Simplified Experimental Estimation of Equivalent Circuit Parameters for Brushless Doubly Fed Machines

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***Abstract*—This paper presents a new and simplified method for estimating the equivalent circuit parameters of the Brushless Doubly Fed Machine (BDFM) using only stator terminal measurements. The proposed method utilises voltage, current, and power factor measurements to estimate the stator and rotor parameters of the BDFM. The stator winding resistances are determined through DC measurements and treated as fixed parameters during the estimation process. The accuracy of the estimated parameters is compared with those obtained from alternative parameter estimation methods for an experimental D180 BDFM to evaluate its accuracy.**

Keywords— brushless double fed machines, equivalent circuit model, coupled circuit analysis, no-load test, locked-rotor test, cascade, and synchronous modes of operation

I. INTRODUCTION

Brushless doubly fed machines (BDFMs) exhibit appealing characteristics as induction-based electrical machines, making them highly attractive for both variable speed motor [1] and generator applications [2]. In the realm of wind power generation, BDFMs offer significant advantages, positioning them as a compelling alternative to the traditional doubly fed induction generators (DFIGs). One notable advantage is their brushless operation, which enhances reliability compared to DFIGs [3]. Additionally, BDFMs operate within a medium speed range, simplifying the associated gearbox system when compared to high-speed DFIGs [4]. Consequently, a drivetrain based on BDFM technology is anticipated to be more streamlined, reliable, and cost-effective than its DFIG counterpart.

The rise in popularity of medium-speed generators for offshore wind generation has underscored the limitations of direct-drive solutions, where low-speed generators and fully-rated power converters tend to be bulky and costly [5]. Herein lies the potential for BDFMs to revolutionise the offshore wind market by supplanting permanent magnet generators with their fully-rated converter requirements. BDFMs present a viable solution that only necessitates a fractional-sized converter, typically around 30-40% of the generator power ratings, along with a simple one or two-stage gearbox system [6]. By leveraging these advantages, BDFMs can address the challenges posed by offshore wind generation, offering a more reliable and economically feasible alternative.

The stator design of the BDFM consists of a single-frame stator core with two sets of three-phase windings [7]. One set, known as the power winding (PW), is directly connected to the grid. The other set, called the control winding (CW), is indirectly connected to the grid through a variable voltage and frequency converter with a rating that is a fraction of the generator rating. The rotor is designed to facilitate indirect coupling between the stator windings using a nested loop rotor winding, which is widely utilised [8]. Through careful design of the stator windings' number of poles and the rotor winding, direct coupling between the PW and CW is effectively avoided [9].

There have been several attempts for constructing prototype BDFMs from small laboratory sizes up to several hundreds of kilowatts including a 250 kW size built by the authors [10] and most recently, an 800 kW machine built for hydropower generation by Chen et al. [11].

The equivalent circuit model serves as a valuable analytical tool, offering a simplified representation of the BDFM's steady-state performance. It enables the quick calculation of operating conditions and proves instrumental in the design, optimisation, and integration of the machine, converter, and grid connection. One approach to determining the equivalent circuit parameters involves analytical methods based on machine geometry, as detailed in [12]. While this method yields parameters with acceptable accuracy, its complex and intricate analytical implementation limits its practicality and accessibility for all machine users. As a result, obtaining the equivalent circuit parameters using this method proves challenging for commercially used BDFMs, which require a more user-friendly approach.

Alternatively, parameters can be derived from steady-state operation data obtained through numerical models or experimental tests, employing curve-fitting techniques [13]. Extracted parameters tend to offer higher accuracy, particularly for quantities such as end-winding leakage reactances, which are difficult to obtain precisely through analytical means. However, the method's reliance on torque readings obtained from a torque sensor restricts its practicality in many cases where such sensors are unavailable.

This paper presents an effective approach to determine the equivalent circuit parameters of the BDFM solely based on a set of straightforward measurements taken at the stator terminals, including voltage, current, and power factor. By employing this method, the parameters of a simplified yet electrically equivalent circuit model can be obtained. The simplified equivalent circuit proves valuable as it enables the prediction of the machine's steady-state performance with acceptable accuracy. To assess the practicality of the proposed method, it is applied to an experimental D180 BDFM, and the determined equivalent circuit parameter values are compared against those obtained from two alternative methods.

