Real Time Simulation of Brushless Doubly Fed Reluctance Generator Driven Wind Turbine Considering Iron Saturation

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ABSTRACT  Brushless doubly fed reluctance generator (BDFRG) provides a good substitute for the doubly fed induction generator for the wind energy applications due to the nonexistence of the slip rings. Real time modelling of the BDFRG is a challenge due to the high leakage inductance of the stator windings. While the magnetic saturation of the iron parts affects the inductances values, therefore studying the effect of magnetic saturation on the BDFRG performance is important. In this paper, a BDFRG model including iron saturation is built. The finite element (FE) analysis using FEMM software is used to generate the relationship between the generator currents and the inductances, the generated data are recorded in a lookup table. A Simulink model of the BDFRG driven wind turbine, with two cases of constant and variable inductances, are developed and verified with FE analyses at range of wind speeds above and below the synchronous speed. The lookup table proposes is verified using finite element analysis at different modes of operation of wind speed and compared with the constant inductance model to show the importance of saturation inclusion in the generator model for accurate generator modelling representation.

INDEX TERMS  Brushless doubly fed reluctance generator, Analytical Model, Finite element Model, Wind Turbine.

I. INTRODUCTION

The interest of using the brushless doubly fed reluctance generator (BDFRG) in wind power applications is remarkably increased in the recent years due to high efficiency, low maintenance and brushless rotor structure. The advantages of BDFRG compared to counterparts makes it a robust and reliable candidate to be used in variable speed wind applications [1]. The BDFRG stator consists of two sets of three phase windings, primary and secondary windings. In wind energy system, the primary winding (grid winding) connected directly to the grid and the secondary winding (control winding) connected to the grid through a partial scale (AC/DC/AC) converter, as shown in Fig 1.

The number of poles of each stator set are different, and the rotor is a reluctance type. The coupling between the two stator windings depends on the presence of rotor saliency. Moreover, the rotor has poles \( p_r \) equal to half the summation of the two stator poles to ensure the mutual coupling between the two stator windings [2]–[4] (i.e. \( p_r = p_p + p_s \) where, \( p_p \), \( p_s \) are the pair poles of the primary and secondary winding respectively).

The BDFRG is similar in operation with doubly fed induction generator (DFIG) and use partial scale converter with variable speeds, moreover, the brushless construction increases the system reliability and compatibility. BDFRG is more efficient when compared with DFIG with the same stator size due to the absence of rotor winding [5]. Thanks to the high leakage inductance of the BDFRG stator windings, increases the capability of low voltage ride through (LVRT) without needing a crow-bar security comparing with DFIG [6].

Usually, the BDFRG is modelled with the assumption of linear inductance, although in nominal operation, the iron nonlinearity is observed, and the generator inductances vary with load currents [7]. Consequently, the generator electromagnetic torque changes, which is directly dependent on the...
A detailed model for the saturation is required for a precise control of BDFRG, besides studying the generator peak power under limitations enforced by saturation. This paper presents a BDFRG model including the saturation using a lookup table generated from the FE model. There are three contributions for this work. First, complete model of BDFRG is presented in FE including the effect of saturation. Second, the paper studies the effect of saturation on the generator inductances and performance for all loading conditions with different modes of operations, in this method, the computational time of the FE analysis is independent of the stepping time of simulation. Third, the developed BDFRG model has been implemented in wind energy system to achieve maximum power point and reactive power control.

The following sections of this paper are organized as follows. Section 2 presents the modelling of the BDFRG driving the wind turbine, including the mathematical analytical models, FE models, and the coupling between them. This includes the magnetic saturation effect. Section 3 presents the used control schematic. Section 4 covers the simulation results with the FE verification. Conclusions are presented in the final section.

II. BDFRG WIND ENERGY CONVERSION SYSTEM

This section presents the modelling of the wind turbine model, analytical model of the generator, FE model of the BDFRG, and coupling between the analytical equations and the lookup table generated from the FE models.

A. WIND TURBINE MODEL

The mechanical power could be extracted from the wind is given by [24]:

\[ P_{mw} = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) u_w^3 \]  

(1)

Where \( \beta \) is the blade pitch angle, \( \lambda \) is the tip-speed ratio, \( \rho \) is the air density, \( R \) is the turbine blade radius, \( u_w \) is the wind speed, and \( C_p \) is the wind power coefficient and the tip speed ratio can be expressed as:

\[ \lambda = \frac{R \omega_{rm}}{u_w} \]  

(2)

where, \( \omega_{rm} \) is the mechanical rotor speed and the wind power coefficient \( C_p \) can be expressed as:

\[ C_p(\lambda, \beta) = 0.5176 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{-\frac{21}{\lambda_i} + 0.0068} \]

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta - \frac{0.035}{\beta^3 + 1}} \]  

(3)

B. BDFRG MODELLING

This section presents the generator mathematical modelling and FE model, to study the generator performance under time to execute one cycle at each simulation stepping time. Other methods are usually used by generating a lookup table from the FE model and use it in the simulation model [8], [21] or by getting an analytical expression between currents and inductances [22], [23].

