Fault Analysis of a PM Brushless DC Motor Using Finite Element Method

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Abstract—**Three-phase trapezoidal back-EMF permanent magnet (PM) machines are used in many applications where the reliability and fault tolerance are important requirements. Knowledge of the machine transient processes under various fault conditions is the key issue in evaluating the impact of machine fault on the entire electromechanical system. The machine electrical and mechanical quantities whose transient behaviors are of importance under fault conditions include the voltages and currents of the coils and phases, the electromagnetic torque, and the rotor speed. Experimental test based on true machines for such a purpose is impractical for its high cost and difficulty to make. Computer simulation based on the finite element method has shown its effectiveness in fault study in this paper. Before the finite element model was used to perform simulations under fault conditions, it was validated by test data under normal conditions. Three types of fault conditions—single-phase open circuit fault, phase-to-phase terminal short-circuit, and internal turn-to-turn short-circuit have been studied.**

Index Terms—**Brushless machines, design methodology, finite element methods, permanent magnet machines, permanent magnet motors.**

I. INTRODUCTION

PERMANENT magnet (PM) brushless DC motors have been widely used because of their attractive features—compactness, low weight, high efficiency, and ease in control. In automotive industry, electrical power steering systems are being developed to replace the traditional hydraulic systems, where an electric motor is used as the actuator [1]. In such a system, high reliability and fault tolerance of the machine is required or strongly desired due to the safety concerns. Therefore, the fault tolerance of a particular design needs to be evaluated before putting it into practice. Knowledge of the impact of various fault conditions on the machine itself or on the entire electromechanical system is the basis of the evaluation. In order to find out the impact of faults, the transient process of the machine under fault conditions must be studied. The fault conditions can be external (phase-to-phase) short-circuit, internal turn-to-turn short-circuit, or open-circuit faults. The transient process of the machine refers to the transient processes of all machine electrical and mechanical quantities—voltages and currents of the coils, phases, and the DC bus, the electromechanical torque and rotor speed. These quantities under fault usually reflect the extreme (worst) cases that the machine designers need to face. Therefore, the results of fault studies provide evidence for the designers to improve the fault tolerance as well as the overall design of the machine and the drive.

Faults of electric machines can be studied through physical experiments and computer simulations. Obviously, the latter approach is much more economical and flexible. Without hardware prototyping, it is easy to change parameters to run different scenarios. Electric machines can be modeled using analytical approaches or time step finite element method (FEM). Compared to the analytical analysis, which is circuit oriented and uses linearized parameters representing magnetic property of the machine, time step FEM studies the behaviors of electromagnetic field inside the machine directly based on its geometry and material properties, and is therefore more informative and precise, especially under saturation. Fast developing computing power has made the time consumption of FEM much less significant. Therefore, FEM has been used in various machine fault studies, such as those addressing synchronous machines [2], [3], switched reluctance machines [4], [5], and induction machines [6]. The development of algorithms [7] to analyze coupled field circuit models expands the applications of FEM to the cases where the behaviors of electrical quantities in the conductors are concerned.

Fault studies of PM machines have been seen in the literature, where most of them used circuit models or experiments, such as in [7] and [9]–[12]. In the work by Goldemburg, *et al.* [13], FEM was also used, but only two fault cases were studied.

In this research, two-dimensional time stepping finite element analysis (FEA) is performed to simulate the transients of the electrical and mechanical parameters of a PM brushless DC machine that was previously studied in [1] and [14] under various fault conditions. The goal of the simulation is first to validate the finite element model against the experimental data measured under normal running conditions and secondly to use the validated model to run fault case simulations.

In this paper, the machine model will be introduced and the method of analysis will be presented. The FEA-based simulation results will be validated using experimental data and Fourier analysis. Three typical fault cases will be studied.

