Study of a Nine-Phase Fault Tolerant Permanent Magnet Starter-Alternator

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***Abstract** – The paper presents a study on a nine-phase permanent magnet synchronous starter-alternator for automotive applications, analyzing different converter topologies, detailing the simulation programs and discussing the results in different operating conditions, from entire healthy machine to several faulted phases. The comparison between the two converter topologies controlling the multiphase machine highlights the increased fault tolerance, hence the reliability of such starter-alternator structures. Nevertheless, the article is within the area of interest of nowadays research in the field of automotive applications. Replacing two machines (the starter and the alternator) of a vehicle is the motivation for designing and studying starter-alternator structures.*

***Keywords:** permanent magnet synchronous machine, starter-alternator, fault tolerance.*

I. INTRODUCTION

The trend nowadays is to preserve energy as much as possible. In automotive applications, this is possible by making lighter vehicles and increasing the combustion engine's efficiency. To have a lighter vehicle reduced number of its assemblies is required. This motivates using only one electrical machine for both starter and alternator purposes, instead of two (one dc starter machine and another one claw-pole alternator).

In the paper a detailed study is presented regarding a nine-phase permanent magnet synchronous starter-alternator and two types of converters that are used for feeding it.

Thanks to the potential of dedicated software several numerical computations were employed in order to characterize the studied electrical machine through finite element method (FEM) by using the Flux 2D-To-Simulink coupling technology [1]. 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 [2]-[5]. All the simulation programs and the procedures will be detail in the present paper.

As the nine-phase permanent magnet starter alternator (PMSA) must be fault tolerant its reliability was studied imposing several fault conditions in order to observe the machine's capability regarding continuous operation despite faults.

II. THE POWER CONVERTERS IN STUDY

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

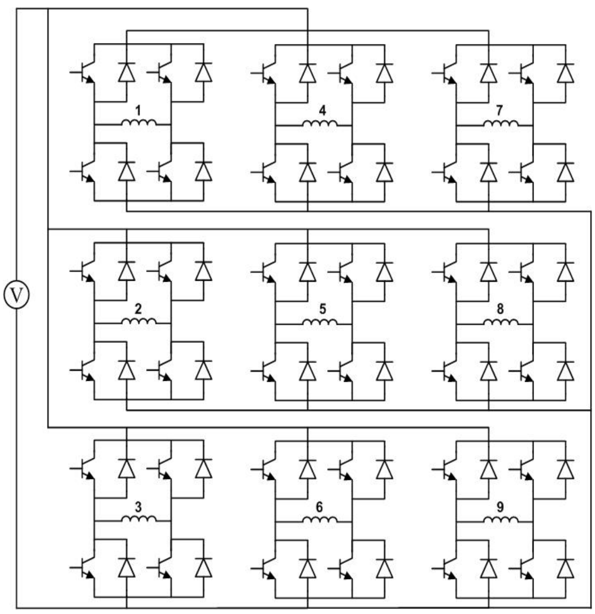

Fig. 1. H-bridge power converter for a 9-phased PMSA

This topology is a quite a 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 [6], [7].

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 nine-phase PMSA a special connection of its phases will be applied (see Fig. 2).

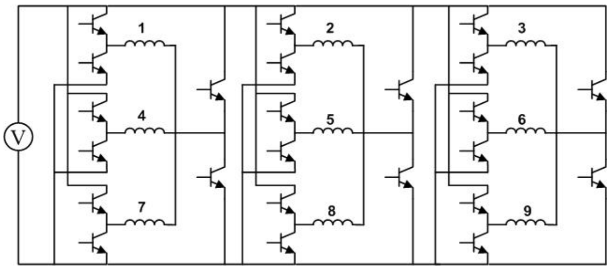

Fig. 2. The proposed converter topology

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 the special connection of the fault-tolerant PMSA needs a particular converter.

