DESIGN OF AN ELECTRICAL MACHINE FOR AN INTEGRATED MAGNETOCALORIC COOLING SYSTEM

C. KIEFFER^{(a)(b)}, F. GUSTIN^(a), S. GIURGEA^(c), C. ESPANET^(a), M. ROZE^(b) ^(a) Université de Franche-Comté, Institut FEMTO-ST (UMR 6174), ^(b) Phénix-International, ^(c) Université de Technologie de Belfort-Montbéliard, Institut FEMTO-ST (UMR 6174)

ABSTRACT

The magnetocaloric effect, and particularly its application to the production of cold at room temperature remain a scientific and technologic challenge. Magnetic refrigeration offers a good energy efficiency. This paper deals with the design and implementation of a magnetic refrigerator prototype. The particularity of our prototype is to integrate a magnetocaloric regenerator in the air gap of a Permanent Magnet Synchronous Machine.

1. INTRODUCTION AND MAGNETOCALORIC EFFECT

The project described in this article consists in the achievement of a pre-industrial air conditioner prototype. The aim of this study is to mutualize the functions of magnetocaloric inductor and rotor of a permanent magnet synchronous machine. The magnetocaloric regenerator is placed inside the motor close to the magnets. A motor with two air gaps has been designed. One of those is attended to receive the magnetocaloric regenerator. In addition to that the induction curve's shape should be as close as possible from a square shaped curve with during a half-period an induction as high as possible and at the same time, during the other half-period an induction value close to zero. This induction profile enables to obtain the magnetization and demagnetization of the magnetocaloric material placed inside the regenerator.

The magnetocaloric device enables to reach very good efficiencies, which can be explained actually by the absence of a compressor, which allows considering many opportunities for this emerging technology. Indeed, the technological advantages of such a system are: less air pollution, no noise or vibration and high thermodynamic efficiency.

1.1. Magnetic refrigeration

The magnetocaloric effect is an intrinsic property of ferromagnetic materials consisting of an emission or absorbtion of heat by the action of a magnetic field (Lebouc et al., 2005). This results in the heating or cooling of the material. Warming and cooling are both reversible and adiabatically achieved (Tura et al., 2002). The material temperature variation is maximum when the working temperature is equal to the Curie temperature of the material.

1.2. Active Magnetic Regenerative Refrigeration

However, the direct use of the magnetocaloric effect is insufficient in the case of magnetic refrigerators equipped with permanent magnets because of the low intensity of magnetic fields generated and therefore the low temperature variation. For operation at room temperature, gadolinium, which is the most commonly used material in magnetocaloric applications, does not achieve a ΔT of 10K under a magnetic field of 5T. It is therefore imperative to improve this temperature difference (Barclay et al., 1982). In order to obtain such results, we use an Active Magnetic Regenerative Refrigeration cycle whose aim is to create, by a succession of heat exchange between the material and the coolant, a temperature gradient along the material. This gradient is increasing with each cycle to achieve the temperatures of hot and cold sources at each end of the system (Allab, 2008); this gradient can reach 10 to 30K.

1.3. Energy consumption

The main advantage of magnetic refrigeration is its high thermodynamic efficiency. The Coefficient of Performance (COP) is close to 10 for a magnetic cycle when it equals only 2 for a classical thermodynamic cycle (Lebouc et al., 2005). Magnetic refrigeration also has many advantages over a conventional thermodynamic cooling device (reduced environmental impact, lower weight and size,

reduced noise and vibration). The cold power (Qcold) of the magnetic refrigerator is proportional to

the volume of the magnetocaloric material placed in the regenerator. Q cold is also a function of the magnetic field, the frequency and the magnetocaloric material characteristics (Roudaut, 2011). When the maximum cold power equal to the intrinsic power, the cold power equals to:

$$\dot{Q}cold = fm_{mcm}c_{mcm}\Delta T_{ad} \qquad [W] \tag{1}$$

In order to determine the coefficient of performance of the magnetic circuit realized in this article, we consider the ratio of the intrinsic power of the magnetocaloric material (Qmcm), the mechanical power (Wmec) needed for generating the variable magnetic field and moving of the fluid.



