Research Article

Fabrication and Mathematical Modeling of the Brushless Doubly Fed Induction Generator-Based Wind Electric Conversion System

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Electricity generation with minimal environmental pollution is required for the world’s sustainable future, and wind electric generation is one of them. Brushless doubly fed induction generator (BDFIG), which derives from cascade induction machine technology, has grown in popularity as a wind electric generator due to advantages over doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) such as the absence of slip rings and brushes and high-cost permanent magnets. Wind energy research is critical for any country’s economic development and long-term sustainability. As a result, an experimental setup in a laboratory is required to replicate the behaviour of a wind turbine in the steady state. This study discusses the emulation of wind turbine characteristics in the laboratory using a prototype of a separately excited DC motor mechanically coupled to a brushless doubly fed induction generator (BDFIG). The wind turbine emulator-brushless doubly fed induction machine (WTE-BDFIM) prototype was tested in the laboratory under high power and low wind speed conditions. As a result, the simulation of the same hardware configuration in MATLAB was performed to investigate the overall performance of the BDFIM-based WECS. To determine the equivalent circuit parameters of the BDFIM, which are required for simulation, tests were performed on a prototype of 3.5 kW, 2/6 pole, 400 V, star/delta-star, and BDFIM in two modes, namely, the simple induction mode and the cascade induction mode. Based on the BDFIM parameters, a MATLAB Simulink model of a BDFIG-based wind electric conversion system (WECS) is created and its performance is investigated. Results of both hardware and simulation show that BDFIG can be used as the wind electric generator over a wider speed range compared to that of DFIG, an important feature that is required to get maximum power extraction from the wind turbine.

1. Introduction

Because of the lack of brushes and slip rings, BDFIG is suitable for offshore wind power applications. The machine has two three-phase stator windings with distinct poles, namely, synchronous power winding (SPW) and asynchronous power winding (APW). As shown in Figure 1, SPW and APW are connected to the power grid. The rotor will be of a special type that indirectly couples both stator fields, a process known as cross-coupling, allowing the machine to operate in synchronous mode. Maximum power output from WECS can be extracted by varying APW frequency using machine-side converter, while grid side converter maintains reactive power exchange with the grid [1–3]. The design and analysis of a BDFIG with a dual cage rotor have been detailed [4]. The dynamic behaviour of BDFIM with and without torque compensation is clearly explained [5].