To improve the power converter's performance / cost ratio of the classical H-bridge scheme given in Fig. 1 is proposed to be changed by a simpler one. The modification regards decreasing the number of power switches / phase and using three additional "stand by" legs, as shown in Fig. 2 [10].

These additional legs are used only in case of faults. This connection can be applied because the PMSA in study has Y-connected winding groups [11]. The advantage of this structure is the lower price due to lower number of switches, but with the drawback of more complex control in case of fault occurrence.

If a winding fault occurs in the PMSA, 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 PMSA, the neutral current caries the phase currents of the remaining phases.

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 SIMULATION PROGRAM

It was stated out in [12] that no significant difference can be observed in the performance of the machine controlled by the two different converters. The most significant 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 the supplementary built-in diagnosis functions. Due to this, in our study the classical converter shown in Fig. 1 was implemented.

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

The model of the PMSA and the electric circuit of the power converter were built up in Flux 2D. The circuit model of the power converter is shown in Fig. 3.

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

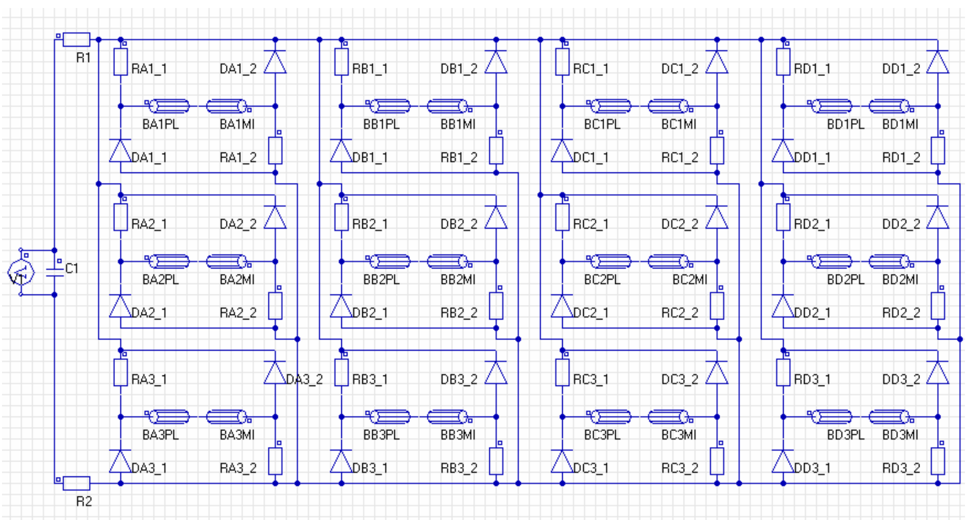

Fig. 3. The circuit model of the first power converter built up in Flux 2D

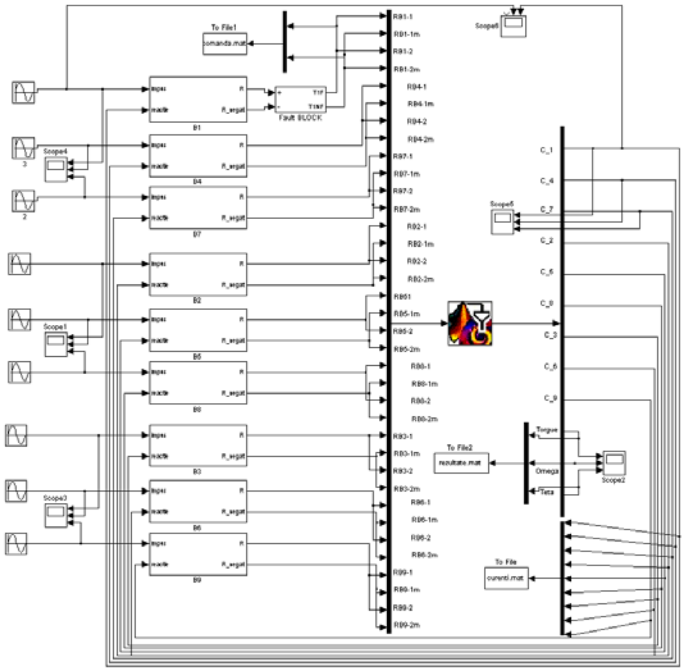

Fig. 4. The main window of the Simulink program

The two programs were connected together using the Flux-to-Simulink coupling technology.

