Double-Excited Synchronous Motor with Wide Speed Range: Numerical and Experimental Results

Daniel Fodorean, Ioan-Adrian Viorel, Abdesslem Djerdir, and Abdellatif Miraoui

***Abstract*—Numerical and experimental results for a double excited synchronous drive are presented in this paper. The finite element method is used to study the performances of a double excited synchronous motor in order to avoid the recurrence. The speed gain in transient operating regime is simulated by coupling the Flux2D® and Matlab®/Simulink software. In order to validate the results obtained via numerical magnetic field computation (2D FEM) some of them are compared with the test bench obtained results for a generator regime.**

***Index Terms*—Double excited synchronous machine, flux weakening, fem analysis, transient simulation, experimental results in generator regime.**

I. Introduction

The electric vehicle drive system requires a wider constant-power speed range (CPSR) operation. The inverter-fed induction motors fulfill this requirement and offer the advantage that one inverter can feed several motors. The lower power factor, efficiency and torque density are the main break points of the induction motor. The permanent magnet (PM) synchronous motor offers higher power factor, efficiency and torque density, but has higher cost and requires a special technique or construction to extend, as necessary, the speed range.

Due to the complicated rotor structure of the permanent magnets synchronous motors with buried PMs the rotor topology with air-gap PM's and excitation winding was considered too in the last several years [1]-[5]. The excitation winding would be supplied only when a large excitation of the speed range is required.

The terms of hybrid excitation or double-excitation are used interchangeably. The double excitation refers to the fact that in the excitation circuit of an electrical machine there are permanent magnets as the main component of the flux source and, additionally, an auxiliary excitation winding. The excitation winding is used to control the airgap field, and consequently the electrical drive speed.

Manuscript received January 24, 2005, revised October 10, 2005.

This work was supported in part by the Romanian National Research and Science Center (CNCSIS) under Grant No. TD-33385/04.

D. Fodorean is with the Electronic, Electrotechnical and Systems Laboratory, Technological University of Belfort-Montbéliard, France (email: daniel.fodorean@utbm.fr).

I. -A. Viorel is with the Electrical Machines Department, Technical University of Cluj-Napoca, Romania (email: ioan.adrian.viorel@mae.utcluj.ro).

A. Djerdir and A. Miraoui are with the Electronic, Electrotechnical and Systems Laboratory, Technological University of Belfort-Montbéliard, France (email: abdesslem.djerdir@utbm.fr, abdellatif.miraoui@ utbm.fr).

Publisher Item Identifier S 1682-0053(06)0344

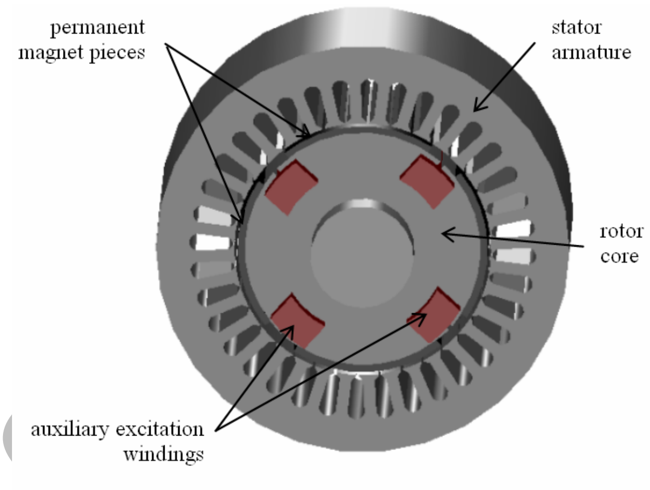

Fig. 1. 3D view of the designed DE topology.

First, a brief presentation of the main classes of hybrid-excited machines is made. A double excited solution with surface mounted permanent magnets and the auxiliary winding placed on the rotor core is presented in Fig. 1 for evaluating its field-weakening capability.

The effect of stator resistance and q-axis saturation is usually small in the field-weakening region, however high iron losses can drastically reduce the field weakening range [6]. The aim of this work is to present the field weakening capability using only the auxiliary excitation winding, via a Flux2D®-Simulink transient simulation. This investigation will clearly emphasize the advantage of such a double excited variant in terms of iron losses reduction while the wide speed range is obtained. The numerical results are compared with the experimental investigation where, in terms of electromotive force reduction for a generator-operating regime, the speed gain can be evaluated. A good concordance between the numerical and experimental result was found.

