# Detection of Inter-turn Faults in Five-Phase Permanent Magnet Synchronous Motors

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*Abstract*—**Five-phase permanent magnet synchronous motors (PMSMs) have inherent fault-tolerant capabilities. This paper analyzes the detection of inter-turn short circuit faults in five-phase PMSMs in their early stage, i.e. with only one turn in short circuit by means of the analysis of the stator currents and the zero-sequence voltage component (ZSVC) spectra. For this purpose, a parametric model of five-phase PMSMs which accounts for the effects of inter-turn short circuits is developed to determine the most suitable harmonic frequencies to be analyzed to detect such faults. The amplitudes of these fault harmonic are analyzed in detail by means of finite-elements method (FEM) simulations, which corroborate the predictions of the parametric model. A low-speed five-phase PMSM for in-wheel applications is studied and modeled. This paper shows that the ZSVC-based method provides better sensitivity to diagnose inter-turn faults in the analyzed low-speed application. Results presented under a wide speed range and different load levels show that it is feasible to diagnose such faults in their early stage, thus allowing applying a post-fault strategy to minimize their effects while ensuring a safe operation.**

*Index Terms*—**permanent magnet motors, fault diagnosis, fault detection, fault tolerance, harmonic analysis.**

## I. Introduction

Multiphase motors are well suited candidates in critical applications requiring high reliability [1-2]. Automotive, marine and aeronautic fields are examples of applications requiring fault-tolerant electric motor drives [3]. Under a fault condition, multiphase motors may provide an appropriate performance even when operating with a reduced number of phases. This is so because the remaining healthy phases may ensure the motor operation without requiring additional hardware, since appropriate motor performance can be attained by applying a suitable control strategy [2,4].

Multiphase motors also present additional advantages over conventional three-phase motors, including reduced torque ripple amplitude with higher frequency, reduced phase currents at the same phase voltage, therefore reducing the requirements of the inverter switches. Multiphase motors also have improved torque per ampere, lower current harmonic content in the dc-bus [5], improved power density, reduced stator copper loss [2], high controllability or smooth torque under fault conditions [6] among others. Multiphase motors are also simple to install and manufacture, they are reliable and need relatively low technological support [7].

Among the multiphase motors, multiphase permanent magnet synchronous motors (PMSMs) are advantageous because they offer improved efficiency, high power and torque densities and high reliability [6],[8-9]. However, when dealing with safety-critical applications, it must be taken into account that PMSMs cannot be de-excited [6]; as a result some of the fault effects may remain active even after disconnecting the faulty phase.

In [10] three permanent magnet motors with three, four and five phases are compared under open circuit faults and it is proved the advantage of increasing the number of phases. Nevertheless, as the number of phases increases, the complexity, cost and probability of a fault grows [7], so the optimum number of phases seems to be five [10]. To deliver the rated power in the event of a single phase failure, five-phase motors have to be over-rated only by 25% [11], whereas three-phase motors have to be over-rated by 50% [7]. Therefore five-phase PMSMs are increasingly studied in applications requiring fault tolerance [3]. Five-phase PMSMs are often fed by a five-leg inverter. This architecture is appealing since it offers modularity, more flexibility and accuracy [12] while allowing reducing the current in each electronic switch when compared with conventional three-phase motor drives [3].

According to [6], to ensure a high-level of fault-tolerant operation capability, some requirements must be fulfilled, including physical, magnetic, electrical and thermal isolation among phases. This arrangement allows minimizing phase-to-phase faults occurrence [13]. For this purpose single-layer fractional slot concentrated windings are especially suitable.

Open circuits in stator windings, inter-turn short circuits or short circuits at the terminals are among the most frequent faults in electric motors [2]. When dealing with PMSMs, demagnetization faults are also troublesome [14].

