Study on a Simplified Converter Topology for Fault Tolerant Motor Drives

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Abstract—**Some of the recent research activities in the area of electrical machines and drives for critical applications (such as aerospace, defence, medical, nuclear power plants, etc.) are focused on looking for various special motor and converter topologies. Nowadays by the help of recent technological advances and developments in the area of power electronics and motor control the fault tolerant electrical machine and drive concept is at a level where it begun to be feasible to be used in practice [1]. Therefore any new results could be of real interest for all the specialists working in these fields. In the paper a simplified power converter topology is proposed for a nine-phase fault-tolerant permanent magnet synchronous machine. By coupled Flux 2D and Simulink transient simulations the behaviour of the drive system under different winding fault conditions is studied. It is proved that using the simplified converter topology near the same torque development capability of the machine in faulty states can be assured. Short discussion on making the converter also fault-tolerant is included in the paper, too.**

I. INTRODUCTION

The fault tolerant concept emerged for the first time in information technology. It meant an increased level of continuous operation of computer equipment. Later more and more fault tolerant equipments were connected together in order to form a fault-tolerant system [2].

The result was an operational unit having certain fault tolerant level, as a sum of the safety levels of each equipment of the system. A system is reliable when it is capable of operating without material error, fault or failure during a specified period in a specified environment. From another point of view a system is dependable if it is available, reliable, safe, and secure [3].

In the field of electrical drives both the machine and the power converter must be fault-tolerant. From the first approach of the fault tolerant concept till today, several proposals to improve the electrical machine's reliability had been published. The fault-tolerance of electrical machines means the rise of the operating level, and also increase in safety of the system that incorporates the electrical machine. As the machines evolution reached a high tech level, the fault tolerance level also required to be increased.

The fault-tolerant machine has to have a special design. An optimum solution has to be found taking into account all the advantages and drawbacks of the changed machine structure. Inherently by increasing the machine's fault-tolerance its losses could be greater and its efficiency less than its usual counterpart [4], [5].

Thanks also to the improvements in the field of power electronics and to digital signal processing today intelligent solutions can be provided in designing a fault tolerant electrical drive system. The separate phase feeding and control of the machines allow an easier approach of the fault tolerant tasks and offer better results.

Permanent-magnet synchronous machines (PMSM) provide a viable alternative to ac induction machines in many variable-speed applications. Given the steady advancements in drive technology over the past 20 years (integrated ASIC, DSP, and power transistor technologies) the PMSM is experiencing new success in variable-speed applications.

The PMSM drives become widely used due to their high efficiency and power density. For example in vehicles PMSM drives can replace traditional mechanical actuators to achieve advantages such as higher efficiency and improved dynamical performance. It is apparent that certain functions such as electrically assisted steering and braking are of outermost importance and that their failure cannot be tolerated [6].

For electric drives used in propulsion applications faults can be critical, since an uncontrolled output torque may have an adverse impact on the vehicle stability, which ultimately can risk the passenger safety.

All these mentioned above have stimulated the researches in the field of fault-tolerant electrical machines and drives [7].

In the paper the power converter and the control system of a nine-phase fault-tolerant PMSM having a special construction will be studied. The topology of the machine is in patenting process.

The study was carried out upon the results of simulations. The transient regime simulation of the entire electrical drive system (the machine and its converter) was performed using the latest coupled simulation technique, the FLUX-to-Simulink link. This technology seems to be the most advanced tool for system designers, because it provides co-simulation capabilities for transient electromagnetic computations with a direct link to the finite element method (FEM) based model. It enables the users to account for drive and control parts within the device. The FLUX to SIMULINK Technology combines the abilities of MATLAB Simulink for drive and control and the power of FLUX for transient electromagnetic computations. Using this link it was taken advantage of the high precision machine analysis capabilities enabled by the FLUX 2D finite element method based numeric field computation program and easy-to-use, but also advanced Simulink/MATLAB environment.

