

Post-Fault Demagnetization Investigation for Partitioned Rotor Permanent Magnet Flux Switching Machine by Transient Co-Simulation Approach

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In this paper, the demagnetization characteristics of the partitioned rotor permanent magnet flux switching (PR-PMFS) machine under short-circuit faults are investigated. Since the investigation requires to be conducted in the magnetic field and driving control simultaneously, a new transient co-simulation approach is proposed for accurate and comprehensive demagnetization analysis. Furthermore, to ensure high-reliability operation of the machine, it is required that the risk of partial irreversible demagnetization of the magnets should be comprehensively assessed under the worst operating scenario, like short-circuit fault. Then, the demagnetization risk and the post-fault performance of the PR-PMFS under symmetrical three-phase short-circuit or asymmetrical two-phase short-circuit fault are quantitatively investigated and compared. The co-simulation results show that the demagnetization risk of the asymmetrical two-phase short-circuit fault is higher than that of symmetrical three-phase short-circuit fault, thus laying a foundation for the high-reliability operation of the ferrite PM machine.

Index Terms—Irreversible demagnetization, transient co-simulation approach, short-circuit faults, flux switching permanent magnet machines, ferrite permanent magnet.

I. INTRODUCTION

RECENTLY, rare-earth permanent magnet (PM) machines have been widely applied in various industrial applications, such as electric vehicles, hybrid electric vehicles, and ship propulsion, due their merits including relatively high torque/power density and high efficiency [1]-[2]. However, the limitation of the rare-earth PM material has emerged, because of the unstable supply and the fluctuating price of it [3]. Therefore, the research of alternative ferrite PM machine has become increasingly popular in the electric machine field [4]. Yet, due to that the coercive force of ferrite PM is relatively low, the partial irreversible demagnetization phenomenon will very possibly to occur. And the risk of irreversible demagnetization can be further intensified, when machines operate under some extreme conditions, such as overload, high temperature, and deep flux-weakening. Furthermore, when machines are exposed to short-circuit faults, the winding short-circuit current can be more than 5 times higher than its maximum rating, which will severely impact the high-reliability operation of machines [5]. Hence, in the ferrite PM machines field, it has been a hot but challenging issue on how to comprehensively assess the machine demagnetization risk, particularly when machines operate under the worst operating scenario like short-circuit faults.

In this paper, the partitioned rotor flux switching permanent magnet (PR-PMFS) machine with the ferrite PM is investigated as an example. To analyze the PR-PMFS machine behavior after the short-circuit faults precisely and comprehensively, a new transient co-simulation approach is proposed, in which the magnetic field and the electric circuit solver are coupled in the same time domain. Then, the demagnetization risk of the PR-PMFS machine during symmetrical and asymmetrical short-circuit fault are investigated by the transient co-simulation approach. And the demagnetization risk of the PR-PMFS machine under different short-circuit faults are compared, indicating that the asymmetrical two-phase short-circuit pose a

more serious demagnetization risk, which lays a foundation for high-reliability operation of the ferrite PM machine.

II. MACHINE STRUCTURE

The 3-phase, 6-slot, 7-pole partitioned rotor flux switching permanent magnet (PR-PMFS) machine with ferrite PM is proposed, as shown in Fig. 1. In the PR-PMFS machine, the inner and outer rotors are connected together as one moving component by an end disk, thus forming the so-called partitioned rotor configuration. Meanwhile, the no-stator-yoke design is adopted in the stator of the machine, assembled by six “I”-shaped modular stators. By the cooperation of partitioned rotor and no-stator-yoke design, the serial magnetic path can be formed between two adjacent modular stators. Hence, the outer flux leakage can be eliminated and the PM utilization can be effectively improved.

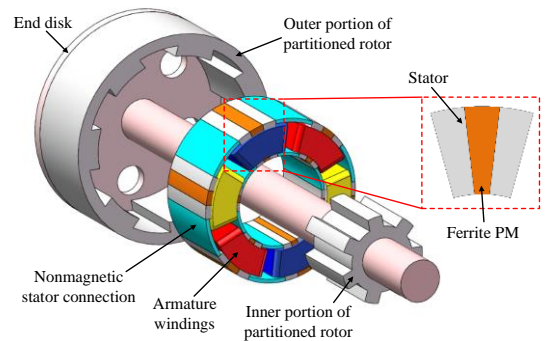


Fig. 1 The three-dimensional structure of the PR-PMFS machine.

III. DEMAGNETIZATION ANALYSIS OF PR-PMFS MACHINE

In order to analyze the demagnetization characteristics of the PR-PMFS machine during the transient fault condition accurately, the transient co-simulation approach based on finite element method is proposed, as shown in the Fig. 2. When the short-circuit fault transient occurs at the machine terminals, the corresponding magnetic field is also reconstructed. Thus, the operating point of the ferrite PM can be calculated, which determines whether the ferrite PM is irreversibly demagnetized.

Then, if the ferrite PM element is considered to be irreversible demagnetized, the residual flux density is renewed by considering the B-H curve. Hence, the post-fault demagnetization characteristics and machine performance can be obtained. In this transient co-simulation approach, the machine magnetic field and the electric circuit analysis are coupled in the same time domain, making the analysis results comprehensive and accurate.