There is a growing interest in the analysis of multiphase motors during fault operation. For example, [11] analyzes the change in machine losses due to the unbalanced magnetic field during fault operation, since power losses limit the torque capability and machine performance during fault-tolerant operating mode. In [2-3] open circuit faults in multiphase PMSMs are analyzed. In [15] an analytical model of a five-phase PMSM is developed to calculate the fault current under inter-turn short-circuit fault conditions, which is based on the estimation of the self- and mutual-inductances of different parts of a phase coil. Recently, a parametric model of five-phase PMSMs which allows investigating the effects of short-circuits in different physical variables of the machine was proposed [16]. In [17]

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demagnetization faults in five-phase PMSMs are diagnosed by analyzing the ninth spatial harmonic of the magnetic field in the air gap.

Many efforts have been done to design and optimize five-phase fault-tolerant motor drives. It is recognized that FEM simulations are a powerful and accurate tool to analyze the effects of open-circuit and short-circuit faults [7].

Stator winding failures are common faults in ac machines [18] and they are difficult to diagnose [19]. Among them, inter-turn faults are one of the most common [16] and potentially harmful [6] stator faults. They are often related to insulation degradation and may progress into more serious faults [16],[20] such as coil-to-coil, phase-to-phase or phase-to-ground faults [21], especially when their effects remain undetected [13],[21]. Such faults generate large circulating currents which can be many times greater than the rated value [14]. As a result, excessive heat and losses are generated [15]. Stator winding faults also may lead to partially demagnetization in PMSMs [20], thus lowering the average torque [22]. Hence, there is an imperious need to perform an accurate detection and diagnosis of inter-turn faults in their incipient stage because if not they may lead to very destructive effects [22].

This paper analyzes the feasibility of detecting inter-turn faults in five-phase PMSMs in their early stage, i.e. when only one turn is short-circuited, by analyzing both the zero-sequence voltage component (ZSVC) and the stator currents spectra. By studying different speed ranges and load levels it is shown that by analyzing specific ZSVC harmonics it is possible to detect inter-turn faults in the early stage. So it is possible to apply a post-fault strategy to ensure a safe operation while minimizing the effects of such faults. It is recognized that the harmonic content of the stator currents spectra may be influenced by the current loops of the PMSM drive [23], thus limiting severely the applicability of the method based on the analysis of the stator currents. It is also known that at low speed operation and depending on the stator windings configuration, the diagnosis based on the analysis of the ZSVC may be more sensitive [20]. In addition, the ZSVC-based diagnosis is appealing since it may be decoupled from the effects of the motor drive [24]. This later method involves having access to the stator windings neutral point, which is highly compatible with fault-tolerant multiphase motor drives [25]. It is worth noting that there are not papers analyzing the harmonic content of the ZSVC to detect inter-turn faults in five-phase PMSMs. This paper deals with a parametric model of the five-phase PMSM that accounts for the effects of inter-turn faults. This parametric model is used to select the harmonic frequencies to be studied to detect such faults. Next, the amplitudes of these harmonic frequencies are further analyzed by means of FEM simulations, therefore showing the potential of the proposed system to detect inter-turn faults in their early stage.

## II. Model Of The PMSM Considering Stator Winding Inter-Turn Faults

In this section the electrical equations of a five-phase PMSM with inter-turn faults expressed in the *abcde* stationary reference frame are presented. These equations are based on the three-phase PMSM model found in [16],[20] and are used to identify the most suitable harmonics of the stator currents and the ZSVC to be used as a fault indicator.

By supposing the inter-turn faults located in phase *e,* the equations are as follows,

$$[V_{sf,abcde}] = [R_{sf}]\cdot[i_{sf,abcde}] + [L_{sf}][\frac{di_{sf,abcde}}{dt}] + [e] + [V_0] \qquad (1)$$

the matrixes in (1) may be expressed as,

$[V_{sf,abcde}]=[V_a\ V_b\ V_c\ V_d\ V_e\ 0]^t$, $[i_{sf,abc}]=[i_a\ i_b\ i_c\ i_d\ i_e\ i_f]^t$,

