Detection of Inter-Turns Short Circuits in Permanent Magnet Synchronous Motors Operating under Transient Conditions by means of the Zero Sequence Voltage

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Abstract

This work proposes the zero sequence voltage component (ZSVC) of the stator three-phase voltages as a method for detecting winding inter-turns short circuits in permanent magnet synchronous motors PMSM operating under transient conditions. Additionally it proves the linear relationship between the ZSVC and speed, which is effectively used as a fault severity index. The acquired ZSVC temporal signal is processed by means of the Hilbert-Huang transform (HHT).

Experimental results presented in this work show the advantages of the method to provide helpful data for online diagnosis of stator winding inter-turn faults.

I. Introduction

Faults in PMSMs are classified into three types: electrical, magnetic, and mechanical faults. Electrical faults involve abnormal connection of the stator windings, stator open turns and stator short circuited turns [1-3]. Inter-turn shorts-circuits are one of most usual failures in PMSM. These kinds of failures are generated by problems in winding insulation. The no detection of such faults may produce other problems in the machine, i.e. demagnetization of the rotor PMSM permanent magnets [4].

There are several techniques for detecting inter-turn short-circuits. For example, when dealing with low-voltage induction motors such faults can be diagnose accurately by using the motor current signature analysis (MCSA) based on the monitoring of the frequency components that are function of the slip of the machine and the fault level [5-6]. In PMSMs the slip is zero and therefore the fault frequency components are superimposed with the ones that appear in a healthy machine [2]. The amplitudes of such harmonics depend on the actual speed and the load of the machine and changes in amplitudes are only appreciated when the short-circuit involve several turns.

In this work, it is proposed the diagnostic of incipient stator winding inter-turns short-circuits in permanent magnet synchronous motors PMSM running under transient conditions by means of the ZSVC [7-8]. The ZSVC first harmonic amplitude is extracted from the HHT transform and its linear relationship with speed is analyzed as a fault severity index.

II. SPMSM with inter-turn short circuits

The severity of inter-turn short-circuit faults depends on the speed of the PMSM and the ratio $\mu = n/N$, being n the number of short-circuited inter-turns and N the total number of turns per phase. Inter-turn short-circuit faults may originate large circulating currents in the shorted turns.

Considering some shorted turns in phase A, the PMSM equations can be written as follows [9]:

$$[V_{s,abc}] = [R_{sh}]\cdot[i_{s,abc}] + [L_{sh}]\cdot\frac{d}{dt}[i_{s,abc}] + \frac{d}{dt}[\lambda_{PM,abc}] - \mu[R_{sh}]\cdot[A_1]i_f - \mu[L_f]\cdot\frac{di_f}{dt} + [V_0] \qquad (1)$$

Where:

$[V_{s,abc}]$: Stator 3-phase voltage matrix.
$[i_{s,abc}]$: Stator 3-phase currents matrix.
$[L_{sh}]$: Stator inductance matrix
$[\lambda_{PM,abc}]$:Stator 3-phase magnetic flux matrix due to permanent magnets.
i_f: Circulating current in the shorted turns.
$[R_s]$: Stator resistance matrix.
$[A_1] = [1\,0\,0]^t$
$[L_f] = [L\,M\,M]^t$
$[V_0]$: Zero-sequence voltage component

Additionally, the fourth equation for shorted turns can be expressed as:

$$V_f = i_f R_f = \mu R_s(i_a - i_f) + \mu[L_f]^t\cdot\frac{d[i_{s,abc}]}{dt} - \mu^2 L\frac{di_f}{dt} + \mu\frac{d\lambda_{PM,a}}{dt} \qquad (2)$$

Where:

V_f: Voltage in the shorted turns
R_f: Resistance between shorted turns.
$\lambda_{PM,a}$: Flux in the phase a due to the permanent magnets

After some algebra operations in equations (1) and (2) the expression for the zero-sequence voltage component (ZSVC) V_0 is obtained as follows [10]:

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) + \frac{1}{3}\mu R_s i_f + \frac{1}{3}\mu(L + 2M)\frac{di_f}{dt} - \frac{d\lambda_{PM,0}}{dt} \qquad (3)$$

Where

$\lambda_{PM,0} = \frac{1}{3}(\lambda_{PM,a} + \lambda_{PM,b} + \lambda_{PM,c})$.

As shown in equation (3), the circulating current i_f in the shorted turns influences the ZSVC, which amplitude may be used as an alternative for inter-turn fault diagnosis.

