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Performance Analysis of a Permanent Magnet Synchronous Generator using SS400 Rolled Steel Sheets for the Rotor Core

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This paper deals with a permanent magnet synchronous generator (PMSG) for diesel engine generators. Generally, a silicon steel sheet is used to minimize eddy current losses of the stator and rotor cores of a generator. However when a silicon steel sheet is employed to produce the core of the stator and rotor, manufacturing costs increase due to the high cost of the silicon steel sheet. To reduce these costs, a 5 mm SSC400 rolled steel can be used as an alternative to the silicon steel sheet. However, the SS400 rolled steel with a thickness of 5 mm can increase the eddy current losses of the core. In this paper, in order to overcome this problem, a slit type rotor core is employed. In this case, eddy current losses can be reduced, resulting in improved THD (Total Harmonics Distortion) of the induced EMF (Electro-Motive Force). The eddy current losses and THD of the induced EMF according to the number of slits is also analyzed. Moreover, a prototype is produced for the final model, and the effectiveness is confirmed through experiments.

Keywords : permanent magnet synchronous generator, rolled steel for general structure, eddy current loss, diesel generator, slit in the rotor

1. Introduction

Electric power generator systems consisting of a wound field synchronous generator and an AVR (Automatic Voltage Regulator) are commonly used for emergency diesel generators due to their relatively low cost. However, since these generation systems cannot provide high quality electrical power, they are not suitable for use in hospitals or research facilities. To obtain high quality electrical power, generator systems with a permanent magnet synchronous generator (PMSG) and inverters are proposed [2-5]. These generator systems have the advantage of a high driving efficiency and high quality electrical power. In general, the rotor and stator cores of PMSGs are laminated with 0.35 mm or 0.5 mm thin silicon steel sheets to reduce eddy current losses. However, thin silicon sheets can increase the system cost: the thinner the steel sheet, the higher the labor costs. Eddy current losses of typical generators and the electrical generators have the following characteristics. First, eddy current losses of the rotor are very low compared with those of the stator. Second, eddy current losses are relatively low in low speed electrical machines [6-8]. By using these characteristic of eddy current losses, in this paper, 5 mm rolled steel for the general structure is applied to the rotor instead of a thin silicon steel sheet. In this case, material and labor costs can be reduced. However, it is obvious that the total losses of the generator will increase. To minimize any increase of the losses, a slit is also applied to the rotor core. In this case, the eddy current losses can be reduced. Moreover, since the 5 mm rolled steel for the general structure is not isolated, insulation films are placed between the steel sheets. In order to improve the electric power quality of the generator, THDs (Total harmonics Distortions) of the phase back EMF according to the slit applied to the rotor are analyzed. In this paper, a 5 mm rolled steel for the general structure is applied to the rotor instead of the thin silicon steel sheet, and losses and the efficiency of the generator are compared through an FEA (Finite Element Analysis). The no-load induced EMF and rated output power is confirmed by a no-load test and load test, respectively.

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2. Characteristics of a Permanent Magnet Synchronous Generator with SS400 Rolled Steel Sheet

2.1. Design specification and generator comparison model

A comparative model of a generator is designed to compare the losses and efficiency of generators prior to performing a characteristic analysis of a PMSG using SS400 rolled steel with a thickness of 5 mm. The specification of the comparative model generator is shown in Table 1. Here, 0.5 mm silicon steel sheets are applied to the rotor of the comparative model generator. Table 1 shows the design specification of the generator. The rated output power and speed are 54 kW and 1800 rpm, respectively. The line to line terminal voltage required is 380 Vrms, and the load power factor is at least 0.8. In this paper, we use TRV (Torque per Rotor Unit Volume) and SR (Shape Ratio) to determine the shape and dimensions of the generator. In general, the lower the TRV, the larger the rotor size of the generator, resulting in a large overall size of the generator. In this case, even though the output power density is lowered, it has an advantage in its temperature characteristics. In addition, the magnetic saturation of the core can be reduced, and the electric power quality can be improved. The SR represents the ratio of stack length to rotor diameter. When the SR is large, the generator will be elongated, and when the SR is small, it will be flat. Since the inductance is relatively small for the large SR, the voltage regulation is small and excellent temperature characteristics can be obtained. However, it can become vulnerable to vibration. In this paper, the TRV of the generator is about 20 kNm/m^3, and is designed with approximately 2.4. Using TRV and SR, the main dimensions such as the rotor dimeter and stack length of comparison models applied with the silicon steel sheet were determined. The 50PN470 is used for the rotor core of the comparison model.

