

Calculation of Equivalent Circuit Parameters of Brushless Doubly Fed Induction Generator Using Finite Elements

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A new method based on two-dimensional finite element analysis is proposed to improve the equivalent circuit calculation of brushless doubly fed induction generator (BDFIG). The calculation is divided into four parts: firstly, the modelling for per-phase equivalent circuit is proposed; secondly, calculation of the basic parameters is given; thirdly, due to the complex distribution and saturation effect of the magnetic fields in the machine, interaction between the two magnetic fields in the calculation of magnetizing reactance is directly considered; finally, the slot leakage reactance and the harmonic reactance are separated. An experimental test is carried out on a 30kW prototype BDFIG to confirm the accuracy of the proposed method.

Index Terms—Brushless doubly fed induction generator, parameters calculation, finite element method (FEM).

I. INTRODUCTION

Brushless doubly-fed induction generator (BDFIG), as an alternative of doubly-fed induction generator (DFIG), has attractive features to be the next generation of wind generators [1–3]. The equivalent circuit method is a helpful tool for predicting the behavior of BDFIG and optimizing design. The parameters can be calculated from the machine geometry using analytical methods [2]. However, this method does not give enough accuracy because it assumes linearity of the iron core and depends on some correction factors. The results obtained from this traditional method are likely to cause even bigger errors in BDFIG as it is hard to analyze the interaction between the two magnetic fields in the air gap [3].

To date, some methods based on finite element method (FEM) for accurately calculating the parameters of induction machine have been presented [4-5]. Considering the complex cross coupling of magnetic fields, this paper proposes a new method for predicting the steady state performance of BDFIG from FEM solutions.

II. METHOD OF CALCULATION

A. Equivalent Circuit of BDFIG

The BDFIG can be represented as two connected induction machines and an equivalent circuit using two standard per-phase models can be developed: Power Winding (PW) & Rotor Winding (RW) coupling circuit and RW & Control Winding (CW) coupling circuit. A complete equivalent circuit for the BDFIG is shown in Fig.1 and all parameters are referred to the PW side, where V_{s1} , I_{s1} and r_{s1} are the PW supplied voltage, induced current and resistance, respectively; V_{s2} , I_{s2} and r_{s2} are the CW supplied voltage, induced current and resistance, respectively; E_r , I_r and r_r are the RW induced voltage current and resistance, respectively; x_{m1} and x_{m2} is the exciting reactance of PW&RW coupling circuit and RW&CW coupling circuit, respectively. In this paper, the leakage reactance for each branch, $x_{s1\sigma}$, $x_{s2\sigma}$ and $x_{r\sigma}$, are divided into three parts:

1) The slot leakage reactances x_{s1s} , x_{s2s} and x_{rs} ;

2) The harmonic leakage reactances $x_{s1\delta}$, $x_{s2\delta}$ and $x_{r\delta}$;

3) The end winding leakage reactances x_{s1e} , x_{s2e} and x_{re} ;

To date, the stator and rotor slots are all straight slots for the BDFIG configurations reported in literatures, so that the skew leakage reactance will not be discussed here.

B. Calculation of Basic Parameters

The EMFs, E_{s1} and E_{s2} , are the intermediaries to connect the electric circuits with the fields. A 2D transient field solution is carried out first and the air-gap flux density is calculated as shown in Fig. 2. The relevant space harmonic spectra obtained from Fourier analysis indicates that the air-gap flux density can be decomposed into two fundamentals and a series of harmonic waves. Then, E_{s1} and E_{s2} can be calculated as,

$$E_{s1,s2} = \sqrt{2}\pi f_{s1,s2} N_{s1,s2} k_{Ns1,Ns2} \left(\frac{\pi dl}{2p_{1,2}} B_{ms1,ms2} \right) \quad (1)$$

where N_{s1} and N_{s2} are the number of the series turns per phase,

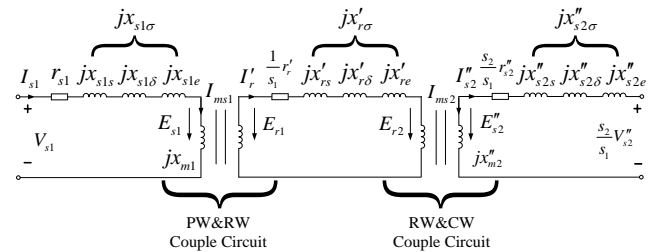


Fig. 1. Per phase equivalent circuit of the BDFIG.

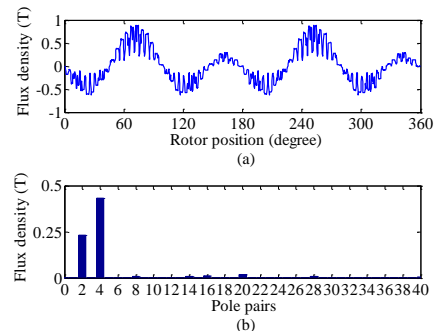


Fig. 2. Diagrams obtained from time-harmonic FEM simulation (a) air-gap flux density (b) relevant space harmonic spectra.

