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# Flux Air gap Reconstruction in Electrical Machines from External Measurements - Application to fault monitoring

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**Abstract** — This paper presents an original approach for fault monitoring of electrical machines. The goal of this work is, from outside magnetic field measurements, to get a reliable expression of the magnetic field flowing in the air gap. Once it is obtained, a fault monitoring can be provided thanks to its analysis. This approach is based on a magnetostatic inverse problem resolution. The direct model is obtained by coupling a distribution of normal dipoles representative of the flux flowing in the air gap with a boundary integral formulation and a magnetic moment method. Measurement is simulated on sensors located outside the machine thanks to a 3D FEM approach. With this simulated measurement, the direct linear model is inverted to get the normal dipoles distribution. The problem being ill-posed, it is solved by using the 0-order Tikhonov's regularization technique. The dipoles distribution obtained permits us to detect faults occurring inside the machine.

## I. INTRODUCTION

Fault monitoring of a rotating electrical machine using external magnetic field measurements is a more and more studied approach. Indeed, the magnetic stray field is a good representation of the induction flowing in the machine air gap. The analysis of this stray field is thus a powerful strategy for diagnosis and sensors present an easiness of instrumentation.

Currently, this approach is carried out with only one sensor located close to the machine. The spectrum analysis of the recorded signal and the recognition of frequency components representative of known faults lead to a reliable diagnosis. However, these techniques offer only few possibilities for the localization or the determination of fault magnitudes.

This article proposes an original approach based on the theory of inverse problem. The goal is, from external magnetic field measurements realized on several sensors, to find the magnetic field distribution inside the machine air gap. By analyzing it, it will be possible to localize the fault and moreover to determine its magnitude.

The first part of this paper presents our direct model. We see, from a known distribution of the induction in the machine air gap, how it is possible to predict the magnetic field outside it, by taking into account the stator and the yoke effect.

In a second step, this model is inverted from external magnetic information. Thus, it is possible to get the induction in the air gap and then to provide a reliable diagnosis. An example of inversion in the case of a faulty

operation mode of a synchronous machine is presented. The proposed method at present time numerical (i.e. measurements are simulated by a FEM), but the instrumentation of a laboratory alternator is in process and real measurements will be available soon.

## II. FORWARD MODELLING

The magnetic stray field computation of the electrical machines is a difficult task. Indeed, it is a 3D modeling (high CPU cost modelling) and is faced to a high ratio between the internal field and the stray field ( $10^6$ ) (cancellation errors problem, mesh of an infinite region, etc...). A methodology was developed that allows to compute the magnetic stray field with a good accuracy [1]. It is based on a 3D finite element modelling coupled with a post-processing based on a volume integral equation. This approach was successfully validated by measurements.

Unfortunately, this model is too heavy to be inverted, because the relation between the sources (the fault) and the stray field is not explicit. Thus, we developed a "lighter" integral model where this relation is explicit and can be easily inverted. Our model is based on several assumptions, in particular a linear law for the materials and a simplification of the machine geometry. It has been already largely presented in [2]. We describe here briefly its principle.

The magnetic stray field created by the machine can be represented by three distinct distributions:

- A distribution of normal dipoles  $T$  located on the average surface of the air gap. These dipoles are directly linked to the induction flowing in the air gap [2]. For the geometry of a known machine, it is easy to find in the literature, analytical expressions of these dipoles distributions. Many references also provide these analytical expressions for failure operation modes [3].

- A charge distribution  $q$  located on the external surface of the stator. These charges represent the flux leakage of the machine itself. They can be calculated by the following integral equation:

$$\frac{\mu_{lr} + 1}{\mu_{lr} - 1} q - \frac{1}{2\pi} \iint_{S_{\text{stator}}} q \frac{r \cdot n}{r^3} dS = 2(n \cdot H_0(T, M)) \quad (1)$$

where  $\mu_{lr}$  is the permeability of the stator and  $H_0(T, M)$  is the field created by other sources (i.e. the air gap dipoles distribution and the magnetizations of the yoke),  $r$  is the vector linking a point of the stator surface to the integration point,  $n$  is the outgoing normal of  $S$ .

- A magnetization distribution  $M$  located in the yoke. It represents the shielding effect of the yoke. The computation of these magnetizations can be made with a classical magnetic moment method:

$$M - (\mu_{2r} - 1) \iiint_{V_{\text{yoke}}} \frac{M_r}{r^3} dV = (\mu_{2r} - 1) H_0(T, q) \quad (2)$$

where  $\mu_{2r}$  is the relative permeability of the yoke,  $V$  is the volume of the yoke and  $H_0(T, q)$  is the field created by the normal dipoles and the charge distribution.