Maximum rotor speed variation of 30% has been reported in the literature in DFIG-based WECS [6]. All published BDFIM research studies discussed the design and fabrication of BDFIM-based WECS with conventional windings, BDFIM mathematical modelling, and various control schemes implemented in BDFIM-based WECS. The presence of torque ripples is a major issue impeding the development of BDFIM, and R. Resmi et al. proposed implementing the star-delta configuration in one stator winding to reduce torque ripples [7]. It is clear that the
literature on BDFIM reviewed thus far has not addressed the development of a wind turbine emulator for BDFIM-based WECS. This study discusses the use of a separately excited DC motor as a WTE [8] that is mechanically coupled to a BDFIM. The laboratory setup results show a wide range of speed variations over a smaller range of wind speed. This feature enables the WECS to operate at varying rotor speeds in response to changes in wind speed in order to extract the maximum power from the wind [9]. Because the hardware implementation has some limitations, the simulation was run with the parameters extracted from hardware testing. The results confirm the performance of BDFIM-based WECS, with a generator speed range of 1.02 p.u–1.78 p.u observed for a variation in wind speed from 5 m/s to 14 m/s, corresponding to a 42.7% change in wind turbine rotor speed between no load and full load conditions, which is better than the speed variation of 40% in reported BDFIG [10]. The CES system can efficiently use wind and solar power and can be dispatched during peak hours of regional power load demand to release energy. It can close the gap, allowing the power system to operate at peak efficiency and accelerating the development of new energy has been reported [11]. The hybrid improved gravitational search algorithm (IGSA)- dual-stage optimization (DSO) employed an adoptive speed inertia coefficient, ensuring both global and local searchability. The proposed model’s features were validated using an IEEE-RTS 24 bus test system with various cases to realise coordinated power grid and energy storage planning. Finally, the simulation shows that the proposed approach (IGSA-DSO) reduces the investment cost by 0.248% in comparison [12]. By optimising the controlling parameters, the FM characteristics and wind energy storage capacity were configured [13]. Also, the economics of energy storage can be improved by determining the design method of its rated power and capacity in accordance with FM requirements. Under high wind speeds, the energy storage capacity is configured to be 5.9% of the installed capacity, a 26% reduction from the 8% capacity required for independent support of energy storage. The coordinated FM control strategy’s comprehensive optimal energy storage capacity configuration is improved. The use of a DFIGs generator in WECS has several advantages, including a robust and flexible system, energy generation across a wide operating range of wind turbines, simplicity of the control system, and cost-effective operation [14]. On the stator side, DFIG is directly connected to the AC grid, while the rotor side is only powered by a power converter. The converter rating typically ranges between 25% and 35% of the rated power, allowing a wind turbine operation speed range of 50% to 120% of the rated speed. The authors present a control for the rotor-side converter (RSC) developed to provide symmetrical and three-phase voltage with minimal harmonic content at the islanded load terminals in [15]. The operation of an island is characterised by the uneven load on each phase and random behaviour. For wind turbine brushless doubly fed induction machines, developments and research challenges have been well addressed [16]. From this study, general performance (such as size, mass, efficiency, power quality, development, and maturity), system stability (such as brushes/slip rings, power electronics converters, crowbars, and vibrations), and control (power electronics rating, complexity, and grid fault and performance) for permanent magnet generator, doubly fed induction machine (DFIM), and BDFIM have been well reported. Among these brushless, DFIM has produced excellent system stability and control but poor general performance.

This study discusses the development of a laboratory setup and mathematical modelling of BDFIM-based WECS, demonstrating the superiority of BDFIM over DFIG as a wind electric generator for maximum power point tracking.

The following are the main contributions of this study:

(i) Laboratory development of a wind turbine emulator for BDFIM that can be used for wind energy research
(ii) Establishing a wider range of rotor speed in BDFIM with star/delta-star winding as WECS versus DFIG-based WECS
2. The Hardware Model of BDFIM

The design of a 2/6 pole, 400V, 3.5kW BDFIM with star connection for SPW, delta-star connection for APW, and nested loop rotor was carried out using BDFIM design equations and standard output equations (15–17). Table 1 lists the machine’s specifications [7]. The inner diameter of the stator is set at 190 mm to account for the availability of standard stampings. Skewing by one slot pitch and delta-star stator winding are used in BDFIM to reduce torque ripples [7]. Stator conductors have been chosen in accordance with the standards, and copper bars have been inserted into the rotor slots of the nested loop rotor. BDFIM windings are installed in the same slot as the layers. Wire cutting occurs in stator slots to accommodate both APW and SPW. Figure 2 depicts the stator core with double stator windings, a nested loop rotor, a complete BDFIM prototype, and 12 APW and SPW stator terminals. The number of rotor slots is set to 40, with a total of 5 loops in each rotor nest.