II. THE POWER CONVERTERS IN STUDY

Initially for the 9-phased PMSM in discussion a special, 9-branches variant of the well-known H-bridge (full-bridge) converter (given in Fig. 1) was proposed.

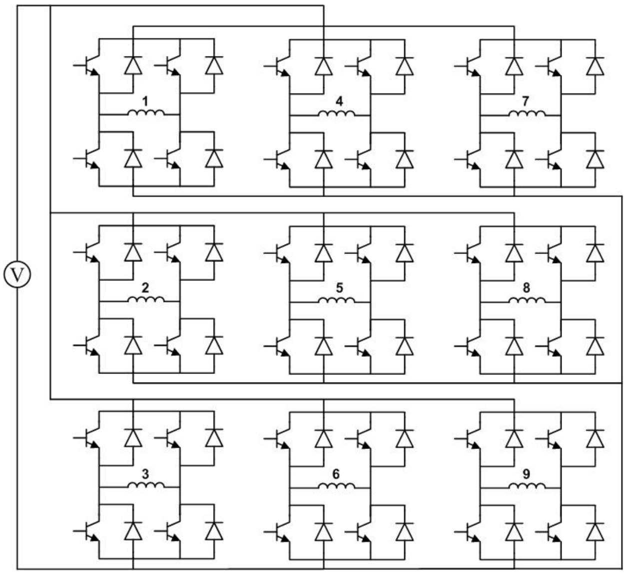


Figure 1. H-bridge power converter for a 9-phased PMSM

This topology has a quite complex one. As it can be seen 36 solid-state power switches are required. Beside this each branch needs separate control and protection circuit. For great currents and voltages, respectively for high chopping frequency the converter could be very expensive.

Discussing about fault-tolerance a fundamental danger of the full H-bridge topology should be mentioned here. A direct short circuit can occur if the top and bottom switches of the same branch are turned on at the same time. In normal conditions the top and bottom stages of a half of the H-bridge of a single branch are never on at the same time, unless a malfunctioning command is received from its control system. This can be avoided by monitoring the work of the control system.

Another problem, a short circuited power switch is more difficult to solve. The solution is the total isolation of the entire branch opening, and keeping permanently opened all the corresponding power switches.

This way the fault tolerance is ensured by the physical separation of the damaged branch [8]. Of course in this case the motor has to be fault-tolerant to be able to continue its work (even at lower torque and at higher torque ripples).

In a more critical case, when both top and bottom switches of a branch failed shorted, the above mentioned branch exclusion method does not have effect a disastrous event will occur whose magnitude will be set only by the acting speed of the fuse or circuit breaker [9].

In order of obtain high level of fault-tolerance for the 9-phase PMSM a special connection of its phases will be applied. In this special scheme the winding is divided in 9 phases, grouped 3 by 3. Y connections are created for each group of 3 windings. The 3 groups are connected to a common power supply. Obviously this winding connection needs a particular converter (see Fig. 2).

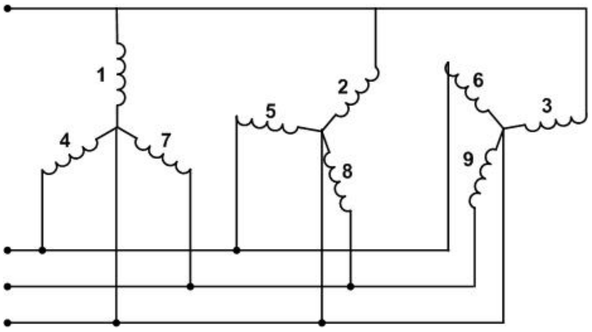


Figure 2. The star connection of the 3×3 phases in the PMSM

To improve the performance / cost ratio of the power converter the classical H-bridge scheme given in Fig. 1 is proposed to be changed by a more simple one.

The starting point was the standard three-phase voltage source inverter. To each of the three groups an extra inverter leg is added, as shown in Fig. 3 [10].

