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Original scientific paper

Comprehensive Analysis of SRM, AFPM BLDC and IM for Light Electric Vehicles

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Abstract: In today's electric vehicle (EV) landscape, the utilization of Switched Reluctance Motors (SRMs), Axial Flux Permanent Magnet Brushless DC Motor (AFPM BLDC), and Induction Motors (IM) has become increasingly prevalent. These types of motors are widely preferred for reducing carbon emissions and their advantages in torque-velocity characteristics. Researchers have been comparing these motor types regarding performance, cost, lifespan, reliability. This study compares the motor behaviour of SRM, AFPM BLDC, and IM under identical output power conditions. Initially, the drive system and the design are conducted to ensure the optimal performance of the motors using the ANSYS program. Subsequently, the efficiency, torque, and currents of the motors are analysed and compared in the context of their application in light EV technology. Finally, the 3D modelling of the motors is obtained using the SolidWorks program, catering to those commercializing the motors. The study will provide a novel and distinctive contribution to the literature by comparing SRM, Axial Flux PM BLDC, and IM motors under identical output power conditions, optimizing motor parameters using a genetic algorithm, evaluating performance parameters through detailed simulations, and presenting SolidWorks 3D models for potential industrial prototyping.

Keywords: analysis; design; efficiency; motors; torque

1 INTRODUCTION

In recent decades, the continued progress of Electric Vehicle (EV) development has led to a situation in which electric motors have become more popular, widespread, and significant. Electric motors are commonly selected for EVs due to their high power density, reliability, and efficiency. Switched Reluctance Motor (SRM), Axial Flux Permanent Magnet Brushless DC Motor (AFPM BLDC), and Induction Motor (IM) are the most preferred in the electric motor family. The SRM, known for its simple structure without windings or permanent magnets in the rotor, has attracted growing interest due to advancements in semiconductor technology. SRM, with its low starting current and high torque characteristics, is well-suited for EV applications that require efficient performance and energy savings [1]. Additionally, it has applications in various fields such as home appliances, wind turbines, robotic systems, and industrial applications [2, 4]. Ansys and MATLAB software programs are predominantly employed for the enhanced optimal design, efficient control, and in-depth performance analysis of SRM [3, 5]. Other than SRM, AFPM BLDCs are a category of motors that deliver exceptional efficiency, high torque-to-weight ratio, and power density, qualities in high demand for EVs, and their popularity has surged due to innovations in magnetic materials. As technology advances, these motors are being fabricated in various configurations, including single stator-single rotor, single stator-dual rotor, single rotor-dual stator, and multi-structure layouts [6-9]. Furthermore, AFPM BLDCs offer several benefits over traditional Radial Flux Permanent Magnets in various applications, including a superior power-to-weight ratio, reduced core material usage, adjustable and planar air gaps, and lower noise and vibration levels [10-12]. The last motor in our comparison is the IMs. They are a popular option for EVs due to their advantages, including a wide speed range, high starting torque, efficient field weakening, and low maintenance [14, 15]. However, they also have some drawbacks, such as considerable losses in the stator and rotor, core losses, and friction losses, which can result in lower efficiency and overheating issues [16]. These challenges can be overcome by optimizing the stator and rotor slot designs, selecting suitable materials and core lengths, and incorporating efficient cooling solutions [17]. Advancements are also present in current studies in the fields of driver systems with motors and battery circuits that supply energy to motors in electric vehicles [27].

The primary contributions of this work are:

- The SRM, AFPM BLDC, and IM motors, whose design parameters are original and optimized using a genetic algorithm (GA), are compared under similar output power conditions in the ANSYS program.
- Evaluation of critical metrics, including torque, efficiency, current, and their implications for EV applications.
- The creation of 3D SolidWorks motor models for potential prototyping or commercializing purposes.
- A discussion on the driver circuits and system optimizations for each motor type.

2 DESIGN OF SRM, AFPM BLDC, AND INDUCTION MOTOR

Three motors were designed with the same power density using the Ansys program. The optimum design parameters and motor structures are provided in Tab. 2 and illustrated in Fig. 1, Fig. 2, and Fig. 3, respectively.

