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Fault detection of a Five-Phase Permanent-Magnet Machine

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I. ABSTRACT

The paper focuses on the fault detection of a five-phase Permanent-Magnet (PM) machine. This machine has been designed for fault tolerant applications, and it is characterised by a mutual inductance equal to zero and a high self inductance, with the purpose to limit the short circuit current.

The effects of a limited number of short-circuited turns were investigated by theoretical and Finite Element (FE) analysis, and then a procedure for fault detection has been proposed, focusing on the severity of the fault (i.e. the number of short-circuited turns and the related current).

II. INTRODUCTION

The employment of multiphase machines (phase number greater than 3) fed by multiphase converters can introduce an improvement in the area of medium to high power sized drives as they are characterised by a better efficiency, torque/weight and torque/volume ratio compared to three phase machines. With same voltage and power, the increase of the number of phases implies a reduction in the current per phase, thus the thermal stress on the power semiconductors is inversely proportional to the number of phases. Hence high voltages IGBT can be used with higher switching frequency without parallelisation techniques.

Fault-tolerant capability of electrical drives is an essential feature in applications such as automotive [1], aeronautic [2], and many others, where continuous operation is a mandatory option. Although less stringent, fault tolerance is a positive feature also in the industrial environment, due to the related productivity enhancement. A five-phase PM machine exhibits a high fault-tolerant capability [3], as it can be designed to reduce the fault occurrence as well as to operate indefinitely in the presence of faults [4].

The degrees of freedom of a multiphase machine can be used to enhance the reliability of the drive, provided that electrical and mechanical fault diagnosis techniques are available. This redundancy might be used for diagnostic purposes. In fact a multiphase machine can continue to operate in case of a phase loss, with a suitable change of power supply, resulting in a reduced torque, but keeping control capabilities.

Diagnosis techniques for three phase electric machine have been extensively studied in the last years with the purpose of detecting the fault at an early state and of compensating its negative effects during scheduled maintenance in order to avoid unnecessary costs [5], [6]. A fault causes asymmetry in the machine, i.e. it produces an electrical signal signature that can be detected by non-invasive techniques based on time domain analysis, frequency analysis and time-frequency analysis. The most common technique, usually referred to as Motor Current Signature Analysis (MCSA), is based on the analysis of the harmonic spectrum of the stator current. It contains information (signature) univocally related to the presence of electrical and mechanical faults [7] and permit a quantitative analysis of faults [8].

The faults of multiphase machines are similar to those of three-phase machines, they can be grossly classified into mechanical (bearing failure), or electrical. The main electrical failures of a multiphase drive are

- Phase windings short-circuit
- Power switch open-circuit fault
- Phase open-circuit fault

Some scientific papers have investigated the effects of faults in multiphase inverter, the methods of bypassing the faulted components and the compensation techniques to increase the reliability of the drive [9], [10], [11], [12]. However a general approach and a systematic analysis of fault effects and compensation is still not available.

This paper proposes a novel fault detection method for a five-phase PM machine, that is capable of an early detection of open and short circuit faults in a drive with current regulation. The advantages of the proposed method are that it is on-line and non-invasive and provides alert signals at an early stage. In fact it does not require any dedicated sensor for the fault detection. Moreover a diagnostic index is proposed that provides quantitative information about fault severity and the capability of identifying the faulty phase in terms of electrical angle. The main drawbacks are that a in case of drives fed by PWM power converters a suitable processing is required to obtain supply voltages and that the measurements of all the phase voltages are required.

Moreover the fault detection of this peculiar type of multiphase machine is an hard task. Specifically short circuit faults are difficult to detect, as the short current is limited by the winding resistance, the distortion of the flux is limited, and the asymmetry is very small in case of a low number of shorted turns.

The structure of the paper is as follows, at first a model of the faulty machine is introduced based on the equivalent

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transformer model. Then the accurate FE modelling of the machine is described, where FE results are used to compute the PM flux linkage in a faulty phase. Eventually the influence of the faults on machine electric quantities is investigated and a fault detection procedure is proposed and validated by simulation and experiments.

