Abstract: Brushless doubly-fed induction machine (BDFIM) has recently gained considerable research interests due to its promising features when incorporated as wind generator or variable speed drive. The BDFIM has two three-phase stator windings with different pole-pair numbers and excitation frequencies. The performance of the machine is based on the magnetic cross-coupling of rotating fields produced by the stator windings through a special squirrel cage rotor. Contrary to the conventional induction machine (IM), the rotor slip and frequency are high throughout the operating speed range. Hence, the rotor core loss cannot be ignored in the steady-state analysis. Although the core loss components have much more study of BDFIM. In this study, analytical expressions are individually derived for a number of core loss components caused by the complicated nature than those of an IM, the precise calculation of these components is important especially on the efficiency of each stator winding field. Then, the modified steady-state electric equivalent model is developed by considering the components. The experiments and finite element analysis based on a 3 kW prototype BDFIM verify the accuracy of the proposed model.

1 Introduction

Brushless doubly-fed induction generator (BDFIG) is an appropriate choice for incorporating in wind turbines due to its superior features in comparison to conventionally used doubly-fed induction machine, i.e. lower cost of maintenance and repair and higher reliability [1–4]. BDFIG has two sets of three-phase winding similar to the induction machine. In addition, the constant core loss in the steady-state model of BDFIG [5] has been used that it is not suitable for special flux distribution in the BDFIM [10]. In fact, the maximum flux density of power winding cannot be equal to the maximum flux density of power winding similar to the induction machine. In addition, the constant coefficients in relations of hysteresis and eddy current losses cannot be as the same as the coefficients in the conventional

Nomenclature

\( P \) electric power
\( V \) voltage
\( I \) current
\( E \) induced EMF
\( B \) flux density
\( R \) resistance
\( L \) inductance
\( s \) slip
\( p \) pole-pair number
\( \omega \) angular frequency
\( f \) frequency

Subscripts and superscripts

\( p \) power winding
\( c \) control winding
\( m \) magnetisation
\( ag \) air gap
\( fe \) iron core
\( cu \) copper
\( sl \) stray load loss
\( f&w \) friction and windage
\( ps \) stator power winding
\( cs \) stator control winding
\( r \) rotor

Furthermore, it is essential the difference between stator pole pairs be greater than one for decreasing unbalanced magnetic pull on the rotor [5]. The rotor carries a special type of cage winding that introduces magnetic cross-coupling between stator fields. The most conventional type of rotor winding with modulation flux capability is the nested-loop arrangement. The number of rotor poles or nests \((p_r)\) for satisfying the cross-coupling becomes

\[
p_l = p_p + p_c
\]

where \( p_p \) and \( p_c \) denote the number of PW and CW pole-pairs, respectively [5].

The calculation of core loss in an induction machine (IM) is difficult due to non-uniform distribution of flux density in the core. However, the core loss value in BDFIG is higher and complicated than a conventional IM because of the following reasons:

- Air-gap field waveform consists of two rotating fields with different speeds.
- The rotor winding produces a high level of spatial harmonic distortion, besides the components which are generated by a rotor with \( p_p \) and \( p_c \) pole-pairs.
- The rotor slip is high in the overall operating speed range of BDFIG [6]. So, the rotor core loss cannot be ignored in the steady-state analysis.

The literature review reveals that few published research works have considered the core loss in the steady-state model of BDFIG [7–10]. In [7], using two-dimensional finite element analysis (FEA), simulation of core loss including of non-linear effects and saturation of iron has been performed. However, to calculate the hysteresis and eddy current losses, the classical model of the conventional induction machines has been used that it is not suitable for special flux distribution in the BDFIM [10]. In fact, the maximum flux density in BDFIM for calculating hysteresis and eddy losses cannot be equal to the maximum flux density of power winding similar to the induction machine. In addition, the constant coefficients in relations of hysteresis and eddy current losses cannot be as the same as the coefficients in the conventional
induction machine. Also, analytic relationships have not been presented for calculating the core loss. In [8], an analytical model was presented for the calculation of hysteresis loss in the stator of BDFIM. However, the authors do not pay attention to eddy current loss and do not develop a model regarding the core loss. Besides, they do not evaluate the accuracy of the proposed model by experiments. In [9], the core loss and the stray load loss are formulated by using the experimental and FEA results. Also, to calculate the spatial harmonic components of the stator and rotor magnetic fields, an analytical method is presented. The components of the core loss, however, are not separated, and the BDFIG equivalent circuit is not introduced. In [10], the equivalent circuit of BDFIM is modified by taking into account the core loss, similar to the approach presented in [11] for cascade doubly-fed machine (CDFM). The stator and rotor core losses are modelled as shunt resistances parallel with magnetising reactances. The accuracy of the proposed model is verified by simulation and experimental studies. However, the authors have neglected the rotor core loss resistances, due to its complexity of calculations and lab measurements.

The presentation of an analytical model with individual core loss components is significantly important, especially when the model-based optimised efficiency strategy is the objective function. In this paper, a modified steady-state model taking account of individual core loss components is developed, so that rotor and stator core loss equivalent resistances due to CW and PW excitations are separately derived. The main contributions of this paper are

- To suggest a method to separately calculate each component of CW and rotor core losses.
- To present an analytical method for calculating the rotor copper and core loss.
- To develop an analytical model taking core loss components into account for BDFIG.

This paper is organised as follows. The operating principle of BDFIG is discussed in Section 2 and the calculation of core loss components is presented in Section 3. The proposed approach for evaluating the BDFIG core loss is presented in Section 4 by describing the core loss components relationships and, the modified equivalent model is finally presented. In Section 5, in order to validate the feasibility and accuracy of the proposed approach, the experimental and finite element results are obtained based on a 3 kW prototype D132s-BDFIG. Eventually, a conclusion of the results is presented.

