Stator Core with Slits in Transverse Flux Rotary Machine to Reduce Eddy Current Loss

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Abstract — This paper shows eddy current analysis in a transverse flux rotary machine (TFRM) with laminated stator cores, which consist of inner and outer cores whose laminated directions are perpendicular to each other. Although the TFRM is laminated to reduce eddy current losses, it exhibits rapidly increasing core losses as frequency increases. To solve the problem, slits are introduced on the stator outer core. The effect of the slits is confirmed experimentally first, then the effect is explained by 3-dimensional finite element analysis of eddy current losses in nonlinear laminated core.

I. INTRODUCTION

Many papers have presented eddy current analysis for laminated cores [1]-[4]. Most of the analysis models are related to large size electric machines such as turbine generators and transformers [1]-[2], or high harmonic applications such as reactors [3]-[4]. In those applications, the eddy current loss by the flux which is perpendicular to the laminated cores is only a few percentages of the total iron losses, but the effect cannot be overlooked because of heat problem. So, it is adopted that segmented stator cores with lapping between adjacent layers [1], or slits on the stator teeth and the reactor cores [1]-[4] to reduce eddy current losses on each steel sheet.

In comparison with above conventional electric machine examples, the transverse flux rotary machine (TFRM) presented in this paper has both different and similar aspects about eddy current loss. Firstly the difference is that the TFRM has low frequency and small volume. The fundamental magnetic frequency is 150Hz at the rated speed, output power is under 1kW, the outer diameter is 206mm, and the axial length is 112mm. If a general longitudinal flux rotary machine (LFRM) has these conditions, eddy current loss is not a quite severe problem because of laminated cores. The TFRM in this paper has also laminated stator cores, which consist of inner and outer cores whose laminated directions are perpendicular to each other considering magnetic flux path, but the TFRM has huge eddy current loss in the stator.

To solve the problem, therefore, slits are introduced on the stator outer core, and this is the similar aspect to the above electric machine examples. Strictly speaking, the effect to reduce eddy current loss is the same because the current circuit length is reduced by the slits, but the slit shape is different from those of LFRM because the condition causing the currents and the current path are different. The slits of the TFRM separate entirely the stator outer core into several fragments rather than partially exist such as those in large size turbine generators in [1] or induction motor in [5].

In this paper, therefore, the effect of the slits is presented experimentally first to show how useful slits are for eddy current loss reduction in the TFRM dealt in here. Then the effect is explained by 3-dimensional finite element analysis (3D FEA) in detail with a simplified analysis model because it takes too much time and efforts if an analysis model for real conditions is used with dense finite element mesh. The simplified analysis model has just reduced dimensions and numbers of pole and slot compared to those of the real prototype. Only one phase is modeled for magnetic field analysis due to the decoupling of magnetic flux paths and armature coils as a unique character in the TFRM with ring coils even though it has multi phases [6]. And nonlinear laminated cores are considered to estimate the losses including the in-plane eddy currents caused by the perpendicular flux.

For the eddy current loss computation, a combination method is used which is introduced and recommended in [2]. The method includes gap elements, anisotropic conductivity, and double nodes. The laminated core is subdivided into each electrical steel sheet, and the insulated layers of the sheets are modelled by the gap elements, which represent the magnetic resistance of the layers with stacking factor of the core. The anisotropic conductivity is adopted to consider the insulation between the steel sheets, and the method of double nodes is used for both lamination and slits.

II. A TFRM WITH LAMINATED STATOR CORE

Fig. 1 shows the configuration of a permanent magnet (PM) type TFRM with laminated stator cores. The phases are arranged in axial direction, and magnetically and mechanically separated each other as shown in Fig. 1 (a). The PMs on rotor are arranged and magnetized in circumferential direction as shown in Fig. 1 (b) to concentrate the magnetic flux to the rotor core.

The stator is divided into two parts, inner and outer cores that are laminated in perpendicular to each other. The inner and outer cores are called yoke and teeth, respectively. The teeth are divided into upper and lower parts again, and the lower teeth are shifted by a half pole-pitch with respected to upper teeth to make magnetic circuits. Fig. 2 shows flux path on cross section of L-L’ in Fig. 1 (b) when current flows in counter-clockwise. From Fig. 2, it is clear to see that both inner and outer laminations accommodate the flux flows and do not interfere. The lamination also intends to reduce core losses. Fig. 3 shows fabricated stator teeth shape.

