Full and Simplified Loss Calculation FEM Models for Segmented Surface Permanent Magnet Machines

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Abstract — In this paper full and simplified finite element method (FEM) models, used for calculation of the eddy current losses in surface magnets found on rotor of synchronous machines, are compared. The presented models range from 3D models to simplified 3D models and 2D models. The results of the numerical simulations are compared with an analytical model

I. INTRODUCTION

Calculation of eddy current losses in segmented magnets of synchronous machine can be done without approximation with 3D models. Unfortunately these models need due to the high number of mesh nodes a considerable calculation time (weeks on standard PC [2]). Simplified 2D models that disregard the end effects during calculation and thus need analytically calculated correction factors are usually used [1], [4].

One application is the direct drive surface mounted magnets generators with concentrated and distributed winding. The additional harmonics found in the air gap due to the unsymmetrical field or slotting effect cause eddy current losses in the magnets, thus loss calculation during generator design is necessary.

II. SIMULATED GEOMETRY

The simulations were done for a linear model with slot, pole and magnet size close on the one of a 3 MW cylindrical direct drive generator (Fig. 1 a). The magnet was assumed to have the size width x height x length of 98mm x 20 mm x 100 mm for a pole pitch of 100 mm. The number of slots per pole was 3, typical for a one layer distributed winding. The slot opening is 16 mm and the stator and rotor yoke are 50 mm high. The axial length is 1 m and the linear speed of the rotor is 1 m/s.

The model considers only half of one magnet segment in axial direction and one pole to reduce the calculation effort. For concentrated winding the number of poles that need to be simulated may increase to the smallest number of poles which have a number of stator slots multiple of the number of phases. The magnet segments are insulated by a small air gap of 2 mm between poles and insulator boundary condition at the axial ends. All the calculations were done using the FE Software JMAG from JSOL Corporation. In the digest only no-load calculations (stator winding has zero current) are presented. The steel and magnet are considered linear, with iron relative permeability $\mu_r = 1000$ and magnet $\mu_r = 1.05$, remanence Br = 1.03 T and conductivity $\kappa = 0.625$ MS/m, in order to reduce the calculation time.

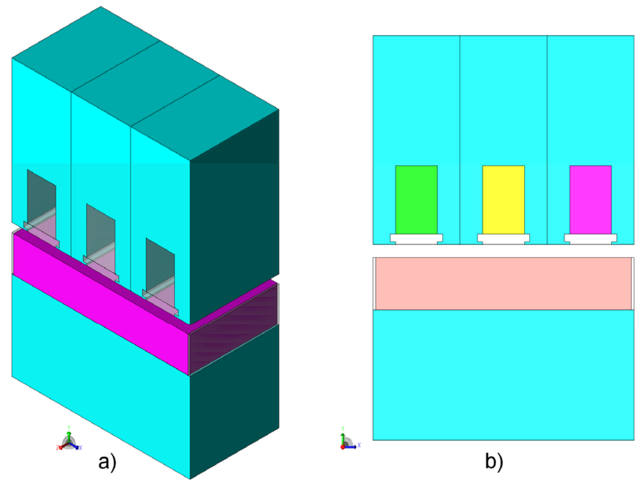

Fig. 1. a) Model A: 3D one pole, half segment model, b) Model B: 2D cross section one pole model (JMAG)

III. 2D AND 3D MODEL

Model A (Fig. 1 a) is a 3D model of half magnet segment in axial direction and model B (Fig. 1 b) is a 2D model of the cross section of one pole. The number of nodes and elements used and the calculation time, for transient calculation of 110% of one period with 220 time steps (dt = 1 ms), are found in Table I for the models A and B but also for the simplified models described in the next section. The mesh size of 1 mm was kept the same in the magnets for all the models. Due to the lower number of nodes model B is much faster than model A (about 155 times). However in model B the end effect in the eddy currents (Fig. 2) can not be considered as the magnet is assumed to be infinitely long in axial direction. The model A1 which is similar to model A but does not have the insulation between segments in axial direction calculates similar losses to model B. In order to correct the 2D results a correction factor like the *Russell-Norsworthy* factor [4] can be applied on the conductivity of the magnets. Assuming the magnet size from the previous section and the 5th harmonic wave length of 20 mm, the conductivity has to be reduced to 87.26% of the magnet conductivity which yields in model B1 a close result to the model A (Table II).

