Investigation of a Leakage Reactance Brushless DC Motor for DC Air Conditioning Compressor

Mohamed Arbi Khlifi
Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Saudi Arabia
SIME Laboratory, ENSIT, University of Tunis, Tunisia
mohamedarbi.khlifi@issatm.rnu.tn

Marwa Ben Slimene
College of Computer Science and Engineering, Haï'l University, Saudi Arabia
SIME Laboratory, ENSIT, University of Tunis, Tunisia
benslimenemarwa@gmail.com

Ahmad Alradedi
Department of Electrical Engineering
Faculty of Engineering
Islamic University of Madinah, Madinah, Saudi Arabia
a-raddadi@hotmail.com

Salah Al Ahmadi
Department of Electrical Engineering
Faculty of Engineering
Islamic University of Madinah, Madinah, Saudi Arabia
sa-alhmadi@hotmail.com

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Abstract-Home appliances using Brushless DC (BLDC) motors, such as Air Conditioners (ACs) and ceiling and pedestal fans, are gaining attention these days due to their low power consumption and low maintenance cost. This paper estimates and analyzes the leakage reactance of conventional and flux-switching permanent magnet BLDC motors. The leakage magnetic field of a high-power BLDC motor will be one of the main sources of interference. The magnetic field characteristics of the leakage field of a BLDC motor must be analyzed in order to acquire correct geomagnetic data. We also show the rotor's leakage magnetic field while the BLDC motor is static, the stator and rotor's leakage magnetic fields when the BLDC motor is functioning, and the near-field characteristic of the BLDC motor's leakage magnetic field.

Keywords-Brushless DC (BLDC); leakage reactance; parameter estimation; Potier and sub-transient reactances

I. INTRODUCTION

Global urbanization, electrification, rising standards of living, and dropping Air Conditioner (AC) prices are all predicted to significantly increase direct and indirect emissions from AC refrigerants and AC energy use [1-3]. The increasing amount of energy consumption by buildings has caused widespread global attention to the social, environmental, and economic implications associated with it. From the scope of reducing global warming and other environmental concerns, there has been an increased demand for making energy-consuming equipment more energy-efficient. Various manufacturers have been actively engaged in energy-saving advancements, particularly with regard to room ACs, which are estimated to consume the most electrical energy in households. Electric power rationalization entails reducing electrical loads in power plants and electric networks, resulting in an uninterrupted supply of electricity, significant cost savings, and environmental preservation. Air conditioning consumes 75% of monthly energy consumption during the summer months, which is an excessively high amount [2, 4-6].

Brush machines are generally inexpensive due to their established design and manufacturing technologies, as well as their simple control [7-10]. The brushes in a brush machine make mechanical contact with a set of mechanical commutators or slip rings that are attached to the rotor and give connections to various armature coils at various rotor positions. Brushless machines, as the name implies, lack brushes, mechanical commutators, or slip rings, and instead rely on an electronic controller. Brushless machines, in comparison to brush machines, have superior efficiency and dependability, lower noise, longer lifetime (no brush degradation), less ionizing sparks from the commutators, and less electromagnetic interference overall. They can run at a higher speed range because the mechanical limits have been removed [11-14]. Because of their great efficiency, high power density, small size, and reliability, PM brushless motors have been widely employed for high-speed applications. Three-phase brushless motors are the most often used PM brushless motors, as they offer the optimum balance of motor iron and copper use and inverter cost. PM brushless motors, on the other hand, can be relatively inexpensive, which is always desirable in cost-conscious home appliance applications [15-17]. The reactance due to the difference between the total flux produced by an armature current and the flux in the air gap produced by the same armature current is known as armature leakage. There are several factors that contribute to stator leakage. Each component represents flux pathways into the rotor that do not cross the airgap [18-21]. The present contribution exposes a direct approach for parameter evaluation of salient or non-salient pole synchronous machines. The information received from the constant excitation test is used in this paper to propose a straightforward approach for estimating the leakage

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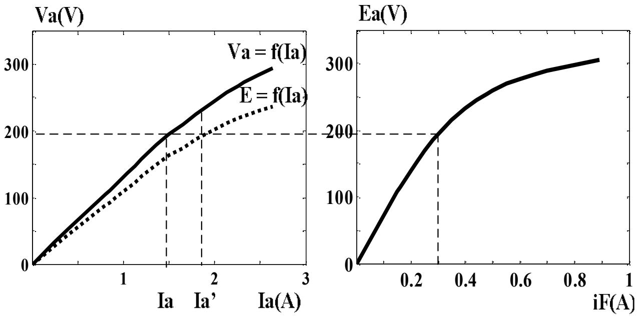
Corresponding author: Mohamed Arbi Khlifi reactance. The technique theory is explained and applied to a variety of systems ranging from laboratories to hydroelectric power plants. The estimates are compared to the Potier and sub-transient reactances in the absence of absolute values of the leakage reactance.