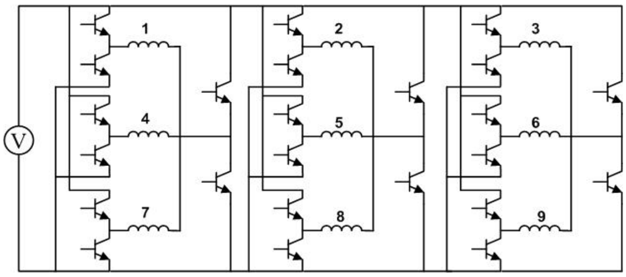


Figure 3. The proposed converter topology

This connection can be used because the PMSM in study has Y-connected winding groups (as shown in Fig. 2) [6].

If a winding fault occurs in the PMSM, the faulted phase is isolated by keeping open the corresponding two power switches.

The supplementary inverter leg will continue to drive the currents, assuring practically the normal current through the remained healthy phases. Since the additional inverter leg is connected to the neutral point of the PMSM, the neutral current caries the phase currents of the remaining phases:

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

It should be also mentioned that for a correct operation of the converter additional fault detection module has to be added, as well also a phase isolation logic which will command the power switches during faulty operation

III. THE COUPLED SIMULATION PROGRAM

The simulations were performed using the co-simulation technique, by coupling two simulation environments to work together.

The model of the PMSM and the electric circuits of the two power converters were built up in Flux 2D. The circuit of the initial power converter (given in Fig. 1) is shown in Fig. 4.

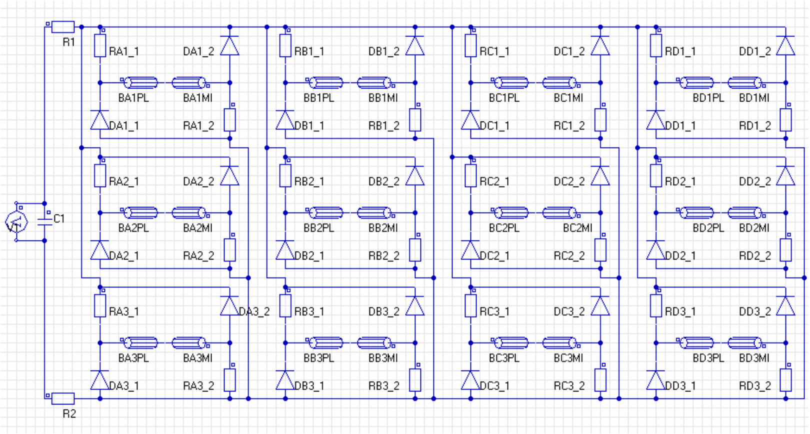


Figure 4. The circuit model of the first power converter
built up in Flux 2D

As it can be seen each phase of the machine is modelled by two coils, the ingoing and the outgoing ones. The diodes are for ensuring the flow of the inverse current.

The solid-state power switches are modelled in the circuit by resistors. The opening / closing of the switches are modelled simply by changing the resistance from 100 kΩ to 4 mΩ.

The command of the electrical circuit is accomplished using MATLAB-Simulink environment. The communication between Flux 2D and Simulink is solved using the Flux-to-Simulink coupling method, as it can be seen in Fig. 4 showing the main window of the Simulink model.

The command system generates the signals with reference values for the resistances for each branch.

The link between Simulink and Flux 2D is implemented by the *Coupling Flux2D* S-function type block. The input values of this Simulink block (practically the signals to be transferred to the field computation program) are the resistance values corresponding to each power switch.

The S-function block will receive the output signals after the field computation (the torque, the phase currents and the rotor position) and will transfer them to Simulink. Using these values the parameters of the next simulation step will computed.

This way the next step of simulation, and so on, will be computed step by step till the time limit is reached.

The control strategy was implemented in SIMULINK, the most widely used platform in dynamic simulations.

The main window of the Simulink program is given in Fig. 5.

