Iron Loss of a Permanent Magnet-Inductor Hybrid Excitation Synchronous Generator

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Abstract — Magnetic field of the permanent magnet-inductor hybrid excitation synchronous generator includes ac field and dc biased field. The characteristic curves of the magnetic loss under dc bias flux are obtained based on the stator iron sheets test. The loss coefficients under dc bias flux are obtained through curve fitting. The magnetic loss of the homopolar inductor section under dc bias flux can be computed by means of Bertottis's formula. The research shows that the generator suffers an increase in magnetic losses while operating under dc bias flux. The magnetic loss variation trend of the homopolar inductor section is quite different from the permanent magnet section. The hysteresis loss under dc bias flux occupies most of the total magnetic loss in the homopolar inductor section.

I. INTRODUCTION

Hybrid Exciting Synchronous Generator (HESG) has increased its popularity in a wide variety of industrial application due to the adjustable output voltage [1, 2]. The HESG's structure and operational characteristics has been researched extensively. Iron loss is an important parameter to estimate the HESG performance. However, there are few studies on the iron loss of HESG. Moreover, the magnetic field distribution in HESG is more complex than that in permanent magnet generator. As a result, the calculation of iron loss of HESG is significant and complicated problem. This paper investigates the iron loss of a permanent magnet-inductor HESG and compares the variation trend of the iron loss of the permanent magnet section with the homopolar inductor section.

II. MACHINE STRUCTURE

The structure of the permanent magnet-inductor HESG is shown in Fig. 1.

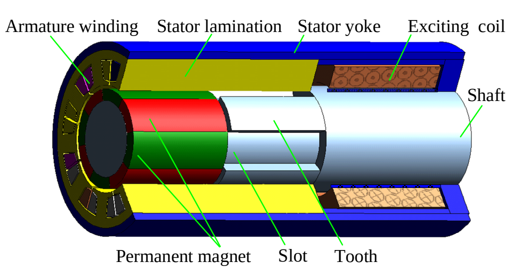


Fig. 1. Structure of the permanent magnet-inductor HESG

The stator of the permanent magnet-inductor HESG is the same as the conventional three-phase ac machine. The rotor of the permanent magnet-inductor HESG consists of two parts. One is a solid core with 4-slot and 4-pole. The other, is an 8-pole surface mounted permanent magnet rotor. The exciting coils are placed beside the end of the armature windings. The total main air gap flux, which is the summation of two fluxes, is able to be adjusted according to the magnitude and direction of the dc exciting current. Reference [3] has provided the more information on the structure and principle of the permanent magnet-inductor HESG studied in this paper.

III. CALCULATION OF IRON LOSS

The magnetic field distributions of the permanent magnet (PM) section and the homopolar inductor (HI) section in the HESG are diverse. As a result, the calculation methods of the iron loss in the two sections are quite different.

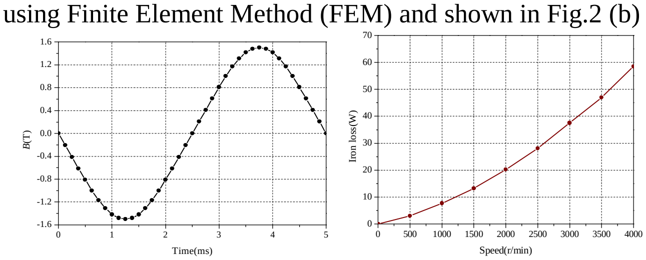
A. *Iron loss of PM section*

The magnetic field of the PM section is an alternating field. The magnetic flux density in the iron core is shown in Fig.2 (a). Therefore, the calculation method of the iron loss in the PM section can be expressed as

$$P_v = k_h fB_m^2 + k_c(fB_m)^2 + k_e(fB_m)^{1.5} \qquad (1)$$

Where, P_v is the iron loss, k_h, k_c, k_e are the hysteresis loss coefficient, the eddy-current loss coefficient and the excess loss coefficient, respectively, f is the operating frequency, and B_m is the amplitude of the ac magnetic flux density component in the iron core.

According to the equation (1), the iron loss in the PM section under the different speeds can be calculated by using Finite Element Method (FEM) and shown in Fig.2 (b)



(a) Magnetic flux density (b) Iron loss-speed characteristic curve
Fig. 2. Magnetic flux density and iron loss of the PM section

Fig.2 (b) shows the relationship between the iron loss and the speed under sinusoidal induction is non-linear obviously.

B. *Iron loss of HI section*

The magnetic field of the iron core in the HI section by the action of a dc exciting current is an alternating field with a constant component. The magnetic flux density in the iron core is shown in Fig.3.