II. BDFM EQUIVALENT CIRCUIT MODELS

The BDFM is conceptually two induction machines that have been cascaded, so it is expected that the per-phase equivalent circuit of the BDFM will be similar to the one for the induction machine. It is possible to represent the BDFM as two connected induction machines and develop an equivalent circuit using the standard per-phase model as presented by Roberts et al. in [14]. The circuit is shown in Fig. 1. R_1 and R_2 are the resistance of the stator windings and R_r is the rotor resistance. $j\omega_1 L_1$ and $j\omega_2 L_2$ are the stator reactances and $j\omega_r L_r$ is the rotor reactance. $j\omega_1 L_{m1}$ and $j\omega_2 L_{m2}$ are the stator magnetising reactances. Stator The stator windings, referred to as stator 1 and 2 in this paper, are linked to the rotor by transformers of turns ratio N_1 and N_2, respectively. Iron losses are neglected and it is assumed that saturation of the iron circuit, if it occurs, does not significantly affect parameter values.

In a BDFM, the shaft speed is a function of the supplied frequencies of two stator windings (ω_1 and ω_2) given by [15]

$$\omega_r = \frac{\omega_1 + \omega_2}{p_1 + p_2} \tag{1}$$

where p_1 and p_2 are the stator 1 and 2 pole pair numbers, respectively. The frequency occurring in the rotor winding is related to the frequencies in the stator windings as the product of the stator frequencies and the slip terms, s_1 and s_2, appearing in the equivalent circuit, defined as

$$s_1 = \frac{\omega_1 - p_1\omega_r}{\omega_1} \tag{2}$$

$$s_2 = \frac{\omega_2 - p_2\omega_r}{\omega_2} \tag{3}$$

When the BDFM is operating in synchronous or cascade modes, the rotor shaft speed and stator frequencies are related as

$$\begin{gathered} \omega_{r1} = \omega_1 - p_1\omega_r = -\omega_2 + p_2\omega_r = -\omega_{r2} \\ \Longrightarrow s_1\omega_1 = -s_2\omega_2 \end{gathered} \tag{4}$$

where ω_{r1} and ω_{r2} are the frequencies of the field in the rotor reference frame, hence the rotor frequencies in the referred circuit are equal in magnitude and as a result, the two rotors can be connected in the equivalent circuit as shown in Fig. 1.

The equivalent circuit parameters can be calculated from the machine geometry using the method described in [15]. The procedure involves deriving the machine's coupled-circuit model, followed by performing a series of transformations to obtain the d-q, sequence components and equivalent circuit parameters, respectively. The procedure is shown in Fig. 2.

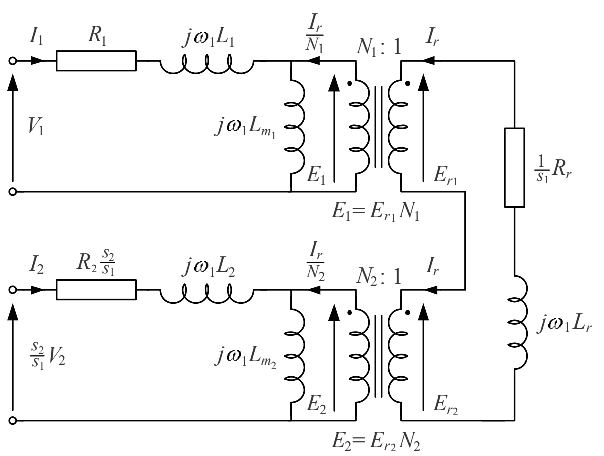

Fig. 1. BDFM per phase equivalent circuit.

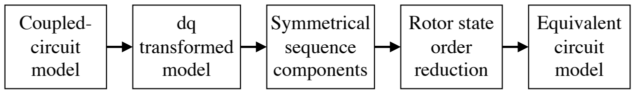

Fig. 2. The transformation procedure from the coupled-circuit model to the equivalent circuit modes.

The equivalent circuit parameters can also be extracted from steady-state measurements, including torque, speed, voltages and currents, obtained from the machine's operation in the induction and cascade modes [15]. The parameter extraction is a nonlinear optimisation method, using a weighted sum of the squares of the errors between predicted values and those measured by experiment or numerically obtained, as a cost function. In [16] different optimisation algorithms to solve the nonlinear least squares problem in estimating the parameter values for the BDFM equivalent circuits are investigated and the most viable algorithm with respect to computational time and error is identified.

