Design, Optimization and Experimental Study of Axial and Hub BLDC Motors in-Wheel Application for Light Electric Vehicles

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***Abstract*—The use of brushless DC (BLDC) motors in electric vehicles have been rapidly increasing. In this study performance analysis was made for BLDC motors used in wheel applications in light electrical vehicles on issues such as efficiency, speed, and power density. In this study, two types of BLDC motors, axial flux (AF) and hub (outer rotor-radial flux) motor were simulated, optimized, and experimented. Both of them were studied considering multi-parameter objectives mainly, stator yoke flux density, rotor yoke flux density, air gap flux density, efficiency, torque/weight, and speed. The credibility of the models performed has been confirmed by comparing the results of simulation and measurement on rated values 10 kW, 72 V (Axial) and 1 kW, 50 V (Hub) 3 phase, star connected motors. To optimize the motor design comprehensively, a genetic algorithm (GA) has been realized for each motor. The design, optimization, and realization of the study are given in detail pointing out some important data on BLDC motors.**

Keywords—Axial flux BLDC, Hub motor, Design, Efficiency, Experiment, Genetic Algorithm, Torque.

I. INTRODUCTION

BLDC motors have rapidly developed over the past decade due to their wide variety of speed, high efficiency, high torque capability, high power density, and high reliability, particularly in the automotive, aerospace, electrical vehicles, and home appliances [1],[2]. As in all other motors, a BLDC motor mainly consists of a stator and a rotor. The rotor is a non-winding structure on which permanent magnets (PM) are assembled and it can be positioned as an inner or outer type. The outer rotor type is a preferred choice for a constant speed operation due to the large inertia of the rotor and is mainly used for in-wheel applications for its suitable geometrical shape[3]. The PMs can have surface or inner mounted structures. The stator consists of windings in slots to create a certain number of poles. But, in some cases, the stator can be created and optimized without the slots [4]. Stator winding type can be concentrated or distributed by selecting the appropriate pole and slot number to improve motor performance and reduce torque ripples [5],[6],[10]. The flux direction type can be radial, axial, or both in some cases with a different number of air gaps [3],[4],[7]. The flux density may be uniform or non-uniform, steady or time-varying. To achieve better motor performance characteristics, computational intelligence algorithms are applied in cooperating with several variants and constraints [8],[11-13]. The distribution of magnetic loading on the slots in the stator is affected due to the structural variation of the rotor in the BLDC motor[14]. In-wheel motors are a mechanism suitable for pure electric vehicles. Fig. 1(a) shows an in-wheel hub electric vehicle[15]. With the development of battery systems for electric vehicles, the importance of electric motors used in light electric vehicles and electric vehicles has begun to increase[16]. In EV applications, the motor has to be capable of providing enough torque when accelerating. At the same time, the efficiency under normal operating conditions must be high enough to save energy and must ensure the heat-dissipating capability [17], [18]. They developed a motor with similar technology as the 2012 motor and achieved an efficiency of 97.9% [3], [4]. High efficiency was studied by J. Buøy [22], and he appointed that the friction losses reduced the efficiency.. There are two types of electric motors used in EVs: an inner rotor and an outer rotor. In models that use internal rotor motors, mechanical differentials and gears are widely used. On the other hand, outer-rotor motors do not require additional mechanical components, since they are normally mounted inside the wheels. As the power used in these models is transferred directly to the wheels, compared to the inner rotor model, higher efficiency can be achieved [14],[16],[19]. Also, the power density is one of the most important factors that determine the efficiency of a vehicle. Where the higher the power density of a motor, it will be the lower the fuel consumption of the vehicle is required [21].

In this study, a surface-mounted PM, concentrated winding, dual air gap axial type motor, and outer hub motor are performed as seen in Fig.1(b) and Fig.1(c) respectively. The motors were analyzed using ANSYS/Maxwell software and experimental studies were realized for verification and GA was also used for optimization to improve motor performance with several variables and constraints. In addition, the suitability of axial and hub BLDC motors for high-performance light electric vehicles was investigated. The advantages and disadvantages of both motors are compared in terms of efficiency, speed, and torque/weight. Axial flux and hub motor were analyzed using Ansys/Maxwell software considering operating conditions such as same power, and same air gap length.