2 Brushless doubly-fed induction generator

Doubly-fed induction generators (DFIGs) are widely used in wind farms [12–15]. It has been known that BDFIG presents several advantages over DFIG such as no need for brushes and ship-rings, lower maintenance cost, requiring two-stage mechanical gear-box than three-stage, better low-voltage ride-through capability, and more robust structure. The operating speed region is considered ±30% around the natural synchronous speed. Therefore, the BDFIG needs a converter with a lower rating compared to generators which requiring full power rating converters in variable speed applications (such as permanent magnet synchronous generator), the disadvantages of BDFIG are related to higher weight and volume, and lower efficiency [9, 16]. Also, the BDFIG converter rating is slightly larger compared to the DFIG in a similar condition due to its lower power factor. Recently, several research efforts have been performed to make it technically and commercially applicable to using BDFIG in wind turbines [17–19]. It is hoped that BDFIG can be a suitable wind energy conversion system besides the other existing machine types shortly.

The frequency of CW-side converter to bring about the cross-coupling and having one specific rotor frequency is

\[ o_\text{c} = p_\text{c} o_\text{s} - o_\text{p} \]  

(2)

where \( o_\text{p} \) and \( o_\text{c} \) are the PW and CW angular frequencies, respectively, \( o_\text{s} \) is the angular rotor speed in rad/s. It can be seen that the CW frequency is zero at the natural operating speed of \( o_\text{r} / p_\text{r} \). The rotor slips due to CW and PW rotating magnetic fields are as (3) and (4), respectively [5]

\[ s_\text{p} = (o_\text{p} - p_\text{p} o_\text{s}) / o_\text{p} \]  

(3)

\[ s_\text{c} = (o_\text{c} - p_\text{c} o_\text{s}) / o_\text{c} \]  

(4)

Contrary to conventional IM the rotor core loss is significant due to high rotor frequency. Also, the presence of a rotating field with two dominant rotating components with different frequencies is the main reason for the complexity of calculating the stator core loss. It can be concluded from (1) to (4) that \( o_\text{c} / o_\text{p} \) ratio is \( (-s_\text{p} / s_\text{c}) \) and \( o_\text{c} \) can be written as

\[ o_\text{c} = o_\text{p} \left(1 - s_\text{c} / s_\text{p}\right) = o_\text{s} (1 - s) \]  

(5)

where

\[ s = s_\text{p} / s_\text{c} \]  

(6)

The slip equation in (5) is similar to the slip relation of conventional IM. For example, the referred CW voltage to PW side is multiplied by 1/s or

\[ s_\text{c} / s_\text{p} = o_\text{p} / o_\text{c} \quad \text{or} \quad o_\text{c} = o_\text{p} / s_\text{p} \]  

(7)

Figs. 2a and b show graphically the dependency of \( s \) and \( s_\text{c} / s_\text{p} \) to mechanical rotating speed for a prototype D132s-BDFIG. The specifications of this machine fabricated for studies in this paper are listed in Table 1.

In practice, the operating speed region is considered ±30% around natural speed [20]. It is predictable that the minimum core loss is happening at the natural speed under zero excitation of CW.
Table 1 Specifications of prototype fabricated D132s-BDFIG

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>frame size</td>
<td>132 S</td>
</tr>
<tr>
<td>stator core length</td>
<td>106 mm</td>
</tr>
<tr>
<td>PW/CW pole-pairs</td>
<td>2/4</td>
</tr>
<tr>
<td>connection of stator PW/CW</td>
<td>star/star</td>
</tr>
<tr>
<td>natural speed</td>
<td>500 rpm</td>
</tr>
<tr>
<td>operating speed</td>
<td>350–650 rpm</td>
</tr>
<tr>
<td>stator/rotor slots</td>
<td>48/36</td>
</tr>
<tr>
<td>PW rated voltage</td>
<td>180 V (at 50 Hz)</td>
</tr>
<tr>
<td>CW rated voltage</td>
<td>200 V (at 50 Hz)</td>
</tr>
<tr>
<td>PW rated current</td>
<td>9.7 A</td>
</tr>
<tr>
<td>CW rated current</td>
<td>4.25 A</td>
</tr>
<tr>
<td>rated torque</td>
<td>25 N·m</td>
</tr>
<tr>
<td>R1 (Ω) direct measurement in 20°C</td>
<td>1.18 Ω</td>
</tr>
<tr>
<td>R1 (Ω) direct measurement in 75°C</td>
<td>1.42 Ω</td>
</tr>
<tr>
<td>R2 (Ω) direct measurement in 20°C</td>
<td>6.32 Ω</td>
</tr>
<tr>
<td>R2 (Ω) direct measurement in 75°C</td>
<td>7.6 Ω</td>
</tr>
<tr>
<td>rotor design</td>
<td>nested-loop</td>
</tr>
<tr>
<td>PW/CW turns ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>inertia</td>
<td>0.04 kg·m²</td>
</tr>
</tbody>
</table>

has two different frequencies. For example, due to operation around natural speed, in the generating mode, the amplitude and frequency of the CW current are usually less than those for the PW, which causes the time oscillation of the PW magnetic field superimposes on the CW field waveform. The time variation of the magnetic field in a stator tooth for prototype D132s-BDFIG using 2D-FE simulation is shown in Fig. 3, in which oscillations with two frequencies are obvious.