II. Double Exited Synchronous Motors

The double excited machines are, from the excitation circuit point of view, in series [1] or in parallel [2]-[4] double excitation circuit machines. The auxiliary winding location gives another classification criterion. The excitation winding could be placed on the rotor armature or on the stator one [5]. The most important advantage of the series excitation circuit variant is the simplicity and the global reduction of the flux density, while a special attention of the PM demagnetization must be taken. For the parallel excitation circuit several topologies are possible to be employed, with the complexity of the construction

1682-0053/06$10 © 2006 JD

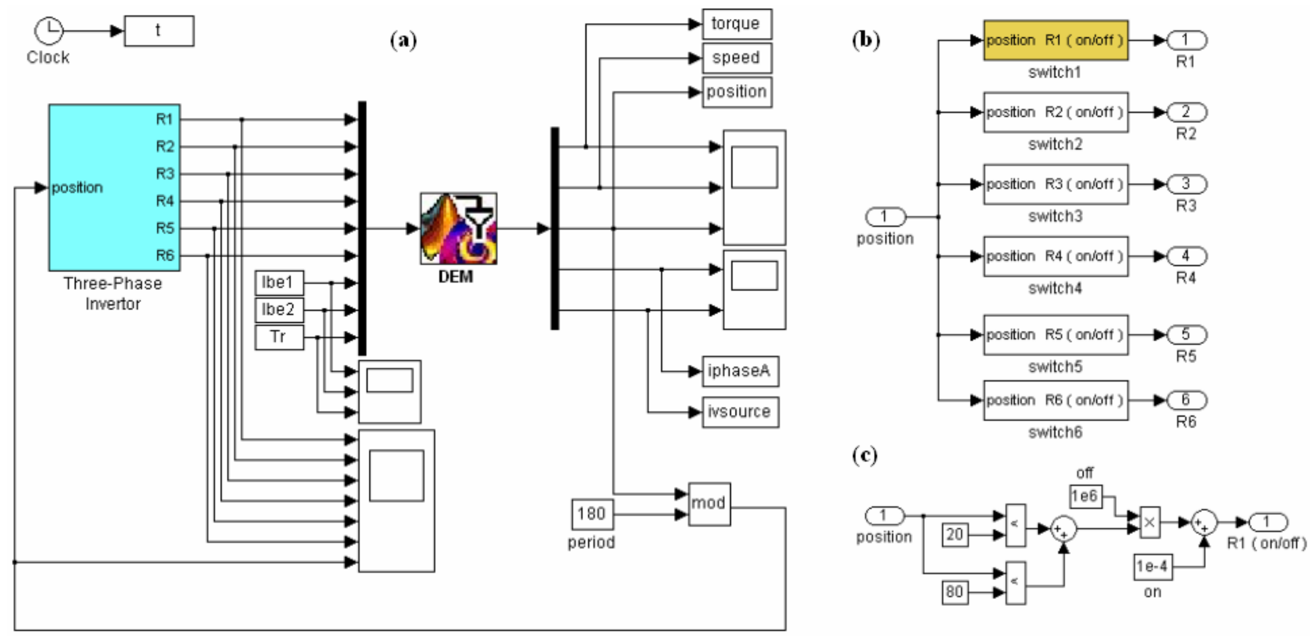

Fig. 2. Simulink-Flux2D® control panel for transient operating of the DE drive, (a) the control panel, (b) the three phase switching inverter, and (c) the logic commutation.

pointed as a drawback. Placing the excitation winding on the rotor armature will facilitate the flux weakening control, but the sliding contact is the major disadvantage of such a structure. When the field coil is placed on the stator armature, the flux density can be controlled locally at the airgap level and the sliding contact is removed. As the main disadvantage, should be mentioned the excitation supply and control complexity (bi-directional). The proposed double excited (DE) topology has the series excitation circuit, with the auxiliary winding placed on the rotor armature. As it is shown in Fig. 1, the primary excitation, namely the PM, is placed on the rotor's poles surface, while the field coils surround each rotor pole – the excitation coils are represented in the 3D view as solid parts for simplicity.

A wound rotor induction motor was used as a basic structure of the DEM construction. It was a quite very practical solution drastically reducing the prototype cost. All mechanical parts of the induction motor were kept unchanged, as was the stator core too. By maintaining the same stator iron-core sheets as for the basic induction motor the number of slots and their topology, as the stator interior diameter became constrains, but they could be over passed by an adequate design. The stator iron core length could be enlarged, the original motor case allowed it, by adding a certain number of core sheets. The rotor steel sheets were manufactured adequately to fulfill the design requirements. The DEM design is fully given, within the imposed constrains, in [7].

In reference [8] the following remark is made: "*Commercial surface mounted permanent magnet designs generally have values of the flux linkage between 0.83 and 0.96 (in p.u.). The constant-power speed range is usually lower than 2:1. A wider constant-power speed range can be achieved by adding series inductors*". So, the studied DE machine respects this demand. Of course, the sliding contact and the additional supplying system are drawbacks, but the double excitation offers a true flux-weakening operating, taking into account the inverter capability.