Table 1 GA optimization values

Parameters	SRM	AFPM BLDC	IM
Bounds of Outer Diameter	150-165 mm	150-165 mm	150-165 mm
Bounds of Air Gap	0.4-1.2 mm	0.4-1.2 mm	0.4-1.2 mm
Bounds of Axial Length	80-88 mm	40-50 mm	132-145 mm
Efficiency before Optimization	87.58%	92.91%	88.62%
Efficiency after Optimization	88%	93.25%	89%

The optimization using the GA aimed to achieve maximum efficiency. In electric motor optimization, the GA iteratively evolves a population of candidate designs, evaluating each with a fitness function based on performance metrics, and generating new designs through selection, crossover, and mutation until the optimal motor parameters are obtained [31].

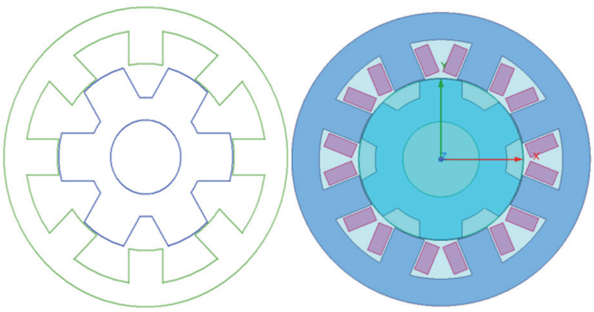
To obtain the optimum values in Tab. 2, the parameters in Tab. 1 were optimized within the given value ranges using GA.

Table 2 Optimum design parameters of SRM, AFPM BLDC and IM

Motor	Parameters	Value
SRM	Rated Power	5 kW
	Speed	2500 RPM
	Voltage	220 V
	Outer Diameter	160 mm
	Air Gap	1 mm
	Axial Length	85 mm
AFPM BLDC	Rated Power	5 kW
	Speed	5000 RPM
	Voltage	100 V
	Outer Diameter	160 mm
	Air Gap	1 mm
	Axial Length	45 mm
IM	Rated Power	5 kW
	Speed	1500 RPM
	Voltage	220 V
	Outer Diameter	160 mm
	Air Gap	1 mm
	Axial Length	140 mm

2.1 SRM

The designed SRM model structures are shown in Fig. 1. It has eight stator poles and six rotor poles. The stator is in the form of a double-layer winding.

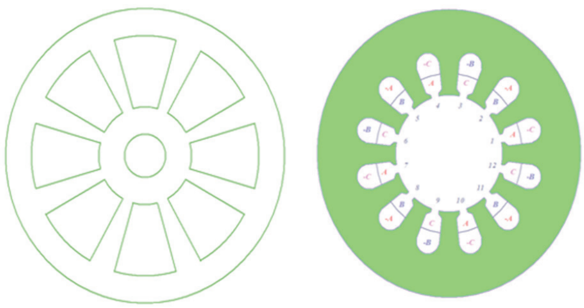


a) Basic structure b) Structure with winding

Figure 1 8/6 SRM Structure

2.2 AFPM BLDC

In this study, a single-stator single-rotor surface-mounted AFPM BLDC motor has been investigated. The investigated AFPM BLDC motor operates at 5 kW, 5000 rpm, and 100 V-rated values [11, 20]. The structure of the 12-slot/8-pole AFPM BLDC motor is shown in Fig. 2.