III. MODELLING OF FIVE-PHASE PM MACHINES

A five-phase PM machine is used to validate the proposed fault detection method. The machine features 20 stator slots and 9 magnetic pair poles without skewing. The stator turns are wound around the teeth with a single layer, [13]. Each phase has a total number of turns $N = 692$.

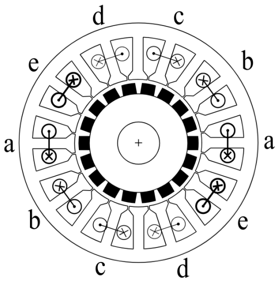

Fig. 1. Single layer winding distribution.

Stator phases are wound with a sequence a, b, c, e, f, a, b, c, e, f and each of them occupies four slots. Each phase is fed by a dedicated H-bridge converter, Fig. 2. Rated speed and phase current are respectively 333 rpm and I_M = 1.2 A.

The photos of the five-phase machine stator and rotor are reported in Fig. 3.

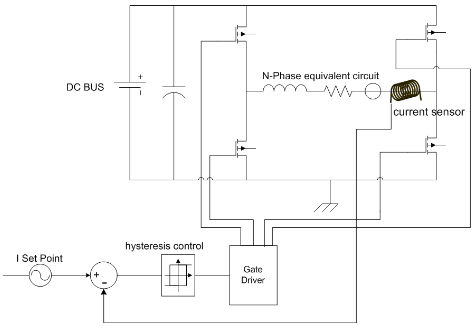

Fig. 2. Schematic representation of a phase of the PM machine.

The special design of Fig. 1 is characterised by a mutual coupling between phases equal to zero, even in the presence of iron saturation [14]. Hence each phase can be modeled independently. The phase voltage can be expressed by

$$v_k(t) = e_k(t) + R\,i_k(t) + L\,\frac{d\,i_k(t)}{d\,t} \tag{1}$$

the back emf is expressed by

$$e_k(t) = \frac{d\,\lambda_{mk}(t)}{d\,t} \tag{2}$$

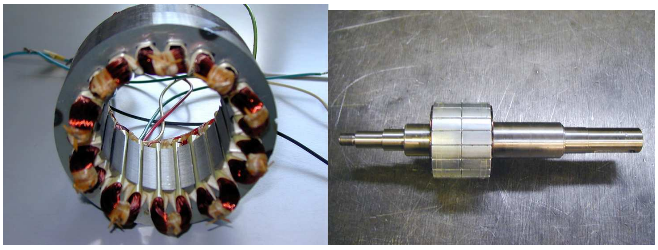

Fig. 3. Photo of the stator (left) and rotor (right) of the the five-phase PM machine.

with k= 0, 1, . . ., 4. $\lambda_{mk}(t)$ is obtained from FE computations. Eventually the phase current is expressed by

$$i_k(t) = I_M\,\sin\left(\theta + \frac{2\,k\,\pi}{5}\right) \tag{3}$$

A current controlled multi-phase drive is used, where symmetrical sinusoidal currents are forced. Specifically each phase current is independently regulated by a hysteresis control that drives the H-bridge switches, Fig. 2.

IV. MODELLING A PARTIAL COIL SHORT CIRCUIT FAULT

The fault modeled is the partial short circuit of a coil, where a part of the turns in a coil is short-circuited due to deterioration of the insulation. Under these conditions the faulty phase can be modeled adding a short-circuited dummy winding mutually coupled to the remaining healthy part of the phase [15]. The model of a healthy phase is described by

$$v \quad = \quad Ri + L\frac{di}{dt} + \frac{d\lambda_{pm}}{dt}, \tag{4}$$

where v and i is the phase voltage and current, and the healthy phase parameters are: resistance R, inductance L and the PM flux linkage λ_{pm}.

