Study on the Fault-Tolerance Concept of the Five-Phase Permanent Magnet Synchronous Generator

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***Abstract*—In this paper an investigation on the fault tolerance capability of the five-phase permanent magnet synchronous generator is presented. The electric machine, which has lap stator winding and surface permanent magnets, has been designed for islanded-use purposes. The study takes into consideration the open-circuit type faults. It was analyzed the operation under healthy, one-phase open-circuited and two-phase open-circuited (adjacent and non-adjacent) conditions respectively. The results derive from FEM-based simulations and experimental tests.**

***Index Terms*—fault-tolerance, FEM simulation, five-phase PMSG, open-circuit fault, multiphase generator.**

I. Introduction

None the less that multiphase machines have been reported as electric drives solution before 1970s, the true development in this area became alive in the last decade of the past century. As generally stated [1], the multiphase machines have more than three phases and probably that is why they waited for better times to come to the fore. Since now the vast majority of electric drives involve the presence of inverters, the difference in phase number between electric machine and grid does not represent anymore an impediment. Consequently, it is not a surprise that more and more the multiphase machines take the place of their three-phase counterparts. However, the first applications of the multiphase motors addressed to ship propulsion, electric traction and hybrid and electric vehicles and aviation for a novel “more-electric” aircraft concept [1-10]. Then they fitted into wind-based electricity generation [11], [12] and marine current turbine applications [13]. But generally, due to some important advantages, which will be mentioned later on, the multiphase machines cover the high power and safety-critical applications.

As regards the number of phases, mainly the five- and six-phase machines are more frequently used. However, nine, 12 and 15 phases are solutions that can be found on the market for particular applications, as well [8]. Since this paper addresses to the five-phase machine, henceforth all the remarks concerning multiphase machine refers particularly to this number of phases.

There are several major advantages that put the five-phase machine in vantage point in comparison to the three-phase counterpart. First of all and of great importance is the higher torque density [1-3], [5-7], [13], which is expectable due to the higher number of phases. Then, the torque pulsations and the magnitude of the torque ripple are reduced [1-3], [6], [7], [13-16]. There is a decrease of the stator copper loss [2], [3], which in case of the five-phase machine goes up to 5.6% [8]. The electric drives with inverter profit by smaller rating per leg. In other words, there is a derating in power of electronic switching elements [1], [3], [4], [6-8], [13], [14]. The magnetic noise is reduced, as well [8], [11], [17]. The content in high order spatial harmonics is also smaller [8]. And finally, but a key point for certain applications is the fault-tolerant capability, which represents the ability to operate with minimal derating in performance under faulty conditions [2]. The maximum number of phases out of action is *m*-3, where *m* is the total phase number. According to this assertion, the five-phase machine is capable to operate even with three phases only, which obviously make this machine as a solid candidate for safety-critical applications. Moreover, the operation under faulty condition can be kept within admissible limits from thermal point of view, as well [4].

A significant number of research reports have been published concerning various aspects of five-phase machines as design [2], [3], [5-7], [10-12], [16-20], mathematical model [1], [9], [13], [18], [21], [23], performance and operation under healthy and faulty conditions, frequently in a comparative way to three-phase machine [3], [13], [15], [22-25]. Our contribution in this paper is a dual study (FEM simulation and experimental tests) concerning the fault-tolerant behavior of a five-phase permanent magnet synchronous generator, which has been designed and built for islanded-type operation (wind-based driving). It was taken into discussion the operation under healthy, one open-circuited phase and two open-circuited phases, respectively. Moreover, for two faulty phases was considered their adjacency or non-adjacency position since there is a significant difference in behavior.

II. Considerations on Machine Topology

When in question is the study of a five-phase electric drive, there are two major elements that has to be taken into discussion: the electric machine and the electronic “interface” (whose most complex topology consists of five-phase rectifier, D.C. link and three-phase inverter). The aim of this paper is to study the fault-tolerant concept taking into consideration only the electric machine.

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The main structural elements that represent key points in study and optimization of multiphase machines are the stator winding (together with the structure of magnetic circuits in terms of slot number) and the rotor excitation system.

As concerns stator winding, generally two solutions are taken into account. The first refers to the "classic" distributed lap winding [6], [17-19], which brings advantages in terms of content in space harmonics [9]. On the contrary, other authors prove that more advantageous is the concentrated winding around the teeth [2-5], which generally implies fractional number of slots per pole per phase. As a matter of fact, this last structure involves a rigorous matching of stator teeth number and rotor pole number for the reduction of torque pulsations [2], [3], [16], [26] and elimination of low order harmonics [11], but also for quasi-total decoupling of the phases [11]. Modular structures with salient stator poles [24] are also used for achievement of high power density. As regards the excitation system, both electromagnetic type [18] for high power units and permanent magnets are used. The permanent magnets can be placed on the surface of the rotor [3], [5], [11], [12], [19-21], [24] or inside the rotor body [2], [10], [16], [25], [26]. A lot of research work focuses on permanent magnets looking for small cogging torque and less torque ripple. The shape of the permanent magnets is also discussed in order to obtain close-to-sinusoidal back emf [20], [27], [28].