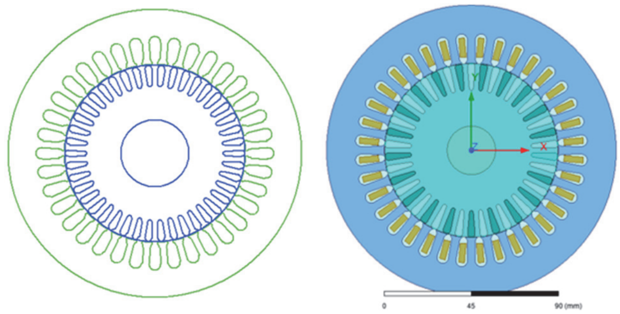


a) Basic structure b) Structure with winding

Figure 2 AFPM BLDC motor structure

2.3 IM

Fig. 3 shows the cross-section of an IM motor designed according to a 4-pole configuration with a power rating of 5 kW. It features 36 stator slots, 42 rotor slots, and one-layer, three-phase, whole-coiled windings with 69 conductors per slot. Additional characteristics of the motor can be found in Tab. 3.



a) Basic structure b) Structure with winding

Figure 3 36/42 IM cross section

3 DRIVERS OF SRM, AFPM BLDC AND IM

The driver circuit details of the motors are given in the following headings.

3.1 Driver Circuit of SRM

An asymmetric bridge converter (ABC) is the most favoured driver circuit for the SRM because of its advantages, such as cost and ease of use [1]. The 8/6 SRM driver is seen in Fig. 4.

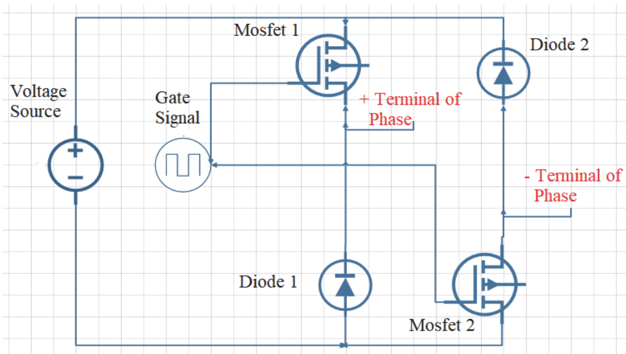


Figure 4 Driver ircuit of 8/6 SRM per phase

3.2 Driver Circuit of AFPM BLDC

Control algorithms play a role in generating the back electromotive force waveform that occurs in the air gap of the BLDC motor. The signals applied to the BLDC motor by the semiconductor driver circuit can be sinusoidal or trapezoidal. When comparing both waveform types, a constant torque can be achieved with a sinusoidal waveform. In the case of a trapezoidal waveform, the size of the inverter and losses decrease at the same power level [21]. The driver circuit of the BLDC motor is shown in Fig. 5.

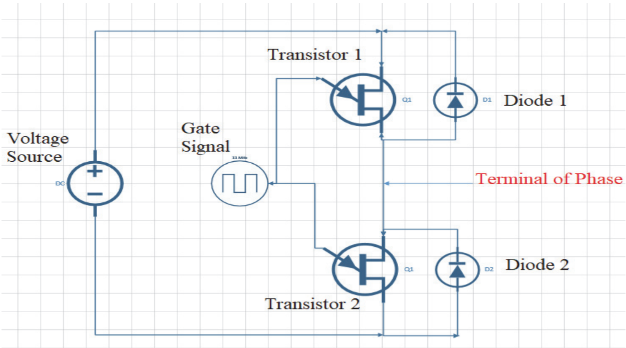


Figure 5 Driver circuit of AFPM BLDC

3.3 Driver Circuit of IM

IMs can be directly powered from an AC network, but an inverter becomes essential when employed in EV applications, necessitating power from battery systems. The drive circuit for IMs typically involves a three-phase bridge inverter, which can be controlled using various modulation strategies such as pulse width modulation, space vector modulation, and space pulse width modulation.

To achieve variable voltage and frequency in three-phase inverters, fixed DC and PWM inverter drive, variable DC and inverter drive, and variable DC from a dual converter and inverter are the preferred circuit arrangements for IM drivers. Fig. 6 shows a 2-level single-phase driver inverter configuration used as the driver circuit for the induction motor [25].