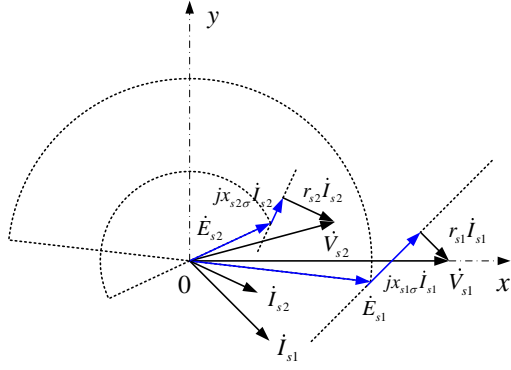


Fig. 3. Vector diagram of the BDFIG equivalent circuit.

k_{Ns1} and k_{Ns2} are the winding factors, B_{ms1} and B_{ms2} are the amplitudes of the two fundamentals, f_{s1} and f_{s2} are the frequencies of the PW and CW supplied voltages, d is average diameter of the air gap and l is the length of the iron core.

The vectors of induced voltages (E_{s1} and E_{s2}) and the vectors of stator leakage reactance ($x_{s1\sigma}$ and $x_{s2\sigma}$) have a geometrical relationship. The values of the induced voltages and the phases of the stator leakage reactance are known. In order to obtain the remaining values and phases, the intersections of a circle of known radius and a radial line of known starting point should be calculated by programming as shown in Fig. 3. Then, the rotor induced voltage can be expressed as,

$$\dot{E}_r = N_{rs1} \dot{E}_{s1} / N_1 - N_{rs2} \dot{E}_{s2} / N_2 = (r_r / s_1 + jx_{r\sigma}) \dot{I}'_r \quad (2)$$

C. Calculation of Magnetizing Reactance

The magnetic path in BDFIG is shared by two types of magnetic fields differing in pole-pair represented as p_1 and p_2 . This distinctive feature brings difficulties in the calculation of magnetizing reactance which varies with the machine's supply condition as well. Considering the PW voltage to be fixed and the CW voltage to vary but less than that of PW in wind generator applications, two fitted curves derived from the finite-element model are as follows:

Step 1: A 2D transient field application is carried out firstly with $V_{s1}=V_{s2}=V_N$, where V_N is the rated voltage of the grid. Then, obtain the winding currents (I_{s1} and I_{s2}) and the two fundamental components of the air-gap magnetic flux density (B_{ms1} and B_{ms2});

Step 2: Build a new static magnetic field model with only PW excited by I_{s1} and make the permeability of each element in this model high enough to ensure that no saturation happens, then obtain the air-gap magnetic flux density of p_1 (B'_{ms1});

Step 3: Repeat *Step 2* with only CW excited by I_{s2} and then obtain the air-gap magnetic flux density of p_2 (B'_{ms2}). The two saturation factors are obtained as the ratio of $B_{ms1,s2}$ and $B'_{ms1,s2}$, hence the magnetizing reactance can be calculated as well.

Step 4: Repeat *Step 1-3* with $V_{s1}=V_N$ and $V_{s2}=kV_N$ ($k=0.1, 0.2 \dots 0.9$). The magnetizing reactance in the whole operation range is calculated by using curve-fitting according to the data obtained in this step.

D. Separation of Leakage Reactance

The procedure of calculating the slot leakage reactance x_{s1s}

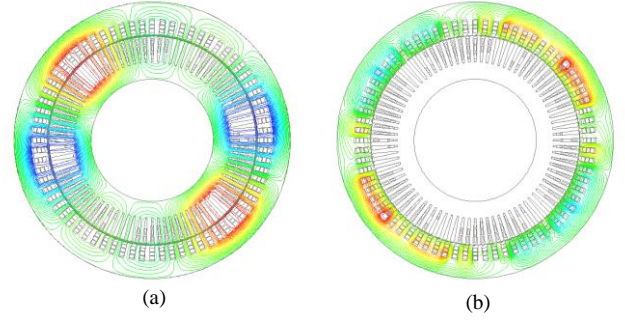


Fig. 4. Magnetic field distribution in BDFIG (a) the main magnetic field (b) the magnetic field of the stator slot leakage flux.

may be described as follows:

Step 1: A 2D static magnetic field application is designed and the excitation of the field is imposed according to the result of the previous transient computation. Then freeze the permeability of each element in this model after it is solved;

Step 2: Create a new design by copying and pasting the model in Step 2 with only PW excited as,

$$I_{s1A} = 1A, I_{s1B} = -0.5A, I_{s1C} = -0.5A \quad (3)$$

Use the permeability that has been frozen in Step 2 as stator cores permeability and make the permeability of all other elements in this model low enough to ensure that no flux crosses;

Step 3: The slot leakage reactance x_{s1s} is obtained by calculating the magnetic energy stored in the stator area.

The other leakage reactance parameters can be obtained in a similar manner as describe above.

III. RESULT AND DISCUSSION

In order to validate the proposed method, an experimental implementation has been carried out on a 250-frame-size BDFIG. The results from the experiments, the conventional method and the proposed method will be compared.

IV. CONCLUSION

An approach for predicting equivalent circuit parameters of BDFIG is proposed.

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