III. Detection of inter-turn short circuits by means of the ZSVC

A) ZSVC measurement scheme

As shown in section I, the ZSVC is an alternative to identify inter-turn faults. A disadvantage of using ZSVC for fault diagnosis is that the method needs an accessible neutral point. However, this configuration can be used for other purposes such as fault tolerant drives, where and extra inverter leg is connected to the neutral point of the SPMSM in order to isolate faulty power semiconductors [11].

PWM inverters inject zero-sequence voltages in the stator windings. Therefore the sum of phase voltages is different from zero and influences equation (3). The ZSVC generated by the inverter can be removed by means of a three-phase balanced resistor network [12]. In Fig. 1. the sum of currents through the balanced resistor network is zero,

$$\frac{V_a - V_{0,c}}{R} + \frac{V_b - V_{0,c}}{R} + \frac{V_c - V_{0,c}}{R} = 0 \qquad (4)$$

From (4) it results,

$$V_{0,c} = \frac{1}{3}\left(V_a + V_b + V_c\right) \qquad (5)$$

$$V_0 = V_{0,c} + V_{0,m} \qquad (6)$$

The balanced three-phase resistor network allows removing the inverter ZSVC from the neutral voltage of the machine. Thus the voltage $V_{0,m}$ is only influenced by the motor with the advantage that the voltage sensor can be scaled according to the ZSVC amplitude [12].

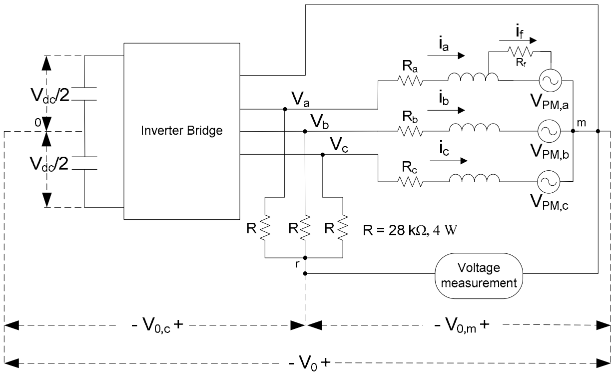


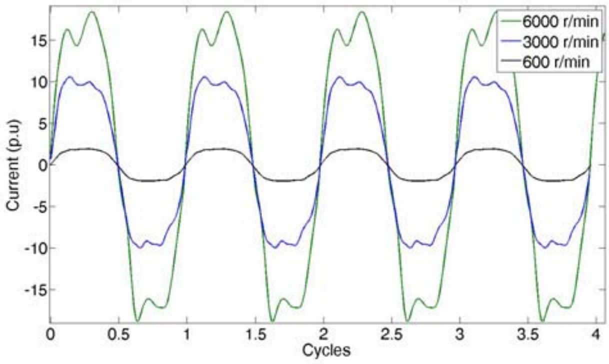
Fig. 1: Inverter-fed SPMSM showing the inverter, the stator windings connections diagram and the resistor network used to generate an artificial neutral point

B) Stationary operating conditions

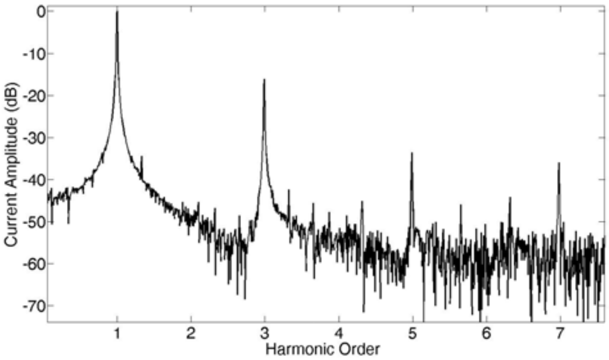
A special 380 V ac SPMSM with adjustable stator winding inter-turn faults and an accessible neutral point was modified to perform experimental tests. The motor has 3 poles pairs, rated torque of 2.3 Nm, rated current of 2.9 A, and rated speed of 6000 r/min. Experiments have been carried out by means of healthy and faulty motors.

