Evaluation and Comparison of Fault Tolerant Switched Reluctance Machines for a Specific Application

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Abstract

In aeronautical as well as in automotive environments more and more hydraulic auxiliary drives are to be replaced by electrical drives. Applications that are of vital importance for keeping up the operability of the whole system (e.g. electrical steering in automobiles) need to be actuated by fault tolerant drives. As switched reluctance machines generally offer a very simple and robust design, they are very suitable for high reliable and fault tolerant applications. This paper compares and evaluates different machine designs including redundancies for one specific application.

Keywords

switched reluctance machine, fault tolerance, redundancy, high reliability

1. Introduction

Switched reluctance machines are characterized by a simple mechanical structure. The fact that the rotor does not carry any windings allows a brushless, maintenance-free and closed design. The lack of permanent magnets extensively provokes independence of the machines behavior from temperature and durable shock resistance of the motor. The solely of laminations consisting rotor predestines the machine for high speed applications [1], [2]. Thus switched reluctance drives suit perfectly for tasks in automotive [3] and aerospace [4] environments as well as for the use in the mining industry [5] or any other conceivable dusty or dirty, vibrations exposed surrounding.

In this paper switched reluctance machines that provide redundancies if short circuits or open circuits in one or more phase windings occur are examined. For an electrical drive this fault tolerance can be achieved by having one multiple phase motor that allows operation even with certain inactive windings, or by having two (not necessarily identical) machines of which one ensures the drives operability in case the second machine breaks down.

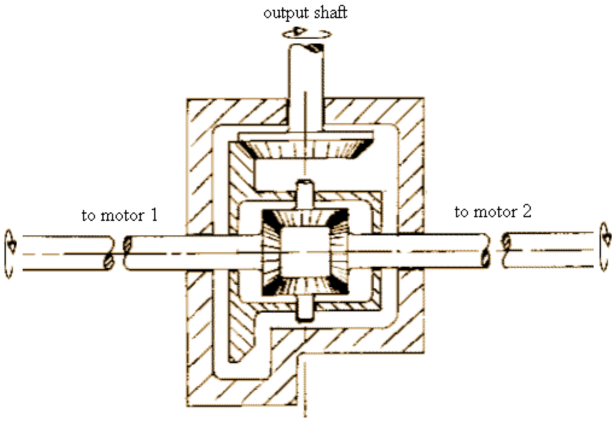


Fig. 1: Differential gear.

When two separate motors are applied to obtain fault tolerance two mechanical principles can be applied: speed summing and torque summing. In case of speed summing the two motors are connected to a differential gear. Fig. 1 shows such a gearbox. When both motors work properly and turn in the same direction (as displayed in Fig. 1) at the same rotational frequency, this speed multiplied by the gear ratio will de transferred to the output shaft. In case one of the motors breaks down the output shaft turns at half of the speed but carries the same torque as before, if the rotor of the inactive motor is locked. Locking the inactive motor is absolutely necessary to keep the drive operable. If this can not be assured and the rotor of the damaged motor can still rotate, the output power of the active motor will be split up between the output shaft and the shaft of the defective drive. In the worst case, if the load is too high, it will not be possible to set the output shaft in motion at all.

Using the torque summing principle simply involves having two motors mounted on a common shaft. The output torques of both motors cumulate. Here it has to be assured that the rotor of the damaged machine does not lock. Further on the damaged motor should not produce any break torque, as it might happen with permanent magnet machines with shorted windings, because here the excitation can not be switched off as it is caused by the magnets.

The researches described in this paper focus on a machine configuration that is applicable for an already designed electromechanical actuator (EMA) that converts the rotational movement of an electrical machine into a linear movement. As the design of the actuator is already complete except for the motor itself, the mounting frame is limited to a certain diameter and axial length. The torque summing principle has to be applied. Thus, as explained above, brushless DC machines are not suitable for this application. Because of their simple geometry and great robustness, switched reluctance machines are examined instead. To keep the weight and inertia of the drive low, the machine should be as small and lightweight as possible, of course taking into account the thermal conditions of the surrounding.