The control performance is highly affected by the direct and quadrature currents which depend on the inductance saturation [8], so, adjusting a single value for the generator inductances is not adequate for a detailed control modelling for the BDFRG. Therefore, dynamic simulation of BDFRG coupled with the converters as shown in Fig. 1, needs an accurate model and a very fast model for the generator.

For BDFRG accurate modelling, several solutions exist in literature [9]–[15], models are classified to either electromagnetic field analysis or electric circuit-based models [9], [10]. For the electromagnetic field analysis, the BDFRG can be modelled using finite element (FE) analysis considering all the non-linearities of the soft magnetic material [1], [11]. The model in this case is accurate compared to experimental results. However, FE models are very time consuming. Therefore, they are not recommended to be used with dynamic circuit analysis.

Analytical tools are a better solution than FE models concerning time computation. One of the tools is magnetic equivalent circuits (MECs) [12], [13]. MECs are faster than FE solvers with a moderate accuracy. However, MECs take time in building the network and need good knowledge in interpreting the flux paths. Analytical formulas presented in [14], [15] to estimate the machine inductances by using winding function approach.

Electric circuit (EC) based model is a better solution when considering the dynamic analysis with the electric grid and the wind turbine mechanical [10]. They give a faster appealing result. DQ and ABC reference frame analysis of the machine are used in many literature [16]–[19]. However, the non-linearities existing in the machine are not considered in those analyses. The inductances in the EC model are assumed to be constant values. Moreover, from the electromagnetic field analysis, it can be shown that it is mandatory to include the effect of saturation on the machine inductances. Therefore, an accurate model includes a real time implementation of the machine inductance saturation is necessary for accurate machine modelling representation.

Studying the impact of saturation in a real time simulation for BDFRG is not presented up to date. However, implementing the inductance variation in real time simulation, has been performed by different methods in conventional machines like, make a live link between the Simulink model and FE model as presented in [20], this method takes a very long
different situations of loading conditions and explain the inductance variation effect.

1) Analytical Dynamic Modelling

The following equations show the BDFRG dynamic equations in rotating reference frame [3]. The d and q axes primary induced fluxes $\lambda_{pd}$ and $\lambda_{pq}$ and the secondary d and q axes induced fluxes $\lambda_{sd}$ and $\lambda_{sq}$ can be expressed as:

$$\lambda_{pd} = L_{p}i_{pd} + L_{ps}i_{sd} \quad (4)$$

$$\lambda_{pq} = L_{p}i_{pq} + L_{ps}i_{sq} \quad (5)$$

$$\lambda_{sd} = L_{s}i_{sd} + L_{ps}i_{pd} \quad (6)$$

$$\lambda_{sq} = L_{s}i_{sq} + L_{ps}i_{pq} \quad (7)$$

where $L_p$, $L_s$ and $L_{ps}$ are the generator primary, secondary and mutual inductances, respectively. $i_{pd}$ and $i_{pq}$ are the primary d-q axes currents and $i_{sd}$ and $i_{sq}$ are the secondary d-q axes currents.

The primary d and q axes induced voltages $v_{pd}$ and $v_{pq}$, and the secondary d and q axes induced voltages $v_{sd}$ and $v_{sq}$ are presented as:

$$v_{pd} = R_p i_{pd} + \frac{d\lambda_{pd}}{dt} - \omega_p \lambda_{pq} \quad (8)$$

$$v_{pq} = R_p i_{pq} + \frac{d\lambda_{pq}}{dt} + \omega_p \lambda_{pd} \quad (9)$$

$$v_{sd} = R_s i_{sd} + \frac{d\lambda_{sd}}{dt} + \omega_s \lambda_{sq} \quad (10)$$

$$v_{sq} = R_s i_{sq} + \frac{d\lambda_{sq}}{dt} - \omega_s \lambda_{sd} \quad (11)$$

where, $\omega_p$ and $\omega_s$ are the primary and secondary electrical angular velocities, respectively, and relation between them is given as:

