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A fast general core loss model for switched reluctance machine

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ABSTRACT

In the present paper, an analytical core loss model is introduced for the SRM (switched reluctance machine) which can be applied to different conventional types of this machine. Using the two mathematical models introduced before, the static characteristic of flux-linkage with a phase is obtained accurately in the core loss model first. Analyzing the machine based on the phase voltage equation, the stator pole flux waveform is then predicted. Considering an available flux model in the developed core loss model, the flux waveforms in various parts of the magnetic circuit of the machine are derived from the predicted stator pole flux waveform. Since the determined flux waveforms are completely non-sinusoidal, the improved Steinmetz equation is utilized in the developed core loss model for core loss estimation. In order to use the core loss model which is implemented totally in MATLAB software, one should just identify the design and control parameters. Due to high computation speed, the developed model can be utilized appropriately for optimal design of the SRM. Experimental results and finite element calculations are given for validation of the developed core loss model.

1. Introduction

The SRM (switched reluctance machine) is a salient pole machine in which there is the concentrated winding only on the stator. Due to absence of the winding and magnetic on the rotor, this machine can be used appropriately in harsh conditions. For performance prediction and optimal design of the SRM, an appropriate electromagnetic model is required. In addition, one of main parts of the electromagnetic model is core loss calculation. It is difficult to model core loss of the SRM because accurate prediction of flux waveforms within the machine is complicated and in addition, the flux waveforms are completely non-sinusoidal. For single-phase excitation of SRM, the flux waveforms in different parts of the machine can be derived from the stator pole flux waveform as it is done in many available core loss models [1–9]. Ignoring the phase resistance, the stator pole flux waveform can be supposed to be a triangular waveform [1,2]. This waveform can be obtained carefully using analyzing the machine with analytical method [3,4] and finite element method [5–9]. Since the flux waveforms obtained in different parts of the SRM are non-sinusoidal, various approaches have been introduced in these core loss models for calculating the corresponding core loss mostly based on the Steinmetz equation.

Nevertheless many works have been reported for core loss modeling of the SRM, it is required to introduce a comprehensive core loss model considering all design parameters and control parameters. To create a quick model with high accuracy which can be applied to different conventional types of SRMs is desirable. The main objective of this paper is to develop a model having all above-mentioned features. The core loss model introduced here is fast because it utilizes an analytical approach for predicting the flux waveforms within the machine. Based on experimental results, the model is evaluated and it has acceptable accuracy in comparison to the core loss model proposed in Ref. [10] where the flux waveforms are predicted using FEM (finite element method). At the following, the proposed core loss model is introduced in detail and all related equations are summarized in Section 2. The simulation and measurement results are given for an 8/6 SRM in Section 3 and the model is then validated. The paper is concluded in Section 4.

2. The core loss model

The developed core loss model is included three separate sections:

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1) Analyzing the machine in order to predict the phase flux-linkage waveform
2) Obtaining the flux waveforms in different parts of the machine from the predicted phase flux-linkage waveform
3) Calculating the core loss for the obtained flux waveforms

2.1. Machine analysis

To predict dynamic characteristics of the SRM, the machine is analyzed based on the phase voltage equation:

$$V = Ri + \frac{d\lambda(\theta,i)}{dt} \tag{1}$$

where R is the phase resistance and $\lambda(\theta,i)$ is the static characteristic of flux-linkage with a phase. Having the static characteristic, phase current waveform $i(\theta)$ is calculated using (1). The phase flux-linkage waveform $\lambda(\theta)$ can be then derived from $\lambda(\theta,i)$ and $i(\theta)$.

To determine the static characteristic of flux-linkage with a phase, two mathematical algorithms introduced in Refs. [11,12] are used in the developed core loss model. Using these algorithms, the static characteristic is obtained separately for two different cases: (1) there is no overlap between the stator and rotor poles, (2) when the poles have overlap. The relevant equations for these two cases are summarized briefly at below.

2.1.1. No overlap

When the stator and rotor poles have no overlap, the static characteristic of flux-linkage with a phase is modeled in Ref. [11], as follows:

$$\lambda(\theta,i) = (L_{nr} + L_{ns})i \tag{2}$$

where:

$$L_{nr} = \frac{n_{ser}}{n_{par}} 4\mu_0 N_p^2 l_{stk} l_r \sum_{nodd} \frac{\frac{\sin\left(\frac{\pi\ n\ l_{r1}}{l_r}\right)}{l_{r1}} + \frac{\sin\left(\frac{\pi\ n\ l_{r2}}{l_r}\right)}{l_{r2}}}{(\pi\ n)^2 \tanh\left(\frac{\pi\ n\ h_r}{l_r}\right)} \tag{3}$$