According to equation (3), in a healthy SPMSM the fault current i_f is equal to zero and the spectral content of the ZSVC must be composed only by the third harmonic and their odd multiples. In a PMSM with inter-turn faults, the ZSVC depends on the circulating current i_f and the spectral content of the ZSVC must have also a large first harmonic. Fig. 1a. shows the experimental circulating current i_f through the four shorted turns of a PMSM running at 600, 3000 and 6000 r/min. Note that the i_f current is several times the rated current of the motor and could severely damage the machine. Fig. 1b. shows the spectral content of the i_f current where is proved that the shorted turns current has odd harmonics. These harmonics, according to equation (3) can affect the ZSVC. Fig. 2. shows the ZSVC spectrum of a healthy and faulty PMSM with two and four shorted turns running at 5500 and 1500 r/min. It proves that the first harmonic amplitude increases with the fault severity (the reference spectrum is the third harmonic amplitude of the healthy PMSM when operating at 6000 r/min).

Table **1** summarizes the ZSVC odd harmonics amplitude differences between healthy and faulty machine.

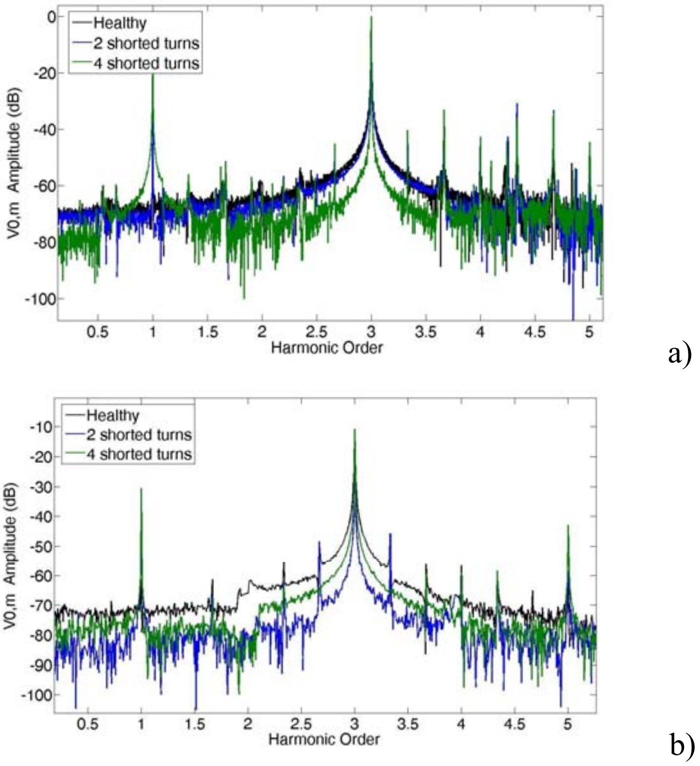


a)



b)

Fig. 2: a) Circulating current in a faulty motor with four shorted turns when operating at 600, 3000, 6000 r/min. b) Spectrum of circulating current in four shorted turns at 6000 r/min.



a)

b)

Fig. 3: Experimental ZSVC spectral content of healthy and faulty PMSM with 2 and 4 shorted turns. a) 5500 r/min. b) 1500 r/min.

Table 1: $V_{0,m}$ odd harmonics amplitude difference in dB between faulty and healthy conditions.

Harmonic order of the $V_{0,m}$ ZSVC	**Healthy**	**2 shorted turns**	**4 shorted turns**
		5500 r/min, rated load	
1th	-55.17	-33.15 /**22.02***	-17.44 /**37.73***
5th	-57.09	-55.04 /**2.05***	-44.52 /**12.57***
		1500 r/min, rated load	
1th	-61.42	-51.36 / **10.06***	-30.56 / **30.86***
5th	-63.17	-58.71 / **4.46***	-42.82 / **20.35***

C) Non-stationary operating conditions

Fourier Transform does not allow to analyze non-stationary signals such as currents and voltages . Thus this method is not appropriate for analyzing the currents and voltages of PMSMs operating under transient conditions such as load variation or speed changes, since voltage and current signals are closely influenced by these variations. In this work, transient signals are analyzed by means of Hilbert-Huang Transform (HHT). HHT represents the signal that will be analyzed in the time and frequency domains by applying the Empirical Mode Decomposition (EMD) followed by the Hilbert Transform[13]. Instead of Fourier analysis that use a constant amplitude series of sine and cosine functions for representing each component of the signal frequency, the HHT technique is based on the instantaneous calculation of the frequencies of the EMD signals which are obtained by applying the Hilbert Transform [14].