II. THE PROPOSED METHOD

BLDC motors rotor is composed of magnetic steel and iron core. In order to study the magnetic field characteristics of the rotor and to obtain accurate values of the leakage reactance X_s, an alternative testing method is adopted which was proposed in [1, 2]. In this method, the terminal voltage/armature current characteristic (V_a/I_a) curve with the machine unloaded and unexcited is needed along with the d-axis Open Circuit Characteristic Curve (OCCC) of the machine (Figure 1).



(a) (b)

Fig. 1. Determination of the armature leakage reactance of the BLDC motor. (a) Characteristic with the machine unloaded and unexcited, (b) The OCCC.

When the machine is unloaded and unexcited, the armature current equals to approximately its d-axis component since its q-axis component is approximately equal to zero. The nonlinear magnetic curve can be obtained at the rated speed by energizing the field circuit and closing the stator terminals, or vice versa. By neglecting copper and core losses, it is supposed that in $V_a(I_a)$, the armature current is a pure magnetizing component. Consequently, for a given stator voltage, the corresponding i_f and I_a are known, defining together the ratio alpha I_f/I_a.

Neglecting the effect of the armature resistance of the machine, which is usually very small, the machine terminal voltage V_t, in this case, is equal to the d-axis synchronous reactance voltage drop I_aX_d. The difference between the terminal voltage V_t and the internal e.m.f. E_i is the armature leakage reactance voltage drop, namely I_aX_l. Thus:

$$V_t = E_i + I_a X_l \quad (1)$$

The internal e.m.f. E_i could be obtained from the d-axis OCCC of this machine. In the "Xmd-base" per unit system [7, 12], the induced e.m.f. due to a certain armature current in per unit is by definition equal to the generated e.m.f. due to the field current E_f which has the same per unit value as this armature current I_a. Thus, (1) could be rewritten as follows:

$$V_t = E_f + I_a X_l \quad (2)$$

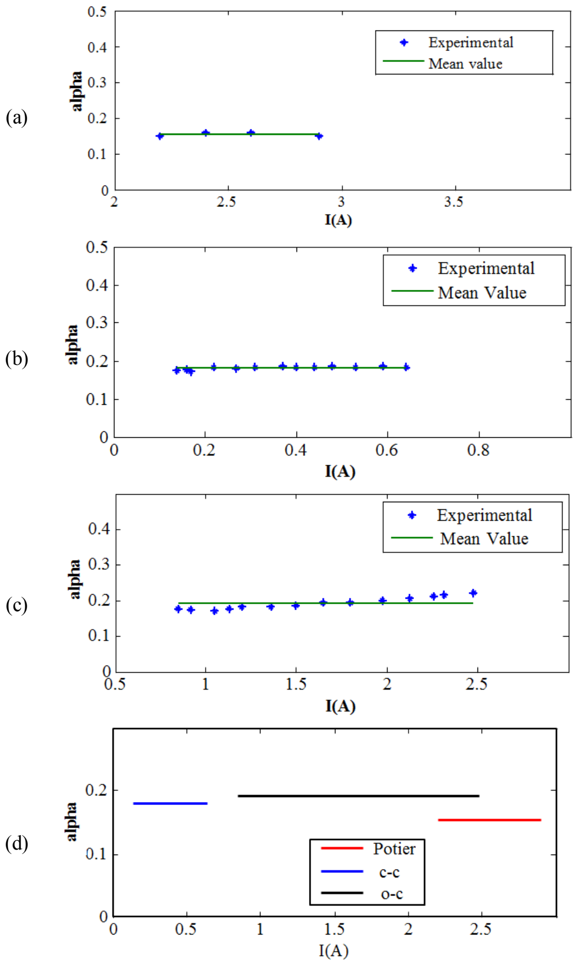


Fig. 2. Field/armature turns ratio versus armature current: (a) unload test, (b) short circuit test, (c) Potier, (d) Potier, c-c and o-c comparison.

The field current I_f which has the same per unit value of the armature current I_a (Figure 2) can be expressed as follows:

$$\begin{aligned} I_f &= \frac{E_{fu}}{k} = \frac{V_{tu} - I_a X_l}{k} \\ &= \frac{I_a X_{du} - I_a X_l}{k} \\ &= \frac{I_a}{k}\left(X_{du} - X_l\right) \end{aligned} \quad (3)$$

where $k = \dfrac{E_{fu}}{I_f}$.