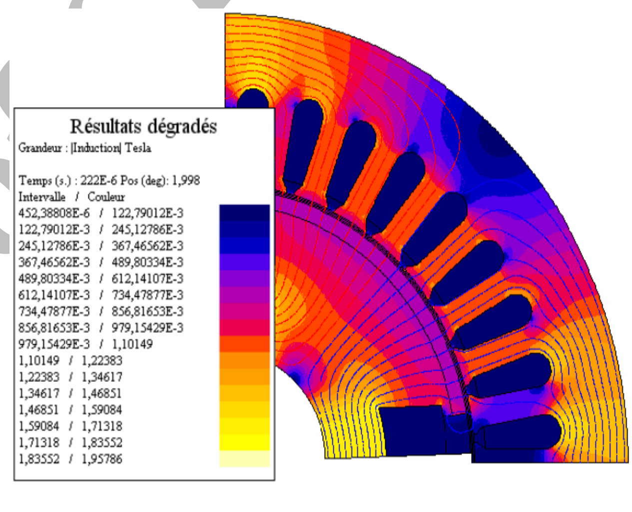

Fig. 3. The field lines and the flux density distribution in the motor core at no-load.

III. NUMERICAL ANALYSIS BY FEM

The numerical analysis was done via a purposefully software which allows to model the motor operating. Because of the motor structure symmetry a 2D model is sufficient. The transient operating regime is simulated using the Flux2D®-Simulink coupled software.

To simulate the transient operating regime, a classical 120° supply is considered. The main control panel is drawn as Simulink block (see Fig. 2(a)). The switches are modeled by resistances with a very low value to simulate *on*-state and very large value to model *off*-state (see Fig. 2(b) for the switching scheme, and Fig. 2(c) for the logic commutation). This approach is adopted since the input parameter can be taken only an electrical (voltage, current, resistance, inductance) or a mechanical (speed, torque, inertia, position) value.

The DEM from Fig. 2 represents the coupling block with our application numerically modeled in Flux2D®. A classical three-phase inverter for brushless PM drive is behind this block. Each phase of the motor winding is

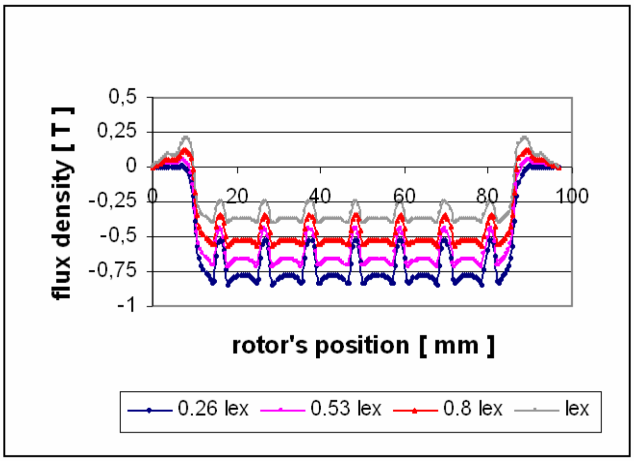

Fig. 4. The air gap flux-density distribution for different excitation current values for the studied DEM.

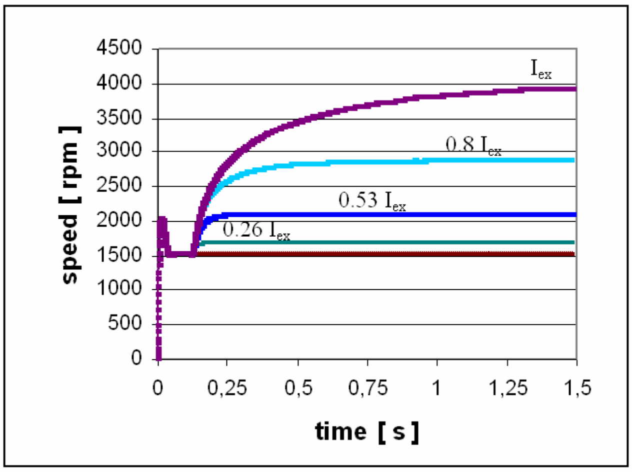

Fig. 5. Speed vs. time for different values of the excitation current.

modeled by a coil, with the correspondent resistance and the number of turns. The end winding inductances were considered too. The associated values for the electrical components must take into account the geometry structure. Only one quart of the motor geometry being represented, all the numerical parameters are divided by 4 - for example, because the DEM phase resistance is 1.7 ohm, the inserted resistance value is 0.425 ohm.

