

Performance Comparison of the Railway Traction IPM Motors between Concentrated Winding and Distributed Winding

Chan-Bae Park*, Byung-Song Lee* and Hyung-Woo Lee[†]

Abstract – This paper presents performance comparison between concentrated winding and distributed winding of IPMSM (Interior Permanent Magnet Synchronous Motors) which is recently used for light-weight railway applications. Motors are designed on various schemes and analyzed by using FEM (Finite Element Method) instead of EMCNM (Equivalent Magnetic Circuit Network Method) in order to take into account saturation and non-linear magnetic property. The overall performance such as torque, torque ripple, losses, demagnetization, efficiency, power density and so on are investigated in detail at the rated and maximum operating speed. The results of the analysis found that both concentrated and distributed winding IPMSMs are promising candidates for high power railway traction motor

Keywords: Concentrated winding, Distributed winding, IPMSM, Power density, Performance

1. Introduction

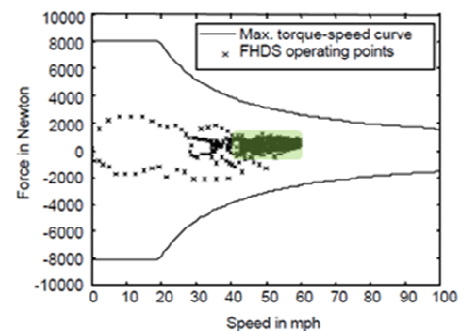
Since conventional trains using an internal combustion engine has low efficiency, causing much pollution and oil shortage problems, electrified trains are used all over the world nowadays. The traction motors for electric trains mostly concern about power density as well as efficiency. Especially the power density of railway traction motors is lower than 1 (kW/kg), which is half of that of electric vehicles. In that regard, IPMSM (Interior Permanent Magnet Synchronous Motor) using permanent magnets is in the limelight for on-board traction motors from low-speed to high-speed trains. IPMSM with concentrated winding is superior to motors with distributed winding in power density because it uses less end coils. Yet, it can cause huge amount of eddy current loss in magnets by slot harmonics with concentrated winding because permanent magnet has inherent conductivity. Additionally, other performances are different between concentrated and distributed winding IPMSMs. It is appropriate time to consider what kind of winding is suitable for IPMSM for train applications. The aim of this paper is to analyze and compare the overall performance of each winding IPMSM, and suggest suitable winding for a light-weight train.

2. Operating Characteristics and Designed Models

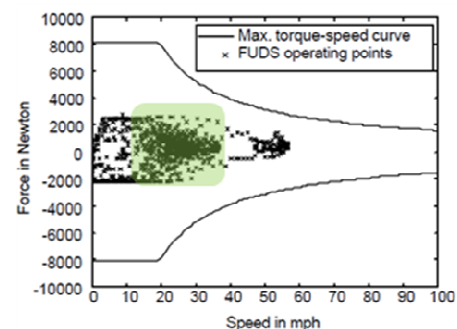
2.1 Operating characteristics

Traction motors are operating within the maximum

torque-speed curve. Frequent operating points for electric vehicle on federal highway driving schedules(FHDS), electric vehicle on federal urban driving schedules(FUDS), high speed train(max. speed of 300 (km/h)) and low speed train(max. speed of 80 (km/h)) are shown in Fig. 1. As the traction motors run mostly in the high speed region for FHDS and high speed trains, it is clear that the performance in the high speed region should be mostly concern.



(a) Electric vehicle on FHDS



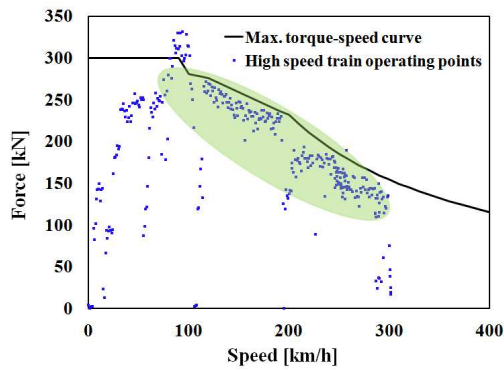
(b) Electric vehicle on FUDS

Fig. 1. Frequent operating points of the traction motor for EV and trains (measured values)

