Comparison of Permanent Magnet Electric Motors Used in Electric Vehicles

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***Abstract*—Lately, PM (permanent magnet) motors have started to be used frequently due to advantages such as high efficiency, high power density, high torque, lower losses, lower magnet costs, and more effective control with the development of power electronics. PMSM (permanent magnet synchronous motor) types and BLDCM (brushless direct current motor) types, two members of PM motors, have become frequently used motors in electric vehicles (EVs). In this study, PMSM and BLDCM are compared by optimizing magnet thicknesses, structures, and stator winding turn numbers, to improve the efficiency, using ANSYS Maxwell and ANSYS RMxprt software. In the study, surface mount magnet synchronous motor SPMSM with the inner rotor, V-shaped PM inner rotor IPMSM (interior permanent magnet synchronous motor), BLDCM with inner rotor embedded channel mount magnet, BLDCM with inner rotor embedded magnet, BLDCM with inner rotor surface mount magnet and BLDCM with outer rotor are compared.**

Keywords— EV, surface PM, embedded PM, channel PM, outer rotor, inner rotor, PMSM, BLDCM.

I. INTRODUCTION

In today's electric vehicle industry, PM motors are used mostly, they have permanent magnets so they don't need additional excitation. Unlike conventional DC motors, brushless DC motors do not have brushes for commutation, so their efficiency is high [1]. Thus, the rotor length is reduced and the motor can be made in smaller sizes [2]. In addition, since the rotor weight is reduced, the moment of inertia is low and the motor with a higher Torque/volume ratio can be obtained. In asynchronous motors, copper losses on the rotor bars and end rings reduce efficiency. As the load increases, the slip becomes larger, and consequently the losses increase [3]. PMSM and BLDCM work at synchronous speed, there is no slippage. There is no friction, which is caused by the ring in the induction motors and brushes in brushed DC motors respectively. In addition, arc and noise excess is not observed in PM motors. Moreover, brushes in the conventional DC motors limit the maximum speed due to the friction [4]. PMSM and BLDCM, which are the most advanced motors, will become much more efficient with the development of better magnets and optimal design considerations. The main difference between PMSM and BLDCM is that while PMSM has sinusoidal supply and sinusoidal back emf, BLDCM has a square wave excitation and trapezoidal back emf. Both motor types are in the synchronous machine category. The main reason for using these motors in this study is that they have PMs and PM motors are the most preferred motor type by EV manufacturers due to speed/torque characteristics, high efficiency, high dynamic response, and small size construction [3],[5]. Motor performance can be improved by optimizing rotor and stator diameters, slot structure, steel material, magnet type, and magnet spacing [6].

In the literature, there have been examining the effects of different rotor types on PM motor design [7]. There is a study in which optimization studies of IPMSM with V-shaped permanent magnets are performed [8]. The effects of slot type, magnet type, and pole structure on PM motors are investigated [9]. The motor selection was made by taking advantage of the advantages and disadvantages to cover many electric motors [10]. Synchronous reluctance motors have been compared with IPMSM. Various IPMSMs have been compared [11]-[14]. In another study, PMSMs were compared with induction motors [15]-[16].

In this study, PMSM and BLDCM are compared on the same basis by taking the same volume, same torque/volume, same winding type, length of PM, and some other parameters (see Table I) to obtain the highest efficiency among the motors. Using ANSYS Maxwell and ANSYS RMxprt the best results have been obtained by optimizing, the length and width of PM, stator-rotor steel, and winding structure. [3],[6]. Although similar studies on EVs are found in the literature, this study differs from other comparisons in terms of both its multi-objective comparison and the type of motors compared. While larger motors than we used in our study can be used in vehicle traction systems, smaller motors can be used to provide vehicle equipment movements.

