Practical Deployment of the Brushless Doubly-Fed Machine in a Medium Scale Wind Turbine

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Abstract—The Brushless Doubly-Fed Machine (BDFM) is a brushless electrical generator which allows variable speed operation with a power converter rated at only a fraction of the machine rating. This paper details an example implementation of the BDFM in a medium-scale wind turbine. Details of a simplified design procedure based on electrical and magnetic loadings are given along with the results of tests on the manufactured machine. These show that a BDFM of the scale works as expected but that the 4/8 BDFM chosen was slower and thus larger than the turbine’s original induction machine. The implementation of the turbine system is discussed, including the vector-based control scheme that ensures the BDFM operates at a demanded speed and the Maximum Power Point Tracking (MPPT) scheme that selects the rotor speed that extracts the most power from the incident wind conditions.


I. INTRODUCTION

The Brushless Doubly-Fed Machine (BDFM), also known as the Brushless Doubly-Fed Induction Machine (BDFIG), is an electrical generator with similar properties to the Doubly-Fed Induction Generator (DFIG) in that variable speed operation is possible with a converter rated at only a fraction of the machine rating. However, due to the BDFM’s design the brush contacts to the rotor are eliminated, increasing machine reliability and lowering maintenance requirements. This is particularly beneficial for wind turbines located offshore where maintenance costs are high [1].

This paper details a practical implementation of a 20kW BDFM-based wind turbine erected by the authors (in collaboration with Durham University School of Engineering) in Cambridge in March 2009. The mechanical parts of the turbine were supplied by Gazelle Wind Turbines and the BDFM was designed to replace the cage-rotor induction machine normally used.

A. BDFM Operation

Instead of a brushed connection to the rotor, the BDFM achieves doubly-fed operation by employing two independent stator windings which are wound with different pole numbers to prevent their direct coupling [2]. The rotor is wound in such a way that it couples both pole number fields. In the simplest case this winding could be two standard polyphase windings (like those of the stator) wired together. Thus the equivalent circuit of the BDFM looks similar to two standard induction machines with their rotor windings wired together, as shown in figure 1. In practice better machine performance can be achieved using other rotor designs, such as the ‘nested-loop’ design, which achieve the same effect using the harmonics of the field produced by a set of independent loops. It is useful to note the frequency relationship between the currents in each of the stator windings:

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

where \(\omega_1\) and \(\omega_2\) are the frequencies of the windings, \(p_1\) and \(p_2\) the pole pairs and \(\omega_r\) the rotor speed.

1) Operating Modes:

In all operating modes one of the stator windings (the power winding, PW) is connected to the grid and the other (control winding, CW) is connected to achieve the desired operation. The connection of the BDFM in its two key modes is shown in figure 2

- Synchronous Mode: In this mode the control winding is connected to a Variable-Voltage Variable-Frequency (VVVF) converter, and the voltage is supplied so that equation 1 holds. In this case the operation is similar to that of a synchronous machine in that (in the ideal case) the phase of the control winding voltage controls the torque of the machine and the magnitude of this voltage controls the active power flow in the machine. However, by adjusting the control winding frequency this synchronous-machine-like performance can be achieved at any speed.
- Cascade Mode: In this mode the control winding is short-circuited. With the control winding current uncontrolled the performance is similar to that of an induction machine with \(p_1 + p_2\) pole-pairs.

B. Turbine Details

The turbine used was a standard commercial 3-blade horizontal axis model from Gazelle Wind Turbines. The tower height was 13m and the blade swept diameter 11m. The blades have a fixed pitch, can safely operate at up to 110rpm and are coupled to the generator via a gearbox. The nacelle is of a downwind design and free to yaw to align itself with the wind. The various power and signal cables pass to the ground through slip-rings. The turbine can be seen in figure 3. The turbine is sited in an urban setting convenient to the Engineering Department. This site provides enough wind for testing the concept of a BDFM-based wind turbine; it is not expected to generate substantial energy in the long term.

