Modeling of Switched Reluctance Motor for Inter-Turn Winding Short-Circuit Fault

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Abstract — A novel method for modeling inter-turn winding faults in Switched Reluctance Machine is presented by artificial neural network.

I. INTRODUCTION

This paper presents a method for modeling inter-turn winding faults in SRM based on artificial neural network (ANN), incorporating a simplified and effective magnetic equivalent circuit method to estimate phase flux-linkages as a function of current and rotor position under inter-turn winding faults.

II. CALCULATION OF THE NONLINEAR MAGNETIC CURVES

As shown in Fig.1, the shaded elements represent saturable portions of the motor. The dashed lines represent linear airgap reluctances between stator poles and rotor poles. Similar reluctances would be included for each stator pole. The saturable pole tips and leakages are included in the pole reluctances and are not represented separately in the figure. Each part of the motor back core between two poles is represented by one reluctance element, because the flux is distributed nearly homogeneously.

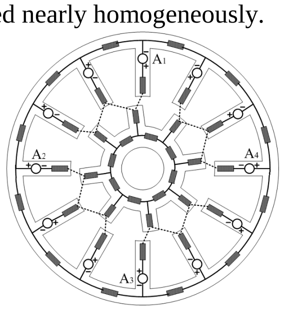


Fig.1. Magnetic equivalent circuit model of SRM.

When a pair of rotor and stator pole exhibit partial overlap, the flux through each pole must pass through a smaller cross sectional area at the airgap. While this flux may be insufficient to saturate the whole pole, its flux density will increase at the airgap near the overlap region. As a result, each overlapped pole will not exhibit an uniform flux density. Considering the assumption of the proposed model [1]-[6] that the magnetic flux should be homogeneously distributed in the cross-section of the tube, it will be hard to get accurate results if the whole pole is represented by a single reluctance element when local saturation occurs. In this paper, segment method is used to deal with the local saturation problem in a pole, which is acceptable for both accuracy and circuit structure. Each stator or rotor pole at the overlap positions is divided into two parts, a saturated pole tip and a pole trunk, represented by two respective reluctance elements in series, as shown in Fig.2. The introduction of saturated pole tips can simulate the local saturation by varying the dimensions of these tips. The key issue of this segment method is how to estimate the cross sectional area and length of these tips appropriately.

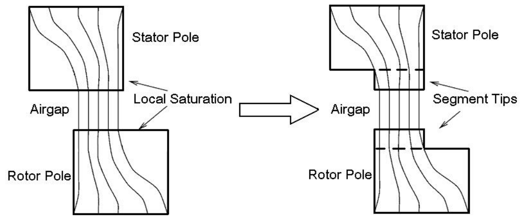


Fig.2. Local saturation and segment method.

From the flux distribution patterns in the overlap region, the equivalent angle corresponding to the width of the saturated pole tips θ_{tip}, has a close relationship with the instantaneous overlap angle and the maximum possible overlap angle between the stator and rotor pole faces, θ_{lap} and $\theta_{\max lap}$, represented as

$$\theta_{lap} \le \theta_{tip} \le \theta_{\max lap} \tag{1}$$

Considering θ_{tip} should be greater than zero when θ_{lap} equal to zero and assuming that θ_{tip} has a linear relationship with θ_{lap}, θ_{tip} can be determined as

$$\theta_{tip} = t_a\theta_{lap} + (1-t_a)\theta_{\max lap} \tag{2}$$

where t_a is a constant between 0 and 1, and t_a =0.8 in this paper. Thus, the cross sectional area of the saturated pole tip is expressed by

$$S_{tip} = [t_a\theta_{lap} + (1-t_a)\theta_{\max lap}]r_{rp}l_{Fe} \tag{3}$$

where r_{rp} is the radius of the rotor pole face, and l_{Fe} is the axial length of the machine iron core.

It is noticed that the dimensions of these saturated pole tips should be increased with the increase of the overlap area between the stator and rotor poles. Then, the length of the saturated pole tip is given by

$$l_{tip} = (\theta_{tip} / \theta_{\max lap})^{1/2} t_{\max tip} l_p \tag{4}$$

where l_p is the radial length of the stator or rotor pole being modeled, and $t_{\max tip}$ determines the maximum ratio of the tip length to the pole length.

