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Effects of Rotor Bar and Cage Numbers Considering Al and Cu Conductors on The Performance of Asynchronous Traction Motors in Hybrid Electric Vehicles

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Abstract
Electric vehicles offer an unmatched experience thanks to their torque profiles. They must be optimized when considering intracity driving cycles (frequent start-stop) by dealing sensitively with the efficiency/performance relationship. Asynchronous motors are commonly used in electric vehicles. Parameters like stator/rotor geometry, number of slots, and materials used are incredibly important in the efficiency/performance relationship. This study has focused on the effect of the change in the number of stator/rotor slots on motor performance by designing an asynchronous motor to be used in primarily urban-use electric vehicles. Afterward, the effect of copper or aluminum cage materials on motor performance was obtained with single- and double-layered squirrel cage structures. The first designed motor has an initial torque value of 96.26 Nm while the optimized motor has a value of 115.34 Nm with its efficiency value and thermal limits being developed by 19.82% without changing. According to the analysis results, the squirrel-cage asynchronous motor with a double-layer, 34/46 structure, and aluminum material exhibited the best performance with initial torque.

Keywords: Electric Vehicle, Squirrel Cage, Traction Motor, Rotor Slots, Starting Torque.

Introduction

It has been possible to design and use highly efficient and environmentally friendly products that make human life easier with the developing technology. Electric bicycles and electric cars which are of use are increasing day by day, are among the best examples [1,2]. In parallel with the developments in the automotive industry, electric vehicle (EV) technology has accelerated due to studies on clean energy sources and energy efficiency. With oil, resources are almost at depletion, and research on alternative propulsion systems for vehicles has intensified. As a result of this research, the use of electric motors in vehicles is in question [3-6].

Electric motors can be defined as the most important element of drive systems. Many different types of drive motors are used in electric cars today. On EVs, mostly Asynchronous Motors (AM) and Synchronous Motors (SM) (both permanent magnet and salient pole types), sometimes DC motors and Switched Reluctance Motors (SRM) are used for traction. Improvement of magnet technology led to increased efficiencies of PM motors. But high prices of magnetic materials and demagnetization risks are still disadvantages of permanent magnet motors. Although DC motors have a linear speed torque curve, the fact that they have a commutator and brushed structure, limits to use of EVs [7-9]. In SRM, the fluctuations in the output torque have limits to use in EV [10,11]. Due to their low requirement for maintenance, easy controllability, high-temperature tolerance, easy production, and low costs, AMs are among the most preferred motors [12-14].

In the study comparing electric motors for EVs, six types of electric machines were compared. In terms of efficiency, weight, cost, cooling, maximum speed, fault tolerance, safety, and durability, AM, SRM, brushless DC motor, brushed DC motor, and SM were examined for the selection of the most suitable electric motor. As a result of the analysis, AM is determined as an electric motor that can be used in EVs in terms of efficiency, weight, and cost after SRM [15]. Gilinsky and Abu-Rub have conducted experiments on prototype EVs drove with AM. 3-phase squirrel-cage asynchronous motor driven by DC voltage is used in the system. It is determined that the use of squirrel-cage asynchronous motors is more advantageous in EVs than in electric motors [16]. Mishra and Saha designed 3.5 kW AM and perform magnetic and electrical analyzes in steady and transient states [17]. Kim et. al. have achieved the starting and operating point characteristics by optimizing the air gap and the geometry of the rotor bars in the asynchronous motor they designed for the electric vehicle [18]. In the first one of the studies investigating the rotor slot structures, the air gap reluctance was reduced by adding wedges to the upper part of the slot of the asynchronous motor with a semi-closed slot structure. Thus, stator current and core losses are reduced. In addition, the vibration level of the machine has been decreased [19]. In another structural analysis, the performance of double and single-cage asynchronous motors has been investigated. Accordingly, it has been determined that the double cage structure has a low starting current. With the low current, the copper loss is reduced and the efficiency of the motor is increased [20]. When the effect of rotor slot structure on current harmonics is examined, it is determined that the 5th and 7th harmonics are much higher in open-slot asynchronous motors in closed rotor slot structure [21]. In the study where the number of different slots was investigated, the numbers of rotor slots were determined as 24, 28, 30, 40, 41, and 48, and the performance of the asynchronous motor was analyzed. In the structure of 28, the efficiency is the best but has a low power coefficient, and the highest power coefficient in the 40 structures has low efficiency. It has been determined that the structure of 41 has a relatively average performance compared to the others and the rotor with the number of 48 slots provides the highest torque and power [22].