IV. SIMPLIFIED MODELS

Two simplified 3D models are used for the calculation of the eddy current losses in the magnets. Both models simplify the structure of the stator. Model C (Fig. 3 a) considers only the slot opening with a height of 15 mm and disregards the teeth and yoke. On the upper side a normal flux condition is used. Model C1 also disregards the rotor yoke again a natural boundary condition is used for the lower boundary. Model D (Fig. 3 b) on the other hand completely removes the stator and the rotor iron. The modulation of the air gap field is generated by a harmonic current loading which contains the slot generated air gap field harmonics calculated with model B. The slot caused harmonics components (5th, 7th, 11th, 13th,…) need to be separated from the harmonics generated by the rotor when the stator has no slots. Thus it is necessary to calculate also a 2D model without slots in the stator. For model D the magnet is not considered to be magnetized, being only conductive. Simulations were done for the first two pair of slot harmonics: 5th and 7th and respectively 11th and 13th with two different simulations. The rotor is fixed for this simulation the current loading harmonics are moving.

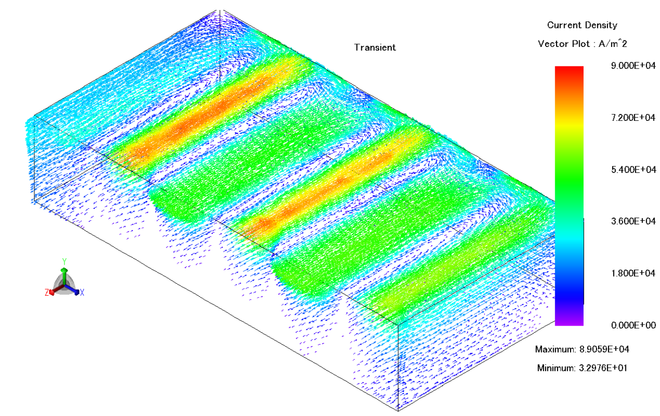

Fig. 2. Calculated vector plot of the current density in the magnet in Model A (JMAG)

Based on the air gap field waves calculated with model B it is possible to do an analytical calculation of the losses in magnets considering end effect segmentation model E and no segmentation model E1 [5]. The calculated average losses in one pole pair of the generator for 1 m long generator are presented in Table II. The relatively low values of the losses are due to the high magnetic air gap which damps the slot harmonics. Higher losses will be obtained during load.

TABLE I
Calculated models types, number of elements and calculation time on Core-I7 950 12GB RAM (single core calculations)

Model	No. Elements	Calculation time
A – 3D model	445291	7.25 h
A1 – like A infinitely long	445291	7.25 h
B – 2D model	3438	2.8 min
C – 3D model, slot opening only	103200	6.0 h
C1 – like C without rotor yoke	101081	6.3 h
D – 3D model current loading, no rotor yoke	107451	2 x 5.3 h
E – analytical model, segmentation[5]	-	< 1 s
E1 – like E without segmentation	-	< 1 s

TABLE II
Calculated loss per pole pair for 1 m axial length

Model	**A**	**A1**	**B**	**B1**	**C**
Loss / W	2.11	2.41	2.31	2.02	1.97
Model	**C1**	**D**	**E**	**E1**	
Loss / W	1.92	1.81	2.16	2.45	

V. Conclusions

Considering the calculation times the only model viable to be used during an optimization is model B1 the 2D calculation with correction factor or the analytical model E with end effect. The correction factor of model B1 depends on the harmonic wave length and is difficult to calculate in case of multiple dominant harmonics. Model E uses superposition of the effect which in some situation may neglect the Models C and D offer better approximation than model B but are quite slow. Model D and E require extraction of the relevant harmonics from 2D calculations. It is sensible to used during optimization the 2D model B1 with correction or the analytical model E and after the optimization or sometime during the results should be checked with a model A.

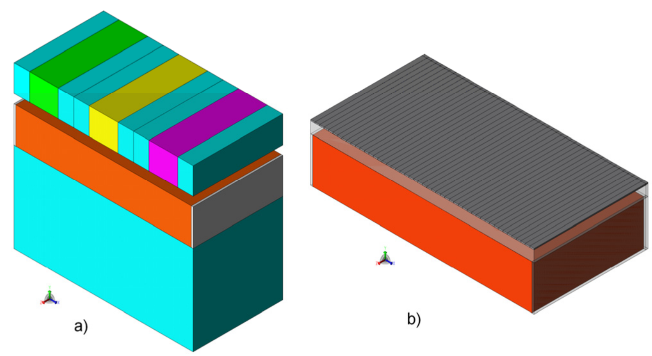

Fig. 3. a) Model C: 3D model, simplified slot openings stator, b) Model D: 3D model no stator field waves generated by a harmonic current loading (JMAG)

VI. References

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