The output parameters are, in our case, the speed, the torque, the position (which is the reaction parameter), the phase current and the inverter current. To obtain the electrical angular position, a Simulink block 'mod' is added to multiply the mechanical angular position with the pole pair number.

In order to determine the DEM transient behavior, a load torque (rated torque) was imposed. This load torque can be controlled from Simulink interface (T_r in the Fig. 2(a)). In order to consider the auxiliary windings, two blocks will feed the excitation coils (*Ibe1*, *Ibe2* in Fig. 2(a)).

The finite element (FE) analysis offers several results; some of them being presented here. The flux density repartition and the field lines in all the motor parts (on no-load operating and for zero excitation current) are shown in Fig. 3. The saturation level is maintained normally. Otherwise, for the load operating, the rotor slots corner seems to saturate, but this will not stumble essentially the field lines course.

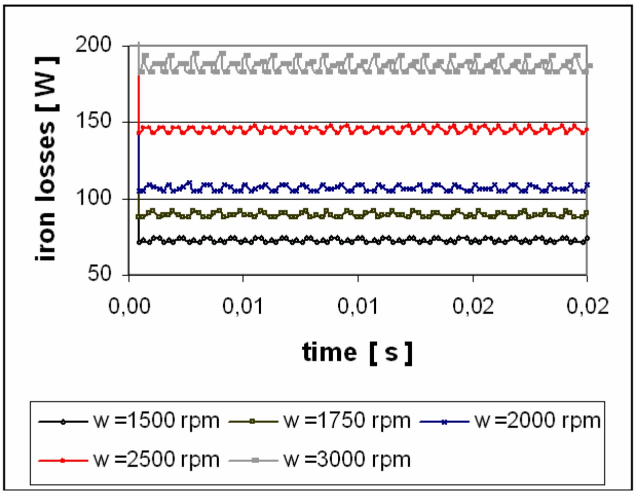

Fig. 6. Iron losses in normal operating (without flux-weakening).

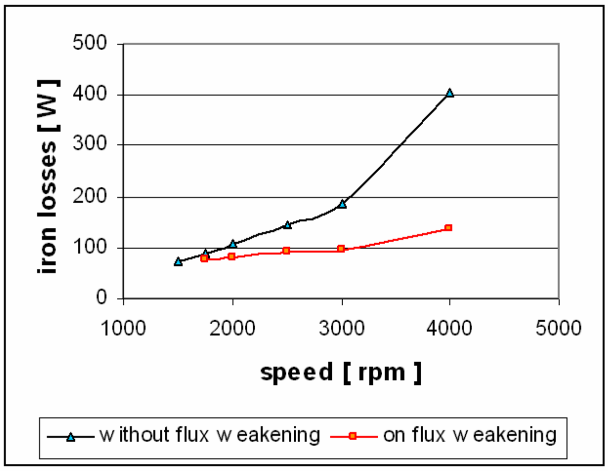

Fig. 7. Iron losses vs. speed characteristic for the hybrid excited motor in normal and flux weakening operating (for different levels of the excitation current).

In Fig. 4 the air-gap flux density function of rotor position is plotted, for different values of the excitation current. The air-gap field diminution is clearly evinced. For each excitation current and air-gap flux density value a corresponding speed is reached.

The speed versus time in transient operating mode for the DE machine is shown in Fig. 5. The motor startup is simulated until the rated steady-state regime is reached (speed at 1500 rpm). At a *t* instant, the excitation current is injected in the auxiliary windings and so the air-gap field is weakened. Finally the speed is increased up to 2.7 times.

The disadvantage of this type of hybrid-excited motor is the presence of the brushes; also a separately feeding system is needed. The flux density diminution is global, not only at the air gap level, but in the entire active motor parts. So, the iron losses are decreased too.

A general evaluation of the iron losses is done by using the formula [9]:

$$P_{iron} = k_h B_m^2 f + \pi^2 \frac{\sigma d^2}{6} \left(B_m f\right)^2 + k_{exc} \left(B_m f\right)^{3/2} \qquad (1)$$

where P_{iron} represents the iron losses, B_m is the flux density variation for unit volume, the coefficients k_h and k_{exc} are the histeresys and excess coefficients, f is the frequency, σ and *d* represents the steel resistivity and the