The purpose of this study is to optimize the starting torque and the nominal operating efficiency of an electric vehicle with an asynchronous motor suitable for urban use. The performance outputs of the different stator-rotor slot number combinations of the motor have been obtained and compared for improvement works. We also compared the single cage and double cage rotor structures for each different slot number combination. Finally, the effect of the aluminum and copper materials on the total performance of the motor for rotor conductors has been investigated. Both rotor slot number and rotor conductor type and single/double cage structure have a significant effect on the torque-speed curve and efficiency of the motor [23]. When literature studies are examined, there are many studies comparing different rotor structures. However, in these studies, different combinations of stator/rotor slot numbers have been compared for double or single-cage structures with aluminum or copper rotor conductors. A comparison study that considers all of these variables was not found as a result of the findings obtained in accordance with the author's own efforts. Thus, in addition to the different number of rotor slots, it is possible to compare the effects of aluminum and copper rotor conductors with double/single cage structures. In this study where all the variables mentioned above are discussed together, the rotor structure of the asynchronous motor which is most suitable for use in an asynchronous electric vehicle can be obtained.

Design Considerations

As is known, the torque characteristics of asynchronous motors are divided into five different design classes A, B, C, D, and E by NEMA (National Electrical Manufacturers Association). In this classification, taking into account the different load characteristics, there are different extremal values in addition to very high starting torque and high slip and low efficiency (NEMA, Class D) designs such as ones with minimum slip, high efficiency, and low starting torque (NEMA, Class E). The selection of an asynchronous motor type in accordance with the operating characteristics of the load has vital importance in terms of system efficiency and expected performance [24]. It is inevitable to design an asynchronous motor for EVs taking into account the above-mentioned criteria. An asynchronous motor with high efficiency and high starting torque is a motor that can be preferred in almost all applications. In terms of EVs, it can be stated that it has a high starting performance and high efficiency in the course of the journey are the two most important features expected from the motor. However, given the different design classes mentioned above, there is no motor class with a squirrel cage with the highest starting torque and the highest efficiency.

In designs that can provide very high starting torque, it is seen that nominal efficiency and the designs which can provide very high efficiency have low starting torque. In this case, a design that can provide the highest possible values for an asynchronous motor selected for electric vehicles, for both the starting torque and the nominal efficiency, must be selected. When the classification details are considered, it is seen that the design that provides the closest values to this expectation is NEMA Class B. In addition, NEMA Class B is the most widely used class of asynchronous motor [25, 26].

As seen in Figure 1, there is no fixed slot geometry in Class B designs, but basically, it is possible to see designs divided into single and double cages. It is a fact that the performance effects of Class B different slot designs on the motor cannot find enough space in the literature. The effects of different rotor slot geometries and the number of different rotor slots on motor performance were tried to be presented in detail in this study.

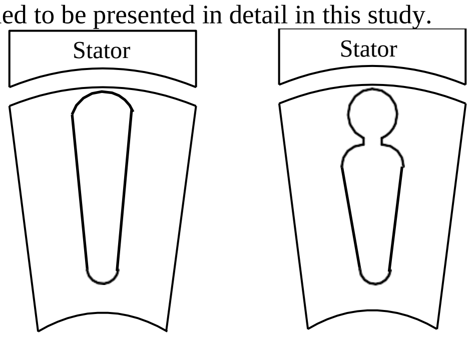


Figure 1. Slot structure

In line with the information above mentioned, when examining the traction motors of top manufacturers, even though an important part of them has single-cage copper rotors, it is known that some manufacturers such as ABB [27] prefer aluminum cages in traction motors. With this study, the effects of different preferences on motor performance can be revealed.

When designing electric motors, electromagnetic, mechanical, thermal, and material-related problems must be considered. The design should be done by considering the cost and the desired performance criteria. There is a need for exhaustive analysis to achieve the desired criteria and to achieve an industrially applicable design. It is necessary to proceed in light of technological developments in order to create a competitive product. The designer should generally be familiar with the standards, magnetic materials, electrical materials, and cooling systems in the field [28, 29]. In recent years, there has been an increase in the energy density of permanent magnet machines with advances in magnet technology. Therefore, higher power density and efficiency can be obtained in such machines. However, an asynchronous motor designed in accordance with its purpose is more reliable and robust than machines with permanent magnets. Asynchronous motors have high-temperature resistance. They can also maintain their rated performance almost without any drop over the life of permanent magnet machines. The long-term experience of the above-mentioned tests shows abovementioned show why the major manufacturers in the market have increased their interest in these motors. In addition, the driving cycle is very important for real motor performance and motor efficiencies should be compared considering the driving cycle [30-32].

