On the Usefulness of Numeric Field Computations in the Study of the Switched Reluctance Motor's Winding Faults

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Abstract—**The switched reluctance machine (SRM) is considered as one of the most inherently fault tolerant electrical machines. Unfortunately despite its robustness and reliability, faults (mainly of its windings and bearings) can appear during its operation. Therefore the SRM's condition monitoring is very important mainly in those safety-critical applications where unwanted shutdowns could have catastrophic effects both on human life and costs. The paper deals with the winding faults of the SRMs and their detection. The effects of winding faults are investigated in details by means of advanced numeric field analysis based on the finite element method (FEM). This numerical method is widely used in electrical engineering to solve complex electromagnetic problems. In the last part of the paper also the effectiveness of the flux differential winding fault detector is taken into study.**

I. Introduction

The switched reluctance motor (SRM) is a double salient machine. Its concentrated windings are placed around the stator poles. The independent phases comprises of two coils on diametrically opposite poles connected in series. Its operation is based on the variable reluctance principle. In motor mode the torque is produced by the tendency of the rotor to reach a position where the inductance and the flux produced by the energized winding are maximized. The excitation is a sequence of voltage/current pulses applied to each phase in turn. The control system requires rotor position information for an optimal phase excitation in order to achieve as smooth as possible continuous torque and high efficiency [1], [2].

Due to their very simple construction the SRMs are robust and reliable, therefore there are ideal for safety-critical applications where the electrical drive system must be fault tolerant [3]. In these applications it is very important to detect a fault in its incipient phase in order to make the correct decision regarding the replacement of the motor..

In the paper the main results of a study on the effects of the SRM's shorted winding faults are given. The changes in the magnetic field distribution and in the torque development capability of the machine were investigated. Also the usefulness of the flux differential windings fault detector was tested. The study was performed by means of advanced electromagnetic field computations. The finite element method (FEM) was applied, one of the most popular and effective numerical methods used for computer simulation in diverse technical areas [4]. The key advantage of the FEM over other numerical methods in engineering applications is its ability to handle nonlinear and time-dependent problems on any, even very complicated geometry [5]. Therefore, this method is suitable for solving various electromagnetic problems regarding the effects of winding faults in SRMs.

II. Fault Detection in SRMs

As it is estimated about half of the SRM's faults are in their windings [6]. The main windings faults are [7]:

i) short circuit in the coil
ii) open circuit in the coil
v) short circuit between two different phases
vi) short circuit from one coil/phase to ground.

These windings failures may be caused by mechanical vibration, heat, age, damage during installation, power converter faults, etc. [8].

To avoid the harmful effects of the winding faults on the systems in which the SRMs are used it is necessary to detect the faults already in their incipient phase. The above mentioned winding faults can be sensed by diverse failure detectors. In [9] several fault detection circuits for SRMs are detailed from very simple ones to complicated diagnosis systems. The most widely used detectors are sensing the over-current in the coils, the magnetic flux difference in the two series connected coils or the rate-of-rise of the phase current.

Comparing their complexity and costs to performance ratio it seems that the best solution is to apply a flux difference detector (see Fig. 1) for each phase of the SRM.

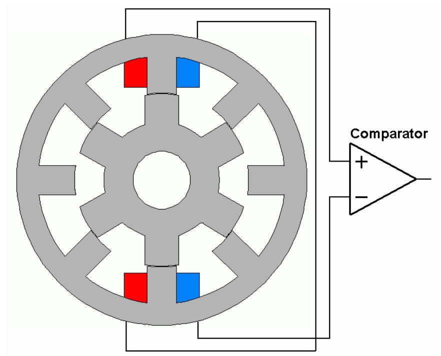

Fig. 1. The flux differential detector

The detector requires additional search coils wrapped around the stator poles. The search coils of each phase are

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connected in series opposing. Hence during normal operation the induced voltages of the search coils are equal and opposite, leaving a zero voltage at the terminals of the series pair. When a fault occur the magnetic flux will be different through the two poles, hence also the electromotive forces induced will be different and this voltage difference can be detected by the bidirectional comparator. The detector circuit can sense ground faults, phase-to-phase faults and also short circuit faults [9]. Its main drawback is that requires additional coils to be placed on poles.