The FEM model of the PMSA is embedded in the SIMULINK program via an S-type function called Coupling with Flux 2D. All the control signals computed in SIMULINK are multiplexed and enter this block. The main characteristics computed via Flux 2D (currents in all the phases, torque and speed) are returned to SIMULINK through another multiplexed signal line.

The main window of the Simulink program is given in Fig. 4.

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. 5.

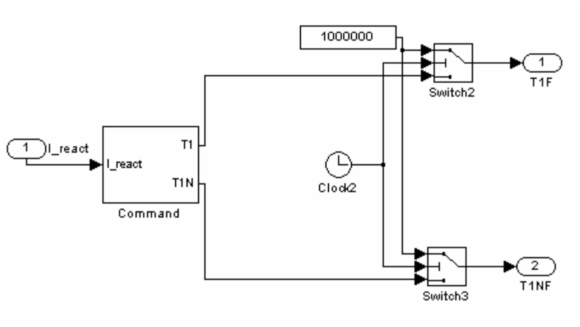

Fig. 5. The "*Fault generator*" subsystem

All the faults studied in this paper are regarded to the open circuit of phase winding. The fault is simulated by imposing OFF state to the power switches, by this, leaving without supply the considered faulted phase.

IV. THE RESULTS OF THE SIMULATIONS

The studied permanent magnet synchronous starter-alternator has 9 phases and 16 poles, as it can be seen in Fig. 6. The phases are compound of concentrated coils around each pole [13]. The rated power is 1.6 kW, to a rated voltage, in starter operation, of 48 Vcc, while the peak current is of 55 A. The currents in the machine are controlled using pulse width modulation (PWM) technique. As the machine operates both in motor and generator regime, it has two rated speeds: 300 r/min as motor and 1000 r/min as generator, respectively.

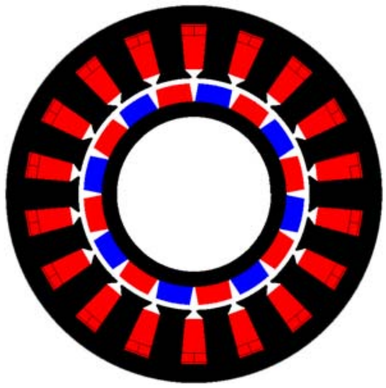

Fig. 6. The 9 phase PMSA for starter-generator application

The system of 9 currents is generated by a complex inverter having 9 H-type bridges, each one separately controlled. To increase the inverter's fault tolerance each bridge is connected in parallel with the main feed bars. The machine was analyzed by using finite element methods (FEM), setting up a model in Flux 2D software. The employed system model contains the converter and the rectifier, for both operating regimes. As detailed already the *Flux 2D-to-Simulink* technology was used for simulations.

The command of each phase is calculated in closed loop based on current regulation.

To prove the machine's ability to operate despite occurred faults different faulty conditions were studied both in motor and generator mode:

a) normal mode;
b) one phase open circuit;
c) two phase open circuit;
d) three phase open circuit;
e) four phase open circuit;
f) five phase open circuit.

In a first study only the motor regime is considered. In the second one the mixed operation is investigated, by passing from the motor to the generator regime (this being the machine's actual working regime). In the case of the second study a special attention will be paid to the generated voltage.

1) Fault Tolerant Motor Regime

The study of the motor regime in all the conditions was performed at 300 r/min. The condition for a starter is to develop a high quantity of torque, which will be able to move the combustion engine, till this can operate independently.

The currents and torque plots for the healthy machine are given in Fig. 7.