In order to study the behavior of the ZSVC under non-stationary conditions, experimental tests were carried out with a healthy and faulty PMSMs. A sinusoidal speed reference with amplitude of 1000 r/min, frequency of 0.1 Hz and offset of 4500 r/min was applied. Therefore the PMSM was operating between 3500 and 5500 r/min. Fig. 4. shows a window of the HHT spectrum (centered in the first harmonic, between 175 and 225 Hz) of a healthy (Fig. 4a) and faulty PMSMs with two (Fig. 4b) and four shorted turns (Fig.4c). While in the healthy spectrum it is not possible to distinguish the first harmonic (referenced to healthy third harmonic amplitude at 6000 r/min), in the faulty spectrums the first harmonic visibility increases with the severity of the short circuit fault.

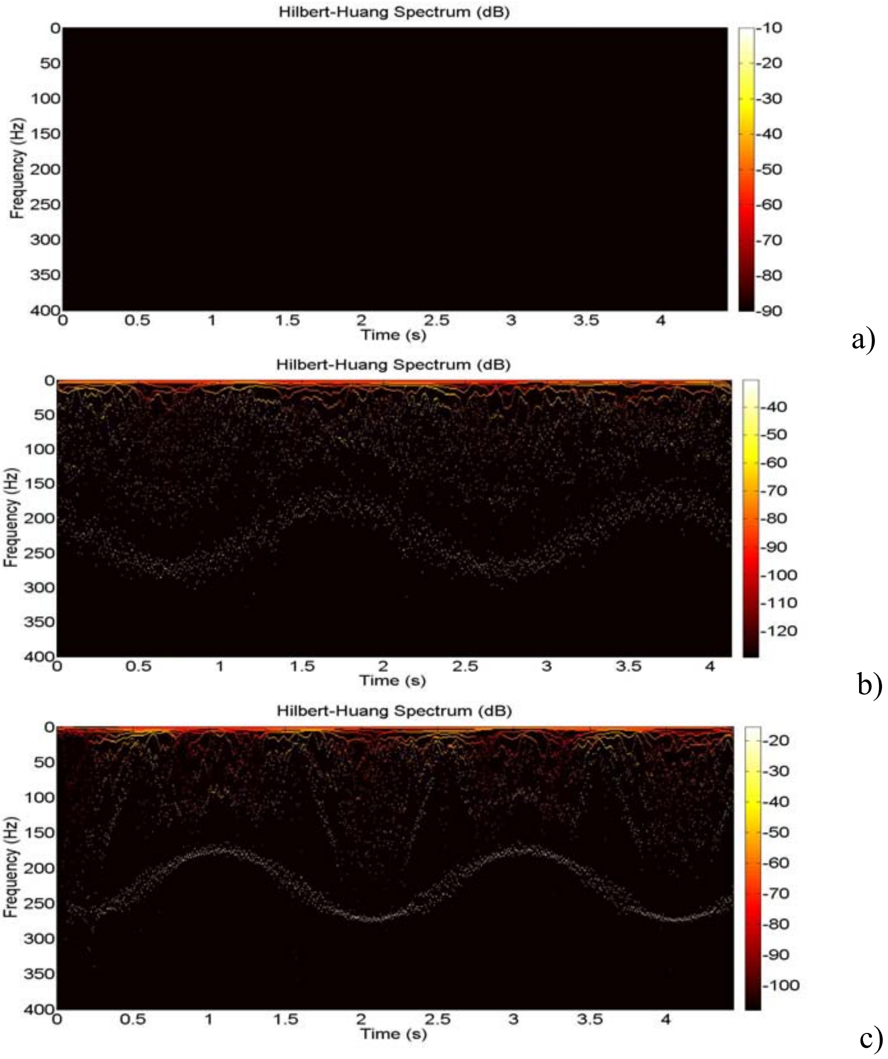


Fig. 4. Experimental ZSVC Hilbert Huang spectrum of a healthy and faulty PMSMs operating under speed changes (3500-5500 r/min). a) Healthy. b) 2 shorted turns. c) 4 shorted turns.

Although it is difficult to analyze the time-frequency representation due to the amount of data provided, the HHT transform has relevant information about the evolution of the ZSVC harmonics with speed. The first harmonic amplitude is tracked and extracted searching for the maximum around the frequency of interest. This frequency is obtained from the actual speed of the motor (with ±10 tolerance). Fig. 5, Fig. 6Fig. 7 show variation with the speed of the first harmonic amplitude for a healthy and faulty PMSMs with two and four shorted turns. Note that the amplitude of the first harmonic increases with the number shorted turns (fault severity).