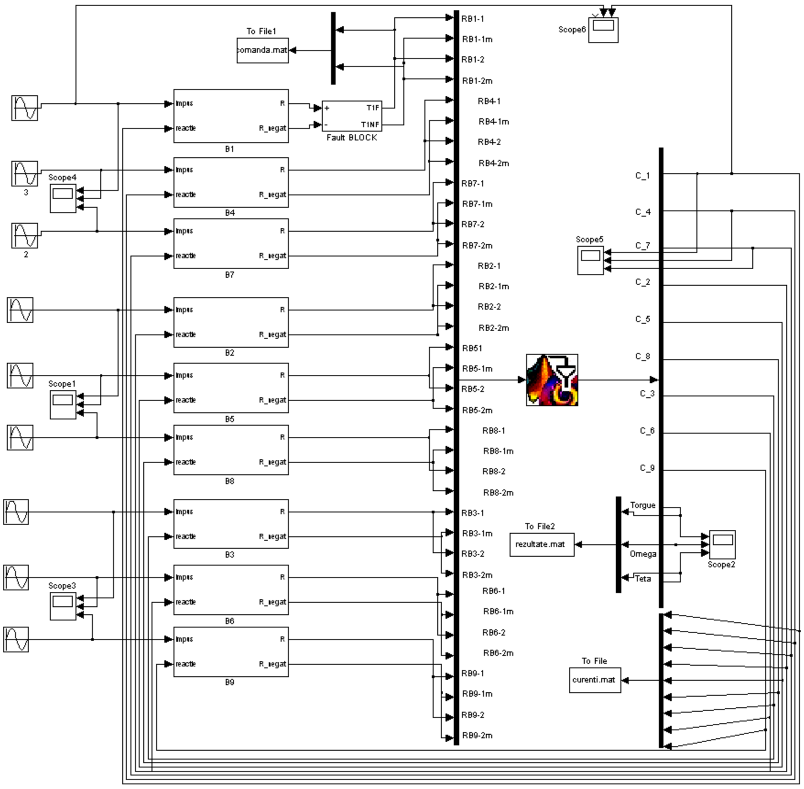


Figure 5. The main window of the Simulink program

For a better transparency of the program it is built up modularly at several levels. For exemplification the *Fault generator* subsystem is shown in Fig. 6.

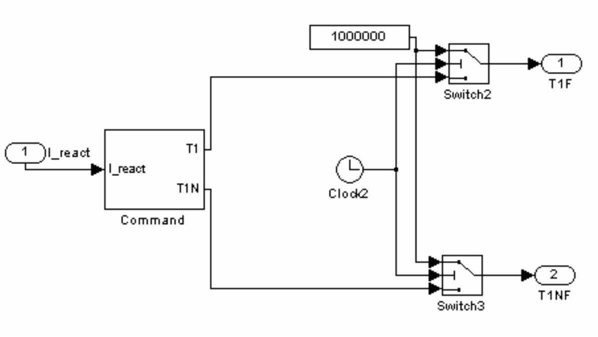


Figure 6. The *Fault generator* subsystem

The results are saved in files on disk, and can be plotted anytime using MATLAB, fully using the advantages of the advanced graphical possibilities of this program.

IV. RESULTS OF SIMULATION

The coupled simulation was performed at low time step in order to obtain accurate results. Hence the required simulation time should be very long. To reduce it an optimized mesh of the machine's model in Flux 2D was imposed. This way a compromise between the simulation time and the required computer memory, respectively the precision of the results was obtained.

As the computer memory is limited to its physical value, the mesh quality had to be set for a lower value in a way to do not reduce significantly the accuracy of the computations.

Four faulty cases had been studied using the previously presented coupled simulation program:

i.) One phase faulty, having open circuit (case 1)

ii.) Two phases faulty from different groups (case 2)

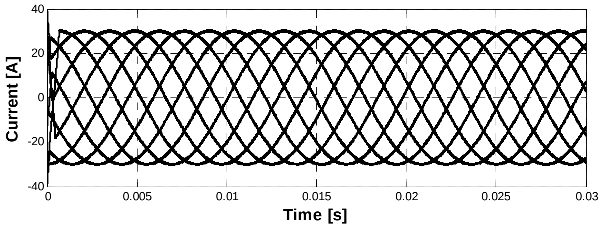
iii.) Three faulty phases from three different groups (case 3)

iv.) Two phases faulty from one group and 1-1 from two other groups (case 4).