Initial Model and Specifications of Proposed AM

The design of electric machines can be started with output equations [29]. The relationship between machine output, core sizes, speed, and specific magnetic and electrical loads is called output equations. Power developed on the armature side based on a machine with *m* phase;

$$Q = 3V_{ph}I_{ph} \times 10^{-3} kVA \quad (1)$$

Variable, I_{ph}, and V_{ph} represent the phase current and the induced emf on the armature which is derived from Equation 2 [.

$$V_{ph} = 4.44k_w \times f \times \varphi \times N_{ph} \quad (2)$$

Where f refers to the frequency, k_{w1} is the winding factor and it is equal to 0.955. Total electrical loading is given in Equation 3.

$$ac = \frac{I_z Z}{\pi D} \quad (3)$$

And total magnetic loading;

$$B_{ort} = \frac{p\varphi}{\pi DL} \quad (4)$$

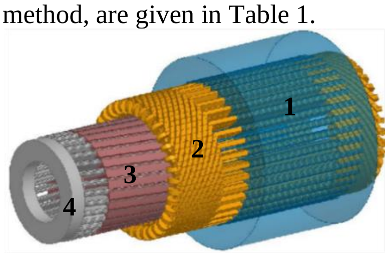
When the output equation is rewritten, considering equations 2, 3, and 4;

$$Q = (1.11\pi^2 B_{ort} ac K_w \times 10^{-3}) D^2 L n_s \quad (5)$$

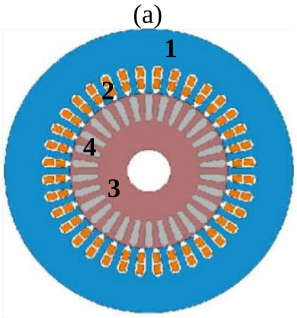
C_0 is known as the output coefficient and is expressed in Equation 6 [33].

$$C_0 = 1.11\pi^2 B_{ort} ac K_w \times 10^{-3} \quad (6)$$

The initial 2D and 3D model of the three-phase, 7.5 kW, 400 V, 2-pole, asynchronous motor whose design and analysis have been achieved is given in Fig 2. With respect to all parameters of the motor calculated by using the analytical method, are given in Table 1.



(a)



(b)

Figure 2. Model of Initial Design (1-Stator, 2-Winding, 3-Rotor, 4- Squirrel Cage): a) 2D, b) 3D

Comparison of Single and Double Cage Rotor Designs

Many parameters affect the performance of electrical machines. In asynchronous machines, the number and structure of the machine slots will change the magnetic circuit of the machine and also affect the electrical performance [25, 34]. The number of stator slots should be an integer, allowing for stable winding. In addition, the number of stator slots must have the full number of phases. The number of stator slots in the study was determined as 36 by considering the reference motor manufacturers. The number of rotor slots should not be equal to or one-half of twofold to the number of stator slots [35, 36]. In the study, the number of stator slots was taken as a constant in order to make the comparison more equitable.

4.1. Single cage rotor with different slot numbers

This section compares the performance effects of different rotor slot numbers for the single cage rotor. The number of rotor slots specified for comparison includes the most common number of rotor slots used by different manufacturers in the industry. In order to ensure that the comparisons are unfairly superior to each other, no changes have been made to the motor geometry except for the rotor slots in all designs. The results of the analysis of the motors with a different number of rotor slots in Table 2 are summarized.

When Table 2 is examined, the efficiency values of the different rotor combinations remained in motors with rotor slot numbers 34, 44, and 46. The speed-torque curves obtained according to the changing number of slots are given in Figure 3.