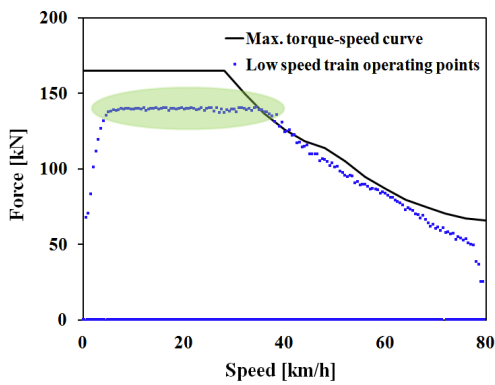
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(c) High speed train



(d) Low speed train

Fig. 1. Frequent operating points of the traction motor for EV and trains (measured values)

On the other hand, traction motors for FUDS and low speed train which make frequent stops run all over the region and especially the motors should have better performance in the low-middle speed region for rapid acceleration and deceleration. These frequent operating characteristics should be considered in making decisions of which winding configuration is suitable. In this paper, the performances of the traction motor for a low-speed train (Fig. 1(d)) are analyzed.

2.2 Concentrated- and distributed-winding IPMSMs

In order to compare the performance of both concentrated winding and distributed winding IPMSMs for a low speed light-weight train, 110 (kW) traction motors are optimally designed by using Taguchi method. Fig. 2 shows the torque-speed curve of the proposed IPMSM to satisfy the required acceleration and climbing ability. Rated power is 110 (kW), required starting torque and maximum speed torque is 433 (Nm) and 75 (Nm), respectively.

The cross-sectional views and specifications of the motors are shown in Fig. 3 and Table 1, respectively. Both motors satisfy the motor current limit and inverter voltage limit which is induced by the coast running in a steep descent, and also accomplish required torque and efficiency.

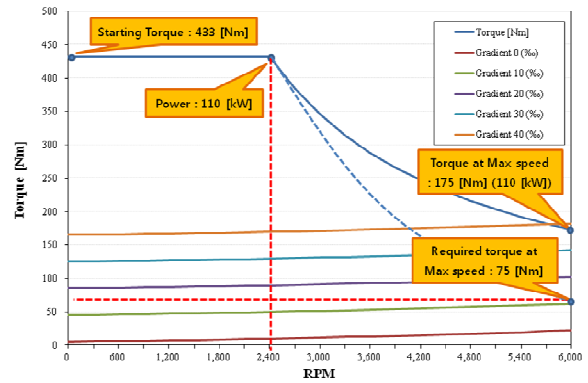
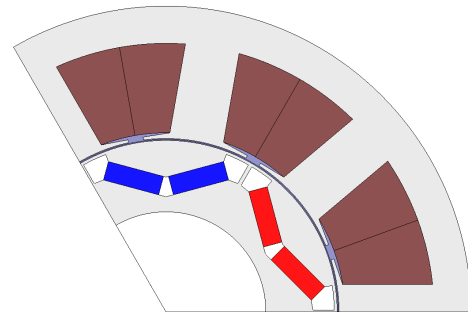
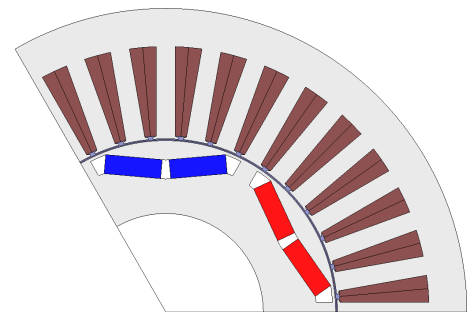


Fig. 2. Torque-Speed curve of the IPMSM for a light-weight train



(a) Concentrated winding



(b) Distributed winding

Fig. 3. Designed concentrated winding IPMSM and distributed winding IPMSM with 6 poles

Table 1. Specifications of each IPMSM

Variables	110[kW] IPMSM	
	Concentrated winding	Distributed winding
Phase / Poles	3 phases / 6 poles	
Rated/Max. Speed	2,400 / 6,000 (RPM)	
Stack length	280 (mm) (without end-turn)	
Permanent magnet	Nd-Fe-B (Br = 1.15(T))	
Number of slots	9 (ea)	36 (ea)
Outer diameter	316[mm]	319 (mm)
Magnet angle	15 (degree)	5 (degree)
Web width	2 (mm)	10 (mm)

3. Comparison of the Performance

Designed concentrated winding IPMSM and distributed winding IPMSM are analyzed by FEM to investigate the overall performance such as torque, torque ripple, manufacturability, losses, efficiency, operating speed range, controllability, demagnetization and power density.

