An Extended Field Reconstruction Method for Modeling of Switched Reluctance Machines

Chenjie Lin, Wei Wang, Babak Fahimi
Renewable Energy and Vehicular Technology Lab, University of Texas at Dallas
800 West Campbell Rd., EC33, Richardson, TX 75080-3021. Room 3.320
cxl106420@utdallas.edu

Abstract —This paper presents an extended Field Reconstruction Method (FRM) to model a Switched Reluctance Machine (SRM), which is set apart from other electric machines by its double-saliency and the magnetic saturation. Traditional magnetic models of SRM developed using Finite Element Analysis (FEA) are computationally inefficient. This, in turn, limits their application in simulation of SRM drive system and iterative optimization. FRM can significantly reduce the computational time by utilizing a small number of magnetic field snapshots to establish the basis functions which are then used to reconstruct the magnetic field with high accuracy. In this paper an extended version of FRM is introduced within which effects of magnetic saturation and double saliency are taken into account. Results from FRM and FEA are compared and good accuracy is observed.

I. INTRODUCTION

Switched Reluctance Machines (SRM) are characterized by their simple and robust structure. However, their nonlinear behavior in terms of magnetic saturation caused by high magnitude of flux density and variable air gap due to the double saliency complicate their modeling and analysis. Accurate modeling of SRM is necessary when it comes to the design of an adjustable speed drive system. Traditional field-based methods such as FEA are costly in terms of simulation time. Multi-objective and iterative optimal design worsens this shortcoming and imposes high computational cost for such attempts [1].This paper presents a new model for SRM based on Field Reconstruction Method (FRM). FRM only utilizes a small number of magnetic field solutions to develop a complete magnetic model of the SRM. Magnetic snapshots obtained in the previous step are then used to develop the basis functions to estimate magnetic field under any arbitrary stator excitation and at any desired location within the SRM. Although FRM has been applied to induction machine and permanent magnet synchronous machines [2]-[3], double saliency and magnetic saturation problems have not been addressed before. In this paper, these attributes of SRM are taken into account and detailed procedure for calculation of basis functions is presented. Magnetic field and torque results from FRM show good agreement with those from FEA simulation while using only a fraction of computational time required by FEA.

II. DEVELOPMENT OF THE BASIS FUNCTION

Development of basis functions for the local region of interest is an integral part of the modeling in FRM [2]. Normal and tangential basis functions $h_{nk}(i,\theta_r)$, $h_{tk}(i,\theta_r)$ are defined as follows,

$$B_{nk}(i,\theta_r) = i \cdot h_{nk}(i,\theta_r) \quad (1)$$

$$B_{tk}(i,\theta_r) = i \cdot h_{tk}(i,\theta_r) \quad (2)$$

In (1) and (2) subscript " k " indicates the order of selected displacements forming a circular contour in the middle of the airgap, θ_r denotes the rotor position, $B_{nk}(i,\theta_r)$ and $B_{nk}(i,\theta_r)$ represent the normal and tangential components of the flux density at the selected point, i represents the stator phase current (single phase excitation is assumed) and h_{nk} & h_{tk} are the normal and tangential basis functions at the targeted point located on the contour(see Fig 1) .

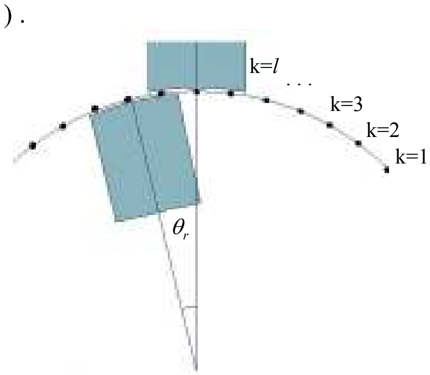

Fig. 1. Geometry of stator and rotor poles

A. SRM modeling under unsaturated condition

In order to compute basis functions, a truncated Fourier series expansion is used at each point on the contour. Dependency upon rotor position reflects the inherent double saliency of the SRM geometry [4]:

$$h_{nk}(i,\theta_r) = C_{nk\_N}(i) \cdot \begin{bmatrix} \frac{1}{2} \\ \cos(P\theta_r) \\ \sin(P\theta_r) \\ . \\ . \\ . \\ \cos(NP\theta_r) \\ \sin(NP\theta_r) \end{bmatrix}, h_{tk}(i,\theta_r) = C_{tk\_N}(i) \cdot \begin{bmatrix} \frac{1}{2} \\ \cos(P\theta_r) \\ \sin(P\theta_r) \\ . \\ . \\ . \\ \cos(NP\theta_r) \\ \sin(NP\theta_r) \end{bmatrix} \quad (3)$$

Where P denotes the number of pole pairs, N represents the truncation order and $C_{nk\_N}(.)$ and $C_{tk\_N}(.)$ are vectors of coefficients for normal and tangential basis functions respectively. To calculate the unknown coefficients FEA snapshots at 2N+1 various rotor positions have to be performed. Under unsaturated condition (a sufficiently low current i_0 is applied to the phase to ensure unsaturated operation) one can compute the coefficients for the normal basis function as follows (viz. similar procedure will be used for the tangential basis function):

$$h_{nk}(i_0) = \lfloor B_{nk\_1}(i_0)/i_0 \quad . \ . \ . \ . \quad B_{nk\_2N+1}(i_0)/i_0 \rfloor$$