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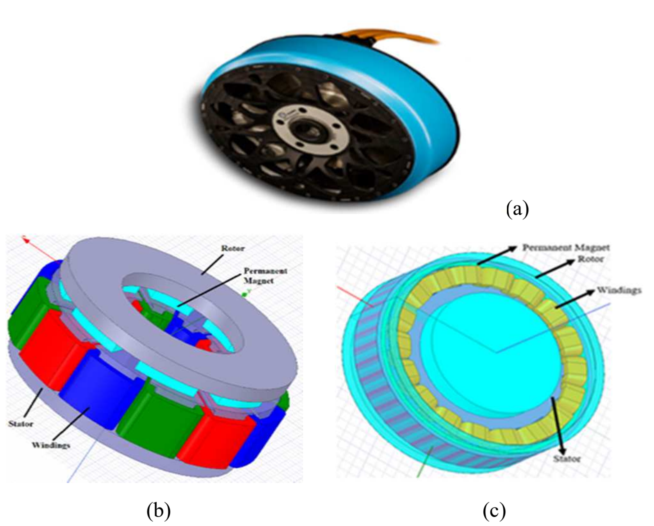


(a)

(b) (c)

Fig. 1. In-wheel motor scheme (a), axial type motor (b), hub motor(c).

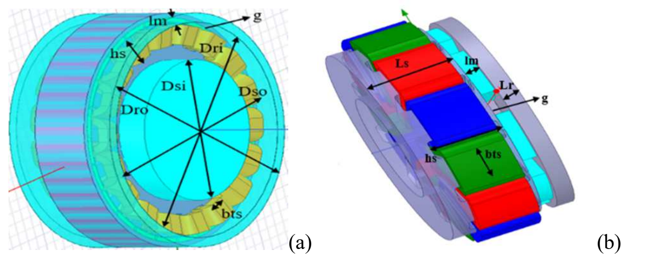
II. ANALYSIS OF AXIAL FLUX BLDC AND HUB MOTOR USING ANSYS/MAXWELL

Axial flux (AF) BLDC motor with output power of 10 KW, speed 4550 rpm, operating voltage of 72 V, and hub motor with output power of 1 KW, speed 300 rpm, operating voltage 50 V were analyzed using ANSYS/RMxprt [21]. The specifications of the AF BLDC and hub BLDC motor are given in Table I.

TABLE I. AXIAL FLUX AND HUB MOTOR SPECIFICATIONS

Symbol	Axial motor and Hub motor Specifications		
	Specification	***AXIAL***	***HUB***
P_m	Rated power	10 KW	1 KW
E	Rated voltage	72 V	50 V
Q_s	Number of slots	12	18
P	Number of poles	8	24
L	Axial Length	115.5 mm	33.7 mm
l_m	Magnet thickness	4 mm	4 mm
g	Air gap length	0.75 mm	0.75 mm
T / v	Torque/Volume (Nm / cm^3)	0.01	0.01

Stator outer diameter (D_{so}), stator inner diameter (D_{si}), rotor outer diameter (D_{ro}), rotor inner diameter (D_{ri}), tooth width (bts), slot height (hs), motor axial length (L), magnet thickness (l_m), air gap length (g) of AF BLDC and hub BLDC motor were determined. In addition, the stator length (L_s), rotor length (L_r), and magnetic length (l_m) in the radial direction of the AF BLDC motor were measured in the axial direction. The stator carrying the windings of the hub motor is inside. The rotor surface is in a magnetic structure and it is in the outer part. AF BLDC motor has a rotor with magnets mounted on both sides and a stator on both sides. The stator windings of the AF BLDC and hub BLDC motors are two-layer, whole-coiled, concentric windings. In Fig. 2(a), the motor identifications of hub BLDC; D_{ro}, D_{ri} ,D_{so}, D_{si}, b_{ts} (tooth thickness) and h_s (slot height) are shown. In Fig. 2(b), the motor identifications of AF BLDC; L_r, L_s, l_m, g, h_s, b_{ts} are shown.



(a) (b)

Fig. 2. Geometric view of Hub BLDC motor parameter (a), Geometric view of AF BLDC motor parameters (b).

The comparison has been based on the torque/volume ratio for the AF BLDC motor and hub BLDC motor. These motors have the same torque/volume ratio. The axial lengths and diameters of motors are important parameters.

