Fault Diagnosis in Brushless Permanent Magnet Synchronous Motor Drive

Thesis submitted in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

by

Adil Usman

Enrollment No. D15042

under the supervision of

Dr. Bharat Singh Rajpurohit

School of Computing and Electrical Engineering

Indian Institute of Technology Mandi
Kamand, Himachal Pradesh-175075, India

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DEDICATED TO MY PARENTS

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Declaration by the Research Scholar

I hereby declare that the entire work embodied in this Thesis is the result of investigations carried out by me in the **School of Computing and Electrical Engineering,** Indian Institute of Technology Mandi, under the supervision of **Dr. Bharat Singh Rajpurohit,** and that it has not been submitted elsewhere for any degree or diploma. In keeping with the general practice, due acknowledgements have been made wherever the work described is based on finding of other investigators.

Place: IIT Mandi
Date: 2nd-June-2020

Signature:
Name: Adil Usman

Declaration by the Research Advisor

I hereby certify that the entire work in this Thesis has been carried out by **Adil Usman,** under my supervision in the **School of Computing and Electrical Engineering**, Indian Institute of Technology Mandi, and that no part of it has been submitted elsewhere for any Degree or Diploma.

Signature:
Name of the Guide: Dr. Bharat Singh Rajpurohit

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Adil Usman

ABSTRACT

Brushless Permanent Magnet (PM) Synchronous Motors are widely used in various industrial applications due to their compactness, high efficiency, high torque density and high dynamic performance. Due to high proliferation of these motors in industrial applications, they are extensively been operated for longer durations. During the continuous heavy operation and unfavorable environmental conditions, Brushless PM Synchronous Motors are subjected to physical and thermal stresses which results in faults. Fault in a machine can be defined as any deviation in the machine quantities (under the conditions in which it is operating) from its normal behavior. Fault can manifest into electrical quantities like current and/or voltage, magnetic quantities like flux, acoustic noise and vibrations and thermal characteristics of the machine. Condition monitoring thus becomes prominent in detecting fault of the machine in its incipient state in order to avoid the failure of the complete system. This research area focuses on the detailed study of various rotor related faults like demagnetization effects in the of PMs and stator related faults like winding inter-turn faults for a Brushless PM Synchronous Motor. Detection and identification of faults in the machine is done through electromagnetic signatures like stator phase current (I_{ph}), back-EMF (E_B), electromagnetic torque (T_E) and mechanical speed (ω_m). However, in addition to the existing fault signatures, this research proposes a new magnetic flux density (B_M) fault diagnostic signature for detecting and identifying the faults in the machine.

The performance analysis of the Brushless PM Synchronous Motors through Magnetic Flux Analysis (MFA) is the significant and novel contribution to the fault diagnosis area. Using the magnetic flux density (B_M) signature, the detection, identification and localization of fault is achieved peculiarly for demagnetization fault analysis where the demagnetized pole is identified against the change in B_M profile for the corresponding half cycle. The distinct changes in the magnetic flux density profile for different types of demagnetization faults give information about the fault severity, thereby indicating the percentage loss of magnetism in the PM of the machine. The experimental validation of estimating demagnetization fault severity through magnetic flux signatures estimated through existing Hall Effect (HE) sensors placed inside the machine, gives more reliable and authentic information thereby adding a novel contribution to the motor fault diagnosis in heavy industrial applications.

Fault in a Brushless Permanent Magnet (PM) Synchronous Motors can be modeled through different available techniques such as Electrical Equivalent Circuit (EEC) based approach or analytical method which accounts several assumptions in order to simplify the analysis. While the modeling done through Numerical Methods (NM) such as Finite Element Analysis (FEA) gives more authoritative solutions. As a part of this research work, both the aforementioned approaches are combined together to develop a novel Hybrid EEC-Numerical model for a closed loop BLDC motor drive using Hysteresis Current Control (HCC) technique. The developed model is simulated both under healthy and fault conditions viz. demagnetization effects and Stator Inter-turn Faults (SITFs) and the performance of the machine is examined under the subjected conditions.

The comprehensive study and investigations on various demagnetization effects like change in magnetic coercivity H_C of poles *(uniform demagnetization),* broken magnet defect and extreme demagnetization of PMs are modeled in the developed Hybrid EEC-Numerical model of a Brushless PM Synchronous Motor. In addition, for emulating the stator winding faults, the insulation breakdown is modeled through the stator inter-turn and inter-phase short-circuit of the motor windings. The performance of the machine through change in electromagnetic quantities is analyzed under both the fault conditions.

For validating the proposed and developed modeling approach, the co-simulation of a numerically (FE) modeled Brushless PM Synchronous Motor with the Simplorer built electric drive is developed. The performance of the closed loop motor drive is examined under healthy, SITF and demagnetization fault conditions. Unlike the existing numerical simulations, the results obtained through the developed co-simulation-based techniques accounts for the change in the quantities affected by the emergence of fault on the complete drive system and not only due to the motor. Therefore, co-simulation analysis gives the actual performance of the machine with more accuracy. However, the computational time is more in comparison to the proposed Hybrid EEC-Numerical based method. The experimental investigation is carried through Field Programmable Gate Array (FPGA) based control drive adopting HCC technique. The experimental results are further validated out in support of the outcomes obtained through both the modeling approaches to gives an authenticity and validity to the proposed fault modeling methods.

It is been evident that during the occurrence of any of the two faults viz. SITF or demagnetization effect, the cause of one becomes the effect for the other. For instance, the breakdown of winding insulation which stimulates SITF in the machine, causes the heavy flow of inrush currents damaging the stator windings. Consequently, the effect of high currents is reflected on the PMs which adversely gets affected, thereby significantly losing its magnetizing characteristics. This cumulative effect induces the demagnetization effect in the machine and thus both the faults exist at the same time. Due to very limited or lack of research been focused on the aspect of identifying the type of fault when both exists simultaneously, this research work also includes the study and investigation in the change of machine quantities during the combined effect of both the SITF and demagnetization fault conditions. The combined fault effects are modeled and analyzed in both the developed models viz. Hybrid EEC-Numerical based model and FE-Simplorer based co-simulation analysis. The significant unique changes encountered in back-EMF and magnetic flux signatures during the combined fault effects, distinguishes and gives identification to each fault distinctively. The experimental analysis gives validation to the unique research findings which makes feasible to classify and identify the faults in the machine.

The research work carried out and the findings thus accomplished is pertinent to both the research and industrial applications as it gives a new fault modeling technique offering less computational time and novel fault diagnostic signature for detecting, identifying and localizing fault in the machine. The demagnetization fault severity estimation through magnetic flux signatures is a novel solution to the existing industrial problem in machine fault diagnosis. In addition, the distinct parameters obtained during the combined effect of SITF and demagnetization fault effects aids to classify and identify the fault distinctively and further is a unique and feasible real time solution to motor fault diagnosis.

***Keywords* — Brushless Permanent Magnet (PM) Synchronous Motor, Demagnetization, Electrical Equivalent Circuit (EEC) based Method, Fault Diagnosis, Finite Element (FE) Method, Hybrid Analytical-Numerical Approach, Magnetic Flux Analysis (MFA), Numerical Method (NM) and Stator Inter-turn Fault (SITF)**

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