Design of Hybrid Hysteresis Motor Rotor by Means of FE Model and Decision Process

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***Abstract*— This work aims at designing a new hysteresis motor rotor with permanent magnets embedded in the magnetic system. A multi-criteria design procedure, consisting of a computer experiment employing a time-stepping finite element model and a search for the feasible design using the decision (analytic hierarchy) process, is used. The feasible design is found uniquely and a prototype motor is constructed and verifyingly tested.**

***Index Terms*—AC motors, hysteresis motors, magnetic hysteresis, finite element methods**

I. INTRODUCTION

The advantages of hysteresis motors (HMs) are diminished by their inability to deliver high output power per unit volume. To increase this quantity the permanent magnets are embedded in its rotor [1], [2]. In this way the motor benefits from mutual torque between the stator winding mmf and flux of the magnets. In addition, an induction torque is generated in a solid hysteresis ring. Such a hybrid HM develops three torque components (hysteresis, mutual, induction) that do not add at every point of a mechanical characteristic [1]. Therefore, a design must be realized to boost the synchronous torque, but also not dramatically detract from the self-starting capability and to satisfy additional requirements.

A new high-speed, hybrid HM is analyzed (see Fig. 1a). In the considered design, restricted to the motor rotor, instead of solving the problem via the multi-objective optimization using continuous variables which often yields a set of compromise designs [3], the search for a single design is carried out using the decision process. It is conducted over a set of computer-generated designs, using the analytic hierarchy process (AHP) [4]. The formers are created via the Latin hypercube sampling and the time-stepping FE model using a vector hysteresis model [5]-[7]. The experimental validation is carried out.

II. DESIGN REQUIREMENTS

The four-pole motor considered must start loaded by inertia requiring at least 0.2 Nm torque at zero speed; synchronize and operate at 50,000 rpm delivering at least 500 W of output power. The motor is driven from a sinusoidal inverter with a DC-terminal voltage limited to 400 V. The axial length (32 mm), outer diameter and winding (see Fig. 1a) are kept unchanged. The rotor must be light and mechanically integral.

III. COMPUTATIONS

A. Finite element modeling

The time-stepping finite element model is elaborated to determine quantities required by the design procedure. The account for hysteresis excursions in the hysteresis ring (FeCrCo magnet in Fig. 1a) is taken via the vectorized Hodgdon model [6], which was identified using the measured hysteresis loops (see Fig. 1b). Due to a very high value of mechanical time-constant the motor is modeled current-driven with a rotating rotor mesh and forced rotor speed. The resultant equations of a discrete model are solved using the fixed-point technique [7].

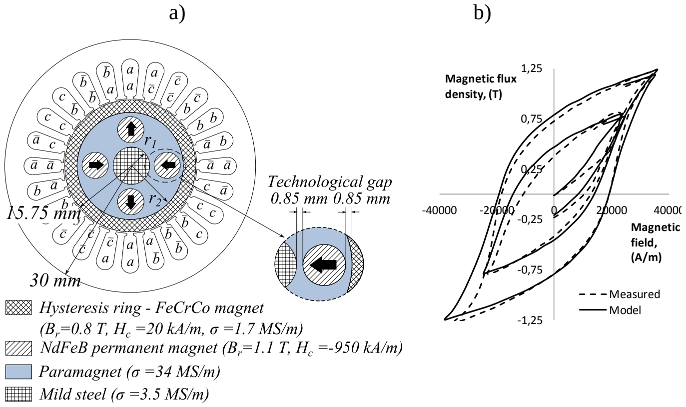

Fig. 1. Hybrid hysteresis motor: a) layout with dimensions, b) hysteresis loops of a hysteresis ring; B_r H_c and σ are remanent flux density, coercivity magnetic field and electric conductivity, respectively.

To emulate the operation at starting the rotor is locked as the winding is fed with maximum allowed sinusoidal current (10 A, rms). To emulate the synchronous operation the current is set to nominal value (6.4 A, rms) as the motor is forced to operate synchronously. The phase angle of stator current is adjusted so as to reach the load angle at which the synchronous torque is maximal.

B. Computer experiment and search for the best design

Considering the two constant gaps within the paramagnet, the diameters of the magnets become dependent on only r_1 and r_2 (see Fig. 1a). Considering feasible variations of the design variables, the fifty sampling points are generated using the rule of Latin hypercube [5]. Then, at each point the computer FE model is executed. As a result, the collection of designs is stored in data files. This computation took approximately 23 hours on a standard contemporary desktop computer. Given requirements (section 2), the five criteria are defined:

criterion 1: high torque at synchronism,
criterion 2: high starting torque,
criterion 3: possibly low terminal voltage,
criterion 4: small moment of inertia,
criterion 5: low mechanical stress in a hysteresis ring.