In (1), the rotor outer diameter is given for the hub BLDC motor. Since D_{so} is 195 mm, l_m is 4 mm, g is 0.75 mm, h_{ry} (rotor yoke height) is 4.25 mm, D_{ro} is 213 mm. The axial length (L) of the rotor is 33.7 mm.

$$D_{ro} = D_{so} + 2l_m + 2g + 2h_{ry} \qquad (1)$$

In Equation (2), the total axial length of the motor is given for the AF BLDC motor. Since L_r is 10 mm, L_s is 48 mm, l_m is 4 mm, g is 0.75 mm, the total axial length (L_{AF}) of the motor is 115.5 mm.

$$L_{AF} = L_r + 2L_s + 2l_m + 2g \qquad (2)$$

The torque/volume ratio is given in (3). Torque/volume ratios for axial flux BLDC motor and hub BLDC motor are 0.01 Nm/cm^3.

$$\text{Torque / volume} = T / \pi (D_{ro} / 2)^2 L \qquad (3)$$

Where T is the rated torque, D_{ro} is 150 mm. To calculate the copper losses, the current drawn from the DC source and the phase resistance must be determined. The slot fill factor is 0.65 and the conductor current density is $4\,A / mm^2$. The current also depends on the slot area and the number of conductors per slot. The slot area is affected by the D_{so}, D_{si}, stator yoke thickness (h_{sy}), a number of slots (Q_s), slot edge height (h_{s0}), tooth width (b_{ts}), and slot opening (w_0) parameters. Phase resistance, on the other hand, depends on the resistivity of the copper conductor, the number of magnet poles, the motor axial length, the stator inner diameter, the slot height, the number of conductors per slot, the slot area, the slot fill factor, the number of slots per pole per phase. After determining the current and phase resistance, copper losses can be calculated.

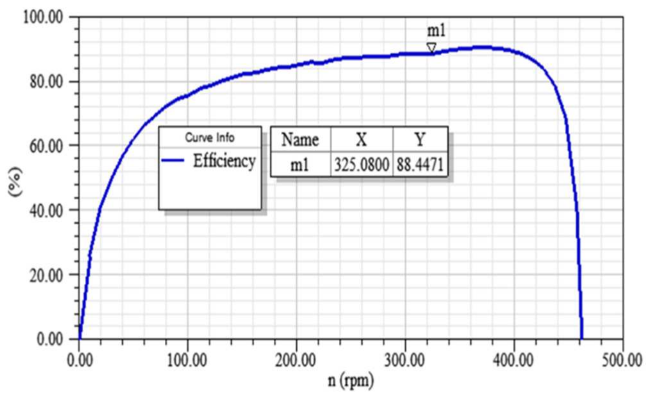
Friction and windage losses are considered to be 1%-3% of the output power[19]. Here, friction and windage losses are accepted as 1% of the output power. The type of ferromagnetic materials used in the stator and rotor core determines core losses. The core volume in the stator where the rotating magnetic field occurs depends on D_{so}, D_{si}, Q_s, and L_s. After calculating the copper losses, core losses, friction and windage losses, the efficiency can be determined.

D23_50 steel was used in the stator and rotor for both AF BLDC and hub BLDC motor. N42H magnet was preferred in both motors due to its high performance[9],[11]. The simulation results obtained for the hub motor are shown in Table II.

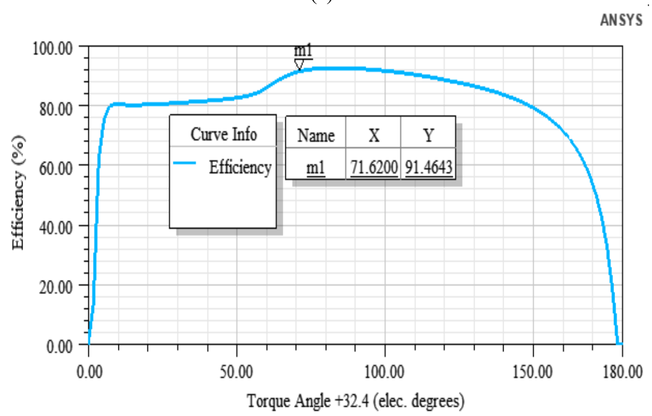
TABLE II. AXIAL FLUX AND HUB MOTOR SIMULATION RESULTS

Symbol	Axial flux and Hub motor Simulation Results		
	Parameter	***AXIAL***	***HUB***
η	Efficiency	91.46%	88.44%
T	Rated torque	20.99 Nm	22.62 Nm
n	Rated speed	4550 rpm	325 rpm
B_{sy}	Stator-Yoke Flux Density	1.43 Tesla	1.06 Tesla
B_{ry}	Rotor-Yoke Flux Density	1.35 Tesla	2.17 Tesla
B_g	Air-Gap Flux Density	0.78 Tesla	0.88 Tesla
m_{net}	Total Net Weight	22.50 Kg	5.21 Kg

