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Energy harvesting from the external magnetic flux generated by AC electrical rotating machines

***Abstract**. This paper deals with a process to harvest energy from the external flux generated by the AC electrical rotating machines. Such an energy harvesting can be useful for energy autonomous devices used to monitor these machines. The goal of the paper is to estimate if the external flux can be a full-fledged energy source or if it constitutes only an extra-energy source.*

***Streszczenie.** Artykuł opisuje proces gromadzenia energii z zewnętrznego pola generowanego przez maszyny elektryczne prądu zmiennego. Uzyskana w ten sposób energia może być wykorzystana do zasilania urządzeń monitorujących pracę maszyn. Celem pracy jest oszacowanie czy zewnętrzny strumień może być w pełni wykorzystanym źródłem energii lub czy jest tylko źródłem naddatku energii (**Uzyskiwanie energii z zewnętrznego pola generowanego przez maszyny elektryczne prądu zmiennego**).*

Keywords: energy harvesting, external magnetic flux.
Słowa kluczowe: uzyskiwanie energii, zewnętrzny strumień magnetyczny.

1. Introduction

The on-line diagnosis of AC electrical rotating machines tends to be generalized. On the one hand, it concerns the monitoring of the machine health [1] and, on the other hand, the monitoring of their efficiency [2]. Both can easily be performed on AC variable speed drives because the tools to diagnose the machine can be integrated in the driver. For instance, the sensors to measure the currents are already set up for the control loop and the monitoring can be easily integrated. However, such a monitoring concerns a restricted machine number. The induction machines directly connected to the grid represent 85% of the electrical rotating machines in the world and specific tools and sensors are more and more developed to monitor them. For instance, the stator vibration measurement or the current analysis [3] allows extracting information on the machine health. The AC rotating machine efficiency can also be performed with devices placed close to the stator yoke by analyzing the external flux [4]. Thus, for machines directly connected to the grid, the sensors have generally to be placed around the machines and one of the major problems concerns the sensor supply. For obvious reasons of organization, security and costs, the terminal box should not be opened. Moreover, supplying the sensor directly with the grid is generally not possible for security and accessibility reasons. As a consequence, the sensors must be able to operate in an autonomous way for several months or even years. The autonomy can be carried out with batteries for the short time monitoring but, when it is made over long periods, other solutions must be found such as the photovoltaic panels, the electromagnetic micro-generator or wireless electricity [5].

This paper proposes another solution to save energy. It consists in using the external flux radiated by the AC machine, with sensors placed directly against the machine yoke. Such a method seems to be fitted to AC machines insofar they radiate a time variable magnetic field outside their external yoke. The goal of the paper, which considers only the fundamental flux density component, is double.

The first purpose is to determine where the external field is maximum around the machine. Explanations are given about the external flux generation, which results from complex phenomena. Indeed, the external yoke and the clamping plates act as shields because of the eddy current influence. A 3D Finite Element (FE) model performed with the Opera 3™ application allows understanding their influence and their distribution. Then, an experimental test bench makes it possible to scan an induction machine with a sensor made of 3 coils moved with a robot. The obtained results are compared to those deduced from the FE model. The objective is to confirm the location of the sensor recovering highest magnitude external flux.

The second purpose of the paper is to determine the energy, which can be saved with an external flux sensor. Conclusions concern the interest of the procedure: question to solve is to determine if such a device can be a full-fledged energy source or if it constitutes only an extra-energy source.

2. External flux around the machine

2.1 Mechanism of flux transmission

The external flux around an electrical rotating AC machine results from the air gap flux and the flux generated by the end-winding [6]. The transmission of the flux from the air gap to the external side of the machine depends on many parameters and the phenomena are complex. Indeed, this transmission requires the crossing of both the sheet stack and the external yoke. It has been shown that the effect of the eddy currents in the stator sheet stack can be neglected to determine there the flux distribution, which depends on the p pole pair number of the air gap flux density wave [7] [8]. On the other hand, the normal flux density component decreases slowly from the internal radius to the external radius for low values of p whereas the tangential component is practically null at the external radius whatever the p value.

The flux is significantly modified when it passes into the external yoke. Indeed, the latter is made of one piece, contrary to the laminated stator magnetic circuit. As a results, eddy currents flow in the yoke, creating a magnetic field, which the effects are opposed to the main field. As a consequence, the external field is attenuated and phase-shifted. It has been shown [6] that those effects are dependent on the magnetic circuit saturation, making the study a little more delicate.