3. Development of Wind Turbine Emulator and Testing with BDFIM

The wind turbine emulator (WTE) is built with a separately excited DC motor and a series resistance to mimic the characteristics of a real wind turbine [8]. The system is made up of a separately excited DC motor, the armature of which is controlled by a variable DC voltage source. The series resistance between the armature and the wind electric generator is crucial in producing the desired power curves. Because the motor efficiency is typically around 80%, a DC motor alone cannot serve as an emulator. The efficiency of the motor, which is designed to function as a wind turbine emulator, must be brought close to the power coefficient of 59% (Betz limit of wind turbine). The series resistance value is determined by running various tests on the motor-generator coupled set with various resistances until a perfect power curve is obtained. In this case, a variable resistance of 3.5 is connected in series with the armature of a DC motor to vary the efficiency of the motor in accordance with the variation of the power coefficient of a wind turbine; the entire setup then functions as a BDFIM-based WECS. The different input armature voltages to the WTE are assumed to correspond to different wind speeds in this case. The DC motor is separately excited with constant field current throughout the operation. The WTE is associated with a 5 kW wind turbine. WTE is powered by a variable DC voltage source ranging from 190 V to 230 V, and the voltage variation is proportional to the wind speed variation, yielding the power coefficient ($C_P$)-tip speed ratio ($\lambda$) characteristic.

Figure 3 depicts a single line diagram of WTE with BDFIM. Table 2 lists the specifications for a prototype model of BDFIM attached to a separately excited DC machine, as shown in Figure 4. Figure 5 depicts the experimental setup of WTE with BDFIM, which is used to obtain the motor output power-rotor speed characteristics. The corresponding power coefficient, the CP-tip speed ratio, is obtained from the plot of motor power outputs versus rotor speed. The motor output is then compared to the output of a 5 kW wind turbine, the specifications of which are cataloged in Table 3, and mapping of WTE voltage and wind speed is performed. $C_P$ curves are commonly used in turbine design to calculate turbine power for any combination of rotor speed and wind speed. The variable load is set to maximum in the experimental setup, and the series resistance is set to 3.5 Ω. The

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SPW</th>
<th>APW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Poles</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Output power (kW)</td>
<td>2.625</td>
<td>0.875</td>
</tr>
<tr>
<td>Current (A)</td>
<td>5.6</td>
<td>7</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>36</td>
<td>36</td>
</tr>
</tbody>
</table>
input armature voltage is now held constant at, say, 200 V. The parameters of the BDFIM-DC machine test setup are recorded in Table 4.

Power from SPW and APW as well as speed, current, and voltage on the AC side are measured. Keeping the input armature voltage constant, the variable load is gradually increased until it reaches a minimum, and the readings are recorded. The input armature voltage is then gradually decreased, and the load is varied from maximum to

**Table 2: Simulation results of BDFIG-based WECS.**

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>BDFIG torque (Nm)</th>
<th>BDFIG Speed (rad/sec)</th>
<th>SPW power (W)</th>
<th>APW power (W)</th>
<th>Total power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.46</td>
<td>77.1</td>
<td>179.9</td>
<td>86.6</td>
<td>266.5</td>
</tr>
<tr>
<td>6</td>
<td>4.68</td>
<td>92.5</td>
<td>266.5</td>
<td>166.5</td>
<td>433</td>
</tr>
<tr>
<td>7</td>
<td>7.71</td>
<td>96.4</td>
<td>456.6</td>
<td>286.2</td>
<td>742.8</td>
</tr>
<tr>
<td>8</td>
<td>10.74</td>
<td>106.5</td>
<td>686.6</td>
<td>457.7</td>
<td>1144.3</td>
</tr>
<tr>
<td>8.5</td>
<td>11.31</td>
<td>119</td>
<td>832.1</td>
<td>513.7</td>
<td>1345.8</td>
</tr>
<tr>
<td>9.9</td>
<td>14.71</td>
<td>126</td>
<td>1230</td>
<td>623.6</td>
<td>1853.6</td>
</tr>
<tr>
<td>11</td>
<td>16.85</td>
<td>133</td>
<td>1520.85</td>
<td>720.5</td>
<td>2241.35</td>
</tr>
<tr>
<td>12</td>
<td>18.77</td>
<td>136.5</td>
<td>1750.67</td>
<td>810.8</td>
<td>2561.47</td>
</tr>
<tr>
<td>13</td>
<td>19.47</td>
<td>140</td>
<td>1865.32</td>
<td>860.34</td>
<td>2725.66</td>
</tr>
<tr>
<td>14</td>
<td>21.30</td>
<td>147</td>
<td>2240.55</td>
<td>890.43</td>
<td>3130.98</td>
</tr>
</tbody>
</table>