The partial short circuit is characterised by n, the number of short-circuited turns, where N is the total number of turns of the phase. The electrical model of the fault is shown in Fig. 4. For the dummy winding a linear relationship is assumed

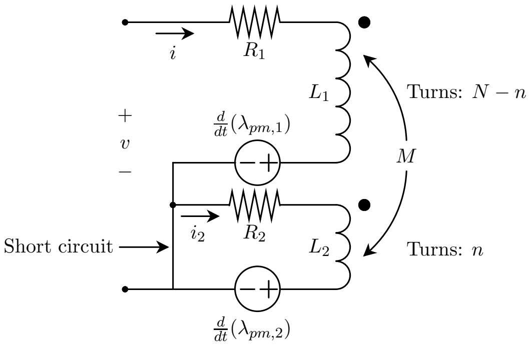

Fig. 4. Phase model of the five-phase PM machine in case of shorted turns fault.

between the number of shorted turns n and the resistance and PM flux linkage, and a quadratic relationship between the number of shorted turns and the inductance.

The electrical parameters for the two windings in Fig. 4 can be expressed as

$$R_1 = R\tfrac{N-n}{N} \qquad R_2 = R\frac{n}{N} \tag{5}$$

$$L_1 = L\left(\tfrac{N-n}{N}\right)^2 \qquad L_2 = L\left(\frac{n}{N}\right)^2 \tag{6}$$

$$\lambda_{pm,1} = \lambda_{pm}\tfrac{N-n}{N} \qquad \lambda_{pm,2} = \lambda_{pm}\frac{n}{N}. \tag{7}$$

It is assumed that no leakage flux is present between the two parts of the coil, so that the mutual inductance is $M = \sqrt{L_1 L_2}$.

Applying the equivalent transformer model the reduced electrical circuit for the phase can be found. The equivalent transformer model is reported in Fig. 5.

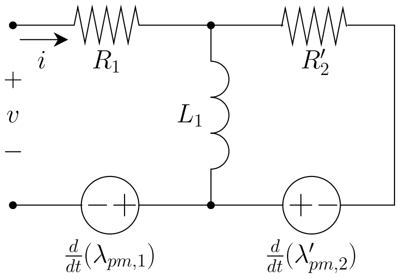

Fig. 5. Equivalent model under fault conditions.

The magnetising inductance of the model is equal to the primary inductance L_1 under the assumption that no leakage flux is present.

The resistance and PM flux linkage on the secondary side (short-circuited part) referred to the primary side are

$$R_2' = R\frac{(N-n)^2}{Nn} \tag{8}$$

$$\lambda'_{pm,2} = \lambda_{pm}\frac{N-n}{N}. \tag{9}$$

The model of Fig. 5 can be rearranged by means of the Thevenin theorem. With simple computations the equivalent Thevenin parameters for a phase under fault are obtained:

$$R_{eq}(\omega) = R\frac{N-n}{N} \cdot \frac{1+\omega^2\frac{L^2 n}{R^2 N}}{1+\omega^2\left(\frac{nL}{NR}\right)^2} \tag{10}$$

$$L_{eq}(\omega) = L\left(\frac{N-n}{N}\right)^2 \cdot \frac{1}{1+\omega^2\left(\frac{nL}{NR}\right)^2} \tag{11}$$

$$\lambda_{pm,eq}(s) = \lambda_{pm}\frac{N-n}{N} \cdot \frac{1}{1+\frac{nL}{NR}s} \tag{12}$$

For frequencies $\omega \ll \frac{NR}{nL}$ the resistance and PM flux linkage decreases linearly and the inductance quadratic with the number of short circuited turns n.

A. Fault Influence

From the equivalent model it is possible to establish the parameters variation due to a fault.

The equivalent phase impedance $Z_{eq} = R_{eq} + sL_{eq}$ normalised with respect to the healthy resistance is reported in Fig. 6 as bode diagrams.

