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Effect of the permanent magnets locations on the voltage generated by permanent magnet generator

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Abstract - *Currently, the permanent magnet generators find wide application in the renewable energies field such as the conversion of the wind energy or the tidal energy to an electrical energy. The main objective of this work is the calculation of the magnetic field created by the permanent magnets of the both selected rotor types (magnets on surface and inset type magnets) by taking into account the rotation of the rotor, and therefore the calculation of the electric field induced in the stator, which allows us to calculate the electromotive force exerted on the conductors of the stator coils in order to know the induced voltage by each generator, then, we make a comparison between them to determine the type of generator most answered in the industry. To reach our goal we use the finite elements method to solve the partial derivative equations those describe this physics problem.*

Résumé - *Actuellement, les générateurs à aimants permanents trouvent une large application dans le domaine des énergies renouvelables telles que la conversion de l'énergie éolienne ou de l'énergie marémotrice en énergie électrique. L'objectif principal de ce travail est le calcul du champ magnétique créé par les aimants permanents des deux types de rotor sélectionnés (aimants de surface et aimants à insertion) en tenant compte de la rotation du rotor, et donc du calcul du champ électrique induit dans le stator, ce qui nous permet de calculer la force électromotrice exercée sur les conducteurs des bobines du stator afin de connaître la tension induite par chaque générateur, puis de faire une comparaison entre eux pour déterminer le type de générateur auquel on peut le mieux répondre dans le secteur. Pour atteindre notre objectif, nous utilisons la méthode des éléments finis pour résoudre les équations dérivées partielles qui décrivent ce problème physique.*

Keywords: Permanent Magnet Generators - Magnetic Field Calculation - Finite Elements Method.

1. INTRODUCTION

With advances in the field of power electronics and advent of high energy permanent magnet materials, permanent magnet machines have enjoyed a boom increasing in much recent applications. They have been adopted in many high performance applications, where they are used as motors in medical equipments, aerospace, robotics, electric and hybrid vehicles, power tools, etc.[1, 2], or as generators in renewable energies domain such as the conversion of the wind energy or the tidal energy to an electrical energy [3, 4].

Generally, in permanent magnet machines, there are several rotor configurations according to the magnets locations [5, 7]; rotor with surface magnets, rotor with inset magnets, rotor with interior magnets, and rotor with buried magnets.

In this work, we are interested by the two first types of rotors. In the first type of the magnets (surface magnets), the permanent magnets with radial magnetization are placed directly on the rotor, the magnets are subjected to centrifugal forces which can cause their detachment of the rotor, so this technical often requires the use of a necessarily a

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magnetic fret so as not to compromise the direction of the magnetic field, another role of this fret is the protection of magnets against corrosion, against shocks, and also the limitation of harmonics in the magnets and therefore the energy loss, but its major disadvantage is the increase in the thickness of the magnetic gap. In the second type of the magnets (inset magnets), like the first one, the inset type magnets are also mounted on the surface of the rotor.

However, the openings between the permanent magnets are filled with iron. The main objective of this work is the calculation of the magnetic field created by the permanent magnets of the both selected rotor types (magnets on surface and inset type magnets) by taking into account the rotation of the rotor, and therefore the calculation of the electric field induced in the stator, which allows us to calculate the electromotive force exerted on the conductors of the stator coils in order to know the induced voltage by each generator, then, we make a comparison between them to determine the type of generator most answered in the industry.

To reach our goal we use the finite elements method to solve the partial derivative equations those describe this physics problem.

2. PERMANENT MAGNET GENERATOR MODELING

In permanent magnet generators, a rotating magnetic field passes through coils made of copper wire, these latter pick up the variable magnetic flux and transform it into an alternative voltage.

The permanent magnets are fixed on the rotor which is driven through speed multiplier by an external energy source (fossil or renewable). Figure 1(**A**) shows photo of permanent magnet generator used to transform the energy pick up by the wind turbines to an electrical energy [8].

And figure 1(**B**) shows the diagram of the generator cross section used as a domain of the magnetic field distribution, where the dimensions are taken from reference [8].

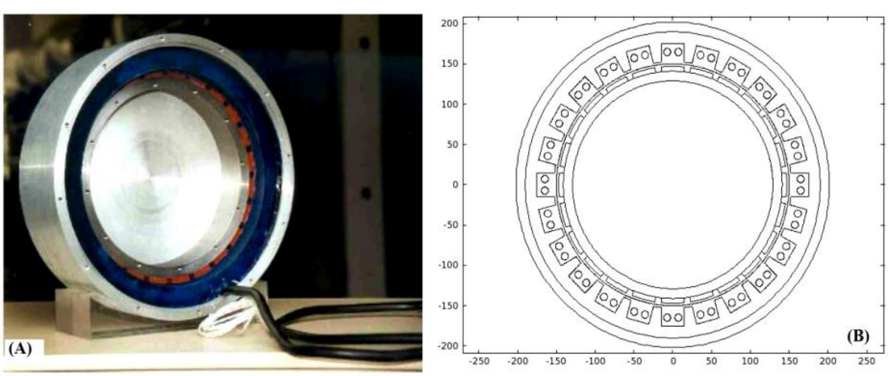

Fig. 1: Permanent magnet generator, (**A**): Photo [8], (**B**): Diagram of the generator cross section, where the dimensions are taken from reference [8]

The calculation of the magnetic field created by a permanent magnets can be calculated by using analytical method based on the Coulomb method or amperian current models [9, 10], or by using numerical methods as the finite difference method [9] or the finite element method.