**Table 3: Wind turbine specifications.**

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power (kW)</td>
<td>5</td>
</tr>
<tr>
<td>Diameter of rotor (m)</td>
<td>4.1</td>
</tr>
<tr>
<td>Rated wind speed (m/s)</td>
<td>14</td>
</tr>
<tr>
<td>Rated rotor speed (rad/sec)</td>
<td>25</td>
</tr>
<tr>
<td>Cpmax</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Table 4: Specification of prototype BDFIM coupled with DC machine.**

<table>
<thead>
<tr>
<th>Separately excited DC motor</th>
<th>BDFIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armature Voltage: 230 V</td>
<td>Voltage: 415 V</td>
</tr>
<tr>
<td>Speed: 1500 rpm</td>
<td>Natural speed: 750 rpm</td>
</tr>
<tr>
<td>Power: 5 kW</td>
<td>Power: 3.5 kW</td>
</tr>
<tr>
<td>Current: 30 A</td>
<td>Current SPW/APW: 5 A/7 A</td>
</tr>
<tr>
<td>Field current: 0.9 A</td>
<td>Pole configuration: 2/6</td>
</tr>
</tbody>
</table>
minimum position at each step, with the corresponding readings noted and tabulated. The input armature voltages are varied between 230 V and 190 V. Experiments are used to determine the armature resistance of a DC motor and the stator winding resistances of a BDFIM, which are required for loss calculation. The flowchart in Figure 6 depicts the steps for mapping wind speed to DC armature voltage.

After determining the corresponding wind speeds to different WTE voltages, the power coefficient and the tip speed ratio for various turbine power outputs are calculated. A plot between $C_p$ and $\lambda$ for different wind speeds is plotted. For an input armature voltage of 230 V, it is considered that...
CPmax occurs at \( \lambda \) equal to 5.68. Using the rotor speed corresponding to maximum power and assuming the value of \( R \), the value of wind velocity \( v \) is calculated. Considering the value of \( \lambda \) to be 5.68 for input armature voltage of 230 V, where the maximum turbine output power is 1646 W and corresponding rotor speed is 115 rad/sec, the value of \( C_p \) is calculated to be 0.43 (\( C_p \) max = 0.43). The value of power coefficient is the same for all maximum turbine power output. To obtain the wind velocity corresponding to other input armature voltages, the values of \( P_T \) max and \( C_p \) max are substituted and the value of wind velocity, \( v \), is calculated. Having found out the wind velocities corresponding to different input armature voltages, the values of \( P_T \) and \( C_p \) are calculated for different turbine power output. To obtain the wind velocity corresponding to other input armature voltages, the values of \( P_T \) max and \( C_p \) max are substituted and the value of wind velocity, \( v \), is calculated. Having found out the wind velocities corresponding to different input armature voltages, the value of power coefficient and the tip speed ratio are calculated for different turbine power output. A plot between \( C_p \) and \( \lambda \) for different wind velocities is plotted. The emulator reproduces the form of the turbine power curves in open loop and no feedback system is needed. Another benefit of this type is that it responds faster. This can be implemented as a closed loop system in WTE with appropriate control schemes. Figure 7 depicts the graphic mapping of DC armature voltage to wind speed. The rotor speed varies by about 21\% over a wind speed range of 9.3 m/s to 11.5 m/s. Figure 8 depicts the corresponding rotor speed and power outputs of both BDFIG stator windings in relation to the mapped wind speed. The WTE was constrained by the rated current of its windings in the experimental setup; otherwise, it would have produced an even higher shaft speed for the generator. WTE also had a limitation on the emulated minimum wind speed, so testing at speeds less than 9 m/s was not possible. Lower WTE ratings also prevented loading up to the rated wind speed of 14 m/s. As a result, a higher loading on BDFIG up to its rated capacity has been performed in a simulated model, as explained in the following section.