In order to obtain a simpler expression for the armature leakage reactance, the following saturation factors can be used:

$$S_t = \frac{V_t}{V_{tu}} \quad (4)$$

$$S = \frac{E_f}{E_{fu}} \quad (5)$$

where S_t and S are the saturation factors found from the terminal voltage/armature current and open-circuit characteristics respectively. Since V_{tu} can be substituted by $I_a X_{du}$ and E_{fu} can be substituted by $I_f k$, (4) can be rewritten as (6) and (5) can be rewritten as (7):

$$V_t = S_t V_{tu} = S_t I_a X_{du} \quad (6)$$

$$E_f = SE_{fu} = SI_f k \quad (7)$$

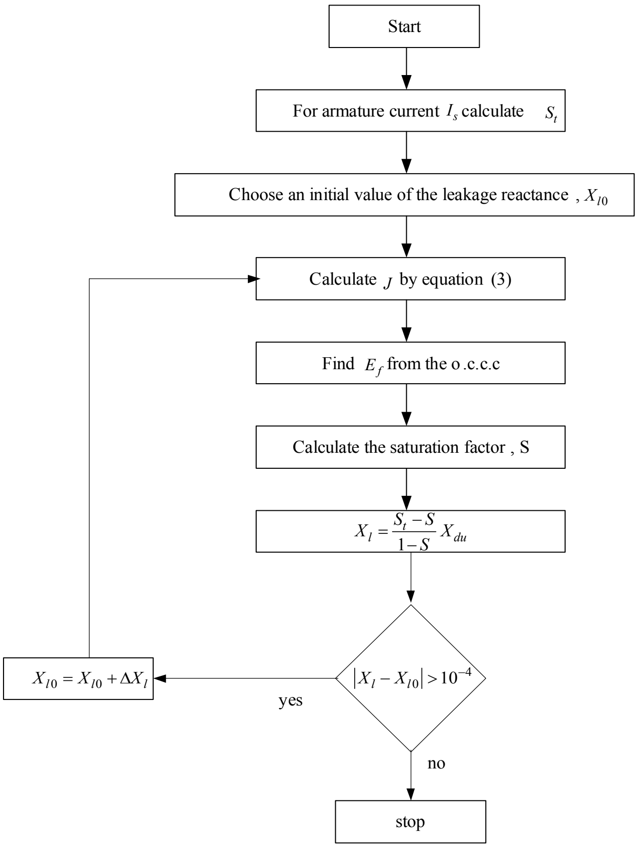


Fig. 3. Flowchart of the BLDC motor leakage reactance estimation.

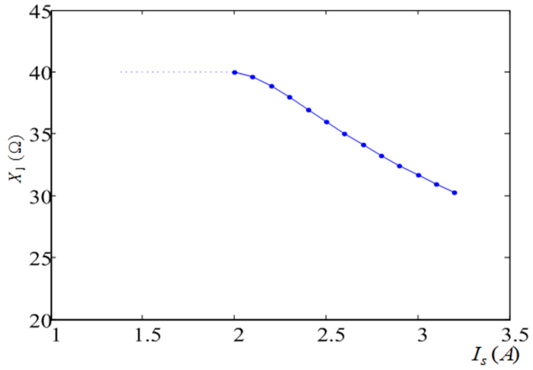


Fig. 4. Armature leakage reactance.

Substituting (3) in (7), gives us:

$$E_f = SI_a \left(X_{du} - X_l \right) \quad (8)$$

Substituting (6) and (8) in (2), results to:

$$S_t I_a X_{du} = SI_a \left(X_{du} - X_l \right) + I_a X_l \quad (9)$$

Equation (9) gives the following expression for X_l:

$$X_l = \frac{S_t - S}{1 - S} X_{du} \quad (10)$$

III. IDENTIFICATION OF THE LEAKAGE REACTANCE

The proposed technology was tested on many synchronous machines of various rated sizes in laboratory and at several hydro power facilities. Measurements were taken as soon as the machines were synchronized to the power system. The units were loaded while the excitation current was kept constant. Voltage and active and reactive powers were recorded. The Potier reactance has largely replaced the armature leakage reactance in many applications. It is calculated using the Potier triangle, which is built using data from open circuit, short circuit, and zero power factor characteristics.

