Effect of Stator Insulation Failure on the Motor Drive System Performance

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***Abstract*—This study investigates the influence of the stator's turn-to-turn failures (TTFs) on the electromagnetic (EM) fields, such as air gap flux density, flux density in the stator, and rotor iron core inside of direct self-control (DSC) driven induction machines (IMs). The purpose of the investigation is to capture the fault signatures in the air gap EM flux for detecting the stator's fault at its embryonic stage**

***Index Terms*—Fault detection, induction machine, inter-turn short-circuit, inverter-fed IM, FEA co-simulation.**

I. INTRODUCTION

TURN-to-turn fault (TTF) is the second most common fault in induction motors (IMs) [1]. That's why it has been investigated extensively for direct online (DOL) connected IMs and for open-loop driven ones from voltage source inverters (VSI) [2]. Although most of the IMs in high-performance industrial applications are driven by closed-loop controllers, very few studies investigated the TTF fault detection (FD) in closed-loop drive systems. The direct self-control (DSC) technique has the merit of being robust and easy to implement. Moreover, DSC has an advantage over the other closed-loop drive techniques, that it is independent of the IM parameters. Consequently, DSC is the most implemented technique among all the vector control ones. However, the FD of TTFs in DSC controlled IM is the least studied in the literature [1].

The studies investigated the TTF effect on the DSC driven IMs focused on the impacts of the fault on the stator's current (i_s) and the developed torque, as in [1] and [3], or on the radiated electromagnetic (EM) flux from the IM, as in [4].

More recent studies investigated the diagnosis of the TTFs using the current signal directly or through its projection on the value of the sequence component impedance matrix [5].

However, the impacts of the TTF on the EM of the air gap and iron core of the motor was not further investigated before. Nevertheless, those impacts are the first step toward the invasive FD, via inserting search coils in the machine's air gap. Therefore, this study presents a comprehensive investigation of the impacts of the stator's turn-to turn failure on the internal EM field of a DSC driven IM for the purpose of FD.

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II. IM DRIVE SYSTEM UNDER STUDY

The co-simulation platform of the vector driven IM under study is shown in Fig. 1. The drive system algorithm is based on two hysteresis controllers, the first is to control the developed torque (T_e), while the other is to control the magnitude of the flux-linkage ($|\boldsymbol{\lambda}_s|$).The switching frequency ($f_s = 10$ kHz). The DSC algorithm procedure could be summarized in the following steps:

Measurement of VSI signals': The first step is the measurement of the DC-link voltage (V_{DC}) and the motor's line current ($\boldsymbol{i}_s$).

Transformation into $\alpha\beta$ coordinates: The measured values are transformed from abc into $\alpha\beta$.

Stator's voltage estimation: The space-vector (SV) output voltage of the VSI ($\hat{\boldsymbol{v}}_s$) could be estimated through the knowledge of V_{DC} and the switching sequence.

Estimation of T_e and $\boldsymbol{\lambda}_s$: T_e and $\lambda_s$are estimated by (1) and (2), respectively. R_s is the stator resistance:

$$\hat{T}_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}\left(i_{s\beta}\hat{\lambda}_{s\alpha} - i_{s\alpha}\hat{\lambda}_{s\beta}\right), \tag{1}$$

$$\hat{\boldsymbol{\lambda}}_s = \int(\boldsymbol{v}_s - R_s\boldsymbol{i}_s)dt. \tag{2}$$

Controllers action: The error between the estimated and reference values of T_e and $\boldsymbol{\lambda}_s$ are the inputs to the controllers. The output indicates the switching requirements.

Sector detection: Based on τ and ψ, the sector (S_x, where$x = \{1-6\}$) where the flux-linkage lies is determined.

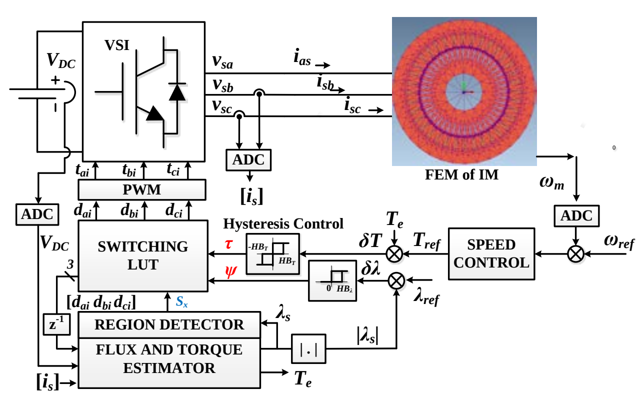

Fig. 1. DSC driven IM under study.

