Investigation of Aluminium and Copper Wound PMSM for Direct–drive Electric Vehicle Application

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Abstract. This paper investigates aluminium and copper windings for a permanent magnet synchronous machine (PMSM) developed for direct–drive electric vehicle (EV) application. Previously, studies have been conducted on comparison of these windings in terms of thermal and electrical conductivity, cost and mass density. However, the impact of these windings on the machine’s performance in terms of efficiency and torque has not been analysed. In this paper, for the same machine volume and geometry, a comparative analysis of PMSMs with copper and aluminium windings has been performed in terms of efficiency, torque, weight, operating speed range, ohmic losses and temperatures. Furthermore, as these machines are developed for direct–drive EV application, drive–cycle-based analysis was conducted for urban and highway cycles for a 2013 Ford Focus vehicle dynamics model. For these drive cycles, analysis in terms of torque speed characteristics and maximum energy density efficiency for both the machines has been performed.

1. Introduction

Conventionally, permanent magnet synchronous machines (PMSMs) are wound with copper conductors due to its high electrical conductivity. However, aluminium windings are being investigated as a potential candidate as they are cost and mass sensitive and offer higher thermal heat capacity when compared to copper conductors [1-4] which is well–suited for high torque density machine applications. In a typical electric vehicle (EV), power output from the motor is transmitted to the wheels through the gearbox, differential and drive shaft [5]. Such a transmission system is found to contribute to a power loss between 2% and 20% of the motor output power [6]. Thus, by removing the gear box, the motor to wheel efficiency can be improved resulting in a direct–drive configuration.

Challenges in designing a direct–drive PMSM are to obtain high torque density along with reduced cost. Thus, for such an application where reduced cost and increased torque density are of prime importance, aluminium conductors appear to be a good candidate to explore to copper conductors. Previously, comparison of aluminium and copper conductors were performed based on mechanical characteristics for induction machines [1]. [2],[4] compares these windings for physical properties, cost, resistivity and mass. In [3], to overcome the disadvantage of low electrical conductivity in aluminium conductors, pre–compressed Litz wires are proposed. However, there is limited literature on the effect of copper and aluminium conductors on the machine’s performance.

In this paper, two electromagnetic models of PMSM developed for direct-drive EV, one with copper conductors and another with aluminium conductors are compared in terms of torque–speed...
characteristics, efficiencies, ohmic losses and temperatures for different scenarios. Furthermore, the two machines with copper and aluminium windings have been analysed for urban and highway drive cycles to understand the feasibility of the machine for direct–drive application. Performance in terms of maximum energy density of these drive–cycles has been discussed.

2. Properties of Copper and Aluminium Windings
The physical properties of copper and aluminium windings used for this study are shown in Table 1 [7-8]. The basic data of the PMSM developed for the direct–drive EV application is shown in Table 2. For the same dimensions, conductor size, turns per slot and slot fill factor of 64%, two PMSMs, one with copper wires and another with aluminium wires were developed and analysed. Due to difference in resistivity of both the materials, the per–phase resistance of copper was found to be 2.1 Ω and for that of aluminium wound PMSM was 3.3 Ω. For the same geometry and material consumption, there was a 14.7% reduction in overall weight of the aluminium wound machine when compared to copper wound PMSM as shown in Table 3.

### Table 1. Physical properties of aluminium and copper conductors at 20°C

| Property                      | Copper | Aluminium |
|-------------------------------|--------|-----------|
| Resistivity [Ωmm²/m]          | 0.01   | 0.03      |
| Mass Density [g/cm³]          | 8.89   | 2.7       |
| Thermal Conductivity [W/mK]   | 388    | 234       |
| Tensile Strength [MPa]        | 248-276| 62-96.5   |
| Melting Point [°C]            | 1085   | 660       |

### Table 2. Basic machine data

| Parameter                | Value |
|--------------------------|-------|
| Outer Diameter [mm]      | 195   |
| Active Length [mm]       | 75    |
| Number of Slots/Poles    | 36/34 |
| Base Speed [rpm]         | 405   |
| Wire Diameter [mm]       | 1.02  |
| Rated Torque [Nm]        | 70    |

### Table 3. Parameters of Aluminium and Copper wound PMSM

| Parameter                 | Copper | Aluminium |
|---------------------------|--------|-----------|
| Slot Fill Factor [%]      | 64     | 64        |
| Phase Resistance [Ω]      | 2.1    | 3.3       |
| Active Weight [kg]        | 10.5   | 8.95      |
| Winding Cost/kg [US$]     | 6.96   | 2.24      |

3. Comparison of copper and aluminium windings for a direct–drive PMSM
In this section, three scenarios are established for which the copper and aluminium wound PMSM machine’s performance was analysed in terms of efficiency, torque, winding losses and temperature are analysed.

