The BDFM as a Generator in Wind Turbines

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Abstract—The Brushless Doubly-Fed Machine (BDFM) is attractive for use in wind turbines, especially offshore, as it offers high reliability by virtue of the absence of brush-gear. Critical issues in the use of the BDFM in this role at a system level include the appropriate mode of operation, the sizing of associated converter and the control of the machine. At a machine level, the design of the machine and the determination of its ratings are important. Both system and machine issues are reviewed in the light of recent advances in the study of the BDFM, and preliminary comparisons are made with the well-established doubly fed wound rotor induction generator.

I. INTRODUCTION

The generation of electrical power from wind energy is a proven technology. There is already a substantial installed capacity in a number of countries and new capacity is being continually added. Various designs of wind turbines have been proposed but horizontal axis, three-bladed machines with a capacity from 600 kW to 3MW or above is the currently preferred option. In these machines a variety of architectures is used, including direct drive, in which the turbine is directly coupled to a low speed generator, and indirect drive, with the turbine coupled through a gearbox to a high speed generator. There is only one large manufacturer of direct drive turbines and they have a significant installed capacity, especially in northern Europe. However, the majority of wind turbines in the world employ the indirect drive architecture. In these machines, generation is normally from a slip-ring induction machine. As the gearbox gives an increased shaft speed, a four or six pole machine can be used. The stator of the generator is connected directly to the fixed voltage, fixed frequency electricity grid and the rotor is supplied through the slip rings with a variable voltage, variable frequency supply generated from a converter.

This form of double feed enables generation to take place over a range of turbine speeds and provided that the range of speeds is moderate, the converter rating need only be a fraction of the total generator output thereby keeping the system cost low yet retaining a reasonable level of reliability. The converter rating is generally about one third of the rating of the generator, allowing speed variations of ±33%. Varying the voltage supplied to the rotor can be used to manage the reactive power flow from the generator. Control schemes have also been developed to enhance the response of the system to changing wind speed and to accommodate varying grid conditions.

However, there are drawbacks to the use of slip ring induction generators, particularly the additional cost and bulk of a machine which incorporates slip rings and the need to maintain brush-gear and to replace brushes on a regular basis. Studies have shown that the reliability of large wind turbines is improving but that faults with generator and converter sub-assemblies contribute significantly to turbine failure rates [1]. Further studies have shown that problems with brush-gear are a significant issue in wind turbine operation and that the problem will be more severe in machines deployed offshore where additional wind resources are available [2].

The Brushless Doubly-Fed Machine (BDFM) is an interesting alternative to the slip ring induction motor which eliminates the need for brush-gear. The BDFM, alternatively known as the self-cascaded machine, is one of a class of doubly fed machines which includes the slip ring induction machine [3]. The key to the machine is the use of two stator windings of different pole numbers, chosen so that there is no direct coupling between them, in combination with a special form of rotor which can couple both fields. This form of self-cascaded machine was patented by Lydall in 1903 [4] and following improvements by Hunt [5] enjoyed a degree of commercial success.

Burbridge and Broadway re-examined the machine and proposed new concepts in the design of the rotor winding and, importantly, proposed the use of double feed, that is the connection of one stator to the fixed frequency mains and the supply of the second stator with an converter giving a variable voltage, variable frequency supply [6]. With double feed, the machine can act in a synchronous mode with a shaft speed related to the two excitation frequencies. Later work by Wallace, Spee and others led to the development of the BDFM in its contemporary form; indeed the term BDFM is due to them. Their interest was very much focused on the use of the BDFM as a variable speed generator for wind generation [7] and, to a lesser extent, on variable speed drive applications such as pumping [8].

Several BDFMs have been constructed in recent years, including the 182 frame size machine used by Brune et al. [7], the 160 frame size machine reported by Williamson and Ferreira [9] and a similar size machine by Roberts et al. [10].
The largest machine appears to be the 100 kW 12/8-pole machine reported by Rüncos et al. [11] but few details are given. Nevertheless, only recently has attention been given to issues such as the design of the machine, its ratings and its operation as a system component. In this paper these, and other relevant issues, are explored for the use of the BDFM as a replacement for doubly fed induction generators for wind turbines, particularly in an offshore environment.