In this work, we used the finite difference method for the modeling of the physical phenomenon that describes the generator operation; we note that this software is based on the finite element method.

In order to take into account the rotation of the rotor, we considered that the rotor geometry is separable to that of the stator, and the mesh nodes of the rotor geometry can be rotate according to the following rotation matrix:

$$\begin{pmatrix} x_r(t) \\ y_r(t) \end{pmatrix} = \begin{pmatrix} \cos(\Omega t) & -\sin(\Omega t) \\ \sin(\Omega t) & \cos(\Omega t) \end{pmatrix} . \begin{pmatrix} x_{r0} \\ y_{r0} \end{pmatrix} \tag{1}$$

where $\{x_{r0}, y_{r0}\}$, and $\{x_r(t),\ y_r(t)\}$ are the components of the initial and last position in the stator reference frame, respectively, and Ω is the rotor rotation speed. So the linear velocity (v) of the magnetic field at each point located in stator located at the position $\{x_s,\ y_s\}$ is given by the following expression:

$$v(x_s, y_s) = \Omega \sqrt{x_s^2 + y_s^2} \tag{2}$$

The physical problem in the electromagnetic system is governed by the general Maxwell's equations.

$$\begin{aligned} \nabla \times H &= J + \frac{\partial D}{\partial t} + \nabla \times (D \times v) + v \nabla . D \\ \nabla \times E &= -\frac{\partial B}{\partial t} - \nabla \times (B \times v) \\ \nabla \times B &= 0 \\ \nabla \times D &= \rho \end{aligned} \tag{3}$$

where ρ is electric charge density, v is the linear speed, H, and B are the magnetic field and the magnetic flux density, respectively, E, and D are the electric field and the electrical displacement, respectively. The quantities $\partial D / \partial t$, $\nabla \times (D \times v)$), and $v \nabla . D$ are the displacement current density, the current density due to the motion of the polarized material, and convection current density, and J is the electric current density which can be expressed as follow:

$$J = \sigma E \tag{4}$$

where σ is the material conductivity. The relation between H, B, and the magnetic potential vector A is given by the following expression:

$$B = \mu_0 \mu_r \times H = \nabla \times A \tag{5}$$

where μ_0, and μ_r are the vacuum permittivity, and the relative permittivity of the considered material. The electric field circulation in a conductor of length l and section s gives an induced voltage e expressed as follows:

$$e = \frac{l}{s} \iint_S E \times dS \tag{6}$$

After the simplification, and the rearrangement of the previous equations, the magnetic potential vector in permanent magnet generator can be written as follow:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times A \right) + \mu_0 \sigma \frac{\partial A}{\partial t} = 0 \tag{7}$$

The magnetic flux density in the permanent magnets is given by:

$$B = \mu_0 \mu_r H + B_r \tag{8}$$

where B_r is the permanent magnetic flux density of the magnets.

3. RESULTS AND DISCUSSION

The results shown below are calculated for two types of permanent magnet generators (magnets placed on the surface of the rotor and magnets inserted in the rotor). The dimensions are taken from the reference [8].

In both cases, 24 magnets of NdFeB material are used; this material is very powerful and seems very suitable for electric machines, its residual magnetic flux is about 1.4 T with 1000 kA/m of coercively, and its maximum energy production is about 400 kJ/m^3 [11].

The magnetic material of stator and rotor is taken of Iron-Cobalt Alloy (UNS K92650); the magnetization characteristic data of this material are shown in figure 2, where they are interpolated according to the following function [12]

$$B(H) = B_s \frac{2}{\pi} \operatorname{atan}(kH) \tag{9}$$

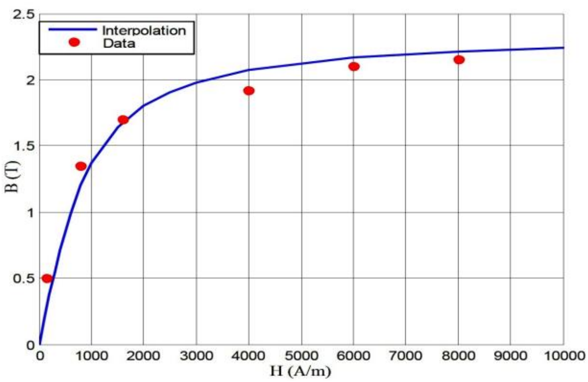

Fig. 2: Magnetization characteristic curve of Iron-Cobalt Alloy ($B_s = 1.36T$, $k = 0.0012886 m/A$)

Figure 3 shows the distribution of the magnetic flux density and the contours of the magnetic potential vector in hollow rotor generators (402 ATK), these generators offer considerable performance for mills, wind turbines, tidal turbines and other renewable energy devices, they contain 24 permanent magnets, and their rotational speeds from 220 to 800 rpm.

