Identification of a 7-phase claw-pole starter-alternator for a micro-hybrid automotive application

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***Abstract*- This paper deals with the identification of a new high power starter-alternator system, using both: a Finite Element Method (FEM) modeling and an elementary experimental vector control. The drive is composed of a synchronous 7-phase claw-pole machine supplied with a low voltage / high current Voltage Source Inverter (VSI). This structure needs specific approaches to plan its electrical and mechanical behaviors and to identify the parameters needed for control purpose. At first, a Finite Element Method (FEM) modeling of the machine is presented. It is used for the predetermination of the electromotive forces and of the torque. Experimental results are in good accordance with numerical results. In a second part, resistive and inductive parameters of the drive are determined by an original experimental approach that takes into account each component of the drive: the battery, the VSI and the machine.**

I. Introduction

Claw-pole synchronous machines with separate excitation are very commonly used to make the alternator function in automotive because of their low cost and ability to work in a very large speed range. The new needed starter function adds new constraint on the machine: the ability to develop a large torque during the car start.

To take up this challenge for powerful Internal Combustion Engine (ICE) without changing the classical (12 Volts) DC-Bus voltage level [1], a new claw-pole starter-alternator with seven phases and permanent magnets between the claws has been developed [2]-[3]. The obtained torque density (Nm/m^3) allows keeping the economical benefits of using a 12-Volts battery [1].

In order to carry out the starter function, a modeling of the machine is at first necessary to plan the ability of the machine to develop the torque during the short duration of the start. In the section II, the predeterminations obtained by a Finite Element Method (FEM) modeling are compared with experimental results for the electromotive forces and for the torque per Ampere.

In the section III, resistive and inductive parameters of the whole drive are determined in order to be able to make the control during the start of the Internal Combustion Engine (ICE). As the voltage is low (12V), the parameters values of the battery and VSI are not negligible in comparison with those of the machine. An experimental approach based on an elementary vector control of the machine is developed to find the six characteristic time constants of the seven-phase drive.

II. Determination of EMF and TORQUE by Finite Element Method

This kind of claw-pole structure is known to be delicate to model with a numerical method as FEM [4] because of their 3D characteristics, a thin airgap and highly saturated magnetic materials. Moreover, the studied machine is a synchronous 7-phase claw pole machine with permanent magnets between the claws and with an unequal number of magnetic pole pairs "p" between the armature and excitation circuits (p_{rotor} = 8 and p_{stator} = 4). It is then necessary to model at least a quarter of the structure (compared with "a third" when modeling a more classical 3-phase car generator, with p_{rotor} = p_{stator} = 6). The aim of the modeling is not only to plan the voltage output, in generator mode, but also to plan the maximum available torque in motor mode, during the start of the car ICE. The first step in order to validate the 3D-modeling is to compare the experimental electromotive forces (emf) with the calculated ones. The second step is to determine, for a defined repartition of the currents among the phases, the maximum possible torque.

The structure of the rotor is described in Fig. 1. This figure gives the repartition of the magnetic flux density **B** under no load condition (the stator phase coils are open), when the excitation coil is supplied with a current I_F = 5A. The excitation field is produced by a hybrid excitation magnet (using a coil and permanent magnets between the claw-poles). The mesh is composed of 380000 tetrahedral elements. The resolution is made using the magnetostatic hypothesis, using the scalar potential formulation. The used software is CARMEL, developed at the L2EP.

Fig. 2 compares the electromotive force waveform "*e(t)*", calculated under no load condition, at a rotation speed N = 1800rpm and I_F = 5A, with an experimental measurement in the same conditions. This figure validates the numerical model good accuracy, at the first order, to calculate the voltage outputs.

Fig. 4 gives the calculated torque T as function of the rotor position θ, when the machine currents are imposed to be the same as in an experimental test, for which the torque is maximized. The maximal numerical torque value is $T_{calculated}$ = 62.4 Nm, to be compared with the experimental torque measured: $T_{measured}$ = 66.5 Nm, which shows a weak difference of about 6 %.