$[V_0]=V_0[1\ 1\ 1\ 1\ 1\ 0]^t$

$$[R_{sf}]=\begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & R_s & 0 & 0 \\ 0 & 0 & 0 & 0 & R_s & -\mu R_s \\ 0 & 0 & 0 & 0 & \mu R_s & -\mu R_s - R_f \end{bmatrix},$$

$$[L_{sf}]=\begin{bmatrix} L & M_0 & M_1 & M_1 & M_0 & -\mu M_0 \\ M_0 & L & M_0 & M_1 & M_1 & -\mu M_1 \\ M_1 & M_0 & L & M_0 & M_1 & -\mu M_1 \\ M_1 & M_1 & M_0 & L & M_0 & -\mu M_0 \\ M_0 & M_1 & M_1 & M_0 & L & -\mu L \\ \mu M_0 & \mu M_1 & \mu M_1 & \mu M_0 & \mu L & -\mu^2 L \end{bmatrix},$$

$$[e]=\frac{d}{dt}\begin{bmatrix} \lambda_{PM,a} \\ \lambda_{PM,b} \\ \lambda_{PM,c} \\ \lambda_{PM,d} \\ \lambda_{PM,e} \\ \mu\lambda_{PM,e} \end{bmatrix},$$

$$\begin{cases} \lambda_{PM,a} = \lambda_{PM,1}\cos(\theta) + \sum_{h=1,3,5...} \lambda_{PM,h}\cos(h\theta - \theta_v) \\ \lambda_{PM,b} = \lambda_{PM,1}\cos\left(\theta - \frac{2\pi}{5}\right) + \sum_{h=1,3,5,...} \lambda_{PM,h}\cos\left(h\theta - \theta_v - h\frac{2\pi}{5}\right) \\ \lambda_{PM,c} = \lambda_{PM,1}\cos\left(\theta - \frac{4\pi}{5}\right) + \sum_{h=1,3,5,...} \lambda_{PM,h}\cos\left(h\theta - \theta_v - h\frac{4\pi}{5}\right) \\ \lambda_{PM,d} = \lambda_{PM,1}\cos\left(\theta + \frac{4\pi}{5}\right) + \sum_{h=1,3,5,...} \lambda_{PM,h}\cos\left(h\theta - \theta_v + h\frac{4\pi}{5}\right) \\ \lambda_{PM,e} = \lambda_{PM,1}\cos\left(\theta + \frac{2\pi}{5}\right) + \sum_{h=1,3,5,...} \lambda_{PM,h}\cos\left(h\theta - \theta_v + h\frac{2\pi}{5}\right) \end{cases} \qquad (2)$$

$R_s$ being the stator phase resistance, $L$ the phase self-inductance and $M_0$ and $M_1$ the mutual inductances, where the subscript "0" denotes adjacent phases and "1" nonadjacent phases. In addition, the stator zero-sequence flux component generated by the permanent magnets is expressed as $\lambda_{PM,0} = (\lambda_{PM,a}+\lambda_{PM,b}+\lambda_{PM,c}+\lambda_{PM,d}+\lambda_{PM,e})/5$, where $h$ is the harmonic order and $\mu = n/N$ is the ratio between the number of short-circuited inter-turns ($n$) and the total number of turns in each phase ($N$). Furthermore, $R_f$ is the resistance that models the insulation failure, whereas $i_f$ is the fault current through the $n$ short-circuited turns.

By adding the first five rows in (1) and taking into account (2), the ZSVC measured between the dc mid-point of the inverter and the center of the stator windings is obtained as shown in (3). Therefore, when considering a five-phase PMSM without neutral conductor it results in,

$$V_0 = \frac{1}{5}\Sigma V + \frac{1}{5}\mu R_s i_f + \frac{1}{5}\mu\left(L + 2M_0 + 2M_1\right)\frac{di_f}{dt} - \frac{d\lambda_{PM,0}}{dt} \qquad (3)$$

where $\Sigma V = V_a+V_b+V_c+V_d+V_e$ and $i_a+i_b+i_c+i_d+i_e=0$.

Commercial PMSMs are fed by electronic inverters which inject ZSVCs in the PMSM. In addition, because the neutral system voltage is not available, the line-to-neutral voltages $V_a$, $V_b$, $V_c$, $V_d$ and $V_e$ are not directly measurable. Fig. 1 shows the stator windings connections, the electronic inverter and a wye-connected resistive network used to measure the ZSVC.