3.1 Torque and torque ripple

As it is well known, the distributed winding motor has lower torque ripple because of the distributed magnetic flux through the teeth. Analysis results show that it has lower torque ripple of 116 (Nm) compared with the 133 (Nm) of concentrated winding motor. And the average torque of the distributed winding motor at the maximum speed is higher than that of the concentrated winding motor. Hence, it results in that the distributed winding motor is better for the torque performance.

Therefore, this kind of divided core increases the manufacturability for concentrated winding IPMSMs. In addition, shorter end coil means lower copper cost.

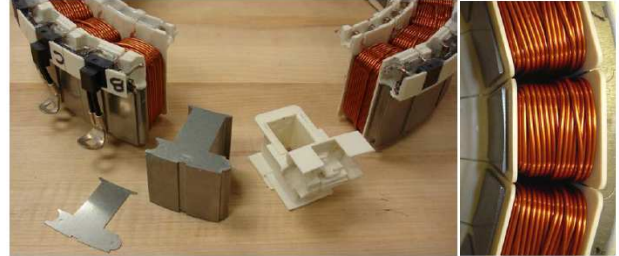
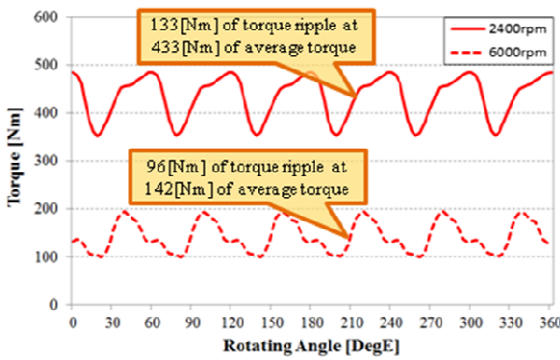
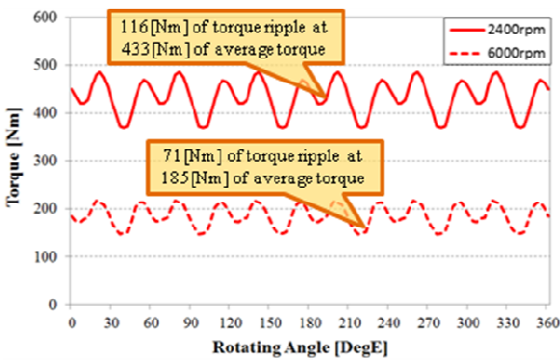


Fig. 5. Divided cores and concentrated winding



(a) Concentrated winding



(b) Distributed winding

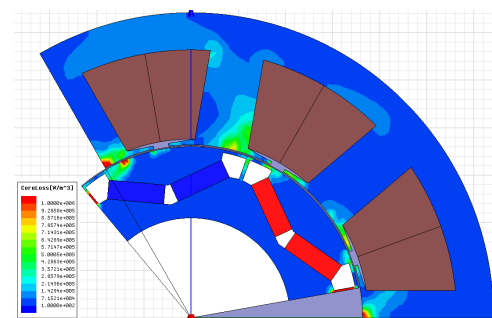
Fig. 4. Torque and torque ripple of each IPMSM

3.2 Manufacturability

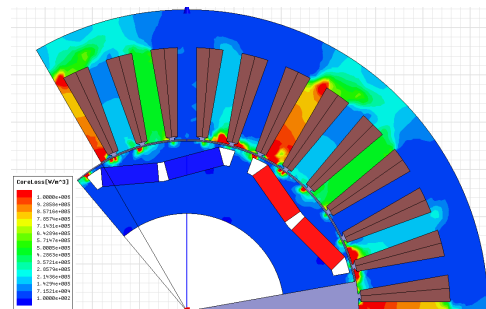
Fig. 5 shows a concentrated winding IPMSM used for an electric vehicle. One pattern of coils is wound around one stator core separately so as to build a piece of stator tooth and winding, and assemble it. This increases the space factor of the slots and makes the slot opening small.

3.3 Losses and efficiency

As the concentrated winding IPMSM has shorter end coil as mentioned, it has lower phase resistance and lower copper loss than the distributed winding IPMSM. In addition, the distributed winding IPMSM has more magnetic saturation parts at the stator teeth as shown in Fig. 6 and core loss is bigger than that of the concentrated winding IPMSM. However, the concentrated winding IPMSM causes huge amount of eddy current loss in magnets by slot harmonics at high speed operation because permanent magnet has inherent conductivity.