The structure of the machine proposed for analysis in this paper has permanent magnet excitation and distributed lap winding. The main electrical and geometrical parameters are presented in Table I.

Some structural details have to be revealed, as well. Each phase of the stator winding has four individual coils. They are series-connected and fill distinct slots. For example, the coils of phase AX are hosted by the slots 1-6, 2-7, 11-16 and 12-17. This is a particular arrangement (Fig. 1) where coil sides that belong to distinct phases are placed in the same slot and determine an important improvement both of the shape of the air-gap flux density wave and the induced voltages. Moreover, for the same purpose, the machine has skewed stator slots with an angle of 18º. The permanent magnets are NeFeB-type and are placed on the surface of the rotor (Fig. 2) covering an angle of 70º, which represents about 78% of polar pitch (more than 80% leads to an increase of the leakage flux and the magnets loose in efficiency [19]). Fig. 3 shows the experimental model with dismantled rotor.

TABLE I. ELECTRICAL AND GEOMETRICAL PARAMETERS

Parameter	Value
Rated power	1.5kVA
Rated phase voltage – Y connection	220 V
Rated current (rectified value)	3.25 A
Number of poles	4
Axial length of the magnetic circuit	75 mm
Outer stator diameter	180 mm
Inner stator diameter	100 mm
Air-gap width	0.3 mm
Number of stator slots	20
Number of slots per pole and phase	1
Pitch winding	5 slots
Number of turns per slot	180
Permanent magnet properties - remanent flux density, Br - coercivity, Hc - volume per unit - magnet width - radial angle of the magnets	 1,1 T 721 kA/m 13.2 cm^3 3 mm 70º
Air-gap width	3 mm

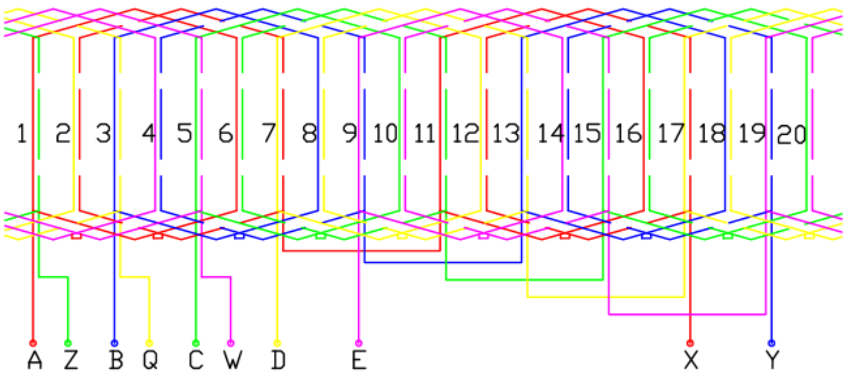


Figure 1. Distributed five-phase stator lap winding

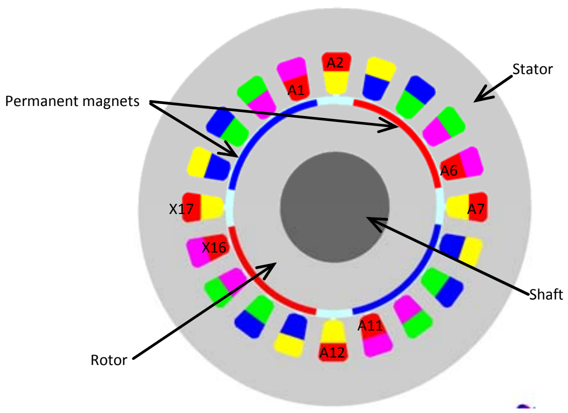


Figure 2. 2D view of machine structure

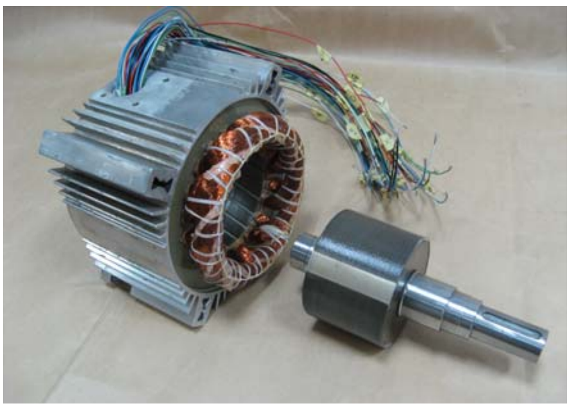


Figure 3. Five-phase PMSG experimental model

III. Evaluation by Finite Element Analysis

The simulation under healthy and faulty conditions has been performed by means of software package based on finite element method and produced by CEDRAT. This is a method and a procedure as well, which turned out to be a very useful tool in the study of electric machines since it can provide pieces of information about magnetic quantities, above all, that usually hardly can be established by experimental tests. It is about, for example, of the flux density values across the entire magnetic circuit or the actual air-gap flux density wave.