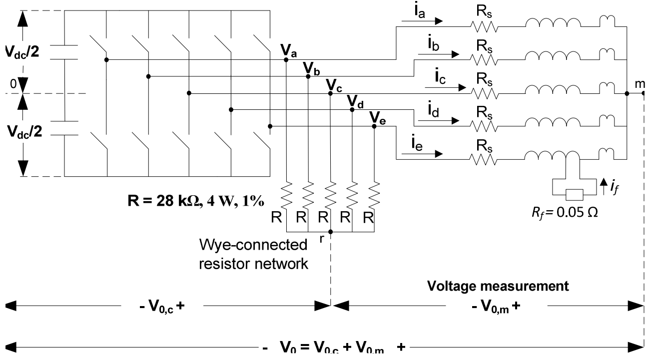


Figure 1. Diagram showing the five-phase PMSM connected to the inverter, the stator windings, the resistor network used to generate an artificial neutral point to measure the $V_{0,m}$ ZSVC, the short-circuited turns, the fault resistance $R_f$, and the circulating fault current $i_f$.

The motor drive may influence the ZSVC if measured as in (3) [20]. However, it is possible to decouple the ZSVC from the drive effects when measured between the central point of a balanced five-phase wye-connected resistor network and the neutral of the stator windings [8],[26], thus obtaining $V_{0,m}$. In this case, since $V_{0,c} = (V_a+V_b+V_c+V_d+V_e)/5$, (3) results in,

$$V_{0,m} = \frac{1}{5}\mu R_s i_f + \frac{1}{5}\mu\left(L+2M_0+2M_1\right)\frac{di_f}{dt} - \frac{d\lambda_{PM,0}}{dt} \quad (4)$$

Since the last term in (4) explains the effects of the magnets, it is the most contributing term. This term induces an important fifth harmonic component since the $d\lambda_{PM,0}/dt$ harmonics different than the fifth and its multiples are null, as proved in Section IV. In consequence, the fundamental frequency of the ZSVC corresponds to the fifth harmonic of the electrical frequency. Since the two first terms in (4) are due to the fault current $i_f$ (which main component is the first harmonic), the ZSVC spectrum of a faulty machine must contain a significant first harmonic component. This indicates that inter-turn faults may be diagnosed by analyzing the first harmonic of the ZSVC.

The induction effect of the permanent magnets is the primary source of the fault current $i_f$. This means that the fault current $i_f$ must contain a fifth harmonic component as occurs with the $V_{0,m}$ ZSVC. Since (1) predicts a link between $i_f$ and the stator currents $i_a$, $i_b$, $i_c$, $i_d$ and $i_e$, the stator currents spectra must also present a fifth harmonic component originated by the shorted turns. However, the induction effect of the permanent magnets greatly diminishes at low speed operation. In addition it is well-known that the motor drive may influence the stator currents harmonic content [23]. These combined effects may make it difficult to diagnose inter-turn faults by analyzing the fifth harmonic of the stator currents, especially at low speed operation as is the case of in-wheel motor applications. The magnitude of the short circuit current depends on the number of partially short-circuited turns as well as on their relative position in the slot where the winding is accommodated [14].

The equations system given by (1)-(2) also allows explaining the emergence of a fifth harmonic component in both the neutral and the phase currents when a healthy wye-connected five-phase PMSM has an accessible neutral point which is connected to the dc midpoint of the inverter by means of a neutral conductor. Under these constrains (4) may be rewritten as,

$$i_n\left(R_n+\frac{1}{5}R_s\right)+\frac{1}{5}\left(L+2M_0+2M_1\right)\frac{di_n}{dt}= \quad (5)$$
$$=\frac{1}{5}\Sigma V+\frac{1}{5}\mu R_s i_f+\frac{1}{5}\mu\left(L+2M_0+2M_1\right)\frac{di_f}{dt}-\frac{d\lambda_{PM,0}}{dt}$$

where $i_n = i_a + i_b + i_c + i_d + i_e$ is the current through the neutral conductor and $R_n$ is its resistance. From (5) it is deduced that the current through the neutral conductor will contain a fifth harmonic component due to the term $d\lambda_{PM,0}/dt$, even when dealing with a healthy machine ($i_f$ = 0). This effect is well known and allows corroborating the strength of equations (4) and (5). This fifth harmonic component will also emerge in the phase currents [27], thus lowering motor performance, so practical motors typically do not have this neutral conductor.

