Modeling of Multi-phase Permanent Magnet Synchronous Motors under Open-phase Fault Condition

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Abstract—This paper deals with the modeling of multi-phase permanent magnet synchronous motors under open-phase fault condition. Multi-phase electrical motors offer high reliability thanks to their capability to operate safely even in case of faults such the loss of some phase. In this paper the model of a multi phase PM machine in the case of open phase fault condition is proposed. The model is suitable for generic number of phases, generic shape of the rotor flux and the open circuit fault can occur to any phase. The motor model in fault condition is presented for faults occurring on one single phase or more than one phase (both adjacent and not adjacent phases). The use of a model is very useful both for simulations and implementation of fault-tolerant control strategies.

I. INTRODUCTION

Multi-phase machines offer some advantages and greater number of degrees of freedom compared to three-phase machines, see [1] and [2]. One of these advantages is the better fault tolerance and this is very important in propulsion and traction applications where high reliability is a very important issue. Many kinds of faults can occur in multi-phase PM machines and the realization of a model can be helpful in analysis and simulation of the machine in faulty operation mode. A great number of fault-tolerant control strategies have been proposed, see [3], [4] and [5], in order to make the motor able to operate safely even in case of fault in particular obtaining ripple-free torque and minimizing losses. In [10] the modeling and control of a three-phase PMSM in the case of open phase fault condition is investigated. However in the literature any effective model for the faulty motor has been provided yet.

In this paper the model of a multi-phase PM machine in case of open circuited phase is proposed. The model is as general as possible, for a generic number of stator phases and for generic periodic shape of the rotor flux. The open circuit fault can occur to any of the phases. The model is obtained with the Power-Oriented Graphs modeling technique and can be directly implemented in a general-type simulator. Thanks to this model the different control strategies for faulty operation of the motor can be tested before the implementation on a real machine.

The paper is organized as follows. Sec. II introduces the main features of POG technique, Sec. III shows the details of the dynamic model of the \( m \)-phase synchronous motors, in Sec. IV the model of the motor in open phase fault condition is presented and Sec. V is devoted to simulation results. Conclusions are given in Sec. VI.

II. POWER-ORIENTED GRAPHS BASIC PRINCIPLES

The Power-Oriented Graphs technique, see [7], is an energy-based technique suitable for modeling physical systems. The POG are block diagrams combined with a particular modular structure essentially based on the use of the two blocks shown in Fig. 1.a and Fig. 1.b: the elaboration block (e.b.) stores and/or dissipates energy, the connection block (c.b.) redistributes the power within the system without storing nor dissipating energy. The c.b. transforms the power variables with the constraint \( x_1 y_1 = x_2 y_2 \). The circle in the e.b. is a summation element and the black spot represents a minus sign that multiplies the entering variable. The POG keep a direct correspondence between the dashed sections of the graphs and real power sections of the modeled system: the scalar product \( x^T y \) of the two power vectors \( x \) and \( y \) involved in each dashed line of a POG, see Fig. 1, has the physical meaning of the power flowing through that particular section. Another important aspect of the POG technique is the direct correspondence between the POG representations and the corresponding state space descriptions. For example, the POG scheme shown in Fig. 2 can be represented by the state space equations given in (1) where the energy matrix \( L \) is symmetric and positive definite: \( L = L^T > 0 \). The dynamic model (1) can be transformed and reduced to system (2) using a “congruent” transformation.

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