- Eddy current loss in stator and rotor core: Eddy current loss in the stator teeth and yoke is proportional to the square of the maximum flux density of the stator core and it is separated to sum of two average waveforms with \( p_\beta \) and \( p_\alpha \) pole pairs. Also, eddy current loss in the rotor teeth and yoke is proportional to the square of the maximum flux density of the rotor core and it can be expressed by averaging on the square of magnetic field waveform. In [9], the relationships of the eddy current loss of the stator and rotor core are expressed for BDFIG.

- Hysteresis loss in stator and rotor core: The BDFIG rotor is single frequency and its hysteresis loss is calculated by using the conventional approaches such as Steinmetz method [21]. At the standstill, the stator core is subjected to a single frequency flux and the hysteresis loss of stator is obtained through the Steinmetz method similar to hysteresis loss of rotor. When the rotor speed is non-zero and generally, at the synchronous mode, the stator core is subjected to two fields with different frequencies. As a result, the calculation of the stator hysteresis loss is very complex. In [9], the modified Steinmetz equation (MSE) proposed in [21] has been used to calculate the hysteresis loss in the stator core. In this approach, an equivalent frequency determined by magnetising rate is substituted in the Steinmetz equation. According to [1], the proper value of BDFIG magnetic loading is recommended as \( \sqrt{B_{\text{st}}^p + B_{\text{st}}^c} \), therefore a method for calculating the stator hysteresis loss is the stator field estimation as a magnetic field with the amplitude of \( \sqrt{B_{\text{st}}^p + B_{\text{st}}^c} \) and the frequency of \( f_\text{st} \). In [10], it is claimed that for the calculation of hysteresis loss that the magnetic fields caused by two stator windings can be roughly separated for the calculation of hysteresis loss. Hence, the hysteresis loss in the stator core can be expressed as

\[
P_{\text{hys}} = P_{\text{hys}}^\alpha + P_{\text{hys}}^\beta
\]

\[
= K_h \cdot N_{\alpha,c} \cdot \left( \left( B_{\text{max}}^\alpha \right)^{\alpha} \cdot v_{\text{st}} + \left( B_{\text{max}}^\beta \right)^{\beta} \cdot v_{\text{st}} \right)
\]

\[
= K_h \cdot N_{\alpha,c} \cdot f_\beta \left( \left( B_{\text{max}}^\alpha \right)^{\alpha} \cdot \left( B_{\text{max}}^\beta \right)^{\beta} \right) \cdot v_{\text{st}}
\]

\[
+ \left( \left( B_{\text{max}}^\alpha \right)^{\alpha} \cdot \left( B_{\text{max}}^\beta \right)^{\beta} \right) \cdot v_{\text{st}}
\]

where \( P_{\text{hys}}^\alpha \) is the hysteresis loss of the stator tooth/yoke, \( K_h \) is the hysteresis loss coefficient, \( N_{\alpha,c} \) is the number of the stator slots, \( B_{\text{max}}^{\alpha,\beta} \) is the magnitude of the \( p_\beta \) (\( p_\alpha \)) pole-pairs component of stator tooth/yoke magnetic field. \( v_{\text{st}} \) is the volume of the stator tooth/yoke. Also, \( \alpha \) and \( \beta \) are constant coefficients depending on magnetic material. If according to [10], the values of \( \alpha \) and \( \beta \) are considered 1 and 2, respectively, hysteresis loss in stator core can be expressed as

\[
P_{\text{hys}} = K_h \cdot N_{\alpha,c} \cdot f_\beta \left( \left( B_{\text{max}}^\alpha \right)^2 + \left( B_{\text{max}}^\beta \right)^2 \right) \cdot v_{\text{st}}
\]

\[
+ \left( \left( B_{\text{max}}^\alpha \right)^2 + \left( B_{\text{max}}^\beta \right)^2 \right) \cdot v_{\text{st}}
\]

It should be noted that (9) is precise in standstill condition. However, it is an adequate approximation while the rotor is rotating.

4 Proposed approach to determine the BDFIG core loss

Fig. 4 shows the BDFIG loss components, including the rotor and stator copper losses, the rotor and stator core losses, the friction and windage losses and the stray load. As previously discussed, the rotor core loss is significant and cannot be neglected.

The core loss of a BDFIG can be separated into four components:

i. Stator core loss due to the PW field \( (P_{\text{er}}^\alpha) \).
ii. Stator core loss due to the CW field \( (P_{\text{er}}^\beta) \).
iii. Rotor core loss due to the PW field \( (P_{\text{ecr}}^\alpha) \).
iv. Rotor core loss due to the CW field \( (P_{\text{ecr}}^\beta) \).
Individual calculation of rotor core loss components is difficult. Therefore, the sum of rotor core loss components is considered $(P_{fe}^r = P_{fe}^{cs} + P_{fe}^f)$. The net core loss can be written as

$$P_{fe} = P_{fe}^{cs} + P_{fe}^f + P_{fe}^{el}$$

(10)

The equivalent resistances caused by core loss components are determined as follows.

### 4.1 Equivalent resistance of the core loss due to PW field

The base core loss resistance due to PW field $(R_{fe,b}^{cs})$ is determined at the rated voltage and frequency of PW. Since these values are constant, $R_{fe,b}^{cs}$ is a constant quantity. $R_{fe,b}^{cs}$ is determined according to (11) by measuring $P_{fe}^{cs}$. This resistance is in parallel with PW magnetising reactance

$$R_{fe,b}^{cs} = \frac{3E_{om}^2}{P_{fe}^{cs}}$$

(11)

where $E_{om}$ is the PW induced back-EMF, which can be approximately considered as $V_p$ under no-load operating condition.