$$\omega_r = p_r \omega_{rm} = \omega_p + \omega_s \quad (12)$$

where, $\omega_r$ and $\omega_{rm}$ are the generator electrical and mechanical angular velocities, respectively. The primary variables rotate with $\omega_p$ frame and the secondary variables rotate with $\omega_s$ frame, hence the variables appear as a DC in their frames. Fig.2 shows the position relation between the primary and secondary reference frames, which is covered by:

$$\theta_r = p_r \theta_{rm} = \theta_p + \theta_s \quad (13)$$

The generator electromagnetic torque is expressed as:

$$T_e = (3p_r L_{ps}/2L_p)(\lambda_{pq}i_{sd} + \lambda_{pd}i_{sq}) \quad (14)$$

The generator inductances depend on the primary and secondary currents due to the iron parts saturation. FE analysis is a good tool to study and estimate the generator inductances using computational techniques by discretising the generator to smaller areas. The following section shows the generator FE modelling.
FIGURE 4. BH curve of M400-50A material used in modelling the stator and rotor parts.

and the rotor flux paths have an average flux density of about 1.5T.

FIGURE 5. The flux density distribution at rated values of primary and secondary currents.

TABLE 2. BDFRG parameters and the turbine parameters

| BDFRG Parameters | Value          |
|------------------|----------------|
| BDFRG Power      | 16W            |
| Rated voltage    | 130V           |
| Max. speed       | 1000rpm        |
| Poles (Prim., Sec., Rotor) | 8/4/6poles |
| Rated Currents ($I_{pm}, I_{sm}$)(Max value) | 3.07A, 3.23A |
| $R_p$, $R_s$     | 3.2Ω, 3.16Ω    |
| $L_p$, $L_s$ and $L_{ps}$ | 0.19H, 0.17H, 0.096H |
| $J_m$            | 0.2kg.m$^2$    |

| Turbine Parameters | Value |
|--------------------|-------|
| Rated power        | 16W   |
| Wind velocity range $V_w$ | 3 − 13m/s |
| $V_{opt}$          | 8m/s  |
| Blade Radius       | 1.6m  |
| $\lambda_{opt}$    | 7.31  |
| Gear box ratio     | 1.8623|

The FEMM model is run at different values of primary and secondary currents up to 3 times the rated values with the help of MATLAB m-file. The resulted relationship between inductances and primary currents are illustrated in Fig. 6. It can be observed that the inductances are remarkably decreased with currents specially at high values of currents, and the inductances may decrease to half the considered constant values listed in table 2.

3) Coupling between FEMM and Simulink Model
To consider the iron parts saturation in real time simulation a live-link has been developed between FEMM software and MATLAB model is presented in the following section.

Live-link between MATLAB m-files and the FEMM software [26] is built to allow the extraction of the electromagnetic characteristics with different rotation angles and currents. The inputs of the FE models are the d and q axes currents, and the generator rotation is done by static steps. The outputs of the FE model are the d and q axes primary and secondary fluxes. Equations (4) to (7) are used to extract the primary, secondary, and mutual inductances.

To generate the lookup table, the FE model is solved at different values of primary currents, secondary currents and different values of current angles (i.e. $\alpha_p, \alpha_s$) where $\alpha_p = \tan^{-1}(I_{pq}/I_{pd})$ and $\alpha_s = \tan^{-1}(I_{sq}/I_{sd})$. The grid data for different d and q axes primary and secondary currents are generated up to 10A. This ensures that the generator is heavily saturated.

A for-loop MATLAB m-file is performed with changing the primary and secondary currents with 3 discretization (1, 3.23, and 10A), and the current angles with 8 discretization from zero to $2\pi$. The number of grid points equal 9 × 64 points. The inductance values are generated and recorded in a 4-D lookup table. The computational time to execute one run take about 3 days using Intel® Core™ i7-3370 CPU @3.40GHz, 8GB RAM desktop. Sample of the lookup table results at constant values of primary currents, secondary currents, and different angles of $\alpha_p$ and $\alpha_s$ is summarized in Fig. 7.

Fig. 7(a) shows that the primary inductance changes form 0.195H to 0.161H with +2% to −15.7% of the constant primary inductance value are given in table 2. In Fig. 7(b), the
secondary inductance changes form 0.17\(H\) to 0.218\(H\) with 0 to 28\% of the constant inductance value, also the change of mutual inductance is 0.04\(H\) to 0.12\(H\) with −50\% to 25\% as shown in Fig. 7(c). It is known that the mutual inductance is directly proportional to the generator torque (back to (14)), so 50\% change in the generator torque is a noticeable value, hence using constant generator inductances in simulation will affect badly on the generator performance when compared to experimental results.