In the following three different drives are investigated that offer redundancies in case of a partly breakdown of the drive. The first configuration to be examined is a five phase switched reluctance machine connected to a five phase power converter. In case of a failure in one of the phases this drive will be capable of running with only four active phases and at about eighty percent of its nominal torque. The reason why at least five phases are required to provide true fault tolerance becomes obvious when Fig. 2 is regarded:

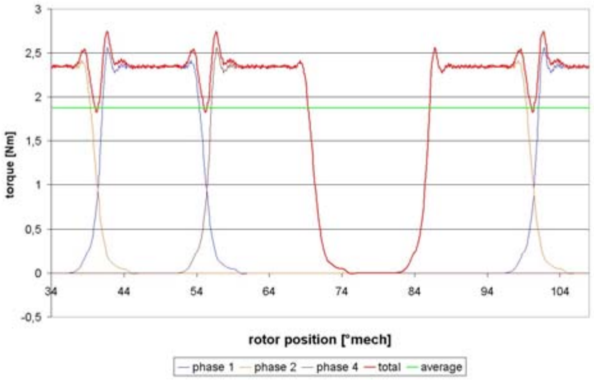


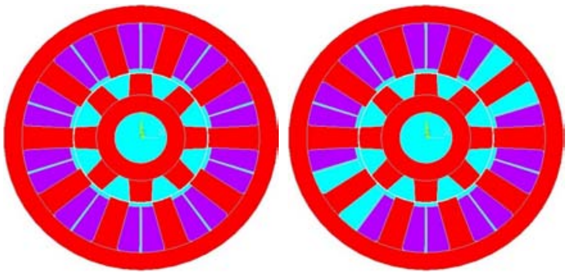
Fig. 2: Torque performance of a four phase SRM, with one inactive phase.

Here the performed torque of the further down introduced four phase machine is displayed with phase 3 inactive. It is obvious that the machine does not produce any torque in rotor positions within about 74 to 84 degrees. Assumed the rotor stood still in such a position, the motor would not be able to start again self-propelling, whereas a truly fault tolerant motor has to be capable of starting under any circumstances.

The second proposal is a six phase switched reluctance machine connected to two independent three phase power converters. This drive can even still run at fifty percent of its rated torque when one complete channel, i.e. one power converter or three of the six phases are inactive, as long as every second phase around the circumference of the machine is still working. The third approach to the problem is to mount two four phase reluctance machines on one shaft. These machines will be connected to two independent converters, too. This drive will still be working properly if one of the two machines or its converter malfunctions as long as the rotor does not lock.

2. Five Phase Single Channel Drive

This proposal appears to be interesting, because the technical demands of the actuator include that about two thirds of its nominal linear force still have to be available even when an error in the drive system has already occurred. Whereas the other two proposals will have to be designed for performing twice the power and torque of the technical demands for operation after the occurrence of a failure (because they allow a breakdown of fifty percent of the system), the five phase configuration will only have to follow the demands for the undisturbed operation. Hence volume and weight of this drive will be smaller than those of the other two suggestions. Fig. 3 shows a cross section of the switched reluctance machine:



a) b)

Fig. 3: Five phase SRM with 10 stator and 8 rotor teeth

a) undisturbed operation,
b) failure in one phase.

For this specific application the main dimensions of the machine are listed in Table I:

Table I. – Dimensions of the Five Phase SRM

outer diameter of stator joke	$D_{joke} = 74.0 mm$
stack length	$L_{stk} = 80.0 mm$
weight of active material	$m = 2.20 kg$
rotational inertia of rotor laminations	$J = 5.20 \cdot 10^{-5} kg\ m^2$

Fig. 4 shows the performed torque of the above specified switched reluctance machine in undisturbed operation simulated with SPEED/PC-SRD. The firing angles of the semiconductor switches of the power converter are set for low torque ripple.

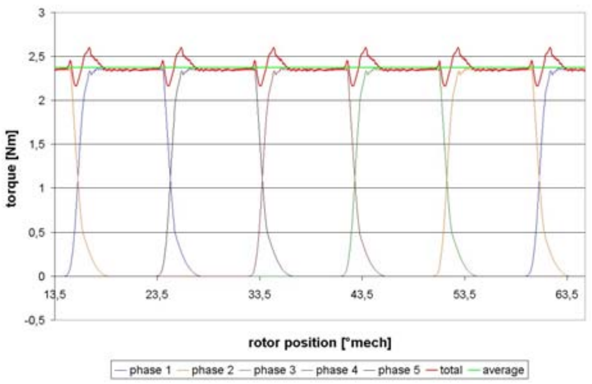


Fig. 4: Torque performance of five phase SRM, undisturbed operation.

Fig. 5 displays the output torque of the motor with one defective phase. Concerning the trace for the total torque it has to be noted that SPEED/PC-SRD does not offer the option to activate or deactivate several phases. The below graph is created by taking the simulation results of the output torque of only one of the machines phases and by adding the same values furnished with the respective phase shift for all other phases except phase 3. This approach is feasible as long as the phases do not influence each other magnetically, i.e. as long as the total magnetic flux does not cause saturation effects in all sections of the stator and rotor yoke due to identically oriented contributions from simultaneously excited phases, which is the case here. The same approach is made to create Fig. 8 in chapter 3.

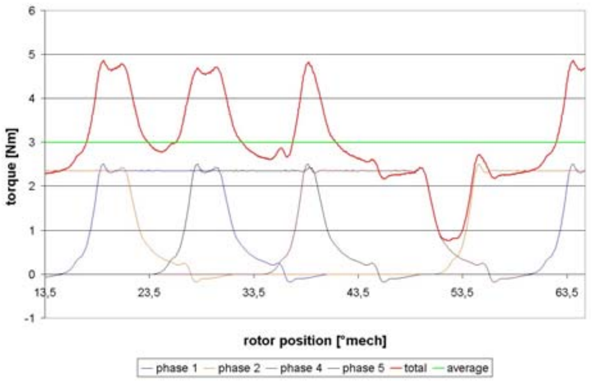
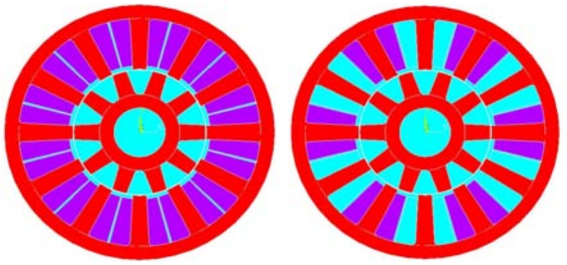


Fig. 5: Torque performance of five phase SRM, phase 3 defective.

The firing angles are set to values, that enable current flow over the whole period of rising phase induction in each phase. Moreover the rated value of the phase current is set higher than the one in the simulation of undisturbed operation. When Fig. 5 and Fig. 2 are compared it becomes obvious, that unlike the four phase machine the five phase machine is capable of producing torque independent of the rotor position and therefore meets the requirements for fault tolerance described in chapter 1.

3. Six Phase Dual Channel Drive

As explained in chapter 1 the idea is to have a six phase drive which allows the breakdown of three phases in case only every second coil around the circumference of the machine is affected by the fault. This machine will be connected to two separate three phase power converters, which tolerates a breakdown of one complete channel. Therefore this drive can not really be compared to the one presented in chapter 2 concerning weight and inertia, as the grade of redundancy is much higher, here. In Fig. 6 the respective cross section can be seen:



a) b)

Fig. 6: Six phase SRM with 12 stator and 10 rotor teeth

a) undisturbed operation,
b) failure in three phases.

The machine data are displayed in Table II:

Table II. – Dimensions of the Six Phase SRM

outer diameter of stator joke	$D_{joke} = 74.0mm$
stack length	$L_{stk} = 120mm$
weight of active material	$m = 3.10kg$
rotational inertia of rotor laminations	$J = 6.40 \cdot 10^{-5} kg\ m^2$

Fig. 7 and Fig. 8 again show the torque performance in undisturbed and disturbed operation mode:

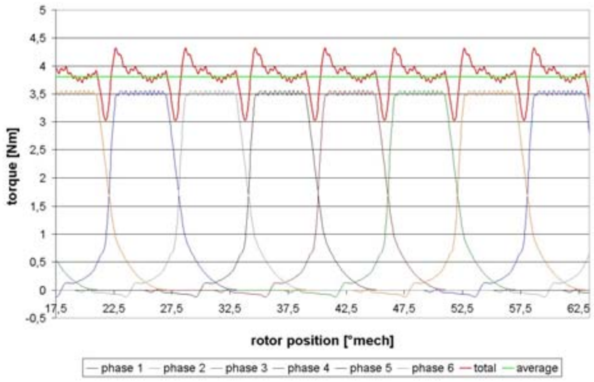


Fig. 7: Torque performance of six phase SRM, undisturbed operation.

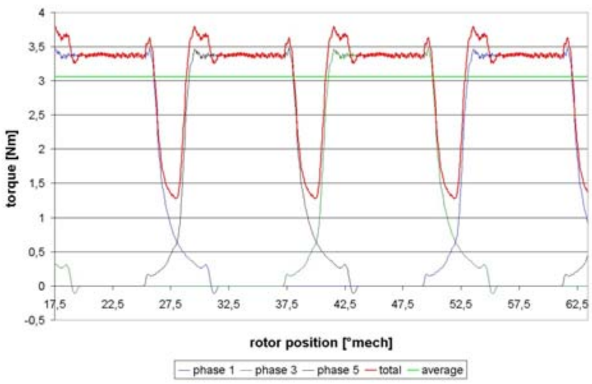


Fig. 8: Torque performance of six phase SRM, three phases defective.

The explanations made with respect to Fig. 5 are valid for Fig. 8, too.

Further on drives with even higher numbers of phases are not investigated, because already the cross section of the six phase machine is very filigree. A machine with eight or more phases would be less robust and also too expensive to manufacture.

4. Two Four Phase Machines, Dual Channel Drive

As explained above this proposal suggests having two identical small machines mounted on one shaft. The fact that the sponsors of this research have the possibility of using four phase power converters off the shelf leads to the decision to prefer a simple four phase machine with eight stator and six rotor teeth instead of a more common and even more simple and robust three phase machine with six stator and four rotor teeth. Last but not least the additional benefit of a higher quality of output torque with less torque ripple confirms this choice.

Fig. 9 shows the cross section of such a machine:

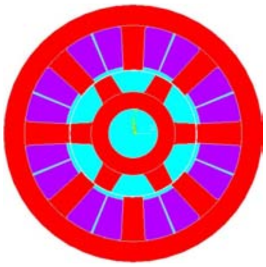


Fig. 9: Four phase SRM with 8 stator and 6 rotor teeth.

The respective data of one single machine are shown in Table III:

Table III. – Dimensions of One Four Phase SRM

outer diameter of stator joke	$D_{joke} = 74.0mm$
stack length	$L_{stk} = 47.0mm$
weight of active material	$m = 1.30kg$
rotational inertia of rotor laminations	$J = 2.50 \cdot 10^{-5} kg\, m^2$

When comparing this configuration to the above ones, of course axial length, weight and inertia have to be doubled. Its performance is shown in Fig. 10:

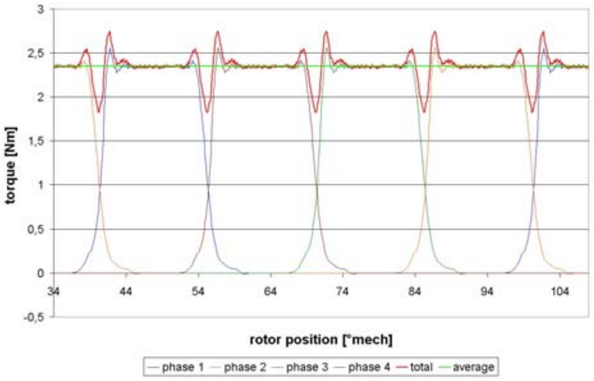


Fig. 10: Torque performance of four phase SRM.

5. Comparison

As the above listed numbers clearly show, the drive system presented in section 2 offers the lowest volume and weight. It can also be expected to be the most cost-effective suggestion, because only one power converter is needed and thus it requires less semiconductor switches than the other proposals. This is not very surprising, as the five phase drive on the other hand also provides the lowest grade of redundancy. Especially for the use in aeronautical and automotive environments, where high degrees of fault tolerance are usually requested, and therefore also a dual channel power supply for the drive is favoured, the last characteristic of this configuration might lead to the decision not to accept this proposal.

When full redundancy is intended, the six phase dual coil machine as well as the two four phase single coil machines mounted on a common shaft appear to be suitable methods. As the diameter of all machines is the same, it has to be noted, that the more filigree cross-section of the six phase machine requires the most precise manufacturing of the laminations of all presented machines and therefore the highest production costs. The slim stator yoke and teeth also cause this machine to be less robust than especially the four phase machine. The greatest advantage of the six phase machine is that it exploits the predetermined axial length best, because only two coil ends (instead of four for the configuration presented in section 4) have to be placed within the given space.

Concerning the two-motor drive it is remarkable that it offers the lowest rotational inertia. Hence its dynamic capabilities exceed those of the other proposals. Compared to the six phase machine this solution is also lighter. Both, the six phase machine and the two four phase machines require the same axial length of about $L = 160mm$ (including winding ends).

6. Conclusions

This paper presents three types of switched reluctance machines that offer partial redundancy with a single channel power supply and full redundancy with a dual channel power supply respectively. These two basic concepts can not be compared to one another that easily. When size and weight are concerned, the first proposal beats the other two. But in case full redundancy is required this configuration is not suitable.

To achieve full redundancy and a dual channel drive the second as well as the third proposed drive can be used. Simulations lead to the perception, that the two-motor drive combines the greatest number of advantages. Because of its simple construction it can be manufactured easier and therefore cheaper. This solution does not even require more space than the six phase dual coil configuration. Altogether this leads to the fact, that the two-motor concept offers a better dynamic performance and a lower weight. At last it provides the highest reliability and operational safety together with the best performance.

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