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A comprehensive power loss evaluation for Switched Reluctance Motor in presence of rotor asymmetry rotation: Theory, numerical analysis and experiments

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ABSTRACT

In this paper, the effect of different rotor asymmetry rotation faults on the power loss variations in Switched Reluctance Motor (SRM) is studied deeply. To fulfill this objective, SRM's core losses including hysteresis and eddy current losses accompanied with its copper losses are firstly introduced theoretically in detail. Then a 6 by 4 SRM is simulated and motor profiles as well as power losses factors are measured in presence of three common eccentricity faults namely as; static eccentricity (SE), dynamic eccentricity (DE), and mixed eccentricity (ME) faults. The numerical analysis and simulations are done by the three-dimensional Time-Step Finite Element Method (3D-TSFEM). In next step, a similar test rig is designed and built for experimental measurements and confirmations. It was realized that, these types of eccentricity faults directly affect the power loss value and can enhance it abundantly. In other word, the more severity in fault levels conclude the more reduction in output power and the more increment in power losses that can be used as diagnosis index.

1. Introduction

Switched reluctance machines have a wide range of application in industry as electric machines, wind turbines, generator starters, ventilators, water pumps, washing machines and so on. Due to the simple and stable rotor structure, superior cooling, flexible geometry, long life, and high working temperature of the rotor, SRMs have a lot of advantages over conventional DC and AC machines [1–3]. Its increasing popularity has urged people in industry and also researchers to operate this machine such that the least torque ripple, power loss and the highest power is attained [4–6]. Thus recognition and evaluation of the losses play a vital role in obtaining the desired condition of operation. Some of the losses, like rotor eccentricity, demagnetization faults are directly proportional to the operation time of the machine [7–9]. An eccentricity fault is a mechanical fault that is a result of errors in manufacturing, defects in rotor installation, or bad bearings in the machine. In reluctance machines air gap length is much smaller than other machines [10], so the existence of such faults and errors results in undesired effects in the electromagnetic behavior of the machine and leads to asymmetric flux under the rotor and stator poles which finally lowers the working hours of the machine [11]. This can also produce noise and vibration, and eventually fatigues and or even ruptures the straps, if there are any [12,13]. Considering the fact that the uniformity of the magnetic field inside the rotor and stator may be interrupted, this can lead core losses and consequently decreases the motor and converter's efficiency [14]. So the effects of the rotor eccentricity on SRM are considerable. There is a serious lack of extensive study about different eccentricity faults which are dynamic eccentricity (DE), static eccentricity (SE), and mixed eccentricity (ME) [15]; and the effects of these on losses and efficiency of reluctance machines. But the most attention about these losses have been on other machines [16,17].

It has been many years since eccentric behavior has been studied in a variety of motors, based on studies of unbalanced magnetic pull (UMP) and also based on flux calculation in the air gap [18], also a lot of methods have been introduced to recognize it. On the other hand, the majority of the papers focusing on rotor eccentricity have utilized analytical methods, but in recent years the importance of numerical methods has been emphasized and consequently FEM [19], nonlinear artificial neural network model [20] and reluctance networks [21] are used. Wide region of applicability, capability to be analyzed in eccentric faults considering saturation and the type

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Nomenclature

Φ	magnetic flux
B	magnetic flux density
s	area
n	normal vector
A	magnetic potential vector
μ	magnetic permeability
σ	conductivity
J	current density
I_{ph}	phase current
v	voltage source
R_{ph}	resistance of the phase
θ	rotor's angle
R_l	wiring resistance
R_w	winding resistance
f	frequency of rotation
K_h	hysteresis loss coefficient
K_e	eddy current loss coefficient
g	air gap length
r	transfer vector
H	magnetic field intensity
Ω	random surface of the air gap
G	Jacobian matrix
T_s	time period of the phase current
m	number of phases
Δt	time of the parameter sampling
N_s	number of stator poles
N_r	number of rotor poles
ω	angular velocity of the rotor
τ	rotor torque
P_{fe}	core losses
P_{ohmic}	Ohmic loss
P_h	hysteresis loss
P_e	eddy current loss
t	lamination thickness ratio
α	exponential coefficients
β	exponential coefficients
η_m	overall efficiency
e	percentage of eccentricity fault