Due to the peculiarity of the stator magnetic circuit, we had to use a special module dedicated to skewed slots (Flux Skewed). This module allows a partition of the studied object in slices along the longitudinal axis and each slice is shifted with a certain angle to the reference position. In this way, from the first to the last slice there is a skew angle similar to the real one. The number of slices is set by the user in concordance to the length and expected accuracy. Basically, the software analyses distinctly each slice as a separate problem but the results reflects the wholly machine. The length of our generator required, for a proper analysis, six slices.

As regards the simulation itself, it was necessary a transient-type analysis, which involves time-dependent characteristics. It has also to be mentioned that this simulation implies coupling with the electric circuit, operation at constant speed but omission of movement equation (which is not needful in this situation).

The fault tolerant concept takes into consideration the operation of electric machines in absence of one or more phases. It can be either short-circuit or open-circuit causes. The short-circuit is quite difficult to be simulated since it can be turn-to-turn or phase-to-phase fact. Moreover, depending on the nature of short-circuit, significant changes in parameter values take place. As consequence, our simulation study took into consideration the open-circuit fault. There are four distinct situations:

- healthy machine – denoted henceforth 5ph,
- one open-circuited phase – denoted 4ph,
- two adjacent open-circuited phases – denoted 3ph-a,
- two non-adjacent open-circuited phases – denoted 3ph-na.

Fig. 4 presents the flux density color maps corresponding to nominal under-load operation (3.25 A). Above all, it has to be noticed that the values of the flux density keep up to the admissible values for all cases. However, the highest rising of the flux density value corresponds to the situation when two adjacent phases are open-circuited (Fig. 4c). In addition to the evaluation of the magnetic quantities, Fig. 5 shows the air-gap flux density waves. It can be noticed the influence of the skewed stator slots since the usual drops in amplitude corresponding to slot-openings are significantly reduced. The Fourier analysis of these curves, which gives the content in high order harmonics, is summarized in Table II for the first three harmonics of each reference system.

The most used mathematical model that describes multiphase machine (including the three-phase one) is the so-called *d-q-x-y-0* model. The *d-q* components are responsible for the producing of the torque while the *x-y* components (which do not exists in a three-phase machine and are decoupled from *d-q* components and rotor circuit) add only extra losses in the machine [1].

TABLE II. AMPLITUDE OF AIR-GAP FLUX DENSITY HARMONICS – NOMINAL OPERATION

Rank	5ph	4ph	3ph-a	3ph-na
H1	0.755 T	0.85 T	0.918 T	0.84 T
-H9	0.06 T	0.1 T	0.1 T	0.1 T
H11	0.042 T	0.06 T	0.053 T	0.06 T
H3	0.19 T	0.175 T	0.176 T	0.175 T
H7	0.053 T	0.11 T	0.1 T	0.105 T
H13	0.01T	0.018 T	0.056 T	0.055 T