II. MODEL OF THE MACHINE

The trapezoidal back-EMF PM motor analyzed in this paper is a 3-phase, 6-pole, 18-slot machine. For torque ripple reduction consideration, a bifurcated tooth structure is used on the stator teeth which reduces the variation in reluctance as seen by

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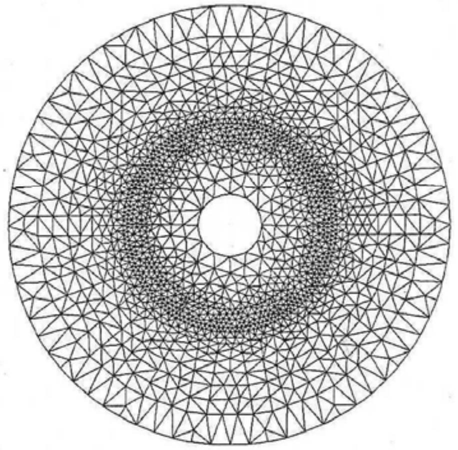

Fig. 1. Elements on the motor cross section for FEA.

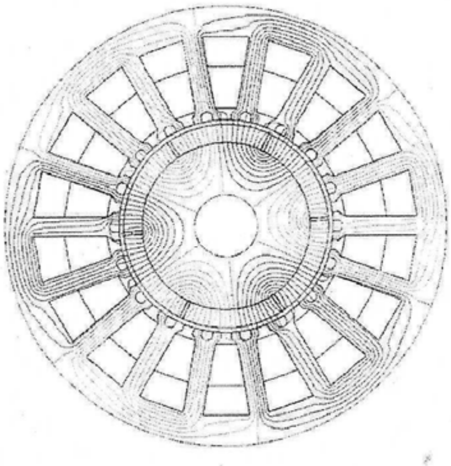

Fig. 2. Equiflux lines on the machine cross section at $t = 0.8$ sec.

the magnet and hence, reduces the cogging torque and doubles the frequency of cogging [14]. The bifurcated tooth structure has been optimized to obtain maximum reduction in cogging torque. The rotor of the motor has six nonsalient high energy Neodymium-Iron-Boron (Nd-Fe-B) magnet poles that are magnetized in the radial direction.

III. METHOD OF ANALYSIS

A. FEA and the Software Used

Two-dimensional time stepping FEA with coupled external circuit has been performed to compute the behavior of magnetic field and current under different fault scenarios. The FEA software tool Magsoft Flux2D was used in this simulation. The preprocessing, calculation, and post processing were performed following [15]. The fundamental theory of finite element method behind the software can be found in [16]. A total number of 3038 elements on the machine cross section are shown in Fig. 1. Flux2D uses exclusively second order elements.

A rotating air-gap and an external circuit are applied in the model for transient simulation and circuit fault studies. Newton-Raphson's method is used to solve the equations. The maximum number of iteration for FEA is 50 and that for circuit solution is 80. Details about the circuit will be discussed in later sections.

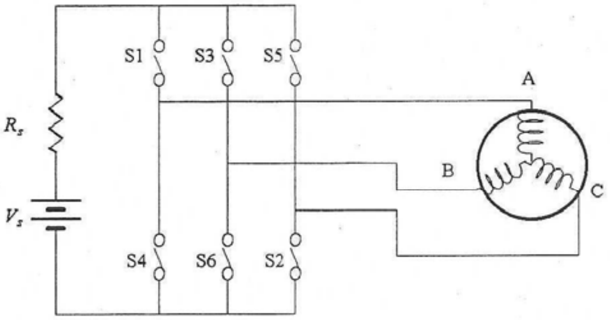

Fig. 3. Drive system for a 3-phase brushless DC motor.

