Comparison of the Main Types of Fault-Tolerant Electrical Drives used in Vehicle Applications

D. Fodorean[*], *Member, IEEE,* M. Ruba[**], L. Szabo[**], *Member, IEEE*, and A. Miraoui[*], *Member, IEEE*
[*] Technological University of Belfort-Montbéliard / Systems and Transports (SET) Laboratory (France)
[**] Technical University of Cluj-Napoca / Electrical Machines Laboratory (Romania)

***Abstract*— A comparative study of several fault-tolerant electrical drives is presented in this paper. As the application is concerned, the authors' attention was oriented towards the vehicle transportation. Thus, the main electrical drives under study are: the induction, the switched reluctance and the permanent magnet synchronous machine, respectively. The present work will explore the aforementioned drives' capabilities in terms of fault-tolerant operation. The authors present a substantial study for the fault-tolerant issue in electrical drives by using finite element method (FEM). During this numerical analysis many phenomenon will be emphasized and, coming together with some tests, final conclusions will be depicted.**

***Index terms*— automobile applications, fault-tolerant electrical drives, FEM, tests.**

I. INTRODUCTION

Even for fuelled automobiles the number of electrical machines and drives placed on board is very important. All operational and comfort aspects are intermediate of these last ones. However, the authors' attention is focused on the electrical machines that are involved in the vehicle propulsion: the electrical motor, the starter-generator and the air generation in compressor-fuel cell systems [1]-[4].

In this way, the authors' have analyzed the most common electrical drives which are best suited for automobile applications, having in mind that the operation must be assured even in the most difficult conditions with good energetic performances [5]. Hence, the following drives were studied: the induction machine (IM), the switched reluctance machine (SRM) and the permanent magnet synchronous machine (PMSM). These drives seem to be very attractive from the fault-tolerant operation point of view [5]-[7]. Even if the direct current (DC) drive, excited with permanent magnets (PMs) is, perhaps, the most present motor on board of traction vehicles (as micro-motor), the authors' attention was focused on the motors used for the main traction or for the air generation in compressor-fuel cells systems [2].

The fault sources of the machine-converter assembly will be briefly introduced, as well as the solutions which can counteract the unbalanced working while the drive operation has desired output performances: smooth torque and speed, improved efficiency (with reduced iron and copper losses).

Thanks to the power of dedicated software, an important number of numerical computations were employed in order to characterize the studied electrical drives through finite element method (FEM) by using the Flux2D-Simulink coupling technology [8]. Different operation regimes will be verified: with or without occurred faults, in motor as well as in generator regimes, with different types of control/converter strategies [9]-[12]. Finally, some tests will prove the numerically obtained results, in order to confer consistency to the present work.

This study is intending to be a useful tool for the industrial and research teams which are trying to exploit the limits of electrical drives in terms of fault-tolerance, for the future replacement of the thermal engine in automobile applications.

II. ELECTRICAL DRIVES AND THEIR FAULT-TOLERANT BEHAVIOR

A fault-tolerant drive is the machine-converter system which has the ability to operate in a satisfactory status even after faults occurred. The potential faults can be divided in two categories: related to the electrical machine (winding open circuit and short circuit), and within the power converter (power device open circuit, power device short-circuit and dc link capacitor failure) [3], [4], [13]. So, the aim is to develop a drive which can continue to operate with any one of these faults.

As for the fault-tolerant drives found in the literature (suited for automobile applications), the authors' attention was oriented towards the IM, [14], the SRM, [15] and the PMSM [16].

The IM is the industry's preferred variant, because of its construction and control simplicity. For the squirrel cage induction motor (SC-IM) different type of windings and coils faults will be analyzed.

The switched reluctance motor (SRM) drive has the phase windings of concentrated type, thus being the researchers' favorite topology in terms of fault-tolerance operation. However, the fault aspect is a subject which cannot be forgotten, and therefore a more accurate characterization has to be made. The open-circuit and short-circuit of a phase will be verified, as well as the influence of the number of phases and poles.

The permanent magnet synchronous machine (PMSM) seems to be the replacement of the IM in traction applications. The influence of the number of phases and poles will be verified, as well as different faults related to the drive. Another analyzed issue is the irreversible demagnetization of permanent magnets (PMs). This problem could be solved with a compensation of the PM

978-1-4244-1663-9/08/$25.00 ©2008 IEEE

loss. This can be done with an auxiliary winding [10].

All analyses were carried out in terms of fault-tolerant operation capability, having in mind to get a smooth torque, as well as ameliorated energetic performances.