To measure $P_{fe}^{cs}$, PW is connected to the grid while CW is open circuit and the machine transfers no power. The measured no-load PW input power comprises stator and rotor copper and core losses, friction and windage losses and stray load loss

$$P_{fe}^{cs} = P_{fe}^{el} + P_{fe}^{cs} + P_{fe}^{cu, NL} + P_{fe}^{cu, NL}$$

(12)

Under this condition, the no-load speed is near the synchronous speed of PW. As a result, the rotor and stray load losses are negligible. This is the same as the conventional IM, comply with IEC 60034-2-1 standard. Therefore, (12) is simplified as

$$P_{fe}^{cs} = P_{fe}^{el} + P_{fe}^{cs} + P_{fe}^{cu, NL}$$

(13)

The no-load value of PW copper loss is calculated by the following equation:

$$P_{fe}^{cu, NL} = 3R_p \cdot I_p^{cu, NL}$$

(14)

The friction and windage losses can be determined based on the approach established in IEEE standard 112. In the manner, the PW copper loss is subtracted from no-load input power and the resulting power, i.e. the sum of core loss and friction and windage losses is depicted versus excitation voltage. The friction and windage losses are approximately obtained by finding the intersection point of this curve and the power axis. The stator core loss due to PW field is resulted using (15) by subtracting the PW copper loss and friction and windage losses from no-load input power

$$P_{fe}^{el} = P_{fe}^{el} - (P_{fe} + P_{fe}^{cu, NL})$$

(15)

It should be noted that the stator core loss due to PW field can be considered constant because of the direct connection of PW to the public grid with deterministic voltage and frequency. The equivalent base resistance for modelling stator core loss due to the PW field is calculated using (11).

### 4.2 Equivalent base resistance modelling stator core loss due to the CW field $(R_{fe,b}^{cs})$

The CW voltage and frequency vary with varying the rotating speed in a synchronous mode of operation. Hence, the stator core loss due to the CW field can be expressed as

$$R_{fe,b}^{cs}(\alpha_r, V_i) = \frac{3E_{om}^2}{P_{fe}(\alpha_r, V_i)}$$

(16)

It can be shown that the magnitude of CW voltage and frequency almost increases linearly by increasing slip $(s)$, which results in the constant magnitude of CW magnetic field [10]. However, the stator core loss due to CW $(P_{fe}^{bcs})$ varies by the CW frequency variation. Hence, it is not possible to assign a constant resistance for modelling the stator core loss due to the CW field $(R_{fe,b}^{cs})$.

The relation of this equivalent resistance, which depends on the CW frequency, is

$$R_{fe,b}^{cs}(\alpha_r) = R_{fe,b}^{cs}(s=0) = \frac{3E_{om}^2}{P_{fe}(\alpha_r)}$$

(17)

To the referred value of $R_{fe,b}^{cs}$ to PW side is calculated using the following equation:

$$R_{fe,b}^{cs}(s) = \frac{R_{fe,b}^{cs}(s=0)}{s} = \frac{N_p}{N_s} \frac{1}{s} R_{fe,b}^{cs}(\alpha_r)$$

(18)

where $N_p(N_s)$ is equivalent turn ratio of PW (CW) to the rotor.

The modified equivalent models of CW with inserting $R_{fe,b}^{cs}$ in CW side and referred to PW side are shown in Figs. 5a and b, respectively.

The base value of $R_{fe,b}^{cs}$ is obtained at zero rotating speed. In this operating point, $f_c$ and $f_r$ are the same and the air-gap field oscillates with a single frequency. The rated values of CW voltage and frequency are also defined at zero speed considering their linear dependency of to slip $(s)$. The base resistance for modelling stator core loss due to CW field is evaluated in a similar manner to that due to PW field using nominal values of CW voltage and frequency in zero speed. Accordingly the relation of $R_{fe,b}^{cs}$ can be expressed as follows:

$$R_{fe,b}^{cs} = \frac{3E_{om}^2}{P_{fe,b}^{cs}}$$

(19)

$P_{fe,b}^{cs}$ is obviously satisfied for zero or CW synchronous speed. Since the stator core loss due to CW field is a function of slip so, its base value obtains at $s=1$ and the relation of this core loss component can be expressed as

$$P_{fe}^{bcs}(s) = P_{fe}^{bcs}(s=1)$$

(20)

$\alpha_r$ coefficient is considered 1.3 in [10] similar to the conventional squirrel cage IM. There is not any reported research on determining the value of $\alpha_r$ coefficient for BDFIG. The procedure of extracting this parameter with more precision is presented in Section 5.

### 4.3 Equivalent base resistance for modelling rotor core loss

The rotor electric quantities oscillate with one frequency in synchronous operation mode. This frequency is dependent on the rotor slip $(f_s = \frac{1}{s} \cdot f_p)$, which is much larger than that of

$$P_{fe}^f = P_{fe}^f$$

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The referred value of rotor copper loss is expressed as

$$ P_{cu,r} = \frac{3E_{in}^2(s_{ph}\omega_h)}{V_p^2} $$

The referred value of rotor copper loss is obtained from

$$ R_{eq}^2(s_b) = \frac{1}{N_p^2} R_{eq}(s_{ph}\omega_h) = (N_p)^2 \frac{1}{V_p^2} \frac{3E_{in}^2(s_{ph}\omega_h)}{P_{cu,r}(s_{ph}\omega_h)} $$

where

$$ E_{in}(s_{ph}\omega_h) = s_q \cdot \left( \frac{1}{N_p} \right) E_{mp}(s_{ph}\omega_h) $$

The modified equivalent models for considering rotor core loss in the rotor side and referred to PW side are shown in Figs. 6a and b, respectively.

