Iron Loss Prediction of a Fractional-Slot Concentrated Winding Surface PM Synchronous Generator Feeding Various Loads

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Abstract — Fractional-slot concentrated windings (FSCWs) are known to introduce rich spatial harmonics into magnetic field distributions in the permanent magnet machines, which induce significant iron losses, especially in the stator teeth-tips. Conventional engineering methods to predict the iron losses give significant errors when applied to the FSCW permanent magnet synchronous generators (PMSGs), especially when the generators feed rectifier loads. This paper intends to develop an improved approach for predicting the stator core iron losses in the PMSGs feeding various loads. The proposed method is carried to predict stator iron loss in a 16-pole/18-slot FSCW PMSG when feeding no load, pure resistance load and rectifier load. The results are analyzed and compared with that obtained by a conventional engineering model adopted in the commercial finite element (FE) software.

I. INTRODUCTION

Permanent magnet synchronous generators (PMSGs) are considered to be suitable for distributed power supply and electric vehicle applications. Nonlinear loads, such as diode bridge rectifiers are often connected to PMSGs in these applications [1]. The phase current time harmonics introduced by these loads may increase the iron losses in the PMSGs.

Fractional slot concentrated windings, when adopted in PMSGs, can result in high copper fill factor, high winding factor, low copper loss, low torque ripple and sinusoidal electro-magnetic-force (EMF) without stator slots or rotor poles skewing [2]. Meanwhile, FSCWs generate rich harmonic and sub-harmonic contents in spatial MMF and magnetic field distributions. These harmonic components lead to excess eddy-current losses in the stator, rotor iron and magnets [3].

Conventionally, the stator iron losses in the rotating PM machines, which exhibit localized rotational fields, are estimated based on the well-known Steinmetz equation or Bertotti's three-term iron loss model [4]: The flux density waveform in two equivalent orthogonal alternating direction (radial and circumferential) in each part of the stator is solved analytically or by finite element method (FEM) at first. By substituting the flux density harmonics and the iron loss coefficients of respective steel sheets into the iron loss equations, iron loss for each of the two orthogonal alternating flux density components can be deduced. Then the total stator iron loss can be obtained by summing them up. This method is acceptable for fairly low rotational flux densities with low frequency. However, it is totally not the case when comes to high speed PM machines, PM machines with large pole numbers, and rare-earth PM machines [5], [6] due to their high frequencies or flux densities. Gmyrek presents a more accurate iron loss calculation model considering rotational hysteresis losses by applying correction factors which are functions of the peak flux density and ellipticity of the flux density vector loci to the hysteresis and excess loss terms in Berttoti's model. However, this model requires the execution of many experiments which requires complex test equipment in order to determine the precise factors.

This paper presents an engineering model to calculate the iron losses based on the flux density vector loci, but only requires the conventional three-term iron loss factors, which can be accessed from the steel sheet manufacturers or identified by the widely available Epstein tester. The presented model is applied to a 16-pole/18-slot FSCW Surface PMSG. Iron losses calculated under different load conditions are analyzed and compared with that obtained from the commercial FE software.

II. IRON LOSS CALCULATION METHOD

This method is based on the 2-D FEM model for a FSCW PMSG under specific load condition. By dividing the FEM model by elements, the instantaneous flux density vector of ith elementary region can be obtained in post-processing mode, viz.:

$$\mathbf{B}_i(t) = B_{ri}(t)\mathbf{e}_{ri} + B_{\theta i}(t)\mathbf{e}_{\theta i} \quad (1)$$

where B_{ri} and $B_{\theta i}$ are radial and circumferential flux density components, $\mathbf{e}_{ri}$ and $\mathbf{e}_{\theta i}$ are unit vectors on corresponding direction, respectively. The jth harmonic **B** vector locus of the ith region, which is an ellipse, can be calculated by involving the Fast Fourier Transformation (FFT):

$$\mathbf{B}_{ij}(t) = B_{rij}\cos(j\omega t + \varphi_{rij})\mathbf{e}_{ri} + B_{\theta ij}\cos(j\omega t + \varphi_{\theta ij})\mathbf{e}_{\theta i} \quad (2)$$

where $\omega=2\pi f$ is the fundamental electrical angular velocity; B_{rij}, and $B_{\theta ji}$ are amplitudes of radial and circumferential flux density, respectively. φ_{rij} and $\varphi_{\theta ij}$ are corresponding initial phases. Then $\mathbf{B}_{ij}(t)$ can be transformed to a reference frame defined by the major axis maj and the minor axis min of the elliptical vector locus using (3):

$$\begin{bmatrix} B_{majij} \\ B_{minij} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} B_{rij} \\ B_{\theta ij} \end{bmatrix} \quad (3)$$

where B_{majij} and B_{minij} are major axis and minor axis components of the **B** vector; α is the angle between $\mathbf{e}_{ri}$ and the major axis. The **B** vector locus expression under the new reference frame is

$$\mathbf{B}_{ij}(t) = B_{majij}\cos(\omega t)\mathbf{e}_{majij} + B_{minij}\sin(\omega t)\mathbf{e}_{minij} \quad (4)$$