$$\begin{aligned} L_{ns} = {} & 2\frac{n_{ser}}{n_{par}}\frac{N_p^2 l_{stk}}{h_s l_w}\left\{\frac{2}{3}csy\, h_s^2 - \frac{1}{2}csx\, l_w + \sum_{n=1}^{\infty} asp(n)\right. \\ & \times\left[\cos\frac{\pi\, n\, l_w}{l_s} - \frac{l_s}{\pi\, n\, l_w}\sinh\left(\frac{\pi\, n\, l_w}{l_s}\right)\right] + \sum_{n=1}^{\infty} ash(n) \\ & \left.\times\left[\cosh\left(\frac{\pi\, n\, h_s}{l_s}\right) - \frac{l_s^2}{h_s l_w (\pi\, n)^2}\sinh\left(\frac{\pi\, n\, h_s}{l_s}\right)\sin\left(\frac{\pi\, n\, l_w}{l_s}\right)\right]\right\} \end{aligned} \tag{4}$$

where:

$$csy = \frac{-\mu_0\ l_w}{2\ l_s} \tag{5}$$

$$csx = -\mu_0 \sum_{n=1}^{\infty} \frac{l_s}{(\pi\ n)^2} \sin^2\left(\frac{\pi\ n\ l_w}{l_s}\right) \tag{6}$$

$$asp(n) = \frac{\mu_0\ l_s^2}{2(\pi\ n)^3} \sin\left(\frac{\pi\ n\ l_w}{l_s}\right) \tag{7}$$

$$ash(n) = -\frac{2\mu_0\ l_w\ h_s\ l_s}{(\pi\ n)^2 \sinh\left(\frac{\pi\ n\ h_s}{l_s}\right)}\left[\frac{\sin\left(\frac{\pi\ n\ l_{s1}}{l_s}\right)}{l_{s1}} + \frac{\sin\left(\frac{\pi\ n\ l_{s2}}{l_s}\right)}{l_{s2}}\right] \tag{8}$$

where l_{r1} and l_{r2} are the distances of the excited stator pole tip with the two adjacent rotor poles and the parameters l_{s1} and l_{s2} are considered equal to l_{r1} and l_{r2}, respectively.

2.1.2. Overlap

For this case, the static characteristic of flux-linkage with a phase is calculated based on below equation [12]:

$$\lambda(\theta,i) = \lambda_m(\theta,i) + \lambda_f(\theta,i) \tag{9}$$

where:

$$\begin{aligned} \lambda_m(\theta,i) = {} & \lambda_0 \frac{R_o\alpha}{\left(1+\frac{g}{l_p}\right)g}\left[\left(1+\frac{2g}{l_p}\right)i + \frac{l_{m1}B_{sat}}{\mu N_p}\right. \\ & \left. - \sqrt{\left(\frac{l_{m1}B_{sat}}{\mu N_p}\right)^2 + \frac{2l_{m2}B_{sat}}{\mu N_p}i + i^2}\right] \end{aligned} \tag{10}$$

and:

$$\begin{aligned} \lambda_f(\theta,i) = {} & \lambda_0 \frac{p_w - R_o\alpha}{\left(1+\frac{g_f}{l_p}\right)g_f}\left[\left(1+\frac{2g_f}{l_p}\right)i + \frac{l_{f1}B_{sat}}{\mu N_p}\right. \\ & \left. - \sqrt{\left(\frac{l_{f1}B_{sat}}{\mu N_p}\right)^2 + \frac{2l_{f2}B_{sat}}{\mu N_p}i + i^2}\right] \end{aligned} \tag{11}$$

where l_p is the sum of the stator and rotor poles heights. The parameters B_{sat} and μ are obtained when B–H curve of the laminations is modeled using below equation:

$$B = \frac{\mu H}{1 + \frac{\mu H}{B_{sat}}} + \mu_\circ H \tag{12}$$

and:

$$\lambda_0 = n_{ser}\mu_0 \frac{N_p^2}{2} l_{stk} s_{tf} \tag{13}$$

$$l_{m1} = l_p + (\mu_r + 1)g \tag{14}$$

$$l_{m2} = l_p - (\mu_r - 1)g \tag{15}$$

$$l_{f1} = l_p + (\mu_r + 1)g_f \tag{16}$$

$$l_{f2} = l_p - (\mu_r - 1)g_f \tag{17}$$

The relative permeability μ_r is equal to μ/μ_0 and the parameter g_f is defined as follows:

$$g_f = g + g_0\left(1 - \frac{R_o\alpha}{p_w}\right) \tag{18}$$

where α is the overlap angle and: