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Performances of a Hybrid Excited Flux-Switching DC-Alternator: Analysis and Experiments

A. Dupas, E. Hoang, S. Hlioui, B. Gaussens, M. Lécrivain, M. Gabsi

***Abstract*—In this paper, a finite elements analysis and experimental results of a hybrid excited flux switching 3kW DC-alternator are presented. The studied machine is presented and its flux control capability is calculated. The short-circuit current is explored by mean of two different methods. One of them cancels all harmonic components of the flux. The second part presents the alternator connected to a diode bridge rectifier with a DC controlled bus. The performances of the studied machine are evaluated by the model and compared to experimental results. Finally, we compared the experimental performance of the studied machine with NdFeB magnets, ferrite magnets and without magnet.**

***Index Terms*—Hybrid excitation machine, synchronous alternator, 2D-FEA, Rectifiers**

I. Introduction

TABLE I
NOMENCLATURE

2-D FEA	Two-dimensional finite-element analysis.
PM	Permanent magnet.
HEM	Hybrid excitation machines
HEFSPM	Hybrid excited flux-switching permanent magnet.
DBR	Diode bridge rectifier.
Jexc	Excitation current density.
Jcc	Short-circuit current density.
Icc	Short-circuit current.

DEVELOPMENT of the embedded systems and the increase of the power production from the wind energy (for example, http://www.venpower.com/ or [1]) make essential research about compact, reliable and powerful alternator. In the quoted examples, it is necessary to work in variable speed and thus to be able to regulate the output voltage of the alternator by means of the flux modulation. In this paper, a hybrid system solution is investigated.

Hybrid excitation machines (HEM) combines advantages of wound excitation machines and permanent-magnet excited machines. Electric excitation offers a better control of the magnetic field by controlling the excitation current while permanent magnet has a high-energy density. Many hybrid excited topologies were proposed in the literature and compared with PM machines [2]-[6]. The idea is to combine the two excitation flux in order to have a high density synchronous machines with good flux control. Researchers have investigated HEM connected to a diode rectifier [17] [18]. One of these topologies is flux-switching machine [7]-[14]. Due to a salient passive rotor, hybrid excited flux-switching permanent magnet machines have high robustness and thanks to permanent magnets localised on the stator the HEFSPM have high torque density. Thanks to these advantages, this machine is a good candidate for a DC-alternator application capability.

Two intrinsic major characteristics are important during an alternator exploration, the no-load flux and short-circuit current. The aim of this article is to examine these two characteristics for a HEFSPM prototype with NdFeB permanent magnet. The output power of HEFSPM connected to a diode bridge rectifier is also explored. A comparison of the output power, no-load flux and short-circuit current calculated with FEA and obtained by measurement is exposed.

The second part of this paper consists to present differences between three permanent magnet configurations. A FEA and measurement comparison between rare-earth magnets and ferrite is proposed. In order to identify the benefits of the hybrid excitation experimental measurements and FEA were performed with and without permanent magnet.

II. Structure of the Hybrid Excited Flux-Switching Permanent Magnet prototype and Experimental Bench

A. Structure presentation

The proposed HEFSPM has 24 stator slots and 20 rotor poles. Two magnetomotive sources are located on the stator, one is produced by permanent magnets and the other one by electrical excitation windings. The rotor is composed by 20 salient poles, and has neither windings nor permanent magnets. The structure investigated in this paper was already reported in [15][16]. The prototype and specifications are shown in Fig.1 and Tab.II.

TABLE II
PROTOTYPE MACHINE SPECIFICATIONS

Number of phases	3
Number of stator slot	24
Number of rotor teeth	20
External stator radius	180 mm
External rotor radius	115 mm
Air gap	0.5mm
Active axial length	15mm

B. Presentation of the experimental benchmark

This paper will focus on generator mode. For experiment, the HEFSPM is associated with a diode-bridge rectifier.[16][18] The scheme of the experimental bench is given in Fig.2 As prime mover of HEFSPM generator, an induction motor of 5.5kW is employed. The DBR is connected on the same DC-bus voltage feeding the 3-phase inverter controlling the induction motor.