Figure 3 (a) shows hub motor efficiency-speed variation. Figure 3 (b) shows axial motor efficiency-torque angle variation.



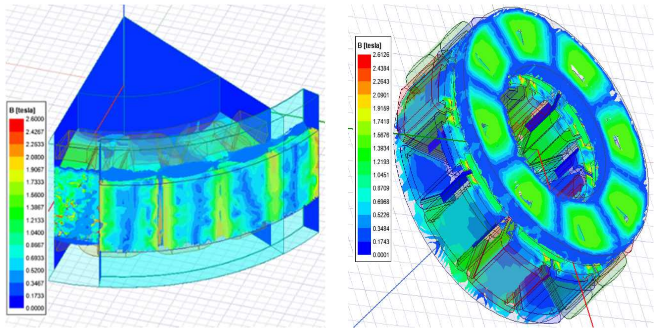
(a)



(b)

Fig. 3. (a) Hub BLDC motor Efficiency Vs Speed (b) AF motor Efficiency Vs Torque Angle.

Hub motor efficiency is 88.44%, speed is 325 rpm. Axial motor efficiency is 91.46%, speed is 4550 rpm.



(a) (b)

Fig. 4. (a) Hub BLDC motor Flux density (b) AF motor Flux density.

Fig.4 depicts the motor flux distribution. The dominant blue and green color on the surface and inner of the stator indicates that the motor operate efficiently with the in limits. In this operating mode (a), for hub motor, the tooth average flux density is 1.4 T, the rotor yoke average flux density is 2.5 T, and the average air-gap flux density is developed as 0.85-0.90 T. (b), for axial motor, the stator yoke flux density is 1.35-1.45 T, rotor yoke flux density is 1.30-1.35 T, air gap flux density is 0.7-0.80 T, and tooth flux density is 1.5-1.55 T.

III. AF BLDC AND HUB MOTOR EXPERIMENTAL STUDIES

In this section, experimental data of 3-phase, star-connected AF and hub BLDC motor were performed. The simulation studies using ANSYS/RMxprt program were verified with the experimental data. Experimental scenarios were prepared to measure the efficiency, torque and current of the motors. In Fig. 5, the experimental setup is shown.

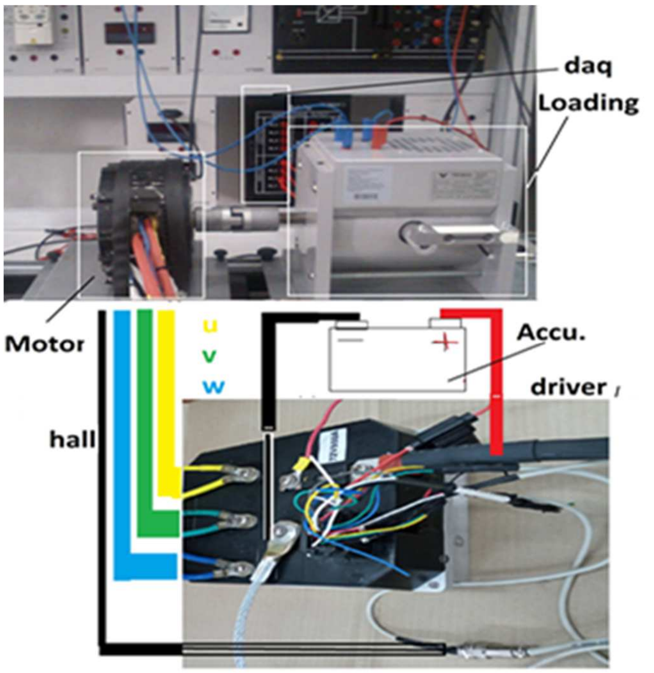


Fig. 5. AF BLDC Motor Experimental Setup

In the experimental study, 72 V voltage source providing axial flux BLDC motor supply was connected to the motor driver. In addition, the signal information from the hall sensors is transferred to the driver. Thus, the stator windings are energized in sequence according to the rotor position. Torque, speed and current values were measured with a load coupled to the axial motor shaft. In Fig. 6, the efficiency-speed curve of the AF BLDC motor experiment is given.