III. NUMERICAL ANALYSIS OF THE STUDIED ELECTRICAL DRIVES

The FEM analysis offered up to now satisfactory results, so one can have confidence in it. Even if it is time consuming, many aspects of the drive operation can be simulated, verified, and different solutions could be employed, optimized or validated.

A. *The Induction Motor-Drive System*

Four topologies of SC-IM were studied, on a given active part with 2 poles, 24 stator slots, 20 rotor bars, while a double layer 3 phase and 6 phase winding (with 4 and 2 coils, respectively) with polar or shortened pitch was used (Fig. 1). A specific electric circuit is associated to it (Fig. 2 – here, the end-winding effect is simulated with an inductance; also, on top of each phase, a resistor of 10^7 Ω, is placed to simulates a voltmeter).

Eight cases were studied on the SC-IM with FEM: **a**: health operation; **b**: one short-circuited coil; **c**: two short-circuited coils (only for 3 phase topologies); **d**: one short-circuited phase; **e**: one open phase; **f**: one short-circuited coil from two different phases; **g**: two short-circuited coils from two different phases; **h**: two open phases (only for 6 phase variant). From simulations one can see the voltage, current, torque and stator/rotor iron losses results, Fig. 3.

From now on, the reader attention will be focused only on the torque and iron loss mean values (Fig. 4-Fig. 6) in order to have a strong comparison of the studied cases (discussions on wave ripples not presented here).

All the studied cases have the same geometry and electrical parameters (the phase resistance of 1.5 Ω; for the IVth case in Fig. 1, the phase resistance is of 0.75 Ω). The voltage RMS value for the first three cases is 540 Vca (50 Hz), while for the IVth case it was chosen at 220 Vca in order to obtain, approximately, the same mean torque value as for the three phase topology in case III.

The computations were made to a constant speed, at 60% of the rated value, in order to simulate a supplementary effort (torque) of the SC-IM. From the mean values of the torque and stator/rotor iron losses (Fig. 4-Fig. 6), one can see that the 3 phase shortened pitch (III) case gives better results than the polar winding (I) in term of maximum torque value, with relatively the same amount of iron losses, since the decrease of the harmonic content. The iron losses decrease it is much obvious for the 6 phase topology (here the iron losses decrease also due to the low level of RMS voltage, meaning that one can reduce the absorbed power and the investment, while there are six electric sources and other network equipments which will increase the costs).

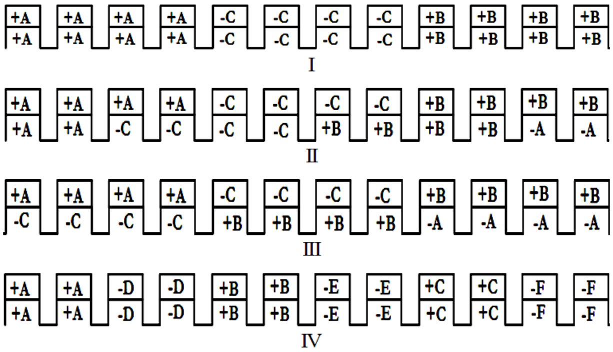

Fig. 1 Phase arrangements in the studied SC-IM: (I) 3-phase winding, with distributed polar pitch; (II), (III) 3-phase winding, with distributed shortened pitch; d) 6-phase winding with distributed polar pitch.

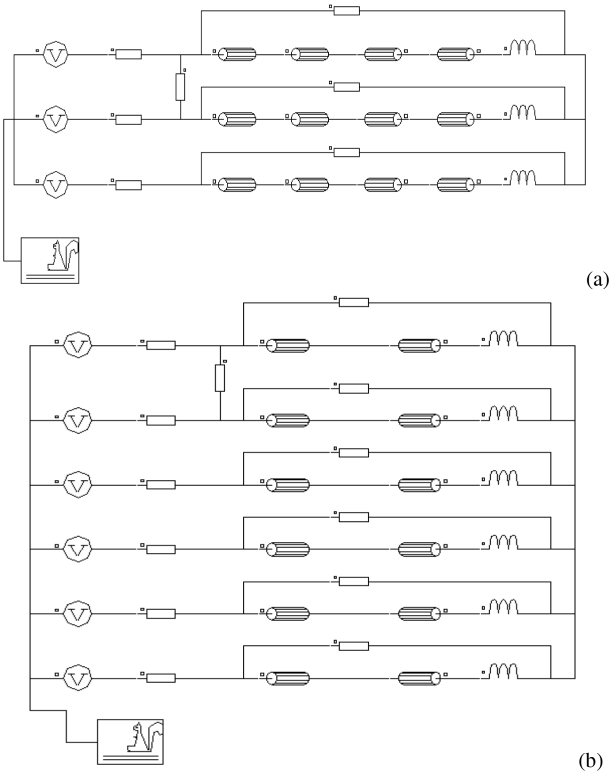

Fig. 2 Electric circuits for the SC-IM supplying: a) 3-phase; b) 6-phase.