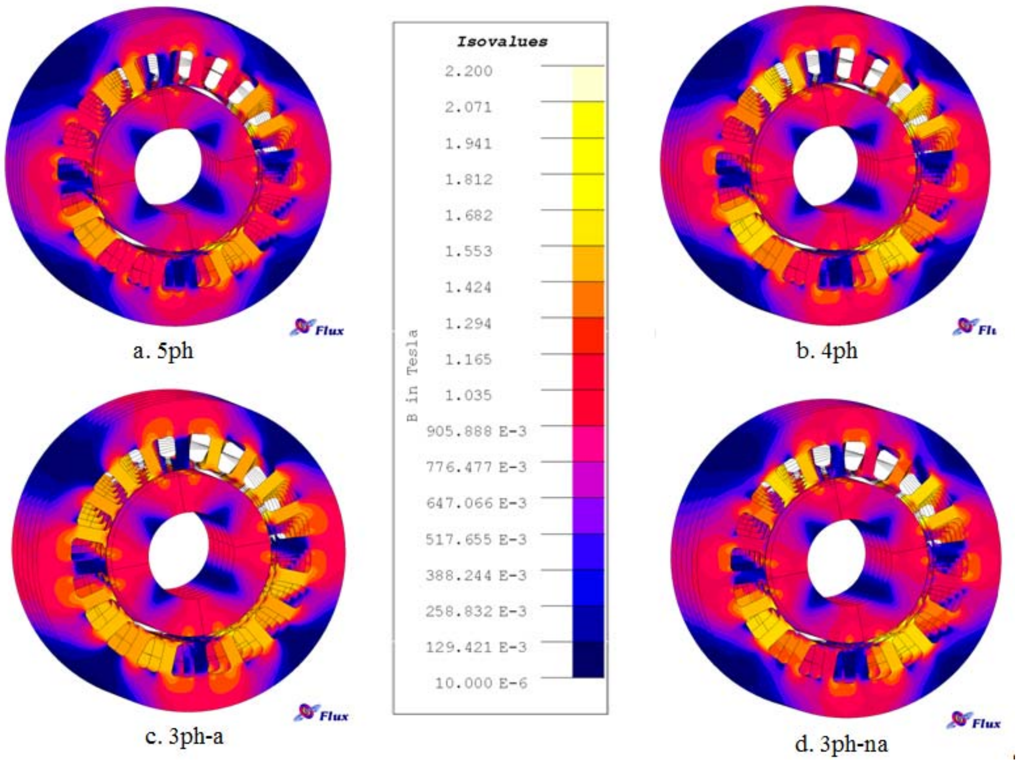


Figure 4. Flux density color maps – nominal operation

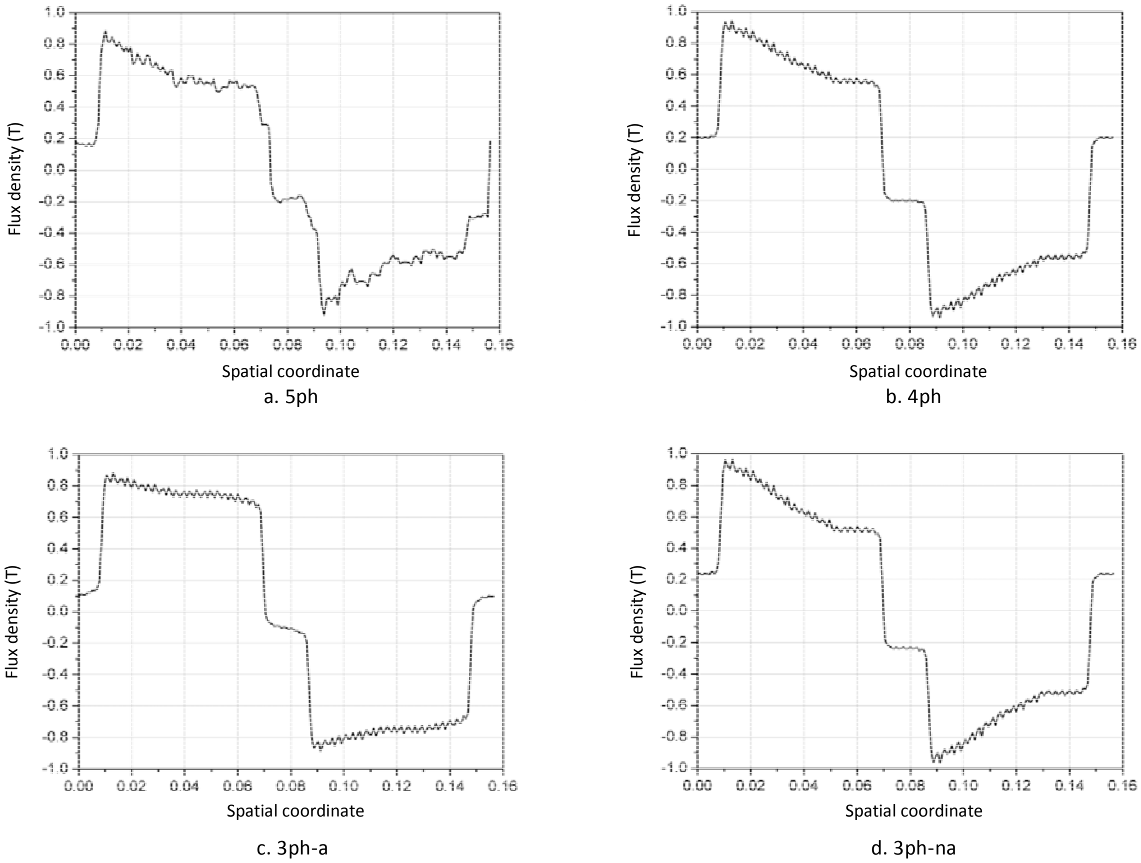


Figure 5. Air-gap flux density wave – nominal operation

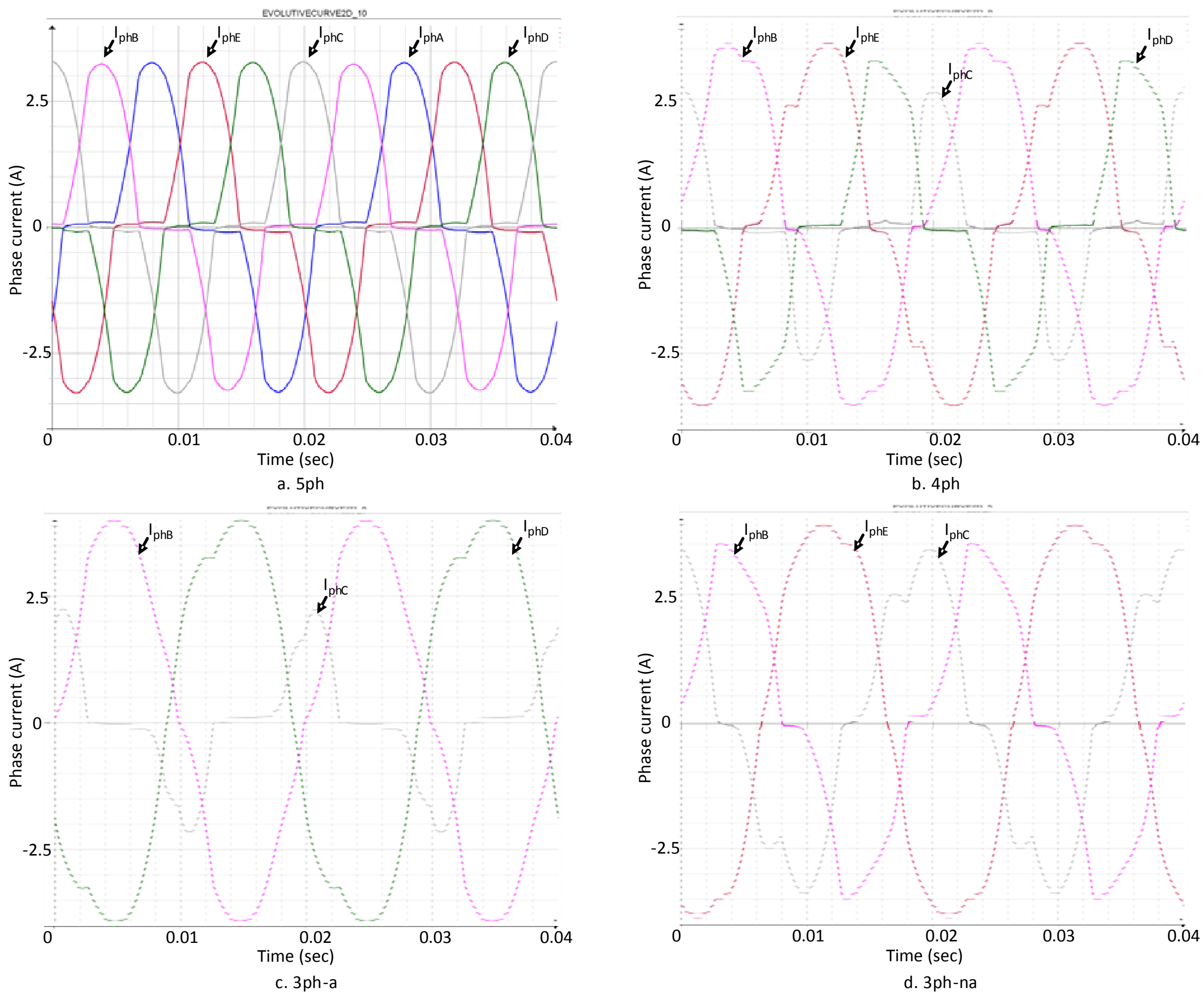


Figure 6. Phase current variation – nominal operation (simulation)

For the five-phase machine the harmonic rank is given by the following expressions ($n = 0,1,2,3\ldots$):

$10n \pm 1$ for d-q components,

$10n \pm 3$ for x-y components,

$10n \pm 5$ zero sequence components.

In other words, H1, -H9 and H11 produce torque components while H3, H7 and H13 produce only additional losses (Table II). It is worth to make two remarks.