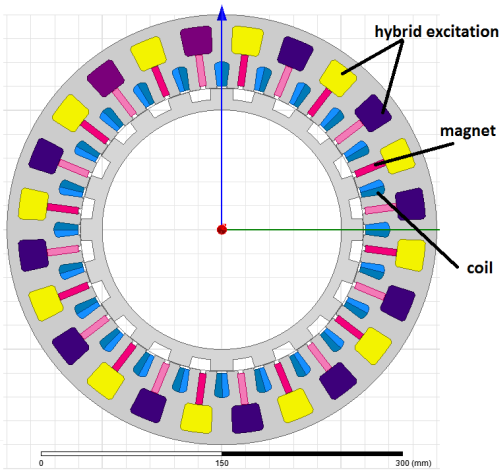

Fig. 1. 2D view of the Hybrid Excited Flux-Switching Permanent Magnet Generator prototype 24-20

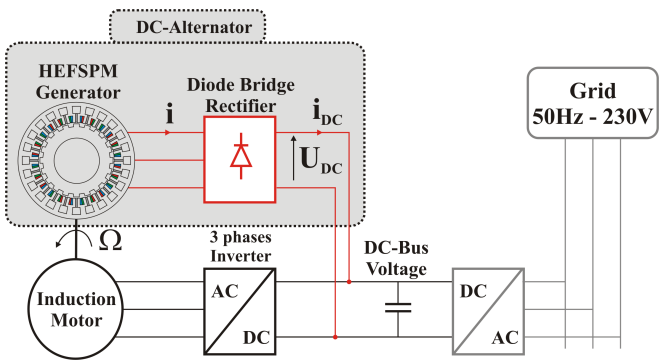

Fig. 2. Schematic diagram of the power generation system

III. "The NdFeB-HEFSPM Prototype"

A. No-load flux

The main advantage of the hybrid excitation is, as wounded excitation for synchronous machine, the flux regulation capability. The flux distribution of the prototype machine at different excitation currents are shown in Fig.3 and Fig.4.

We can notice that without excitation current, the main permanent magnet flux is short-circuited in the external stator yoke. Thanks to excitation current, air-gap magnetic field is adjustable.

All measured and calculated maximum flux correspond to the rotor's position given in Fig.3, a stator slot and a rotor teeth are aligned. The no-load flux value is calculated for one conductor in one slot.

Figure 5 shows the no-load flux for different excitation current density values (0 to $6A/mm^2$). When the excitation currents equal to $0A/mm^2$, the no-load flux is due to the permanent magnet. When we supply the exciting windings, the no-load flux increases.

Figure 6 presents differences between FEA model and experimental results. Differences between curves can be explained by the lack of precision on B(H) characteristic and the 3D effect. Actually, the studied structure has 15 mm axial length and 180 mm external radius, thus the 3D effects are important. Further investigations are needed to estimate the impact of the B(H) characteristic and 3D effects on FEA results. However, the difference is less than 5% and it is considered as acceptable in this study.