3.1 Case 1: Considering same output torque of 70 Nm in copper and aluminium wound PMSM
As previously discussed in section 2, the copper and aluminium wound PMSMs have the same geometry and conductor gauge. For a rated peak current of 9 A in the copper wound PMSM, the
output torque at base speed of 405 rpm was found to be 70 Nm. To deliver the same torque for the aluminium wound PMSM, a rated peak current of 13 A was calculated for the aluminium wound PMSM based on the ratio of difference in resistivity of these two materials. These peak current values were used to analyse efficiency, torque and speed maps for the entire speed range which are illustrated in Figure 1.

Both the machines deliver a rated torque of 70 Nm until a speed of 405 rpm. However, to deliver the same torque in aluminium wound PMSM the rated current was increased by 1.4 times. Efficiency was calculated based on the mechanical output and losses. Losses in a PMSM are categorized as core, ohmic, mechanical and magnet loss. For direct–drive application the base speed is low when compared to high speed machine in traction application, therefore, speed related losses such core and mechanical loss are low, and the total machine loss is most dependant on ohmic loss. Ohmic loss in any machine is dependent on square of current and resistance of the conductor used. In this study, the per phase ohmic losses are 156 W and 225 W in copper and aluminium wound PMSMs, respectively. Due to this difference in ohmic loss, the efficiency of aluminium wound PMSM was found to be 4.15% lower than the one in copper wound PMSM at rated speed and torque condition of 405 rpm and 70 Nm as shown in Figure 1(c).

3.2. Case 2: Considering same ohmic loss of 156 W in copper and aluminium wound PMSM
In this scenario, for different per phase resistances of 2.1 Ω and 3.3 Ω in copper and aluminium wound PMSMs respectively, the current magnitudes were computed to obtain the same ohmic loss of 156 W per phase and output of 3 kW in both the machines. The resulting difference in output torque is shown in Figure 2(a). Aluminium wound PMSM delivered a torque of 58 Nm at base speed of 405 rpm.
whereas, copper wound PMSM delivered 70 Nm. This 18% reduction in torque production is due to lower conductivity of aluminium. Furthermore, torque–speed characteristics for both machines were analysed and are shown in Figure 2(b). Both the machines have maximum speed of 1,200 rpm. However, the base speed of aluminium wound PMSM increased by 20% when compared to copper wound PMSM, thereby offering wider constant torque region. This increase in base speed is attributed to reduced voltage and current in the aluminium wound PMSM.

3.3. Study of ohmic losses and efficiency as a function of temperature for copper and aluminium wound PMSMs

To deliver the same output torque of 70 Nm at a base speed of 405 rpm, copper and aluminium wound machines were analysed for ohmic losses and efficiencies at varying winding temperature. Resistance temperature coefficient of 0.00393 and 0.004 were considered for copper and aluminium wires, respectively [7]. Based on the temperature coefficients, the change in resistance from 20°C to 100°C was computed. Due to variation of resistances with temperature, corresponding magnitudes of currents were calculated to deliver 70 Nm torque for both the machines. The variation of ohmic loss and efficiency for aluminium and copper wound PMSMs as a function of temperature is shown in Figure 3. 3.8% and 2.65% reduction in efficiency were observed in aluminium and copper wound PMSMs, respectively. The larger reduction of efficiency in aluminium wound machine is attributed to reduced thermal conductivity of the material as seen in Table 2 when compared to copper windings.

![Figure 2](image1.png)

**Figure 2.** Comparison of torque profile for copper and aluminium wound PMSMs. (a) Torque comparison at rated speed of 405 rpm. (b) Torque–speed characteristics over entire operating range.

![Figure 3](image2.png)

**Figure 3.** Ohmic losses and efficiency variation with temperature for copper and aluminium wound PMSMs.
4. Drive cycle–based performance analysis of copper and aluminium wound PMSMs

In this section, drive–cycle-based analysis is performed on the copper and aluminium wound PMSMs. The torque–speed characteristics of these PMSMs are analysed for case 1 scenario and efficiencies are analysed for case 2 scenario. This analysis simulates real–life driving conditions; specifically, the two most common drive-cycles which are UDDS (urban) and HWFET (highway). The characteristics used for analysis of these drive cycles are shown in Table 4. These drive cycles are variations of speed as a function of time which act as inputs to the vehicle dynamics model. Parameters of the vehicle dynamics model were selected for a 2018 Ford Focus vehicle [9]. Based on the speed variation for the aluminium wound PMSM, the torque demand is computed from the vehicle dynamics model using tractive forces acting on the vehicle. Three tractive forces were considered: aerodynamic drag, rolling resistance friction and force due to gravity. Since this is for a direct–drive EV, gear ratio was considered as unity, however a final drive ratio of 2.57 was considered for calculating the torque delivered by the motor [9].