II. MATHEMATICAL MODEL OF MOTOR STRUCTURE

A. PMSM main equations

PMSM main equations can be written depending on the d axis λ_d and q axis λ_q fluxes as follows:

$$\left.\begin{aligned}\frac{d\lambda_d}{dt} &= V_d - R_s.i_d + w_e.\lambda_q \\ \frac{d\lambda_q}{dt} &= V_q - R_s.i_q - w_e.\lambda_d\end{aligned}\right\} \quad (1)$$

D axis i_d and q axis i_q currents:

$$\left.\begin{aligned}i_d &= \frac{\lambda_d - \lambda_{af}}{L_d} \\ i_q &= \frac{\lambda_q}{L_q}\end{aligned}\right\} \quad (2)$$

Electromagnetic Torque T_e

$$T_e = \frac{3}{2}.\frac{P}{2}.\left[\left(\lambda_d.i_q\right) - \left(\lambda_q.i_d\right)\right] \quad (3)$$

Rotor mechanical angular speed w_m

$$\frac{d}{dt}w_m = \frac{\left(T_e - T_L - B.w_m\right)}{J} \quad (4)$$

Rotor electric angular speed w_e , rotor rpm n_r

$$\left.\begin{aligned}w_e &= w_m\frac{P}{2} \\ n_r &= w_m\frac{30}{2\pi}.P\end{aligned}\right\} \quad (5)$$

B. BLDCM main equations

BLDCM three phase main equations can be written as follow:

$$\begin{bmatrix}V_a\\V_b\\V_c\end{bmatrix} = \begin{bmatrix}R&0&0\\0&R&0\\0&0&R\end{bmatrix}.\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}L-L_m&0&0\\0&L-L_m&0\\0&0&L-L_m\end{bmatrix}\frac{d}{dt}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}e_a\\e_b\\e_c\end{bmatrix} \quad (6)$$

Where $R, L\ and\ L_m$ are the stator resistance, inductance and mutual inductance respectively. Electromagnetic Torque T_e is given as follow:

$$T_e = \frac{\left(e_a.i_a + e_b.i_b + e_c.i_c\right)}{w_m} \quad (7)$$

Where $e_a, e_b, and\ e_c$ are a, b and c phase electromotive force (emf). The rotor mechanical equations are the same as (4) and (5).

III. Modelling and Comparison of BLDCM and PMSM Types

The stator, rotor and PM structures of the motors which are used in this study are shown as below from Fig. 1. to Fig. 5.

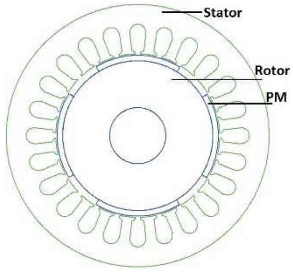


Fig. 1. SPMSM and BLDCM inner rotor surface PM.

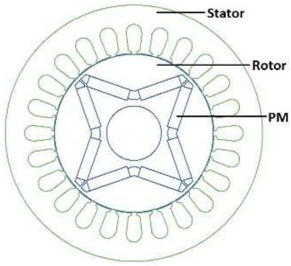


Fig. 2. IPMSM inner rotor V-shaped embedded PM.

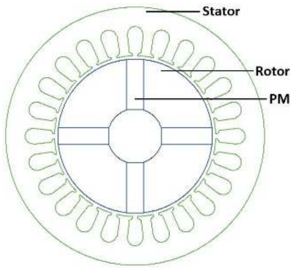


Fig. 3. BLDCM inner rotor channel mount embedded PM.

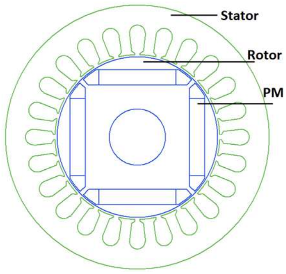


Fig. 4. BLDCM inner rotor embedded PM.

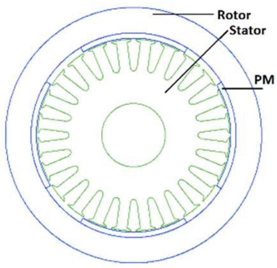


Fig. 5. BLDCM outer rotor surface mount PM.