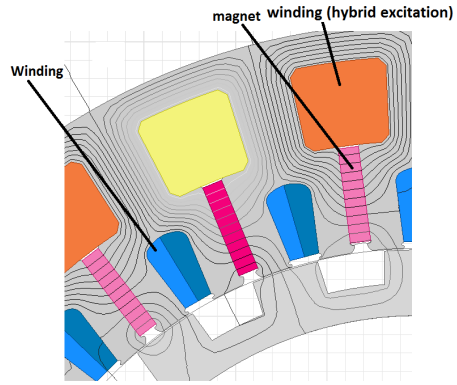

Fig. 3. FEA: Flux distributions for $J_{exc} = 0A/mm^2$

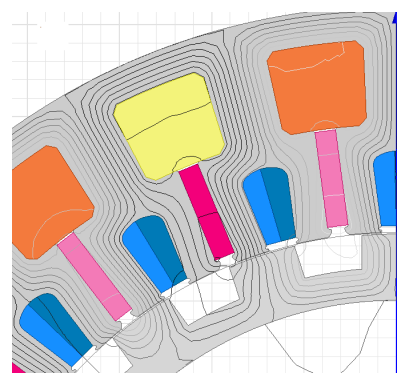

Fig. 4. FEA: Flux distributions for $J_{exc} = 10A/mm^2$

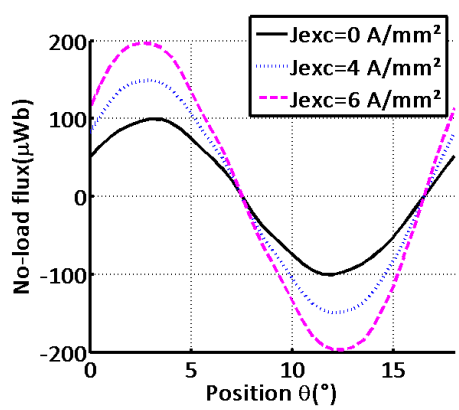

Fig. 5. FEA: Evolution of no-load flux (per turn) as function of mechanical position θ under different exciation current density

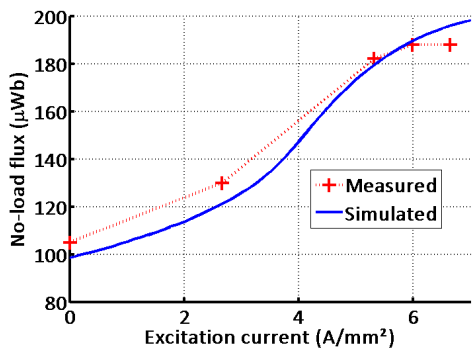

Fig. 6. Maximum no-load flux versus excitation current density, comparison between model and experimental results

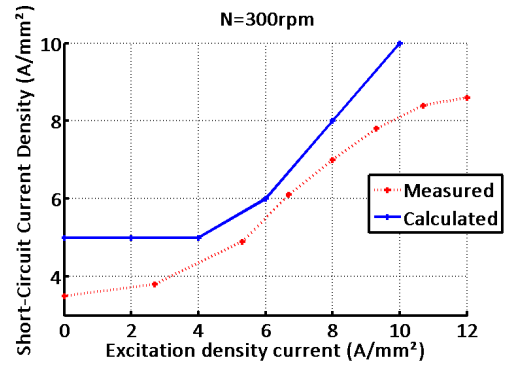

Fig. 7. Evolution of short-circuit current density as function of excitation current, comparison between models and experimental results

B. Short-Circuit Current

The experimental bench scheme is given Fig.2. In order to explore the output power, the DC-bus is replaced by a short-circuit in experimental bench. Relations between output power and short-circuit current are explored in [16].

Two methods are used to calculate the short-circuit current density. The short-circuit current corresponds to the current that cancels total excitation flux in the machine. The first method consists of firstly to determine the *d-axis* position. Secondly, three-phase currents, in phase opposition with the no-load flux, are injected. Thirdly the total excitation flux in the machine is computed and compared to zero (in this case only the fundamental part of the flux is considered). If the flux is nul, the short-circuit current is obtained, otherwise the amplitude of the current increased until the fundamental component of the flux is cancelled. Indeed the harmonics are almost no impacted.

Figure 7 presents results obtained by the first method, the calculated short-circuit current density is compared to the measured. An important difference can be noticed between simulation and experimental results. This difference may be explained by the harmonics.

The second method is similar to the experimental method. The output of the armature windings are in short-circuit and the current is computed by the circuit model. The FEA are coupled to a circuit model, the simulations are performed in transient. This method allows to obtain the current that cancels all harmonics of the flux. Figure 8 shows one short-circuit current for $Jexc = 0A/mm^2$. The result obtained from the FEA shows that the short-circuit current is not sinusoidal. As we can see on Fig.9, short-circuit current waveform is distorted and the spectra of I_{cc} contains harmonic contents. . The results of the two methods are compared with experimental results in Fig10. The second method overestimate I_{cc}, as the first method, but the difference is more acceptable. This difference can be explained by the end winding inductances that is neglected in the 2D model. The end windings measure approximatively 20 mm when the active length is 15 mm.