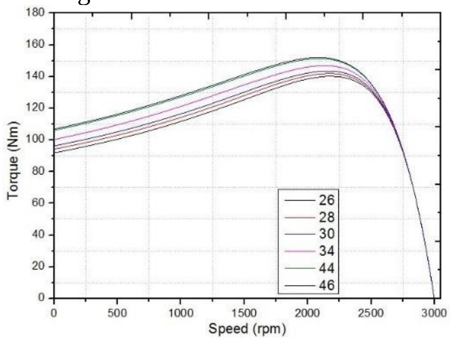


Fig. 3. Torque-speed characteristic curves in a single cage rotor

4.2. Double cage rotor with different slot numbers

This section compares the effects of different rotor slot numbers on motor performance. But this time the rotor slots are designed as a double cage. There was no change in motor geometry except for rotor slots and the best possible values were obtained for each different rotor slot number design. Table 3 summarizes the motor structures and the results of the analysis.

As in the single cage rotor, the efficiency values of the motors remained approximately the same. In order to obtain similar flux values in rotor slots, slots are narrowed in motors with rotor slot numbers 34, 44, and 46. The torque changes obtained according to the changing number of slots are given in Figure 4.

4.3. Comparison of copper and aluminum rotor conductors

Another important design parameter for squirrel-cage asynchronous motors is the cage material. In squirrel cage machines, usually aluminum or copper-type squirrel cage is used. The conductivity of copper is 60% higher than aluminum. However, due to the high melting point in the squirrel cage production stage, this can damage the steel plate used in the rotor [36-39]. The use of copper is also disadvantageous in terms of cost and ease of production. Table 4 presents the performance of 36/46 motors with single and double-cage rotors made of copper and aluminum squirrel cages. In the analysis, the geometry of the rotor was kept constant and only the effect of the cage material was examined.

As expected, the rotor resistance of motors with aluminum cage rotor is higher than that of copper. Therefore, rotor copper losses were higher and their efficiency was low. However, high rotor resistance allowed high starting torque. In this case, the maximum starting torque value of 36/46 is obtained in an aluminum double-cage rotor motor. Figure 5 shows the torque-speed curves for copper and aluminum cages in all combinations.

Table 1. Design Parameters

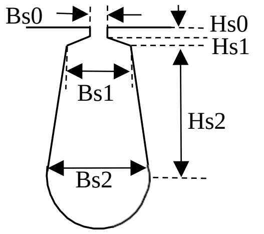
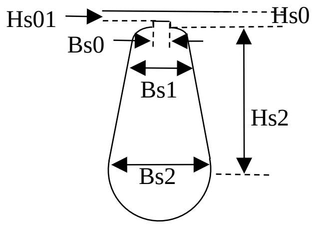
Description		Details of parameter	
Motor type		3 phase, squirrel cage	
Output power		7.5 kW	
Rated frequency		50 Hz	
Number of poles		2	
Rated speed		2949 rpm	
Slot fill factor		53.52 %	
Stator		Rotor	
Description	Value	Description	Value
Outer diameter	200 mm	Outer diameter	109.4 mm
Inner diameter	110 mm	Inner diameter	35 mm
Length	140 mm	Length	140 mm
Number of slots	36	Number of slots	30
Skew width	0	Skew width	1
Number of conductors perslot	28	Type of Steel	M530-50A
Type of Steel	M530-50A	Squirrel cage material	Aluminum
	$H_S\ 0 = 0.7\,mm$		$H_S\ 0 = 0.8\,mm$
	$H_S 1 = 1.8\,mm$		$H_S\ 01 = 0\,mm$
	$H_S\ 2 = 13.4\,mm$		$H_S\ 2 = 14\,mm$
	$B_S\ 0 = 2.8\,mm$		$B_S\ 0 = 1\,mm$
	$B_S 1 = 5.64\,mm$		$B_S 1 = 6\,mm$
	$B_S\ 2 = 7.98\,mm$		$B_S\ 2 = 4\,mm$

Table 2. Performance of motors with different rotor slot

Number of stator/rotor slots	Efficiency (%)	Rated Torque(Nm)	Starting Torque(Nm)	Total Weight(kg)
36/26	86.61	24.28	91.88	30.20
36/28	86.64	24.29	94.21	30.22
36/30	86.67	24.28	96.26	30.24
36/34	86.73	24.28	100.27	30.26
36/44	86.79	24.28	106.04	30.29
36/46	86.8	24.28	106.83	30.29

Table 3. Performance of motors with different rotor slot

Number of stator/rotor slots	Efficiency (%)	Rated Torque(Nm)	Starting Torque(Nm)	Total Weight(kg)
36/26	86.3	24.38	100.32	30.58
36/28	86.36	24.37	103.13	30.56
36/30	86.41	24.37	104.54	30.57
36/34	86.48	24.36	108.17	30.54
36/44	86.55	24.33	114.95	30.42
36/46	86.60	24.34	115.34	30.45