The steady-state data can be obtained from numerical models or experimental tests. The stator winding resistances, R_1 and R_2 are either calculated from the machine geometry at a certain operating temperature or obtained from DC measurements. The magnetising inductances L_{m1} and L_{m1} are obtained from the magnetising tests where a single stator winding is supplied in turn whilst the other winding is left open. As the self-induction torque of a BDFM is relatively small, an external drive may be needed to run the machine at synchronous speed. It will improve the accuracy of measurement because the rotor currents are eliminated. Finally, the rotor parameters L_r and R_r are obtained from applying a curve fitting method to the data from cascade tests, assuming the stator resistance and magnetising parameters are fixed [14].

III. PROPOSED PARAMETER ESTIMATION METHOD

The method presented here derives the BDFM equivalent circuit parameter values from a set of basic tests. The tests are performed in induction and cascade modes of operation. Since the measurements are restricted only to stator terminal quantities including voltages, currents and power factors, the parameter values for the full equivalent circuit cannot be determined uniquely. Therefore, the simplified, but electrically equivalent, form of the equivalent circuit shown in Fig. 1 will be used. The circuit is shown in Fig. 3. For the circuit to be electrically equivalent to that of Fig. 1, the inductances, and turns ratios, will assume slightly different values:

$$\begin{gathered} \hat{L}_{m1} = L_1 + L_{m1} \\ \hat{L}_{m2} = L_2 + L_{m2} \\ \hat{L}_r = L_r + \frac{1}{N_1^2}\frac{L_1 L_{m1}}{L_1 + L_{m1}} + \frac{1}{N_2^2}\frac{L_2 L_{m2}}{L_2 + L_{m2}} \\ \hat{N}_1 = \left(1 + \frac{L_1}{L_{m1}}\right) N_1 \\ \hat{N}_2 = \left(1 + \frac{L_2}{L_{m2}}\right) N_2 \end{gathered} \tag{5}$$

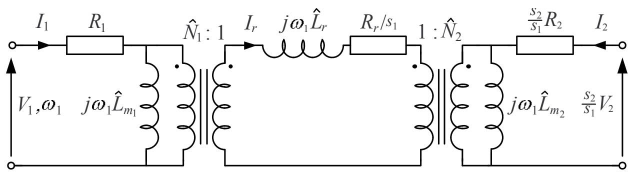

Fig. 3. BDFM per phase simplified equivalent circuit.

A. Test 1: DC Measurements

The stator winding resistances $R_1$and R_2can be obtained from DC measurements at working temperature.

B. Test 2: No-Load Test in Induction Mode

The no-load test can be applied in turn to each stator winding, with the other open circuit, to determine the magnetising reactances $\hat{L}_{m1}$ and $\hat{L}_{m2}$. As the self-induction torque of a BDFM is likely to be relatively small, an external drive is needed to run the machine at synchronous speed.

C. Test 3: Locked-Rotor Test in Cascade Mode

The machine is operated at standstill with one stator winding supplied from a voltage source and the other winding shorted. The slips s_1 and s_2 are therefore unity and the equivalent circuit can be represented as in Fig. 4. The measurements include the supply voltage, current and power factor, and the shorted current. The parameters which can be determined from this test are: the stator 1 - stator 2 turns ratio and the rotor referred resistance.

Assuming that stator 2 is shorted, the turns ratio may be calculated as

$$I_r' = \left| I_1 - \frac{V_1 - R_1 I_1}{j\omega_1 \hat{L}_{m1}} \right| = \frac{\left|\left(R_1 + j\omega_1 \hat{L}_{m1}\right) I_1 - V_1\right|}{\omega_1 \hat{L}_{m1}} \qquad (6)$$

$$I_2 = \frac{\hat{N}_1}{\hat{N}_2} \frac{\omega_1 \hat{L}_{m2}}{\sqrt{R_2^2 + \left(\omega_1 \hat{L}_{m2}\right)^2}} I_r' \qquad (7)$$

$$\frac{\hat{N}_1}{\hat{N}_2} = \frac{\sqrt{R_2^2 + \left(\omega_1 \hat{L}_{m2}\right)^2}}{\hat{L}_{m2}} \frac{\hat{L}_{m1}}{\left|\left(R_1 + j\omega_1 \hat{L}_{m1}\right) I_1 - V_1\right|} I_2 \qquad (8)$$

where ω_1 is the supply frequency in $rads^{-1}$, V_1 and I_2 are the amplitude of the supply voltage and the shorted current, and I_1 is the supply current. The rotor resistance R_r' can be determined by

$$P_{loss} = V_1 I_1 \cos\phi = R_1 I_1^2 + R_2 I_2^2 + R_r' I_r'^2$$
$$\Rightarrow R_r' = \frac{V_1 I_1 \cos\phi - R_1 I_1^2 - R_2 I_2^2}{I_r'^2} \qquad (9)$$