(a) Concentrated winding



(b) Distributed winding

Fig. 6. Magnetic flux density of each IPMSM at the maximum speed

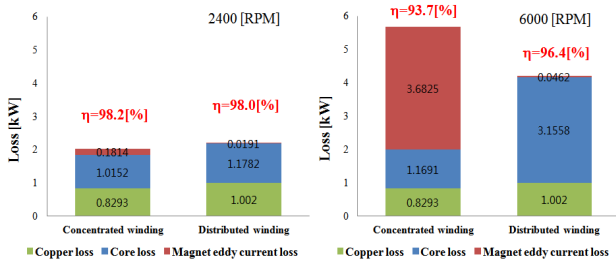


Fig. 7. Each Loss and efficiency of each IPMSM

From the FEM analysis, total losses calculated for the distributed winding IPMSM are 2.2 (kW) and 4.2 (kW) at the rated speed and maximum speed, respectively. For the concentrated winding, the losses are 2.0 (kW) and 5.7 (kW), respectively as shown in Fig. 7. The efficiency for the concentrated winding IPMSM is slightly higher at the rated speed and it is a bit lower at the maximum speed. As traction motors for a low speed train usually operate in the low and middle speed range, the concentrated winding IPMSM is better than the distributed winding IPMSM. Each red letter in Fig. 7 represents the efficiency in each case.

3.4 Operating speed range

In general IPMSMs, reluctance torque is dominant at the maximum speed and this decides the operating speed range. This reluctance torque is generated by the inductance difference (L_q-L_d) as is well known. The calculated q-axis and d-axis inductances of the designed concentrated winding IPMSM are 0.2867 (mH) and 0.2692 (mH), respectively. And those of the distributed winding IPMSM are 0.6077 (mH) and 0.2946 (mH), respectively. Therefore, concentrated winding IPMSM has smaller reluctance torque and shortened possible operating speed range. Fig. 8 shows the torque-speed curve of both winding IPMSMs [1]. As shown in the figure, the speed range of the concentrated winding IPMSM is shorter than that of the distributed winding IPMSM. It seems that the concentrated winding IPMSM has no problem with this because the frequent operating points are usually in the constant torque region as mentioned before. However, it did not show favorable climbing ability at maximum speed.

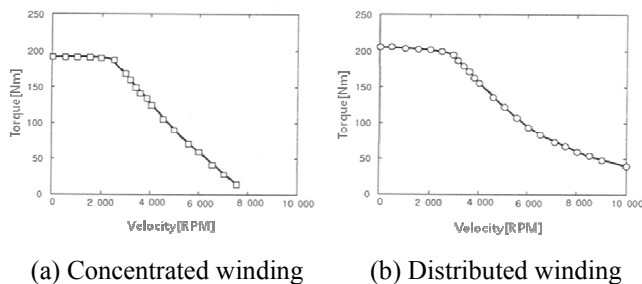
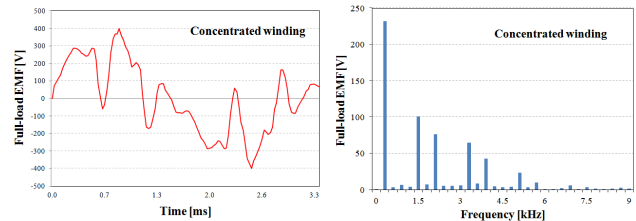


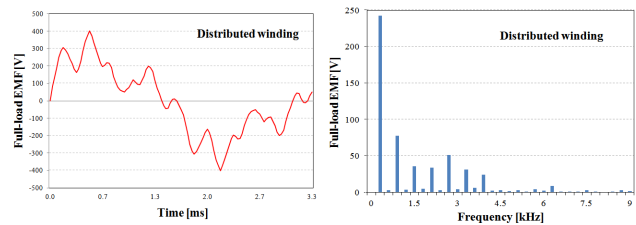
Fig. 8. Operating speed range of both motors [1]

3.5 Harmonics of EMF and controllability

Harmonics and controllability are also considered. Fig. 9 shows the full-load EMFs (Electro Motive Forces) and their harmonics of both winding IPMSMs. Fundamental frequency at the maximum speed is 300 (Hz).