### III. CONTROL SCHEME

The primary of the BDFRG is directly connected to the grid and the secondary is connected to grid via grid side converter and generator side converter to control the active and reactive power to/from the grid. Basically, the control techniques tune the d-q currents of the secondary winding to control the total active and reactive power.

The grid side converter control is used to adjust active and reactive power from BDFRG to the grid and maintain the DC bus voltage at a constant value, by controlling the d-q axes grid currents [10]. On the other hand, the generator side converter is used to obtain the maximum power from the wind turbine and to control the total power factor of the generator [27]. Many control techniques introduced in literature with BDFRG to meet the grid requirements of controlling the generator output active and reactive power [28]–[31]. Field-oriented control (FOC) is a prime technique used in decoupling the active and reactive power. Therefore, FOC is used in this paper to control the generator side converter.

The total active power (\(P_{\text{tot}}\)) of the generator and hence the torque can be computed from (15). The primary angle (\(\theta_p\)) is generated using the phase locked loop (PLL), so that the d-axis primary voltage equals to zero. According to FOC alignment of \(\lambda_{pd}\) with \(d_p\) axis will result in \(\lambda_{pq} = 0\) and \(\lambda_p = \lambda_{pd}\). Hence, from (15), the primary active power is directly proportional to secondary quadrature current \(i_{sq}\) (\(\lambda_p\) is constant as the primary winding connected to the grid bus). Therefore, by controlling the \(i_{sq}\), the generator torque can be easily controlled.

In addition to the active power control, the reactive power of the primary side can also be regulated by controlling the secondary d-axis current (\(i_{sd}\)). The value of \(i_{sd}\) can be driven from the reference desired reactive power (\(Q_{\text{ref}}\)) shown in (16), or by setting \(i_{sd} = 0\) when the generator operates with maximum torque per secondary current MTPA approach [31].

\[
P_{\text{tot}} = T_e \omega_{\text{rm}} = \frac{3p_r L_{ps} \omega_{\text{rm}}}{2L_p} (\lambda_{pq} i_{sd} + \lambda_{pd} i_{sq}) \tag{15}
\]

\[
Q_p = \frac{3}{2} P \omega_{\text{pd}} \lambda_{pd} (\lambda_{pd} - L_{ps} i_{sd}) \tag{16}
\]

The optimum speed of the wind turbine system depends on the optimum value of the tip speed ratio (\(\lambda_{opt}\)) and the measured wind speed (\(V_w\)). Therefore, there are two loops of control. One is used to control the speed and the inner loop

![FIGURE 7. The lookup table outputs (generator inductances) at different values of d-q axes currents. (a) \(L_p\), (b) \(L_s\), (c) \(L_{ps}\).](image)
The control procedure of generator side converter.

**IV. SIMULATION RESULTS AND DISCUSSION**

The grid connected BDFRG wind turbine model is used to study the generator behaviour under the wind speed variation. The wind speed range is selected from 4 m/s to 8 m/s to cover the generator modes of operations in sub-synchronous and super-synchronous modes.

To take into consideration the effect of the saturation, two different models of the BDFRG are used. In the first model, the values of inductances ($L_p$, $L_s$, and $L_{ps}$) are assumed constant as given in table 2. While in the second model, the values of the inductances are variable based on the lookup table generated from the FE model described in section 2. The inductances in this case are function of the current magnitudes ($I_{pm}$, $I_{sm}$) and the current angles of the primary $\alpha_p$ and secondary $\alpha_s$, therefore the inductances in the generator modelling equation can be rewritten as ($L_p(I_{pm}, I_{sm}, \alpha_p, \alpha_s)$, $L_s(I_{pm}, I_{sm}, \alpha_p, \alpha_s)$, $L_{ps}(I_{pm}, I_{sm}, \alpha_p, \alpha_s)$). The whole system simulation block diagram including the lookup table is shown in Fig. 9.

A comparison between the results of the two models is obtained to study the effect of saturation in normal operation. The simulations are implemented with MTPA approach and the reactive power control strategy. Results are measured at steady state, where at each wind speed the simulations are performed till the steady state is reached and then the results are recorded.

**A. MTPA RESULTS**

In case of MTPA operation, $i_{sd}$ is set to be zero and $i_{sq}$ is regulated from the reference wind speed to obtain the max-
FIGURE 10. The generator d-q current results in case of constant and variable inductance, (a) the primary d-axis current, (b) the primary q-axis current, (c) the secondary d-axis current, (d) the secondary q-axis current.