## III. THE ANALYZED PMSM MACHINE AND THE FEM MODELS

This work deals with a five-phase radial flux surface-mounted PMSM with outer rotor configuration which is shown in Fig. 2. It has wye-connected stator windings without neutral conductor. This motor was specially designed to be applied in electrical traction systems like electrical bicycles, electrically assisted velomobiles or wheelchairs among others.

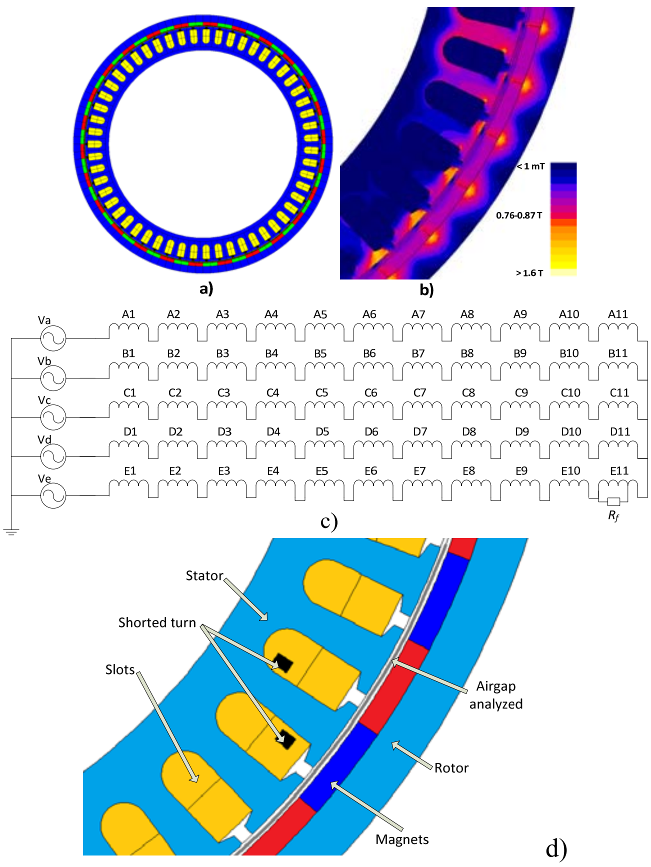


Figure 2. a) Diagram showing section of the stator and rotor. b) Magnetic flux density distribution in a section of the PMSM. c) Connection diagram of the 11 coils in each phase of the stator. d) Location of the short-circuited turn and 2D mesh applied in the FEM simulations.

Simulations of the faulty PMSM have been conducted by using a fault resistance $R_f = 0.05\ \Omega$. This value is within the range found in [28-30]. It is worth noting that the black area shown in Fig. 2 is proportional to the number of short-circuited turns in the slot.

The 2D-FEM model of the experimental PMSM was generated by means of the FLUX® commercial package. Specifically, the transient magnetic module was used since it allows the analysis of the phenomena created by a time variable magnetic field. This module also calculates induced currents in conducting regions, skin effects and proximity effects. The model consists of approximately 44000 triangular surface elements and 88692 nodes. All simulations presented in this work assume balanced sinusoidal line voltages and consider a time step of 0.204 ms (4.9 kHz sampling frequency) and 0.84 s are simulated to obtain 4096 points with a resolution of 30 points/cycle. The FFT leads to an output of 2048 points with a frequency resolution of 1.2 Hz.

The main parameters of the machine dealt with in this work are shown in Table I.