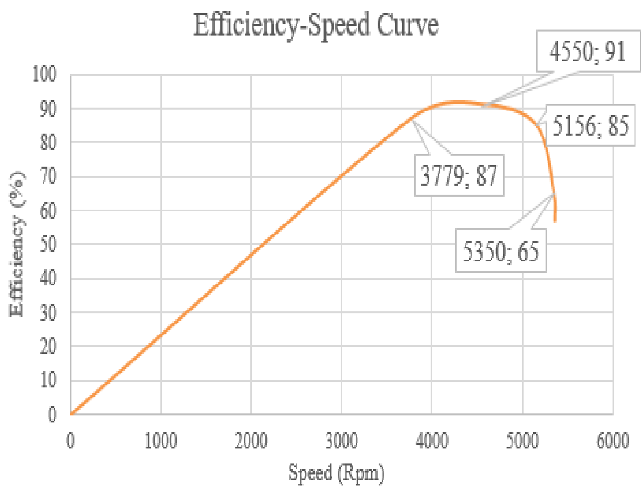


Fig. 6. AF BLDC Motor Experiment Efficiency-Speed Curve

The experimental and simulation results of the AF BLDC motor are given in Table III. The results are seen in good agreement. The simulation result is verified with experimental results.

TABLE III. EXPERIMENTAL AND SIMULATION RESULTS OF AF BLDC MOTOR

AXIAL	Experimental and Simulation Results of AF BLDC Motor		
	Efficiency	***Torque***	***Current***
Simulation	91.46 %	20.99 Nm	149 A
Experimental	91 %	19.36 Nm	140 A

Similarly, experimental studies were carried out for the hub motor by energizing 50 V and loading in sequence. Fig. 7 shows the experimental setup of the hub motor.

Fig. 7. Hub BLDC Motor Experimental Setup

In Fig.8, the efficiency-speed curve of the hub motor experiment is given.

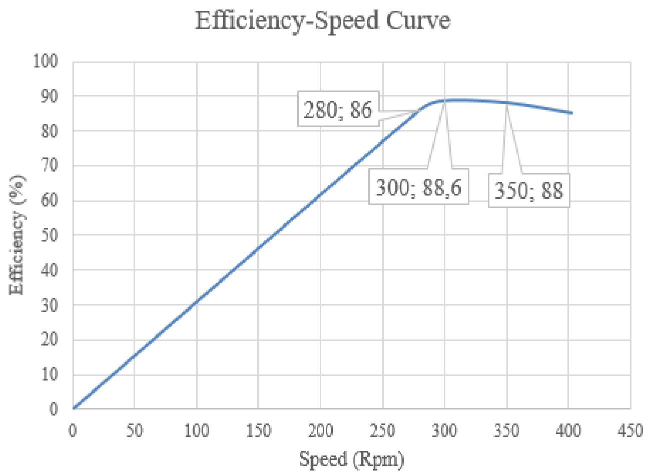


Fig. 8. HUB Motor Experiment Efficiency-Speed Curve

The experimental and simulation results of the hub BLDC motor are given in Table IV.

TABLE IV. EXPERIMENTAL AND SIMULATION RESULTS OF HUB MOTOR

HUB	Experimental and Simulation Results of Hub Motor		
	Efficiency	***Torque***	***Current***
Simulation	88.44 %	22.62 Nm	18.18 A
Experimental	88.69 %	23.44 Nm	20.5 A

In some main points advantages and disadvantages of AF and hub, BLDC motor is given in Table V.