4. Simulation Study of BDFIM-Based WECS

BDFIM-based WECS is simulated in MATLAB Simulink using wind turbine and BDFIM mathematical models [18]. The equivalent circuit parameters of the prototype BDFIM are used to model the BDFIM, and the wind turbine specifications used are the same as those of the WTE.

4.1. Equivalent Circuit of BDFIM. An equivalent circuit was developed using the per-phase model based on the concept that BDFIM is thought of as two induction machines housed in a single frame [19, 20]. Two equivalent induction machine circuits can be merged as one using two induction machines with different number of poles sharing the same frame. (1) gives the angular velocity of the rotor in synchronous mode, which leads to the definition of slips for the SPW and APW fields, which are given by (2) and (3), respectively:

\[
\omega_r = \frac{2\pi (f_{SP} + f_{AP})}{p_{SP} + p_{AP}}.
\]

Slip of SPW field:

\[
s_{SP} = \frac{\omega_{SP} - p_{SP}\omega_r}{\omega_{SP}}.
\]

Slip of APW field:

\[
s_{AP} = \frac{\omega_{AP} - p_{AP}\omega_r}{\omega_{AP}}.
\]

\[
\omega_{SP} = \omega_{SP} - \omega P_{SP}\omega_r,
\]

\[
\omega_{AP} = -\omega_{SP} - \omega P_{AP}\omega_r,
\]

\[
s_{SP}\omega_{SP} = -s_{AP}\omega_{AP}.
\]
where \( \omega_{SP} \) and \( \omega_{AP} \) are the angular frequencies due to the stator fields by taking rotor as the reference. The special type of rotor for BDFIM can be represented by a combination of a resistance and a reactance. Figure 9 shows the equivalent circuit of BDFIM, where \( R_{SP} \) and \( R_{AP} \) are the stator winding resistances and \( R_{r} \) is the rotor resistance. \( j \omega_{SP} L_{SP} \), \( j \omega_{AP} L_{AP} \), and \( j \omega_{r} L_{r} \) are, respectively, the reactances of SPW, APW, and rotor. SPW and APW are coupled to the rotor by a transformer with Turns ratio \( N_{SP} \) and \( N_{AP} \), respectively. The voltages on the secondary of the transformers are in proportion to slips, \( s_{SP} \) and \( s_{AP} \), for the SPW and APW, respectively. Like the conventional machine, it is appropriate to refer all parameters with respect to the stator, here referred to SPW. Figure 10 depicts the equivalent circuit of BDFIM referred to stator SPW. Due to limitations in the test data obtained, all parameters cannot be determined. The core loss of BDFIM is ignored for dynamic analysis and is not shown in the equivalent circuit. So, as shown in Figure 11, the equivalent circuit is simplified so that all of the parameters can be calculated from the test data.

Performance of any electrical machine can be analyzed by using its equivalent circuit. By using analytical methods and experimental tests, it is possible to find out the equivalent circuit parameters of the machine [20]. In this study, the data needed for equivalent circuit parameters calculation of BDFIM are obtained from the experimental tests in the cascade induction mode and the simple induction mode. The synchronous and asynchronous winding resistances, \( R_{SP} \) and \( R_{AP} \), can be calculated from the geometry of the machine or by using DC measurements in the winding. The magnetizing inductances of two windings, \( L_{mSP} \) and \( L_{mAP} \), are obtained from the magnetizing tests. Finally, the rotor parameters, \( L_{r}' \) and \( R_{r}' \), are calculated based on circuit theory calculations using the data received from magnetizing and cascade tests. In [21], modelling of different components involved in BDFIM-based WECS is done in MATLAB Simulink, which forms the base model for the closed loop model of BDFIM [17].