TABLE I. MAIN PARAMETERS OF THE ANALYZED PMSM

| **Outer Rotor Characteristics** | |
|---|---|
| Rated power | 1 kW |
| Rated torque | 23 Nm |
| Rated speed | 379 r/min |
| Outer diameter | 220 mm |
| Axial length | 36 mm |
| Air gap length | 1 mm |
| Number of phases | 5 |
| Poles pairs | 26 |
| Rated phase voltage | 18 V |
| Max current | 10 A |
| Rated electrical frequency | 164 Hz |
| Resistance per phase | 0.1 Ω |
| Self-inductance per phase | 107 μH |
| Mutual inductance between adjacent phases | 15 μH |
| Mutual inductance between nonadjacent phases | 10 μH |
| Number of stator slots | 55 |
| Number of coils per phase | 11 |
| Number of turns per coil | 10 |
| Number of wires in parallel per turn | 10 |
| Number of magnets in the rotor | 52 |
| Permanent magnets material | SmCo |
| Permanent magnets remanence | 0.8 T |

## IV. FEM RESULTS

In this section the effects of inter-turn faults in the analyzed five-phase PMSM are diagnosed by means of 2D-FEM simulations. The faulty machine model supposes only one turn short-circuited out of 110 turns in phase *e*, which is located in the position depicted in Fig. 2d.

As stated, inter-turn faults may lead to catastrophic motor effects if not detected in their early stage. Therefore it is highly advantageous their early detection, so remedial actions may be taken into account. For this purpose this section analyzes the feasibility to detect inter-turn faults when only one turn is short-circuited.

From the parametric model of the five-phase PMSM developed in Section II it was deduced that inter-turn faults may be diagnosed by analyzing the first harmonic of the ZSVC. It is also possible to analyze the fifth harmonic of the stator currents if this method gives enough sensitivity. These hypotheses will be analyzed in detail by means of the FEM simulations carried out in this section.

Fig. 3 shows the stator currents spectra of both a healthy and a faulty machine without neutral return conductor. Results from Fig. 3 clearly show that both healthy and faulty spectra are quite similar, thus being unpractical to diagnose an incipient inter-turn fault from the analysis of the stator currents in this particular machine. However, it is possible that better results may be attained depending on the machine speed or load level, so this point will be analyzed in this section.

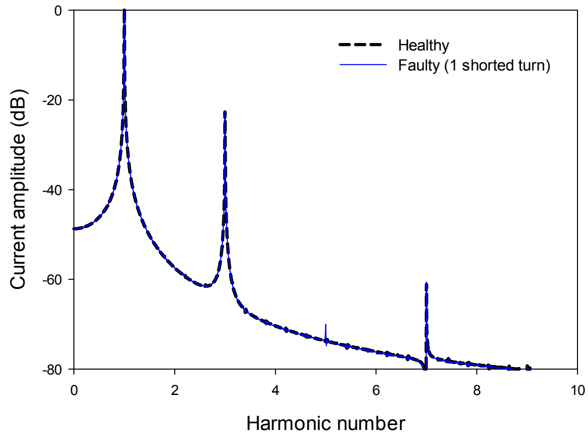


Figure 3. Stator currents spectra of the analyzed healthy and faulty (1 turn in short circuit) PMSMs when operating at rated speed under rated load conditions.

Fig. 4 shows the ZSVC spectra of both, the healthy and faulty machines. Contrarily to the case of the stator currents spectra, the ZSVC show important changes when a faulty turn is simulated, as shown in Fig. 4. Therefore, the analysis of the ZSVC is suggested in this paper. As derived from (4), in the case of a faulty machine the influence of the fault current in the ZSVC is reflected in the first harmonic component of the ZSVC. This theoretical result is corroborated by means of the FEM results provided by Fig. 4. In addition, the ZSVC spectrum of the faulty machine also contains third and seventh harmonic components, but due to their low amplitude, they will not be analyzed in this paper.

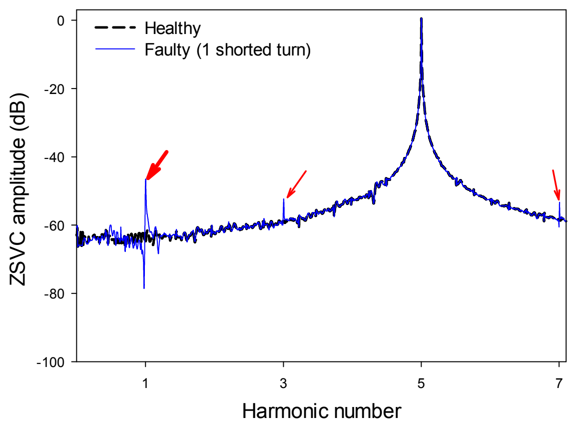


Figure 4. ZSVC spectra of the analyzed healthy and faulty (1 turn in short circuit) PMSMs when operating at rated speed under rated load conditions.