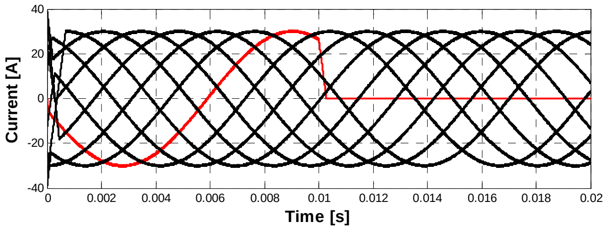
During the transient simulation the machine is started without any faults. The first fault is imposed at 0.01 s, the second one at 0.02 s. When more faults are simulated these are set to appear also at 0.01 s.

Next, in Fig. 7, the current waveforms obtained by simulation are given for the healthy machine, respectively for the four faulty cases mentioned above. With red line are plotted the currents of the faulty phases.

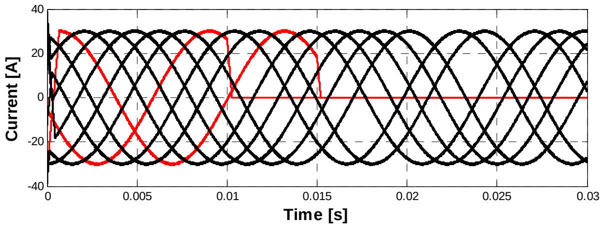
The startup of the machine is a short transient period. As it can be also observed the fall to nil of the current is not happening instantly due to the phase inductances of the phases.



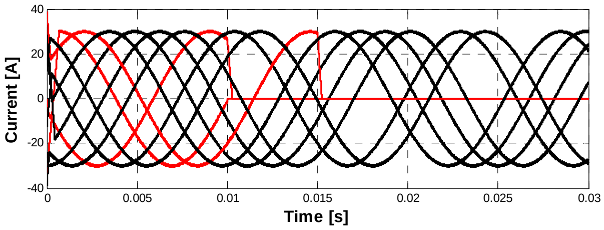
a) Healthy machine



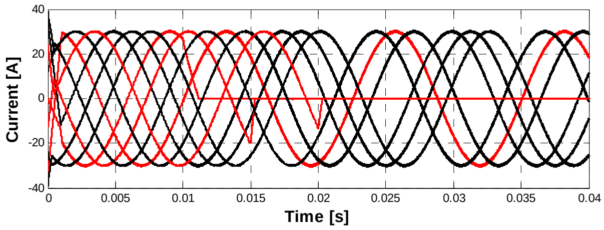
b) Faulty machine (case 1)



c) Faulty machine (case 2)



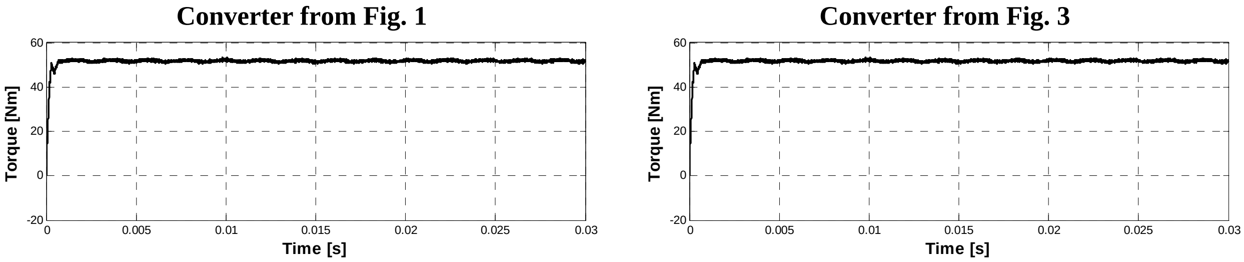
d) Faulty machine (case 3)