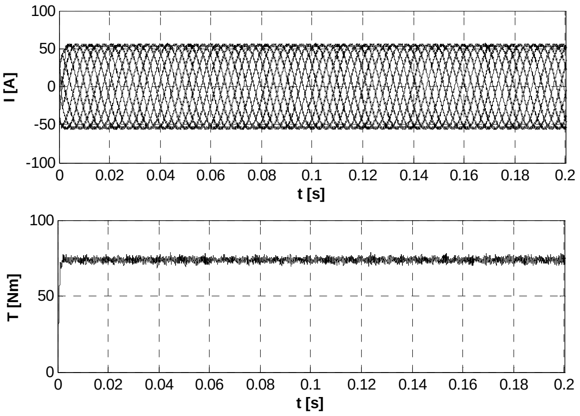

Fig. 7. Currents and torque characteristics for healthy starter operation

In healthy (normal) operation mode, the machine is able to develop a torque of 73 Nm. As it can be seen in Fig. 7, due to the high number of phases, the torque presents a quite stable characteristic, with very small ripples. On the other hand, as the fault's level rises (the number of faulted phases is increased) the developed torque is lower and lower and the ripples are increased consistently.

In one phase open circuit fault (Fig. 8.a) the machine is able to develop a torque very near to the rated one. In counterpart, the ripples which take place due to the missing currents' contribution are increased. In case of two and four missing phases (Fig. 8.b and 8.d) the torque ripples present the highest ripple value. The reason is the lack of phases to complete the rotating field of the rotor.

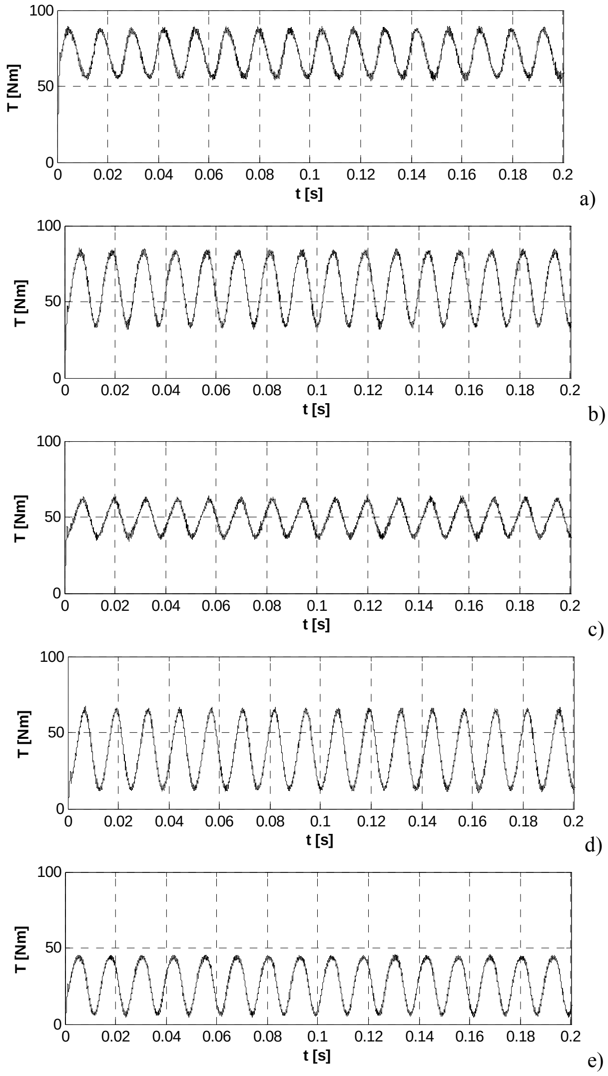

Fig. 8. The developed torque in faulty motor regime

Table I contains the mean values of the developed torque, their ratio against the healthy machine's torque and the torque ripples for all the conditions taken into study.