Figure 1. Energy consumption of magnetocaloric refrigerator (Roudaut, 2011)

Similarly, the coefficient of performance of the thermal-hydraulic circuit can be written as:

$$COP_{th} = \frac{Q \, cold}{W \, fluid} \tag{3}$$

The energy balance of the magnetocaloric device studied in this paper is presented in the diagram in Figure 1 (Roudaut, 2011).

2. SIZING OF THE SYNCHRONOUS MACHINE

The main goal of the study proposed in this paper is the integration of a magnetocaloric regenerator in the air gap of a permanent magnet synchronous machine in order to share the magnetocaloric inductor and rotor function of a permanent magnet synchronous machine and minimize the overall size and weight of the device.

2.1. Problems

The regenerator has the form of a hollow cylinder whose dimensions are adapted to the dimensions of the air gap of the synchronous machine. The regenerator is intended to contain the magnetocaloric material. The sizing of the electric motor is carried out in order to obtain a maximum induction variation ΔB in the air gap in order to have a temperature difference ΔT as large as possible, thereby improving the performance of the magnetocaloric device. In order to obtain such interesting results, it is imperative to use the principle of flux concentration by arranging the magnets in the rotor of the electric motor to maximize local induction by focusing the field lines in a large area of air gap (area where the induction is maximum) while deflecting the flux out of the air gap, in order to obtain at the same time in another area of the air gap an induction value close to zero. To obtain an induction value as high as possible, our choice is focused on rare earth magnets of the type Neodymium-Iron-Boron with a remanent induction value of 1.43T at 20 ° C.

2.2. Rotor sizing

Among the various architectures for the flux concentration, one appears most frequently in the field of magnetic refrigeration: it's the Halbach cylinder. This assembly is composed of a minimum of 4 magnets, the orientation of the magnetization of each segment is as close as possible to the path of the flux lines in the rotor. This configuration has the advantage of generating a homogeneous induction which may be higher than the residual induction of magnet (Bjork, 2010).

In the case of the configuration in Figure 2 (2 segments per pole), we note that the proximity of magnets in the regenerator results in obtaining a relatively poor induction profile in the center of the regenerator with a Bmin value over 0.2T and a Bmax value below 0.9T i.e. a ΔB value of 0.6T which is insufficient (Figure 4).

The distance between inter-pole magnets and regenerator can significantly improve the results in terms of induction in the regenerator: the inductive variation exceeds 0.9 T with a magnet volume lower than in the previous case. In order to obtain a profile of induction with a rectangular shape, we also proposed to split the magnets inter-pole (Figure 5).

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rotor angular position

2.3. Stator sizing

In order to improve the compactness, performance and industrialization of motors, it is more convenient to use concentrated windings. Contrary to the diametric pitch winding, the concentrated windings around the teeth has small end-windings, which has the advantage of greatly reducing the mass of copper, the copper losses and reduces significantly the axial length of motor (Ishak et al., 2004). We present here some elements of the design of the machine. The magnetocaloric device specifications imposed us to choose a polarity p = 2, that's why we choose a machine with 6 teeth. The relationship which allowed us to calculate the resistance of a coil (R_{bobine}) according to the number of turns (*ns*) of a coil can be obtained with the resistivity of copper, the average length of a coil turn and the total section of copper conductors in a slot.

$$R_{bobine} = ns^2 \times \rho_{cu} \times (L_{spire} / S_{cu}) \tag{4}$$

By neglecting the iron and mechanical losses (because both iron and mechanical losses are small due to the low rotating speed and frequency), the expression linking the mechanical power to the rms value of the electromotive force for one turn (e_{f1}) is obtained with the current (i) the number of turns (ns) and the phase shift between the back EMF and the current (ψ) :

$$P_{m\acute{e}ca} = \sum_{k=1}^{3} e_{f1_k} \times i_k \times ns \times \cos(\psi) \qquad [W]$$
⁽⁵⁾

The minimal iron losses are obtained with $\psi = 0$ for this type of machine.