TABLE V. COMPARISON OF AF AND HUB BLDC MOTOR

Motor Type	Comparison of Axial and Hub Motor			
	Efficiency	***Torque/weight***	***Speed***	***Power density***
Axial BLDC	+++	+	+++	+++
Hub BLDC	++	+++	+	+

+: normal; ++: medium; +++: high

IV. EFFICIENCY OPTIMIZATION OF AXIAL FLUX BLDC AND HUB MOTOR USING GA

The genetic algorithm process basically consists of five stages. In the first step, the population of the problem is created. Then the fitness value of each individual is calculated. Selection is made using methods such as the roulette wheel and the tournament method. After selection, the crossover operator is applied. In the last step, the individuals obtained by applying the mutation operator form the new population. GA continues until it finds the criterion for the best solution of the problem [21]. In this section, efficiency optimization of hub BLDC motor and axial flux BLDC motor is done by GA. There are common parameters that affect the efficiency of both motors. However, since there are different parameters, lower and upper limit values are given in two different tables (see Table VII and VIII). Table VI shows the constant parameters of the axial flux BLDC and hub motor.

TABLE VI. AXIAL FLUX AND HUB MOTOR CONSTANTS

MOTOR TYPE	**Bsy**	**Bry**	**Bt**	**Eph**	**T**	**N**
AF MOTOR	1.6 T	1.4 T	1.6 T	36 V	20.99 Nm	4550 rpm
HUB MOTOR	1.6 T	1.4 T	1.6 T	25 V	22.62 Nm	325 rpm

The electromechanical power given in (4) is the same for axial and hub BLDC motors. The flattop value of phase back emf and electromechanical torque in (5) and (6) belong to the hub BLDC motor. The flattop value of phase back emf and electromechanical torque in (7) and (9) are written for the axial motor [16].

In (4), Pm is electromechanical power, E_{ph} is flattop value of phase back emf, Ip is dc link current or peak value of phase current.

$$P_m = 2.E_{ph}.I_p \quad (4)$$

In (5), Nph is number of turns per phase, *Bg* is flattop value of air gap magnetic flux density, *L* is axial length of motor, D_{ri} is inner diameter of hub motor.

$$E_{ph} = N_{ph}.B_g.D_{ri}.w_m \quad (5)$$

In (6), T is electromechanical torque.

$$T = 2.N_{ph}.B_g.D_{ri}.L.I_p \quad (6)$$

In (7) and (8), R_0 , R_i are the inner radius and outer radius of the axial motor.

$$E_{ph} = N_{ph}.B_g.R_o^2.(1-K_r^2).w_m \quad (7)$$

$$K_r = \frac{R_i}{R_o} \quad (8)$$

In (9), T is electromechanical torque.

$$T = 2.N_{ph}.B_g.R_o^2.(1-K_r^2).I_p \quad (9)$$

Parameters affecting efficiency are given in the equations. Considering the motor design limits, constants and variables were determined for genetic algorithm optimization. After the population was created for the motor parameters, the fitness value was calculated for each individual. According to these fitness values, surviving individuals were determined by the roulette wheel method. Thus, the one-point crossover operator (0.90) was applied to the new individuals formed. The mutation operator with a probability of 0.01 was applied to the individuals obtained as a result of the crossover. Efficiency was obtained according to the lower and upper limit values in the population created at the beginning. When the genetic algorithm process was run for the hub motor, the optimum efficiency (90.35%) and parameter values were obtained after the 30th iteration. The highest efficiency (94.91%) and the most suitable parameters were obtained after the 50th iteration in the axial motor. Efficiency optimization was achieved by developing Delphi software for the GA method.

The motor parameters with lower and upper limits given in Tables VII and VIII were optimized by GA and optimized new values were placed in the last column. The efficiency value obtained as a result of the optimization is given in the last line.

TABLE VII. OPTIMIZATION RESULTS OF HUB MOTOR USING GENETIC ALGORITM

HUB MOTOR	**Optimization Results of Hub Motor Using Genetic Algorithm**		
	Lower limit	***Upper limit***	***GA Result***
Stator outer diameter(D_{so})	190 mm	196 mm	195 mm
Stator inner diameter(D_{si})	122 mm	128 mm	125.27 mm
Rotor outer diameter(D_{ro})	210 mm	215 mm	211.4 mm
Air gap length(g)	0.5 mm	1.5 mm	1.45 mm
Slot height(hs)	18 mm	25 mm	19.5 mm
Axial length(L)	30 mm	35 mm	30.65 mm
Air gap flux density(Bg)	0.2 T	1 T	0.83 T
Magnet thickness(lm)	3 mm	8 mm	4.92 mm
Tooth thickness(bts)	3 mm	5 mm	4.74 mm
Efficiency	**88.44 %**		**90.35 %**