II. BASIC SYSTEM CONFIGURATION

A BDFM can operate in several modes but the synchronous, or doubly fed, mode is used for controlled variable speed operation. In this arrangement, shown in Fig. 1, one winding, the power winding, is connected directly to the mains or grid. The other winding, the control winding, is supplied with variable voltage at variable frequency from a converter connected to the mains or grid. Details can be found in [9], [10].

![Fig. 1. BDFM system configuration](image)

Stator and rotor quantities are shown for the synchronous mode in Fig. 2. The shaft angular velocity is given by

\[
\omega_r = \frac{\omega_1 + \omega_2}{p_1 + p_2}
\]

where \(\omega_1\) and \(\omega_2\) are angular frequencies of the supplies to the power winding (\(p_1\) pole pairs) and the control winding (\(p_2\) pole pairs) respectively, and slips \(s_1, s_2\) for the two windings can be defined as

\[
s_1 = \frac{\omega_1 - \omega_1 \omega_r}{\omega_1}
\]

\[
s_2 = \frac{\omega_2 - \omega_2 \omega_r}{\omega_2}
\]

A further relationship for the so-called natural speed \(\omega_n\), that is the synchronous speed when the control winding is fed with dc, is given by

\[
\omega_n = \frac{\omega_1}{p_1 + p_2}
\]

III. EQUIVALENT CIRCUIT FOR THE BDFM

The analysis of the performance of the BDFM as a generator is greatly aided by the use of an equivalent circuit, and a form due to Roberts et al. is shown in Fig. 3 [10]. Quantities are shown referred to the power winding and iron losses are neglected. The circuit is valid for all other modes of operation, including the synchronous mode. Most parameters are as found in a standard induction machine but the referred rotor reactance \(L_r'\) will be relatively larger than that for a standard cage rotor machine. The design constraints on the rotor generally lead to a larger harmonic, or differential, leakage component than normal and this component is likely to be the largest component of rotor leakage inductance. Furthermore, with complex rotors, such as the nested loop design, the presence of multiple sets of independent rotor circuits means that the bulk equivalent circuit parameters associated with the rotor change with rotor frequency, but these changes are normally not significant.

![Fig. 2. BDFM synchronous mode of operation](image)

![Fig. 3. BDFM Referred Per-Phase Equivalent Circuit](image)

![Fig. 4. Alternative Referred Per Phase Equivalent Circuit](image)

In general, values for parameters can be found by analysis, numerical simulation or experimental determination. In the case of the BDFM not all the parameters can be found from terminal measurements so an alternative, but electrically equivalent, form of circuit has been proposed, shown in Fig. 4 [10]. The equivalent circuit as shown assumes that the saturation of the iron circuit, if it occurs, does not significantly affect parameter values. The parameters are defined in Table I.
The equivalent circuit can be simplified for a core or ideal BDFM. Noting that the rotor reactance is likely to dominate the overall rotor impedance leads to a core BDFM as shown in Fig. 5(a). In an ideal BDFM, the rotor impedance will be zero and that leads to the model in Fig. 5(b). These simplified models are useful in deriving certain benchmark results.

From Fig. 5(a) the equation for the synchronous component of BDFM torque, \( T \), can be derived:

\[
T = \frac{3|V_1 V_2'| s_2}{\omega_n |\omega_1 L_1' s_1|} \sin \delta \tag{5}
\]

where \( \delta \) is the load angle.

The widely quoted relationship relating the power in the control winding, \( P_2 \), to that in the power winding, \( P_1 \), is obtained from the circuits in Fig. 5.

\[
P_2 = P_1 \frac{\omega_r}{\omega_n} \tag{6}
\]

### IV. PARAMETER EXTRACTION

Parameters for the equivalent circuit can be calculated or measured experimentally. If calculated it is desirable to confirm values experimentally. Some parameters are relatively straightforward to measure, for example the resistances of the two stator windings by dc measurements, although allowance must be made for temperature changes. The magnetizing reactances of the two stator windings can be measured by driving the BDFM externally at the appropriate synchronous speeds. The extraction of further parameters is not easy but a method based on fitting to measured torque speed curves is given by Roberts et al. [10]. The referred rotor resistance and reactance can be obtained as well as the ratio of the turns ratios for the two couplings of different pole number.