(a) Concentrated winding



(b) Distributed winding

Fig. 9. Full-load EMFs and their harmonics

As it is shown, the 3rd, 9th and 15th harmonics of the concentrated winding IPMSM are removed inherently, but the magnitudes of harmonics are bigger than those of the distributed winding IPMSM. As the concentrated winding IPMSM has more harmonics than the distributed winding IPMSM, torque ripple would be bigger and the controllability would be worsened. It can be said that the distributed winding is superior to the concentrated winding IPMSM. However, this torque ripple can be ignored in case the moment of inertia of the rotor and load is big enough.

3.6 Demagnetization tolerance

Demagnetization is generally occurred by high temperature, airgap variation and high locked-rotor current. For both concentrated and distributed winding IPMSMs, demagnetization from high temperature and airgap variation would be similar and demagnetization tolerance is relatively stronger than SPMSM (Surface Permanent Magnet Synchronous Motor) because permanent magnets of IPMSM are inserted in the rotor. However, demagnetization from locked-rotor current is different.

Fig. 10 shows the demagnetization analysis of both motors when 1,600 (A) (around 4 times of the rated current) of locked-rotor current is fed. For the concentrated winding IPMSM, the intensive flux from the stator core affects directly on the permanent magnet and the minimum magnetic flux density of the permanent magnet is 0.2515

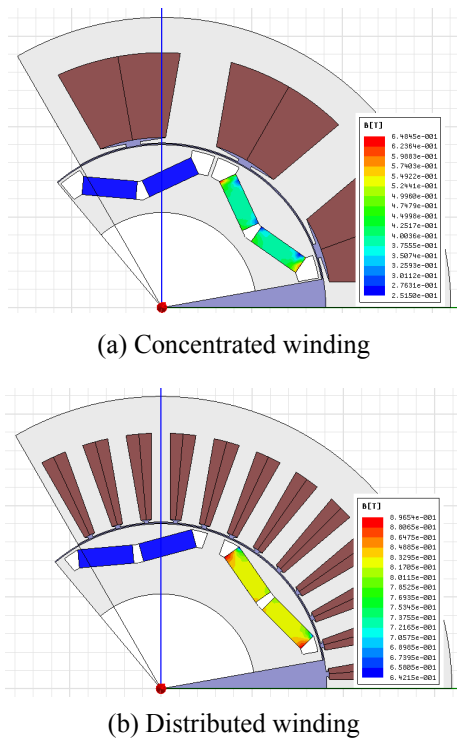


Fig. 10. Demagnetization analysis

(T). On the other hand, the minimum magnetic flux density of the permanent magnet in case of the distributed winding IPMSM is 0.64215 (T). This analysis result elicits that the distributed winding IPMSM has much higher demagnetization tolerance than the concentrated winding IPMSM.

3.7 Power density

In general, IPMSM with concentrated winding is superior to IPMSM with distributed winding in power density because of the use of less end coils. The calculated weight of the designed model with concentrated winding is 162.6 (kg) and its power density is 0.67 (kW/kg). On the other hand, the calculated weight of the designed model with distributed winding is 182.9 (kg) and its power density is 0.596 (kW/kg). Major sources of difference is the weight of stator and coil. From the calculation, it is confirmed that the concentrated winding IPMSM is better in the power density point of view.

4. Conclusion

Various performance characteristics of both concentrated winding IPMSM and distributed winding IPMSM used for low-speed railway traction motors are investigated and compared in detail. For the comparison, 110 (kW) light-weight train motors are optimally designed and analyzed by FEM. In terms of copper loss, manufacturability and power density, the concentrated winding IPMSM presented better results. In the points of efficiency at high speed,

torque ripple, controllability, demagnetization tolerance and operating speed range, the distributed winding IPMSM performed better. Table 2 shows the summary of performance comparison of each IPMSM for a low-speed, light-weight train. Among many issues considered, efficiency and power density are the most important one for on-board traction motors and the analysis results elicit that the concentrated winding IPMSM can also be a good candidate for a traction motor in that regard.

Table 2. Summary of the performance comparison of the each IPMSM for a low-speed train

Variables	110[kW] IPMSM	
	Concentrated	Distributed
Torque	○	○
Torque ripple	○	⊙
Manufacturability	⊙	⊙
efficiency	Low speed	⊙
	High speed	⊙
Operating speed range	○	⊙
Controllability	○	⊙
Demagnetization tolerance	○	⊙
Power density	⊙	○

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