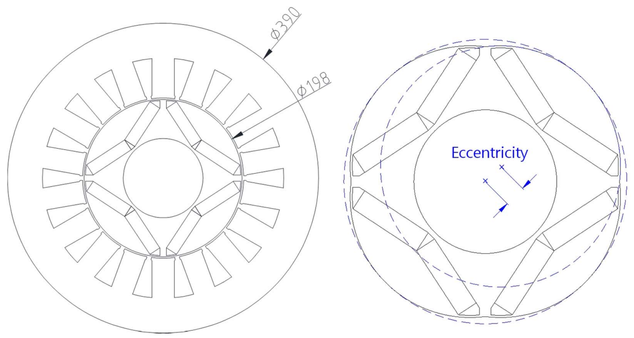


Fig. 1. (Color online) Shape of 54 kW comparative generator model.

Table 1. Design specification of generator.

Item	Value	Unit
Rated power	54	kW
Rated speed	1800	rpm
Rated frequency	60	Hz
Line to line voltage	380	Vrms
Load power factor	1, 0.8	-
Cooling method	Passive cooling	-

The stator of the comparative model with 50PN470 is applied by calculating the dimensions of the stator yoke and stator tooth so that the equivocal magnetic resistance is minimized. In addition, the passive cooling method is considered and the current density is less than 2 Arms/mm^2 to minimize copper losses. The pole-slot of the comparative model is set as 4pole-18slot to improve the THD of the induced EMF. For a generator with high torque, when a permanent magnet is placed on the rotor surface, the permanent magnet can be damaged by a large magnetic attractive force. Therefore, in this paper, the generator is designed with a permanent magnet inserted inside the rotor core. The generator's air-gap and the thickness of the permanent magnet are 2 mm and 15 mm, respectively. The stator diameter, rotor diameter and stack length are 390 mm, 198 mm and 470 mm, respectively. The thickness of the rib of the rotor core is 1.5 mm. The stability is confirmed through a stiffness analysis. The core material of the stator and rotor is 50PN470, and NdFeB is used for the permanent magnet. The coil pitch of the armature windings is 4, the number of parallel circuit is 2, and the number of wire is 10. Fig. 1 shows the shape of the designed comparative model. In order to improve the waveform of the induced EMF, 10 mm eccentricity is applied to the rotor core to minimize the induced EMF THD.

2.2. Characteristic analysis and comparison of the generator

Fig. 2 shows the B-H curve of 50PN470 and SS400. As shown in Fig. 2, the B-H characteristics of SS400 are significantly worse than those of 50PN470. In the case of the 50PN470, the B-H curve rapidly increases. It means that a relative permeability of the iron core is considerably high. On the other hand, since the relative permeability of the SS400 is low, the B-H curve of SS400 smoothly increases. When the relative permeability is low, the induced EMF is reduced because the magnetic flux is not generated well. When the input EMF decreases, the generator's efficiency decreases, and the size must be increased to produce the same output power. In addition,

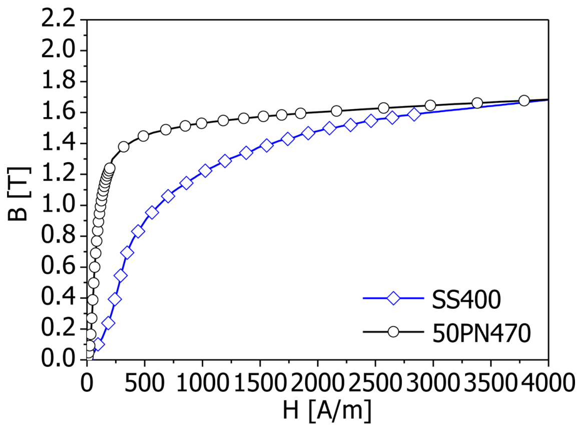


Fig. 2. (Color online) B-H curve according to steel sheet materials.