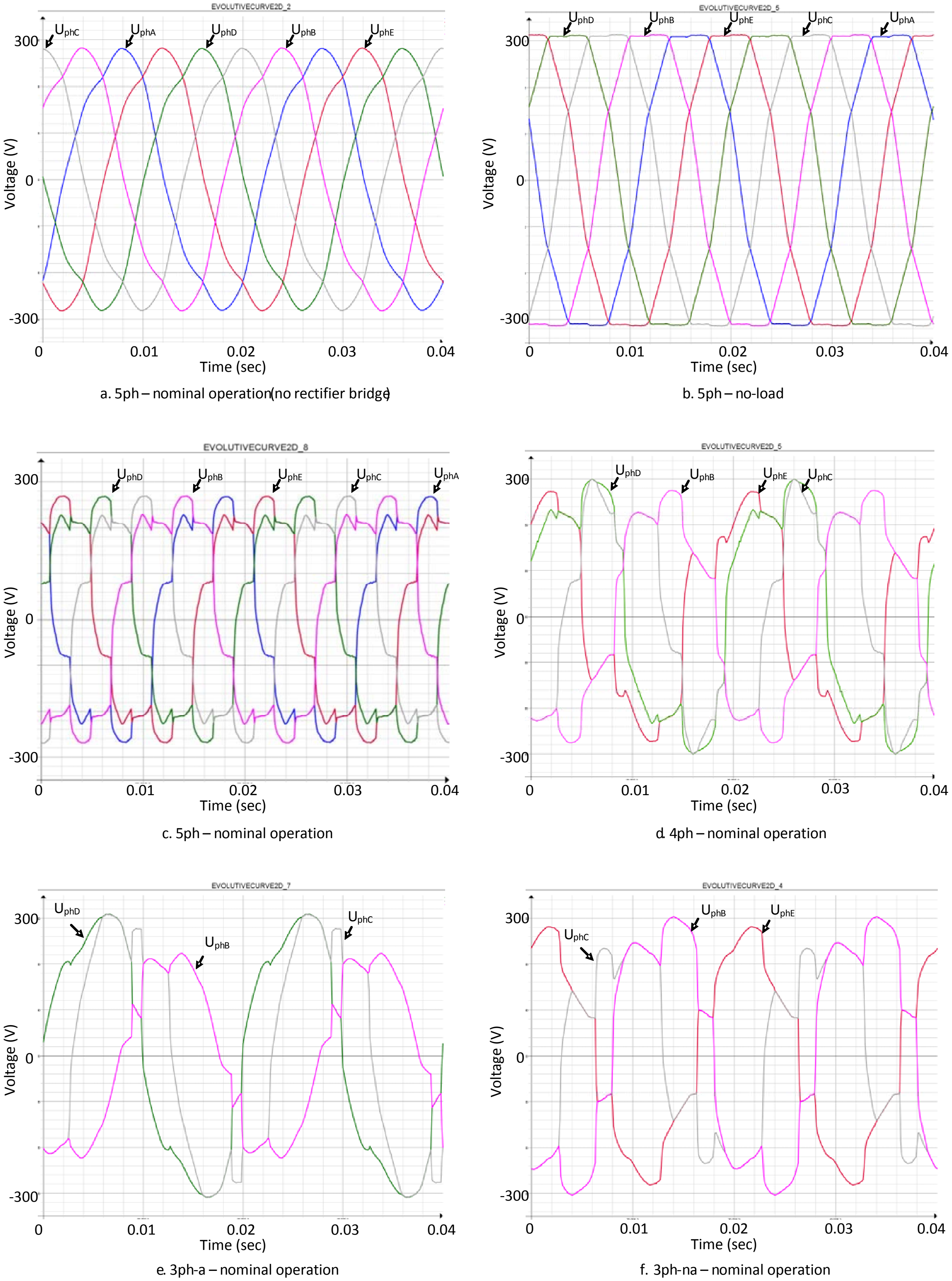


Figure 7. Phase voltage variation (simulation)

First of all, the amplitude of the fundamental produced by the system with two adjacent open-circuited phases is the highest. This is somehow strange but the explanation derives from the behavior of the phase currents (Fig. 6) where the maximum increase of the current values corresponds to the mentioned faulty operation.

Then there is a great similarity of the results obtained for 4ph and 3ph-na cases. Practically, there is a similar operation (see also the flux density color maps, Fig. 4b and d) no-matter one or two non-adjacent phases are open circuited.

Fig. 6 and Fig. 7 present the time variation of the phase currents and voltages and put in view the distortion of the curves with the fault degree. For example, no rectifier bridge (Fig. 7a) gives quasi-sinusoidal voltages. The presence of rectifier bridge (Fig.7b) leads to a flattening of the shapes and then a distortion (even for healthy operation, Fig.7c), which becomes more significant with the fault degree.

Since the presented generator is meant to operate with a rectifier bridge, of great importance is the output rectified voltage, Fig. 8.

Considering as reference the rectified healthy voltage, the absence of one or two phases leads to an increase of the pulsation amplitude.

The most inexpedient operation corresponds to 3ph-a when there is a huge ripple factor of 51% (the healthy machine has a ripple factor of 3.3%). One can see again the similarity between 4ph and 3ph-na.