A complete set of parameters is then available for the equivalent circuit of Fig. 4. Unfortunately, measurements at the machine terminals do not allow the independent determination of the two stator leakage reactances. However, if rotor quantities can be measured, then they can be determined. Abdi Jalebi et al. have shown how this is possible using wireless transmission of current measurements by Bluetooth [12]. The ability to separate parameters has the advantage of being able to compare stator leakage reactances with manufacturers’ estimates.

Parameters can also be obtained by calculation and this is particularly useful for the inductances and rotor resistance. Williamson et al. provide a method of machine analysis based on the harmonic decomposition of machine mmfs [13]. Although the method was described in the context of a machine with a nested loop rotor, the method of analysis is applicable to other rotor designs. An alternative approach based on coupled circuits was described by Wallace et al. [14] and this was developed and generalized by Roberts to enable parameter values to be found for BDFMs with different rotor configurations [15]. Kroitzsch and Riefenstahl have also recently applied coupled circuit analysis to the study of cascaded machines, including the BDFM [16].

Finite element methods can also be used to analyse electrical machines and they can take into account saturation. The time stepping approach has been used by Ferreira et al. [17] and more recently by Jagiela et al. [18]. However, this type of numerical analysis does not yield parameter values directly and so far have not been used to generate parameter values. In addition, there are some special issues in the BDFM relating to the field pattern which are described later.

### V. GENERATOR OPERATION

The BDFM is operated as shown in Fig. 1. Under these conditions the power winding voltage and frequency are fixed. The control winding frequency is set by the shaft speed by equation (1). The real power flow is determined by the mechanical input power, i.e. the torque multiplied by the shaft’s angular velocity, less losses in the machine. The remaining variable is the control winding voltage which controls the flow of reactive power, as in a conventional synchronous machine. However, the flow of VArS is subject to an amplification factor, that is the ratio of VArS generated in the power winding to the input VArS on the control winding, which falls with increasing speed deviation. The flow of VArS has a major effect on the rating of the machine and associated converter or, put another way, the real power that a machine of fixed rating can handle is influenced by the reactive power regime.

An illustration of the control of reactive power is given in Fig. 6. The power winding VArS have been calculated using the core model of Fig. 5 (a) and the equivalent circuit of Fig. 4 for generating at 750 rpm with a driving torque of 25 Nm. The machine is the frame size 180 machine described in [10]. The progressive reduction to zero of the lagging VArS drawn by the power winding and the subsequent rise in VArS exported as the control winding voltage is increased is seen. The effect of stator impedances and magnetizing reactances make the actual control winding voltage greater than that predicted from the core model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Power winding</th>
<th>Control winding</th>
<th>Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>( R_1 )</td>
<td>( R_2' )</td>
<td>( R_r )</td>
</tr>
<tr>
<td>Inductance</td>
<td>( L_1 )</td>
<td>( L_2' )</td>
<td>( L_r' )</td>
</tr>
<tr>
<td>Magnetizing</td>
<td>( L_m )</td>
<td>( L_m' )</td>
<td>-</td>
</tr>
<tr>
<td>Turns ratio to rotor</td>
<td>( N_1 : 1 )</td>
<td>( N_2 : 1 )</td>
<td>-</td>
</tr>
</tbody>
</table>

### TABLE I

**DEFINITION OF PARAMETERS**

- \( P \): Power winding, \( I_1 \): Control winding voltage greater than that predicted from the core model of Fig. 5 (a) and the equivalent circuit of Fig. 4 for generating at 750 rpm with a driving torque of 25 Nm.
- \( V_1 \), \( V_2 \): Stator windings by dc measurements, although allowance must be made for temperature changes.
- \( \omega_n \), \( \omega_1 \): Angular velocities.
- \( s_1 \), \( s_2 \): Load angle.
- \( \omega_r \): Angular velocity, less losses in the machine.
- \( T \): Mechanical input power.
Fig. 6. The control winding VAr changing with the power winding VAr. The power winding voltage is fixed at 120 Vrms. Negative sign of the VAr stands for absorbing VAr from the grid; positive sign of the VAr stands for providing VAr to the grid.