II. BDFM

A. Design

Normal variable speed operation of the turbine is achieved with the BDFM running in its synchronous mode. It is useful designs, however it is important to start from a good first-order design. A modified version of the classic electrical and magnetic loading based induction machine design procedure was used. The optimal ratio of turns between the two effective rotor windings was given in [4] by:

\[
n_{r_{\text{opt}}} = \left( \frac{n_{r_1}}{n_{r_2}} \right)^{2/3} = \left( \frac{p_1}{p_2} \right)^{2/3} \left( \frac{\cos(\phi + \delta)}{\cos \phi} \right)^{2/3} \tag{4}
\]

Assuming the cosine fraction term is close to unity, this gives an optimum of 0.63 for the 4-pole/8-pole machine; this was closely matched in the nested-loop rotor design used. In the same paper, the relative field strengths are given by:

\[
B_2 = \frac{n_r \cos \phi}{p_2} \left( \frac{p_1}{p_2} \right) \cos(\phi + \delta)\tag{5}
\]

where \(B_1\) and \(B_2\) are the magnetic flux densities in the airgap due to the two stator windings. It is also shown that the total magnetic loading is approximated by:

\[
B = \sqrt{B_1^2 + B_2^2}\tag{6}
\]

Equations 5 and 6 combine to give the optimal split of field strengths as:

\[
\frac{B_1}{B} = \frac{1}{\sqrt{1 + \left( \frac{n_{r_1} p_2}{p_1} \right)^2}} \quad \frac{B_2}{B} = \frac{1}{\sqrt{1 + \left( \frac{n_{r_2} p_1}{p_2} \right)^2}} \tag{7}
\]

The BDFM was constructed by rewinding a commercial 4-pole induction machine with a 4-layer BDFM stator. Thus with the dimensions of the original machine and its original operating magnetic loading, equation 7 allows the stator turns numbers to be determined using the loading limit given in table 1. With the turns ratio known the slot area can be allocated between the two stator windings and appropriate wire sizes chosen. [4] suggests that the effective electrical loading of the two windings may simply be added:

\[
J = J_1 + J_2 = \frac{6}{\pi d} \left[ N_{s_1} k_{w_1} |I_{s_1}| + N_{s_2} k_{w_2} |I_{s_2}| \right] \tag{8}
\]

This may be used to determine the combined-heating current limit for the two windings. It is suggested in [5] that further limits should be placed on the electrical loading in each of the two windings to prevent either winding becoming excessively hot. The three electrical loadings used are shown in table 1. The rotor teeth were chosen to have the same combined area as the stator teeth, and the slot depth chosen to keep the current density in the bars below a certain limit. Table II shows the key dimensions of the BDFM.

B. Performance

The BDFM is typically operated in its synchronous mode, thus, like a synchronous generator, its performance limits are best described as a safe operating region in which the machine can be operated without exceeding its thermal and magnetic limits. The structure of such a chart for the BDFM is presented in [5]. The chart must be calculated from equivalent circuit parameters. These were extracted from

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Fig. 2. Typical configuration of the BDFM as a variable speed generator or drive. The contactors allow switching between synchronous and cascade modes.

Fig. 3. A photograph of the wind turbine as installed in Cambridge.
cascade mode tests as detailed in [2] and are presented in table III. As explained in [2] parameters cannot be uniquely extracted for the circuit of fig. 1 but are for an equivalent form in which all leakage inductances are referred to the rotor section.

The structure of the BDFM operating chart is similar to the standard chart of the synchronous machine with real power on the y-axis and reactive power on the x-axis. Because the BDFM is doubly-fed, the real power shown is the sum of the PW and CW powers. As the converter can be made to operate with a unity power factor only the PW reactive power is shown on the x-axis. Because the BDFM is a variable speed machine a chart must be drawn for each speed to map out the safe operating volume.

Figure 4 shows the calculated operating chart (stator thermal limits only) at 400rpm and 750rpm. For verification the BDFM was operated continuously for 1-2 hours at each of the points A – D marked on the chart, with the temperatures of PT100 thermistors embedded in the slots and in the 4-pole and 8-pole end windings recorded every 5 minutes. An assumed exponential decay to a final temperature was then fitted to the data, with the best-fit final temperatures presented in table IV.

As expected, the table shows that the closer the points are to the boundaries of the safe operating area, the hotter the windings become. Unfortunately it was not possible to collect more data before the BDFM had to be fitted to the turbine, however a comparison of the temperatures observed to the maximum permitted temperature of the class F insulation used (155°C) suggests that the region predicted by the chart is safe if rather conservative. If we assume a simple model of a heat source with a thermal resistance to ambient, raising the maximum observed temperature from 120°C to 155°C allows 35% more heat to be dissipated, allowing the machine currents (and, roughly, output power) to be raised by 16% if we assume all the heat is $I^2R$ losses in the windings. Finally, the chart is for continuous operation. Under duty cycle operation (like the gusty wind generally experienced by the turbine) the BDFM may be worked much harder for short periods of time. Tests show the dominant thermal time constant of the BDFM to be approximately 30 minutes, so for example the BDFM may be run at 20kW output at 750rpm.
for 12 minutes (from cold) without damage.