III. EXPERIMENTAL EXPLANATION ABOUT SLIT EFFECT

The stator teeth of first prototype are made as shown Fig. 3 (a). When the no-load electro-motive force (EMF) is measured by the rotor rotating, the curve of EMF according to rotation speed is severely nonlinear like the case of Ns = 0 in Fig. 4 (Ns is number of slit). To find out the reason, several types of stator material combinations are considered for previous work [7]. From the EMF test results in [7], the ring shaped teeth and laminated silicon steel core seems to cause the core loss problem.

The stator cores of general LFRMs are also ring shaped, but the magnetic flux path is totally different from TFRMs. In the case of LFRMs the number of magnetic polarities in circumference direction is as many as number of rotor poles, so they have several magnetic flux paths in stator core. In the case of the TFRM here, however, the number of magnetic polarities in circumference direction is only one. For example, as shown in Fig. 2, the polarities of upper teeth are all N and the polarities of lower teeth are all S. The flux path is only one way from lower teeth to upper teeth. It makes that eddy current can flow along stator outer core in circumferential direction, so that large eddy current loss occurs. In order to reduce eddy current loss, the length of eddy current flow should be shorter. Therefore, slits are adopted as shown in Fig. 3 (b).

It is to ascertain experimentally the effect of slits that EMFs are measured according to increasing frequency and number of slits into the teeth of prototype. The mechanical support frame becomes weak as the number of slits is increased because the slits are added into one stator after finishing test instead of making several stators for each slit model. Therefore, transformer EMF by changing winding current frequency is measured instead of motional EMF by rotation of the rotor. Fig. 4 shows the results of the EMF tests as a function of electric frequency under no load condition. The EMF value is normalized with the base value being the EMF at 50 Hz. When the stator has no slit (Ns = 0), the curve of EMF is highly non-linear with respect to frequency, but as the number of the slits increases the EMF characteristic become more linear. This experimental result indicates that the core losses are reduced with increasing the number of slits.

The analytical explanation about slit effect will be presented in extended paper.

IV. REFERENCES

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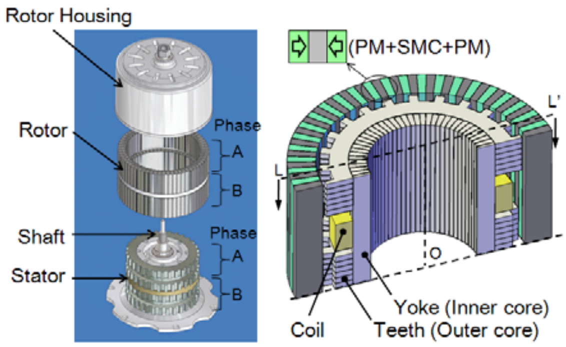

(a) Configuration of a TFRM (b) one phase rotor and stator

Fig.1. Conceptual drawing of a prototype TFRM with laminated stator core

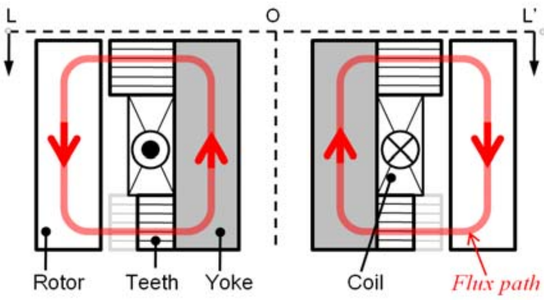

Fig.2. Flux path on the cross section area along L-L’

(a) Teeth without slits (b) Teeth with slits

Fig.3. Partial configuration of fabricated stator teeth

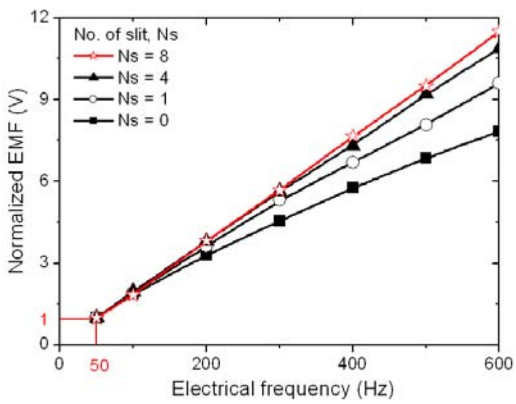

Fig.4. Normalized EMF from experimental results