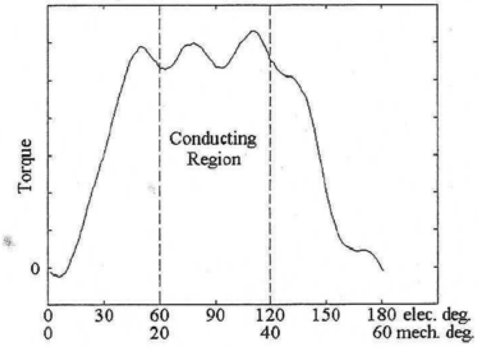

Fig. 4. Torque waveform over 180° (elec.) under fixed switching pattern.

The equiflux lines on the machine cross section under regular working condition at a certain moment are shown in Fig. 2.

B. Commutation Scheme in the Simulation

The commutation scheme of the motor studied is described here for better understanding of the torque waveform presented in later sections for the validation of the FEA model. A three phase brushless DC motor fed by an inverter (as shown in Fig. 3) has six switching patterns S1 + S2, S2 + S3, S3 + S4, S4 + S5, S5+S6, and S6+S1 sequentially. Each of the switching patterns lasts for a period of 60 electrical degrees (20 mechanical degrees for a 6-pole machine). During each switching period, two of the three phases are conducting. Under a stationary stator MMF generated by any certain switching pattern, motoring magnetic torque is generated, while the center axis of the rotor MMF rotates from the position of 180 electrical degrees apart from the center axis the stator MMF to the position aligned with the center axis of the stator MMF. The torque waveform over this 180° (electrical) region is approximately trapezoidal as shown in Fig. 4, where the rotor starting position is set to be 0°. In practical applications, a given pair of switches conducts only 60° (electrical) out of the 180° due to the commutation. In order to maximize the output torque, the 60° region centered at 90°, i.e., from 60° to 120°, is selected to be the conducting region (the area between the dashed lines in Fig. 4). As for the studied 6-pole PM machine, the conducting region is 20 mechanical degrees, i.e., from 20° to 40° (mechanical).

C. Fault Patterns to be Studied

In this paper, a single-phase open circuit fault, a machine terminal phase-to-phase fault, and an internal turn-to-turn fault are studied.

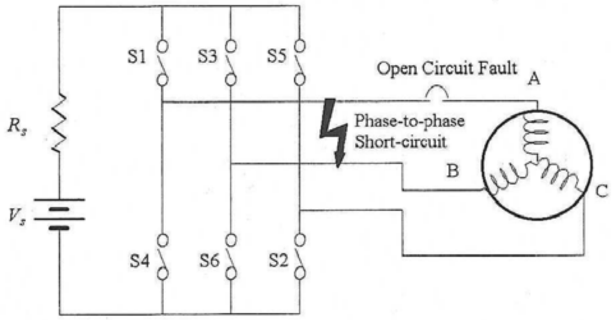

Fig. 5. Single phase open circuit fault and phase-to-phase short-circuit.

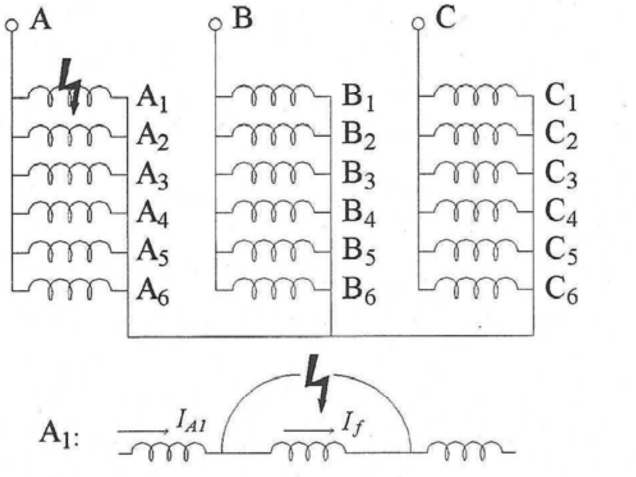

Fig. 6. Winding diagram with internal turn-to-turn short-circuit in coil A_1.

