The Thrust Density Optimal Design of Single Sided PMLSM for Considering Temperature Rise of Winding

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Abstract — This research deals with design of the maximum thrust density with considering winding temperature rise of single-sided PMLSM. The temperature rise of winding which caused to machine characteristics such as copper loss, iron loss and efficiency was analyzed by FEM. The maximum allowable current density was calculated within the allowable temperature. The effects of loss and efficiency according to temperature characteristic were confirmed.

I. INTRODUCTION

The PMLSM has high thrust density, high speed and low maintenance costs. So it has been widely used in industries such as manufacturing equipment of semiconductors and PDP/LCD. The productivity of these devices depends on the acceleration and deceleration characteristics of PMLSM[1]. In order to increase productivity, the winding temperature which is much closer to the allowable temperature is severely operated. Therefore, the winding temperature must be considered from the magnetic circuit design process. However, in conventional design methods, the current density is determined by the designer's experience and the thickness of winding is selected to design parameter, but the temperature rise was not considered. So continues redesign is necessary to meet the performance requirements. Thus, a magnetic field of PMLSM was analyzed with thermal analysis to minimize trial error in this paper. The maximum allowable current density was calculated within the allowable temperature according to changing height of the winding. The effects of changing temperature on the machine performance were analyzed.

II. THERMAL ANALYSIS OF SINGLE-SIDED PMLSM

A. Temperature rise test

TABLE I. PRINCIPAL SPECIFICATION

Item	Symbol	Value	Unit
Thickness of Core	T_t	16.80	mm
Number of Coil	N_c	608	Turn/2ea
Air-gap length (mm)	-	1.4	mm
Continuous Current Density	-	6.4955	A/mm^2
Continuous Force	-	657	N
Allowable Coil Temperature	T	105	℃

Table I represents the principal specification of single-sided PMLSM. The temperature rise test which determined the rating of machine was tested on the condition of duty type S5 (Periodic control including electrical brake) at a Fig. 1. The test motor was installed on a test jig and the operating conditions were set up as following. An acceleration was 20(m/s^2), a maximum velocity was 2(m/sec), a moving distance was 600(mm), and the additional weight was installed in a mover to supply sufficient load at the acceleration. The temperature sensor was inserted in the mover. The results of this test are as following. Continuous thrust was 657(N) at natural cooling, continuous current density was 6.48(A/mm^2) and internal temperature of winding was 96.6(℃) at that time.

(a) test pattern(S5) (b) experiment equipment

Fig. 1. Temperature rise test

B. Thermal Analysis

A heat transfer mechanism is classified into a conduction, convection and radiation. The heat transfer by radiation is generally neglected in the motor. In case of conduction, thermal analysis can be easily analyzed since the thermal conductivity coefficients of every material are already specified. However, convection coefficients are very difficult to determinate accurately. The 'convection heat transfer coefficient' is not a property of materials; this value is determined by the surface shape and the flow property which generates convection heat transfer. Thus, the selected design parameter which is winding height does not change convection surface shape and flow property. It means convection heat transfer coefficient is not altered.

The convection heat transfer coefficient is inversely calculated by the experiment result of basic model. This was deducted from experiment and applied to thermal analysis.

TABLE II.
RECALCULATION THE MAXIMUM ALLOWABLE CURRENT DENSITY OF BASIC MODEL

Input Current [A]	Current Density [A/mm^2]	Winding Temperature [℃]	Thrust [N]
6.53	6.5	96.40	668.35
6.85	6.8	104.885	709.125

In comparison with internal temperature at 96.4(℃) of coil by thermal analysis and internal temperature at 96.6(℃) of coil by experiment, convection heat transfer coefficient was properly selected. Also, the spare coil temperature was about 8(℃) that was compared to allowable temperature at 105(℃) of coil. Thus, the maximum allowable current density was recalculated within the allowable temperature. Table II shows the maximum thrust in this model.

C. Calculation the maximum current density

In conventional design method to maximize the thrust density, it was a general method that increases winding turns to grow magnetic force when the experiment value of the current density was fixed. The height of the core has to be increased as much as winding turn is increased. When the height of copper is getting higher, the cooling effect

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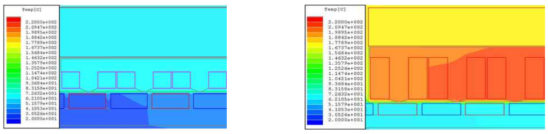
becomes worse. So the temperature of the copper is rapidly increased. Therefore, the thrust is not increased as much as the increments of the winding turn because copper loss is increased by internal resistance of the winding. Thus, the continuous current density was recalculated under the allowable temperature of winding according to the winding height in this paper. Fig. 2 shows the distribution chart of PMLSM according to the change of the copper height in case of fixing current density.