since the core thickness of the SS400 is 5 mm, large eddy current occurs when applied to the generator. This eddy current causes eddy current losses. This drawback can arise when a 5 mm rolled steel for the general structure (SS400) is applied instead of the 0.5 mm silicon steel sheet (50PN470) to the rotor of the designed comparative model. In order to improve this drawback, an improvement design is carried out on the shape of the generator rotor.

Fig. 3 shows three rotor shapes applied with SS400. Fig. 3(a) is a non-slit model with a core thickness of 5 mm, and Fig. 3(b) is a 7-slit model with a core thickness of 5 mm. Fig. 3(c) is a 7-slit model with a core thickness of 470 mm. The core thickness of Fig. 3(c) is the same as the stack length of the comparative model generator. Fig. 4 shows the results of the eddy current losses analysis of the three rotors applied with SS400. The analysis is carried out through a 3D-FEA (Finite Element Analysis). Eddy current losses analysis of the rotor is performed under conditions of output power 54 kW, load power factor 1, and rotor speed 1800 rpm. As shown in the Fig.

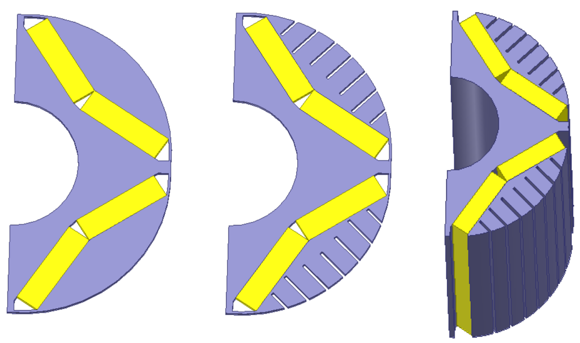


Fig. 3. (Color online) Structure according to the rotor shape with SS400 rolled steel sheet.

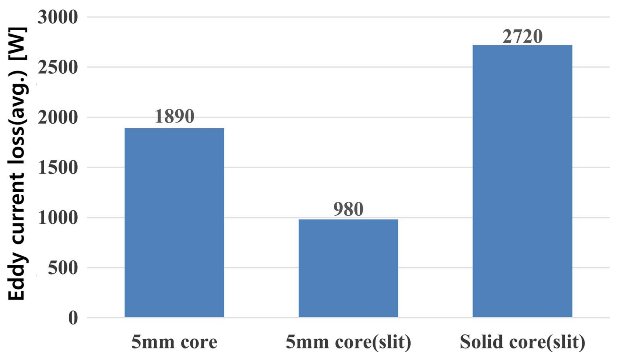


Fig. 4. (Color online) Eddy current losses according to the rotor shape with SS400 rolled steel sheet.