4.2. Hardware Setup and Its Test Results. Extraction of equivalent circuit parameters of BDFIM can be done by conducting appropriate tests on the prototype model of BDFIM. BDFIM can be operated in three different modes of operation. If APW has \( P_{AP} \) poles and SPW has \( P_{SP} \) poles, then this machine will operate as an induction motor of either \( P_{AP} \) poles or \( P_{SP} \) poles, by connecting APW or SPW to the grid and keeping the other winding open in each case. This mode is referred as the simple induction mode [17, 19–22]. The performance of the BDFIM in this mode will be poor compared to conventional motor. If the non-excited winding is short-circuited, then the machine operates like cascaded induction motor with \( P_{AP} + P_{SP} \) poles. However, if both SPW and APW are connected to the grid, BDFIM operates in synchronous mode, in which the machine is usually operated.

4.2.1. Simple Induction Mode Test. During the simple induction mode, SPW or APW is provided with a 3\( \phi \), 400V supply, keeping the other winding in the open condition. Tables 5 and 6 respectively, show the readings of simple induction mode of operation of SPW and APW. From the reading, it is clear that the hardware machine is working properly as an induction machine corresponding to the designed number of stator poles.

4.2.2. Cascade Induction Mode Test. In the cascaded mode, any one of the stator windings will be provided with a three-phase supply and the other winding is shorted so that the BDFIM runs at a speed near an induction machine with \( P_{SP} + P_{AP} \) poles, where \( P_{AP} \) is the number of poles in APW and \( P_{SP} \) is the number of poles in SPW. Tables 7 and 8, respectively, show the readings of cascade induction mode of SPW and APW.

4.2.3. Turns Ratio and Slip Ratio Test. The conventional tests determine the Turns ratio and the slip ratio in order to compute the equivalent circuit parameters. The Turns ratio is calculated using formula (5), where \( N_{SP} \) and \( N_{AP} \) are the number of turns in SPW and APW, respectively, and \( v_{SP} \) and \( v_{AP} \) are the respective voltages across SPW and APW.

The Turns ratio:

\[
\frac{N_{SP}}{N_{AP}} = \frac{v_{SP}}{v_{AP}} \quad (5)
\]

The slip ratio can be calculated based on (2) and (3), where \( \omega_{SP} \) and \( \omega_{AP} \) are the angular speeds of the machine with respect to SPW and APW, respectively, \( f_{SP} \) is the SPW frequency, and \( f_{AP} \) is the APW frequency. Table 9 shows the values of the slips and voltages in SPW and APW.

Equations (6)–(19) are used to find the equivalent circuit parameters of 3.5 kW BDFIM. Table 10 shows the equivalent circuit parameters of BDFIM.

No load power factor for SPW:

\[
\cos \varnothing_{0SP} = \frac{P_{0SP}/3}{V_{0SP} \times I_{0SP}} \quad (6)
\]

Magnetizing current/phase:

\[
I_{mSP} = I_{0SP} \sin \varnothing_{0SP} \quad (7)
\]

Magnetic circuit reactance:

\[
X_{mSP} = \frac{V_{0SP}}{I_{mSP}} \quad (8)
\]

Magnetizing inductance:

\[
L_{mSP} = \frac{X_{mSP}}{2 \times \pi \times 50} \quad (9)
\]

No load power factor for SPW:

\[
\cos \varnothing_{0AP} = \frac{P_{0AP}/3}{V_{0AP} \times I_{0AP}} \quad (10)
\]

Magnetizing current/phase:

\[
I_{mAP} = I_{0AP} \sin \varnothing_{0AP} \quad (11)
\]
Magnetic circuit reactance:

\[ X_{m_{AP}} = \frac{V_{DAP}}{I_{m_{AP}}} \]  

(12)

Magnetizing inductance:

\[ L_{m_{AP}} = \frac{X_{m_{AP}}}{2 \pi f \times 50} \]  

(13)

\[ j\omega_{SP} L_{m_{AP}}^{'} = jX_{m_{AP}} \times \frac{n_{SP}}{n_{AP}} \]  