(a) height of the core: 9.75 [mm] (b) height of the core: 32.73 [mm]

Fig. 2. Distribution temperature chart according to height of the core

When the winding turns were 176 (the height of copper is 9.75mm), the highest temperature was calculated at 68.2(℃) in the winding because the good heat releases characteristic and the thrust can be increased by increment of the current density. However, when the winding turn was 592 (the height of copper is 32.73mm), the machine was damaged because the highest temperature, which was 202.7(℃), exceeded in allowable temperature. The maximum current density was not exceeded in the allowable temperature, which was shown in Table III.

TABLE III. RECALCULATION OF CURRENT DENSITY

T_t [mm]	N_c [Turn]	Current Density [A/mm^2]	Temperature of Coil [℃]	Continuous Thrust [N]
9.75	176	8.57	104.8	553.1
16.85	304	6.67	104.9	715.6
32.73	592	4.92	104.9	967.7

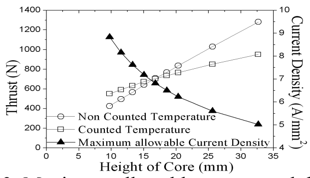


Fig. 3. Maximum allowable current and thrust

Fig. 3 represents the comparison with thrust which was without consideration of temperature rise when the current was fixed and thrust which was with consideration of coil temperature when the allowable current flowed. In case of considering the temperature characteristic in the winding as shown in Fig. 3, when the height of the core is 9.75(mm), the current density was increased from 6.5(A/㎟) to 8.57(A/㎟), and the thrust was also increased from 475.71(N) to 549.734(N). However, in case the height of the core was 32.73(mm), the current density was decreased from 6.5(A/㎟) to 4.92(A/㎟). So the thrust was decreased. Thus, the trial error will be minimized in the process of the design for considering temperature characteristic when the magnetic circuit is designed with the consideration of thermal analysis. Fig. 4 shows the peak force per unit weight according to the changing height of core. If the load is 10(kg) and the height of core is 23.03(mm), the maximum acceleration will be 128.6(m/s^2). In other words, that is the optimal model.

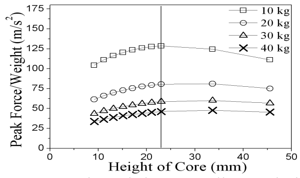
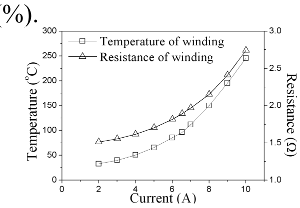


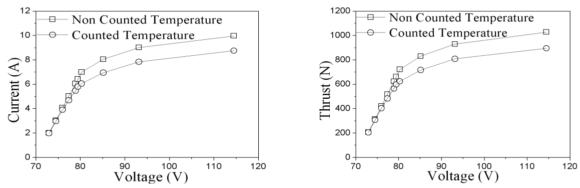
Fig. 4. Peak force per unit weight according to height of the core

III. LOSS EVALUATION FROM TEMPERATURE RISE

The resistance was increased by temperature rise of winding, then the additional voltage drop was produced. Therefore, the voltage should be increased to generate same thrust. Fig. 5 (a) shows changing of temperature and resistance according to currents. The temperature and the resistance were rapidly increased when the current which was over the allowable temperature was flowed. To generate same thrust, high voltage should be supplied than in case of without consideration of temperature rise by increased resistance according to temperature rise as a Fig. 5 (b) and (c). Thus, in case of supplying 79.42(V) without consideration of temperature rise, the current was 6.42(A) in coil. However, in case of considering temperature rise, the 82.95(V) was supplied for flowing the same current in the coil. The total loss was 274(W) by temperature rise and the efficiency was decreased by additional loss from 86.6(%) to 82.9(%).



(a) temperature rise and resistance



(b) voltage and current (c) changing of thrust

Fig. 5. The effect of machine characteristic according to temperature

IV. CONCLUSION

The characteristic of temperature rise and the maximum allowable current density were calculated according to changing core height by thermal analysis. Finally, the maximum thrust model was designed. In contrast with conventional design methods, when core height was 9.75(mm), the cooling effect of coil was good so the higher current density could be calculated. As a result, the thrust was increased.

V. REFERENCES

[1] David L. Trumper, Won-jong Kim and Mark E. Williams, 1996, "Design and Analysis Framework for Linear Permanent-Magnet Machines", IEEE Trans. on Industry Applications Society, vol. 32, no. 2, pp. 371~379