of core, temperature, winding, method of driving and finally high precise controllability can be mentioned as the advantages of employing FEM. For example, copper losses of a SR motor in [22] have been considered via a new torque control method. In [23] by using FEM, core losses were computed in different parts of the SRM. In [24] by using Transient-FEM, copper losses in the SRM and core losses in different parts of the motor have been analyzed. In [25], utilizing FEM the Ohmic and core losses are computed. Furthermore, the temperature rise due to these losses has been analyzed. Also in [26] the effect of DE and SE on power losses of induction machines using PWM voltage control is analyzed by 2D-FEM.

In the recent works, authors have assessed SE [27], DE [28], ME [29] and AE (axial eccentricity) [30] in the SRM. In [31], the fault signature is achieved by processing the differential currents resulted from injected high frequency diagnostic pulses to the motor windings. This method is proposed for the detection of fault location, severity and its occurrence. Paper [32] presents a new method for noninvasive diagnosis of static, dynamic and mixed eccentricity faults in SRMs. This method made it possible to precisely determine the eccentricity fault features. In [33], a comprehensive off-line sensorless method is presented. This method is able to detect occurrence, location, direction and severity of the eccentricity fault in SRM, based on voltage signature analysis.

The aim of this paper is to analyze the effects of different eccentric faults (DE, SE, ME) on typical losses of the SR motor using the analytical result, simulation and experiments with comparing them. This paper is organized in the following way: In Section 2 a simple model of a SR motor is introduced which allows a faster solution. In Section 3 the theory of losses due to asymmetrical faults in the SRM, is analytically evaluated. In Section 4 simulation is utilized in order to compute the variety of losses in DE, SE, and ME faults. In Section 5 the experimental results showing the effect of the faults, are shown and compared with the results of the simulation. In Section 6 the main points of the paper are gathered and some concluding remarks are presented.

2. SRM modeling

The three-dimensional finite element modeling considers all the fringing and leakage field components, which some of them are ignored in two dimensional models. In this method, electric vector potential (T) has been utilized for solving the magnetic field problems. This method is based on the variational energy minimization technique to solve for the electric vector potential. This method is known as $T - \Omega$ technique. For this purpose, the MagNet CAD package is utilized, that in this solution the total number of nodes is 35,891. Also, the total number of edges and faces are 109,502 and 73,661, respectively. The modeled SRM without peripheral equipment is illustrated in Fig. 1a (shaft, driver, stack, fan, pins, bearings and etc. are not shown for simple view).

In this paper, it is assumed that speed of rotation has reached steady-state and immediately after opening the switch of one phase, the corresponding winding current drops to zero. In order to obtain a better simulation for the rotor rotation, the air gap region is modeled with two separate co-axial circular regions (Fig. 1).

The equations that are related to the field are solved individually for different parts of the motor (e.g. stator, rotor, and air gap). The mesh in the stator and rotor does not change compared to the pre-fault condition and only the region of mesh in the air gap changes (That is the "Mesh region" in Fig. 1b) which is also solved faster by FEM.

3. Analytical assessment

In order to compute the variety of losses in the SRM, first the magnetic flux Φ (Wb) in the stator winding, the pole air gap, and rotor and stator cores should be computed by the following equation:

$$\Phi = \iint_s (B \cdot n) ds \qquad (1)$$

In the above equation n is the normal vector to s and B is the magnetic flux density (Tesla) which crosses s (mm^2). In order to obtain the desired outcome, Maxwell's equations can be used as same as what illustrated in [34,35] due to the fact that electric machines operate like quasi steady-state systems. In addition, to calculate hysteresis and eddy current, using the "Lorenz Gauge" hypothesis [36], Maxwell's equation is written as follows:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A \right) = J - \sigma \frac{\partial A}{\partial t} \qquad (2)$$