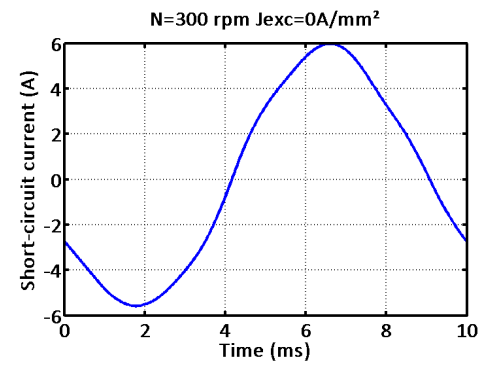

Fig. 8. FEA: Evolution of short-circuit current as function of time

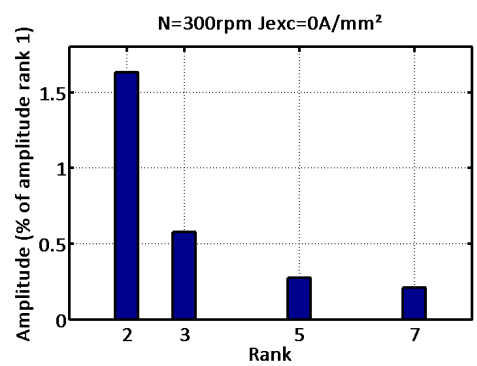

Fig. 9. FEA: Spectra of short-circuit current

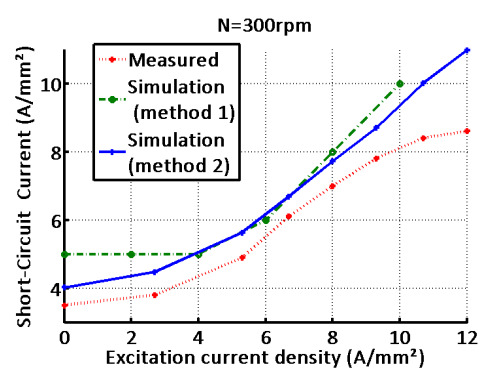

Fig. 10. Short-circuit current density as function of excitation current density, comparison between measurements and simulations

C. Machine connected to a Diode Rectifier

In this section the HEFSPM Generator is used with the DBR as presented in Fig.2. The DC-bus voltage equals 300V. A DC excitation current is applied to wounded excitation and output power is calculated with FEA model for a speed: N=2000 rpm. Figure 11 presents output power waveforms for different J_{exc}. We can notice that if the excitation current are greater than $12A/mm^2$, the output power decreases. This is due to magnetic saturation phenomena in the stator of the HEFSPM, the saturation is located in the upper stator yoke. Moreover, the relation between electric period oscillation and the mechanics period is verified, $T_e = \frac{T_m}{6N_R}$. For example, at N=2000 rpm, $T_e = 0.25ms$, as shown in Fig.11.
From FEA, the output power as function of the speed N can be obtained. Its evolution is presented in Fig12. The values obtained from the FEA are higher than experimental results, this difference is due to all neglected losses, that are not take into account in our model. Moreover differences between experimental and simulated values of no-load flux and short-circuit current are cumulative. So this significant difference can be explain.

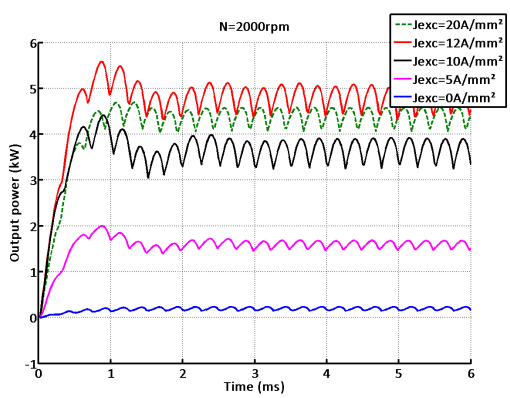

Fig. 11. FEA: Output power evolution for J_{exc} different values (N=2000rpm)