(14)

\[ R_{r} = \frac{s_{AP}}{n_{SP}} \times \frac{n_{SP}}{n_{AP}} \times \frac{R_{AP}}{s_{SP}} \times \frac{s_{SP}}{s_{AP}} \]  

(15)

\[ \frac{n_{AP}}{n_{SP}} = \frac{n_{r}}{n_{s}} \]  

(16)

\[ L_{m_{AP}} = \left( \frac{l_{m_{SP}}}{n_{r}^2} \right) \times \frac{P_{SP}^{2}}{P_{AP}^{2}} \]  

(17)

\[ R_{r} = \frac{R_{r}^{'}_{SP}}{n_{SP}^2} \]  

(18)
4.2.4. Simulation Results of BDFIM-Based WECS.

BDFIM-based WECS is simulated in MATLAB Simulink using wind turbine and BDFIM mathematical models. (Y_he equivalent circuit parameters of the prototype BDFIM are used to model BDFIM.

A wind turbine is a rotating machine which converts the kinetic energy of air into mechanical energy. The mechanical power output of the wind turbine, \( P_T \), is given by (18) [23–28]:

\[
P_T = \frac{\rho AC_p(\lambda, \beta)v^3}{2},
\]

where \( \lambda \) is the tip speed ratio, \( A \) is the turbine swept area, \( \rho \) is the air density, \( \beta \) is the blade pitch angle in degrees, \( v \) is the speed of wind in m/s, and \( C_p \) is the performance coefficient of the wind turbine. Expression for \( C_p \) is given by (19):

\[
C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{-12.5/\lambda_i},
\]

(21)

where

\[
1 = \frac{1}{\lambda} + 0.08 \frac{\beta}{\lambda^2} - \frac{0.035}{\beta^2 + 1}.
\]

(22)

The tip-speed ratio,

\[
\lambda = \frac{\omega R}{v}.
\]

(23)

Equation (21) gives the expression for the tip-speed ratio, where \( R \) is the radius of swept area in meter and \( \omega \) is the angular speed of turbine in radians per second.

The wind turbine model is created in MATLAB Simulink using the above equations and wind turbine specifications. The wind turbine simulation model is shown in Figure 12, and the simulation results are shown in Table 11. The wind turbine simulation results show that, at the rated wind speed of 14 m/s, the turbine power output is 4530 Watts. For the given air density and swept area, the output power increases proportionally to the cube of wind speed until it reaches the rated wind speed. In order to protect WECS from damage, the turbine is stalled if the rated value is exceeded.

Dynamic equations of BDFIM in d-q reference frame can be derived using generalized machine theory [19, 20]. Equations (23–25) provide voltage equations for one rotor winding and two stator windings, flux equations, electromagnetic torque equations, and real power through the SPW and APW (27):

| Table 5: Results of the simple induction mode of BDFIM with excited SPW. |
|-----------------------------|---------------------------|----------------|------------------------|------------------------|
| Winding | Voltage, \( V_{OSP} \) (V) | Current, \( I_{OSP} \) (A) | Speed, \( N_{OSP} \) (rpm) | Power, \( P_{OSP} \) (W) |
| SPW | 415 | 2.1 | 993 | 240 |

| Table 6: Results of the simple induction mode of BDFIM with excited APW. |
|-----------------------------|---------------------------|----------------|------------------------|------------------------|
| Winding | Voltage, \( V_{OAP} \) (V) | Current, \( I_{OAP} \) (A) | Speed, \( N_{OAP} \) (rpm) | Power, \( P_{OAP} \) (W) |
| APW | 415 | 2 | 2990 | 700 |

| Table 7: Results of the cascade induction mode of BDFIM with excited SPW. |
|-----------------------------|---------------------------|----------------|------------------------|------------------------|
| Winding | Voltage, \( V_{CSPP} \) (V) | Current, \( I_{CSPP} \) (A) | Speed, \( N_{CSPP} \) (rpm) | Power, \( P_{CSPP} \) (W) |
| SPW | 415 | 3.7 | 758 | 400 |