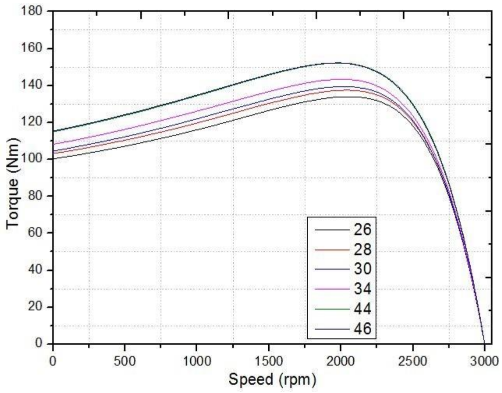
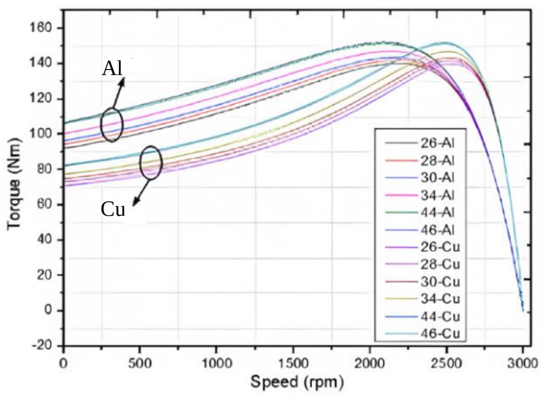
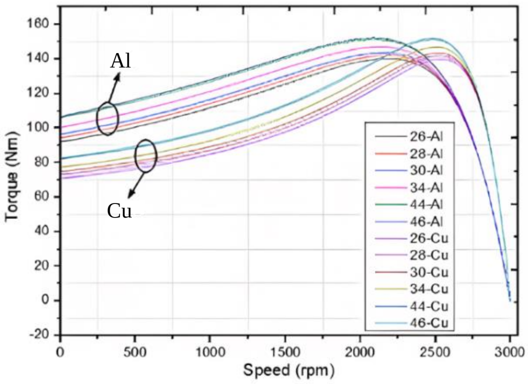


Fig. 4. Torque-speed characteristic curves in a double cage rotor



(a)



(b)

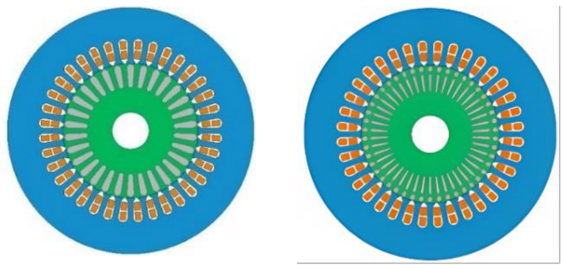
Fig. 5. Torque-speed characteristic curves a) single cage, b) double cage

Optimized Design Based on Comparisons

The maximum value of the starting torque, which is the main purpose of the study, has been obtained in 36/46 structures and aluminum double cages. 2D models of the initial and optimized motor are shown in Figure 6.

Table 4. Comparison of rotor structure with aluminum and copper cage

	Aluminum cage (36/46)		Copper cage (36/46)	
	Single cage	Double cage	Single cage	Double cage
Rotor ohmic losses (W)	134.54	151.71	75.41	84.87
Rotor resistance (Ω)	0.8604	0.9651	0.4895	0.5491
Efficiency (%)	86.8	86.60	87.38	87.26
Starting torque (Nm)	106.83	115.34	82.63	91.85
Rated torque (Nm)	24.28	24.34	24.09	24.13
Total net weight (kg)	30.29	30.45	33.71	33.46



(a) (b)

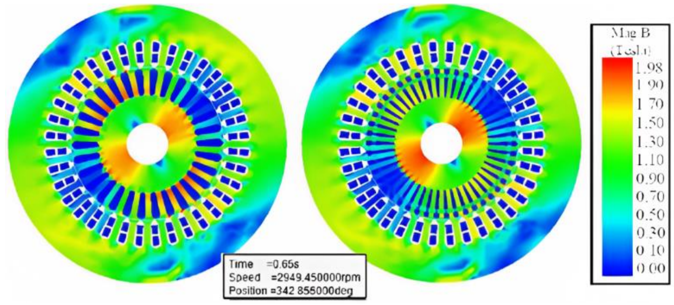
Fig. 6. Motor model a) initial design, b) optimized motor

The performance comparison of the initial and optimized motor is summarized in Table 5. In the finite element analysis performed at nominal load, the flux distributions of the designs are given in Figure 7. Considering the core material used in both distributions, it is seen that the flux densities of the designs are appropriate. When the initial design is examined, the high flux density is obtained, especially in rotor bars. The speed-torque curves of the motors for both designs are given in Figure 8.