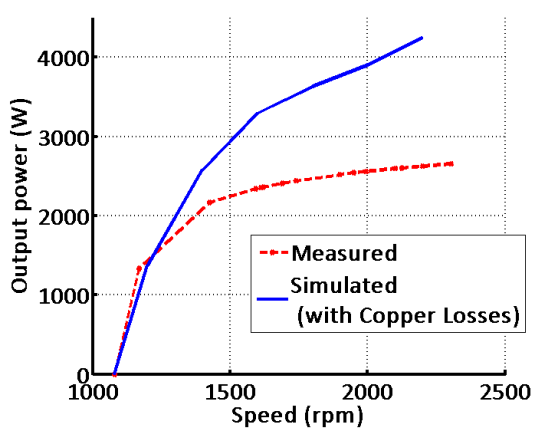

Fig. 12. Output power of the DC-Alternator as function of speed, comparison between FEA and measurement

IV. Comparison with "Ferrite" and "No permanent magnet prototypes"

The previous part has analysed the main intrinsic characteristics of a NdFeB-HEFSPM prototype. In this part a comparison between three prototypes are presented in order to show the impact of the permanent magnet type on the power generation capability of this machine. The difference between these prototypes is the permanent magnet type: NdFeB, Ferrite and the last one have not permanent magnets.
Please notice that the machine was optimised for a hybrid excitation use. Thus, this comparison between the three configurations could be improved by the optimization of each machine according to its permanent magnet configuration.

A. No-load flux

The figure 13 and 14 provide no-load flux comparison between the three permanent magnet configurations. Before $4A/mm^2$, the difference between ferrite and no-magnet is not significant but, for higher current density the hybrid excitation contribution is important. With NdFeB permanent magnet, the main advantage is the no load flux is higher even if $Jexc = 0A/mm^2$. The no-load flux with ferrite isn't equal to zero at $Jexc = 0A/mm^2$ but only $10\mu Wb$.
Another important finding was that the permanent magnet type affect the control capability flux. Although rare-earth magnets provide a more important flux at $0A/mm^2$, the flux variation range is only $100\mu Wb$ while with ferrite it is $180\mu Wb$.

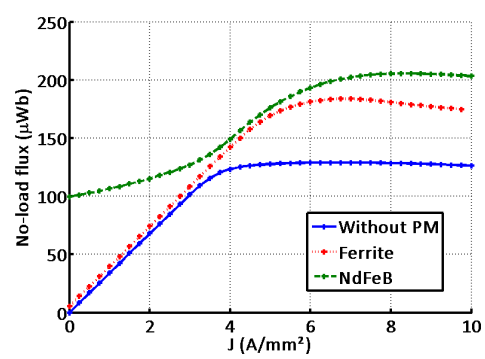

Fig. 13. FEA: Maximum no load flux versus excitation current density

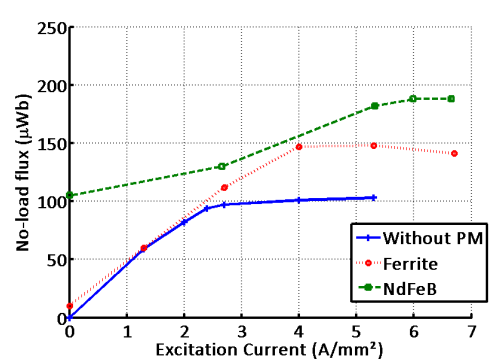

Fig. 14. Experimental results: Maximum no load flux versus excitation current density

B. Short-circuit current

As described on the previous part, the short-circuit current is measured for the three configurations. The mean value of J_{cc} is measured as function of excitation current and its evolution is given Fig.15.

As remind on the previous section, the short-circuit can be linked with output power. So, as predicted, the main advantage of hybrid excitation is the output power control capability, the output power increase with excitation current. The range with NdFeB is almost 5A whereas without magnet the range is 3A so the range of power control is larger with hybrid excitation.

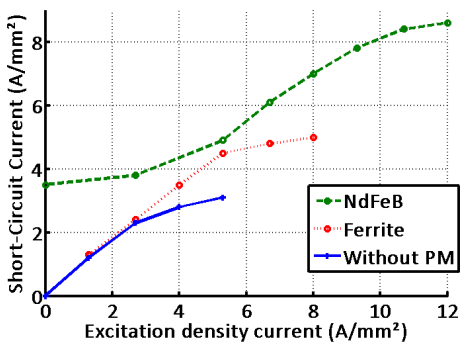

Fig. 15. Experimental results: Short-circuit Current versus excitation current density

C. Output power

The same experimental bench as Fig.2 is used in this section. The output power is compared for two permanent magnet configurations. The advantage of rare-earth magnet is highlighted on Fig16. This figure confirms that, depending on the desired output the type of magnet will be different and thereby the cost.