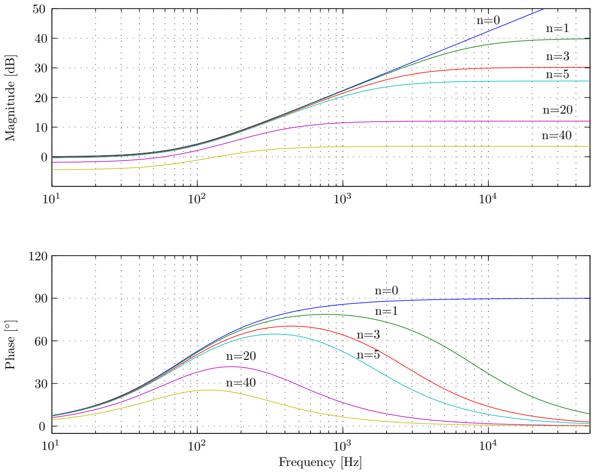

Fig. 6. Bode diagram of the phase impedance $\frac{Z_{eq}}{R}$.

For frequencies $\omega \gg \frac{NR}{nL}$ the phase impedance becomes dominantly resistive. For frequencies below, the impedance change are more attenuated.

Hence the detection of a small short circuit e.g. $\frac{n}{N} < 5\%$ at low frequencies may be difficult, as the electrical charateristic of the phase does not change significantly. Using a high frequency signal (i.e. a frequency above $\frac{NR}{nL}$) is it possible to detect small short circuit faults because the phase impedance angle changes significantly as observed in Fig. 6.

V. FE Modelling of the five-phase PM Machine

Fluxes are obtained from a two–dimensional Finite Element (FE) analysis [16], neglecting the end–winding effects. A cross–section of the machine is shown in Fig. 7.

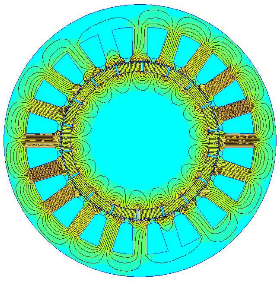

Fig. 7. Cross–section of the motor and flux plot..

FE simulation computes the magnetic flux linkages of the machine for each phase at no-load. To this aim a zero winding current is forced while the rotor spins with small angular steps $\delta\theta$ up to a polar pitch equal to $360\,/\,p$ = 40 degrees.

The choice of the angular step $\delta\theta$ is critical. In fact it is inferiorly limited by the resolution of results, and it is upperly limited by the size of the parts of the assembly. In fact a numerical high frequency noise would be generated if a very small angular step is used. An angular step $\delta\theta$ = 0.2 mechanical degrees was chosen as an optimal trade-off.

A dynamical model is used for the machine simulation where the back emf are computed from the fluxes obtained by FE simulations. The lumped parameters of the machine, i.e. phase inductance and resistance are obtained from measurements. The dynamic model allows to compute phase voltages as a function of the phase current forced by the regulators.

The spectral analysis of the voltages allows to compute the signatures in case of faulty conditions.

FE simulations in case of shorted turns are made forcing in the slots where shorted turns occur the short circuit current i_2 (see Fig. 4).The value of shorted current is changed as a function of rotor position, as the shorted current depend on $\frac{d}{dt}(\lambda_{pm,2})$. Simulation parameters are tuned so that the harmonics of the shorted current are the same of the back emf, i.e. fundamental, 3rd and 5th harmonics.

VI. DIAGNOSTIC INDEX

A solidly built diagnostic index should give information about occurring faults in the machine, here considering asymmetry due to a partial short circuit. The index should not give a false indication on e.g. healthy harmonic components.

It is sensible to analyze the influence caused by a partial coil short circuit using stator fixed orthogonal components. Introducing the transformation from phase components to orthogonal components by the matrix $\boldsymbol{p2o}$

$$\boldsymbol{p2o} = \frac{2}{5}\begin{bmatrix} \mathcal{R}e\big(a^0 & a^1 & a^2 & a^3 & a^4\big) \\ \mathcal{I}m\big(a^0 & a^1 & a^2 & a^3 & a^4\big) \\ \mathcal{R}e\big(a^0 & a^2 & a^4 & a^6 & a^8\big) \\ \mathcal{I}m\big(a^0 & a^2 & a^4 & a^6 & a^8\big) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \quad (13)$$

where $a = e^{j\frac{2\pi}{5}}$. Then the orthogonal components $v_{\{\alpha,\beta,\alpha_2,\beta_2,0\}}$ are obtained from the phase values as

$$\begin{bmatrix} v_\alpha & v_\beta & v_{\alpha_2} & v_{\beta_2} & v_0 \end{bmatrix}^T = \boldsymbol{p2o}\begin{bmatrix} v_a & v_b & v_c & v_d & v_e \end{bmatrix}^T,$$