III. FEM Analysis Of The SRM Having Different Faulty Conditions

All the winding faults of a SRM cause unsymmetrical field distribution inside the machine. The best way to emphasize these changes is to perform a precise numeric field analysis of the SRM.

The main data of the simulated SRM are:

i.) Rated power 350 W

ii.) Rated voltage 300 V

iii.) Rated current 6 A

iv.) Rated speed 600 1/min

v.) Number of stator poles 8

vi.) Number of rotor poles 6

The cross section of the motor together with its pole's notations is given in Fig. 2.

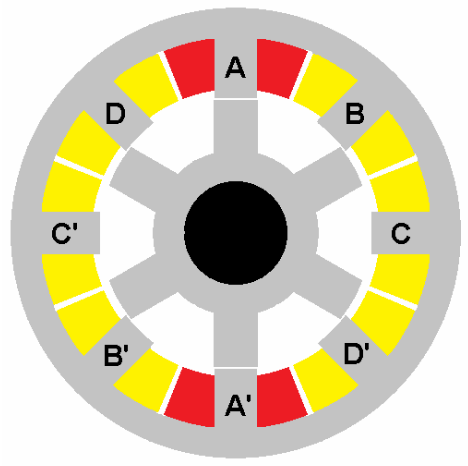

Fig. 2. The cross section of the SRM in study

The numeric field computations were carried out by using the FEM based Flux 2D program package produced by Cedrat (France) [10], [11].

The simulations were performed for the healthy machine and for the following three winding fault conditions:

i.) coil *A* having 20% of turns shorted

ii.) coil *A* having 50% of turns shorted

iii.) coil *A* having all its turns shorted.

The most significant results are given in Figs. 3 and 4, where the flux lines obtained via field computations are shown for the *A* stator pole being aligned, half-aligned and unaligned