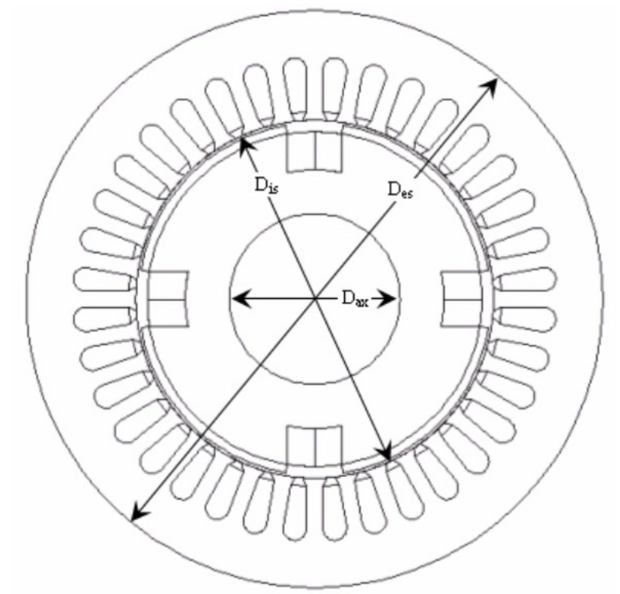

Fig. 8. The cross-section through the DEM.

lamination sheet thickness [9]. The values of the material constants were taken in accordance with the DEM iron core material properties.

For different speed values and electrical frequency values the iron losses in normal operating mode are plotted in Fig. 6. In a flux-weakening regime the iron losses are well decreased because of the fact that the flux density reduction is global for this type of double excited machine. For the higher possible speed the iron losses are finally decreased almost up to 3 times (see Fig. 7). This means that a good efficiency level is maintained even if the joule losses increase while feeding the auxiliary windings. These advantages make this type of DE drive an interesting solution for electrical vehicle propulsion.

One can notice that the speed gain for such a DE topology is not very significant in comparison with the buried PM motors. For the IPM machines the speed increases up to 4 times, but also the iron losses are enlarged consistently. For the rotor surface mounted permanent magnet motor it will proved that the best choice in extending the speed domain would be the proposed double excited solution, with its advantages and drawbacks.

The demagnetization effect can be evaluated from the numerical approach by regarding the minimum level of the flux density in the permanent magnets. This minimum level must not be smaller than the irreversible demagnetization limit [10]. A complete study of the irreversible demagnetization limits could be accomplished by considering the thermal phenomena too, but it was not the aim of this work.

IV. DEM Data and Test Results

A slightly modified induction machine stator armature was used and the rotor structure for the given purpose constructed. The main data of the designed machine are given in Table I. The cross-section through the DEM is shown in Fig. 8.

The basic experimental set up employed to test the synchronous double excited machine in a generator-operating mode is presented in Fig. 9. A parallel-excited DC motor is rotating the synchronous generator.

TABLE I
THE MAIN GEOMETRIC, ELECTRO-MAGNETIC AND MECHANIC QUANTITIES OF THE DESIGNED DE DRIVE

Symbol	Quantity	Value
P_n	rated power	5.5 kW
V_r	rated voltage	380 V
I_r	rated current	10.5 A
f	supply frequency	50 Hz
L	motor's length	100 mm
D_{es}	outer stator diameter	200 mm
D_{is}	inner stator diameter	124 mm
N_s	number of slots	36
p	pole pair number	2
g	air-gap height	1 mm
h_m	permanent magnet's thickness	3.5 mm
B_g	airgap flux-density	0.86 T
R_{ph}	phase resistance	1.7 Ω
R_{be}	excitation coil resistance	1.3 Ω
-	total weight of the active parts	26.4 kg
-	total cost of the active parts	301 €
$cos\varphi$	power factor	0.92
η	efficiency	0.93
n	rated speed	1500 rpm
T	rated torque	35 Nm

Because of the manufacturing requirement (the rotor core diameter is quite large) the pieces of the surface mounted permanent magnets are glued on the rotor core (transversally and axially) and consolidated with a nonmagnetic strip. The auxiliary winding, the permanent magnet pieces and the rings for the field coils supplying are shown in Fig. 10. The rotor winding was fed, for this experimental prototype, from an auxiliary VCC source. If such a variant would be implemented in an electric vehicle system its excitation winding can be adequately feed from the vehicle's battery. The test bench view is presented in Fig. 11.

From the generator operating mode the speed gain evaluation is made in terms of electromotive force reduction. The following dependence between the EMF and the angular speed can be written:

$$E = k_E \Omega \Phi \tag{2}$$

where k_E, Ω, and Φ are the electromotive force constant , speed, and the flux. Thus, the EMF and the angular speed are directly proportional. Moreover, the speed can be increased in the case of the flux linkage reduction. So, in order to evaluate the real speed gain of the studied synchronous double excited machine in generator regime operating, the following steps are pursued: the synchronous generator is rotated up to the desired speed with the DC motor and the induced electromotive force in the synchronous stator windings is measured for several excitation current values. The flux weakening performances of the designed machine were shown by comparing the numerical and experimental results, Fig. 12. A good concordance was found between the FEM and experimental results, and a 2.8 speed gain was obtained on the experimental test bench.

