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PERMEANCE BASED ALGORITHM FOR COMPUTATION OF FLUX LINKAGE CHARACTERISTICS OF NON-LINEAR 6/4 SWITCHED RELUCTANCE MOTOR (SRM)

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ABSTRACT

The concept of permeance is used in the analysis of flux linkage of 6/4 SRM. The aim of this paper is to develop an efficient algorithm exploiting the nonlinear feature of the 6/4 SRM using the aforementioned concept of permeance. The first step is to generate the relevant equations related to permeances of the 6/4 SRM under study. The 6/4 SRM's magnetization curve is then derived from the summation of mmf drops at various blocks representing the motor. The air gap permeances are derived at various angles and 3-D leakage effects are taken into account. These permeances are used for the mmf drop computation. The algorithm is capable of efficiently computing mmf drop at every block to consequently yield a complete accurate nonlinear flux linkage feature of the 6/4 switched reluctance motor. In this way, the capability of the SRM to produce the expected four times the specific output torque due to operation in high saturation region compared to an equivalent induction motor as special the attribute of the SRM is demonstrated.

Keywords: switched reluctance motor, assumed flux pathway, energy saving, environment.

INTRODUCTION

Present SRM design programs tend to be structured principally to deal with either single-tooth or multi-tooth per pole SRM geometries achievable (Krishnan, R. *et al*., 1988) and (Faiz, J., 1988). The author proposed to extend this limitation to include all machine geometries of practical importance and to make it an interactive PC and work-station based package. The program is built in such a way that it can be integrated with Finite Element software and linked with industry and standard drafting packages such as AutoCAD, to produce accurate and professional output.

A simple iterative loop forms the framework of the design process. Advanced numerical and programming techniques are needed in order to develop several block models that are not only sufficiently accurate to yield acceptable estimates, but are also sufficiently fast to be used iteratively in the design routine. The fluctuation of magnetic saturation in SRMs during the electrical cycle for each phase complicates the accurate prediction of mean torque to an extent that it is not found in other forms of electrical machines. Therefore the block shapes of the magnetic circuit have to be chosen wisely in order to represent the saturable iron part accurately.

Where possible, the curved regions of the tooth, pole-head, pole-neck, and back-of-core are sub-divided into a reasonable number of relatively small sets of blocks to minimise the error involved in calculating the flux pattern. Further difficulties are encountered in calculating

the magnetic permeances of the air-gap regions between the toothed profiles of the stator and rotor, and also of the inter-pole flux leakage paths near the tooth tips (Harris, M.R. *et al*., 1975). Analytical Conformal Transformation method and Assumed Flux Pathway (AFP) technique derived from FE method are used in estimating the permeances of known flux paths and the end of core leakage fluxes.

The magnetic circuits of SRM are complex and angle dependent. Deep saturation is common for operations of such motors. Hence, flux variations are completely different from those of more conventional motors. Both flux frequency and wave form are different in various parts of the magnetic circuit. Core loss variations associated with these flux wave forms are complex and are difficult to predict theoretically (Materu, P. *et al*., 1988). Accurate evaluation of non-linear magnetisation characteristics is essential to the method, and the back-of-core region usually contributes much of the saturation that occurs, particularly in the aligned rotor position. Leakage fluxes can contribute substantially to the total back-of-core saturation, with end winding and interpole leakage fluxes representing up to 20% and more of the total flux Metwally, H. M. B., 1985) .

Computation of magnetisation characteristics is done iteratively. This forms the major part of the total computing effort presented in the program. It is consequently important to minimise the number of computed points that delineate a non-linear characteristics

so as not to slow down the computation time and yet sufficient to represent what is needed. The author found that about 13 points are sufficient for the aligned position, with cubic spline interpolation filling in the gap to obtain more accuracy. Mean torque per phase at a given phase current may then be calculated from the co-energy area enclosed by the magnetisation characteristics (aligned and unaligned flux linkages versus phase current). The next sections will describe the proposed model used and the results obtained from the analysis.

PERMEANCE AND ANALYSIS OF THE 6/4 SRM's NONLINEAR CHARACTERISTICS

Permeance calculation of regular shaped 6/4 SRM using assumed flux pathway (AFP)

At aligned position, the air gap at C is 0.298mm. Hence, we assume that the space in between the two unaligned stator and rotor respectively are at 0.298mm from bottom of rotor to top of stator; and the space in between the right of rotor to the left of stator is also 0.298mm.
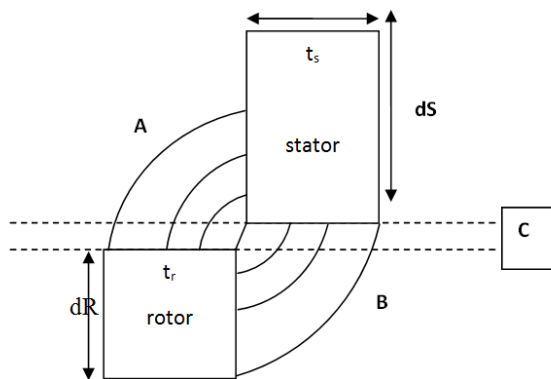

Figure-1. Idealized unaligned position of rotor relative to stator of 6/4 SRM.

