Journal of Engineering and Applied Sciences 12 (Special Issue 3): 6481-6486, 2017
ISSN: 1816-949X

Effective Design on Induction Motor for Electric Vehicle

Ki-Chan Kim
Department of Electrical Engineering, Hanbat National University, Daejeon, South Korea

Abstract: In an application of a traction motor for high power electric vehicle, it is needed to be designed with small size, light weight and low temperature rise. In the study, the design method of an induction motor satisfying improved performance is proposed by using design parameters of stator yoke. First in order for small size and light weight, a parameter related to cutting edge without magnetic saturation is suggested. Second in order for low temperature rise, a parameter related to ventilation hole in stator yoke is suggested. The characteristics are analyzed by using FEM according to motor speed within driving region which is divided into constant torque region and constant power region (field weakening control region).

Key words: Cutting edged yoke, finite elements method, induction motor for electric vehicle, stator yoke design, ventilation hole, design parameters

INTRODUCTION

Now a days, electric motors such as permanent magnet synchronous motor and induction motor are used for the traction motor of electric vehicle due to high torque performance at low speed and high speed performance without gear system compared with an engine (Zeraoulia *et al*., 2005; Boldea *et al*., 2014). Although, a permanent magnet synchronous motor with rare-earth magnet has higher torque density than other motors, it has demerits of high cost and low stability on control system due to back-emf increase according to motor speed (Jahns, 1987). In case of brushless dc motor, it is difficult to operate the motor with high speed due to demagnetization of permanent magnet. On the other hand, an induction motor has reliability on structure and control system (Alberti *et al*., 2011; Harson *et al*., 1995; Wang *et al*., 2005). However, induction motor has higher frame size and lower efficiency than the permanent magnet motor. For the application of electric vehicle, the traction motor should be designed with suitable size for limited vehicle space without decrease in performance such as efficiency and torque.

In general, induction motors are designed with cutting edge and ventilation holes in stator core due to compact size and low temperature rising. However, excessive level of these design variables deteriorates permeance at stator yoke. Therefore, they have a strong influence on motor performance including current, torque, efficiency and power factor especially in traction system operated with wide speed range.

In the study, characteristic analysis of base model without cutting edge and ventilation hole in a stator core is performed by using FEM (Finite Element Method) within operation region which is divided into constant torque region and constant power region. Next, the characteristics of induction motor with cutting edge are compared with those of base model according to depth of cutting edge. Finally, the induction motor with cutting edge and ventilation hole is suggested for the light weight and high cooling capacity without changing the performance according to driving speed.

MATERIALS AND METHODS

Characteristic analysis of base model

Analysis model: As a traction motor for railway transit, an induction motor with output power of 1,325 kW is designed as shown in Fig. 1. The induction motor has no ventilation hole and cutting edge in stator core. The brief specification of base model for the analysis is in Table 1. As shown in Fig. 2, the driving performance curve of base model has two different control regions across the base speed of 1,610 rpm. In the first region with low speed and high constant torque, the induction motor is controlled with constant ratio of input voltage to frequency of voltage. In the second region with constant power, it is controlled with field weakening topology by adjusting slip-frequency due to limitation of input voltage. If load torque at high speed satisfying constant power is bigger than maximum torque of slip characteristic curve at the speed, the induction motor should be controlled with 2nd field weakening control which decreases output power.

Analysis load points: As an analysis points, two speed points in the constant torque region and three speed points in the field weakening control region are selected.

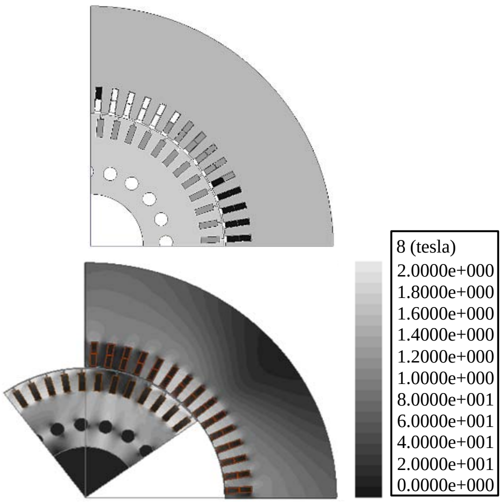

Fig. 1: 1/4 base model and magnetic flux density

Table 1: Rated specification of base model

Parameters/Units	Specification
Rating power (kW)	1,325
Rating torque (Nm)	7,861
Rating speed (rpm)	1,610
Phase voltage (V_{rms})	1079.645
Phase current (A_{rms})	500.55
Efficiency (%)	98.16
Power factor	0.878

First, the torque according to input frequency in the stator winding is calculated with fixed input voltage and rotor speed in an analysis point in order to find the rated frequency in the analysis point. Rated slip can be obtained by the analysis. Next, a slip characteristic curve with the rated frequency is induced by changing the rotor speed. At the other 4 analysis points, the slip characteristic curves are calculated in the same way.

Finally, the performance can be analyzed at the operation points which are crossing points of the slip characteristic curves and an arbitrary driving performance curve. However, the reference torque of driving performance curve may be higher than that of slip characteristic curve in the high speed due to field weakening control which decreases maximum torque of slip characteristic curve according to motor speed. In that case, driving performance curve should be modified less than maximum torque of slip characteristic curve. In the study, slip of 90% torque level of maximum torque is selected for the operation. It is 2nd field weakening control by using constant slip-frequency.

Figure 2 shows slip characteristic curves at 5 speed points by FEM and driving performance curve on torque of base model. By using the results, slip frequency for controller as well as efficiency and power factor of induction motor can be analyzed as shown in Table 2.

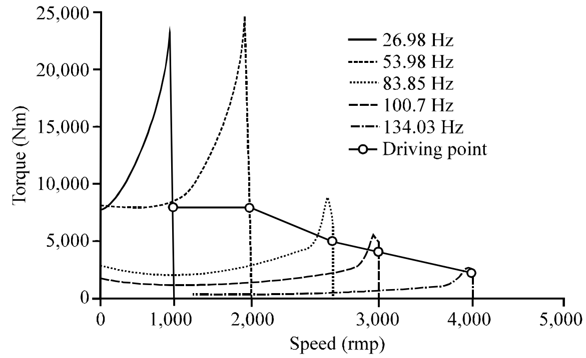

Fig. 2: Slip characteristic curves according to speeds

Table 2: Rated specification of base model

	Speed (rpm)				
Parameters/Unit	800	1,610	2,500	3,000	4,000
Frequency (Hz)	26.98	53.98	83.85	100.7	134.03
Slip	0.0115	0.0058	0.0062	0.0070	0.0052
Phase voltage (V_{rms})	539.56	1079.65	1079.65	1079.65	1079.65
Phase current (A_{rms})	494.31	500.55	485.52	512.92	377.15
Torque (Nm)	7861	7861	5052.4	4186.3	2258.8
Power factor	0.873	0.878	0.883	0.840	0.824
Efficiency (%)	96.9	98.16	98.07	97.8	96.34

RESULTS AND DISCUSSION

Effecton performance dueto cutting edge: For compact size and low cost of induction motor, it is usually designed with cutting edge of stator core. However, decreased stator yoke due to cutting edge deteriorates performance of induction motor due to unbalanced three phase current. Figure 3 shows the design parameter of cutting edge in an induction motor and shape of stator after cutting edge. As an induction motor with four poles, narrowed yoke is placed over a phase winding. In case of other poles, the phase winding affected by narrowed yoke is different.

Figure 4 shows the slip characteristic curves of base model and cutting model with 100 mm cutting edge according to driving points. Torque characteristics according to slip between base model and cutting model in the constant torque region with high air-gap flux density are slightly different due to magnetic saturation in the narrowed yoke. However, the difference is gradually weakened in constant power region due to field weakening control.

At the rated operation point of 7,861 Nm and 1,610 rpm, slip is slightly decreased and phase currents are increased due to cutting edge parameter as shown in Fig. 5. Table 3 shows the performance comparison at five operation points, respectively.

Figure 6 shows the comparison result of magnetic flux density in the stator yoke. As the same input voltage

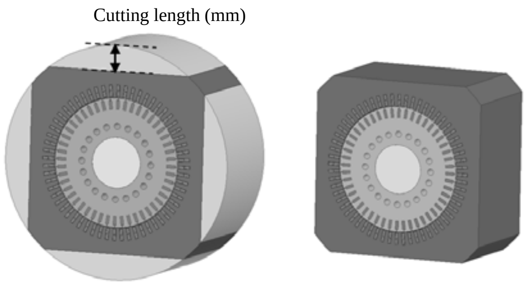

Fig. 3: Cutting edge model in stator core

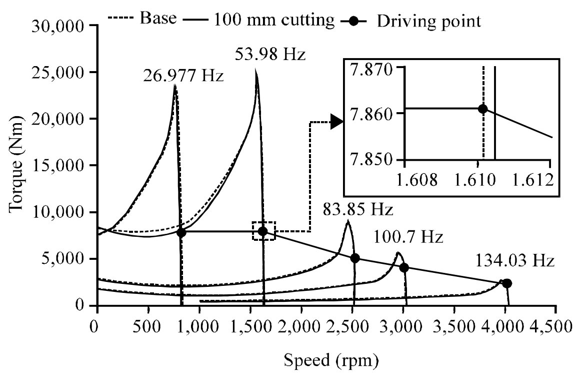

Fig. 4: Slip characteristic curves of base model and 100 mm cutting model

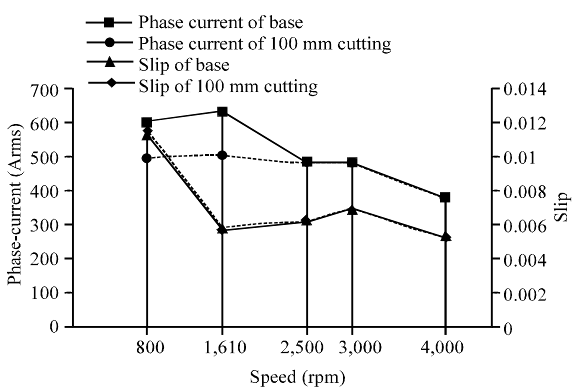

Fig. 5: Comparison of phase current and slip between base model and cutting edge model with 100 mm

Table 3: Performance comparison at base speed (100 mm)

Model	Slip (%)	Current (Arms) Phase A	Phase B	Phase C	Torque (Nm)	Efficiency (%)
Base	0.57	500	507	503	7,861	98.17
100 mm cutting	0.56	752	545	605	7,861	97.33

Fig. 6: Magnetic flux density of base model and cutting edge model with 100 mm at base speed

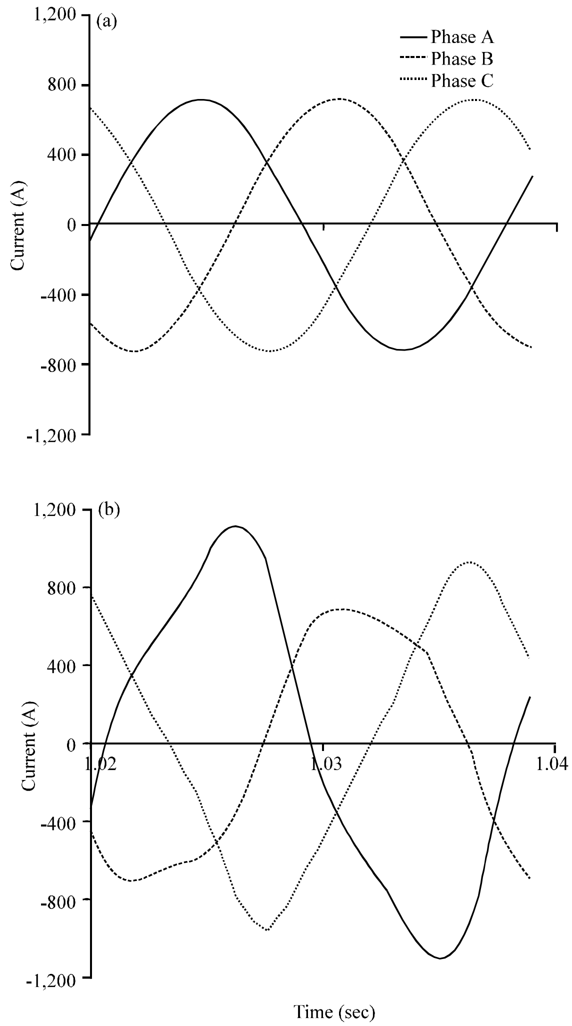

Fig. 7: Phase current waveforms of base model and cutting edge model with 100 mm at base speed

and frequency are applied in the motor, they have the same air-gap flux density. However, magnetic saturation is occurred at the narrowed yoke over one phase winding in case of cutting model. The current waveforms of cutting model in Fig. 7 are unbalanced and even not sinusoidal.

In case of cutting edge with 60 mm, magnetic saturation effect due to narrowed yoke is not critical to

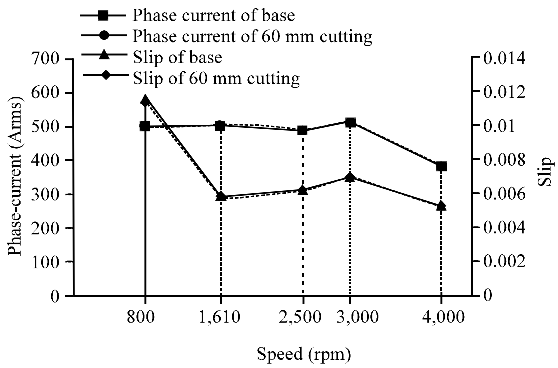

Fig. 8: Comparison of phase current and slip between base model and cutting edge model with 60 mm

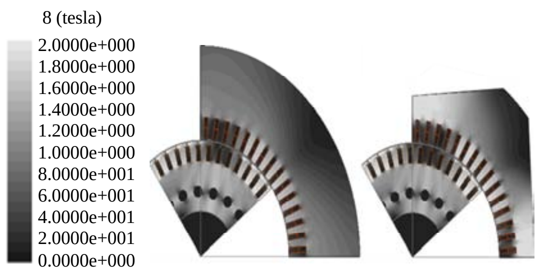

Fig. 9: Magnetic flux density of base model and cutting edge model with 60 mm at base speed

deteriorate performance of induction motor. Figure 8 shows the comparison results on phase current and slip according to operation points. The current and slip of cutting model with 60 mm cutting edge is almost similar to those of base model within driving region. Detailed analysis results are shown in Table 4. Magnetic flux density in the stator yoke is about 1.4 T which correspond to under magnetic saturation level as shown in Fig. 9. In Fig. 10, the current waveforms of cutting model are almost sinusoidal similar to base model.

Effect on performance due to ventilation holes: Induction motor generates core loss mainly in the stator core. Core loss is one of heating sources of induction motor especially in high speed operation. Ventilation holes not affecting magnetic saturation are designed in order to increase cooling capacity of stator core with 60 mm cutting edge.

Although, the 60 mm cutting model has a different yoke width, the motor characteristic hardly changed such as slip, torque and current. Furthermore, magnetic saturation is not occurring at narrow yoke width. It means that the overall stator yoke width could be decreased as much as dotted lines as shown in Fig. 11a. However, in condition of thermal emission, it is not desirable. Otherwise, proper ventilation hole makes the weight of motor decreased but the surface for thermal emission is not changed. In order to consider the magnetic characteristic, the position of ventilation hole is situated out of dotted lines. Therefore the final model is selected like (Fig. 11b).

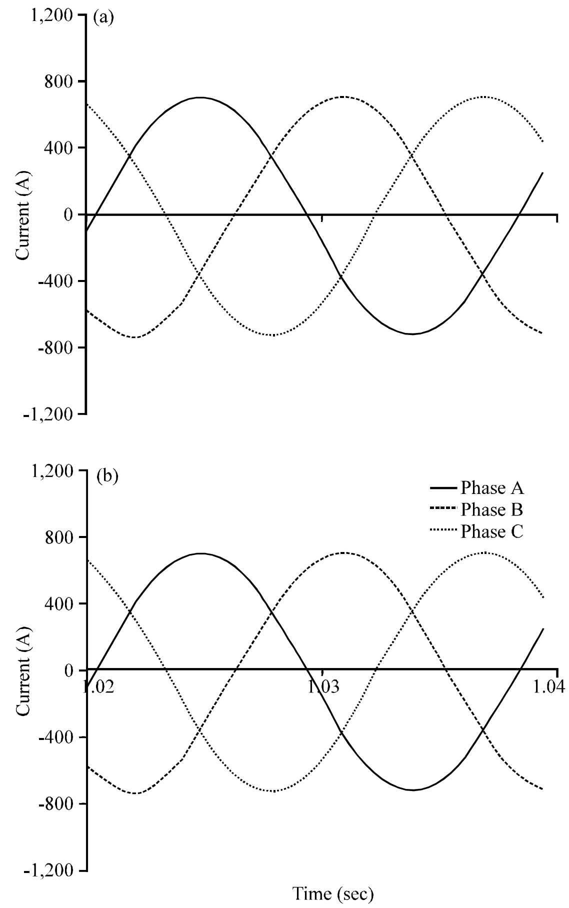

Fig. 10: Phase current waveforms of base model and cutting edge model with 60 mm at base speed

Table 4: Performance comparison at base speed (60 mm)

Model	Slip (%)	Current (Arms) Phase A	Phase B	Phase C	Torque (Nm)	Efficiency (%)
Base	0.57	500	507	503	7,861	98.17
60 mm cutting	0.57	498	501	499	7,861	98.15

Figure 12 shows the slip characteristic curves of base model and final model according to driving point. There are no much different characteristics between two models such as a slip condition for same torque and current value.

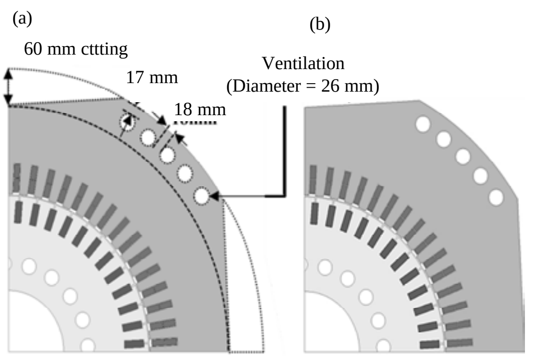

Fig. 11: Ventilation holes as: a) design parameter and b) final analysis model

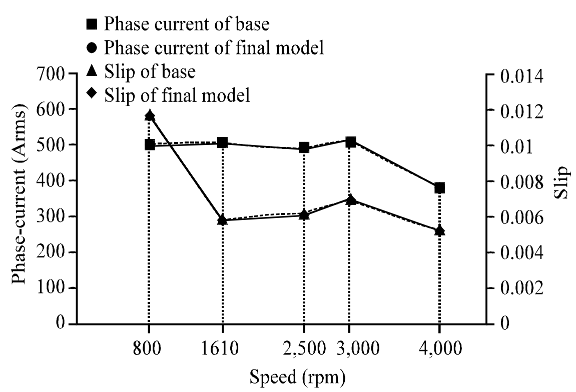

Fig. 12: Comparison of phase current and slip between base model and final model with cutting edge and ventilation holes

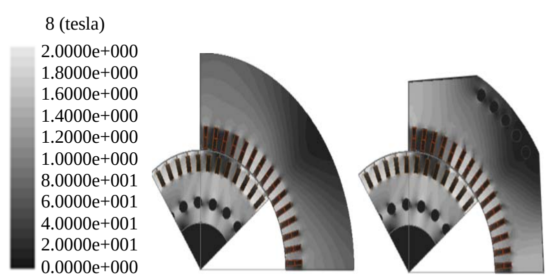

Fig. 13: Magnetic flux density of base model and final model at base speed

The ventilation holes are located to the outermost radius of the stator. The distance from the center of ventilation holes to the center of the motor is longer than the outer diameter of stator cut as much as 60 mm. Therefore, compared with 60 mm cutting, the magnetic flux is not saturated like Fig. 13. Table 5 shows that the slip is not changed to output the rated torque. Furthermore, each of the phase current has an equivalent value like Fig. 14.