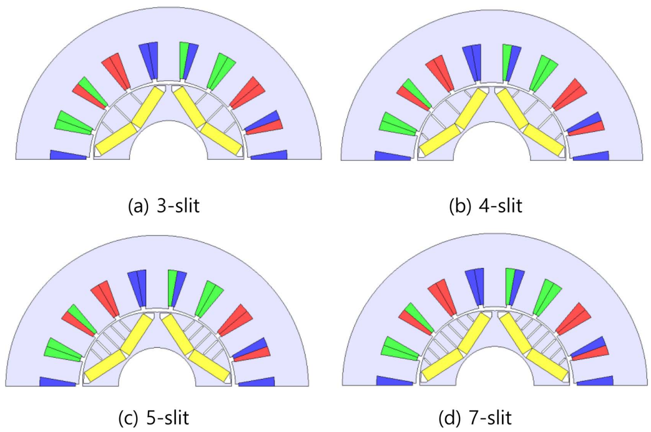
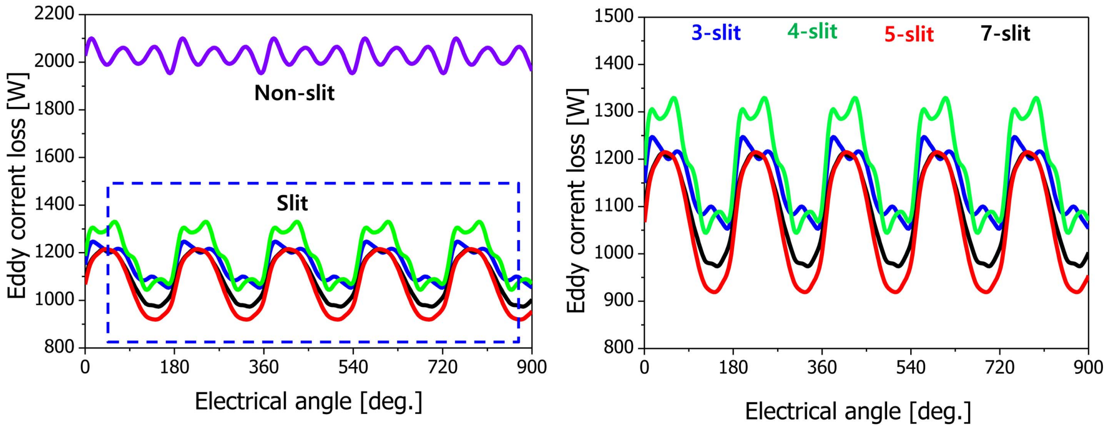


Fig. 5. (Color online) Structure of the rotor according to the number of slits.

4, eddy current losses of models with the 7-slit applied with a core thickness of 470 mm is the largest. Eddy current losses of models without the slit applied with a core thickness of 5 mm is shown to be in the middle. The model with the smallest eddy current losses is a 7-slit model with a core thickness of 5 mm.

We analyze how eddy current losses and indented EMF THD vary according to the number of slits. By applying such slits to the rotor core of the generator, it is possible to reduce the rotor eddy current losses of the generator and improve the induced EMF THD. As shown in Fig. 5, three to seven slots are applied in the rotor. Using 3D-FEA, eddy current losses are analyzed according to the number of rotor slits. Fig. 6 shows the eddy current losses wave of the rotor core according to the number of slits. As shown in Fig. 6(a), eddy current losses are largest when the slit is not applied. When a slit is applied, eddy current losses can be significantly reduced. Fig. 6(b) shows the blue dotted line of Fig. 6(a). Fig. 7 shows the average value of the rotor eddy current losses according to the number of slits. From Fig. 7, it can be seen that



(a) Non-slit / slit (b) 3~7 slit

Fig. 6. (Color online) Analysis results of eddy current losses according to the number of slits.

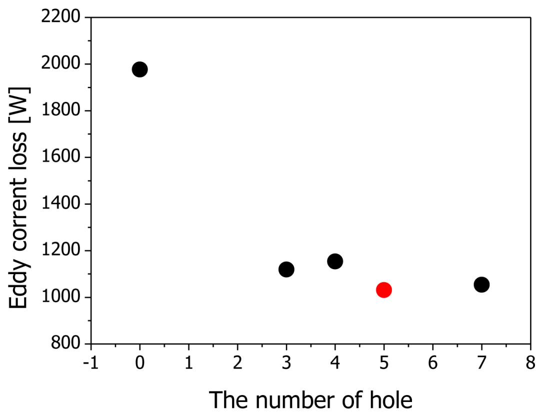
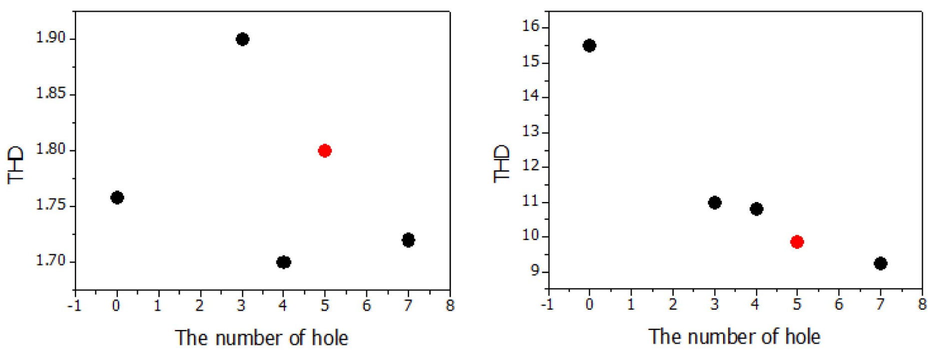