In normal operation, the flux density outside the machine results from the effects of end-winding and those of wires placed in the slots. Consequently the external field depends also on the machine load state.

2.2 3D FE model for external flux distribution

A 3 phases - 2 pole pair - 7.5kW - 400V induction machine has been modelled with Opera3D™. The simulation is performed at no-load and, as the rotor currents are very low in this case, there is no winding on the rotor and its magnetic circuit is non-slotted. It allows decreasing the computation time. The modelled stator is composed of a slotted magnetic circuit and a winding made of 3 phases forming 2 pole pairs with 2 slots per pole per phase. As the effects of eddy currents can be neglected to analyse the magnetic flux distribution in the magnetic circuits, the latter can be regarded as solid masses with a null conductivity and relative permeability equal to 5000. The external yoke, assumed to be a smooth-wheel roller, and the clamping plates are respectively made of aluminium and cast iron. Their relative permeability and conductivity are 1 and 0.0278 10^{-6} Ω.m for the first material and 60 and 10^{-6} Ω.m for the second one. The resultant model is made of 7.2 10^{6} elements.

The Fig. 1 shows the eddy currents flowing in the external yoke. Let us point out that the eddy current distribution depends on the resistivity and the magnetic permeability of the external yoke [9. This figure shows that the eddy current form loops each side the machine, corresponding to the magnetic poles in front the end-winding. The external flux density obtained with the FE model is shown in Fig. 2.

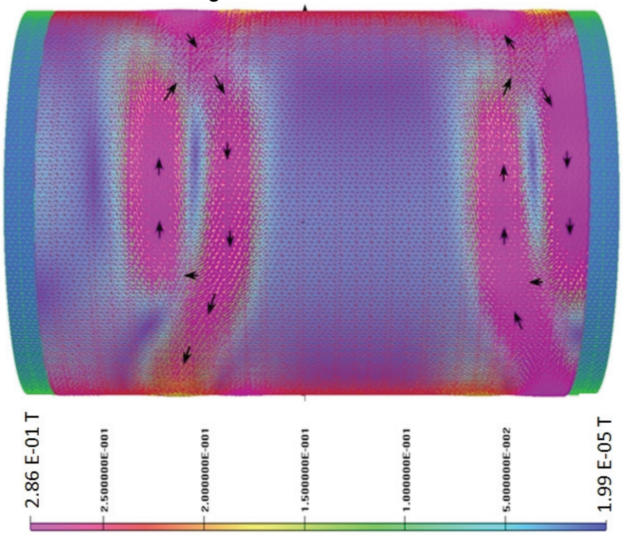


Fig.1. Eddy currents in the external yoke

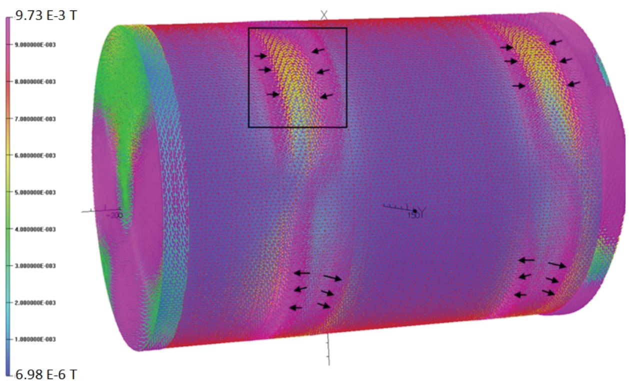


Fig.2. External flux density

It shows that the magnetic flux is concentrated near the end-windings. It is explained by the fact that no iron canalizes the flux, contrary to the middle side of the machine. The maximum external flux density magnitude is about 10^{-2} T at a distance of 1 mm from the yoke. However, in reality, the cooling ribs do not allow placing the sensor against the yoke. It means that the flux, which is measured by the sensor to save energy, will be lower.

2.3 Experimental model for external flux distribution

An experimental test bench makes it possible to compare the distribution and the magnitude order of the external flux with the distribution obtained with a FE model. A 3 phase - 1 pole pair - 18.5kW - 400V induction machine is scanned with a sensor moved with a robot Denzo™. It allows determining how placing the sensor and where the external flux around the machine has the highest magnitude. The Fig. 3 shows the scanned part and the movement around the external housing.

