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Research article

On-line diagnosis of inter-turn short circuit fault for DC brushed motor

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ABSTRACT

Extensive research effort has been made in fault diagnosis of motors and related components such as winding and ball bearing. In this paper, a new concept of inter-turn short circuit fault for DC brushed motors is proposed to include the short circuit ratio and short circuit resistance. A first-principle model is derived for motors with inter-turn short circuit fault. A statistical model based on Hidden Markov Model is developed for fault diagnosis purpose. This new method not only allows detection of motor winding short circuit fault, it can also provide estimation of the fault severity, as indicated by estimation of the short circuit ratio and the short circuit resistance. The estimated fault severity can be used for making appropriate decisions in response to the fault condition. The feasibility of the proposed methodology is studied for inter-turn short circuit of DC brushed motors using simulation in MATLAB/Simulink environment. In addition, it is shown that the proposed methodology is reliable with the presence of small random noise in the system parameters and measurement.

1. Introduction

Fault diagnosis of electrical machines has attracted the attention of many researchers because of its potential applications in industry. Different types of faults and their diagnosis of AC motors are reviewed in Ref. [1]. In general, DC machines are viewed as simpler than AC machines. As a result, most of the research work focus on AC machines. However, DC motors are widely used in industry for its low cost, high power density, and simplicity to control. The fault detection capability is of important value for industry. DC machines are different from AC machines and many research findings in AC machine cannot be directly applied to DC machines. The widespread applications of DC machines in industry require more attention in the area of fault diagnosis for DC machines.

As stated in Ref. [2], one can view the diagnostic decision making process as a series of mappings on measurement data. Data features extracted from measurement data through these mappings are used to make fault diagnostic decisions. Previous works reviewed in Refs. [1,3–6] have succeeded in appropriately selecting and extracting data features. However, in practice, data features can be affected by deviations in data. These deviations may be caused by measurement error and random noise in the signal. If the data feature is too sensitive to data deviations, the result may not be reliable. This in turn can cause false detection in fault diagnosis. This important issue of impact from data deviations was not discussed in the literature in fault diagnosis of AC/DC machines.

Another topic of great importance is the determination of fault severity. Instead of a binary decision on fault detection, it is desirable to have an estimation of how severe the fault is. If a fault is minor, the motor may be allowed to run while waiting for a scheduled maintenance. On the other hand, if the fault is severe, the motor may need to be immediately stopped to avoid further damage to itself and other related components. The fault severity estimation was more challenging than fault detection and was discussed in several papers [7–13]. However, in these papers only specific faults were addressed for AC motors or motor coil arcing fault.

Based on the above discussion, the research effort presented in this paper focuses on the fault severity estimation of inter-turn short circuit (SC) of DC motors. The Hidden Markov Model (HMM) is proposed for the fault severity estimation.

One of the important aspects of on-line diagnosis is that one must be able to implement the algorithm in a micro-controller. The simplicity of HMM algorithm makes the on-line diagnosis feasible.

HMM has been extensively used as a statistical modeling tool in areas such as hand gesture recognition, speech recognition, and text segmentation. The successful applications of HMM in fault diagnostics can be found in manufacture processes and monitoring systems [14,15]. HMM has also been used to monitor bearing faults [16,17], tool wear detection and prediction [18], and insulation failure [19]

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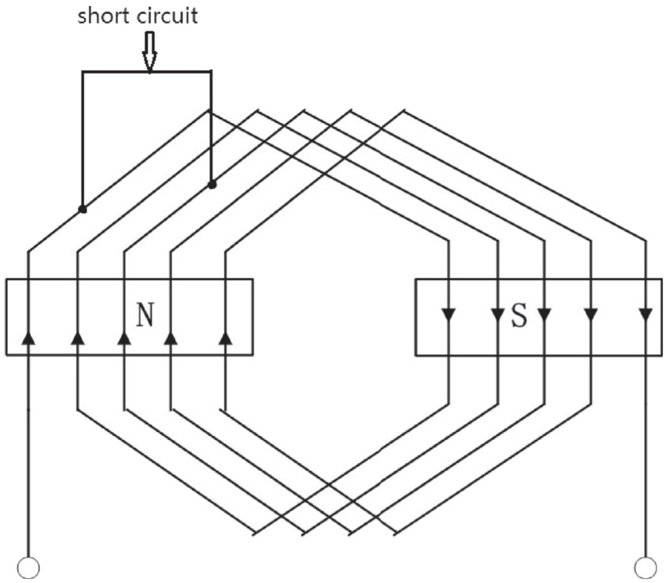

Fig. 1. The winding diagram with inter-turn SC.

for electric machines.

For induction motors, it was found that the winding current will be distorted from sinusoidal form depending on the short circuit turns. Based on this, short circuit turns can be estimated [20] using HMM. The winding current in DC motors is never sinusoidal, therefore, DC motors require completely different treatment in applying HMM.