TABLE VIII. OPTIMIZATION RESULTS OF AF MOTOR USING GENETIC ALGORITM

AXIAL BLDC	**Optimization Results of AF BLDC Motor Using Genetic Algorithm**		
	Lower limit	***Upper limit***	***GA Result***
Stator outer diameter(D_{so})	145 mm	155 mm	145.28 mm
Stator inner diameter(D_{si})	76 mm	82 mm	81.81 mm
Air gap length(g)	0.5 mm	1.5 mm	0.50 mm
Slot height(h_s)	32 mm	38 mm	35.33 mm
Air gap flux density(B_g)	0.2 T	1 T	0.57 T
Magnet thickness(l_m)	3 mm	8 mm	3.36 mm
Tooth thickness(b_{ts})	3 mm	5 mm	3.15 mm
Stator length(L_s)	45 mm	55 mm	45.49 mm
Rotor length(L_r)	8 mm	13 mm	8 mm
Efficiency	**91.46 %**		**94.91 %**

V. CONCLUSION

In this study, the comparison was made by considering the torque values per volume of the axial and hub motors. A two-stage study was carried out for axial and hub motors for light electrical vehicle applications. First of all, simulation and experimental studies were carried out for both motors. Thus, the simulation data was confirmed by the experimental results. Then, the efficiency optimization of both motors was carried out with the help of GA. The efficiency values of both motors have been significantly improved.

As a result of the analysis, the efficiency of the hub motor is 88.44%, and the efficiency of the axial flux motor is 91.46%. Moreover, the hub motor torque value is 22.62 Nm, while the axial flux motor torque value is 20.99 Nm. Rated speed values are 325 rpm and 4550 rpm for hub and axial motors, respectively. When evaluated in terms of flux density in the air gap, the hub motor is 11.3 % more than the axial flux motor.

Also, the flux density in the rotor flux density for the hub motor is 37.78 % higher than the axial flux motor. The stator yoke flux density of the axial flux motor is 25.87 % higher than that of the hub motor. According to the result of efficiency optimization with GA for axial flux motor; GA efficiency value is found 94.91 %. In the efficiency optimization of the axial motor with GA, the motor volume was reduced by 15%. Especially, these changes in stator outer diameter and stator axial length caused a decrease in core losses. Similarly, as a result of optimization of hub motor GA, motor volume decreased by 16.66%. According to the axial and hub motor simulation and experiment results, the efficiency values obtained are close. It has been observed that the axial motor is superior in terms of efficiency, speed, and power density. Hub motor was found to be superior when considering torque/weight.

REFERENCES

[1] M. Jagiela, T. Garbiec, J. Gwozdz, J. Kolodziej, "Fast Steady-State Field-Circuit Model for SMPM-BLdc Motors Driven From 120° and 180° Quasi-Square Wave Inverters," in IEEE Transactions on Magnetics, vol. 52, no. 3, pp. 1-4, March 2016, Art no. 8101104, doi: 10.1109/TMAG.2015.2482986.

[2] G. Tatar, K. Toker, N. F. Oyman Serteller, H. Korkmaz, "A dynamic analysis of BLDC motor by using Matlab/Simulink and mathematica," 2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON), 2017, pp. 1-5, doi: 10.1109/CHILECON.2017.8229540.

[3] H. Shin, K. Shin, G. Jang, S. Cho, K. Jung, J. Choi, "Experimental Verification and 2D Equivalent Analysis Techniques of BLDC Motor With Permanent Magnet Overhang and Housing-Integrated Rotor Core," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 5201805, doi: 10.1109/TASC.2020.2972233.

[4] F. Messine, B. Nogarede, J. Lagouanelle, "Optimal design of electromechanical actuators: a new method based on global optimization," in IEEE Transactions on Magnetics, vol. 34, no. 1, pp. 299-308, Jan. 1998, doi: 10.1109/20.650361.

[5] B. Stumberger, G. Stumberger, M. Hadziselimovic, A. Hamler, M. Trlep, Viktor Goricˇan, Marko Jeseni "High-performance permanent magnet brushless motors with balanced concentrated windings and similar slot and pole numbers " Journal of Magnetism and Magnetic Materials 304 (2006) e829–e831.