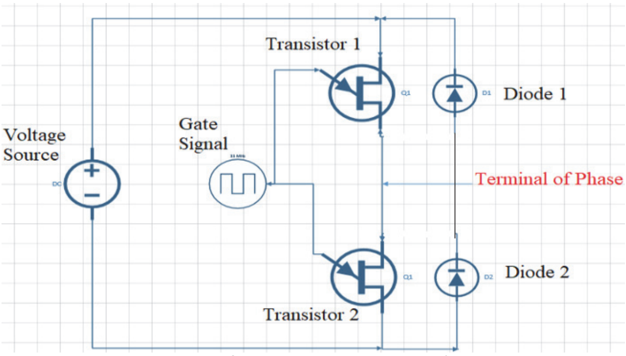


Figure 6 Single phase driver circuit of IM

4 COMPARISON

The driver circuits of BLDC and SRM motors designed with the same power density are different from each other. While looking at the simulation results, differences arising from the drivers were examined. The advantages and disadvantages of both drivers are given in Tab. 3 below [22-24]. The following table was created with the data obtained from the literature review explicitly made for drive systems.

Table 3 Comparison of driver circuits

Motor	Comparison	
	Advantages	Disadvantages
SRM	Simple Switching	High Torque Ripple
	Control of one phase is independent of the other phases	Vibration Noise
	The variable frequency drives	Difficult to Control

Table 3 Comparison of driver circuits - continuation

Motor	Comparison	
	Advantages	Disadvantages
		Expensive
AFPM BLDC	High efficiency	Complex control
	Low maintenance	Torque ripple
	Easy construction	Cost of magnets
	Dynamic response	Operating temperature
IM	Robustness and reliability	Complex control requirement
	Cost-Effectiveness	Low efficiency at low speed
	Simple structure	Poor transient behaviour.
	High starting torque	Operating temperature
	Wide operating range	High starting currents

5 SIMULATION RESULTS

The simulation of the three motors designed under the same output power and speed conditions was conducted using ANSYS RMxprt and 2D software. The simulation was run for 180 milliseconds with steps of 0.5 milliseconds. In the analyses, the load type was selected as constant power. The results of Ansys/Maxwell simulations have been demonstrated with figures and tables in this section. They were analysed and evaluated comprehensively. The behaviour of SRM's currents, torque, and efficiency speed are given in Fig. 7, Fig. 8, and Fig. 9, respectively.

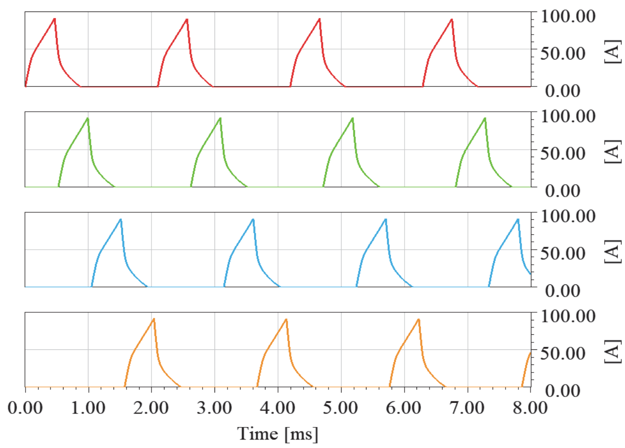


Figure 7 Phase currents of 8/6 SRM

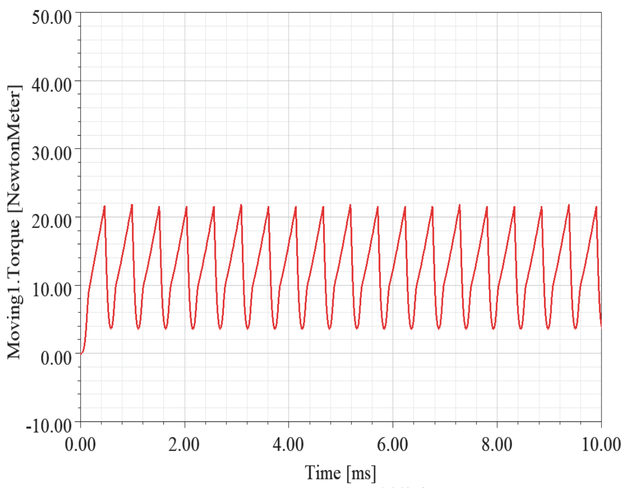


Figure 8 Torque behavior of 8/6 SRM

The current behaviour of the SRM, which is switched according to the turn-on and turn-off angles, is given in Fig. 7. There are always 2 phases energized about 5 ms.