In accordance with the main purpose of the study, the torque at start-up and low-speed range is increased in the optimized motor.

Table 5. Comparison of rotor structure with aluminum and copper cage

Description	Rotor Structure	
	Initial Design (Single cage 36/30)	Optimized Design (Doublecage 36/46)
Efficiency (%)	86.6	86.6
Rotor teeth flux density (T)	1.783	1.543
Rated torque (Nm)	24.28	24.34
Starting torque (Nm)	96.26	115.34
The total weight (kg)	30.24	30.45



(a) (b)

Fig. 7. Magnetic flux density distributions, a) initial design, b) optimized design

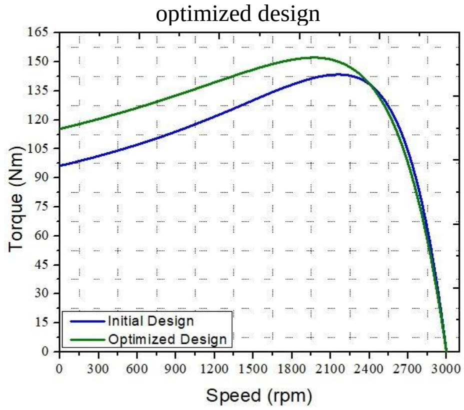


Fig. 8. Torque-speed characteristic curves

If we evaluate Figures 8 and 9 together, the start-up current is reduced and the starting torque value is increased in the optimized motor.

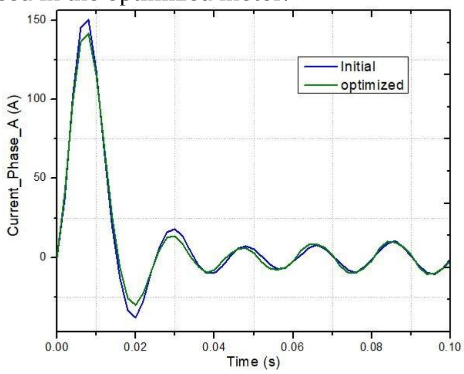


Fig. 9. Phase current waveforms of the motors in transient-state

Conclusion

The motor whose design is made initially in the study was designed as a single cage rotor structure and has a 36/30 slot number. Then, the single cage and double cage rotor which have same all the physical and magnetic properties except the slot structure are analyzed by design in different slot numbers and materials. For motors with the same number of slots, it is seen that a higher starting value is obtained in the double cage rotor type. Therefore, a double cage-type rotor is preferred in this study. The combination of slot numbers was selected as 36/46. The efficiency value of this type of motor is obtained as 86.6% while the starting torque value is determined as 115.34 Nm. The value of the starting torque is developed at the rate of 19.82% compared to the initial design. Also, the efficiency value is preserved. The following conclusions can be made as a result of the analysis;

- In the single and double cage, the number of stator slots is kept constant and the starting torque value is increased when the number of rotor slots is increased.
- The double cage rotor motor, which has the same number of stator slots/rotor slots, has a higher starting torque value than a single cage rotor motor.
- In the motor with aluminum squirrel cage material, the loss of rotor copper is higher than that of copper.
- The efficiency of the motor, which is the squirrel cage with copper material, is higher than that of aluminum.
- As the specific weight of copper is higher than that of aluminum, the weight of the motor that uses copper is greater.

References

[1] Ocak, C., "Design, Analysis and Application of a New Three Level Brushless DC Motor for Electric Vehicles", Ph. D. Thesis, Graduate School of Natural and Applied Sciences, Gazi University, Ankara, 2013.

[2] Tousizadeh, M., Che, H.S., Selvaraj, J., Rahim, N.A., Ooi, B. T., "Performance Comparison of Fault-Tolerant Three-Phase Induction Motor Drives Considering Current and Voltage Limits", IEEE Transactions on Industrial Electronics, Vol. 66, No. 4, pp. 2639-2648, April 2019.