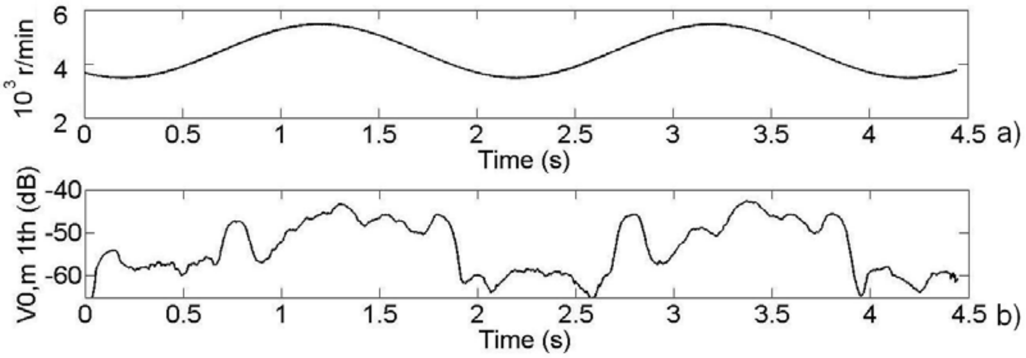


Fig. 5: Experimental ZSVC of a healthy PMSM. a) Speed variation. b) ZSVC first harmonic amplitude.

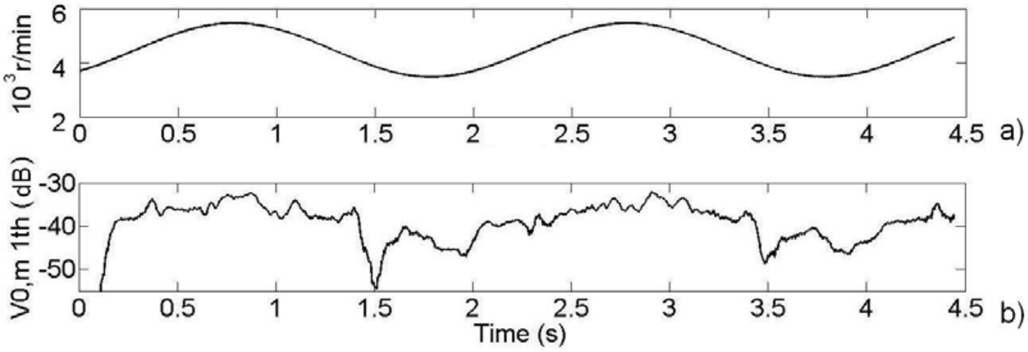


Fig. 6: Experimental ZSVC of a faulty PMSM with two shorted turns. a) Speed variation. b) ZSVC first harmonic amplitude.

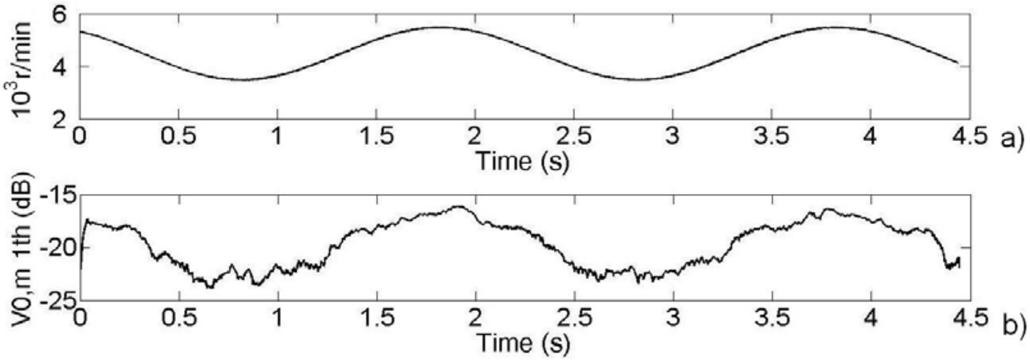


Fig. 7: Experimental ZSVC of a faulty PMSM with four shorted turns. a) Speed variation. b) ZSVC first harmonic amplitude.