III. SYSTEM IMPLEMENTATION

A number of different layers of hardware and software are required to keep the turbine under control and to extract the most energy from the wind, shown in 5. At the lowest level, a VVVF supply must be applied to the control winding of the BDFM to make it run in its synchronous mode. Next a control system is needed to specify the VVVF supply to make the BDFM (and thus the blades) run at a particular speed. Finally a system is required specify the blade speed at each instant that will extract the most power from the current wind conditions. In addition a system is required to detect and react to fault conditions that may occur.

A. Electrical System

The key components of the electrical system are shown in figure 2. At the heart of the system is a IGBT-based commercial machine drive used in a regenerative mode to provide a constant voltage DC-link while allowing bi-directional power flow between the DC-link and the three-phase grid. At the other side of the DC-link is a standard IGBT three-bridge inverter which, when supplied with the appropriate PWM signals provides the required VVVF supply for the BDFM control winding. Because the whole capacity of the grid-side converter will not be required most of the time, any spare capacity can be used as a static compensator, generating VARs to improve the power factor of the turbine. Additionally capacitors are provided for power factor correction.

1) Starting the Turbine

In the synchronous mode the control winding (and thus the converter) handles only a fraction of the machine power given by equation 3. However at zero speed this suggests that the converter rating must be equal to the machine rating which is clearly undesirable. To allow the use of a small converter the turbine is instead started in its cascade mode, with its control winding shorted with the contactor K3 of figure 2 (note that the wind cannot start the turbine). Once the machine has reached a sufficiently high speed the machine switches to synchronous mode by changing the positions of contactors K2 and K3.

B. BDFM Speed Controller

This subsystem ensures that the BDFM operates at the speed and control winding reactive power demanded by the turbine controller. To do this a controller implemented in Simulink takes inputs of the machine speed and winding currents and voltages and uses them to generate PWM switching patterns for the converter discussed in section III-A. The controller uses a scheme oriented with the power winding flux reference frame fully detailed in [6]. In this scheme the two PI controllers discussed below manipulate the control winding voltage quantities $v_{2d}$ and $v_{2q}$ to regulate the shaft speed and PW reactive power ($Q_1$).

1) Speed control loop

The following description of the control loop follows that given in [6]. A linear relation can be established between the electromagnetic torque, $T_e$, and the $q$ component of power winding voltage in power winding flux reference frame, $v_{2q}$:

$$T_e = K_w v_{2q} + D q$$  \[9\]

where $K_w$ is the product of a term composed of a linear combination of the machine parameters (resistances and leakage and coupling inductances) and the PW flux. $D_q$ is the cross-perturbation.

The machine’s mechanical differential equation is:

$$T_e = J \frac{d\omega_r}{dt} + B \omega_r + T_i = (Js + B)\omega_r + T_i$$  \[10\]

where $J$ is moment of inertia and $B$ is friction coefficient. Thus $\omega_r$ is related to $v_{2q}$ so the control loop shown in Fig. 6 may be used.

To determine the value of $K_w$ the PW flux must be known. This can be retrieved from the terminal quantities by an estimator discussed in [6]. In this estimator the PW magnetizing voltages are found by subtracting the resistive drops of the windings from the terminal voltages, which may then be integrated to give the flux. Because of the reference frame used this appears as a stationary flux vector.

2) VAR control loop:

Similarly, a linear relation exists between $Q_1$ and $v_{2d}$ [6]:

$$Q_1 = K_{Q1} v_{2d} + D_{Q1}$$  \[10\]

where $K_{Q1}$ is similarly the product of a term composed of a linear combination of machine parameters, the power winding flux and the power winding frequency. $D_{Q1}$ is the cross-perturbation.

The control loop of reactive power is shown in Fig. 7. It is interesting to note that because of the three-phase measurement of the terminal voltages and currents, when transferred to the synchronous reference frame it is possible to take instantaneous estimates of the reactive power as well as the real power.