Fig. 7. (Color online) Mean value of eddy current losses according to the number of slits.

eddy current losses are approximately 1977W without a slit, and eddy current losses are about 1119W with three slits. When five slits are applied, eddy current losses are about 1031W. When the five slits are applied to the rotor core of the generator, the eddy current losses can be the smallest. In this paper, five slits, the smallest rotor eddy current losses, are applied to the generator rotor. The slit of the generator rotor improves the induced EMF THD. In particular, when operating under loads, the magnetic saturation of the generator rotor core increases, thus causing the induced EMF THD to deteriorate. By applying a slit to the generator rotor core, the magnetic saturation of the rotor core can be uniform, which can improve the induced EMF THD. The induced EMF THD of the generator depends on the number of rotor slits.

Fig. 8 shows the no-load phase induced EMF THD and the load induced phase EMF THD according to the number of slits of the rotor core. The 2D-FEA is employed for the analysis. As can be seen from Fig. 8, the no-load induced phase EMF THD exists between 1.7 % and 1.9 % both with and without slits. In the case of the no-load, since the magnetic saturation of the rotor core is low, the induced EMF THD is low regardless of the slit. However, there is a big difference in the load induced EMF. When no slit is applied, the load induced EMF THD is about 15.5 %, and when 7 slits are applied, it decreases to about



(a) No-load Back-EMF THD (b) Load Back-EMF THD

Fig. 8. (Color online) Analysis results of Back-EMF THD according to the number of slits.