Calculation of unaligned position, P_2

Taking into account just 2 flux pathway at (A):

1. $G_2 = \frac{1}{4}(25.4136 + 0.298)\left(\frac{3.142}{2}\right) = 10.098$
2. $G_1 = 0.4214$ (using solutions of triangle)

$$\frac{\Sigma g}{N} = 0.4214 + 10.098 = \frac{10.5196}{2} = 5.2598$$

$$T = \frac{(Tr + Ts)}{2} = \frac{25.4136 + 25.3882}{2} = 25.4009$$

$$P_2 = \frac{T}{\frac{\Sigma g}{N}} = \frac{25.4009}{5.2598} = 4.829$$

Calculation of aligned position, P_1

$$P_1 = \frac{(Tr + Ts)}{2g} = \frac{25.4136 + 25.3882}{2(0.298)} = 85.235$$

Permeance calculation of irregular shaped 6/4 SRM using assumed flux pathway (AFP)

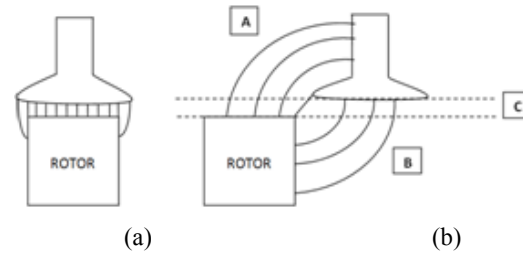(a)   (b)

Figure-2. (a) Aligned position of rotor relative to stator with actual stator tooth shape (b) Unaligned position of rotor relative to stator with actual stator tooth shape.

The block model

For single-tooth per pole SRM, the block model is chosen to represent the following regions (Figure-1):
a)   Back-of-core
b)   Stator pole
c)   Rotor pole
d)   Rotor body
e)   Air-gap

while the multi-tooth per pole SRM is represented by the following regions:
1.   Back-of-core
2.   Stator pole
3.   Stator tooth
4.   Rotor pole
5.   Rotor body
6.   Air-gap

Calculation of unaligned position, P_2

Considering the dR is equal to t_r, we can assume that the air gap is equal to the horizontal position between rotor and stator. Thus;

$$\sqrt{0.298m^2 + 0.298m^2} = 0.409m$$

At B, we take the radius at 0.1, 0.2 and 0.3

$$(1.517)(0.1)(0.298 + 25.3882) = 3.8966$$
$$(1.517)(0.2)(0.298 + 25.3882) = 7.7932$$
$$(1.517)(0.3)(0.298 + 25.3882) = 11.6898$$

Considering flux pathway at A and C,

$$\frac{\Sigma g}{N} = 5.9472$$

$$P_2 = \frac{\left[\frac{(25.3882 + 25.4136)}{2}\right]}{5.9472} = 4.2711$$

Calculation of aligned position, P_1

$$P_1 = \frac{(Tr + Ts)}{2g} = \frac{25.4136 + 25.3882}{2(0.298)} = 85.235$$

Analysis

Standard equations are used, as in reference 2 covering equations 1 to 8, starting from an initial value of flux-linkage (Ψ) and peak excitation current (I_p), the flux density in part x of the magnetic current (B_x) is determined by:

$$\Psi = B_x T_{ph} A_x$$
Or

$$B_x = \Psi/(T_{ph} A_x),$$ [1]

For each value of B_x, the corresponding value of H_x is determined from the B-H characteristics of the core material. Hence:

$$F_x = H_x L_x$$ [2]

Therefore, the total MMF for y parts of the magnetic circuit can be calculated by:

$$F = \sum_{x-1}^{y} H_x L_x$$ [3]

where y is equal to total number of parts of the magnetic circuit being considered.

Equation [3] can be written in another form:

$$F_p = I_p T_{ph}$$ [4]

As stated in (2), to determine the correct value of B_x used in the calculation, the results obtained from Equation [3] is compared with the value from Equation [4]. If $|F-F_p|$ is more than the acceptable limit, the calculations are repeated again using the next value of Ψ. The value of Ψ is incremented at regular interval while I_p remains the same. This iterative process is repeated until $|F-F_p|$ is within the acceptable limit.

Next, the value of I_p is set to another value and the whole processes are repeated. Value of I_p is not necessarily incremented at regular intervals. The end results will be tha value of Ψ for different parts of the magnetic circuits (within acceptable tolerance limit) corresponding to each value of I_p, (2).