D. Test 4: Locked-Rotor Test in Induction Mode

The locked-rotor test, as similar to known for standard induction machines, may be applied to the BDFM in order to determine the rotor referred inductance value. It can be applied to either of the stator windings. The measurements include the supply voltage, current and power factor, and the open-circuit voltage. Applying the test to stator 1, the equivalent circuit may be expressed as shown in Fig. 5. The referred open-circuit voltage is

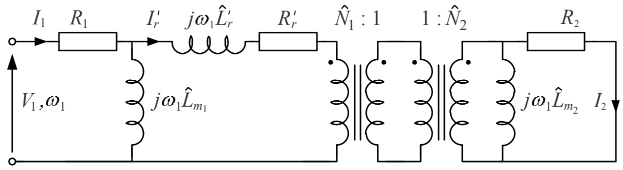

Fig. 4. BDFM equivalent circuit for test 3: the rotor is at standstill, stator 1 is supplied, and stator 2 is shorted. Rotor quantities are referred to stator 1.

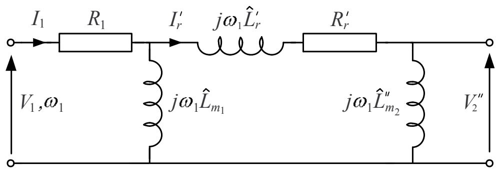

Fig. 5. BDFM equivalent circuit for test 4: the rotor is at standstill, stator 1 is supplied, and stator 2 is open circuit. All parameters are referred to stator 1.

$$V_2'' = \frac{\omega_1 \hat{L}_{m2}''}{\sqrt{R_r'^2 + \omega_1^2\left(\hat{L}_{m2}'' + \hat{L}_r'\right)}} \left|V_1 - R_1 I_1\right| \qquad (10)$$

Hence, the rotor referred inductance may be calculated as

$$\hat{L}_r' = \frac{1}{\omega_1}\left(\sqrt{\left(\frac{\omega_1 \hat{L}_{m2}'' \left|V_1 - R_1 I_1\right|}{V_2''}\right)^2 - R_r'^2} - \omega_1 \hat{L}_{m2}''\right) \qquad (11)$$

A summary of the experimental tests to estimate the BDFM equivalent circuit parameter values are listed in Table I.

IV. Experimental Tests

Experimental tests were carried out on a prototype D180 BDFM to estimate its parameters for its equivalent circuit model shown in Fig. 3 based on the proposed method described in Section III as well as the two existing methods described in Section II. The BDFM has 4/8 pole number configuration for the stator windings and the rotor has six nests, each consisting three loops. The detailed specifications of the prototype BDFM is given in Table II and the test rig is shown in Fig. 6. The BDFM is mechanically coupled to a DC drive which enables running the BDFM as a motor or generator. The mechanical coupling is through a torque transducer. The shaft speed is measured using an incremental

TABLE I. The Experimental Tests to Estimate the BDFM Equivalent Circuit Parameters

Test	Measured quantities	Determined parameters
DC measurements		R_1, R_2
No-load tests	$\{V_1, I_1\}$ & $\{V_2, I_2\}$	$\hat{L}_{m1}$, $\hat{L}_{m2}$
Cascade locked- rotor	V_1, I_1, pf, I_2	$\frac{\hat{N}_1}{\hat{N}_2}$, R_r'
Induction locked-rotor	V_1, I_1, pf, I_2	$\hat{L}_r'$

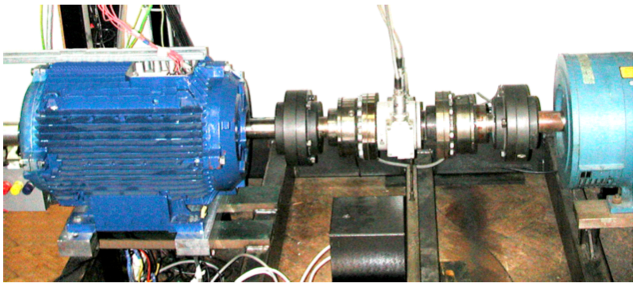

Fig. 6. Prototype D180 BDFM set up on test bed.

encoder with a resolution of 2500 cycles/rev. The stator voltages and currents are measured by LEM LV 25-p and LEM LTA 100-p transducers with measurement accuracies 0.9% and 0.5%, respectively.

To minimise the error in the no-load test arising from the rotor currents, an external drive was required to run the machine at synchronous speed. In order to limit currents to acceptable values throughout the range of the machine rating and to avoid saturating the iron circuit, reduced supply voltages were applied. The results and the parameter values calculated using the estimation process described in Section III are shown in Table III.

The parameters were also obtained from the main two methods described in Section II and the results are compared with the proposed method in Table IV showing acceptable agreement which confirms the validity of the proposed technique in estimating the BDFM equivalent circuit parameters with simple terminal measurements and no requirements to torque measurements.

V. Conclusions

In this study, a novel and straightforward parameter estimation method is proposed for the BDFM equivalent circuit model to accurately estimate its stator and rotor parameters. The method exclusively relies on readily available stator terminal measurements, including voltage, current, and power factor. Stator winding resistances are determined through DC measurements and treated as fixed parameters during the calculation of other parameters. The estimated parameter values are compared with those obtained from the two prominent parameter estimation methods developed for the BDFM, demonstrating an acceptable level of accuracy in parameter estimation.

TABLE IV. Specifications of the Experimental BDFM

Parameters	**Value**
Frame size	D180
PW/CW pole pairs	2/4
Natural speed	500 rpm
PW rated voltage	240 V (50 Hz, delta)
PW rated current	13 A (line)
CW rated voltage	240 V (30 Hz, delta)
CW rated current	13 A (line)
Rated torque	100 Nm
Stator slot number	48
Rotor slot number	36
Rotor design	Nested loop design, consisting of 6 nests of 3 concentric loops

TABLE II. The BDFM Parameter Estimation Results Obtained from the Method Described in Section III

Test	**Measured quantities**	**Determined parameters**
DC measurements		$R_1 = 2.42\Omega$ $R_2 = 4.04\Omega$
No-load tests	$\begin{cases} V_1 = 90V \\ I_1 = 1.05\,A \end{cases}$ $\begin{cases} V_2 = 90V \\ I_2 = 1.00\,A \end{cases}$	$\hat{L}_{m1} = 273mH$ $\hat{L}_{m2} = 286mH$
Cascade locked-rotor	$V_1 = 90V$ $I_1 = 7.93A$ $pf = 0.433$ $I_2 = 4.88A$	$\frac{\hat{N}_1}{\hat{N}_2} = 0.699$ $R_r' = 1.24\Omega$
Induction locked-rotor	$V_1 = 90V$ $I_1 = 2.74A$ $pf = 0.086$ $V_2 = 98.8V$	$\hat{L}_r' = 41.6mH$

TABLE III. Comparison of the Parameter Estimation Values Obtained for the Equivalent Circuit Model of Fig. 3

Parameters	Proposed simplified experimental method	Curve-fitting experimental method	Coupled-circuit analytical method
$R_1(\Omega)$	2.42	2.42	2.31
$R_1(\Omega)$	4.04	4.04	3.89
$\hat{L}_{m1}$(mH)	273	287	280
$\hat{L}_{m2}$ (mH)	286	302	295
$\frac{\hat{N}_1}{\hat{N}_2}$	0.699	0.706	0.701
R_r' (Ω)	1.24	1.30	1.33
$\hat{L}_r'$(mH)	41.6	44.5	45.3

The key advantage of this method lies in its reliance solely on the simple terminal measurements of stator electrical signals, eliminating the need for torque signal measurements. Furthermore, it obviates the requirement for complex analytical models based on coupled circuit analysis. As a result, the proposed method proves suitable for determining the BDFM equivalent circuit parameters in various commercial applications.

The successful application and reliable accuracy achieved through this method contribute to the advancement and practical implementation of the BDFM, particularly in scenarios where extensive torque signal measurements or complex analytical models may not be feasible or cost-effective. Future research can explore further refinements and enhancements to this parameter estimation method to continue improving its effectiveness and applicability in commercial settings.

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