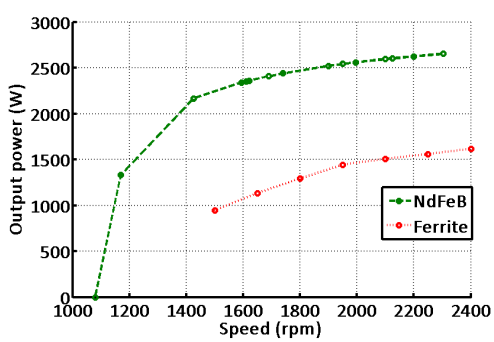

Fig. 16. Experimental results: Output power versus speed

V. Conclusion

In this paper, a 24 stator slots and 20 rotor poles hybrid excited flux-switching permanent magnet (HEFSPM) was presented. This study set out to determine performances of this prototype. FEA models are determined in order to assess no-load flux and short-circuit current. In generator mode, the HEFSPM is connected to a diode bridge rectifier with constant DC-voltage and output power is examined. The comparison of the predicted no-load flux values with experimental results gave us a good agreement. A further study could assess 3D effect in order to improve short-circuit current and output power calculations.

In the second part of this paper, three permanent magnet configurations were presented. The no-load flux, short-circuit current and output power were compared. Thanks to this comparison the influence of hybrid excitation machine is examined.

Acknowledgment

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VI. Biographies

Agathe Dupas is currently working toward the Ph.D. degree in electrical engineering at SATIE laboratory, from the Ecole Normale Superieur of Cachan, France. She received a M.Sc. degree from the ENS in 2012. Her current research interests include modelling of innovative topology of machines with 2D and 3D FEA models.

Emmanuel Hoang was born in Antibes, France, in 1966. He received the agrgation and Ph.D. degree from the Ecole Normale Superieure de Cachan, Cachan, France, in 1990 and 1995, respectively, both in electrical engineering.Since 1990, he has worked with the electrical machine team in the SATIE Laboratory. His research interests include the modelling of the iron losses in switched reluctance machines (SRMs) and the design, modelling, optimization,and control of novel topologies of PM machines.

Sami Hlioui is lecturer in the CNAM, Paris and researcher in the SATIE laboratory of the ENS, Cachan, France. He obtained his electromechanical engineer diploma from the National School of Engineering of Sfax - Tunisia (ENIS) in 2004, his M.Sc. degree in electrical engineering from the ENS de Cachan - France and his Ph.D. degree in electrical power engineering from the University of Technology of Belfort-Montbeliard - France (UTBM) in 2008. His main research interest are the multidisciplinary modelling of electromagnetic actuators and the optimal design of these actuators for embedded applications.

Benjamin Gaussens was born in Toulouse, France, in 1987. He received the M.Sc. degree in electrical engineering from the Institut National Polytechnique (ENSEEIHT), Toulouse, France and the Ph.D. degree in electrical engineering from the Ecole Normale Superieure de Cachan, Cachan, France. His current research interests include design of innovative topology of electromagnetic actuators and their modeling.

Michel Lécrivain was born in Barneville, France. He received the degree in electrical engineering from the CNAM, Paris, France, in 1981. In 1997 he joined SATIE laboratory, ENS de Cachan, Cachan, France, as a research engineer. His research interests include the design and control of new hybrid machines and novel permanent magnet machines for automotive application

Mohamed Gabsi received the Ph.D. degree in electrical engineering from University of Paris-VI, Paris, France, in 1987, and the HDR from the University of Paris-XI, Orsay, France, in 1999. Since 1990, he has been working with the electrical machine team SETE of SATIE Laboratory, UniverSud, Cachan, France, where he is currently a Full Professor. His research interests include SRM, vibrations and acoustic noise, and PM machines