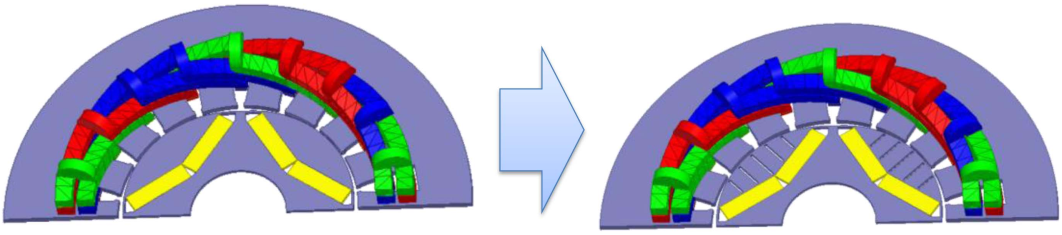


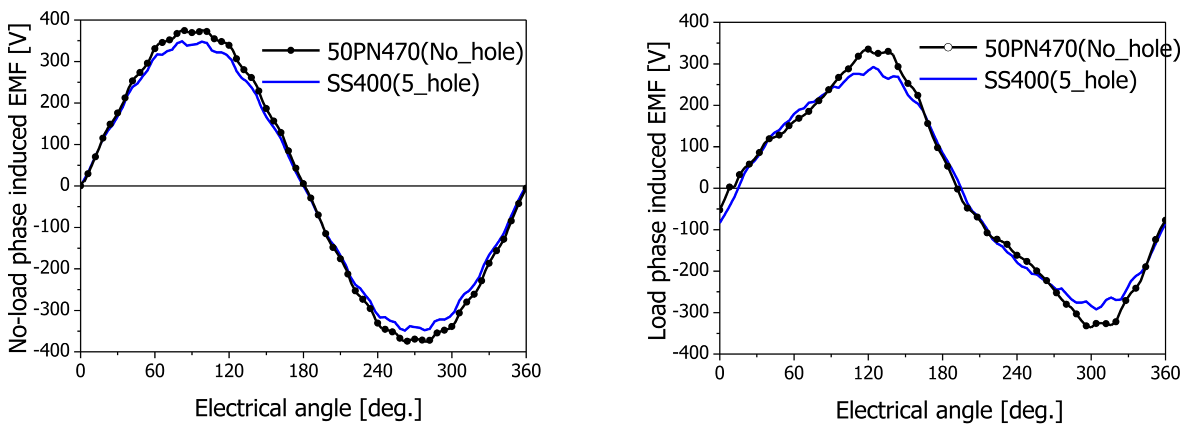
Fig. 9. (Color online) Shape Comparison of No-slit and 5-slit.

7 %. This is the effect of improving the magnetic saturation of the rotor core due to the slit application. In this paper, the 5-slit model with the smallest eddy current losses is chosen as the final model.

Fig. 9 shows the shape of the comparison model applied with 50PN470 and the 5-slit model applied with SS400. Generally, the silicon steel sheet is coated with a very thin layer. This coating plays the role of insulation between each layer of the silicon steel sheet. This coating prevents the eddy current generated in the silicon steel sheet crossing to another layer, resulting in the reduced eddy current losses. The coating thickness of the steel sheet of the model to which 50PN470 is applied is about 0.7 μm. Rolled steel for general structures such as SS400 is not coated. There is no insulation between the layers and eddy current losses can be increased. In this paper, an insulation film is inserted between layers to improve eddy current losses. The thickness of the insulation film placed between the steel sheets of the model to which the SS400 is applied is about 0.18 mm. In the case of the 50PN470 applied model, the coating ratio is about 3 % of the stack length. In the case of the model to which SS400 is applied, the ratio of the insulation film to the stack length is about 3.5 %. This means that the model to which the SS400 is applied can have a lower no-load induced EMF than the model to which the 50PN470 is applied.

Fig. 10 shows the no-load/load induced EMF wave of the comparative model with 50PN470 and the 5-slit model with 5 mm SS400. The rms value of the fundamental wave of the no-load induced EMF of the SS400 applied model is about 7.5 % smaller than that of the 50PN470 applied model. This is due to the B-H characteristics of the SS400 core and the insulation film placed between the SS400 steel sheet. The rms value of the fundamental wave of the load induced EMF of the SS400 model is about 6.7 % smaller than that of the 50PN470 model. Table 2 shows the losses and efficiency of the two models. For the SS400 model, copper losses increased by about 7.8 % under the same output power condition due to the decrease in no-load induced phase EMF. The iron losses of the model to which the 50PN470 is applied is 1210W, and most are losses of the stator. The iron losses in the stator of the SS400-applied model are 1283W, and the eddy current losses in the rotor are 967W. The model with SS400 also increase the total losses of the generator due to the rotor eddy current losses.

However, when the efficiencies of the two models are compared, there is a difference of about 1.8 %. The efficiency of the SS400-applied model was reduced by 1.8 %. The efficiency of the SS400-applied model does



(a) No-load Back-EMF wave (b) Load Back-EMF wave

Fig. 10. (Color online) Back EMF Comparison of no-load and load according to type of steel sheet.

Table 2. Characteristic comparison of 50PN470-applied model and SS400-applied model.

Item	Value		Unit
	50PN470 (No-slit)	SS400 (5-slit)	
Rated power	54		kW
speed	1800		rpm
No-load phase back EMF	266	246	Vrms
Load phase back EMF THD (PF 0.8)	15.5	9.8	%
Copper loss	460	496	W
Iron loss	1210	2250	W
Mechanical loss	171	171	W
Efficiency	96.7	94.9	%

not decrease significantly. The reason is that the proportion of the eddy current losses in the electric input power of the generator is not large. In other words, for a generator of high output power and high efficiency that does not have a large proportion of eddy current losses, the efficiency does not significantly decrease even if a 5 mm structural rolled steel sheet is applied. Thus, by applying a 5 mm rolled steel for the general structure, material costs and labor costs can be reduced.