FIGURE 11. Generator power in case of MTPA control.

FIGURE 12. Generator reactive power factor in case of MTPA control.

minimum power form wind speed. Fig. 10 shows the generator d-q primary and secondary currents at different wind speeds, with the two cases of constant and variable inductances. The calculations of inductances using the lookup table reveal a marginal difference to the constant inductance results especially for the direct component of the primary current, in consequence of saturation.

Fig. 11 depicts the ability of the proposed control to trace maximum power point. Basically, the difference between the developed power and the output power shown in Fig. 11 due to the copper losses, on the other hand, a small difference occurred in output power calculation between the use of constant inductance and variable inductance models. The difference is more notable in super-synchronous speeds (synchronous speed = 500 rpm at 6.15 m/s) as a result to the high values of currents and inductance saturation.

The FE analysis presented in [7] gives good agreement between the experiments and the simulation results. Therefore, the FEMM model is used to verify the lookup table validity, through an active link between the MATLAB m-file and the FEMM model [26]. The FEMM model is performed for each wind speed (with the values of primary and secondary currents recorded from the variable inductance case) and the FEMM results are compared with the generator simulation results at each wind speed.

The primary reactive power $Q_p$ needed by the generator is shown in Fig. 12. At high values of wind speeds, i.e. the currents become high, the difference in $Q_p$ becomes noticeable between the constant and variable inductance models. This is a consequence of the saturation on the value of $L_p$. Back to (16) with a fixed value of $\lambda_{pd}$ and $i_{sd} = 0$, this results that $Q_p$ is inverse proportional to $L_p$.

Fig. 13 presents the generator power factor at different wind speeds for the three models, a small difference occurs at super-synchronous speeds as expected. The inductances generated from the lookup table during simulation are compared with that obtained from FEMM at same values of currents.
Comparing the simulation results with the FEMM results to test the lookup table validity. Figs. 11-14 reveal a partial agreement in results, which can be treated by increasing the number of points used to run the lookup table and hence, get a detailed lookup table.

**B. REACTIVE POWER CONTROL RESULTS**

The two models are simulated to adjust the generator’s reactive power at a constant value of \( Q_p = 500 \text{VAR} \) at different wind speeds in the cases of constant and variable inductances. Moreover, the FEMM model is used to validate the variable inductance model. Fig. 15 shows the primary reactive power at different wind speeds for the three models.

Fig. 16 shows the generator d-q primary and secondary currents at different wind speeds in case of variable inductances. The notable differences in the secondary d-q currents between the two models are shown in Figs. 16 (c and d). There are notable differences in the controller performance between the two models at wind speeds higher than 5.8 m/s, due to the increase of saturation.

Fig. 17 depicts the difference of output generator power of variable inductance model (at super-synchronous speeds) dropped to more than 30 % of the output power in case of constant inductance, due to the increase of the copper power losses. The saturation effect is clearly observed in the generator power factor as shown in Fig. 18.

**V. CONCLUSIONS**

Brushless doubly fed reluctance generators (BDFRGs) real time modelling can be done using the assumption of linear inductances assuming the BH characteristics of the machine is linear. However, in this paper, it is proven out that inclusion of the inductance relationship with the currents gives more accurate results.

A direct link between the Simulink model of the BDFRGs, driven wind turbine system, and the finite elements using FEMM software is developed via a lookup table. This lookup table is generated via the FEMM software. It relates the inductances of the machine with the input currents. Afterwards, this lookup table is included in the Simulink model. Different investigations are carried out to show the importance of the inclusion of the material non-linearities.

Comparable study between the effect of constant inductance and the lookup table is studied. It is done with the maximum torque per ampere (MTPA) and the reactive power control. It shows that with the reactive power control, the output power difference between the constant and variable inductances reaches 30% at some points. Therefore, it is important to include the non-linearity of the material. Notable
FIGURE 16. Generator d-q primary and secondary currents with reactive power control. (a) the primary d-axis current, (b) the primary q-axis current, (c) the secondary d-axis current, (d) the secondary q-axis current.

FIGURE 17. Generator power in case of reactive power control.

FIGURE 18. Generator power factor in case of reactive power control.

differences between the two models can be observed in the power factor, output power and output currents of the machine. At the end, the variable inductance Simulink model is verified using the FEMM software. Lastly, the inclusion of inductance current variation in the generator modeling is very important for accurate generator representation and more precise control performance in normal and abnormal conditions studies.

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