The three phases are balanced and connected in star. The value of the cyclic inductance of one phase can be obtained by considering coils composed of a single turn and by short-circuiting one phase of the machine. The value of the cyclic inductance obtained for a one turn coil (L_{phl}) is then expressed as a function of the value of the electromotive force (E_1) , of the short-circuit current (I_{cc_1}) , of the resistance of a phase obtained for one turn coils (R_{phl}) and the electrical pulse (ω) .

$$L_{phl} = \sqrt{\frac{\left(\frac{E_1}{I_{cc_1}}\right) - R_{phl}}{\omega^2}} \qquad [H]$$
(6)

The power supply voltage (U_{bat}) formula is obtained with the number of turns depending on the ampere-turns (AT):

$$ns(U_{bat}) = \frac{U_{bat}}{\sqrt{(E_1 + R_{ph1} \times AT)^2 + (L_{ph1} \times \omega \times AT)^2}}$$
(7)

The electromotive force and the short-circuit current are obtained with 2D finite element simulations for a given rotating speed and with one turn coils. This enables to determine the number of winding turns in series from the equation of voltages (see equation 7). The slot section and the wire section are obtained for a maximum current density of $6A/mm^2$.

3. EXPERIMENTAL REALIZATION

3.1. Prototype

The main goal of the study proposed in this paper is the integration of a magnetocaloric regenerator in the air gap of a permanent magnet synchronous machine in order to share the magnetocaloric inductor and rotor function of a permanent magnet synchronous machine and to minimize the overall size and weight of the device. Such a structure has been designed by the Femto-ST Institute and Phenix-I French Company. It is presented in Figure 8 and it corresponds to the geometry defined and presented above. But for budgetary reasons, the axial length of the prototype has been reduced (60% reduction). The resulting prototype should rather be seen as a technical demonstration of the principle of magnetocaloric system for integrated actuator. The rotor consists of an assembly of magnets, each of the four-pole component is composed of 4 magnets as described in Figure 9.

3.2. Experimental validation

The tests were conducted in order to compare the results obtained by finite elements with the results obtained during tests of the prototype. Many theoretical parameters have been compared with experimental results obtained during prototype testing. A study on the shape of the stator teeth was achieved using the commercial Software Flux2D. This study was aimed to obtain a trapezoidal shaped electromotive force. The shape of the teeth was improved to obtain the desired shape of the electromotive force. These results are compared with experimental ones: the electromotive force waveform and amplitude is close to theoretical results obtained by 2D FEM (Figure 10); the gap between the theoretical and the real curve is relatively low and the small difference can be explained by slight deviations of the shape of metal plates and coils that can occur during assembly of the prototype. The results of electromotive forces obtained are very satisfactory.



Figure 10. Electromotive force depending of time



A comparison between theoretical and experimental results was also performed for the induction profiles measured at the center of the air gap. The theoretical results of induction obtained by finite elements are square shaped with amplitude of 0.9T. The results observed during the tests of the prototype showed relatively large variations (30%) between theoretical and experimental results (Figure 11). This difference can be explained by the impact of the 3D effect. Indeed, as previously explained, the length of the prototype has been reduced. The segmentation of the rotor magnets made in order to make the assembly of the rotor easier had also the effect of inducing many gaps between different segments of magnets and may have an impact on the induction in the air gap of device. However, the waveform of the induction obtained in the tests is rectangular and, from this point of view, conform to our expectations. With a full scale device with sufficient axial length, the flux density would be improved and a value close to 2D simulations can be obtained when the 3D end effect are not so important.

4. CONCLUSION

This study leads to the realization of a demonstrator which is the first step towards achieving an integrated magnetic refrigerator. The aim of this integration is to develop a compact system which could be introduced in an automobile. This type of magnetic refrigerator could replace current air-conditioners offering comparable performances with significantly lower energy consumption. The obtained results have shown that it is possible to incorporate a magnetocaloric regenerator in the air gap of a synchronous machine, thereby reducing the size of the system. The motor shaft sized in this study can be coupled to a pump allowing the flow of the coolant in the regenerator.

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