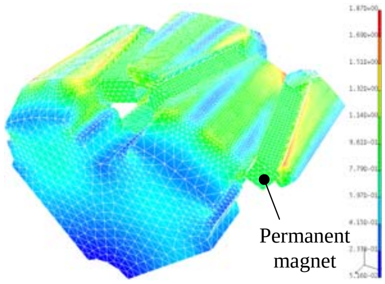

Fig. 1. Rotor magnetic flux density **B**

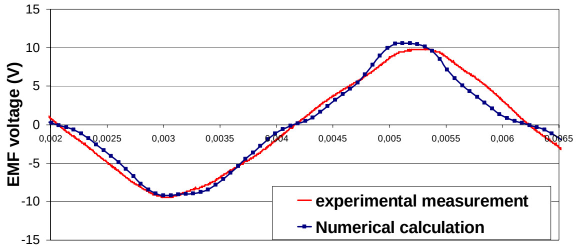

Fig. 2. Electromotive force under no load condition; N=1800rpm, I_F = 5A and comparison with an experimental measurement

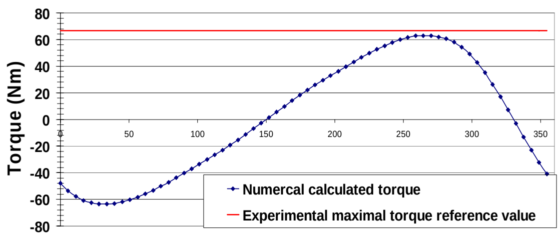

Fig. 4. Calculated torque as function of the position θ and comparison with an experimental maximal torque reference value

III. Inductive and Resistive Parameters Identification by Experimental Vector Control

To control the drive during transient operations such as starts, electrical time constants are relevant parameters. For a wye-connected three-phase machine without reluctance effect, only one time constant is sufficient to characterize the drive. In case of a 7-phase machine, at least three time constants characterize the machine. These time constants can be determined either with the knowledge of resistance and inductances values or by direct approach.

In the studied case, the values of the resistances and inductances are very low (a few mΩ and μH). It is due to the weak value of the DC-bus (12V). As consequence, the resistance values of the VSI, battery but also of the connections can not be neglected. It is then preferable to consider a direct method of identification that takes into account implicitly the complete drive and gives the time constants. An experimental method based on an elementary vector control for a seven-phase machine has been developed. The control is a generalization of the classical vector control in dq-reference frame developed for three-phase machines. In this case, two L_d and L_q parameters are obtained for a machine with reluctance effect (leading to 2 time constants values, on d- and q-axes). For a 7-phase machine, three different dq-reference frames, or “subspaces S1, S2 and S3”, can be determined: consequently six time constants can be then evaluated.

Fig. 4, gives experimental results of the time constants measurements. These parameters depend on the excitation currents. Also, for one of the 3 dq-reference frames, the S1-subspace, two different values of time constants, on d- and q- axes, can be clearly identified: the difference can be explained by a reluctance effect in the machine. For the two others dq-reference frames, only one inductive parameter appears.

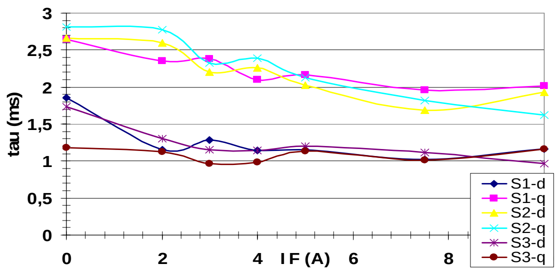

Fig. 4. Experimental time constants on d- and q- axis in the 3 subspaces as a function of the excitation current

IV. Conclusion

A mixed approach has been used to identify a seven-phase starter-generator. The FEM modeling allows planning the main output values of the machine, as electromotive force and torque. This result is particularly interesting for the design step. A comparison with experimental results shows a good accuracy of the numerical model for the determination of these values. For parameters which are more characteristics of the whole drive such as time constants (or resistances and inductances), a complementary experimental approach using a vector control has been proposed. A global modeling is then obtained.

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