Fig. 8 shows the structure of the whole speed controller as implemented.
C. Turbine Controller

The turbine is managed by a controller implemented in LabVIEW, which also provides a graphical user interface for the turbine operator. Wind speed and direction information is input to LabVIEW from an anemometer and wind vane mounted on the top of the turbine and power information from the electrical system. The controller runs a Maximum Power Point Tracking (MPPT) algorithm to specify the speed and reactive power demands for the speed controller in order to extract the most energy from the wind. A schematic of the algorithm is shown in Figure 9.

The behaviour is summarised as follows:
- Start with an initial speed $\omega_0$, a speed change $\delta \omega$, and a measurement time, $T_{DEC}$.
- At the end of the $k$th measurement time, calculate the average power output of the turbine.
- If output increases, preserve the sign of $\delta \omega$, and if output decreases, reverse it.
- If $\omega$ is already the highest permitted, set $\delta \omega$ negative, and vice versa for the lowest allowed $\omega$.
- Set $\omega_{k+1} = \omega_k + \delta \omega$.

Although much more data will be required to optimise the parameters above, an $\omega_0$ of 550rpm, a $\delta \omega$ of 10 rpm, and a $T_{DEC}$ of 2 minutes has been used here successfully. A small $T_{DEC}$ results in random behaviour since the MPPT responds to fast variations in wind speed rather than a long term trend, while a large $T_{DEC}$ will cause the tracker to miss out on periods of good wind by responding too slowly.

On a faster timescale, the reactive power of the turbine is managed by setting the PW reactive power to a value that minimises machine losses for a given torque, and correcting to a good overall system power factor by using a fixed passive capacitance and additional converter capacity. This algorithm is executed on a shorter timescale, and is shown in Fig. 10.

In addition to these procedures, a routine is used to determine when the turbine is turned on and off, depending on the wind conditions and power output.

IV. PERFORMANCE ANALYSIS

Detailed high-resolution measurements have been available for several weeks of operation, and during this time the behaviour of the MPPT algorithm described here has been observed.

Fig. 11 shows the output of the turbine over a period between 14th and 15th July 2009. Firstly the figure shows that the wind conditions are rather poor at the site and the wind is very gusty. This is as expected because the turbine is located on an urban site chosen for its location on Engineering Department land. The spiky nature of the graph shows that for relatively small gusts of say 6m/s the turbine may output
5kW if it is properly aligned with the wind but that very often the turbine is not properly aligned.

Secondly the performance of the MPPT routine is shown. After around 48,000 seconds the wind energy (proportional to the cube of the wind speed) improves significantly, and the tracker increases the rotor speed in response and the turbine produces a larger power output. This continues until the wind speed drops, power output decreases, and eventually the blade rotation slows to the lower speed limit in response. The resulting reduction in power loss is shown in the period after 76,000 seconds. Note that ordinarily the turbine would be deactivated with such a drop in wind speed and power output, but here the effect of MPPT is being demonstrated.

Tests under very still wind conditions show that the power draw when no wind is present, due to aerodynamic drag, friction and machine losses, varies from 1.75kW at 350rpm to 4kW at 700rpm. Note that at any given speed the machine losses are minimised and power output maximised, since the reactive power controller indirectly optimises the CW excitation for minimum loss. This, combined with a good strategy for choosing the speed in parallel, ensures that the turbine system as a whole converts the most input energy available into output power. It was also seen that when operated in this way the BDFIG itself operates at high efficiency, typically over 80% and improving with machine torque.

An advantage of the scheme described is that it does not rely on any measurement of the wind speed to determine the rotor speed, the only measurement required is an integration of the system output power over time. However, it was seen in many cases that taking into account the wind speed measurement would also eliminate more erroneous speed changes, despite the fact that no complete $C_p$ curves for this blade set exist yet. For example, if the blade speed were low and the wind speed were to increase suddenly, the blade speed could be increased in one large step in response.

In a full-scale turbine system, such strategies are likely to be very different, since pitch control is also used, and turbulence for such turbines is a much smaller problem due to their location and height. Here the turbine is situated for accessibility rather than wind characteristics, and it is only necessary to prove the concept of a turbine operating under BDFIG technology rather than to obtain a continuous power output.

V. CONCLUSIONS

From this work we can conclude that a BDFM-based wind turbine is practical. We may also conclude that the speed control and MPPT algorithms presented work effectively. Though the siting of the turbine is not ideal, from the modest wind resource available the system is able to generate significant power. The 4/8 BDFM design works well but is larger than the 4-pole induction machine it replaces due to its high number of poles and slower speed. Future work will also consider the 2/6 BDFM, which potentially offers a higher power density.

REFERENCES