The rotor core loss is a function of $s_q$. The base value of $P_{r,eq}$ can be obtained at $s_q = 1$, then the relation of this core loss component can be expressed as

$$ P_{r,eq}(s_b) = P_{r,1.0}\left| s_b \right|^b $$

The procedures for determining the values of $b$ and $P_{r,1.0}$ are presented in Section 5. The direct measurement of the rotor and CW core losses is very difficult. In this paper, however, an appropriate approach is presented by (20) and (24).

4.4 Determination of rotor core loss and stator core loss due to CW field

According to Fig. 4, the summation of stator core loss due to CW field and rotor core loss can be written as follows:

$$ P_{st,eq}^s + P_{r,eq}^s = \Delta P - (P_{cu}^s + P_{cw}^s) + P_{sw}^s + P_{cw}^s $$

where $\Delta P$ consists of the total loss of BDFIG. This relationship is true for all the operating regions of the BDFIG. The copper losses of PW and CW, friction and windage loss and stator core loss due to the PW are measured, as described previously. The stray load loss $P_{st,eq}$ is due to the slotting and MMF spatial harmonics. The value of stray load loss depends on the winding currents. Most of the researches on stray load loss have been performed for IM [22]. It is shown in [23] by measurements that the stray load loss is in the range of 0.4 – 0.6% and 3.5 – 4% for small and large rated IMs, respectively. It is stated in [9] that the value of stray load loss is higher in BDFIM than IM. For conventional induction machines, the stray load is 0.5% of output power, according to IEC 60034-2, 1.8% of the output power, according to IEEE standard 112-2017 (ratings below 125 hp), and 1.2% of the output power, according to the NEMA MG1 standard (ratings below 2500 hp). The stray load loss of BDFIG is higher than IM even at no-load condition because of the no-load condition, stator and rotor surface loss, and teeth pulsation loss can be significant in comparison with conventional IM. Since it is not intended to accurately calculate the stray load loss, this value is almost 2.5% of input power at each point of test, in accordance to IEC 61972 (for our prototype D132s-BDFIG).

The equivalent circuit presented in [24] is used to calculate $P_{cu,eq}$. This equivalent circuit, which is shown in Fig. 7 is valid for all the operating modes of BDEIM.

The referred value of rotor current is obtained by applying the voltage law to the middle loop of equivalent circuit

$$ I_i = \frac{E_{mp} - E_{in}^2/s}{(R_i/\beta_i) + jX_i} = \frac{E_{mp} - (E_{in}^2/s)(\cos \delta + j\sin \delta)}{(R_i/\beta_i) + jX_i} $$

where $\delta$ is the angle between $E_{mp}$ and $E_{in}^2$ [24].

The rotor copper loss is

$$ P_{cu,r} = 3|R_i|^2 $$

$$ P_{cu,r} = 3R_i \left[ (E_{mp} - (E_{in}^2/s))^2 + 2(E_{mp} \cdot E_{in}^2/s)(1 - \cos \delta) \right] $$(27)

The $\delta$ is calculated by using presented the Thevenin equivalent circuit in [25]. According to the proposed relationship, the $\delta$ is determined to calculate the active power of the PW

$$ \delta = \xi - \cos^{-1} \left( \frac{V_p \cdot \cos \xi - ZP_{cw} \cdot 3V_p V_c}{3V_p V_c} \right) $$

where $\xi$ and $Z$ are impedance angle and impedance of machine at the Thevenin equivalent circuit, respectively [25]. The equivalent circuit parameters of prototype D132s-BDFIG, which are implemented using a coupled circuit approach presented in [5], are given in Table 2.

In this case, the rotor copper loss will be calculated at any rotor speed. To verify the calculated rotor copper loss, the FEA is used. In this way, with calculate $P_{cu,eq}$, the sum of the rotor and stator core losses due to the CW ($P_{r,eq}^s$), is determined by (25). By calculating the core loss from the proposed method, the per-phase equivalent model of Fig. 8 is obtained on the PW side.

$R_{eq,eq}^s(s)$ in the modified equivalent model of Fig. 8 is evaluated using the following equation:

$$ R_{eq,eq}^s(s) = \frac{N_q^2}{N_p^2} \frac{1}{s} \frac{3E_{in}(s_{ph}\omega_h)}{P_{cu,eq}^s(s)} $$

Using (20) and (24), the relation of $P_{r,eq}^s$, which is a function of $s$, can be written as

$$ P_{r,eq}^s(s) = P_{r,1.0}(s) + P_{r,eq}^s(s_b) = P_{r,1.0}(s) + P_{r,eq}^s(s_b) $$

(30)

It is possible to separately determine the core loss components of rotor and stator core loss due to the CW field. To separate the rotor and CW stator core losses, by measuring the base core loss due to the CW filed ($P_{st,eq}$) and rotor ($P_{r,eq}$), and $P_{r,eq}(s_b)$, the coefficients $\alpha$ and $\alpha_c$ can be achieved. To verify the results, the FEA is performed and the rotor core loss is achieved. Then, the CW core loss is derived and the results are compared, according to the following equation:

$$ P_{st,eq}(s) = P_{st,eq}(s) + P_{st}(s_b) = P_{st,eq}(s) + P_{st}(s_b) $$

The referred value of rotor core loss is obtained by applying the voltage law to the middle loop of equivalent circuit

$$ I_i = \frac{E_{mp} - E_{in}^2/s}{(R_i/\beta_i) + jX_i} = \frac{E_{mp} - (E_{in}^2/s)(\cos \delta + j\sin \delta)}{(R_i/\beta_i) + jX_i} $$

(26)
The induced CW voltage at different speeds with fixed excitation of PW is shown in Fig. 12a. PW is fed with a three-phase voltage source of 90Vrms and 50 Hz, while CW is left open circuit. Under these conditions, the cross-coupling capability of BDFIG can be recognised. As can be seen, the induced voltage decreases at speeds very close to the natural synchronous speed. The PW input power curve versus PW voltage is shown in Fig. 12b.