Although the ability to export VAr to the grid appears attractive, it does require the VA rating of the machine to be increased, assuming a constant power output. The increase in the rating of the power winding depends on the load power factor and the increase in the rating of the control winding will reflect the parameters of the particular machine. The effect on the control winding is dependent on the speed deviation from natural speed as a result of the VAr amplification effect. This derating is likely to be modest up to a speed deviation of say 25%, but above a deviation of say 75% the derating is severe and in reality more than one VAr on the control winding may be needed to provide one VAr on the power winding. The effect of VAr generation on available power generating capacity is shown in Fig. 7. For the same conditions as in Fig. 6, viz. a shaft speed of 750rpm and a driving torque of 25 Nm, the power output of the BDFM relative to the maximum power is plotted as a function of control winding voltage. Plots using the core model of Fig. 5(a) and the equivalent circuit of Fig. 4 are shown. The figure shows that the power handling of the machine is compromised by both under and overexcitation of the control winding, as expected. The degree of excitation has therefore to be chosen with care.

VI. CONVERTER ISSUES

Varying the control winding voltage affects the rating of the inverter supplying the control winding as well as the rating of the winding itself. The link between the grid and the control winding will be a bi-directional converter. The machine-side inverter will handle real power and reactive power and will be matched to the control winding. In contrast, the line-side inverter need only transfer real power, and therefore in principal could have a lower rating. The ratings of the two inverters are shown in Fig. 8 as a function of speed deviation. The operating conditions are 120 Vrms on the power winding, a load torque of 25 Nm and the control winding voltage is adjusted to give unity power factor on the power winding. Note that this condition involves transfer of VAr to the control winding to supply the magnetizing VAr. The line side inverter is equal to the real power transferred to the mains.

The results show that power factor correction, that is the transfers of VAr to the power winding in this case, comes at a substantial penalty in machine-side inverter rating, and that penalty becomes larger the greater the speed deviation. An alternative strategy is to supply some VAr to the grid from the line side inverter and allow the power winding to draw lagging VAr. Although this will increase the rating of the line-side inverter, the control winding voltage can be reduced, reducing both the ratings of the control winding and the machine-side inverter. At each speed the total converter
rating can be minimized. A plot showing the minimized rating compared to the rating used in Fig. 8 against a base of speed deviation is shown in Fig. 9.

![Comparison of minimized total inverter rating and total inverter rating shown in Fig. 8](image)

The strategy of using both inverters to supply VArS reduces the total converter rating. In practice, it is likely to be convenient to make both inverters of equal size and the optimization can be carried out to equalize the loadings. There is also the possibility of optimizing converter ratings and machine size as supplying the VArS on the power winding side of the machine reduces the rating of the control winding, permitting the use of a smaller machine or allowing a higher output. Such an optimization would aim to minimize system cost and the relative cost of machine and converter would be needed as inputs. Finally it should be noted that the prototype machine has somewhat larger resistances and reactances than a production machine of similar rating and so the VArS and losses are greater than normal. Furthermore, large machines are proportionately less resistive than small machines.

VII. MACHINE DESIGN

A. Principles of operation

The design of the rotor is key to operating of a BDFM as it must couple two fields. Lydell proposed a rotor with two distinct windings, as in the stator. This approach leads to a large rotor resistance and hence losses. Hunt realized that conductors in the rotor were carrying currents producing mmfs of opposite sign and he showed how a winding with lower resistance could be devised. As a result, the self-cascaded machine enjoyed some commercial success but the winding was irregular and therefore expensive to manufacture. Broadway and Burbridge re-examined the issue of rotor design and proposed two classes of design, the nested loop design and the progressive loop design. The nested loop design has been generally adopted in recent designs [9] although the practicality of progressive loop designs has recently been shown. Both types of design have a regular pattern, simplifying construction, but the relative sparsity of conductors brings increased space harmonics. Analysing the detailed effects of the space harmonics is not straightforward but an increased rotor leakage inductance is one important consequence.