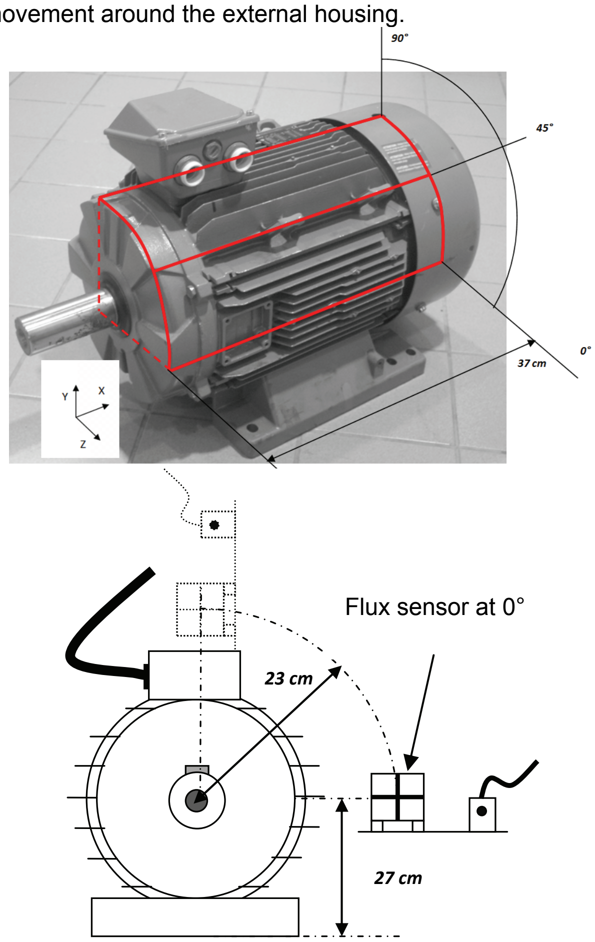


Fig.3. View of the scanned part

The flux sensor is made of 3 coils of 200 turns. The Figure 4 shows the coil positions to measure the 3 external flux components, which are called tangential (“TAN”), axial (“Z”) and Normal (“NOR”) positions [6]. Each coil voltage is amplified by 1000. The Fig. 5 shows the distribution of the “TAN” and “Z” external flux components. The colors indicate the magnitude of the RMS coil voltage, which is an image of the flux. It shows that the TAN component has the highest amplitude in front of the magnetic sheet stack because this component is not influenced by the end-windings. Contrariwise, the Z component distribution presents two hot zones each side of the machine. They correspond to the end-winding effects. The Fig. 6 shows the “NOR” component distribution. The coil voltage magnitude is maximum for this “NOR” position compared to the other ones. The variations along three lines parallel to the machine at 0°, 45° and 90° (drawn in Fig. 3) shows that the external flux is high all along the machine. It is justified by the fact that the “NOR” component results from the combined effect of the end-windings and the active parts of the wires. There are small differences between the three curves because the cooling fans are all horizontal as it can be seen in Fig. 3. As they drive the flux, the latter, which passes through the coil, is different with the coil position around the machine. The influence of the terminal box can be seen for 90° with values lightly higher.