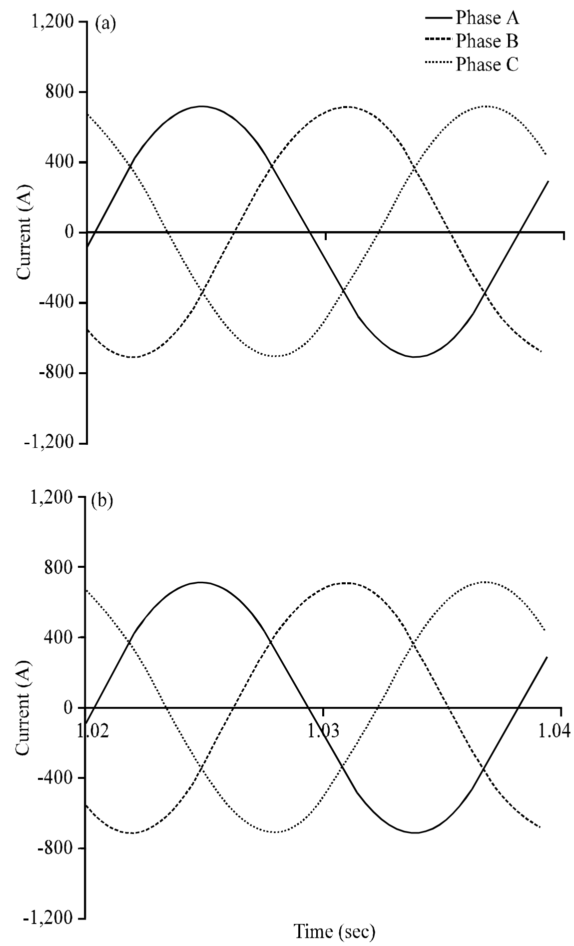

Fig. 14: Phase current waveforms of base model and final model at base speed

Table 5: Performance comparison at base speed (ventilation holes+60 mm cutting edge)

Model	Slip (%)	Current (Arms) Phase A	Phase B	Phase C	Torque (Nm)	Efficiency (%)
Base	0.57	500.55	506.79	502.96	7,861	98.17
60 mm Cutting	0.57	498.20	501.37	499.21	7,861	98.10

Table 6: Comparison of weight of stator core (light weight)

Model	Volume (m^3)	Density (kg/m^3)	Mass (kg)
Base model	0.1417	7,650	1083.80
Final model	0.1125	7,650	860.29

The proper cutting method and ventilation holes are applied to the final model for mass reduction without magnetic saturation which made the driving characteristic changed. The total stator mass is decreased above 200 kg like Table 6.

CONCLUSION

In the study, the design method of an induction motor satisfying improved performance is proposed by using design parameters of stator yoke. First, in order for small size and light weight, a parameter related to cutting egde without magnetic saturation is suggested. Second, in order for low temperature rise, a parameter related to ventilation hole in stator yoke is suggested.

ACKNOWLEDGEMENTS

This research was supported by the Technology Innovation Program (10063006, Development of Electric Vehicle Drive System based on HighEfficiency Cooling System) funded by the Ministry of Trade, Industry and Energy (MI, South Korea).

REFERENCES

Alberti, L., N. Bianchi and S. Bolognani, 2011. Variable-speed induction machine performance computed using finite-element. IEEE. Trans. Ind. Appl., 47: 789-797.

Boldea, I., L.N. Tutelea, L. Parsa and D. Dorrell, 2014. Automotive electric propulsion systems with reduced or no permanent magnets: An overview. IEEE. Trans. Ind. Electron., 61: 5696-5711.

Harson, A., P.H. Mellor and D. Howe, 1995. Design considerations for induction machines for electric vehicle drives. Proceedings of the 7th International Conference on Electrical Machines and Drives 1995, September 11-13, 1995, IET Publisher, Durham, UK., ISBN:0-85296-648-2, pp: 16-20.

Jahns, T.M., 1987. Flux-weakening regime operation of an interior permanent-magnet synchronous motor drive. IEEE. Trans. Ind. Appl., 23: 681-689.

Wang, T., P. Zheng, Q. Zhang and S. Cheng, 2005. Design characteristics of the induction motor used for hybrid electric vehicle. IEEE. Trans. Magn., 41: 505-508.

Zeraoulia, M., M.E.H. Benbouzid and D. Diallo, 2005. Electric motor drive selection issues for hev propulsion systems: A comparative study. Proceeding of the IEEE Conference on Vehicle Power and Propulsion, September 7-9, 2005, Brest, France, pp: 1756-1764.