The value of friction and windage losses near 1500 rpm (PW synchronous speed) can be obtained by fitting a curve on the measured data, which is obtained almost 53.8 W using the method described in Section 4.

To measure the friction and windage losses of BDFIG at the speed range of 300–700 rpm, first, the desired speed is set by adjusting the PW supply frequency. Similar to the procedure described in Fig. 12b, the friction and windage losses are obtained by decreasing the PW voltage. This procedure should be done for measuring friction and windage losses at each desired speed. The reduction of the PW frequency to achieve the desired speed can change the PW core loss. Hence, it is necessary to reduce the PW voltage to almost zero in order to accurately calculate friction and windage losses, according to the IEEE standard 112.

The friction and windage loss curve of the studied machine at different speeds is shown in Fig. 12c. It is obvious that the value of this loss component is lower in the case of BDFIG with 4/8 pole-pair windings than a 4-pole IM. Fig. 12d shows the stator core loss due to the PW field while CW is left open-circuit. According to this curve, the value of stator core loss due to the PW field is 30.5 W when exciting PW with rated voltage and frequency. According to (11) by neglecting voltage drop due to winding impedance, the cross-coupling capability of PW and CW sides is 570 Ω. It is should be noted that at the no-load conditions of both windings are recorded.

It is possible to test the BDFIG at all operating areas and different slips at the no-load. To obtain $P_{cu}$ and $P_{fe.eq}$, the no-load test is carried out in two manners:

- PW is exited via a constant voltage and frequency of 180 V and 50 Hz, respectively, and the rotating speed is varied from standstill to 1500 rpm. CW is open-circuited, and the electrical quantities of both windings are recorded.
- CW is exited via a voltage-source inverter with constant $V_l/f_c$ ratio and the rotating speed is adjusted so that the induced PW voltage be of rated magnitude and frequency, and the measured data are recorded. Using this collected information and the other required loss components; i.e., stator core loss due to PW field, base core loss due to CW field, friction and windage losses, stray load loss, it is possible to determine $P_{cu}$ and $P_{fe.eq}$ as described in Section 4. From this test, the base core loss due to the rotor is 56.9 W, and the base resistance of the rotor core loss the PW sides is 570 Ω. It is should be noted that at the no-load conditions of both windings are recorded.

### Table 2: Equivalent circuit parameter values for D132s-BDFIG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R_p$, Ω</th>
<th>$L_p$, H</th>
<th>$L_{eqcs}$, H</th>
<th>$R_s$, Ω</th>
<th>$L_s$, H</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>1.3012</td>
<td>0.0047</td>
<td>0.1863</td>
<td>1.1237</td>
<td>0.0206</td>
</tr>
</tbody>
</table>

The specifications of this machine, which are used for studies in this section, three rotor speed intervals are considered and the related $s_p$, $s_c$ and $s$ intervals are stated in Table 3.

The induced CW voltage at different speeds with fixed excitation of PW is shown in Fig. 12a. PW is fed with a three-phase voltage source of 90Vrms and 50 Hz, while CW is left open circuit. Under these conditions, the cross-coupling capability of BDFIG can be recognised. As can be seen, the induced voltage decreases at speeds very close to the natural synchronous speed. The PW input power curve versus PW voltage is shown in Fig. 12b.

The value of friction and windage losses near 1500 rpm (PW synchronous speed) can be obtained by fitting a curve on the measured data, which is obtained almost 53.8 W using the method described in Section 4.

To measure the friction and windage losses of BDFIG at the speed range of 300–700 rpm, first, the desired speed is set by adjusting the PW supply frequency. Similar to the procedure described in Fig. 12b, the friction and windage losses are obtained by decreasing the PW voltage. This procedure should be done for measuring friction and windage losses at each desired speed. The reduction of the PW frequency to achieve the desired speed can change the PW core loss. Hence, it is necessary to reduce the PW voltage to almost zero in order to accurately calculate friction and windage losses, according to the IEEE standard 112.

The friction and windage loss curve of the studied machine at different speeds is shown in Fig. 12c. It is obvious that the value of this loss component is lower in the case of BDFIG with 4/8 pole-pair windings than a 4-pole IM. Fig. 12d shows the stator core loss due to the PW field while CW is left open-circuit. According to this curve, the value of stator core loss due to the PW field is 30.5 W when exciting PW with rated voltage and frequency. According to (11) by neglecting voltage drop due to winding impedance, the resistance modelling stator core loss due to the PW field is evaluated as 1060.3 Ω.

The magnitude of CW induced voltage at different speeds obtained by FE Analyses and experimental measurements is shown in Fig. 13.

It can be seen that $V_l/f_c$ ratio is almost a constant value by changing the rotating speed. Therefore, the CW flux is almost a constant at studied operating speed interval. The stator core loss due to the PW field is 31.5 W at rated excitation condition. According to (19), the base resistances for modelling stator core losses due to CW field in CW and PW sides are 1270, and 688 Ω, respectively.