The organization of this paper is as follows. In Section 2, the fault model is derived for simulation and analysis purpose. In Section 3, the HMM-based approach is introduced. In Sections 4, HMM is applied to diagnose the inter-turn SC fault of DC motors. Validation results based on simulation are presented in Section 5. Section 6 summarizes the work and discusses future work.

2. Inter-turn SC fault model of DC motor

This paper studies the inter-turn short circuit fault in the armature winding of DC motors, which is shown in Fig. 1. Severe inter-turn SC causes large current, which in turn generates excessive heat. Te excessive heat may cause catastrophic shorts [21]. Therefore, severe SC faults need be detected quickly.

A similar short circuit model was studied by Nakamura *et al.* [20] for induction motors, where the short circuit path is always assumed to have zero resistance. The objective of Nakamura's work was to estimate the SC ratio defined as the ratio of shorted turns and total turns. This is a big step from binary fault detection to fault severity estimation. Zhang *et al.* used the same intern-turn SC model proposed by Nakamura [20] in their initial attempt to apply HMM to DC motor fault detection [22]. However, in reality any such short circuit path must have a resistance. The short circuit resistance may take different values, but considering that the motor coil have low resistance value and the coil and short circuit are connected in parallel, it makes sense to model the short circuit path by a resistor with relatively low resistance value. If the short circuit resistance value is high, regardless of its value the impact on the motor is negligible. In other words, the fault severity is low.

Fig. 2 illustrates the new circuit model for DC motor with inter-turn SC fault. SC resistance is an important parameter, which determines the current through the SC point and how serious the fault is. Even with high SC ratio, it can be safe to run the motor without much loss in performance if the SC resistance is relatively high. On the contrary, low SC resistance may lead to high temperature and cause

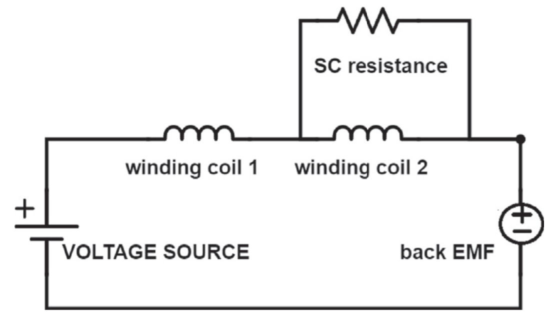

Fig. 2. Circuit model of DC motor.

other faults. Therefore, SC resistance is as important as SC ratio in the evaluation of fault severity. This new model increases the difficult level for fault severity estimation compared to the existing model in the literature in that it has two parameters instead of one.

The objective of diagnosis is to effectively estimate both SC ratio and SC resistance provided that the armature current is available as an input to the diagnostic algorithm.

For the inter-turn SC circuit model illustrated in Fig. 2, the following equations are derived as a model for DC motors with inter-turn SC fault

$$V = E + (1-u)L_a\frac{di_a}{dt} + (1-u)iR_a + uL_a\frac{d(i_a - i_f)}{dt} + u(i_a - i_f)R_a \tag{1}$$

$$uL_a\frac{d(i_a - i_f)}{dt} + uR_a(i_a - i_f) + uE = i_f R_f \tag{2}$$

where V is the supply voltage (V), E is the back EMF (V), L_a is the armature inductance (H), R_a is the armature resistance (Ω), i_a is the armature current (A), i_f is the current through the SC resistance (A), u is the SC ratio and R_f is the SC resistance (Ω). Equation (1) is derived with Kirchhoff Voltage Law applied to the loop excluding the SC resistance. Equation (2) is derived with Kirchhoff Voltage Law applied to the fault loop.

The torque-current equation is modified to reflect the SC effect as follows

$$T = Ki_a(1-u) + Ku(i_a - i_f) = K(i_a - i_f u) \tag{3}$$

where K is the torque coefficient (Nm/A) and T is the generated torque (Nm).

The torque equation is derived according Newton's second law:

$$T - T_L = J\frac{d\omega}{dt} \tag{4}$$

where T_L is the load torque (Nm), J is the rotor inertia (kgm^2) and ω is the rotor speed (rad/sec).

The DC motor drive system to achieve constant speed is modeled in MATLAB/SIMULINK environment using a closed-loop current and closed-loop speed control.

Since the armature resistance and inductance are linearly affected by the SC ratio, the coil resistance and inductance in winding coil 1 can be calculated as in Equations (5) and (6).

$$R_{a1} = R_{a0} * (1-u) \tag{5}$$

$$L_{a1} = L_{a0} * (1-u) \tag{6}$$

where R_{a0} is the nominal armature resistance and L_{a0} is the nominal armature inductance when there is no fault.

Motor parameters and other simulation parameters used in this model are listed in Table 1.