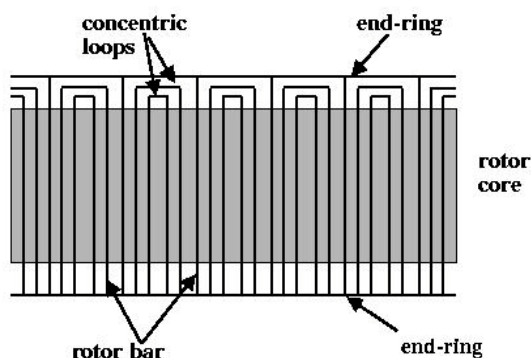Fig. 3. BDFM rotor configuration 2

Fig. 4. BDFM rotor configuration 3

III.   BDFM CHARACTERISTICS

This section will present some of the BDFM characteristics when operating at synchronous speed. In this analysis, the winding connected direct to the supply is referred to as *power winding* or *winding 1*, and the winding

fed from a converter is referred to as *control winding* or *winding 2*. The simulations were carried out with a steady-state model developed previously [16,18].

A.   Power balance

The division of power between the stator windings is related to the frequency at which they excited. Neglecting all the copper losses we may write:

$$\left|\frac{P_1}{\omega_1}\right| = \left|\frac{P_2}{\omega_2}\right| = 3\frac{V_1 V_2}{L\,\omega_1\omega_2}\sin\delta, \qquad (15)$$

where P_1 and P_2 are the power flowing in windings 1 and 2, V_1 and V_2 are the rms voltages applied to the windings, ω_1 and ω_2 are the angular frequency of the voltages, L is an inductive term and δ is a load angle. Although the relationship presented in (15) is modified when copper losses are taken into account, the general concept that the winding that is supplied at higher frequency carries more power still holds. This can be seen in Fig.5 and Fig. 6, where winding 1 is supplied at 50 Hz and winding 2 at 30 Hz. Those figures suggest that if winding 2 is supplied at low frequencies (e.g. 0 − 5 Hz), the converter may be rated for a fraction of the total system rating.

B.   Effect of converter on performance limits

It was shown in the previous section that for operation in a limited speed range, the converter used in the DFM system might have a reduced rating compared to the overall system rating. Also of interest is the effect of the converter on the drive performance. A first insight into this effect may be get from Fig. 7, which shows plots of calculated maximum torque as a function of speed and maximum voltage in winding 2. The stator currents were limited to 20 A due to thermal considerations and winding 1 was supplied at 100 V. Fig. 7 shows that the machine has almost the same torque capability operating either as a motor or as a generator. It can also be seen that the major effect of limiting the voltage of winding 2 is to determine the range of operating speeds. However it does not affect the maximum torque available. Fig. 7 also shows symmetry about a line drawn through the speed of 500 rpm. That speed may be recognized as the natural speed of the machine, where winding 2 is supplied with DC current.