$$A = \begin{bmatrix} 0.5 & \cdots & 0.5 \\ \cos(P\theta_{r1}) & \cdots & \cos(P\theta_{r(2N+1)}) \\ \vdots & \vdots & \vdots \\ \sin(NP\theta_{r1}) & \cdots & \sin(NP\theta_{r(2N+1)}) \end{bmatrix}^{-1}$$

$$C_{nk\_N}(i_0) = h_{nk}(i_0) \bullet A \tag{4}$$

B. SRM modeling including saturation effects

To include nonlinear effects of saturation, the matrix of Fourier coefficients needs to be conditioned using a saturation multiplier. This saturation multiplier is a function of excitation current and is expressed using a polynomial (similar derivation can be performed for the tangential basis function),

$$sf_{nk\_N}(i_n) = \frac{h_{nk\_N}(i_n)}{h_{nk\_N}(i_0)} = \frac{\dfrac{B_{nk\_N}(i_n)}{B_{nk\_N}(i_0)}}{\dfrac{i_n}{i_0}} \tag{5}$$

$$sf_{nk\_N}(i) = \sum_{m=0}^{M} p_{km} i^m \tag{6}$$

At rotor positions which are selected to obtain the basic Fourier coefficients, M different excitations are applied (the selected currents are large enough to saturate the SRM within a reasonable range of operating flux density) to capture the polynomial coefficients illustrating the saturation factor defined by (5) and (6).

$$\lfloor p_{k0\_N} \quad p_{k1\_N} \quad p_{k2\_N} \quad . \ . \ . \quad p_{k(M-1)\_N} \quad p_{kM\_N} \rfloor$$

$$= [sf_{nk\_N}(i_1) \ldots sf_{nk\_N}(i_M)] . \begin{bmatrix} 1 & 1 & \cdots & 1 \\ i_1 & i_2 & \cdots & i_M \\ \vdots & \vdots & \vdots & \vdots \\ i_1^M & i_2^M & \cdots & i_M^M \end{bmatrix}^{-1} \tag{7}$$

Finally, the Fourier coefficient matrix conditioned by saturation factor is derived by combining (4)-(7),

$$C_{nk\_N}(i) = h_{nk\_2N+1}(i) \bullet A \tag{8}$$

III. COMPARISON BETWEEN FRM AND FEA

In order to validate the FRM model, arbitrary excitation current is applied to equations (1) and (2). Magnetic fields estimated by FRM are compared with the results from FEA (1.2 Tesla is considered as the kneel point for magnetic saturation). Maxwell Tenser Method is applied to estimate the force densities, both saturation and unsaturation conditions are compared.

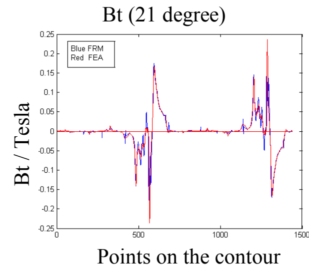

Fig. 2. Bt (T) distribution over the contour

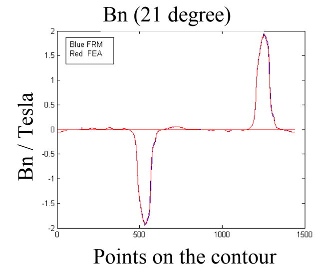

Fig. 3. Bn (T) distribution over the contour

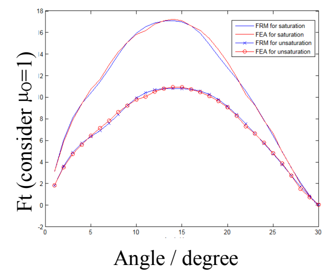

Fig. 4. Ft density over 30 degree of rotor positions

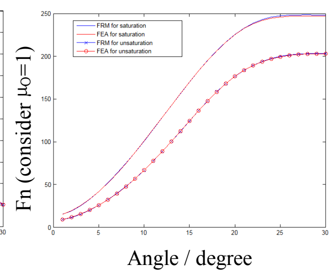

Fig. 5. Fn density over 30 degree of rotor positions

Based on the comparison, estimated field from FRM fits well with the results obtained from FEA under severe saturation condition.

IV. CONCLUSION

This paper introduces an extended version of FRM for modeling of SRM. Double saliency and magnetic saturation problems are addressed. The accuracy and feasibility have been proven by the comparison with FEA results. The number of samples taken from the FEA to establish the basis functions is still relatively large, leaving the room for improvement in the future. Nevertheless, this method can substantially minimize the computational time required for high accuracy machine modeling and design especially when multi-objective and iterative optimization is involved. More results and details will be given in the full version of the paper.

V. REFERENCES

[1] Wei Wang, Kiani, M., Fahimi, B., ”Optimal Design of Doubly Fed Induction Generators using Field Reconstruction Method”, *IEEE Trans. on Magn.*, vol.46, no.8, pp. 3453-3456, 2010

[2] Weidong Zhu, Fahimi, B., Pekarek, S., “A field reconstruction method for optimization of permanent magnet synchronous machines”, *IEEE Trans. on Engery Conversion.*, vol.21, no.2, pp. 305-313, 2006.

[3] Dezheng Wu, Pekarek, S.D., Fahimi, B., “A Field Reconstruction Techneique for Efficient Modeling of the Fields and Forces within Induction Machines”, *IEEE Trans. on Engery Conversion.*, vol.24, no.2, pp.366-374, 2009.

[4] Salmasi F. R , Fahimi, B., “Modeling switched-reluctance Machines by decomposition of double magnetic saliencies”, *IEEE Trans on Magn.*, vol 40, no3, pp1556-1561, 2004