B. Air gap flux

The air gap flux is the resultant of three mmfs - those of the two stator windings and that of the rotor. The resulting air gap flux distribution contains fields of the pole numbers of the two principal couplings, plus rotor space harmonics and slotting harmonics. Space harmonics from the distributed stator windings exist, but are small. A flux plot is shown in Fig. 10, derived from finite element analysis. The flux pattern is unconventional, being primarily the sum of two asynchronous fields of different pole number. An instantaneous plot, as in Fig. 10, gives an apparent 6-pole pattern. The presence of two different air gap field components creates a difficulty in determining the magnetic loading; the issue is considered by McMahon et al. [19] and a simple closed form of the quadrature sum of the two fields is shown to be a good representation.

C. Determining the relative magnitude of the air gap fields

At first sight, the ratio of the amplitudes of the two principal field components, $B_1$ and $B_2$, might appear a free parameter, but it can be shown that for maximum machine output there is an optimum ratio, which can be approximated to

$$\frac{B_2}{B_1} \approx \sqrt[3]{\frac{p_2}{p_1}}$$

This translates into a rotor turns ratio of $\sqrt[3]{\frac{p_1}{p_2}}$ and this has important implications for rotor design. Obviously, with normal distributed windings, it is relatively easy to achieve a given turns ratio, but with nested loop and progressive loop designs it is not so easy. The rotor turns ratio $n_r$ is given by

![Flux pattern in the BDFM; $V_{s1}=90V_{rms}$, (power winding voltage), $f_1=50hz$, $V_{s2}=64 V_{rms}$, (control winding voltage), $f_2=30hz$, $\omega_r=83.78$ rad/sec, t=0.2s](image)
where \( N_{1r} \) and \( N_{2r} \) are turns for the 2\( p_1 \) and 2\( p_2 \) pole fields respectively, with constant winding factors \( K_{\omega_1r} \) and \( K_{\omega_2r} \).

For the nested loop type rotor with single turn loops, only the winding factor can be changed. The following discussion is based on a BDFM with one loop in each nest. Adjusting the turns ratio by changing a winding factor essentially degrades the coupling to a winding and increases referred resistances and hence losses. If the ratio of the pole numbers approaches unity, the desired winding factors become approximately equal and the correct pitch for the loop can be calculated. However, if the ratio of the pole numbers is large, as in the case with the 2/6-pole combination, which is attractive as it offers the highest natural speed, the \( n_r \) is not close to unity. For a 2/6-pole machine, the required \( n_r \) is 0.48 so one winding factor will necessarily be small and lead to a high referred resistance. The use of multiple loops is more favourable, although the analysis is not straightforward. To aid analysis, Roberts has shown that, to a good approximation, a nest of loops can be represented by an electrically equivalent single circuit [15]. In addition, alternative rotor windings such as the progressive loop approach may give better performance.

### D. Balancing the magnetic and electric loadings

It is well known in machine design that the magnetic and electric loadings need to be balanced to obtain maximum output from a given frame size machine. This procedure is more difficult in a BDFM as there are two principal air gap flux components present. The rotor design is likely to be the most challenging as the smaller diameter compared to the stator restricts the space available. Making the rotor teeth larger allows a higher magnetic loading to be achieved but this takes place at the expense of rotor slot area and hence electric loading. At the same time there must be enough back iron to carry the flux without saturation, allowing for the presence of a shaft, and the problem is more critical as the pole numbers of the fields are reduced.

A view has to be taken of the acceptable current density in the rotor conductors, which can generally be higher than the stator as the rotor can run hotter. Set against this is the uneven distribution of current in the loops within one nest in the nested loop type of winding; the progressive loop winding is better in this respect. At present there is not a simple procedure for rotor design but an iterative design scheme to optimize machine rating has been proposed [20], [21].

Similar considerations apply to the stator. The windings are generally multi-turn coils, and normal slot fill factors will apply. Also, experience suggests that the two stator windings, which of course occupy the same slots, must be mutually insulated. Again there is no simple design procedure to balance the tooth width and slot areas, and also enough stator back iron must be provided. The iterative design procedure used for the rotor can be applied to the stator. It is worth noting [22] that some economy in stator conductors could be obtained by ingenious windings, as for example used by Hunt, but the benefit of electrically isolated windings is more valuable.

### VIII. Machine rating

The rating \( S \) of a BDFM at natural speed is given by

\[
|S| = \frac{\pi^2 d^2}{\sqrt{2} 2} \left( \frac{l B J |\omega_s|}{p_1} \right) \left( \frac{1}{n_r} \right)^2 \left( 1 + \frac{1}{n_r} \right) \left( 1 + \frac{n_r p_2 \cos \phi}{p_1 \cos (\phi + \pi)} \right) \]

where \( \cos \phi \) is the power factor of the power winding, \( B \) the magnetic loading, \( J \) the electric loading, \( d \) the rotor diameter and \( l \) the stack length.

As has been shown earlier, careful management of real and reactive power flows will enable the machine to generate an amount of real power approaching the theoretical rating, assuming that resistive losses are low. For the frame size 180 4/8-pole machine reported by the authors, realistic values of electric and magnetic loadings are 31.9 kA/m and 0.33 T respectively. The reduced magnetic loading \( \bar{B} \) is a consequence of premature saturation of rotor teeth and there seems no practical barrier to a \( \bar{B} \) of 0.45 T or higher in a commercial machine. The natural speed is 500 rpm on a 50 Hz supply. The rating of the machine is then 76 Nm at 500 rpm, equalling 4 kW. Under these conditions the load angle \( \delta \) is about 40 degrees and the pull out torque is 117 Nm, using parameter values published in [10].

This performance can be compared to that of a wound rotor induction machine. The rating of such a machine is given by

\[
S_{rm} = \frac{\pi^2 d^2}{\sqrt{2} 2} \left( \frac{\omega_s}{p} \right) \bar{B} J
\]

where \( \omega_s \) is the synchronous angular frequency.

A direct comparison to a 4/8-pole BDFM is a wound rotor induction machine with a synchronous speed of 500 rpm, i.e. a 12-pole machine. The output of the BDFM is about 20% less for the same volume of active materials. However, when the removal of brush gear is allowed for, the BDFM may in fact be smaller and cheaper.

### IX. Machine control

The BDFM is a synchronous system but its control is complicated by the presences of unstable regions, as first noted by Spee et al. [23]. Li et al. from the same research group first investigated the open loop stability of the system [24]. Various control algorithms for the BDFM have been published, for example by Zhou et al. [25]. The realization that a d-q model of the machine in the rotor reference frame could be rotated into synchronism with the stator currents, represented a significant step forward [26]. This realization was generalized and used to present a general eigenvalue stability analysis in [15]. Recent investigations into the implementation of control schemes are also given in [15].

Considerable research has gone into control schemes for the BDFM; the most promising control scheme to date is a rotor flux oriented scheme [26]. The rotor flux oriented
scheme (and other schemes, see for example [15]), depend on complex theoretical models, some involving the linearization of the inherently non-linear BDFM.

There is a need for further work to develop the rotor flux orientated control scheme, and other control schemes, into usable practical schemes. For example, how the control scheme will respond when issues of grid-load interaction has not yet been considered, and whether the schemes will be effective for a wide range of machine designs, particularly those prone to considerable unstable regions. At that stage meaningful modelling of the expected behaviour of the BDFM and its associated converter in a wind turbine application can be undertaken.

X. Concluding remarks

Recent advances in the study of the BDFM allow more complete consideration of the application of this machine to variable speed generation in wind turbines. However, work remains to be done in devising a simpler method of determining the balance of electric and magnetic loadings in the machine, especially in the rotor. Further investigation of rotor windings would be also valuable. The control of the machine remains a challenge and, as well as further development of practical control schemes, fundamental studies of the influences which determine the unstable regions of operation are needed.

BDFMs are relatively slow speed machines, and the highest speed machine, the 2/6-pole, is the counterpart of an 8-pole wound rotor induction machine. Nevertheless, both the 4/8-pole and 2/6-pole BDFMs with natural speeds of 500 and 750 rpm respectively are practical contenders for use in indirect drive wind turbines, especially bearing in mind the balance between generator speed and the gearbox ratio. However, the great prize which the BDFM offers is the elimination of brush-gear, an objective which has been the goal of electrical engineers for many years. The next step is a comparative costing of a BDFM based system using the design procedures outlined in this paper.

References