The simulation results are obtained for 1.4 T of residual magnetic flux density in permanent magnets, and under 250 rpm of rotational speed. In left results, the permanent magnets are located on the rotor surface, and in the right results, the permanent magnets are inset in the rotor. The upper results are calculated at $t = 0s$, and in the lower results at $t = 0.005\,s$.

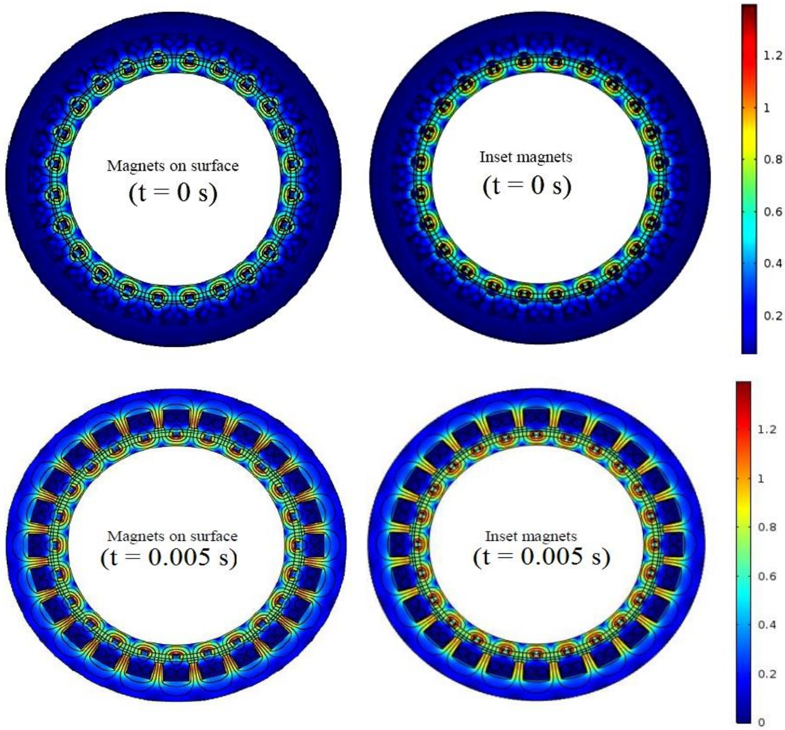

Fig. 3: Magnetic flux density distribution and magnetic potential vector contours calculated in permanent magnet generators; with magnets on rotor surface and inset magnets type

Figure 3(**A**) shows a comparison of the voltages generated by the two generators (with surface magnets and inset magnets) to the sine wave; where both voltages have a shape close to the sine wave {the Total Harmonic Distortion of the first one is 4.28 %, and of the second one is 6.34 %}.

And figure 3(**B**) illustrates the normalized voltages generated by each generator, it shows that the voltage generated by the generator with inset permanent magnets is 5 % lower than the voltage generated by the generator with surface magnets.

This result can be explained by the saliency due to the Iron-Cobalt Alloy between the permanent magnets which gives a reluctant torque.

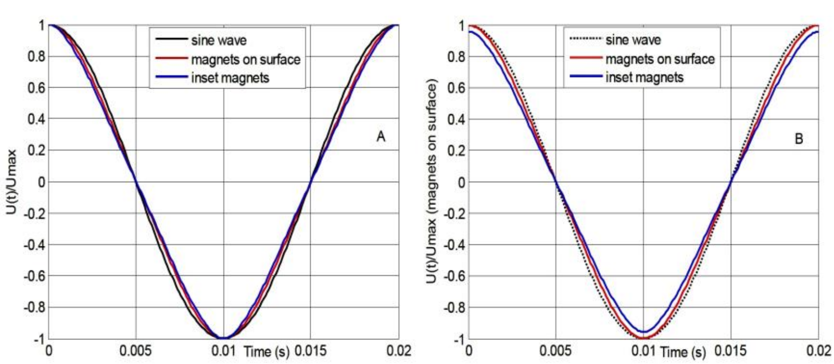

Fig. 4: Effect of magnets location on the generated voltage (**A**): Distortion, (**B**): Magnitude

4. CONCLUSION

In this work, we have used the finite element method in order to know the effect of the Permanent Magnets Locations on the Voltage Generated by two types of Permanent Magnet Generators (magnets on surface and inset type magnets).

The results show that the voltages generated by these generators have a shape close to the sine wave, where the Total Harmonic Distortion of the first one is 4.28 %, and of the second one is 6.34 %, and they show also that the voltage generated by the generator with inset permanent magnets is 5 % lower than the voltage generated by the generator with surface magnets.

These results can be explained by the saliency due to the Iron-Cobalt Alloy between the permanent magnets which gives a reluctant torque.

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