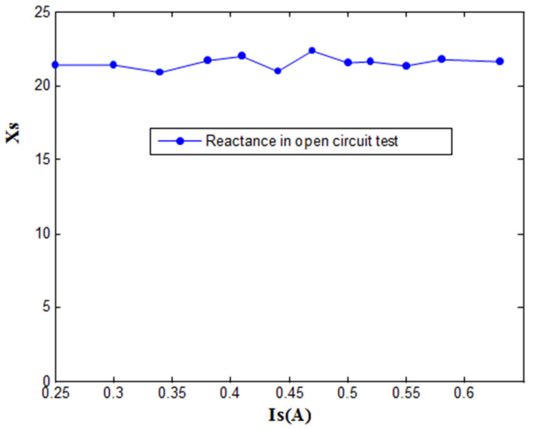


Fig. 5. Armature leakage reactance with open inductor test.

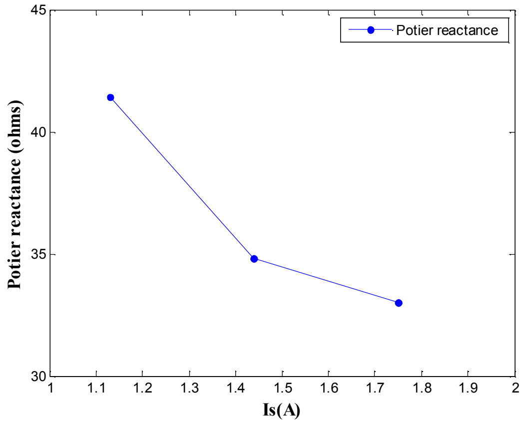


Fig. 6. Armature leakage reactance with the Potier method.

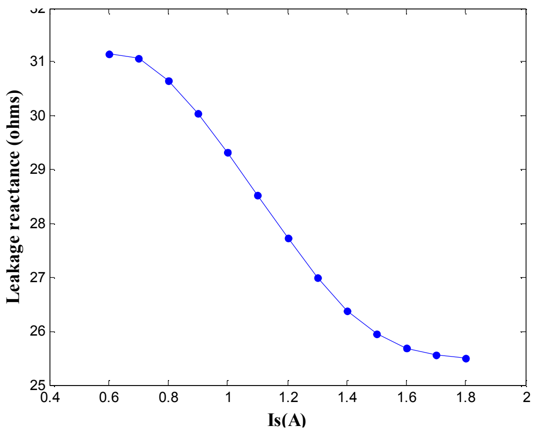


Fig. 7. Armature leakage reactance with open circuit test.

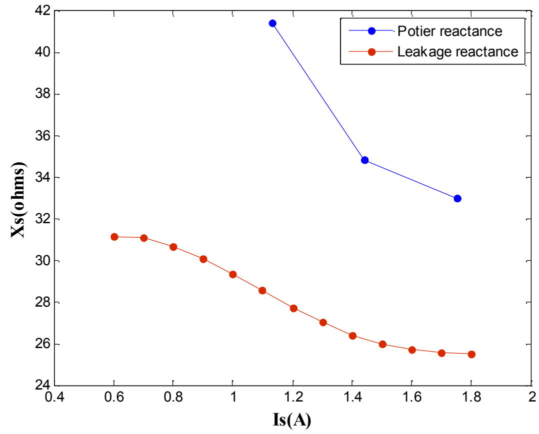


Fig. 8. Comparison of the leakage reactance and Potier reactance.

The resulting leakage reactances were compared to the available Potier reactance values or the direct axis subtransient reactance with the aim of evaluating the results. For steady-state conditions, computing the synchronous reactance first, then the mutual reactance, and finally the slot and differential leakage reactance as a difference between Potier and mutual reactances yields similar accuracy. A standard approach for determining armature inductance is to remove the rotor. However, it would be tough to implement in those BLDC computers. As a result, we offer an approach that includes a zero sequence reactance approximation.

The Potier reactance has a greater value than the leakage reactance, especially when the zero power factor test is performed at the rated voltage. Furthermore, because it is an intrinsic element of the formers, the leakage reactance may have a lower value than the d- and q- axis sub-transient reactances. As a result, when making comparisons, one has to keep in mind that the genuine leakage reactance value is lower than the Potier and subtransient reactances.

IV. CONCLUSION

Using the constant excitation test and simple computations over the collected data, this research proposed a novel way to estimate the armature leakage reactance of a BLDC motor. The procedure was applied to a variety of tests with excellent results. Rather than providing any error measure, the resultant leakage reactances were simply compared to the values declared by the manufacturers, derived through normal procedures, or to the d-axis sub-transient reactance. This was done since the percentage errors appear to be bigger even for slight variations due to the modest values of the leakage reactance.

It should be emphasized that the test is straightforward to perform and that it can be performed on a BLDC machine in operation at virtually no cost or danger of damage. Rather than prototypes or laboratory machines, the technology is ideal for medium to large scale power units that are currently installed or being built in the field.

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