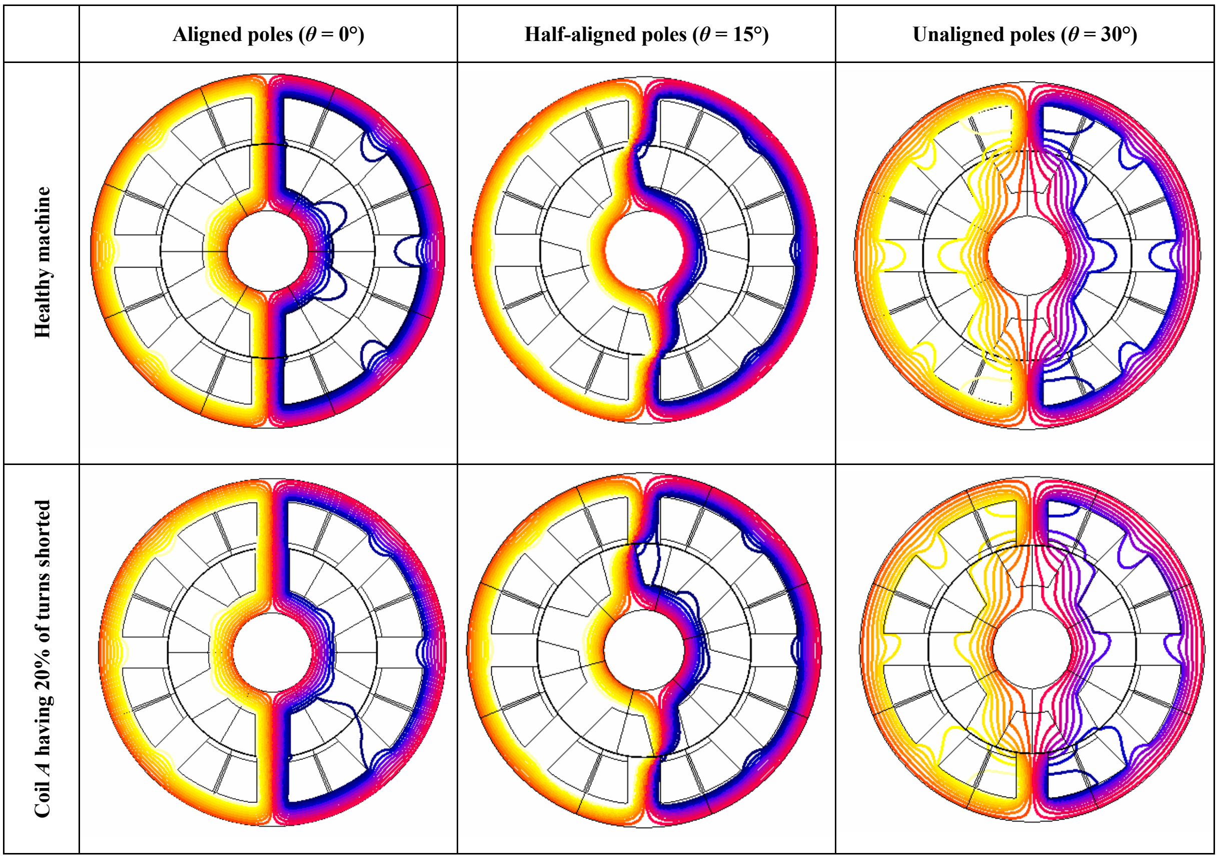

Fig. 3. The results of the field computations

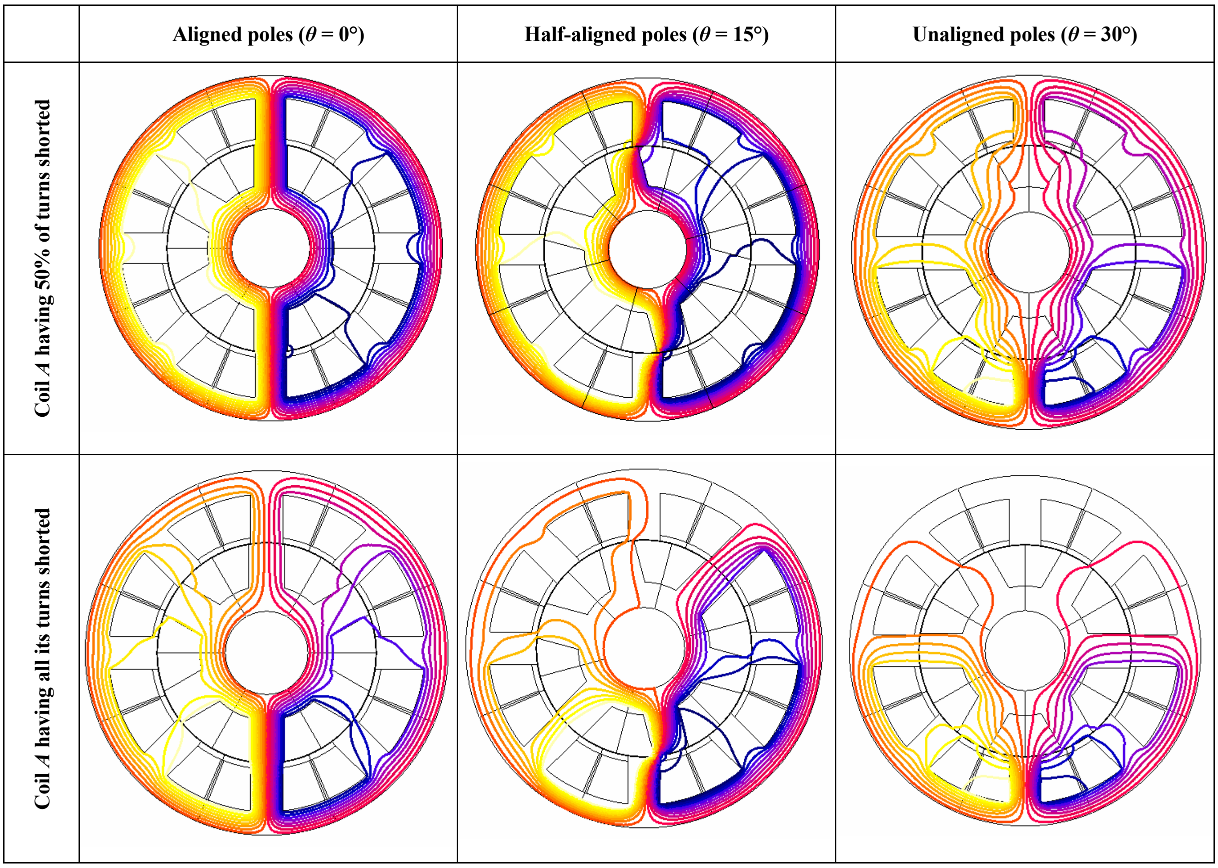

Fig. 4. The results of the field computations

relatively to the rotor poles, respectively for all the four conditions of the SRM in study.