| Table 8: Results of the cascade induction mode of BDFIM with excited APW. |
|-----------------------------|---------------------------|----------------|------------------------|------------------------|
| Winding | Voltage, \( V_{CAP} \) (V) | Current, \( I_{CAP} \) (A) | Speed, \( N_{CAP} \) (rpm) | Power, \( P_{CAP} \) (W) |
| APW | 415 | 1.25 | 755 | 700 |

| Table 9: Slip and voltage values in SPW and APW. |
|-----------------------------|---------------------------|
| Parameter | Value |
| \( v_{SP} \) (V) | 117.31 |
| \( v_{AP} \) (V) | 41 |
| \( s_{SP} \) | 0.0999 |
| \( s_{AP} \) | 0.5 |

\[
L_{r} = \frac{L_{r}^{\prime}}{n_{AP}^{2}}
\]

(19)
BDFIM modelling in MATLAB Simulink was done using the above equations and equivalent circuit parameters extracted from hardware. Figure 13 depicts the Simulink model of BDFIG, while Figure 14 depicts the Simulink model of BDFIG-based WECS connected to the grid. The results of the Simulink model of BDFIM-based WECS connected to the grid are shown in Table 2. It can be seen that, as the wind speed increases, so does the generated real power. Figure 15 depicts the plot of BDFIM rotor speed in per unit, while Figure 16 depicts the variations in SPW power, APW power, and total BDFIM power in per unit with respect to wind speed using the rated value as the base value. The rotor speed variation in conventional induction generator-based wind electric generators is less, but in BDFIM-based WEG, a wide speed variation is seen ranging from 1.02pu to 1.78pu, which helps to maximise the power conversion of the wind turbine, indicating the superiority of BDFIG over DFIG. The obtained $C_p - \lambda$ characteristic of WTE bears a close resemblance with that of the simulated wind turbine, which is seen in Figure 17. This also resembles the curve of a real wind turbine. As a result, a DC motor with series resistance effectively represents all of the characteristics of a wind turbine.

Figure 18 depicts a graph of WEG output power versus wind speed for both hardware and simulation, with varying WTE armature voltages mapped to wind speed. The power output of BDFIG at the rated wind speed is 3130.98 W; the rotor speed variation is from 1.02 p.u. to 1.78 p.u., or 42.7% between no load and full load. There is a 40% rotor speed variation with BDFIG [10] and a 30% speed variation with DFIG [6]. A wide range of rotor speed variation is required for maximum wind turbine power extraction. As a result, the proposed work validates the superiority of BDFIG over DFIG; it also demonstrates the improved performance of the BDFIM with delta-star winding in stator over the standard design of conventional windings. At the rated wind speed, the power delivered by
BDFIG and wind turbine is 3130.98 W and 4561.42 W, respectively; the low efficiency of BDFIG is due to its smaller power rating and laboratory scale manufacturing. Based on the findings, it is possible to conclude that BDFIG is suitable for WECS with maximum power extraction.

The proposed work can be expanded for future research by taking into account the following issues:

<table>
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<th>Wind speed (m/s)</th>
<th>Turbine torque (Nm)</th>
<th>Turbine speed (rad/sec)</th>
<th>Turbine power (W)</th>
<th>$C_p$</th>
<th>$\lambda$</th>
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</tbody>
</table>
(i) The proposed BDFIM’s performance can be improved further by optimising the machine’s dimensions

(ii) In variable speed applications, the proposed BDFIM motor can be compared to other conventional machines

Figure 14: Simulink model of grid connected BDFIG-based WECS.

Figure 15: Plot of BDFIM rotor speed with wind speeds.

Figure 16: Plot of generated power of BDFIG with wind speed.

Figure 17: $C_p$–$\lambda$ characteristic of wind turbine emulator and simulated wind turbine.
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Conflicts of Interest
The authors declare that they have no conflicts of interest.

References