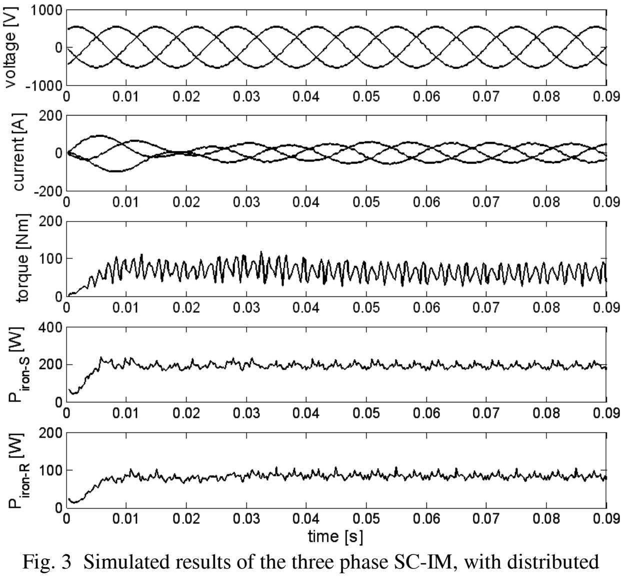

Fig. 3 Simulated results of the three phase SC-IM, with distributed winding, at a given speed.

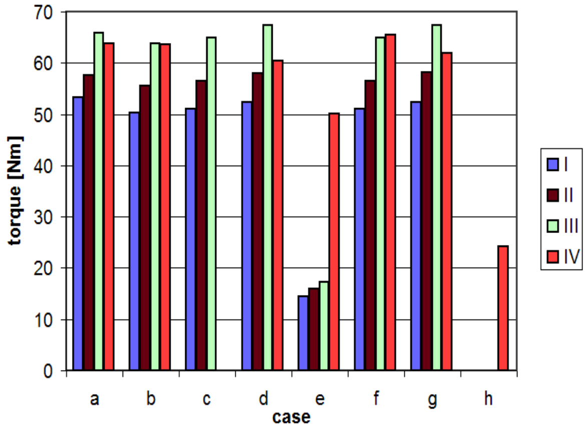

Fig. 4 Mean values of the torque for the studied SC-IM

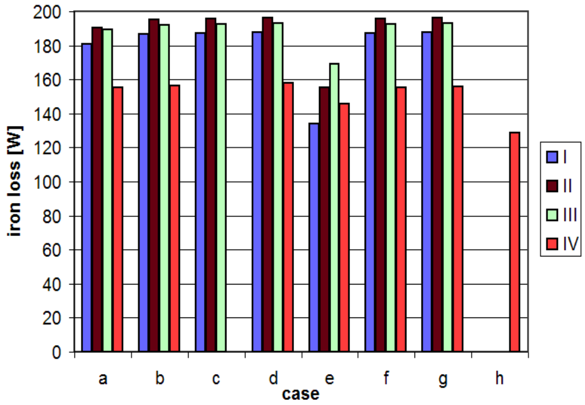

Fig. 5 Mean values of the stator iron core loss for the studied SC-IM

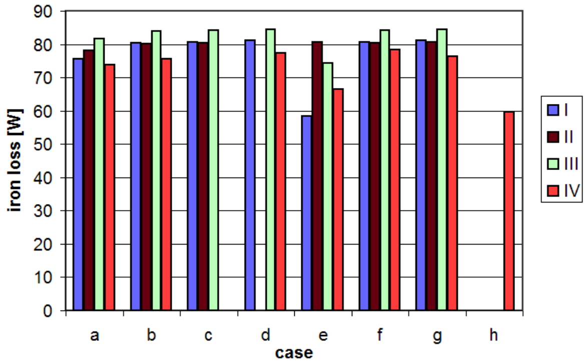

Fig. 6 Mean values of the rotor iron core loss, for the studied SC-IM

For several occurred faults (cases b, c, d, e, f, g, h), the mean values are approximately the same (the wave ripples are increasing as the faulted is more important, thus producing losses). The main differences appear for 1 phase or 2 phase open-circuit faults. The 6 phase topology offers a quite important torque capability even for 1 phase open circuit, while for 2 phases open circuit the torque reaches 40% of its mean value in health operation.