TABLE I
THE DEVELOPED TORQUE VALUES FOR ALL STUDIED CASES

CONDITION	TORQUE [Nm]	PERCENT [%]	RIPPLE [Nm]
NORMAL	73.7	100	7
ONE FAULTED PHASE	71.7	96.8	21
TWO FAULTED PHASES	60.2	81.3	42
THREE FAULTED PHASES	49.2	66.5	18
FOUR FAULTED PHASES	38.1	51.4	53
FIVE FAULTED PHASES	27.0	34.2	37

In the case of three and five open phases (Fig. 8.c and 8.e) the ripples are lower, but lower is rated developed torque too.

2) Fault Tolerant Starter-Alternator Regime

The changing from motor regime to alternator is accomplished by disconnecting the feed circuit of the machine and connecting the rectifier to obtain the generated voltage, measured on a 10 Ω resistance. Also

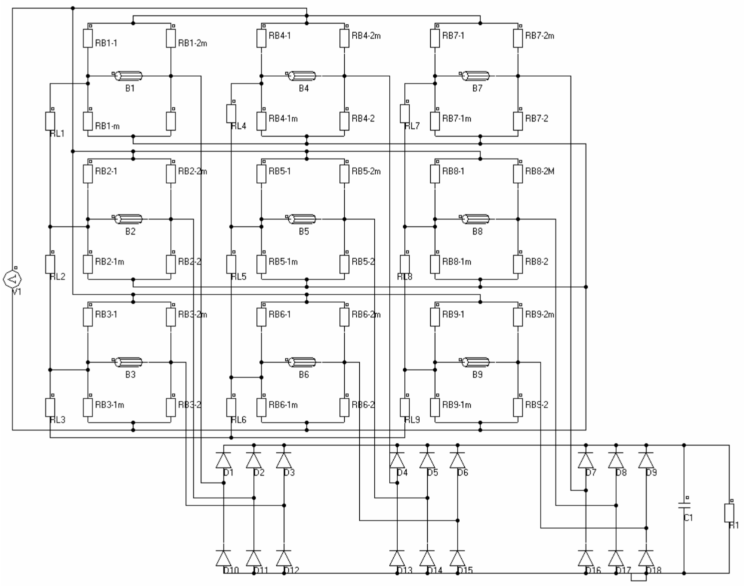

Fig. 9. Electrical circuit to simulate the motor and generator regimes

a capacity is connected in parallel with the rectifier's output to filter the voltage to a smooth wave. The speed is increased in alternator regime from 300 r/min to 1000 r/min, as now the rotor is rotated by the combustion engine. In Fig. 9 is presented the electric circuit of the power static converter which was used to simulate both operational regimes. Here, the switches were replaced by resistors [12]. Also, the faulted cases were modeled by means of resistors with large resistance value, placed on each phase.

The motor regime is simulated for 0.05 s long time, after which the feeding is decoupled, and the energy produced in generator regime is directed to the rectifier. The results of the simulation are given in Fig. 10. The phase currents that are seen in alternator regime are due to the load connected to the output.

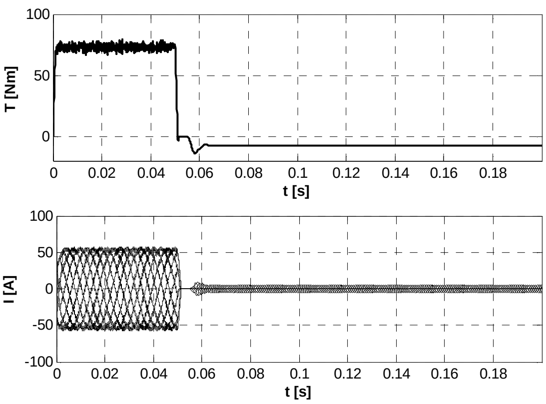

Fig. 10. Torque and current characteristics in motor and alternator regime of the studied PMSA

At a rated speed of 1000 r/min the machine is able to develop a voltage of 100 V. If the measurement resistance's value is decreased, the current will rise and the output voltage falls to about 80 V (see Fig. 11.) The output current's rated value is 8 A. All the simulations will be reported to these values as rated ones. It is important to specify that the current and voltage peaks are resulted from capacitor charging/discharging cycles.