The transient co-simulation of the PR-PMFS machine is carried out under the symmetrical three-phase short-circuit and asymmetrical two-phase short-circuit fault, and the transient behavior is observed. The post-fault transient behaviors of the PR-PMFS machines are demonstrated in the Fig. 3 and Table I, including torque, phase currents, and d - q -axis current. When short-circuit faults occur at machine terminals at 24ms, the phase currents declines sharply, as seen in Fig. 3. It is indicated that the PR-PMFS machine suffer from serious risk during short-circuit fault than normal operating condition, due to large negative fault demagnetizing current during fault transients. It is observed from the Table I that the amplitude of peak d -axis current flowing in machine in event of two-phase short-circuit is larger than that after the three-phase short-circuit, indicating that the asymmetrical two-phase short-circuit pose a more serious risk demagnetization for PR-PMFS machine.

Additionally, the demagnetized regions before and after two short-circuit faults in PR-PMFS machine are compared in the Fig. 4. As expected, the demagnetized area of PR-PMFS under three-phase short-circuit is less than half of that under two-phase short-circuit.

In conclusion, the analysis results not only verify the effectiveness of the proposed transient co-simulation approach for demagnetization analysis, but also prove the validity that asymmetrical two-phase short-circuit pose a more serious risk demagnetization, which lays a foundation for high-reliability operation of the ferrite PM machine.

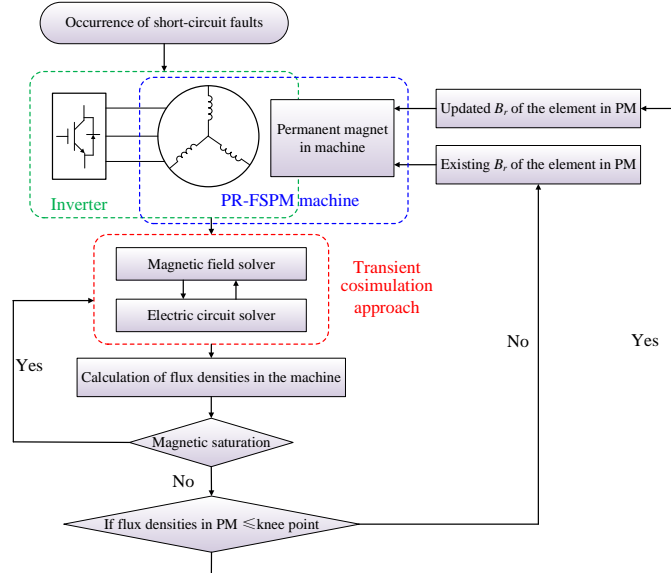


Fig. 2 Flowchart of partial demagnetization analysis of PR-PMFS machine by the transient co-simulation approach.

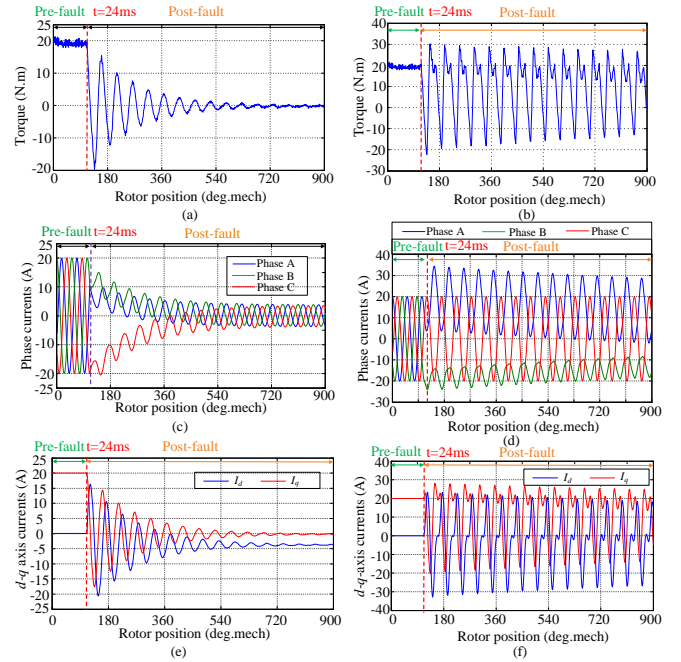


Fig. 3 Transient response of PR-PMFS machine under short-circuit faults. (a) Torque during three-phase short-circuit. (b) Torque during two-phase short-circuit. (c) Phase currents under three-phase short-circuit. (d) Phase currents under two-phase two-circuit. (e) d - q -axis currents under three-phase short-circuit. (f) d - q -axis currents under two-phase two-circuit.

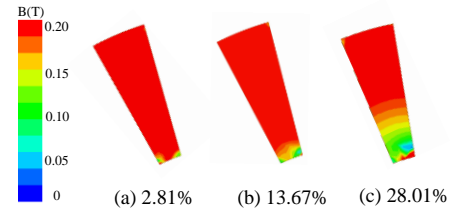


Fig. 4 Demagnetized regions of PR-PMFS machine under short-circuit faults. (a) Pre-fault demagnetized region of PR-FFPM machine. (b) Post-fault demagnetized region after three-phase short-circuit fault. (c) Post-fault demagnetized region after two-phase short-circuit fault.

TABLE I
DEMAGNETIZATION CHARACTERISTICS COMPARISON OF PR-PMFS MACHINE UNDER TWO SHORT-CIRCUIT FAULTS

Item	Three-phase short-circuit	Two-phase short-circuit
Maximum generating torque (N.m)	-19.76	-22.01
Maximum d -axis current (A)	-20.64	-32.8
Corresponding q -axis current (A)	-9.16	-4.97
Steady-state short-circuit current (A)	-3.62	-15.06
Minimum operating point of PM (T)	0.18	0.05
Maximum demagnetized area ratio (%)	13.67	28.01

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