SRM, which can reach high torque values due to its reluctance feature, exhibits a torque performance with a 28.6 SI ripple rate, reaching a max of 8.75 Nm torque in Fig. 8.

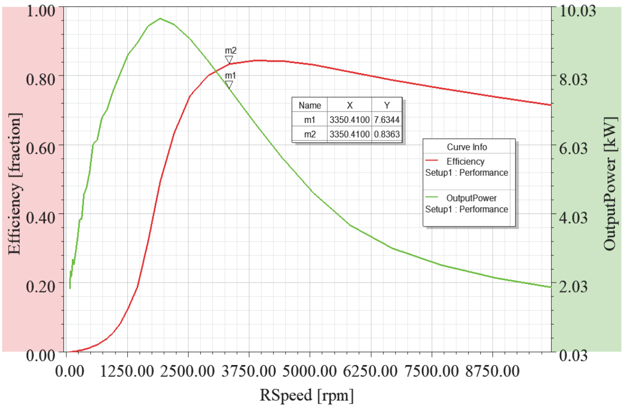


Figure 9 Efficiency-speed graph of 8/6 SRM

SRM, which has high copper losses, has an efficiency of 80% in Fig. 9.

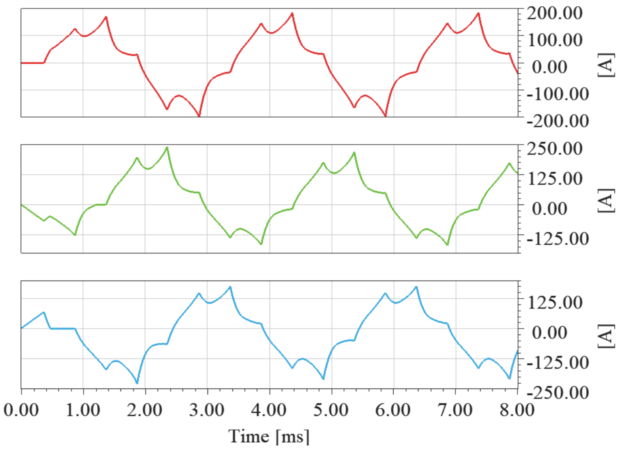


Figure 10 Phase currents of AFPM BLDC motor

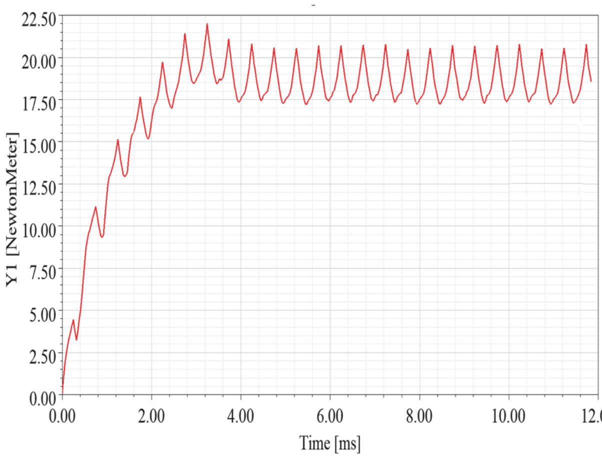


Figure 11 Torque behavior of AFPM BLDC motor

Considering the number of windings and phases, it is a typical result that the efficiency is at this rate. It is observed that at the nominal speed of 3500 rpm, In Fig. 10, the graph depicts the winding current of the AFPM BLDC motor. The current of phase C (blue) is in the positive alternation, the current of phase B (green) is in the negative alternation, and the current of phase A (red) is in the positive alternation 0.36 ms later. The high peak points of the winding currents cause torque fluctuations.