The air gap surface,  $S_{\text{stator}}$  and  $V_{\text{yoke}}$  are meshed. The magnetic stray field of the machine is the sum of the field created by  $T, q$  and  $M$  distributions. This relation can be written thanks to a linear system:

$$[A_T]T + [A_q]q + [A_M]M = B_{\text{external}} \quad (3)$$

Let us remember that the dipoles distribution  $T$  located in the average air gap surface is known, surface distribution  $q$  (on the external surface stator  $S$ ) and volume distribution  $M$  (in the yoke) have to be determined.

Equations (1) and (2) can be solved thanks to a point matching approaches. Thus we get two new linear systems linking  $T, q$  and  $M$ . By combining these to systems with system (3), we get a new linear system linking the  $T$  distribution to the stray field  $B_{\text{external}}$ .

$$[A_1]T = B_{\text{external}} \quad (4)$$

where  $A_1$  matrix depends on the meshes, the material characteristics and the points where we want to compute the field.

Our model is applied to a laboratory alternator of 30kW, 2 pairs of poles without fault. This simple model has been compared with a 3D finite element modelling associated to a post-processing with volume integral equation.  $T$  has been determined by analyzing the field in the air gap. By multiplying  $T$  by  $A_1$  matrix,  $B_{\text{external}}$  is obtained. The error of our model is always lower than 20% in comparison with the field returned by FEM which is very interesting regarding its simplicity.

### III. INVERSE MODELLING

24 sensors have been regularly set around the machine. The instrumentation of our lab machine being not finished yet, external field is computed by finite element method. The machine is modeled with a rotor short-circuit fault. The presence of this fault removes a part of symmetries of the problem. The 3D modelling thus becomes very heavy. To simplify the mesh, a homogenized approach is used [4]. As a consequence, the whole machine is modeled (see fig. 1) and the simulated "measurement" can be obtained.

From the external magnetic field measurements, the aim is to determine the induction in the machine air gap. Thus, the analysis of the external induction will allow us to detect the presence of faults. We have then to solve the linear system similar to (4) (i.e. to determine  $T$  by knowing  $B_{\text{mes}}$ ).

$$[A_2]T = B_{\text{measured}} \quad (5)$$

where  $A_2$  depends on the mesh, material characteristics and sensors positions.

Like most parts of inverse problem, our problem is obviously ill-posed (i.e. the condition number on  $A_2$  is very bad). To obtain a reliable  $T$  distribution, we use a 0-order Tikhonov's regularization technique. The parameter of regularization is selected thanks to the technique of the "L-curve".

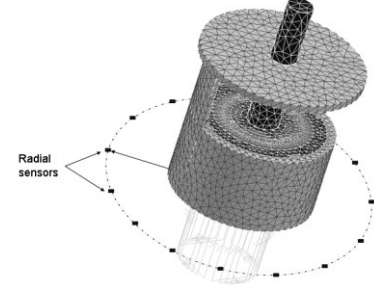


Fig.1. Homogenized FEM model of the machine with 24 magnetic sensors around it.

Once the problem has been inverted with Tikhonov's regularization, the normal dipoles distribution  $T$  is obtained. Figure 2 presents the Fourier transform of this distribution.

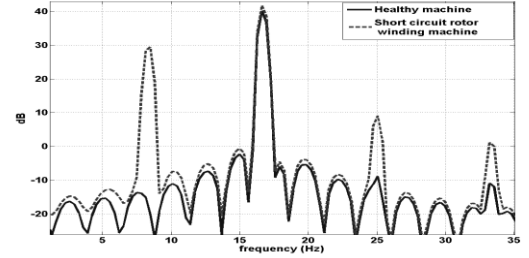


Fig. 2. Fast Fourier transform of the dipoles distribution obtained by solving the inverse problem at low frequency.

The main frequency component at 16.67Hz represents the double of the rotation frequency (two pairs of poles). In the case of a healthy machine, only this component appears at low frequency. The additional components at the other frequencies (in particular at the rotation frequency 8.33Hz) show symmetry loss due to rotor short-circuits fault. Let us notice that by analyzing the induction in the machine air gap obtained with the FEM, we get a very similar spectrum. These results show the relevance of our approach because by solving the inverse problem, we succeed in determining the field in the air gap with only external magnetic measurements. The following step will consist in validating our approach with real measurements.

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