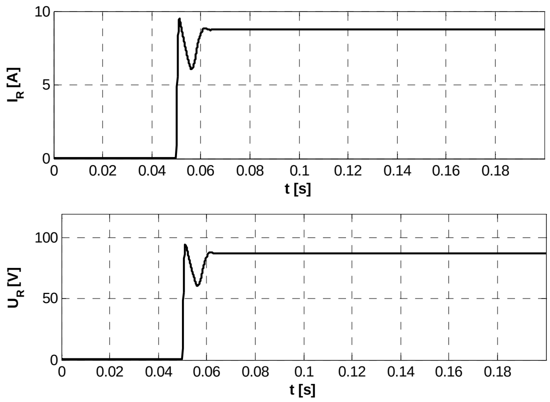

Fig. 11. The current and the voltage on the load resistance

In Fig. 12, the output characteristics of the torque, current and voltage are given for both regimes.

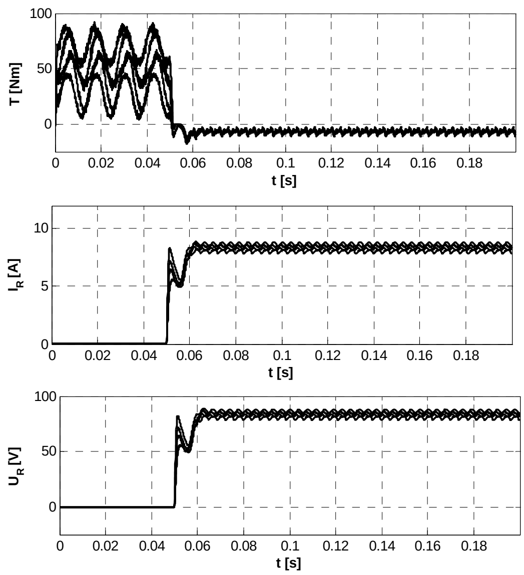

Fig. 12. The torque, current and the voltage developed by the alternator in all faulty regimes

As it can be seen, the alternator is able to generate the same voltage due to all types of considered faults. Due to parallel connection of the 3 rectifier groups and the filtering capacitor (Fig. 9), the output voltage, in all faulty regimes, is quite close to the health case, as well as the current, which can be supplied by the remaining operational phases. Hence, there is a "reserve" to supply the missing current of the faulty phases.

The command of the circuit is handled using floating resistance's values controlled by Simulink. In motor regime the detailed torque characteristics were presented in Fig. 8.

As it could be seen due to the generated currents a negative torque is developed (which is a characteristic of the alternator regime).

The worst case of study is the five phases open circuit fault that characterizes the lowest torque development in motor mode and the lowest charge slope for the capacitor, as the generated energy is now distributed on only four phases.

The faulted alternator regime has a very good behavior in terms of energy development. As seen in Fig. 12, both the voltage and the current present small ripple, quite close to the rated value. Moreover, the decrease of the mean value of the developed quantities in faulty regime are nearly negligible, hence the fault's influence in alternator regime are just in manner of small voltage, hence current ripples.

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 operated as starter alternator for automotive applications.

The behavior in these regimes was detailed regarding the machine's operation in healthy and faulted conditions. Also two types of power converters are proposed to be studied. These were already analyzed in [12]. Hence, only describing both and using the classical H-bridge power converter for the present study was considered to be the best approach. 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 can be seen that the nine-phase PMSA operates in motor regime developing a low noise torque. Imposing several open circuit faults, it was proved that the machine is able to handle continuous operation developing in each case a significant torque. The same study conditions were applied in starter-alternator regime. An important conclusion is the capability of the machine to develop nearly the same emf in all faulty cases as it does in healthy condition, as it can be seen in Fig. 12.

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