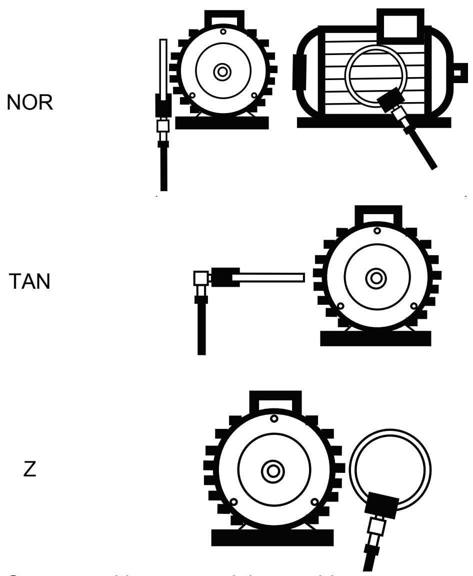
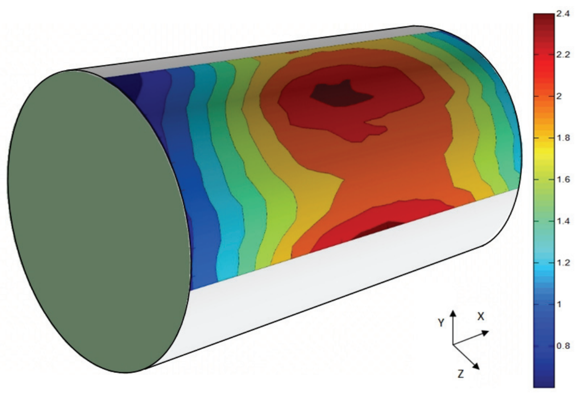
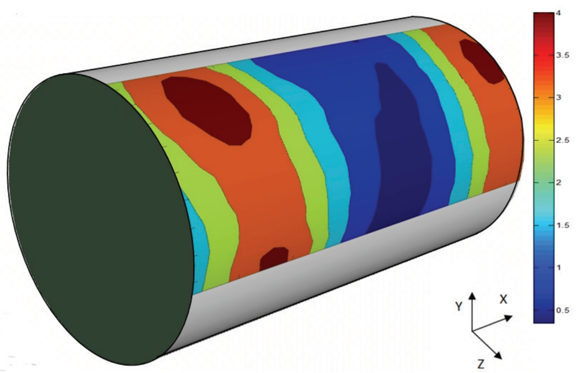


Fig. 4. Sensor positions around the machine



Tangential position



Axial position

Fig. 5. Distribution of the TAN and Z external flux components

3. Energy harvesting from external flux

3.1 Coil position and dimension for energy harvesting

The FE model and the experimental results show that the maximum part of the external flux can be harvest in front of the end-windings with coil placed in the "NOR" position, as close as possible. It is the best solution to harvest energy for two reasons. First, setting up a sensor against an external housing is easier, especially if the sensor is large. Then, the sensor placed in the TAN and Z positions is not crossed by a uniform flux because in the air, the external flux varies inversely with the distance. For a given sensor size, the picked up flux is lower in the TAN and Z positions. Therefore the "NOR" position ensures to pick up the most of external flux.

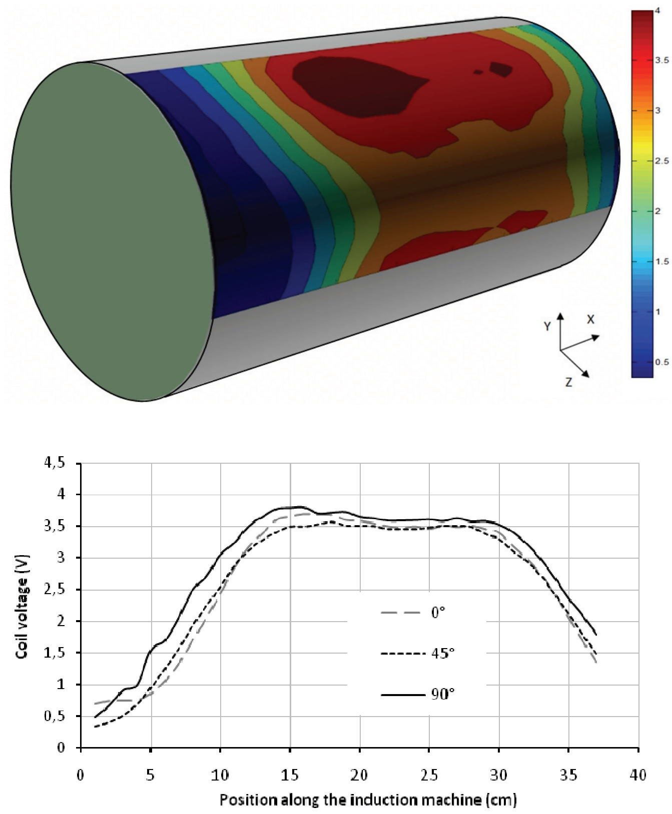


Fig. 6 Distribution of the NOR external flux components

Then, the size of the coil has to be defined. Let us consider an idealized case: the external b flux density is supposed to be a p pole pair sinusoidal waveform:

(1) $$b = \hat{b}\cos(\omega t - p\alpha_s)$$

Let us suppose that this wave crosses a n_c turns rectangular ($L_c \times l_c$) coil located at a distance R_c from the machine axis (Fig. 7). Insofar the coil dimensions are small compared to R_c , l_c can be replaced by $R_c\Delta$. The external flux through $dS = L_c dl_c = L_c R_c d\alpha_s$ can be expressed as:

(2) $$d\varphi_c = bL_c R_c d\alpha_s$$

So, the ψ_c flux linked by the coil results from:

(3) $$\psi_c = n_c \int_{\alpha_{s0}-\Delta/2}^{\alpha_{s0}+\Delta/2} \hat{b} L_c R_c \cos(\omega t - p\alpha_s) d\alpha_s$$

that leads to the following relationship:

(4) $$\psi_c = 2n_c \frac{L_c R_c}{p} \hat{b} \sin\left(p\frac{\Delta}{2}\right)\cos(\omega t - p\alpha_{s0})$$

It appears that Δ, ie l_c, has to be optimized with p and that some configurations must be avoided. For instance, for $p = 4$, Δ has to be different from 90° whereas $\Delta = 45°$ gives the highest magnitude.

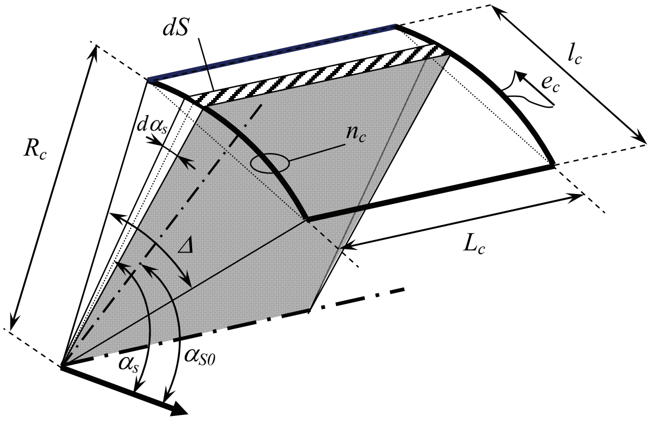


Fig. 7 Coil model

3.2 Quantification of the harvested energy

The theoretical analytical model allows determining the coil voltage which can be obtained from the external field:

(5) $$e_c = \frac{d\psi_c}{dt} = -2n_c \frac{L_c R_c}{p} \hat{b}\, \omega sin\left(p\frac{\Delta}{2} \right) sin\left(\omega t - p\alpha_{s0} \right)$$

Thus, for $p = 1$, $n_c = 200$, $L_c = 0.05\ m$, $R_c = 0.2\ m$, $p = 1$, $\omega = 2\pi 50\ rd/s$, $\hat{b} = 10^{-3} T$ and $\Delta = 180°$, the $\hat{e}_c$ maximal value of e_c is 1.26 V. Then, the internal voltage "generator" drop depends on the characteristics of the coil, especially the coil diameter and lenght, which influence the internal impedance of this equivalent generator. 100 and 200 turns sensors with such dimensions have been placed close to the external yoke of the induction machine and they have been connected to a variable R resitor. The Fig. 8 shows the variations of the power given by these coils with R. The maximum power consumed in R can be over 1mW.

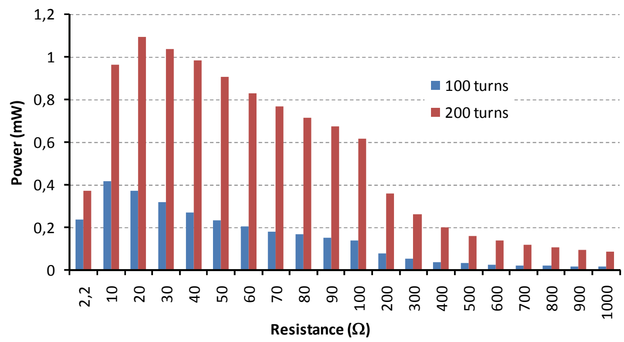


Fig. 8 Variations of the power consumed by R with R

Conclusion

The study that has been carried out clearly shows the feasibility of the harvesting from electromagnetic field radiated by an AC machine. The theoretical study takes only into account the fundamental harmonic at 50Hz and harmonics can also act positively on the energy which can be harvested. The experimental system shows that a power of 1mW can be consumed on a resistive load. It means that the device can not constitute a full-fledged energy source itself for many applications. It is rather an extra-energy source. Such a device will be applied to increase the working time of autonomous cell used to diagnose AC machine. The next step is to determine the rectifier circuit that allows having the least loss as possible.

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