For frequency analysis in $\alpha\beta$ and $\alpha_2\beta_2$ space, the following two complex values are defined as

$$v_{\alpha\beta} = v_\alpha + jv_\beta \quad (14)$$

$$v_{\alpha_2\beta_2} = v_{\alpha_2} + jv_{\beta_2}. \quad (15)$$

There are different variations of the transformation in literature, in particular of the second set $[v_{\alpha_2} v_{\beta_2}]$. Here the second set is based on double incrementation of a similar to [17]. The other variation is where a triple incrementation of a is used instead [18]. The difference between using double or triple incrementation is inversion of the frequency observed in $\alpha_2\beta_2$ i.e. $f_{\alpha_2\beta_2} = -f_{\alpha_3\beta_3}$. Besides this, the two variations contains the same information, so they are identical from the frequency analysis point of view.

The voltage space vector in $\alpha\beta$ system is defined as:

$$\vec{sv}_{\alpha\beta} = \begin{bmatrix} a^0 \; a^1 \; a^2 \; a^3 \; a^4 \end{bmatrix} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \\ v_d(t) \\ v_e(t) \end{bmatrix} \quad (16)$$

while in $\alpha_2\beta_2$ system it is defined as:

$$\vec{sv}_{\alpha_2\beta_2} = \begin{bmatrix} a^0 \; a^2 \; a^4 \; a^6 \; a^8 \end{bmatrix} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \\ v_d(t) \\ v_e(t) \end{bmatrix} \quad (17)$$

where $v_i(t)$ are the phase voltage waveforms.

VII. SIMULATION AND EXPERIMENTAL RESULTS

A. FE results

In case of shorted turns the negative sequence component is increased. In case of open circuit the current of the open phase vanishes, hence the current regulation will try to force all the available voltage, i.e. the DC bus voltage. The fault detection procedure should simply monitor the voltages in order to monitor overcomes the average of the current of a suitable threshold.

Simulations were made relying on the procedure described in the previous section, that uses data from FE computations to provide back emf waveforms to the dynamic simulations. Results validate the use of the spectrum of the five-phase space vector as a reliable diagnostic index.

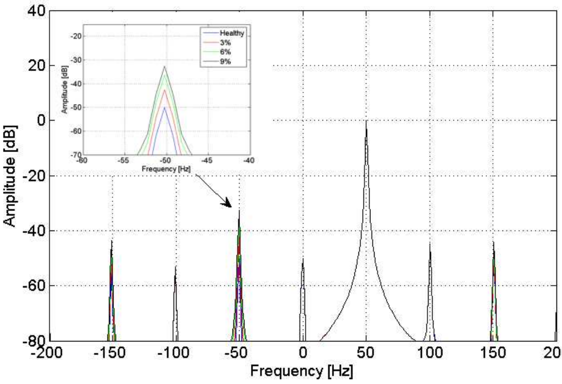

Fig. 8. Spectrum of $\vec{sv}_{\alpha\beta}$ for the five-phase PM machine in case of healthy machine (blue solid line), n/N = $\simeq$ 3 % shorted turns (red solid line), in case of n/N = $\simeq$ 6 % shorted turns (green solid line) and n/N = $\simeq$ 9 % shorted turns (black solid line).

Fig. 8 shows the spectrum of the space vector of $\vec{sv}_{\alpha\beta}$ for the five-phase PM machine in case of healthy machine (main part of the figure) and in case of machine with 20, 40 and 60 shorted turns (on the little window on the upper left side of the figure, that is the enlargement of the behaviour around the frequency $-f$). Being N = 692 it turns out that the percentage of shorted turns is of about 3%, 6% and 9% respectively.