Static-torque production

In SRM, the most general expression for instantaneous torque is

$$T = \frac{\partial W^i}{\partial \emptyset}$$ [5]

Where W^i is the co-energy defined as in Equation 5.

$$W^i = \int_0^i \Psi di$$ [6]

The electromagnetic energy that is available to be converted into mechanical work is equal to the area W. In one revolution each phase conducts as many strokes as there are rotor poles, so that there are qN_r strokes or steps per revolution. The average torque is therefore given by:

Average torque = work per stroke x Number of strokes per revolution/2π; or

$$T_a = W \frac{qN_r}{2\pi} \text{Nm}$$ [7]

The average electromagnetic power is converted

$$P_e = \omega T_a$$ [8]

Where ω = speed in rad/sec. From this must be subtracted the friction, wind age (copper loss) and rotor core losses.

The above equations 1 to 8 are used to compute the 6/4 SRM under study.

Total mmf drop of the 6/4 SRM

The total mmf drop for the 6/4 SRM is equal to the summation of mmf at the air-gap, at the rotor teeth, stator teeth and the stator back-of core.
In concept, we know that:
$$B = \mu_0 H$$
$$\varphi = BA$$

From this, mmf drop at the air-gap can be expressed as
Mmf drop at the motor's air-gap:

$$Hg = \frac{\varphi}{PLu_0}$$

Mmf drop at the rotor and stator are based on the B-H curve of the material used.

Mmf drop at the back-of-core:

$$\frac{\varphi}{2} \frac{1}{L_{BOC}}$$

The computation is proceeded for complete flux linkage characteristics.

RESULTS AND DISCUSSIONS

The calculated values of the mmf drop for both unaligned and aligned position of rotor and stator are as stated in Table-1 and Table-2. Table-1 indicates that the values of relevance to mmf drop calculation at unaligned position of the rotor and the stator. On the other hand, Table-2 showed that the values of relevance to mmf drop calculation at aligned position of rotor and stator.

Table-1. Unaligned position of rotor and stator.

Φ(m)	HdR	HdS	H$_g$	H$_{BOC}$	Mmf drop (At)
0.2	1.52	1.52	2771.92	8.41m	2774.97
0.3	3.18	3.17	4157.88	0.013	4164.25
0.4	10.17	10.16	5543.84	0.017	5564.19
0.5	127.07	126.94	6929.81	0.021	7183.84
0.6	762.41	761.65	8315.77	0.025	9839.86
0.7	2541.36	2538.82	9701.73	0.029	14781.94
0.8	17789.52	17771.74	11087.69	0.034	46648.98

Table-2. Aligned position of rotor and stator.

Φ(m)	HdR	HdS	H$_g$	H$_{BOC}$	Mmf drop (At)
0.2	1.52	1.52	157.04	8.41m	160.09
0.3	3.18	3.17	235.57	0.013	241.93
0.4	10.17	10.16	314.09	0.017	334.44
0.5	127.07	126.94	392.61	0.021	646.64
0.6	762.41	761.65	471.13	0.025	1995.19
0.7	2541.36	2538.82	549.65	0.029	5629.86
0.8	17789.52	17771.74	628.17	0.034	36189.46

Based on these values and equations 5 until 8, the motor performance can be calculated.

The closer the flux is to the centre of the initial point of calculation, the more it affects the relative value of the permeance. This is because as the flux pathway moves outward, the value becomes less as the magnetic strength reduces in proportion to the distance. This is proven via the calculation using the Assumed Flux Pathway (AFP) in which it proves that as the flux pathway moves outwards, the effects on the total permeance reduce. In terms of material used for the various parts of the motor, different components will derive a different value of mmf drops as in reference to the B-H curve for the particular material used. The total mmf drop for the Switched Reluctance Motor (SRM) is the summation of mmf drop at the air-gap, rotor-teeth, stator-teeth and the stator back-of-core. The computed data is expressed in a graph of Ampere-turn (A-t) against phi (ψ) with range of values from φi to φsat. 3-D leakage fluxes have a major effect on the performance of the SRMs. These leakage fluxes increase with the number of stator and rotor teeth. In addition, the percentage of the leakage flux relative to the total flux inside the motor varies in accordance to the aligned and unaligned positions of the rotor and stator. However, in the 6/4 SRM, the leakage permeance due to leakage flux between adjacent stator poles is small in comparison with the total air-gap permeance.

CONCLUSIONS

This research concludes that the concept of permeance can be incorporated in the analysis of the 6/4 SRM. The advantage of using this concept the non-linearity is maintained throughout the computation of the performance of the 6/4 SRM. This implies that more accurate performance of the 6/4 SRM can be computed compared to researchers using linearize model. The consequent torque characteristics computed can serve as a guide for comparison with equivalent induction motor. In this way the SRM can confidently be chosen as a candidate to help save energy in various applications, notably in water treatment plants, where the electricity bills on average amount to easily one million per month per plant. This saving is due to the inherent characteristic of SRM itself, that it is driven into high saturation region during operation.

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