A single-phase open circuit fault and a terminal phase-to-phase fault short-circuit are illustrated by Fig. 5, where an open circuit occurs in one of the three phases at machine terminal under normal running condition, and a two-phase short-circuit happens at the terminal under normal running condition. These two cases will be studied separately in this paper.

An internal turn-to-turn short-circuit can happen within one coil or between two coils of the same phase, or between two different phases. In this paper, only the first case illustrated by Fig. 6 is studied. As shown in the winding diagram, parallel winding is used due to the low voltage, high current nature of the machine. In Fig. 6, short-circuit happens in coil A1. I_{A1} is the current through the normal portion of A1 while I_f is the current through the shorted portion.

D. Fault Modeling for FEA and Preliminary Considerations

As discussed in the above section on the principle of FEA, two-dimensional (2D) FEA of transient magnetic field is coupled with an external circuit where a fault pattern is applied. In the external circuit modeling, short-circuit is modeled by a switch closed at fault time, whose open resistance is infinity, and closed resistance is zero. An open circuit fault is modeled by a switch that is opened at fault time, whose closed resistance is zero and open resistance is a large finite number for numerical computation considerations.

Since the motor studied is designed for power steering applications in which the motor provides assisting steering torque following the driver's operation. In such a system, the transient response must be fast, which requires very small rotor inertia, and the load torque must be damping type, which is always against the rotor speed. Therefore, once the motor loses driving torque due to a fault, the rotor speed tends to decay fast and the motor will not be able to run as a generator in a sustainable manner, which reduces the possibility of over current in stator windings under short circuit.

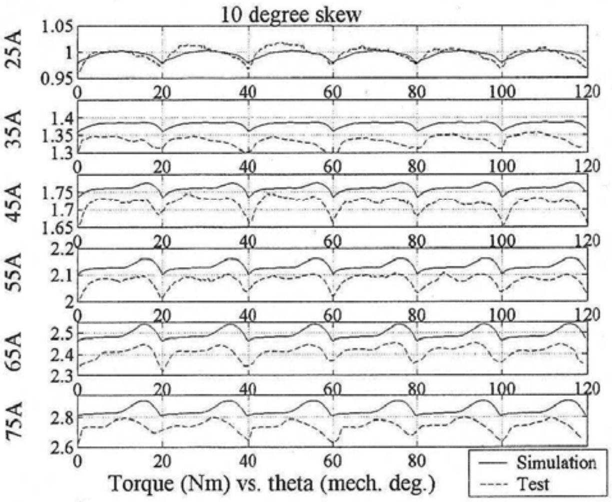

Fig. 7. Simulation and test torque waveforms under different currents over an electrical revolution (120 mechanical degrees).

IV. Simulation Results and Analysis

A. The Validation of the Simulation Results

Before the simulation model is used for fault case simulation, it is used to run normal operating condition. Steady state simulations for the purpose of validation under various current excitations—25, 35, 45, 55, 65, and 75 amperes are performed and experimental measurements have also been conducted. Electromagnetic torque has been computed. In Flux2d, the magnetic torque calculation is performed by a method based on the virtual work, sometimes referred as the Coulomb Method named after Jean Louis Coulomb who introduced this method 20 years ago [15]. The computed torque waveforms over 120° (one electrical revolution) have been plotted together with the corresponding test results and shown in Fig. 7. The test results are obtained through torque measurement calibrated and kept under QS 9000 requirements. The accuracy is about ±2.5 mN-m. Fig. 7 shows that the simulation-based torque waveforms are generally close to the test results. The mean torque values of the simulation-based torques are slightly greater than those of the test-based torques in most cases. This is due to the existence of mechanical and core losses, measurement, modeling, and computation errors. Skew effect is considered in the simulation.

Further comparison between the simulation-based ripples and the test-based ones have been performed by observing the Fourier contents of these signals. Considering the six pulses per electrical revolution as the fundamental frequency, the Fourier decomposition shows that the harmonics with an order above three are insignificant and negligible. Fig. 8 shows the magnitudes of the first three harmonics of the torque ripples under one excitation condition. The situations are similar under the other running conditions.

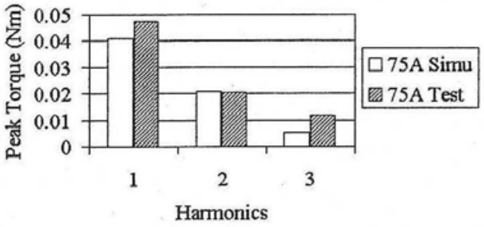

Fig. 8. Fourier contents in simulation and test torque ripples at 75 amperes.

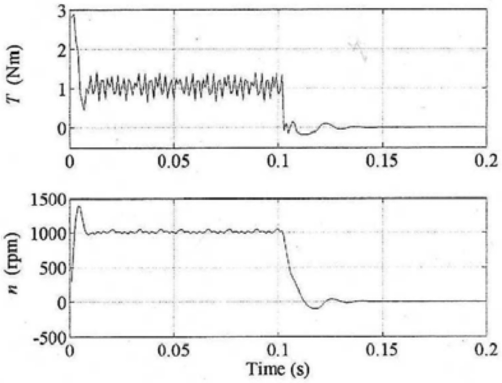

Fig. 9. Rotor torque and speed responses under an open circuit fault.

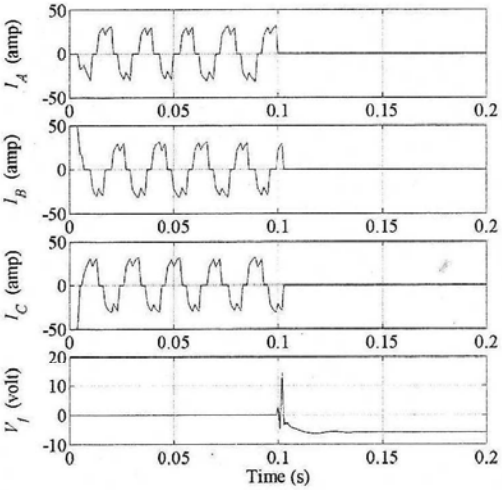

Fig. 10. Phase currents and the open circuit point voltage.

These comparisons demonstrate the similarity between the simulation-based torque ripples and the test-based ones from two aspects—the absolute values of the simulation data and the test data are reasonably close and the relative relation of the first three harmonics of the simulation data are generally the same as that of the test data. Please also note that the analysis did not consider miscellaneous effects like position sensor accuracy and skewing accuracy.

B. Open Circuit Fault Study

The validated finite element model is used to perform fault simulations. The machine mechanical and electrical transient responses under a single-phase open circuit fault are shown in Figs. 9 and 10.

In the simulation, a 6 V DC voltage source and a damping load ($\lambda = 0.01\ \mathrm{N \cdot m \cdot s}$) are used and the fault occurs on phase A at $t = 0.1$ sec. In Fig. 9, it is easy to notice that the electromagnetic torque and rotor speed curves have significant ripples which is because no skew effect is considered in the simulation and the machine has a very small moment of inertia $J = 4.0 \times 10^{-5}\ \mathrm{kg \cdot m^2}$. Again, because of the low mechanical inertia, the machine speed exhibits very fast response to the driving torque decay. Phase A current jumps to zero and a big spike voltage is induced across the break point due to the instant open circuit as shown in Fig. 10. Notice that a large finite open circuit resistance is used in the simulation instead of infinity for numerical computation purposes. Phase B and C currents also decay to zero after the last B-C conducting because the commutation is stopped.

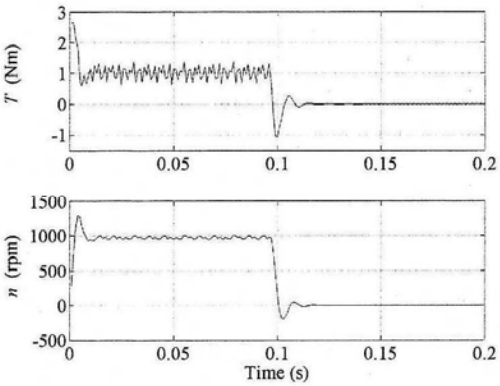

Fig. 11. Rotor torque and speed responses under a terminal short-circuit between phase A and B.

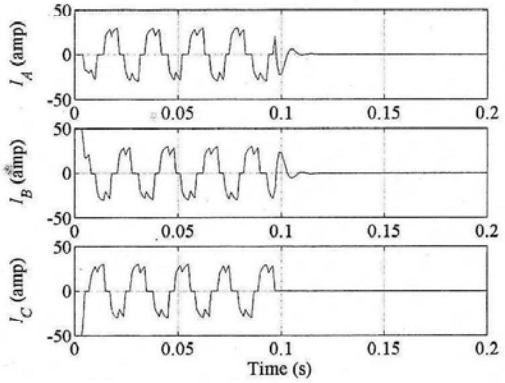

Fig. 12. Winding phase currents under a terminal short-circuit between phase A and B.

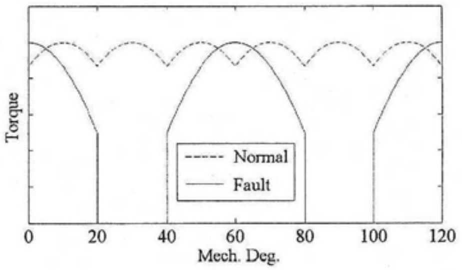

Fig. 13. Static torque profiles under normal condition and under a terminal short-circuit between phase A and B.

C. Terminal Phase-to-Phase Short-Circuit Study

A short-circuit between phase A and B at the machine terminal is applied in the simulation. The fault occurs at $t = 0.1$ sec. The torque and speed curves are shown in Fig. 11 and the phase currents waveforms are shown in Fig. 12.

Fig. 13 shows the static torque profiles under normal condition and under the A-B terminal short-circuit condition from

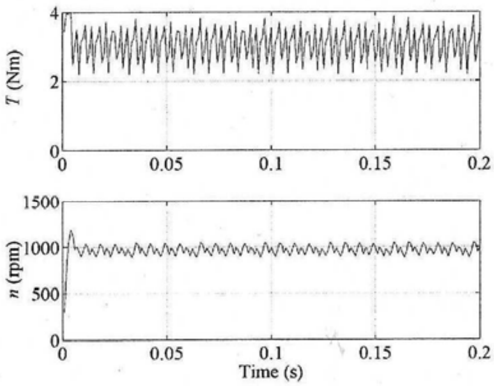

Fig. 14. Mechanical responses under an internal turn-to-turn short-circuit.

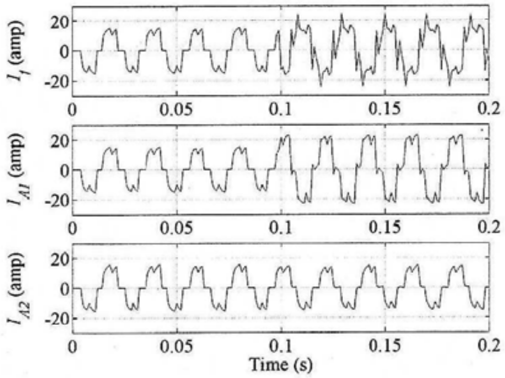

Fig. 15. Currents through the shorted and normal portions of coil A_1 and a normal coil A_2.

a theoretical view. Notice that for a 6-pole machine, 120 mechanical degrees is an electrical cycle. Under the fault condition, there exist two zero-torque regions (i.e., the 20°–40° region and the 80°–100° region in terms of the rotor position) within one electric cycle. Once the rotor position enters either of the zero-torque regions, the rotor will lose driving torque and stop running quickly due to its small inertia and the damping load. This analysis has been demonstrated by the simulation results shown in Figs. 11 and 12.