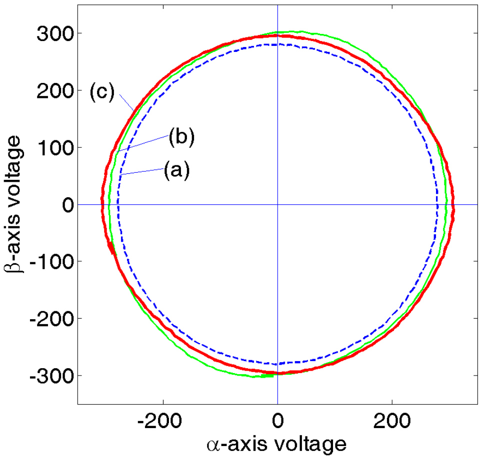

Fig. 9. Polar representation of the space vector $\vec{sv}_{\alpha\beta}$ in case of healthy machine (blue, curve (a)), machine with a short circuit (10%) in the phase 1 (green, curve (b)) and with a short circuit (10%) in the phase 4 (red, curve (c)).

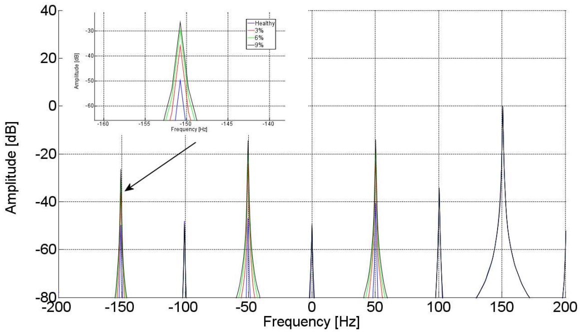

Fig. 10. Spectrum of $\vec{sv}_{\alpha_2\beta_2}$ for the five-phase PM machine in case of healthy machine (blue solid line), n/N = $\simeq$ 3 % shorted turns (red solid line), in case of n/N = $\simeq$ 6 % shorted turns (green solid line) and n/N = $\simeq$ 9 % shorted turns (black solid line).

Results show that the amplitude of the component at $-f$ (in Fig. 8 the supply frequency is $f = 50\,Hz$) increases almost proportionally with the number of shorted turns. On the contrary, the amplitude of other components, at different frequencies, yield no useful informations for a reliable fault detection.

Since the variation of the amplitude of the component at $-f$ of $\vec{sv}_{\alpha\beta}$ is significant, it can be an efficient quantitative diagnostic index. Together with the fault detection, this index can yields informations about its severity (i.e. the number of short-circuited turns). The identification of the faulty phase is possible referring to the polar representation of the space vector $\vec{sv}_{\alpha\beta}$; this representation is an ellipse that change the position of its axis according to the faulty phase, as Fig. 9 highlights (curve (a) refers to healthy machine, curve (b) to a 10% short circuit on phase 1, curve (c) to a 10% short circuit on phase 4).

Fig. 10 shows the spectrum of the $\vec{sv}_{\alpha_2\beta_2}$. Results show that in this case, the component at $-3f$ increases almost proportionally with the number of the shorted turns.

B. Experimental results

Some experimental tests were made to validate the equivalent model.

A prototype five-phase machine was made where 4 turns have been added in a coil of one phase, 2 wound in a direction and 2 in the other. In this manner 2 little windings have been introduced, and they have been connected in series with the main phase winding. In this way the short circuit current and the induced voltages can be measured in only a portion of the winding. The motor have been spinned at various speed, starting from zero up to 600 rpm.

Experiments confirm that for a low number of short-circuited turns, the circuit impedance is mainly resistive. Fig. 11 shows the measured short circuit current in 2 short-circuited turns and the induced voltage in the other 2 opened turns, with a rotating speed of 600 rpm (i.e. about $565.5\,rad/s$). Induced voltage and current are in phase, in nice agreement with the model results. Hence with a low number of shorted turns the reactive part of the impedance is negligible.