[6] Y. Bektas, N. F. Oyman Serteller, "Brushless direct current (BLDC) motor driving experimental set Energy Education Science and Technology Part A: Energy Science and Research 2011 Volume (Issue) 27(2): 455-466.

[7] A. N. Patel, B. N. Suthar, T. H. Panchal, R. M. Patel, "Comparative Performance Analysis of Radial Flux and Dual Air-Gap Axial Flux Permanent Magnet Brushless DC Motors for Electric Vehicle Application," 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), 2018, pp. 804-808, doi: 10.1109/ICPEICES.2018.8897459.

[8] M. Khelifa, M. Mordjaoui, A. Medoued, An inverse problem methodology for design and optimization of an interior permanent magnetic BLDC motor, International Journal of Hydrogen Energy, Volume 42, Issue 28,2017, P.17733-17740, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2017.02.017.

[9] D. C. Hanselman, Brushless Motors: Magnetic Design, Performance, and Control of Brushless DC and Permanent Magnet Synchronous Motors. USA: E-Man Press LLC, 2012.

[10] K. Aiso, M. Takahashi, "Study of High-Speed SRM Using Vector Control for Electric Vehicle", 10th International Conference on Power Electronics- ECCE Asia, 2019.

[11] O. Tosun, N. F. O. Serteller and G. Yalcin, "Comprehensive Design and Optimization of Brushless Direct Current Motor for the Desired Operating Conditions," 2021 25th International Conference Electronics, 2021, pp. 1-6, doi: 10.1109/IEEECONF52705.2021.9467459.

[12] N. Umadevi, M. Balaji and V. Kamaraj, "Design optimization of brushless DC motor using Particle Swarm Optimization," 2014 IEEE 2nd International Conference on Electrical Energy Systems (ICEES), 2014, pp. 122-125, doi: 10.1109/ICEES.2014.6924153.

[13] J.M.D. Coey, "Permanent magnet applications", Journal of Magnetism and Magnetic Materials 248 (2002) 441–456.

[14] A. Vadde and S. Sachin, "Influence of Rotor Design in BLDC Motor for Two -Wheeler Electric Vehicle," 2021 1st International Conference on Power Electronics and Energy (ICPEE), 2021, pp. 1-6, doi: 10.1109/ICPEE50452.2021.9358520.

[15] K. Yilmaz, "Comparison Of Axial Flux And Radial Flux Brushless Dc Motor Topologies For Control Moment Gyroscope Wheel Applications", Middle East Technical University, 2009, Ankara, Turkey, 83-88.

[16] S. Yuechao, L. Man, L. Cong, "Analysis of Wheel Hub Motor Drive Application in Electric Vehicles", Matec Web of Conferences, 2017, Vol. 100, p. 01004, doi: 10.1051/matecconf/201710001004.

[17] A. Vadde, S. Schin , "Influence of Rotor Design in BLDC Motor for Two -Wheeler Electric Vehicle", 2021 1st International Conference on Power Electronics and Energy (ICPEE-2021).

[18] K. Ahn, A. E. Bayrak and P. Y. Papalambros, "Electric vehicle design optimization: integration of a high-fidelity interior-permanent-magnet motor model," IEEE Transactions on Vehicular Technology, vol. 64, pp. 3870-3877, 2015.
X. Sun,L. Chen,H. Jiang,Z. Yang,J. Chen,W. Zhang. "High performance control for a bearingless permanent magnet synchronous motor using neural network inverse scheme plus internal model controllers," IEEE Tran. on Indust. Electronics, 2016, 63(6),pp 3479-3488.

[19] Ansys Electronics Desktop/Help, 2022.

[20] M. Çunkaş, R. Akkaya, "Design Optimization of Induction Motor by Genetic Algorithm and Comparison with Existing Motor" Mathematical and Computational Applications, 2006, no.3: pp.193-203. https://doi.org/10.3390/mca11020193.

[21] K.Prasetio, M. Yuniarto,A.Surabaya," Design and Performance Test of Axial Halbach Brushless DC Motor with Power Density 1.5 Kw/Kg Jurnal Teknik Vol. 5 No. 2 , 2016 .

[22] J. Buøy," Development of High-Efficiency Axial Flux Motor for Shell Eco-marathon" , Norwegian University of Science and Technology, 2013.