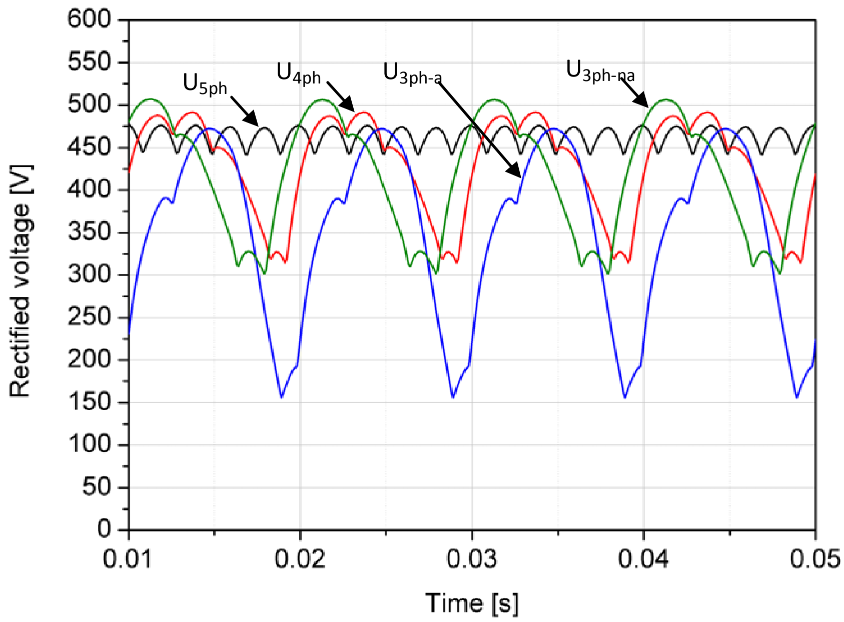


Figure 8. Rectified voltage (simulation)

IV. Experimental Results

The proposed PMSG generator, which has been primarily designed and then simulated, was physically built (Fig.3) in order to be evaluated by experiment. It was used an experimental set-up, which included an acquisition card coupled with PC for a more accurate data processing.

The most important results, that are the output voltages, are presented in Fig. 9.

There is a great similarity between simulation and experiment starting with the type of variation of the voltages and then with the amplitude values and type of distortion. For example, the ripple factor of the rectified voltage for healthy machine is 2.7% and for the worst situation (3ph-a) is 45%.

Definitely one cannot expect sinusoidal voltages neither for no-load or so much the less for under-load operation. On one hand, it is a regular construction with surface permanent magnets of customary shape and, on the other hand, the stator winding could be improved in terms of number of slots (including number of slots per pole per phase) and a more proper matching with the pole number.

V. Conclusion

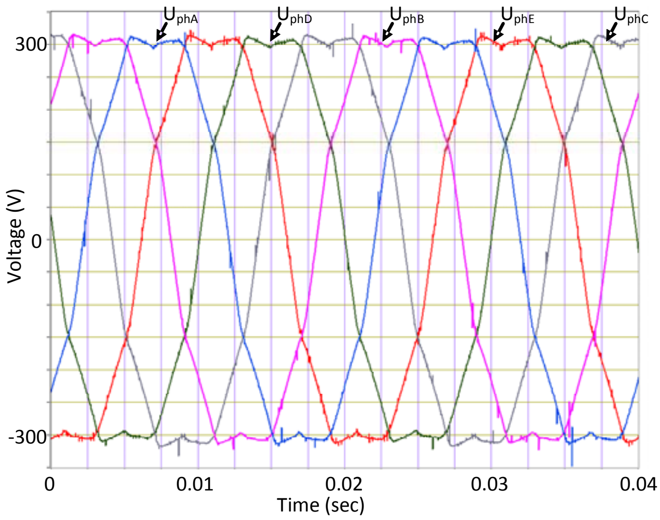
In this paper a dual analysis (simulation and experiment) of a five-phase permanent magnet synchronous generator has been performed. The main goal was to evaluate the fault tolerant concept. For this purpose the study took into account the operation with five (healthy machine), four and three (adjacent and non-adjacent) phases. The fault of the phases consisted in open circuit. The results allow some interesting conclusions to be formulated:

- the operation of the generator is possible under all the faulty conditions without any immediacy in stopping it. Neither the values of the phase currents nor the thermal regime require the stop of the machine. This plus makes the machine as a proper solution for safety-critical applications;

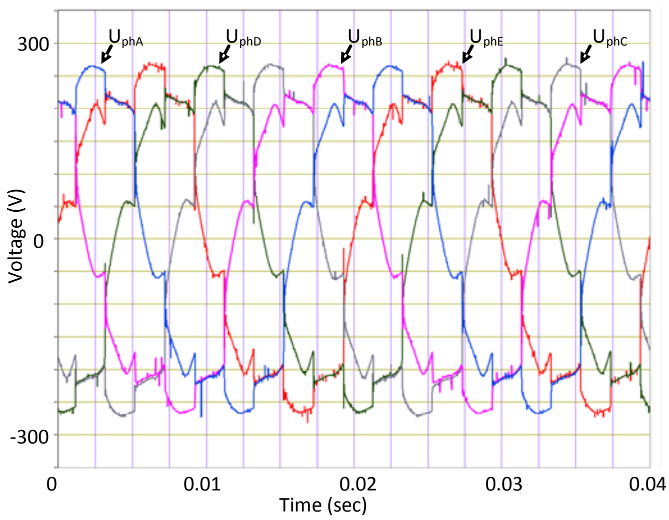
- the faulty operation under the worst parameters take place with two-adjacent open-circuited phases;

- the operation with one open-circuited phase or two non-adjacent open-circuited phases is rather similar. The values of the flux density across the magnetic circuit or in the air-gap, the amplitude and shape of the phase voltages and the ripple of the rectified voltage are all very close;