As it can be clearly seen in these figures the symmetry of the magnetic flux distribution is more and more lost as the severity of the simulated faults is increasing. The magnetic flux in pole *A* versus the angular displacement is plotted in Fig. 5.

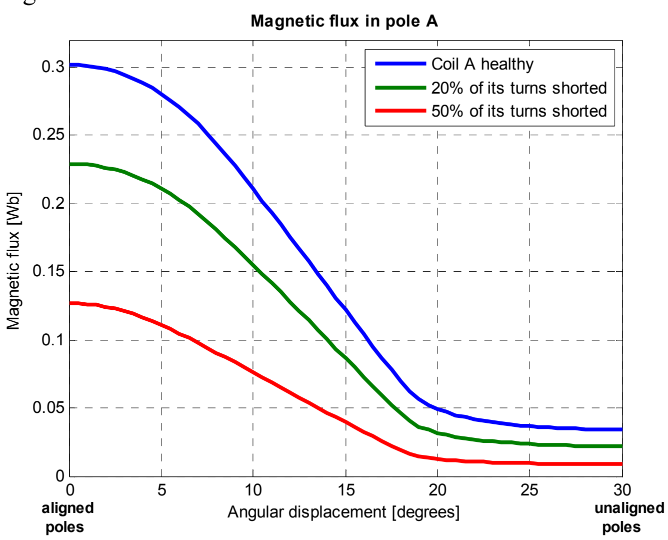

Fig. 5. The magnetic flux in pole *A* plotted versus the angular displacement

As it can bee seen in Fig. 5 as the number of shorted turns in the coils is increased the magnetic flux in pole A is decreasing. Of course the lower flux in one of the motor's pole will have influence also on the torque development capability of the machine. The plots of the torque developed by the SRM versus the angular displacement for different machine conditions are given in Fig. 6.

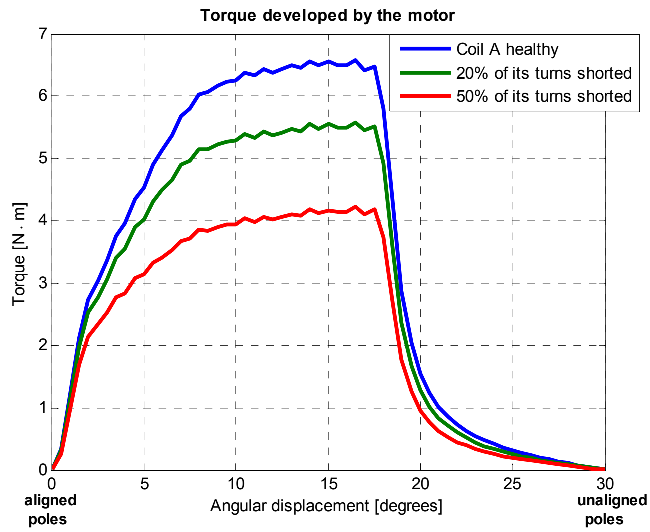

Fig. 6. The torque developed by the SRM plotted versus the angular displacement

The mean value of the developed torque during a displacement from the aligned to the unaligned position in the case of the healthy SRM is 3.41 N·m. When 20% of the turns of one coil are shorted the torque development capability of the motor is reduced by 15% to 2.92 N·m. When only half of *A* coil's turns are working the developed torque of the SRM is 65% of the healthy machine's one (2.22 N·m).

As also the testing of the flux differential winding fault detector given in Fig. 1 was proposed, the variation of the emf induced in the 100 turns search coil wound round pole A was plotted, too (see Fig. 7).