In Fig. 11, the torque-speed graph of the BLDC motor is shown. After reaching a steady state, fluctuations of approximately 3 Nm occur every 0.50 ms in the torque graph.

The efficiency-speed graph (red line) and output power-speed graph (green line) of the AFPM BLDC motor are shown in Fig. 12. It is observed that at the nominal speed (5000 rpm), the efficiency value is approximately 94.70 percent, and the output power is 4990 watts.

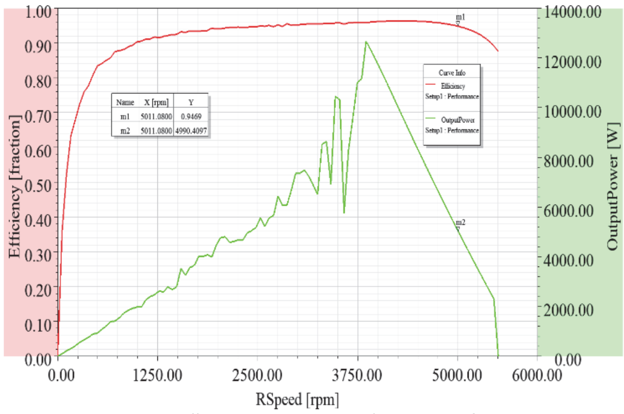


Figure 12 Efficiency-speed graph of AFPM BLDC motor

Fig. 13 shows the three-phase current of the stator of the IM under full load conditions. In the transient state, the motor draws a high stator current and reaches a steady state after 0.65s, with a maximum phase current of 14 A. It affects the torque behavior, as in Fig. 14.

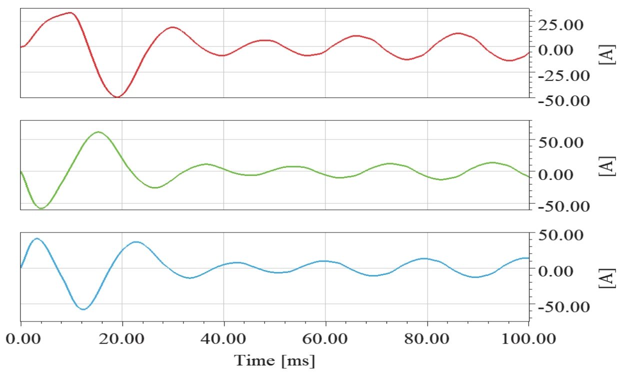


Figure 13 IM stator currents behavior

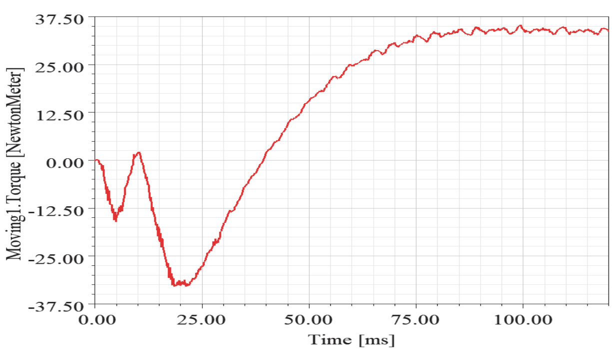


Figure 14 IM torque behavior

Fig. 14 illustrates the dynamic behavior of the IM torque, recorded at 32.9 Nm with a ripple of 16% in the steady state.

Fig. 15 indicates the output power and efficiency characteristics of the IM. It can be seen that the maximum efficiency of the designed 5 kW motor is 89%. It is observed at the nominal speed of 1460 rpm. In addition to the simulation results at a constant speed, constant power, and constant torque simulations were also performed. The results of these analyses are given in Tab. 4.