[3] Nour, M., Said, S.M., Ali, A., and Farkas, C., "Smart Charging of Electric Vehicles According to Electricity Price", International Conference on Innovative Trends in Computer Engineering, Aswan, Egypt, 2019.

[4] Hori, Y., "Future Vehicle Driven by Electricity and Control-Research on Four-Wheel- Motored "UOT March II", IEEE Transaction on Industrial Electronics, 51(5), pp. 954-962, 2004.

[5] A. Mousaei and M. B. B. Sharifian, "Design and optimization of a linear induction motor with hybrid secondary for textile applications," 2020 28th Iranian Conference on Electrical Engineering (ICEE), 2020, pp. 1-6, doi: 10.1109/ICEE50131.2020.9260773.

[6] Ünlü, N., Karahan, Ş., and Tür, O., "Electric Vehicles", Energy Systems and Environmental Research Institute, 6-22, pp. 42-100, 2003.

[7] Dorrell, D.G., Popescu, M., Evans, L., Staton, D.A., and Knight, A.M., "Comparison of Permanent Magnet Drive Motor with a Cage Induction Motor Design for a Hybrid Electric Vehicle", 2010 International Power Electronics Conference, pp. 1807-1813, 2010.

[8] Grilo, N., Sousa, D.M., and Roque, A., "AC motors for application in a commercial electrical vehicle: Designing aspects", 16th IEEE Mediterranean Electrotechnical Conference, pp.277-280, March 2012.

[9] Ehsani, M., Gao, Y., and Gay, S., "Characterization of electric motor drives for traction applications", The 29th Annual Conference of the Industrial Electronics Society, pp. 891-896, 2003.

[10] Nanda, G., and Kar, N.C., "A survey and comparison of characteristics of motor drives used in electric vehicles", Canadian Conference on Electrical and Computer Engineering, pp. 811-814, 2006.

[11] Tiecheng, W., Ping, Z., Qianfan, Z., and Shukang, C., "Design Characteristic of the Induction Motor Used for Hybrid Electric Vehicles", 12th Symposium on Electromagnetic Launch Technology, pp. 523-527, 2005.

[12] Damiano, A., Gatto, G., Marongiu, I., Porru, M., Serpi, A., "Real-time control strategy of energy storage systems for renewable energy sources exploitation," IEEE Transactions on Sustainable Energy, vol. 5, no. 2, pp. 567-576, 2014.

[13] A. Mousaei, M. B. Bannae Sharifian and N. Rostami, "Direct Thrust Force Control (DTFC) of Optimized Linear Induction Motor with Super Twisting Sliding Mode Controller (STSMC)," 2021 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), 2021, pp. 1-5, doi: 10.1109/PEDSTC52094.2021.9405903.

[14] Dedid, C., Soebagio, M., Purnomo, M.H., "Induction motor speed control with fast response using the Levenberg Marquardt method for electric cars," International Journal of Computer Applications, vol. 42, no. 13, pp. 14-18, 2012.

[15] Xue, X. D., Cheng, K. W. E. and Cheung, N. C., "Selection of electric motor drives for electric vehicles", Australasian Universities Power Engineering Conference, Hong Kong, pp. 170-175, 2008.

[16] Guzinski, J. and Abu-Rub, H., "Sensorless induction motor drive for electric vehicle application", International Journal of Engineering, Science and Technology, 2 (10), pp. 20-34, 2010.

[17] A. Mousaei, M. B. Bannae Sharifian and N. Rostami, "An Improved Predictive Current Control Strategy of Linear Induction Motor Based on Ultra-Local Model and Extended State Observer," 2022 13th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), 2022, pp. 12-18, doi: 10.1109/PEDSTC53976.2022.9767535.

[18] Kim, K.T., Song, H.E., and Park, G.S., "A study on the design of induction motor in low speed urban electric vehicle", IEEE Transportation Electrification Conference and Expo, pp. 1-4, Korea, 2016.

[19] Li, K., Cheng, G., Sun, X., Yang, Z., Fan, Y., "Performance optimization design and analysis of bearingless induction motor with different magnetic slot wedges", Results in Physics, 12, pp. 349-356, 2019.

[20] Yahaya, E. A., Omokhafe, T., Agbachi, E. O., James, A. G., "Advantage of Double Cage Rotor over Single Cage Rotor Induction Motor", Innovative Systems Design and Engineering, Vol.6, No.12, pp. 1-4, 2015.