For an urban drive cycle shown in Figure 4(a), the torque–speed points were computed using the vehicle dynamics model. These points were analysed for the torque–speed characteristics obtained from copper and aluminium wound PMSMs as shown in Figure 4(b). Even though the aluminium wound PMSM delivers a rated torque of 58 Nm, all of the torque speed points from the urban drive–cycle are satisfied by both the machines. Further, analysis of effect of drive–cycle points on efficiency maps were conducted. Figures 4(c) and (d) shows the urban drive cycle points on efficiency maps of copper and aluminium wound PMSMs respectively. A reduction of 1.17% efficiency was observed in aluminium wound PMSM when compared to copper wound machine at maximum energy density points of the urban drive–cycle.

Table. 4. Drive–cycle characteristics

|                | Urban | Highway |
|----------------|-------|---------|
| Average Speed (km/h) | 34.1  | 77.7    |
| Duration (sec)       | 1,874 | 765     |
| Total Distance (km)  | 17.77 | 16.51   |

Similarly, for highway drive–cycle shown in Figure 5(a), the torque speed points were computed using vehicle dynamics model and were analysed for the torque –speed characteristics of both machines as shown in Figure 5(b). As seen from the figure, all the torque–speed points of highway drive–cycle are well within the characteristics of both the machines. Analysis of the highway drive cycle points on efficiencies of copper and aluminium wound machines are illustrated in Figures 5(c) and (d) respectively. A reduction of 1.7% efficiency was observed in aluminium wound PMSM when compared to copper wound machine at maximum energy density points for the highway drive–cycle.

5. Conclusion

Comparative analysis of copper and aluminium windings for direct–drive PMSM has been performed in this paper in terms of torque–speed characteristics, efficiencies, ohmic losses and temperatures. Analysis of both the machines for urban and highway drive–cycles was also conducted. Even though the efficiency of aluminium wound PMSM was approximately 1.7% less than copper wound PMSM for the two drive–cycles at maximum energy density points, it satisfies all the speed and torque load points offering 14.7% less motor weight and 67% less winding cost per kg when compared to copper wound PMSM. This difference in efficiency between both the machines is significant as they were designed for low–speed application where the predominant losses are from the windings. However, there is a scope of implementing these windings for high–speed application, where winding losses are low and have less impact on efficiency.
Figure 4. Urban drive–cycle performance characteristics. (a) Urban drive cycle. (b) Torque–speed load points. (c) Torque speed points of urban drive–cycle on efficiency map of copper wound PMSM. (d) Torque speed points of urban drive–cycle on efficiency map of aluminium wound PMSM.
Figure 5. Highway drive cycle performance characteristics. (a) Highway drive–cycle. (b) Torque–speed load points. (c) Torque speed points of highway drive–cycle on efficiency map of copper wound PMSM. (d) Torque speed points of highway drive–cycle on efficiency map of aluminium wound PMSM.

6. References

[1] M. Iorgulescu, "Study of single–phase induction motor with aluminum versus copper stator winding," in proc. of International Conference on Applied and Theoretical Electricity, Craiova, pp. 1–5, 2016.
[2] C. R. Sullivan, "Aluminum windings and other strategies for high–frequency magnetics design in an era of high copper and energy costs," IEEE Transactions on Power Electronics, Vol.23, pp. 2044–51, 2008.
[3] J. D. Widmer, R. Martin and B. C. Mecrow, "Pre–compressed and stranded aluminum motor windings for traction motors," IEEE Transactions on Industry Applications, Vol 52, No.3, May 2016.
[4] R. Wrobel, D. Salt, N. Simpson and P. H. Mellor, "Comparative study of copper and aluminum conductors - Future cost-effective PM machines," in proc. of IET International Conference on Power Electronics, Machines and Drives, Manchester, 2014, pp. 1-6.
[5] K. L. V. Iyer, S. Mukundan, H. Dhulipati, K. Mukherjee, B. Minaker, and N. C. Kar, “Design considerations for permanent magnet machine drives for direct–drive electric vehicles.” in proc. of Electric Machines Drives Conference, pp. 1170–1176, 2015.
[6] BorgWarner Drivetrain Systems, 2011, Available: http://www.evwest.com/support/borgwarneredrive.pdf
[7] Superior Essex Data Sheet, Available: https://www.superioressex.com/uploadedFiles/Magnet_Wire_and_Distribution/North_America/Magnet_Wire_-_Winding_Wire/EngData_book_linked.pdf
[8] ASM Handbook, Available: http://sme.vimaru.edu.vn/sites/sme.vimaru.edu.vn/files/volume_2_properties_and_selection_nonf.pdf
[9] 2018 Ford Focus Electric Specifications, [online], Available: https://www.ford.ca/cars/focus/models/focus–electric