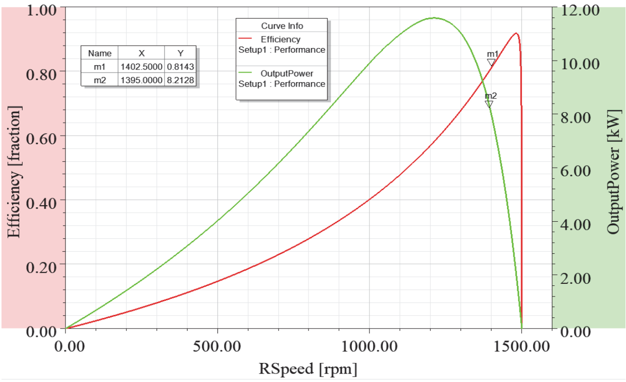


Figure 15 IM output power and efficiency characteristics

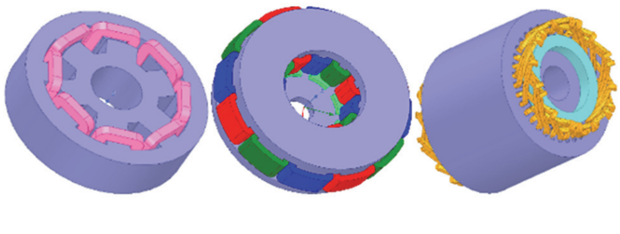
The analysis results also support the references [12, 23, 28, 29], particularly regarding the superior characteristics of the motors in their comparative evaluation. SRM has high torque but low efficiency, AFPM BLDC offers high efficiency and IM is durable and cost-effective. In [30] BLDC motor's efficiency of 91.9%, while the SRM's efficiency of 94.6%. The torque ripple of the BLDC motor was significantly lower (0.73 pu) compared to the SRM (1.19 pu).

Table 4 Comparison of simulation

Motor	Parameter	Comparison		
		Load Type: Constant Power	Load Type: Constant Speed	Advantages and Disadvantages
SRM	Average Input Current	48 A	48 A	+ + +
	Average Torque	12 Nm	12 Nm	+ + + +
	Efficiency	88%	88%	+ + +
	Torque Ripples	28.61 SI	28.61 SI	+
AFPM BLDC	Average Input Current	53.62 A	53.62 A	+ + +
	Average Torque	9.55 Nm	9.55 Nm	+ + +
	Efficiency	93.25%	94.35%	+ + + +
	Torque Ripples	22.67 SI	22.67 SI	+ + +
IM	Average Input Current	14 A	14 A	+ + +
	Average Torque	10 Nm	10 Nm	+ +
	Efficiency	89%	89%	+ + +
	Torque Ripples	18 SI	18 SI	+ + +

6 SOLID MODELS

The 3D models of the motors analyzed in Ansys were also drawn in the Solid Works program because in industry, companies that will produce electric motors need 3D solid work files [18, 19]. The solid works models of SRM, AFPM BLDC, and IM are shown in Fig. 16. Solid Works project files are also given in [26].



a) SRM b) AFPM BLDC c) IM

Figure 16 Solid models of SRM, AFPM BLDC, and IM, respectively

7 CONCLUSION

This study presents a concise comparison of SRM, AFPM BLDC, and IM for light EVs, emphasizing their efficiency, torque, and operational parameters. Motor parameters were optimized using a GA, and detailed ANSYS simulations were performed to provide a quantitative evaluation of performance metrics such as torque, current, and efficiency. 3D SolidWorks models of all motors were generated to facilitate industrial prototyping and practical applications. It was observed that SRM has high torque but low efficiency, AFPM BLDC is efficient and power-dense but costly, and IM is robust but less efficient at low speeds. Simulation results show that the AFPM BLDC achieved the highest efficiency at 93.25%, followed by the IM at 89% and the SRM at 80%.

Overall, the study provides novel insights into motor selection and design, and contributes both practical and scientific value to the field of light EV motor technologies. In future studies, more detailed comparisons can be conducted, particularly using advanced optimization and AI-based control methods, as well as addressing varying load conditions, thermal behavior, material improvements, multi-objective optimization, lifetime and reliability, renewable energy integration, and fault-tolerant control.

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