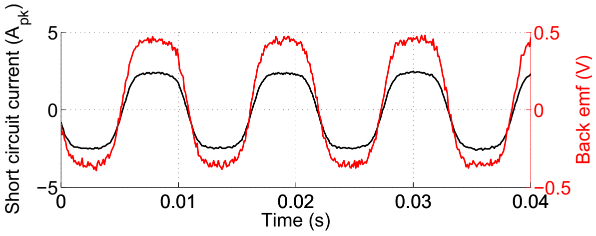

Fig. 11. Short circuit current and back emf with a 2–turns fault

Full-fault short circuit current and voltage were measured at various speed, connecting the two terminal of the phase under study. Fig. 12 shows a nice agreement between the phase equivalent model and the measured peak current and voltage in this condition. In first part of Fig. 12 the measured back-emf decreases more than the model at speeds higher than about 450 rpm. This deviation is probably due to eddy currents. In second part of Fig. 12 the measured I_{cc} decreases more than the model. This deviation is probably due to a little increase of L_1, moving away from the saturation. In fact, with the whole winding short circuited, the induced current causes a flux that drives down the PM flux. At high speed, i.e. for high ω, the short circuit current behavior is linear according to the equation $I_{cc} = \lambda_{pm}/L_1$.

In Fig. 13 the whole winding short circuit current and the induced voltage waveforms in the little winding of 2 turns can be observed at 600 rpm. The phase displacement between them confirms that with a large number of short-circuited turns the inductance cannot be neglected.

VIII. CONCLUSIONS

A five-phase PM machine has been designed for fault tolerant applications. It is characterised by a mutual inductance

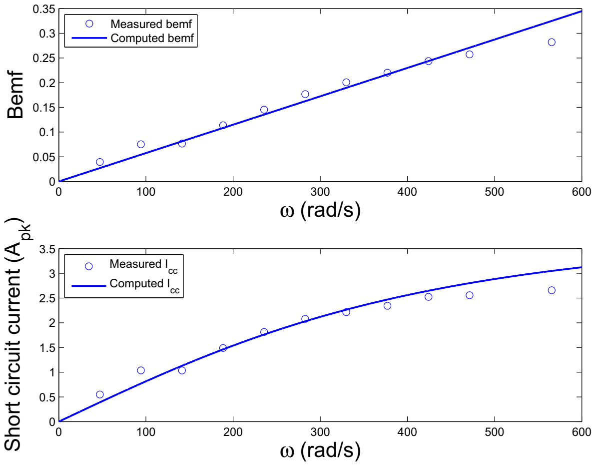

Fig. 12. Short circuit current versus rotation speed

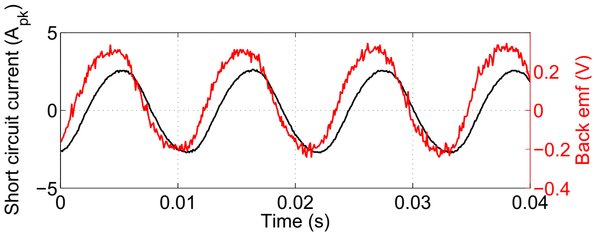

Fig. 13. Short circuit current and back emf with a whole winding fault

equal to zero and a high self inductance, in order to limit the short circuit current. However, with a limited number of short-circuited turns the current in the short-circuited turns increases with ω and the behavior is almost purely resistive, so that back emf and current are in phase. Only the resistance limits the short circuit current, thus it is mandatory to detect quickly the fault in case of a limited number of short-circuited turns. A dedicated model was developed to investigate the behavior of the machine under these conditions, and experiments were made to validate it.

The detection of short circuit faults was investigated relying on the frequency analysis of the phase voltages for a current-controlled drive. Symmetrical components transformation were investigated in order to seek for the most robust indicator. It is proved that the partial short circuit fault can be efficiently detected by monitoring the amplitude of the harmonic component of voltage space vector in the $\alpha\beta$ and $\alpha_2\beta_2$ space at the frequency $-f$ and $-3f$ respectively. The above mentioned amplitude can be used to monitor the fault severity, and the faulty phase can be identified, relying on the polar representation of the voltage space vector.

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