B. *The Switched Reluctance Motor-Drive System*

The Switched Reluctance Machine (SRM), with its simplicity, offers the possibility to be used in many applications nowadays, especially for fault-tolerant issues. By coupling SRM with an intelligent drive will result in a fault tolerant system. The machine studied in this paper, is a 12 stator poles against 14 rotor poles. Thus, it is possible to use the “two phase on” current feed technology. The present study was concentrated on the classical method of currents feeding, by using the pulse width modulation (PWM) method. The stator winding contains six channels, and each of them includes two phases which are fed for the same rotor position.

The electrical circuit of the drive is presented in Fig. 7. One fault tolerance case is given by the phase separation from the drive. The switches are simulated by using resistances with floating levels between high and low values, corresponding to on/off states.

Four study cases were employed: **(a)** normal (health) operation, **(b)** one phase fault, **(c)** two faulted phases from different channels, **(d)** whole channel failure.

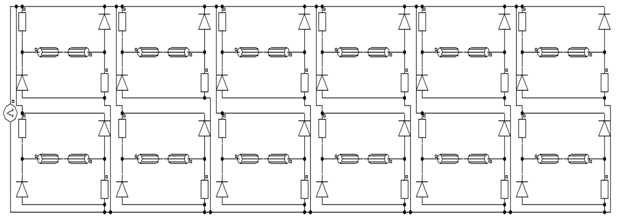

Fig. 7 Electrical circuit for the SRM drive.

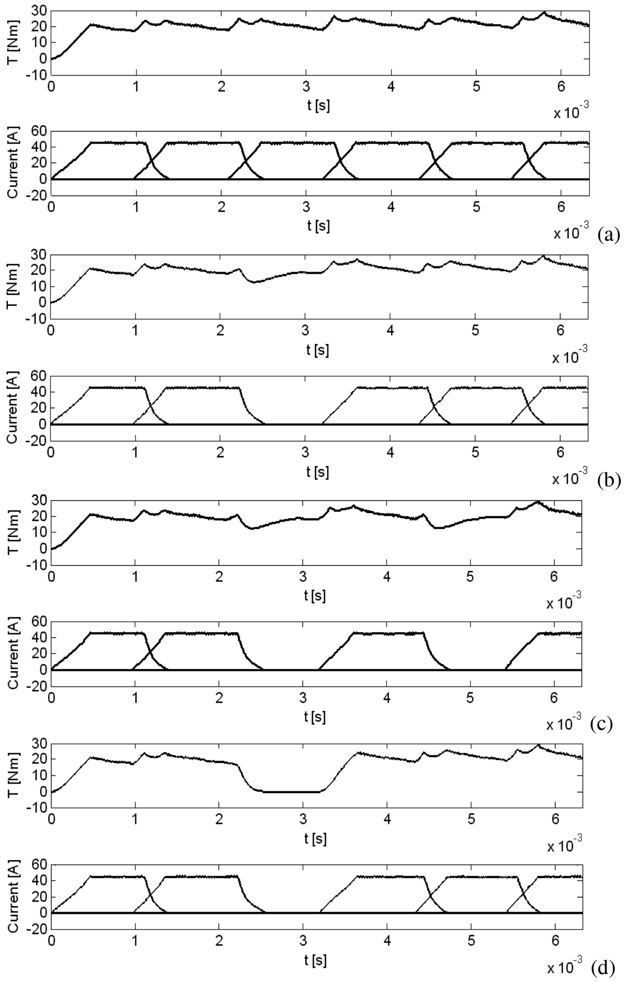

Fig. 8 Torque and current wave forms for the SRM in heath (a) and faulty (b),(c),(d) operation.

In Fig. 8 one can see the torque and the current waveforms for each study case. For of one phase fault, the torque will suffer a decrease corresponding to the missing current contribution. The loss of two currents from two different channels will provide two decrease regions in the torque characteristic, but its mean value still remains in the desired range.

In case of drive failure a sever fault can occur when there is no possibility to control one channel. Practically the machine will have now a dead zone. For passing through this zone only the machine's inertia will be helpful. A serious problem interferes since the drive has to be able to use the rest of phases to take the rotor out from this situation. This corresponds to (d) case in Fig. 8.

In the Table I there are the torque development values versus the normal operating mode as reference.