Data for evaluation of the first three criteria is provided by the computer experiment, whilst the two remaining ones are evaluated analytically. Figure 2 depicts variations of functional quantities as the rotor evolves. It can be seen that some designs do not meet requirements in Section 2. In the entire experiment there are forty-two such designs. Consequently, only eight designs are taken to the next stage. To provide support for design selection the analytic hierarchy process is used [4]. This method is a formal structured technique which supports analysis of complex decisions. In accordance with the simple AHP, each design will be judged with respect to the given criteria and their priorities, to emerge the leader (here the feasible design).

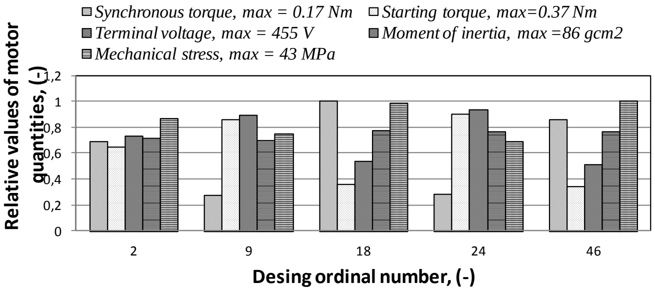

Fig. 2. Evolution of the most important motor quantities for five random designs.

The priorities (weights) for the criteria are determined by forming the importance matrix $\boldsymbol{S}_c$ [4], and then by determining its right eigenvector $\boldsymbol{\lambda}_c$. The importance matrix contains entries that are set by the designer using a heuristic approach which binds knowledge and experience with design goals and restrictions. A next stage qualifies designs with respect to each criterion and results in definition of a set of importance matrices $\boldsymbol{S}_{di}$, where i=1..5 stands for the criterion number. Entries of these matrices are calculated via assessing quantities, attributed to the criteria considered, with respect to their expected values. Next, by determining the right eigenvector $\boldsymbol{\lambda}_{di}$ for each $\boldsymbol{S}_{di}$ the synthesis of designs can be carried out by evaluating the ranking vector $\boldsymbol{r} = \sum_{i=1}^{5} \lambda_{ci}\, \boldsymbol{\lambda}_{di}$, from which the leader design (with the highest rank) is emerged. Figure 3 exposes the ranking and indicates the leader (design 49 with r_1=5.2 mm and r_2=13.1 mm). This design provides 0.31 Nm of starting torque and 559 W of output power at synchronous speed at terminal voltage equal to 395 V, and best satisfies the requirements in Section 2.

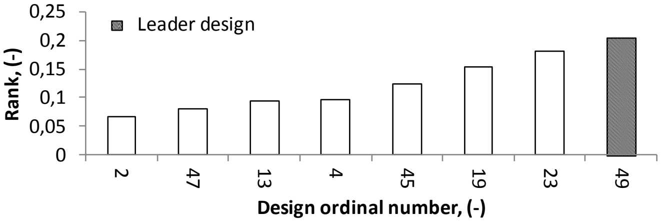

Fig. 3. Synthesis of eight final designs indicating the leader.

IV. EXPERIMENTAL VALIDATION

Based on results of this study the physical motor was built and put under laboratory tests (see Fig. 4). The initial measurements, depicted in Fig. 4c, involve the locked-rotor operation at which the voltage was varied so as to obtain the same phase currents value as that used in the current-driven finite element model. As it can be noticed, the predictions compare well with measurements which confirms adequacy of the numerical model.

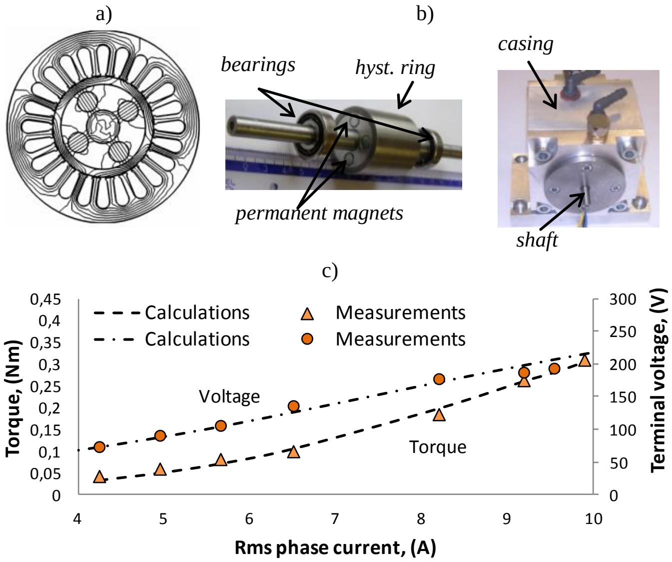

Fig. 4. Results of investigation: a) steady-state flux distribution over cross-section of the leader design, b) manufactured physical rotor and final assembly of a prototype fluid-cooled motor, c) comparison of calculated and measured values of torque and terminal voltage at locked-rotor operation.

CONCLUSION

The approach employing detailed finite element model and the analytic hierarchy process has uniquely recognized design which best satisfies the given requirements in terms of the considered criteria. Due to involvement of heuristics into formation of the criteria importance matrix it enables realization of the more experience-based designs which is especially useful in realizing challenging multi-criteria designs of electrical machines.

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