V. Speed Domain

For a synchronous motor, neglecting the stator phase resistance, the stator voltage is [11]

$$u_s^2 \cong \omega_s^2 \left[L_q^2 i_q^2 + (\lambda_F + L_d i_d)^2 \right] \tag{3}$$

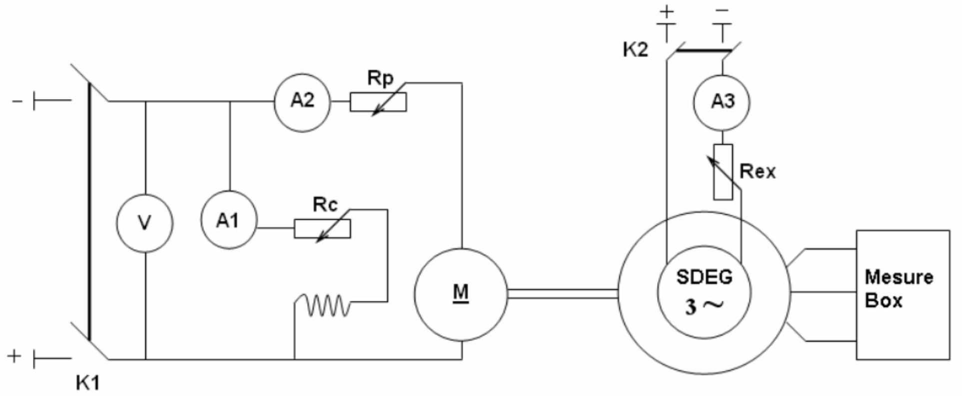

Fig. 9. Experimental scheme.

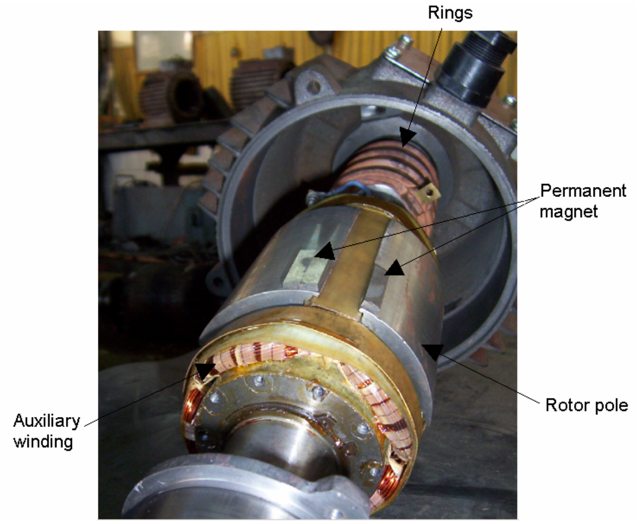

Fig. 10. Rotor armature of the DEM.

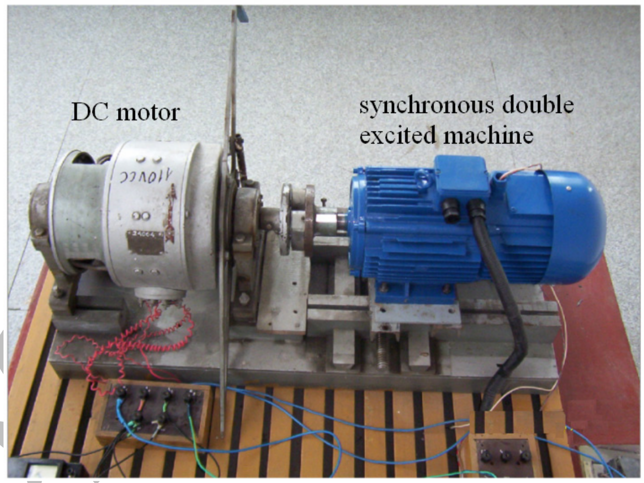

Fig. 11. Experimental bench.

If the motor operates at no load, the torque and the torque current i_q are zero

$$\begin{array}{l} T \to 0 \\ i_q \to 0 \end{array} . \quad (4)$$

Consequently, the no load synchronous speed is

$$\omega_{s0} \cong \frac{u_s}{\lambda_F + L_d i_d} . \quad (5)$$

The total field flux results as a sum of the flux generated by the permanent magnet and by the field winding, where the field current i_F flows

$$\lambda_F = \lambda_{pm} + M_d i_F , \quad (6)$$

$$u_{q0} = \omega_{s0} \lambda_F . \quad (7)$$

The d-and q-axis synchronous inductances are

$$\begin{array}{l} L_d = M_d + L_{s\sigma} \\ L_q = M_q + L_{s\sigma} \end{array} \quad (8)$$

The notations are quite the usual ones: u_s - input voltage, λ_F - field flux, i_F - field winding current, λ_{pm} - permanent magnet flux, i_d, i_q - d- and q-axis stator current, and ω_s, ω_{s0} - synchronous speed at load and at no load.