TABLE I
MEAN TORQUE VALUES FOR THE SRM OPERATION

case	(a)	(b)	(c)	(d)
Torque [Nm]	20.75	19.99	19.15	16.73

The loss of torque in case of one and two phase failure is very small. On the other hand, a high amount of torque is lost when a whole channel falls. Nevertheless, the operation could continue till the machine is replaced.

C. The Permanent Magnet Synchronous Machine-Drive System

1) Permanent magnet synchronous drive fault-tolerance

The study was carried out on a nine-phase PMSM. The converter attached to this topology is divided in 9 phases, grouped 3 by 3. Star (Y) winding connections are created for each group of 3 windings. The 3 groups are connected to a commonly power supply. Obviously this special connection of the fault-tolerant PMSM needs a particular converter, given in Fig. 9.

Each phase is fed by using a pair of switches and there is an additional inverter leg, used when a fault occurs. So, every Y group of phases has an additional leg attached. This last one is connected to the neutral point, so the neutral current is zero. The current equation system which models the drive in health and faulty operation is

$$\begin{aligned} i_0 &= i_a + i_b + i_c \\ i_0 &= i_a + i_c; \quad i_b = 0 \end{aligned} \tag{1}$$

When a fault occurs on one phase, this last one is isolated by using the power switches. The additional leg participates now, replacing the contribution of the switches from the faulted phase. So, the current in the faulted phase is zero, and the one in the neutral point will be equal with the sum of the healthy currents, see (1).

The link between Flux2D and Matlab was used in order to achieve results, using FEM. The opening / closing of the switches are modeled simply by changing the resistance from 100 kΩ to 4 mΩ. The results obtained with this drive emphasize the system fault-tolerant status. The currents in the machine are shown in Fig. 10. Four study cases were carried out: **(a)** health operation, **(b)** fault on one phase, **(c)** fault on three phases(from different phase groups), **(d)** fault on three phases(two from one group and one from another group). Torque plots from Fig. 11 shows that as faults are more severe, the ripples are more obvious. The mean value of the torque in the worst case of operation is 77.03%, as ratio from the healthy torque value of 51.9Nm. The torque values can stand up as an answer for the fault-tolerance of both the machine and the converter. The torque ripples can be optimized using a recomputation method for the phase delays and setting them in accordance with the remaining phases (not presented here).

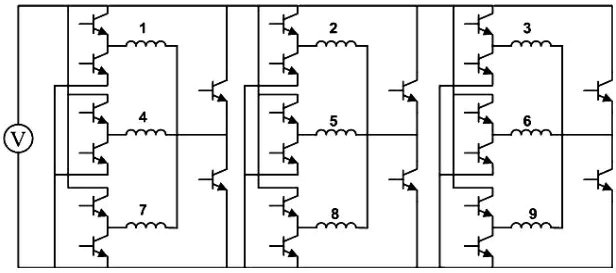

Fig. 9 Nine-phase inverter for the PMSM supply

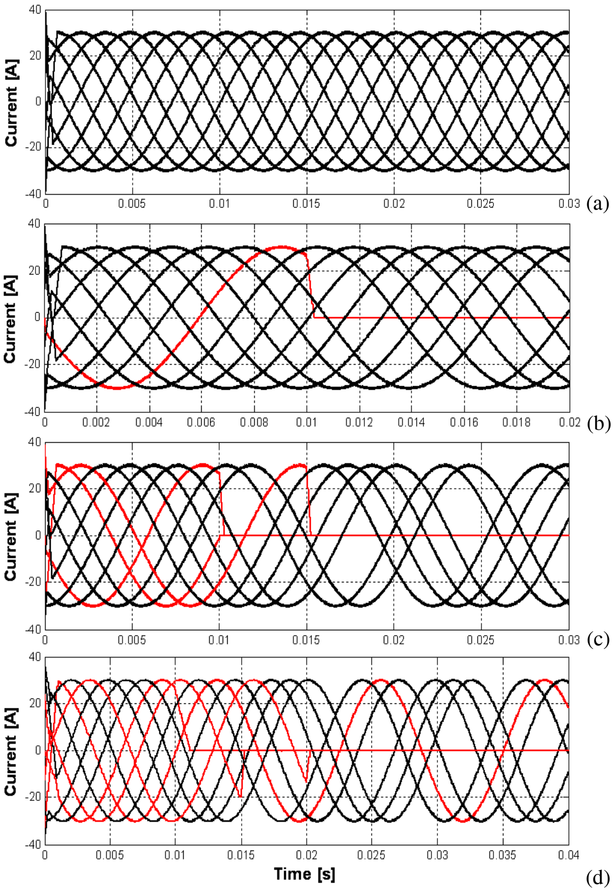

Fig. 10 Current waveforms in the PMSM: (a) healthy machine; (b) faulty machine, case 1; (c) faulty machine, case 2; (d) faulty machine, case 3.

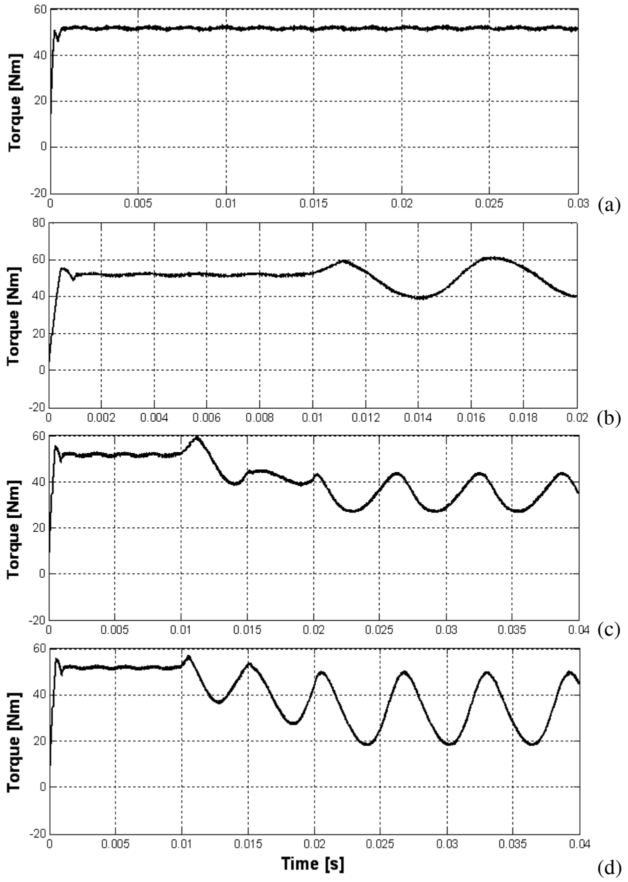

Fig. 11 Torque waveforms in the PMSM: (a) healthy machine; (b) faulty machine, case 1; (c) faulty machine, case 2; (d) faulty machine, case 3.

2) PM demagnetization fault-tolerance

The specific problem which interferes in the operation of PM machines is the irreversible demagnetization [17]. In the case of high power/weight ratio PM material, such as Neodymium-Iron-Boron, the risk of loosing its magnetic properties is important, for transient torques or high speed values (in flux weakening region) operation, since the point operation depends on temperature.

For common PM machines, the magnets will be sooner or later irreversibly demagnetized, partially or totally. The solution in this case is to replace the entire rotor core with new PM pieces.

On the other hand, for a double excited synchronous machine topology, DESM [10], the loss of PM flux can be replaced by the auxiliary field obtained when the second excitation source (auxiliary rotor coil) is supplied. (The rotor topology of the DESM is presented in the “tests” section.)

For different remanent flux density values one can see in Fig. 12-up the airgap flux density repartition. Thus, in order to get the desired airgap field (corresponding to 1.15T in this case) one should supply the auxiliary source with a proper level of current, Fig. 12-down.

IV. PM FAULT-TOLERANCE TESTS ON DESM

For test validation, the case of the DESM fault-tolerance was studied. A common three phase stator was constructed (not presented here). The rotor core has 4 poles, with PMs placed in the airgap and a field winding of concentrated type placed around the poles, Fig. 13. In order to show the fault-tolerance capability of the constructed machine, the authors have chosen to measure the induced electromotive force (EMF) while a field current is injected in the auxiliary winding, in generator operation. For a given speed (1500rpm) several values of field currents are chosen in order to prove the machine capability to reduce, or strengthen the main flux, and finally the EMF. (The study of PM real faults supposes that the magnetic material, and finally the machine, will be irreversibly compromise; thus, one can understand why the authors have studied this phenomenon on EMF measure). For the studied machine one can get:

$$E = K_E \cdot \Omega \tag{1}$$

where the electromotive force coefficient, K_E, depends on the number of turns (constant), winding type (constant), frequency (constant), flux (variable); the speed, Ω, is kept constant. Thus, by controlling the flux, one can vary the EMF, proving the fault-tolerance capability of the DESM.