Fig. 7 also shows the effect of imposing a stricter limit on the current in winding 2. Namely the maximum current allowed was reduced from 20 A to 10 A, and the figure shows a reduction on the maximum torque.
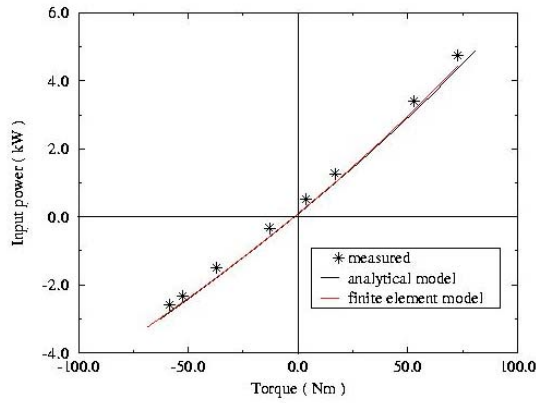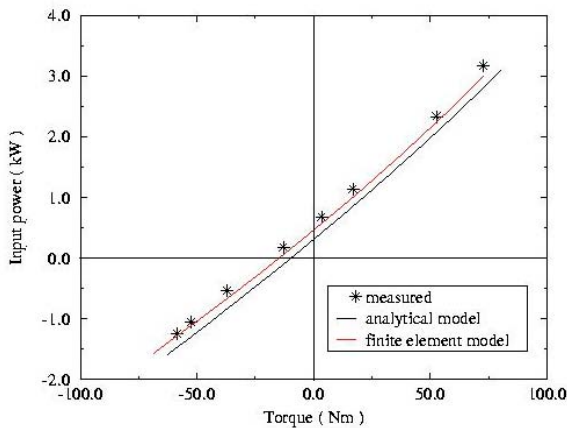
Fig. 5. Winding 1 input power
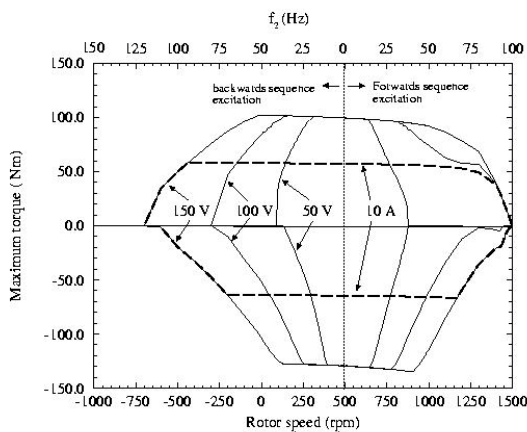

Fig. 6. Winding 2 input power

Fig. 7. Maximum torque/rotor speed limits for the BDFM

C. *Power flow in the control winding*

The operation over the full operating limits of Fig. 7 would require the use of a bi-directional converter. A further step in order to reduce the cost of the BDFM system may be taken if a unidirectional converter could be used. It can be shown that, to a good approximation, the direction of power flow in the control winding depends on the quadrant in which the drive is operating, i.e. above/below the natural speed and generating/motoring. This implication can be better illustrated in Fig. 8, which depicts one of the torque-speed characteristics presented in Fig. 7. In this case

$V_1=V_{2max}=100V$ and $I_{1max}=I_{2max}=20A$. The (+) and (-) signs indicate the direction of power flow in the converter, where the plus sign indicates that power is flowing into the BDFM and the minus sign indicates that power is being extracted from the machine to the system as in a slip-energy recovery mode.

D. *Power factor control*

The BDFM was developed from the concepts used in induction motor design. However, when operating synchronously, it behaves like a synchronous machine. In this sense, Fig. 5 and Fig. 6 indicates that the input power to each stator winding has a closely linear relationship to the load applied to shaft. Furthermore, a load-angle characteristic is suggested in (15). If the parallel between the BDFM and a synchronous machine is to be completely established, the machine should provide means of power factor control.

This can be seen in Fig 9 which shows how the reactive power in winding 1 is affected by a variation of the voltage applied to winding 2. In this case the machine is running with no mechanical load connected to its shaft. It is easy to relate the curves presented in Fig. 9 to the V-curves of synchronous machines. The voltage in winding 2 acts as the field winding in a synchronous machine.
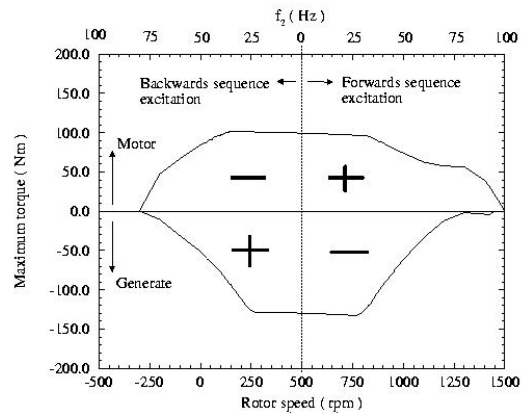