IV. Inter-turn short circuits fault severity index

The goal of a diagnosis system is to distinguish and quantify faulty operation modes from healthy one. Therefore it is highly desirable to dispose of a fault severity index which enables the proper diagnosis of the fault under different operating conditions. In this work it is analyzed the behavior of inter-turn short circuits in PMSM running at several speeds and it is proposed the ZSVC as a fault diagnosis method. Fig. 8 shows the evolution with the speed of the ZSVC first harmonic for healthy and faulty PMSMs. Note that the correlation coefficient and the slope of the linear fit between the first harmonic amplitude and the speed increases with the fault severity. Thus, these two mathematical coefficients may be used as fault severity indexes. Table 2 summarizes the slope and the linear correlation coefficient values obtained from the linear fit.

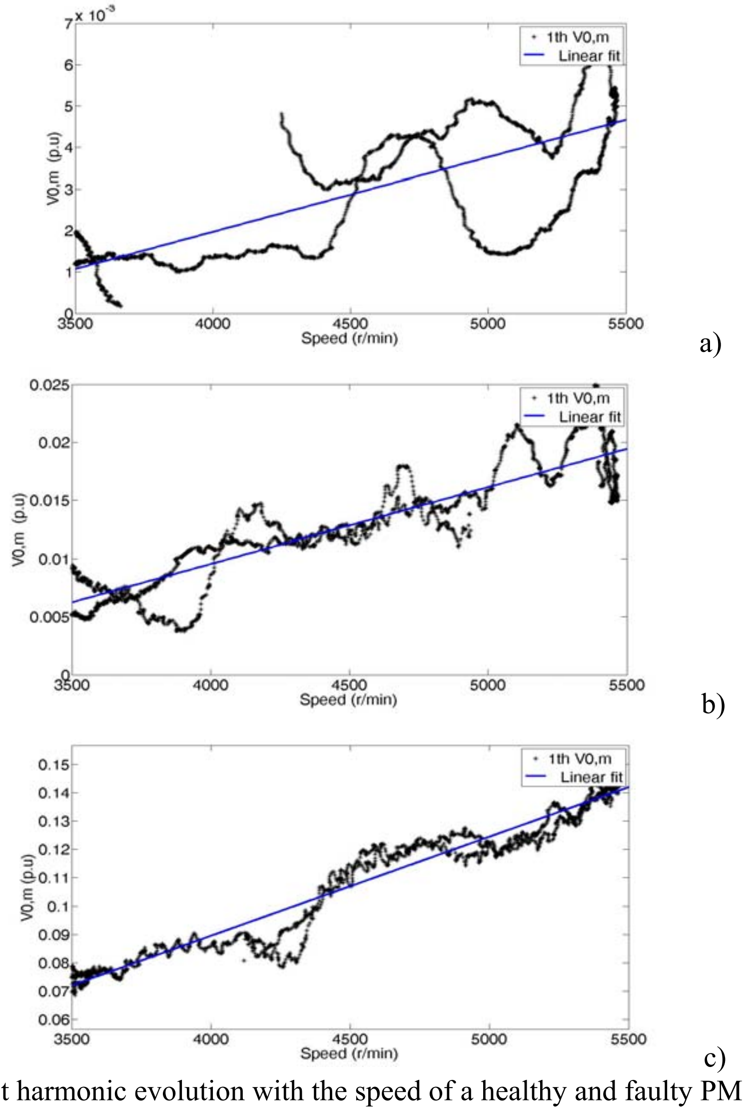


Fig. 8: ZSVC first harmonic evolution with the speed of a healthy and faulty PMSMs. a) Healthy. b) Two shorted turns. c) Four shorted turns.

Table 2: Linear relationship between ZSVC fist harmonic and speed.

	Healthy	2 shorted turns	4 shorted turns
Slope	1.797×10^{-6}	6.589×10^{-6}	3.492×10^{-5}
Correlation coefficient (R)	0.7201	0.8650	0.9687

V. Conclusion

In this paper it is proposed the diagnosis of inter-turns short circuits faults in a PMSM running under stationary and non-stationary conditions by means of the first harmonic of the stator winding zero sequence voltage components. It has been proved that its amplitude depends on the circulating current through the shorted turns. For non-stationary conditions it is proposed the data processing by means of the Hilbert-Huang transform, followed by the extraction of the first harmonic amplitude with a frequency tolerance interval of ±10%. Experimental results show the linear relationship between the first harmonic amplitude of the ZSVC and the actual speed of the PMSM. Additionally it has been proved that both the slope and the correlation coefficient arising from the linear fit between the ZSVC first harmonic amplitude and the speed increases with the fault severity, which can be used as fault indicators.

VI. Acknowledgements

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VII. References

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