Base on (4) and Berttoti's three term model, considering the effect of rotating magnetization, the new method is derived. Here just gives the final expression, detailed derivation will be presented in the full paper:

$$P_{hij} = k_h f(B_{majij})^h + \alpha_h k_h f(B_{\min ij})^h \quad (5)$$

$$P_{eij} = k_e (fB_{majij})^2 + k_e (fB_{minij})^2 \quad (6)$$

$$P_{aij} = \frac{k_a}{15.74T} \int_0^T \left[\left(\frac{\mathrm{d}B_{majij}(t)}{\mathrm{d}t} \right)^2 + \left(\frac{\mathrm{d}B_{minij}(t)}{\mathrm{d}t} \right)^2 \right]^{3/4} \mathrm{d}t \quad (7)$$

$$P_{TOT} = \sum_{j=1}^{j\max} \sum_{i=1}^{i\max} \rho V_i (P_{hij} + P_{eij} + P_{aij}) \quad (8)$$

where P_{hij}, P_{eij}, and P_{aij} are hysteresis, eddy-current and excess loss per unit mass of ith elementary region caused by jth **B** vector harmonic locus. P_{TOT} is the total stator core iron loss. k_h, k_e and k_a are constant coefficients which depend on the material. α_h is a factor depends on the machine's saturation level. ρ is the mass density of stator steel. V_i is the volume of the ith region.

III. IRON LOSS PREDICTION OF FSCW PMSG

The proposed method is applied to a 16-pole/18-slot FSCW PMSG, feeding no load, pure resistance load, and rectifier load, respectively. The structure and winding distributions of the PMSG are showed in Fig. 1. Parameters of the generator and steel sheet are showed in Table I.

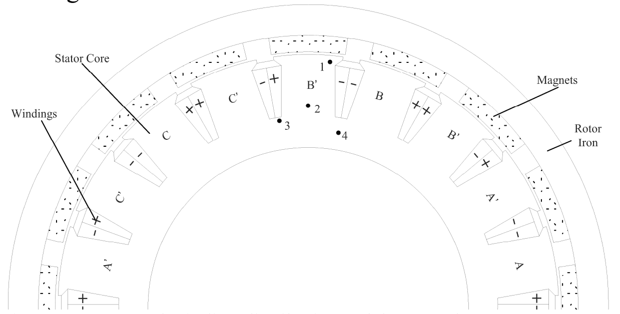

Fig. 1 Structure and winding distributions of the 16-pole FSCW PMSG

TABLE I SPECIFICATION OF THE FSCW PMSG

Item	Value	Item	Value
Number of phases	3	Stator outer radius	101mm
Rotor outer radius	117mm	Magnet grade	N35
Rotor inner radius	107mm	Magnet arc	16.88°
Air-gap radial length	1mm	Steel sheet grade	50DW470
Generator axial length	50mm	h	1.775
Steel mass density ρ	7.65g/cm^3	k_h	2.8e-2
k_e	1.9e-4	k_a	1.12e-5

Coupled-circuit 2D transient FEM is adopted to compute instantaneous **B** vector in each element of the generator. The sliding surface method is adopted to model the air-gap. The outer part of the air-gap belongs to the rotor and the inner part belongs to the stator. Steps of rotor moving through 360° mechanical angle should be an aliquant part of the number of divisions of the mid-air-gap circle. This keeps the mesh topology remain the same, which is essential for the proposed method, and can improve precision as well.

IV. RESULTS INVESTIGATION AND COMPARISON

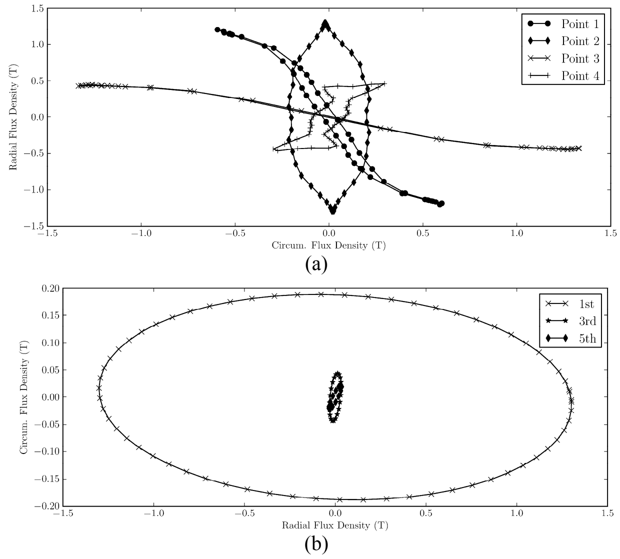

Fig. 2 **B** loci under no load condition: (a)**B** loci of point 14 in Fig. 1, (b)-dominant harmonic loci of point 1.

Applying the proposed method to the FEM model of the FSCW PMSG, **B** vector locus in every elementary region and corresponding spectrum are obtained (see Fig. 2(a)-(b)); hence stator iron losses at 3000rpm under different load conditions are calculated, as is illustrated in Table II.

TABLE II IRON LOSS UNDER DIFFERENT LOAD CONDITION

Model	No load	Resistance, 7.3kW	Rectifier, 7.3kW
Proposed Model	569W	582W	593W
commercial software	558W	535W	527W

Interestingly, the commercial FE software underestimates the iron loss when loaded. This will be investigated in the full paper.

V. CONCLUSION

This paper presented a new method to calculate stator iron loss of a 16-pole/18-slot FSCW PMSG. Further investigation will be presented in the full paper.

VI. REFERENCES

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