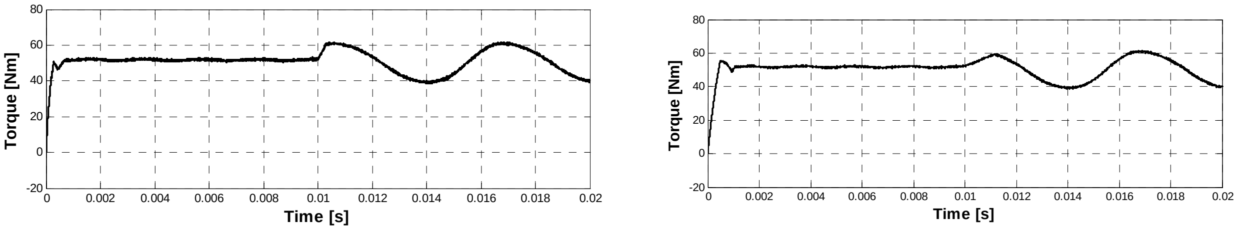
e) Faulty machine (case 4)

Figure 7. The current waveforms obtained by simulation

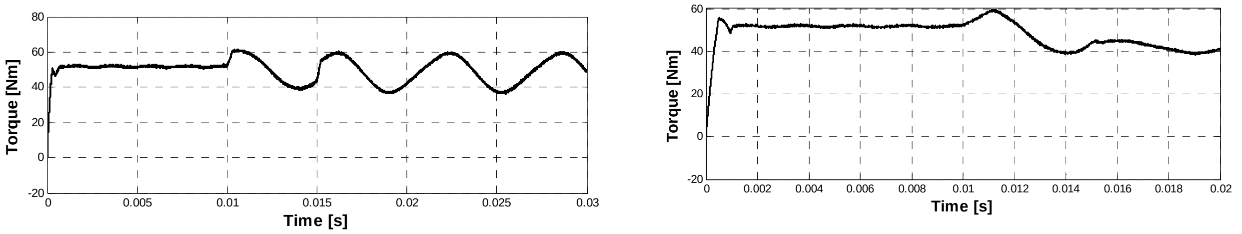
More decisive are the plots of the developed torques of the machine. In Fig. 8 the torques versus time plots are given for the two power converter topologies in discussion, respectively for the healthy motor and the motor having the four types of winding damages.



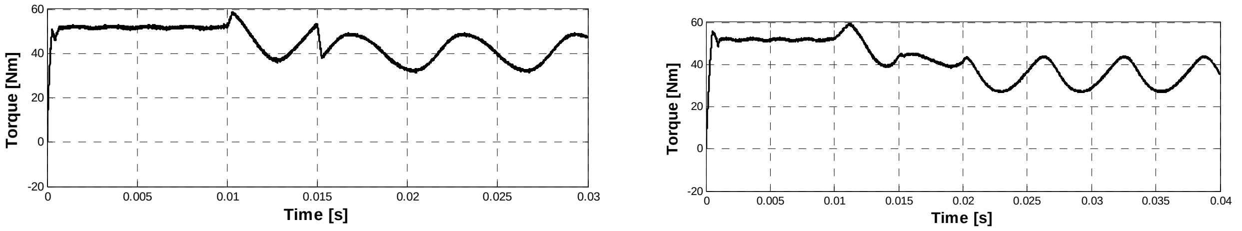
a) Healthy machine



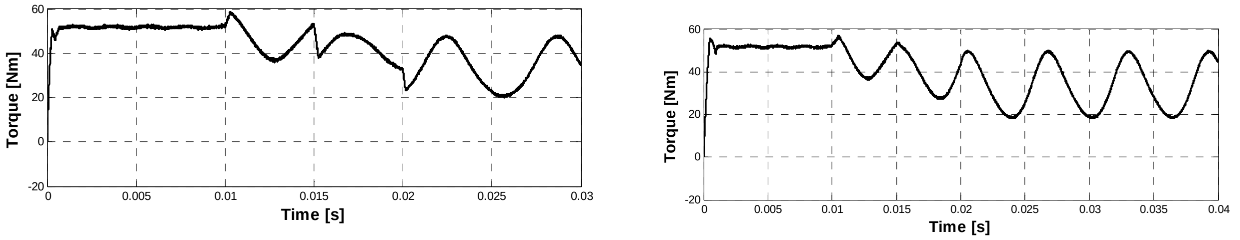
b) Faulty machine (case 1)



c) Faulty machine (case 2)



d) Faulty machine (case 3)



e) Faulty machine (case 4)