Figs. 5 show the amplitudes of the fifth harmonic of the stator currents for both healthy and faulty (one shorted turn) PMSMs when operating under different speed and load conditions. However, results presented in Fig. 5 show almost no difference between the healthy and faulty conditions of the analyzed machine since both results are virtually superimposed. Therefore, it is concluded that for the analyzed machine, the detection of inter-turn short circuit faults in the very incipient stage is not feasible from the analysis of the harmonic content of the stator currents.

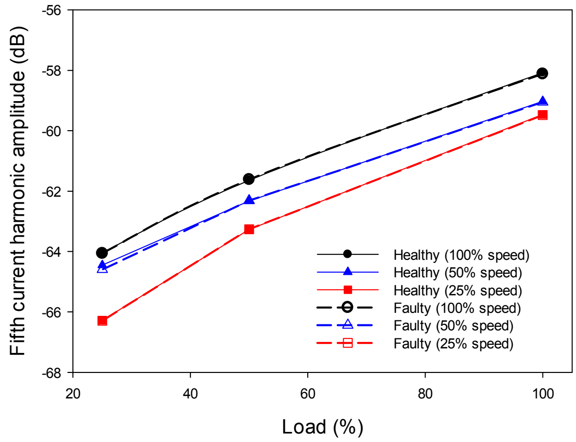


Figure 5. Healthy and faulty (one shorted turn) PMSMs operating under different speed and load conditions. Fifth harmonic amplitude of the stator currents.

Fig. 6 shows the amplitudes of the first harmonic of the ZSVC for both the healthy and faulty (one shorted turn) PMSMs when operating under different speed and load conditions.

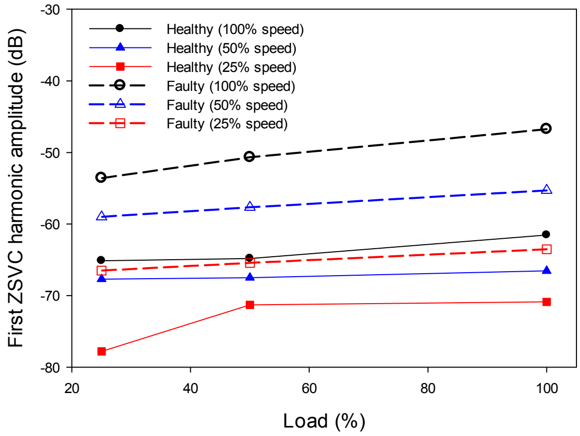


Figure 6. Healthy and faulty (one shorted turn) PMSMs operating under different speed and load conditions. First harmonic amplitude of the ZSVC.

According to the results presented in Fig. 6, the faster the PMSM speed, the higher the amplitude of the first harmonic. However, this amplitude is almost constant for a given load level. In addition, despite of the incipient fault level analyzed, always there is an increment of the first harmonic amplitude of the ZSVC when comparing a faulty motor with a healthy one. For better understanding, results presented in Fig. 6 are summarized in Table II.

From the results presented in Table II, it is concluded that in the case of a faulty PMSM with only one short-circuited turn, the amplitude of the first ZSVC harmonic experiments a sharp increment of at least 5.85 dB (the minimum value in Table II). Therefore, to let some security margin, a threshold value of 4 dB may be used to detect such incipient fault, i.e. one turn in short circuit. Note that although these results have been obtained under stationary speed and load conditions, they may be generalized to non-stationary conditions by applying a tracking process similar to the one detailed in [20].