[21] Zhou, G. Y., Shen, J. X., "Current Harmonics in Induction Machine with Closed-Slot Rotor", IEEE Transactions on Industry Applications, Vol. 53, No. 1, pp. 134- 142, 2017.

[22] Gyftakis, K. N., Kappatou, J., "The Impact of the Rotor Slot Number on the Behaviour of the Induction Motor", Advances in Power Electronics, Vol. 2013, pp. 1-9, 2013.

[23] Elhaija, W.A., Ghorbanian, V., Faiz, J., Nejadi-Koti, H., "Significance of Rotor Slots Number on Induction Motor Operation under Broken Bars", IEEE International Electric Machines and Drives Conference, Miami, May 2017.

[24] Emadi, A., "Energy-Efficient Electric Motors", Marcel Dekker, New York, 2005.

[25] Lee, G., Min, A., and Hong, J.P., "Optimal Shape Design of Rotor Slot in Squirrel-Cage Induction Motor Considering Torque Characteristic", IEEE Transactions on Magnetics, Vol. 49, No. 5, pp. 2197-2200, 2013.

[26] Arash Mousaei, Nasim Bahari, Guo Mieho. Artificial Neural Networks (ANN) of Proposed Linear Induction Motor with Hybrid Secondary (HLIM) Considering the End Effect. American Journal of Electrical and Computer Engineering. Vol. 5, No. 1, 2021, pp. 32-39. doi: 10.11648/j.ajece.20210501.15.

[27] Vishnu Murthy, K.M., "Computer-Aided Design of Electrical Machines", BS Publications, Hyderabad, 2008, ISBN:978-81-7800-146-3.

[28] Saygın, A., Ocak, A., Dalcalı, A., Çelik, E., "Optimum Rotor Design of Small PM BLDC Motor Based on High-Efficiency Criteria", ARPN Journal of Engineering and Applied Sciences, Vol. 10, No. 19, pp. 9127-9132, 2015.

[29] Dalcalı, A., Ocak, C., "Effect of Different Magnet Materials on The Performance of Surface Mounted Direct Drive PMSM", Journal of Awareness, 3, pp. 217-224, 2018.

[30] Sundaram, M., Mohanraj, M., Varunraj, P., Kumar, T.D., Sharma, S., "FEA Based Electromagnetic Analysis of Induction Motor Rotor Bars With Improved Starting Torque For Traction Applications", Automatic Control, Mechatronics and Industrial Engineering, pp. 103-110, Taylor&Francis Group, London, ISBN:987-1-138-60427-8.

[31] Popescu, M., Goss, J., Staton, D.A., Hawkins, D., Chong, Y.C., Boglietti, A., "Electrical Vehicles—Practical Solutions for Power Traction Motor Systems", IEEE Transactions on Industry Applications, Vol. 54, No. 3, pp. 2751-2762, May/June 2018.

[32] A. Mousaei, M. B. Bannae Sharifian and N. Rostami, "An Improved Fuzzy Logic Control Strategy of an Optimized Linear Induction Motor Using Super Twisting Sliding Mode Controller," 2022 13th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), 2022, pp. 1-5, doi: 10.1109/PEDSTC53976.2022.9767465.

[33] Ünlükaya, E., Yetgin, A.G., Çanakoğlu, A.I., and Turan, M., "Effect of Rotor Slot Shapes on Induction Motor Performance", Symposium on Electrical-Electronic-Computer and Biomedical Engineering, pp.168-172, Bursa, November 2014.

[34] Besnerais, J. L., Lanfranchi, V., Hecquet, M., Brochet, P., "Optimal Slot Numbers Combination for Magnetic Noise Reduction in Variable-Speed Induction Motors", IEEE Transactions on Magnetics, Vol. 45, No. 8, pp. 3131-3136, 2009.

[35] Finley, W.R., Hodowanec, M.M., "Selection of Copper vs. Aluminum Rotors for Induction Motors" Industry Applications Society Forty-Seventh Annual Petroleum and Chemical Industry Conference, pp. 1-11, 2000.

[36] Gieras, J.F, "Advancements in Electric Machines", Springer, 2008.

[37] Brush E.F., Cowie, J.G., Peters, D.T., and Van Son, D.J., "Die-cast Copper Motor Rotors: Motor Test Results, Copper Compared to Aluminum", Energy Efficiency in Motor Driven Systems, pp. 136-143, 2003.