β_s is stator pole arc factor, β_r is rotor pole arc factor, 0^0 rotor position is that the axis of the rotor slot is aligned with the axis of the stator pole. As shown in Fig.3, the rotor relative A phase from 0 degrees turned clockwise θ angle,

θ_{lap} is the overlapping angle between the stator pole and the rotor pole, θ_{maxlap} is the maximum overlapping angle between the stator pole and the rotor pole, θ_{tip} is the pole arc of the half of the stator pole, and,

$$\theta_{lap} = \beta_s - [\theta - (\pi/N_s - \beta_s/2)] = \beta_s/2 + \pi/N_s - \theta \quad (5)$$

$$\theta_{maxlap} = \min\{\beta_s, \beta_r\} \quad (6)$$

$$\theta_{lap} \le \theta_{tip} \le \theta_{\max lap} \quad (7)$$

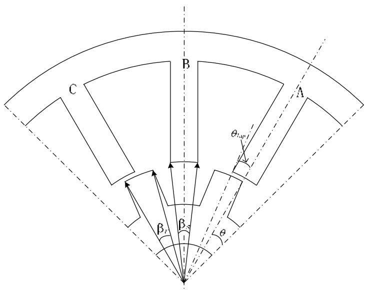


Fig.3. Some parameter illumination.

The nonlinear models for the stator and rotor poles are built up after the dimensions of the saturated pole tips are determined. The magnetization curves of SRM calculated by the method is shown in Fig.4.

III. ANALYSIS OF INTER-TURN SHORT-CIRCUIT FAULT

The sketched circuit in inter-turn short circuit fault of stator winding is shown in Fig.5. The voltage equation of the fault phase is as follows,

$$U_d = i_{ph}R_r + i_s R_s + (N_p - N_s)\frac{d\Phi_s}{dt} + N_p \sum_{j=2}^{4} \frac{d\Phi_j}{dt} \quad (8)$$

where, i_{ph} is health phase current, i_{ps} is inter-turn short circuit phase current, i_s is short circuit line current, U_d is the supplied voltage, Φ_j is the magnetic flux of coil j, Φ_s is the magnetic flux of inter-turn short circuit coil, R_r is the resistance of health coil turns, R_{ps} is the resistance of inter-turn short circuit coil turn, R_s is the resistance of short circuit line, N_p is the turn numbers of each health coil, N_s is the short circuit turn numbers.

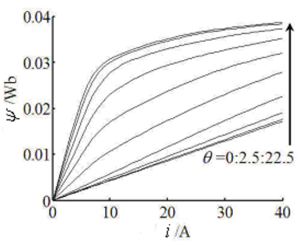


Fig.4. Magnetization curves.

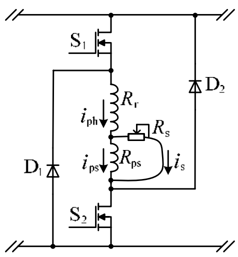


Fig.5. Sketched circuit.

IV. MODELING METHOD BASED ON GA-BP NETWORK

Considering fast computation and the huge number of discrete magnetization curves data needed to get good accuracy, a multilayer backpropagation (BP) feedforward neural network is used to model the flux-linkage characteristics of SRM under healthy and faulty conditions. The final goal of BP network is to estimate the phase flux-linkage for a given set of phase current, rotor position and the healthy/faulty condition of the SRM. Thus, the input layer consists of 3 nodes, and a fault condition parameter, f_{con} is added to the typical two input variables, phase current I_{ph} and rotor position θ. The network output is the phase flux-linkage. In order to get a fast convergence speed, two hidden layers with 15 and 5 neurons are selected after a strict comparison with various numbers of layers and neurons. The structure of the four-layer BP network is shown in Fig.6. The GA algorithm is used to train the BP network.

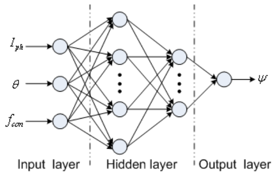
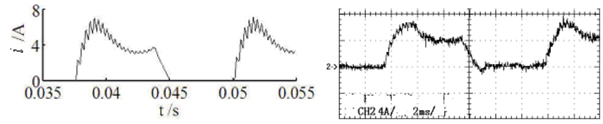


Fig.6. Structure of the proposed four-layer BP network.

V. RESULTS

The results for the case that an inter-turn stator winding fault occurs are obtained from the developed model modeling and the developed prototype testing. The phase current waveforms in modeling and testing are shown in Fig.7. It is shown that the modeling results tally with the testing results.



a) Modeling b) Testing

Fig.7. Phase current waveforms

VI. CONCLUSIONS

An effective model for the dynamic simulation of SRM with the inter-turn stator winding faults is developed based on ANN with GA algorithm on four-layer BP network.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

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