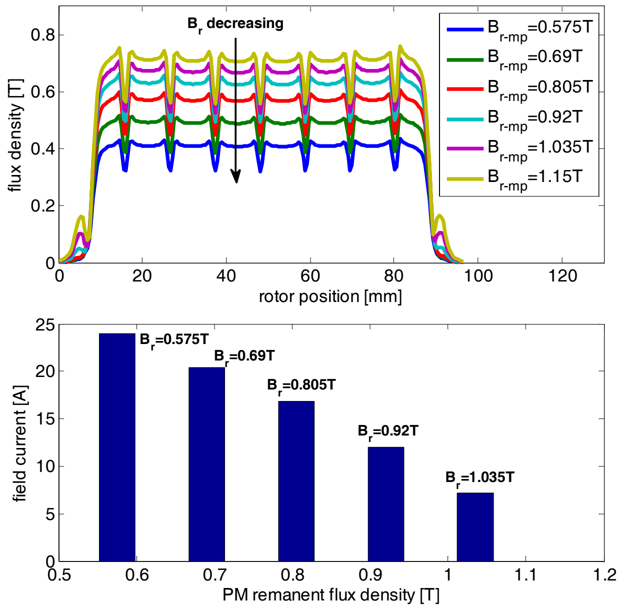

Fig. 12 Airgap flux-density (up) and the field current values in faulty PMs conditions (down) for different values of the remanent flux density.

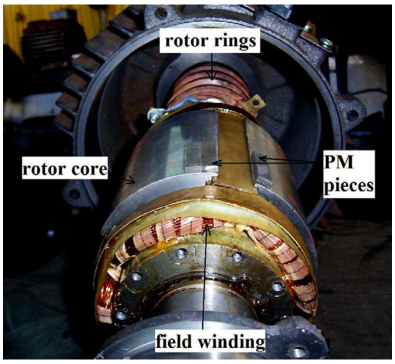

Fig. 13 The rotor of the studied DESM.

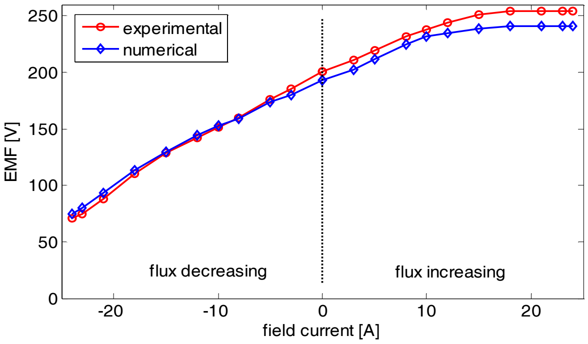

Fig. 14 The simulation of faulty PMs.

The results of the numerical and experimental performances, for different levels of field current are presented in Fig. 14. Here, one can see that, at the given speed, the EMF can be reduced considerably, or increased also (when the magnetic field is increased, one can observe the core saturation effect). For the maximum auxiliary current the EMF is approximately three times smaller in flux decreasing mode, meaning that the DESM offers a significant operation range even if more than a half of the magnetic property of the PM is lost.

V. CONCLUSIONS

The very important number of electrical machines found on board of an automobile raises the necessity of testing their limits in fault-tolerant operation. The paper presents a resume on the most suited fault-tolerant electrical drives. The induction, switched reluctance and permanent magnet drives were studied. The influence of the winding type, the number of poles, and the drive topology and control strategies were analyzed, from the mean value of the smooth-torque and efficiency point of view. Thus, some conclusions could be carried out and other interesting points should be revealed:

- the electrical isolation of the phases: is an essential requirement if continued operation is to occur with either a power device or winding short-circuited. For instance, in a star connected system the star point may rise to the dc link voltage, so that no net torque capability remains;

- the magnetic isolation of the phases: without magnetic isolation, fault currents in one phase induce large voltages in other phases. In a surface mounted permanent magnet machine, with a retaining sleeve employed, the presence of this last one, combined with magnets height reduces the airgap component of the armature reaction field, so that the mutual coupling is not significant;

- limiting the short-circuit fault current: while a short current occurs, the current which flows is limited by the phase inductance and resistance. If one limits the current to the rated value (due to inductance parameter), the net braking torque due to loss in the phase resistance is very small;

- the physical separation of phases, by using the concentrated winding type;

- the number of phases (or poles): a big number of phases (or poles) increases the drives capability for working in fault-tolerant regime, but involves supplementary costs. Thus, a compromise is necessary;

- a supplementary converter leg can be considered in order to assure the machines operation even if one phase is permanently lost.

REFERENCES

[1] Diallo, D. Benbouzid, M.E-H. and Makouf, A. "A fault-tolerant control architecture for induction motor drives in automotive applications", *IEEE Trans. on Vehic. Tech.*, vol.53, no 6, pp.1874-1855, November 2004.