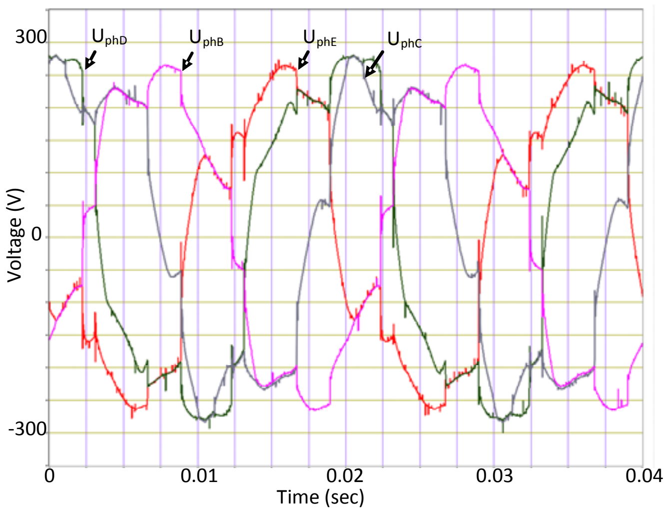
- the output voltages get distorted with the load increase.



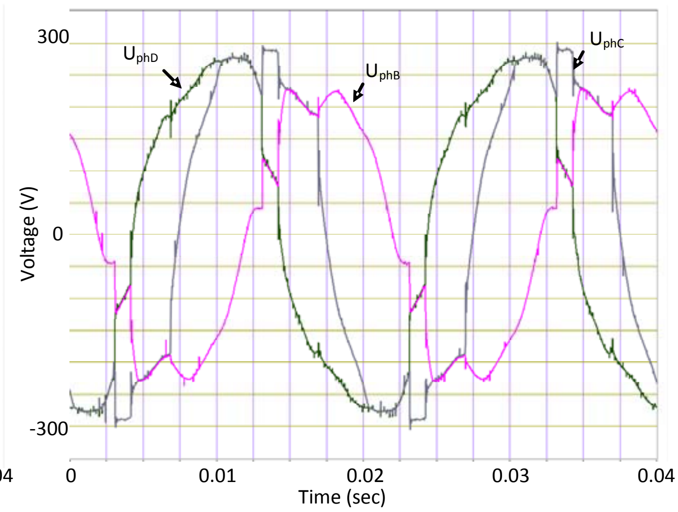
a. 5ph – no-load



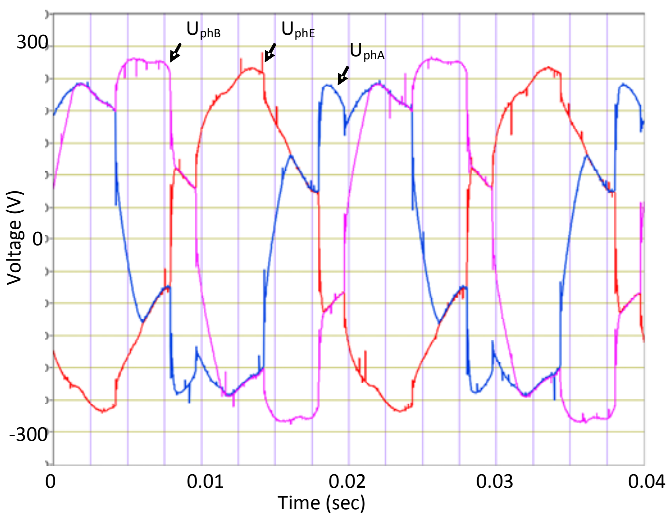
b. 5ph – nominal operation



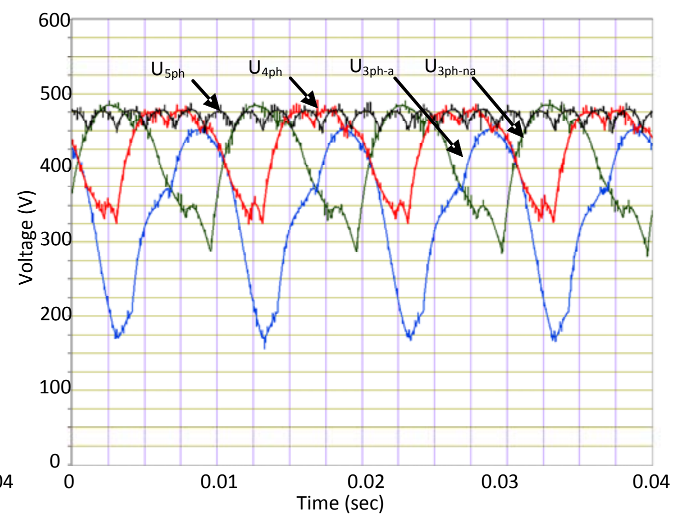
c. 4ph – nominal operation



d. 3ph-a – nominal operation



e. 3ph-na – nominal operation



f. Rectified voltage – nominal operation

Figure 9. Phase voltage variation (experimental)

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