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The TTF inserts inter-harmonics in i_s as in (3), where p is the number of pole pairs. The DSC react to the TTF through the insertion of $3f$ harmonic component in i_s [1]:

$$f_{TTF} = f\left[\frac{m}{p}(1-s) \pm l\right],\ m = 0,1,2\ldots, l = 0,1,3,5\ldots \quad (4)$$

III. FEA Model Results

A. Details of the Motor

With a 1-hp induction motor, the electromagnetic fields, such as air-gap flux density, flux density in stator, and rotor iron core are investigated systematically. The motor is made out of iron core M19 USS with 36 slots, while the rotor bars are made of aluminum 3.8e7 Siemens/m, and there are 44 of them (R=44). The air gap is 0.31 mm. Each phase has 6 coils connected in series, with the total number of turns per phase is N_{sa}=510. Four taps were done on the physical IM and the FEA model to study the ITSC. The fault severity factor (μ_f) is a ratio (in percentage) between the number of turns short-circuited and N_{sa}.

TABLE I: Details of the Motor

Rating	Value	Param.	Value
Pr (W)	750	Stator outer diameter	160
U (V)	460	Stator inner diameter	100
I (A)	1.47	Rotor inner diameter	22
f (HZ)	60	Air-gap length	0.31
n (rpm)	1730	Parallel branch	1
J (kgm^2)	0.053	Slot numbers (Z1/Z2)	36/44

B. FEA Results

The different faulty cases, including μ_f=1.08%, 2.68%, 3.98%, and 4.7%, are computed, respectively. The fault resistance is $R_f = 0.67\ \Omega$. The faulty case of μ_f= 2.68% is analyzed in this digest, as it could be detected from i_s signatures. Comparisons of current and air-gap flux density with healthy and faulty conditions are given in Fig. 2 (a). It can be found that.

1) With the healthy condition, three-phase currents are balance and the amplitude is 1.93A. However, with the faulty condition, the phase-A current increase to 2.02A, which is obviously higher than the other ones. It is the reason that the turn-to-turn fault can lead to the unbalance MMF and the current in faulty winding may increase correspondingly.

2) As seen from in Fig. 2 (b), it can be found that, comparing to the healthy condition, there are more abrupt variations (dot circled area) in air-gap's flux density waveform with the faulty condition. Besides the slot opening effect, the interaction between the additional EM flux introduced by the short-circuited windings and the main rotating field caused those abrupt changes. The aforementioned effect is influenced by the relative position between the faulty windings and the main rotating flux.

IV. Conclusion

The Study presented the impacts of the TTFs on the magnetic field harmonics and power loss componentsof a DSC driven IM. The FEA co-simulation results showed the air gap's magnetic field sensitivity to the TTF more than i_s. The results demonstrate that FD based on air gap flux density can detect TTFs at their incipient stages.

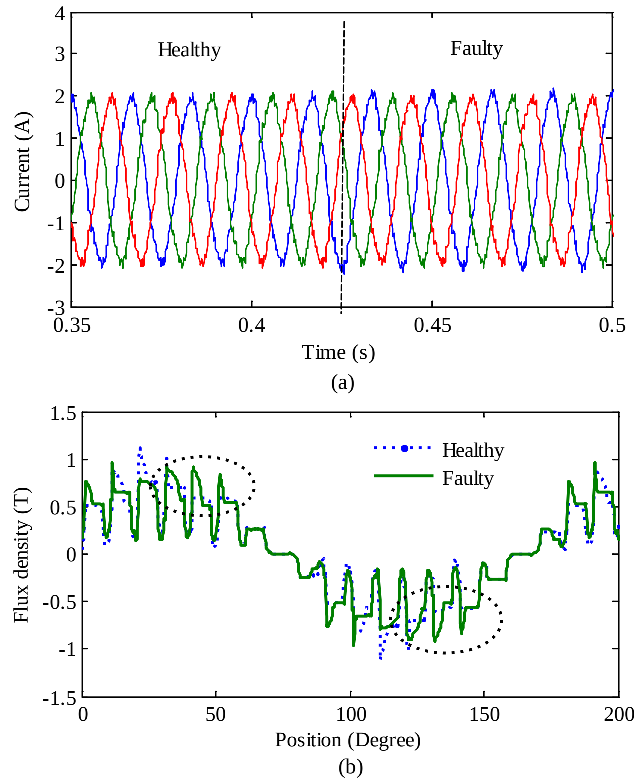

Fig. 2. Comparison of electromagnetic fields under healthy and fault conditions: (a) Stator current; (b) air-gap flux density.

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