Fig 8. Operating quadrants for the BDFM related to power flow in the converter
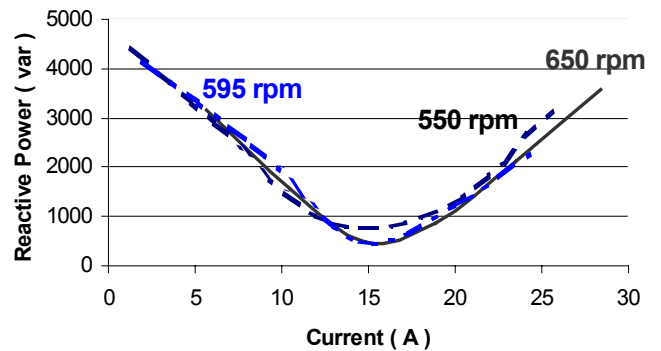

Fig. 9. V-curves of a BDFM

V SOME BDFM ISSUES

Over the past years, several papers have been published, addressing various issues related to the BDFM system. In the following sections some of these issues will be outlined.

A. Modelling of the BDFM

In order to simulate the machine performance, its interaction with the converter and also to explore design alternatives, a detailed dynamic model was presented by Wallace et al. [19,20]. The detailed model was then simplified to a two axis model [21,22] which was used to analyse the stability of the BDFM [23]. The two-axis model, however, only allowed the simulation of a machine with stator windings of the combination 6/2 pole numbers and lumped the rotor circuits in a two-axis representation. Those two factors denied the model as a tool to investigate design alternatives.

In 1993 Perera and Smith [24] presented a model which accommodated any pole numbers combination. In addition, the currents in each rotor circuit were readily available. Boger et al. [25] extended the two-axis model to a `general pole number' model. This model, whilst being a significant improvement, still denied the determination of the currents flowing in each rotor circuit. This model was later improved in order to determine the rotor current [26].

The drawback of the last two models is that they only take the fundamental fields into account. Therefore they cannot be used during design to eliminate unwanted harmonics. Williamson, Ferreira and Wallace [16], presented a rigorous analytical model based on general harmonic theory. This model has been validated against a prototype machine and has been shown to give very good predictions when the machine is excited at low voltages [18]. A time-stepping finite-element model was also presented that could represent the effect of saturation [27]. It was shown that this model coul readly accommodate the calculation of iron losses.

B. Applications

The BDFM has been proposed as an adjustable speed drive or a variable speed generator [1][7][28]. As presented in Section III the converter rating will depend on the speed range. Therefore the proposed applications are those where the machine will operate in a limited speed range, such as pump drives [29,30,31,32] and wind generators [33,34,35].

C. Cost

The cost of a BDFM system will depend on the cost of the converter and the cost of the machine itself. The cost of the converter will depend on its type and rating. As indicated in (15), the rating of the converter is directly related to the speed range required by the application, whilst for a conventional induction motor drive the converter would be rated for 100 % of the machine being controlled. The type of the converter will also depend on the application. Generally a bidirectional converter would allow for full use of the machine's capability. However, as indicated in Fig. 8, for some applications an unidirectional converter may be adequate, thus further reducing the cost.

As for the cost of the machine, it is the author's opinion that a comparison with a conventional induction machine, manufactured in large scale, is not straightforward and no attempt will be made in this paper and the readers are referred to [36]. However, some points may be highlighted:
- in order to reduce the cost, if large scale manufacturing is envisaged, the rotor should be diecast, which will require some modification in the casting process;
- as the two windings share the same magnetic path, some care will have to be taken in order to avoid excessive saturation, resulting in oversized stator and rotor laminations when compared to a conventional induction machine of the same output power.

VI CONCLUSIONS

The paper has presented the main characteristics of a system using a brushless doubly fed machine.

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