A voltage source inverter excites CW, which consists of several electronics boards shown in Fig. 11, i.e. driver board, sensor board, TMS320F28335 signal processing board produced by Texas Instrument Co. The rotating speed is measured by a 1024 pulses incremental encoder mounted on BDFIG, shaft. Two Hall-effect current sensors of LEM LTS-6-NP type measure stator phase currents. The line voltages measurements are done using voltage sensors of type LEM LV-25-p. The output signals of these current sensors measure stator phase voltages and currents. The line voltages measurements are done using voltage sensors of type LEM LV-25-p. The output signals of these current sensors are filtered through an analogue second-order low-pass filter with a cut-off frequency of 2.6 kHz. The IGBT modules of SKM40GD124D type are used as inverter switches, which are controlled by HCPL 316-J type intelligent IGBT drivers for acquiring gate signals.

For studies of this section, three rotor speed intervals are considered and the related $s_p$, $s_c$ and $s$ intervals are stated in Table 3.
To predict this loss component precisely and to compare with the proposed approach, a 2D magneto-dynamic FE model has been used. The finite element simulation has been done using the Ansoft Maxwell v16.0. Due to the complex rotor structure, the suitable external circuit has been designed and used. The analytical equations required to calculate the resistances and leakage inductances of the outer region of the rotor has been presented in [27].

The non-linear $B-H$ characteristic of the magnetic steel sheet used in the rotor and stator core (M470-50A grade) is exactly defined in the finite element simulation. The required parameters for core loss calculation are considered in accordance with Table 4. The number and quality of the generated mesh of the model play a significant role in the accuracy and stability of the numerical computation. In the 2D-FE simulation due to the special geometric structure of nested loop rotor, the complete machine cross-section has been used with 63,998 triangular elements. Fig. 14 shows the distribution of mesh elements in the 2D-FE model of D132s-BDFIG cross-section.

The curve of $P_{fe,eq}(f)$ versus rotating speed is experimentally obtained using the proposed approach (Fig. 15). To calculate $\alpha_c$ and $\alpha_r$ coefficients of presented analytical equations, and separating the rotor core loss and stator core loss due to CW field, curve fittings are performed. In this way, $\alpha_c$ and $\alpha_r$ are determined as 0.3 and 1.1, respectively.

The rotor core loss predicted by (24) is compared with the simulated values using the FEM in Fig. 16a. Also, Fig. 16b shows this comparison for the stator core loss due to the CW field, according to (20). The coefficients of developed analytical expressions have been obtained from laboratory practical results. Also, the saturation effect has been completely considered in finite element simulation. A very good convergence of both simulation and experimental results confirms the validity of the proposed model.

There is a good coincidence between the results of the proposed methods and the results of the FE method, which proves the acceptable accuracy of the presented approach. It should be noted that contrary to the conventional IM, the BDFIG rotor core loss over the studied speed interval is not negligible and even is greater than the stator loss due to CW field. By getting away from the natural synchronous speed, the value of CW core loss increases. Also, the rotor core loss increases at sub-synchronous speeds and decreases in the super-synchronous region.

Although the stator CW and rotor core losses are not directly measured, the coefficients of their two derived analytical equations are calculated using practical results. Therefore, these two components of the core loss are indirectly measured. The obtained results have a very good convergence compared with the results of the finite element method, as shown in Fig. 16.

The total core loss curves of the studied D132s-BDFIG over the desired operating speed interval are illustrated in Fig. 17a that are obtained from analytical equations, experimental measurements, and FE simulations. Close agreement is observed between the results.

Fig. 17b shows the no-load rotor copper loss curves over the practical operating speed region of the studied machine, which are obtained using experimental and numerical methods. It can be revealed that the rotor copper loss is high even at no-load operating condition due to the large value of slip.

Finally, the core loss of prototype D132s-BDFIG over its operating speed range is measured with considering and omitting the rotor core loss, as shown in Fig. 18. The comparative performance presented in Fig. 18 indicates that ignoring the rotor core loss causes a significant error from 34.7% up to 45.1% over the operating speed range of prototype D132s-BDFIG.

The main conclusions which can be drawn from these plots are that the curves for different above methods are very close and one may notice that the errors are not too great (approximately <4%). According to the studies of this paper, the modified equivalent model of studied D132s-BDFIG with considering core loss is depicted in Fig. 19.
According to the obtained results, (20) and (24) have been rewritten as

\[ P_{\text{fe}}^{s}(s) = P_{\text{fe}}^{b}\csc^{0.3} \]  
\[ P_{\text{fe}}^{r}(s) = P_{\text{fe}}^{b}\csc^{1.1} \]  

(32)

(33)

By substituting (32) into (17) and (18), the stator core loss due to CW is derived as illustrated in Fig. 19, where \( R_{\text{fe}}^{s}/\csc^{0.3} \) corresponds with the stator CW core loss and \( R_{\text{fe}}^{s}/\csc^{1.1}(1/s_{r}) - 1 \) is the torque component of the stator CW core loss. Also, by substituting (33) into (21) and (22), the rotor core loss is derived as shown in Fig. 19, where \( R_{\text{fe}}^{r}/\csc^{0.3} \) and \( R_{\text{fe}}^{r}/\csc^{1.1}(1/s_{r}) - 1 \) corresponds with the rotor core loss and torque component of the rotor core loss, respectively.

The obtained parameters of the proposed model for D132s-BDFIG are listed in Table 5.