Since the d-axis synchronous inductance, due to the permanent magnet, has a smaller value compared to the q-axis one, when the field current i_F is zero in order to enlarge consistently the no load synchronous speed one has to increase dramatically the stator d-axis current. It means

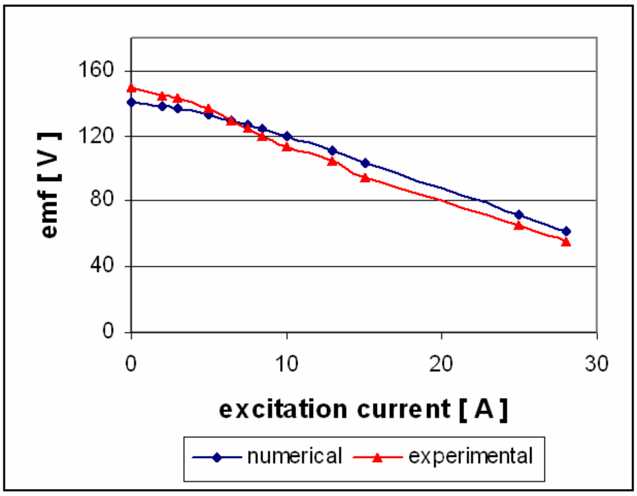

Fig. 12. FEM and experimental comparison of the back-EMF for different values of the excitation current.

that the electronic converter must be able to assure much larger values for the stator current than the rated one. It is clear now that an adequate way of consistently enlarging the motor speed domain, in such a case, is offered only by the double excitation variant. The motor cost would be increased, but the speed domain is much larger, at a convenient efficiency.

VI. Conclusions

The speed gain of a double excited machine was analyzed in this paper. After a brief classification of the main topologies of double excited machines encountered in the literature, one hybrid-excited variant was proposed to be studied. Taking into the account the inverter capability the true speed gain of the proposed DEM is given based on FEM analysis. The transient operating mode of such a machine was modeled by using Flux2D® coupled to Simulink software. Instead of the brushes presence drawback, the proposed solution has a true 2.7 speed gain, while for the commercial surface-mounted permanent magnets machines the constant-power speed range is usually lower than 2:1. Moreover, the iron losses are reduced almost by 3 times, and this represents one of the most important advantage of the DEM. In order to validate the analytical design and to confirm the numerical approach the experiments were conducted with the synchronous machines working on generator regime. A good concordance between the numerical and experimental results was found. From experimental measurements the speed gain of the designed hybrid excited machine reaches up to a true 2.8 value of the rated speed.

It resulted that a synchronous double-excited machine works in a wider speed range at the demand output power than a PM machine, maintaining a very good efficiency level and a safe operating regarding the permanent magnets demagnetization.

REFERENCES

[1] G. Henneberger, J. R. Hadji-Minaglou, and R. C. Ciorba, "Design and test of permanent magnet synchronous motor with auxiliary excitation winding for electric vehicle application," in *Proc. of European Power Electronics Chapter Symposium*, pp. 645-649, Lausanne, Switzerland, Oct. 1994.

[2] X. Luo and T. A. Lipo, "A synchronous permanent magnet hybrid AC machine," in *Proc. of IEEE IEMDC*, pp. 19-21, Seattle, May 1999.

[3] J. Wroblewski, "Magnetization of brushless synchronous generator with permanent magnets additionally excited – analysis conditions," in *Proc. of IEEE/KTH Power Tech. Conf.*, pp. 351-355, Stockholm, Jun. 1995.

[4] Y. Amara, M. Gabsi, M., Lecrivain, J. Lucidarme, and A. H. Ben Ahmed, "Structures of hybrid synchronous machines: principles and comparison," in *Proc. ICEM*, vol. 3, pp. 1688-1691, Helsinki, Finland, Aug. 2000.

[5] D. Fodorean, I. A. Viorel, A. Miraoui, and M. Gutman, "Comparison of hybrid excited synchronous motors for electrical vehicle propulsion," in *Proc. of ACEMP'04*, pp. 52-57, Istanbul, May 2004.

[6] R. E. Betz, M. Janovic, R. Langerquist, and T. J. E. Miller, "Aspects of the control of synchronous reluctance machines including saturation and iron losses," in *Proc of Ind. Appl. Society*, Annual Meeting, pp. 456-463, Oct. 1992.

[7] A. Miraoui, D. Fodorean, and I. A. Viorel, "Hybrid synchronous motor with flux weakening winding," in *Proc of the Workshop on Variable Reluctance Electrical Machines*, pp. 10-15, Cluj, Romania, Jun. 2002.

[8] S. Meier, *Theoretical Design of Surface-Mounted Permanent Magnet Motors with Field-Weakening Capability*, M.Sc. Thesis, Royal Institute of Technology, Stockholm, Mar. 2002.

[9] —, *FLUX2D User Guide - Physical Properties, Parameterization, Solving and Results*, vol. 3, Apr. 2002.

[10] M. Rosu *et al.*, "Permanent magnet synchronous motor for ship propulsion drive," in *Proc. of ICEM*, vol.2, pp. 702-706, Istanbul, Turkey, Sept. 1998.

[11] G. Henneberger and I. A. Viorel, *Variable Reluctance Electrical Machines*, Shaker Verlag, Aachen, Germany, 2001.

Daniel Fodorean received the Diploma degree in electrical engineering and the Master of Science degree in electrical drives, both, from the Technical University of Cluj-Napoca (TUCN), Romania, in 2001 and 2002, respectively. He also received the Ph.D. degree in electrical machines from the TUCN and the Technological University of Belfort-Montbéliard (TUBM), France, in July 2005.

For 2001-2003, 2004-2005, he was an Associate Lecturer at the Electrical Machines Department of the TUCN. For 2003-2004 and since 2005 he has beenwith the Electrical Engineering Department of the TUBM as a Lecturer-Researcher. His research activities include the design, the control and the optimization of the electrical machines and drives.

Ioan-Adrian Viorel a Romanian native, graduated in electrical engineering from Technical University of Cluj, Romania in 1965. He received the Ph.D. degree in electrical machines, drives and apparatus from Technical University of Timisoara, Romania in 1978. He was an Associate Lecturer (1965-1972), an Assistant Professor (1972-1980) and an Associate Professor (1980-1990) at Technical University of Cluj, where he is a Professor from 1990. He was the first Head of the Electric Machines Department, 1990-1992, scientific secretary of the Technical University (TU) Senate, 1992-1996 and vice-Dean of Electrical Engineering Faculty, TU of Cluj, 2000-2004.

He was a Fulbright scholar, 1975-1976, at University of Maryland in College Park, and visiting professor or visiting researcher at RWTH Aachen, Germany, EPF Lausanne, Switzerland, Ohio State University in Akron, USA, Technical University of Berlin, Germany, Technical University of Chemnitz, Germany, Korean Electrotechnology Research Institute (KERI) in Changwon, South Korea, Technical University of Budapest, Hungary.

He published more than 200 scientific paper in journals and conference proceedings and 14 books and text books, three of them in English. His research interests includes induction machine, synchronous machine, variable reluctance machines, transverse flux machines and related topics as CAD and magnetic field calculation in electrical machines domain. He is a member of the Editorial Boards of *Electromotion* Journal and was member in steering committees of some international conferences as Electromotion'95, SIELMEC'98, EPE-PEMC'2000 and 2002. He acted as reviewer for journals and international conferences.

Prof. Viorel is an IEEE member and a member of the Association of Professional Engineers of Romania. He was awarded the Medal "Teaching Merit" second class in 2004 by the President of Romania.

Abdesslem Djerdir received his B.S degree in Electrical Engineering from National Institute of Electrical Engineering Bejaia, Algeria, in 1993 and Ph.D. degree in Electrical Engineering from University of Franche Comte Belfort, France in 1999.

Currently he is working as Associate Professor of Electrical Engineering in the L2ES laboratory at University of Technology Belfort-Montbeliard (UTBM), France.

He is also a member of International Compumag Society. His research interests include modeling and design of electric vehicle systems (electric machines, energy storage devices, power converters).

Abdellatif Miraoui is a Professor of electrical engineering (Electromechanics) at Belfort-Montbéliard University of Technology (UTBM) since 2000. Before that he was the Associate Professor in electrical machines at Franche Comté University. He is the head of the Electrical Engineering department (in UTBM) from 2001, the head of Integrated Actuator research Team of L2ES laboratory and the editor of the IJEET journal. He is a Doctor Honoris Causa of Cluj-Napoca Technical University, Roumania.

His special interest includes permanent magnet machines, high and low speed electrical motors, design and optimisation of electrical machines, creative problem solving and electrical propulsion/traction. Abdellatif Miraoui was born in Morocco in 1962. He received the M.Sc. degree in 1988 from Haute Alsace University, the Ph.D. in 1992 and the HDR in 1999 from Franche Comté University, France.