2.3. Stiffness analysis of rotor of generator

In order to verify the mechanical stability, a stiffness analysis for the rotor core is performed. The permanent magnet and material properties are summarized in Table 3. The condition of the operating speed is 1800 rpm. Generally, in the case of a structure in which the permanent magnet is inserted into the rotor core, the stress is maximum at the bridge of the rotor core. Since the maximum stress is dependent on the number of slits, a stiffness analysis is required. Figs. 11 and 12 show the results of the stiffness analysis for the rotor core. Fig. 11 shows a deformation of the rotor core. From Fig. 11, it can be seen that the significant deformation occurs in the middle of the rotor

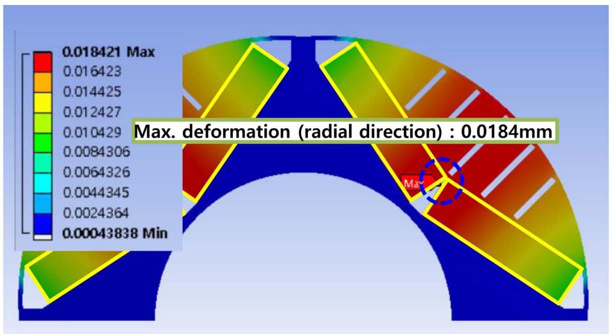


Fig. 11. (Color online) Deformation of rotor.

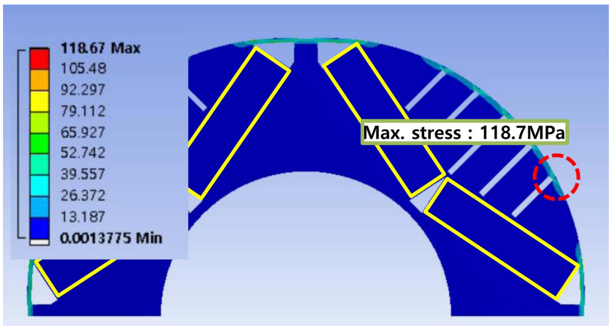


Fig. 12. (Color online) Stress of rotor.

Table 3. Material property of steel sheet and permanent magnet.

Item	Value		Unit
	Permanent magnet (NeFeB)	SS400	
Density	8400	7850	Kg/m^3
Young's modulus	120	190	GPa
Poisson's ratio	0.3	0.26	-
Yield strength	-	220	Mpa

core. The value of the maximum deformation is 0.0184 mm. Fig. 12 shows the analysis results of the rotor stress. As it can be seen from Fig. 12, the maximum stress of the rotor core is 118.7 MPa. Given that the yield strength of SS400 is 220 MPa, it can be confirmed that there is no problem in mechanical stability.

3. Generator Production and Performance Test

In this paper, a prototype is produced for a SS400 applied model. A 5 mm SS400 sheet for the rotor core and the insulation film placed between steel sheets are shown in the right and left of Fig. 3, respectively. QMFZ2.E110983 is employed for the insulation film, which is a plastic material. Fig. 14 shows the stator and

(a) Insulation film (b) Rotor core

Fig. 13. (Color online) Rotor and insulation film.

Fig. 14. (Color online) Prototype.

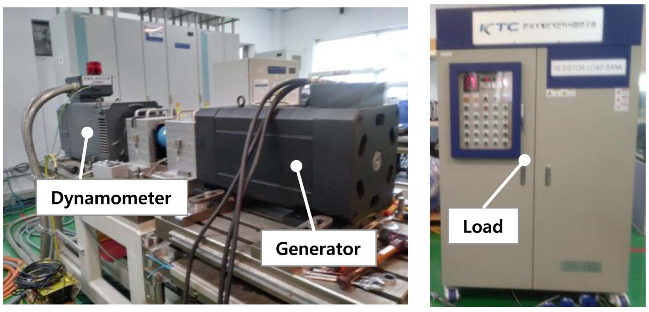


Fig. 15. (Color online) Test Configuration.