In order to study the effectiveness of the proposed model (Fig. 19e) for estimating the machine variables such as torque, current, and power, the BDFIG has been tested for two sub-synchronous and super-synchronous speeds, at the generating operation mode. To fix the PW power, the CW supply has been controlled for a given speed. The torque and the variations of CW current and power signals are measured. These quantities are also calculated at the steady-state case, with and without considering

---

**Table 3** Speed and slip range for D132s-BDFIG

<table>
<thead>
<tr>
<th>( \omega_{r} ), rpm</th>
<th>300–700</th>
<th>350–650</th>
<th>400–600</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_{r} )</td>
<td>0.533 &lt; ( s_{r} &lt; 0.8 )</td>
<td>0.567 &lt; ( s_{r} &lt; 0.767 )</td>
<td>0.6 &lt; ( s_{r} &lt; 0.733 )</td>
</tr>
<tr>
<td>( s_{c} )</td>
<td>2 &lt; ( s_{c} - 1.333 &gt; s_{c} )</td>
<td>2.556 &lt; ( s_{c} - 1.889 &gt; s_{c} )</td>
<td>3.667 &lt; ( s_{c} - 3 &gt; s_{c} )</td>
</tr>
<tr>
<td>( s )</td>
<td>-0.4 &lt; ( s &lt; 0.4 )</td>
<td>-0.3 &lt; ( s &lt; 0.3 )</td>
<td>-0.2 &lt; ( s &lt; 0.2 )</td>
</tr>
</tbody>
</table>

---

**Table 4** Specification of the iron core (M470-50A) for D132s-BDFIG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>hysteresis loss coefficient</td>
<td>159</td>
</tr>
<tr>
<td>eddy current loss coefficient</td>
<td>0.871</td>
</tr>
<tr>
<td>lamination thickness</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>resistivity</td>
<td>420 n( \Omega )·m</td>
</tr>
<tr>
<td>mass density</td>
<td>7750 kg/m(^3)</td>
</tr>
<tr>
<td>packing factor</td>
<td>0.96</td>
</tr>
</tbody>
</table>

---

**Fig. 12** Measured curves for the PW stator core loss and the friction and windage losses, and the PW cross-coupling

(a) PW cross-coupling characteristic, (b) Input power in terms of PW voltage (NL. Test-in PW synchronous speed), (c) Friction and windage losses curve of the D132s-BDFIG, (d) Core loss due to PW in terms of voltage

**Fig. 13** Variation of CW voltage amplitude as a function of rotational speed for D132s-BDFIG
the rotor core loss. The results are shown in Table 6. The comparison of the results shows that for the proposed model, the average values of error have reduced for torque from 6.6 to 1.9%, for CW power from 10.7 to 2.5%, and for CW current from 7.8 to 2.3%. Accordingly, the precision of quantities estimation for the model without rotor core loss and for the proposed model (with regarding rotor core loss) is about 91 and 97.4%, respectively.

6 Conclusion

In this paper, a new approach for measuring core loss components and rotor copper loss of BDFIG was proposed. Then, analytical relations were presented to model each core loss component as an equivalent resistance in a modified electric equivalent circuit model. Also, the base values of core loss components and their dependencies to rotating speed were derived. To validate the accuracy of the presented method, analytical results were compared with finite element and experimental results of a prototype D132s-BDFIG. A close agreement can be seen between FEA and practical results and a little disagreement seen between these two sets of results may be because of inaccuracies that exist in stray load loss, and our data acquisition system. It should be noticed that the rotor core loss cannot be obviously neglected, because the contribution of the rotor core loss is almost 38% of total core loss. For generating operation mode, the proposed model shows a significant error reduction in estimation of the BDFIG quantities so that the accuracy of the BDFIG quantities estimation is about 97.4%.
References


7 References

Fig. 19 Modified equivalent model of D132s-BDFIG with considering core loss
(a) Model of stator CW, (b) Model of stator CW referred to stator PW, (c) Model of rotor, (d) Model of rotor referred to stator PW, (e) Modified complete model referred per-phase

Table 5 Obtained parameters of the proposed model for D132s-BDFIG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R_{fe,b}$, Ω</th>
<th>$P_{fe,b}$, W</th>
<th>$R_{fe,b}^{'\prime}$, Ω</th>
<th>$P_{fe,b}^{'\prime}$, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>1060.3</td>
<td>30.5</td>
<td>688</td>
<td>31.5</td>
</tr>
</tbody>
</table>

Table 6 Comparison of D132s-BDFIG of quantities estimation results obtained by the experimental tests, the proposed method (with rotor core loss) and without rotor core loss consideration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-synchronous</th>
<th>Super-synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_r$, rpm</td>
<td>300</td>
<td>650</td>
</tr>
<tr>
<td>$s_p$</td>
<td>0.8</td>
<td>0.56</td>
</tr>
<tr>
<td>$s$</td>
<td>0.4</td>
<td>-0.3</td>
</tr>
<tr>
<td>$R_{fe,b}^p$, Ω</td>
<td>1060.3</td>
<td>1060.3</td>
</tr>
<tr>
<td>$(\mu_0 R_{fe,b}^p/</td>
<td>s_p</td>
<td>)^{1.1}$, Ω</td>
</tr>
<tr>
<td>$P_{pw}$, W</td>
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<td>-580</td>
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<td>$I_{cw}$, A</td>
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<td>2.90</td>
</tr>
<tr>
<td>calculated with rotor core loss</td>
<td>2.85</td>
<td>2.87</td>
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<tr>
<td>calculated without rotor core loss</td>
<td>2.71</td>
<td>2.69</td>
</tr>
<tr>
<td>$P_{cw}$, W</td>
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<td>calculated with rotor core loss</td>
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<td>296</td>
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<tr>
<td>calculated without rotor core loss</td>
<td>371</td>
<td>285</td>
</tr>
<tr>
<td>$T$, N·m</td>
<td>18.9</td>
<td>-16.0</td>
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<tr>
<td>calculated with rotor core loss</td>
<td>-18.5</td>
<td>-17.8</td>
</tr>
<tr>
<td>calculated without rotor core loss</td>
<td>-17.6</td>
<td>-16.9</td>
</tr>
</tbody>
</table>


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