D. Internal Turn-to-Turn Short-Circuit Study

A normal coil has 26 turns. A short-circuit across 6 turns in coil A_1 (see Fig. 6) is applied in the simulation. Such a fault may not affect the sustainability of the motor operation. Due to the concerns of over current and demagnetization, the worst case—a short circuit under full load (phase current 75 A) condition is considered. The fault occurs at $t = 0.1$ sec. The simulation results are shown in Figs. 14–16.

In Fig. 14, no change can be observed from the torque or speed curve as the fault occurs. Fig. 15 shows currents in the shorted portion and the normal portion of coil A_1 and a normal coil A_2, which are denoted by I_f, I_{A1}, and I_{A2} respectively. It can be observed that the peak values of I_f and I_{A1} increase for approximately 60% and I_{A2} does not change. The net current in phase A increases slightly as shown in Fig. 16. Further calculation exhibits that RMS values of I_f and I_{A1} increase for 40% and 64% respectively on the full load basis, which tends to damage coil A_1 in practical applications.

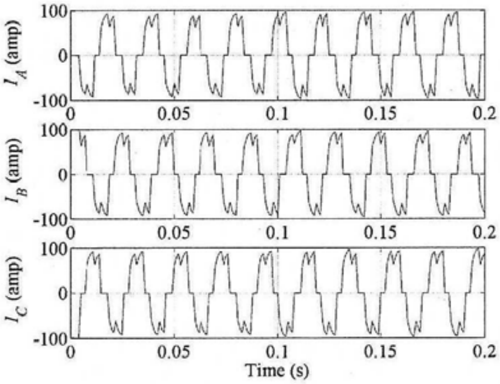

Fig. 16. Phase currents under an internal turn-to-turn fault.

E. Demagnetization Issue

According to permanent magnet theory, the operating point of a permanent magnet moves along either its demagnetizing curve or its recoil line when external field changes. Over current in stator windings may cause high demagnetizing field intensity to force the operating point of the permanent magnet to a recoil line with lower energy product, which is so called demagnetization. However, the demagnetizing curve of Nd-Fe-B materials is a straight line, i.e., it is overlapped with the recoil line. As long as the demagnetizing field would not reverse the flux density in the pole (operating point remained in the second quadrant of B-H plane), demagnetization could not occur. In above simulation scenarios, over current only occurs in some coils under internal turn-to-turn fault. In order to study the possibility of demagnetization in this case, flux density values on 18 points evenly distributed on rotor circumference are recorded during the whole simulation. The minimum flux density value is 0.5095 Tesla, which would not cause demagnetization. Since this is already the worst case—full load operating condition, demagnetization would not occur under given fault scenarios.

V. CONCLUSIONS

A FEA based simulation study has been performed to analyze the transient processes of the mechanical and electrical quantities of a three phase trapezoidal back-EMF PM machine under three types of fault cases—single phase open circuit fault, phase-to-phase terminal short-circuit between two phases, and an internal turn-to-turn short-circuit within one coil. The finite element model of the machine has been validated using experimental test data under different steady state running conditions. The test-based validation substantially consolidates the accuracy of the finite element model and the fault study results that cannot be validated directly using experimental data. The open circuit fault study shows that an open circuit fault stops the machine from running and causes significant voltage impulse across the breaking point. The terminal phase-to-phase short-circuit stops the machine from running due to the zero-torque region, in terms of the rotor position. In the turn-to-turn fault study when a small number of turns of a coil are shorted, the current through the faulted coil increases significantly and could damage the coil in practical applications, although the overall performance of the machine may not be significantly affected at the short-circuit moment. Demagnetization of the magnets will not occur under studied fault scenarios. Although the above results may not complete the fault tolerance research of the machine, this paper has provided an effective methodology for that purpose.

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