Figure 8. The torque waveforms obtained via simulation in the case of the two compared power converter topologies

As it can be seen from Fig. 8a in the case of healthy machine no significant difference can be observed in the torque waveforms of the machines fed from the two different converters. The machine can develop torque and continue its movement also when up to four of its nine phases (more than 44%) is destroyed! Of course as the number of faulty phases is increased the torque development capability of the machine is diminished. The magnitude of the torque is less, and in parallel the torque ripples are greater in the case of both power converters in study.

To emphasize the difference between the two compared converter topologies Table I was filled out with the minimum, maximum and mean value of the torques obtained via simulation for the cases of the two converters and five machine winding statuses taken into detailed study.

TABLE I.
THE MAIN CHARACTERISTICS OF THE TORQUES FOR ALL THE CASES TAKEN INTO ACCOUNT

	Studied cases	**Torques [Nm] and percentage of the rated torque**	
		Mean	**Ripple**
Converter from Fig. 1	Healthy case	51.9 (100%)	1.7 (3.28%)
	Faulty case 1	50.93 (98.13%)	22.3 (42.97%)
	Faulty case 2	49.99 (96.32%)	21.8 (42%)
	Faulty case 3	45.32 (87.32%)	17.2 (33.14%)
	Faulty case 4	44.24 (85.24%)	22.4 (43.16%)
Converter from Fig. 3	Faulty case 1	50.59 (96.9%)	22.2 (42.77%)
	Faulty case 2	48.02 (92.52%)	6.3 (12.14%)
	Faulty case 3	41.43 (79.83%)	16.2 (31.21%)
	Faulty case 4	39.98 (77.03%)	30.8 (59.34%)

When a single phase is damaged practically the torque development capability of the motor remains unchanged (over 98%), only the torque ripple is increased.

The two faulted phases cause a diminishing of 6% of the torque, and the three about 20%. Of course with the increase of the number of the damaged windings the torque ripple increases up to 30 Nm. But in the case of such machines the most important issue is to maintain the movement of the motor and to keep its torque developing capability as high as possible.

Comparing the torque characteristics of the two converter topologies taken in discussion it can be stated out, that there is not a significant difference between them. The initial construction variant, having 36 solid-state power switches, seems to be a little better than the other one from this point of view.

On the other hand the proposed converter topology has only 24 power switches, less by 12 than the other one. The decrease of the switches means not only cost reduction, but less converter losses and smaller housing.

The torque ripples can be reduced by optimizing the control of the converter: by recomputing of the phase delays, and setting them in accordance with the number of the remaining phases.

V. CONCLUSIONS

The study was focused on the comparison of two possible power converter topologies for a nine-phase fault-tolerant permanent magnet synchronous machine. The torque development capabilities of the two converters were compared upon the results obtained via transient simulation of the drive system.

The applied model, a coupled one, connecting two programs (FLUX 2D and SIMULINK) fitted excellent to the requirements of the proposed study. The computing power of FLUX 2D thus joined the facilities of Simulink in simply describing the different working regimes of the power electronic systems taken into study.

It was stated out that no significant difference exist in the performance of the machine fed from the two converters. The great difference consists in the relative simplicity of the proposed converter topology added to its reduced price and housing volume. A drawback of the proposed converter should be the necessity of reconfiguration of its control strategy in case of motor winding faults, and of course a required built-in diagnosis function.

Further researches will concern the fault-tolerance of the converter itself.

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