TABLE II. FIRST HARMONIC OF THE ZSVC AMPLITUDE. DIFFERENCE BETWEEN FAULTY AND HEALTHY PMSMS

| | First ZSVC harmonic | | |
|---|---|---|---|
| | 100% full load (dB) | 50% full load (dB) | 25% full load (dB) |
| 100% rated speed | 14.81 | 11.26 | 7.35 |
| 50% rated speed | 14.15 | 9.85 | 5.85 |
| 25% rated speed | 11.56 | 8.71 | 11.29 |

It is worth noting that PMSMs are usually controlled in a closed loop mode, so the effect of the controller may be significant. However, as shown in Fig. 7, both the magnetic flux density in the air gap region just in front of the short-circuited turn and the phase currents are virtually not affected by the incipient fault. Therefore, the current loop hardly will perceive any difference between the healthy case and the very incipient fault condition, so no influence of the controller and consequently no distortion of the ZSVC spectrum are expected. However, as shown in Figs. 4 and 6, this incipient fault is clearly reflected in the ZSVC spectrum because of the contribution of the fault current $i_f$, as explained by equation (4).

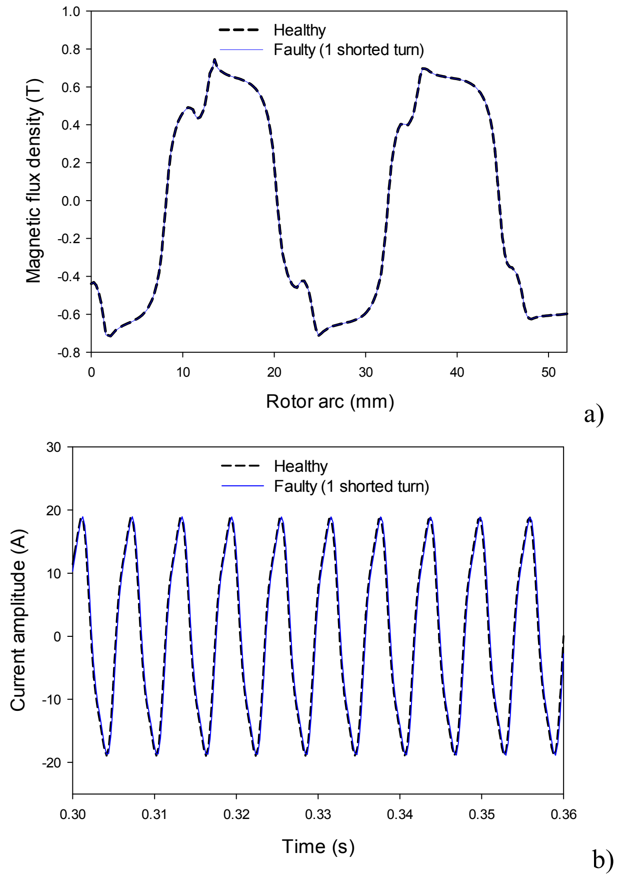


Figure 7. Healthy and faulty (one shorted turn) PMSMs operating under rated speed and load conditions. a) Magnetic flux density in the air-gap region just in front of the faulty slots. b) Stator currents.

## V. CONCLUSION

This paper has analyzed and compared two spectral methods for detecting inter-turn short circuits in five-phase PMSMs, which are based respectively on the analysis of the stator currents and the ZSVC spectra. It is well known that inter-turn short circuits may lead to very severe consequences, thus the detection of such faults in their early stage is of paramount importance. Once these faults have been detected, a post-fault strategy may be applied for ensuring a safe operation while minimizing their effects. Results attained under a wide speed range and different load levels show that for the analyzed machine, which exhibits a low rotational speed, the method based on the analysis of the stator currents does not allow detecting such inter-turn faults in their early stage, i.e. when only one turn is short-circuited. This is so because there is very little change in the instantaneous values of the stator currents as well as in their spectra. However, it has been shown that the ZSVC spectrum, and specially the first harmonic component is much more sensitive to the effects of the analyzed fault since the circulating fault current has a direct impact on both the ZSVC instantaneous values and in its spectrum. Therefore it is concluded that it is feasible to diagnose inter-turn short circuit faults in their early stage by analyzing the ZSVC spectrum.

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