When a dc component exists in the flux density, the core loss formula is modified to the following [4]

$$P_v = k_{dc}k_h fB_m^2 + k_c(fB_m)^2 + k_e(fB_m)^{1.5} \qquad (2)$$

Where, k_{dc} is the modification coefficient considering the dc flux bias effects, and k_{dc} >1.

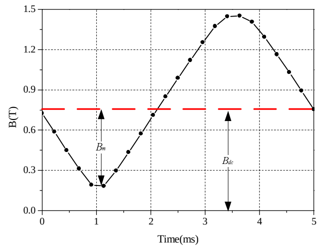
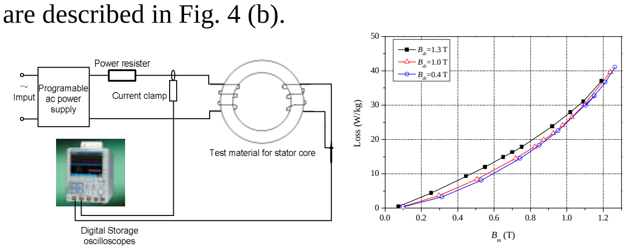


Fig. 3. Magnetic flux density in the iron core of the HI section

Equation (2) shows that the electrical machine operating under dc bias flux may suffer an increase in magnetic losses. However, using the equation (2) to calculate the magnetic loss under dc bias conditions is still a challenge in the design of electrical machines. This difficulty is due to the uncertainty of the coefficient k_{dc}.

Another method to calculate the magnetic loss under dc bias flux B_{dc} is to carry out magnetic loss tests to obtain the representative characteristic curves of the magnetic loss-B_m, firstly. Then, the hysteresis loss coefficient, the eddy-current loss coefficient and the excess loss coefficient under dc bias flux can be fitted by using the above test curves. At last, the magnetic loss under dc bias flux can be computed by means of Bertottis's formula.

The magnetic loss experiments under different dc-bias fluxes are implemented by using a specially designed measurement system shown in Fig. 4 (a), and the test results are described in Fig. 4 (b).



(a) Test system (b) Magnetic loss-B_m characteristic curves

Fig. 4. Test system schematic diagram and test result

Fig. 4 (b) shows that with the increase of the dc bias flux, the magnetic loss of the stator core material for the same B_m rises. According to the magnetic loss-B_m characteristic curves, the iron losses of the HI section at the action of 1000 A magnetic potential under different speeds are calculated by using FEM and shown in Fig. 5.

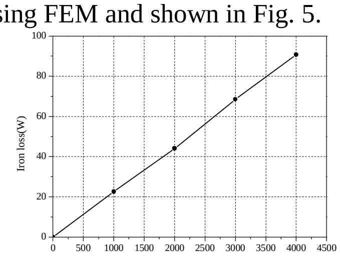


Fig. 5. Iron loss of the HI section

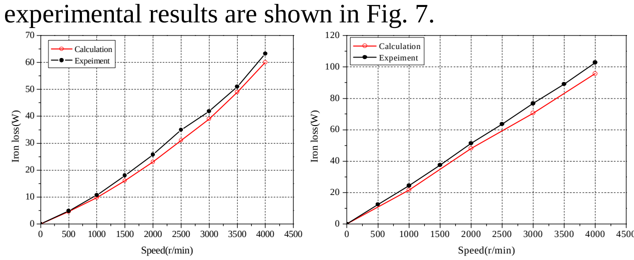
Fig. 5 suggests that the variation trend of the magnetic loss in the HI section with the increase of the speed is quite different from the PM section. The reason lies in that the hysteresis loss of the stator iron core in the HI section occupies most of the total magnetic loss. And then, the hysteresis loss is proportional to the operating frequency *f*.

IV. EXPERIMENT

A prototype of permanent magnet-inductor HESG has been made and shown in Fig. 6. Experiments are carried out to verify the validity of the numerical computations.

Fig. 6. Permanent magnet-inductor HESG prototype

Keeping the prototype running at no-load, when the exciting current is equal to zero, the magnetic loss of the prototype can be considered as the iron loss of the PM section. After that, applying a magnetic potential of 1000A, the magnetic loss increment of the prototype can be considered as the iron loss of the HI section. The experimental results are shown in Fig. 7.



(a) PM section (b) HI section

Fig. 7. Experimental results of the iron loss of the HESG prototype

The experimental results coincide with the calculation. And the previous theory analysis and calculation are correct.

V. CONCLUSION

The following conclusions can be drawn from the calculations and experiments above:

(1) Operating under dc bias flux, the electrical machine suffers an increase in magnetic losses.

(2) Magnetic loss of the homopolar inductor section is quite different from the permanent magnet section.

(3) Hysteresis loss under dc bias flux occupies most of the total magnetic loss.

VI. REFERENCES

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