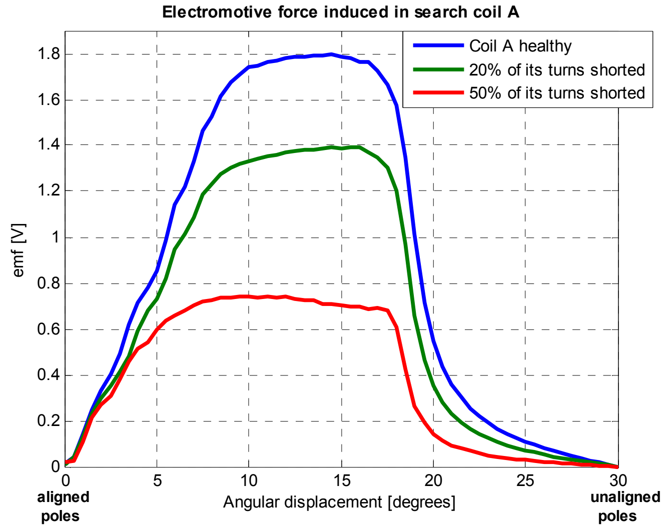

Fig. 7. The emf induced in the search coil from pole *A* plotted versus the angular displacement

As it was expected also this quantity is strongly influenced of the SRM's faults.

The numeric field computations performed permitted also the computation of the voltage differences between the electromotive forces induced in two search coils from opposite poles (*A* and *A'*). This voltage difference is practically the one sensed by the flux differential detector. In Fig. 8 the input of the detector is plotted versus the angular position of the SRM for three conditions of the winding from pole *A*.

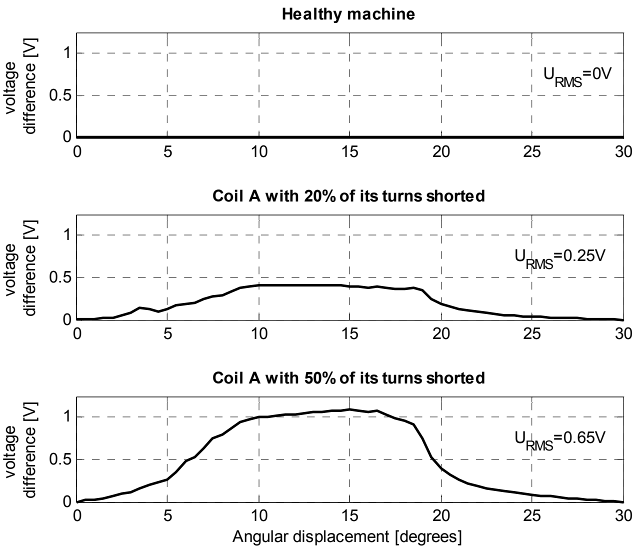

Fig. 8. The input of the flux differential winding fault detector plotted versus the angular displacement

All the results in Fig. 9 confirm the sensing capability of the detector in study. The voltages of hundreds of mV at the input of the operational amplifier are enough for an effective detection of the winding faults.

IV. Conclusions

The paper emphases the usefulness of advanced field computation tools in studying the effects of the SRM's main winding faults on its performances. All the presented results highlight clearly the effects of the faults and the effectiveness of the flux differential detector.

Due to the faults the flux thru both the energized and un-energized coils are changed, but also the emf in these coils. These observations can stand on the basis of new fault detection methods to be developed in the future.

Acknowledgment

This paper was supported by the project "*Doctoral studies in engineering sciences for developing the knowledge based society – SIDOC*" contract no. POSDRU/88/1.5/S/60078, project co-funded from European Social Fund through Sectorial Operational Program Human Resources 2007-2013, respectively by the research grant "*Improved performance variable reluctance machines for safety-critical industrial process applications*" funded by the by the Romanian National Authority for Scientific Research (ANCŞ) project no. 472/2011 and the Slovak Research and Development Agency (SRDA) project no. SK-RO-0016-10 in the framework of the "Romanian-Slovak Intergovernmental S&T Cooperation Programme for 2011-2012".

The authors should like to sincerely thank this way for the financial supports.

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