[2] Tirnovan, R., Giurgea, S., Miraoui, A. and Cirrincione, M., "Surrogate modelling of compressor characteristics for fuel-cell applications", Journal of Applied Energy, vol. 85, n° 5, pp.394-403 May 2008.

[3] Welchko, B. A., Lipo, T.A., Jahns, T.M. and Schulz, S.E., "Fault Tolerant Three-Phase AC Motor Drive Topologies: A Comparison of Features, Cost, and Limitations", *IEEE Trans. on Pow. El.*, vol.19, no 4, pp.1108-116, July 2004.

[4] Qin, D., Luo, X., and Lipo, T.A., "Reluctance motor control for fault-tolerant capability", *Proc. of the IEEE Int. Conf. on Electric Machines and Drives*, pp.WA1/1.1–WA1/1.6, 18-21 May 1997.

[5] Atkinson, G.J., Mecrow, B.C., Jack, A.G., Atkinson, D.J., Sangha, P. and Benarous, M., "The analysis of losses in high-power fault-tolerant machines for aerospace applications", *IEEE Trans. on Ind. Appl.*, vol.42, no 5, pp.1162-1170, September-October 2005.

[6] Sawata, T., Kjaer, P.C., Cossar, C., Miller, T.J.E. and Hayashi, Y. "Fault-tolerant operation of single-phase SR generators", *IEEE Trans. on Ind. Appl.*, vol.35, no 4, pp.774-781, July-August 1999.

[7] Ede, J.D., Attalah, K., Jiabin, W. and Howe, D. "Fault detection and fault-tolerant control of interior permanent magnet motor drive system for electric vehicle", *IEEE Trans. on Magnetics.*, vol.38, no 5, pp.3921-3923, September 2002.

[8] Fodorean, D., Djerdir, A., Viorel, I.A. and Miraoui, A. "A double excited synchronous machine for direct drive application - design and prototype tests": *IEEE Trans. on Energy Conversion*, vol.22, n.3, pp.656-665, September 2007.

[9] Li, S. and Xu, L. "Strategies of fault-tolerant operation for three-level PWM inverters", *IEEE Trans. on Pow. El.*, vol.21, no 4, pp.933-940, July 2006.

[10] Fodorean, D., Viorel, I.A., Djerdir, A. and Miraoui, A. "Performances for a Synchronous Machine with Optimized Efficiency while Wide Speed Domain is Attempted", *IET Electric Power Applications*, vol.2, n°1, pp.64-70, January 2008.

[11] Benbouzid, M. El-H., Diallo, D. and Zeraoulia, Mounir "Advanced Fault-Tolerant Control of Induction-Motor Drives for EV/HEV Traction Applications: From Conventional to Modern and Intelligent Control Techniques", *IEEE Trans. on Veh. Tech.*, vol.56, no 2, pp.519-528, March 2007.

[12] Duran, M. J., Duran, J.L., Perez, F. and Fernandez, J. "Induction-motor sensorless vector control with online parameter estimation and overcurrent Protection", *IEEE Trans. on Ind. Elec.*, vol.53, no 1, pp.154-161, February 2006.

[13] Jacobina, C.B., Ribeiro, R.L.A., Lima, A.M.N. and Silva, E.R.C. "Fault-tolerant reversible ac motor drive system", *IEEE Trans. on Ind. Appl.*, vol.39, no 4, pp.1077-1084, July-August 2003.

[14] Mendes, A.M.S., and Cardoso, A.J.M. "Fault-tolerant operating strategies applied to three-phase induction-motor drives", *IEEE Trans. on Ind. Elec.*, vol.53, no 6, pp.1807-1817, December 2006.

[15] Ruba, M. and Anders, M. "Fault tolerant switched reluctance machine study", *Proc. on the Int. Conf. in Power Electronics, Intelligent Motion and Power Quality (PCIM 2008),* Nuremberg, Germany, 2008 (*in press*).

[16] Wallmark, O., Harnefors, L. and Carlson, O. "Control algorithms for a fault-tolerant PMSM drive", *IEEE Trans. on Ind. Elec.*, vol.54, no 4, pp.1973-1980, August 2007.

[17] Farooq, J., Srairi, S., Djerdir, A. and Miraoui, A. "Use of permeance network method in the demagnetization phenomenon modeling in a permanent magnet motor", *IEEE Trans. on Mag.*, vol.42, n° 4, pp. 1295 - 1298, April 2006.