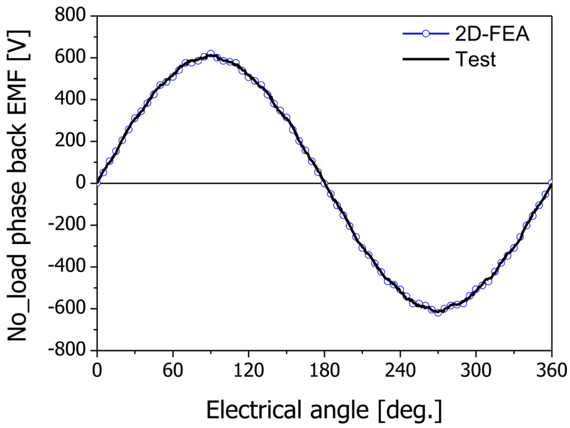


Fig. 16. (Color online) Comparison of experimental and analysis for No-load phase back EMF.

rotor of the generator and the assembly. The stator of the generator is manufactured without housing. Since the housing is not provided during production, it is constructed in a rectangular shape instead of a circular shape to facilitate movement and placement. In this case, there is a small reduction of iron core magnetic saturation in the stator yoke, which did not significantly affect generator performance. The generator rotor core is fixed using the end plate and pin. The balancing of the rotor is carried out to reduce vibration. Fig. 15 shows the test configuration for a no-load and load test for the prototype. Torque is applied to the generator using a dynamometer. The output

Table 4. Comparison of test and analysis results.

Item	Value		Unit
	Analysis result	Test result	
Rated power	54		kW
speed	1800		rpm
No-load line to line back EMF	426.1	425.7	Vrms
No-load phase back EMF THD	1.8	1.1	%
Efficiency	94.9	94.6	%

terminal is connected with load registers. Due to a lack of research funds, load tests were performed only if the load power factor was 1. Fig. 16 shows the test and analysis results for no-load induced EMF waves in the prototype. The test conditions are room temperature and 1800 rpm. The test and analysis results are summarized in Table 4. The test results are almost coincident with the analysis results for the fundamental wave rms value of the no-load line to line back EMF. The test results of the THD for the no-load line to line back EMF is 1.1 %, and the analysis results is 1.8 %. The load test is performed for the condition of 54 kW output power, 1800 rpm operating speed, 1 load power factor. As a result of the test, the efficiency of the prototype is 94.6 %. Since the analysis results of the efficiency is 94.9 %, the test and analysis results are almost the same.

4. Conclusion

In this paper, the characteristics of the generator were analyzed when a 5 mm rolled steel for the general structure (SS400) was applied instead of a 0.5 mm silicon steel sheet (50PN470) to the rotor of a 54 kW generator. A model with 50PN470 was selected as a comparative model. For the SS400-applied model, a slit was applied to the rotor core to reduce eddy current losses. The shape and dimensions of the 50PN470 and SS400 models are the same except for the slit of the rotor core. For the

SS400-applied model, the eddy current losses of the rotor were analyzed according to the number of slits. Moreover, a no-load induced EMF THD according to the number of slits was confirmed. The induced EMF and eddy current losses were analyzed through the 3D/2D-FEA. As a result of the comparison, the fundamental wave rms value of the no-load induced EMF for the SS400-applied model was 7.5 %. This rms value is lower than that of the 50PN470-applied model. As a result, copper losses of the SS400-applied model increased by about 7.8 %. In addition, iron losses increased by about 86 % due to eddy current losses generated in the rotor with SS400. As a result, the efficiency of the SS400-applied model was 1.8 %. This rms value is lower than that of the 50PN470-applied model. However, the reason that the efficiency of the SS400-applied model did not drop significantly is that the proportion of the eddy current losses in the electric input power of generator is not large.

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