All of these 6 (In Fig.1 two motor structures are shown in the same picture only their terminal voltages differ) motor types used in the comparison are shown from Fig. 1. to Fig. 5. The stator outer diameter and axial length are taken to ensure that the volumes $(\pi(\frac{D_{outer}}{2})^2 L$ of all motors are equal. Friction and ventilation losses are assumed to be equal in all motors. The outer rotor BLDCM rotor diameter is taken as indicated in Table I.

The PM geometry of the motors was determined using regression analysis, taking into account the maximum efficiency.

Table I shows input parameters for the motors and motor parameters that have been taken the same.

TABLE I. INPUT PARAMETERS

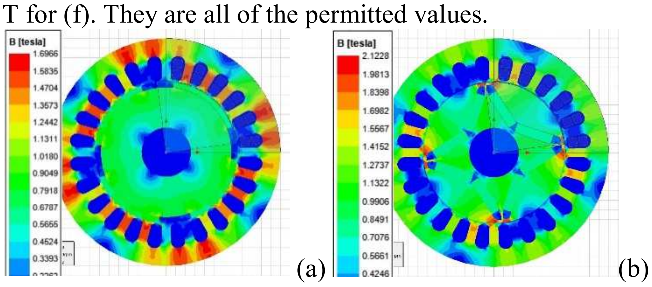
INPUT	SPMSM	IPMSM	BLDCM	BLDCM	BLDCM	BLDCM	Unit
Rotor Position	Inner Rotor	Inner Rotor	Inner Rotor	Inner Rotor	Inner Rotor	Outer Rotor	
Magnet Position	Surface	Interior	Channel	Embedded	Surface	Surface	
Number of Poles	4	4	4	4	4	4	
Frictional Loss	10	10	10	10	10	10	Watt
Windage Loss	2	2	2	2	2	2	Watt
Reference Speed	1500	1500	1500	1500	1500	1500	rpm
Control Type	PWM	AC	DC	DC	DC	DC	
Circuit Type	Y3	Y3	Y3	Y3	Y3	Y3	
Stator Outer Diameter (D_{so})	120	120	120	120	120	90[a]	mm.
Stator Inner Diameter (D_{si})	75	75	75	75	75	30	mm.
Stator Length (L)	150	150	150	150	150	150	mm.
Stator Stacking Factor	0.95	0.95	0.95	0.95	0.95	0.95	
Stator Steel Type	M19_24G	M19_24G	M19_24G	M19_24G	M19_24G	M19_24G	
Stator Number of Slots	24	24	24	24	24	24	
Stator Slot Type	2	2	2	2	2	2	
Stator Skew Width	0	0	0	0	0	0	
Rotor Outer Diameter (D_{ro})	74	74	72	73	74	120	mm.
Rotor Inner Diameter (D_{ri})	26	26	26	26	26	91	mm.
Rotor Length	150	150	150	150	150	150	mm.
Rotor Steel Type	M19_24G	M19_24G	M19_24G	M19_24G	M19_24G	M19_24G	
Rotor Stacking Factor	0.95	0.95	0.95	0.95	0.95	0.95	
Rotor Magnet Type	XG196/96	XG196/96	XG196/96	XG196/96	XG196/96	XG196/96	
Load Type	Const. Power	Const. Power	Const. Power	Const. Power	Const. Power	Const. Power	
Rated Output Power	1200	1200	1200	1200	1200	1200	Watt
Rated Voltage	225	220	370	524	472	530	Volt
Rated Speed	1500	1500	1500	1500	1500	1500	rpm
Operating Temperature	75	75	75	75	75	75	°C

[a] Rotor outer diameter is taken same.

IV. DISCUSSION AND RESULT

In this study, except for outer rotor PM, the stator structure is taken as identical. In general, outer volume, torque/volume, stator-rotor material, PM material, length of PM, and air gap length have been taken the same. Fig. 6. (a), (b), (c), (d), (e), and (f), the flux densities (B) increase in all motors where the magnets are closest to the stator windings.

The flux densities in motors have their scales. Maximum flux density is shown dark red 1.69 T for Fig.6 (a), and 2.12 T for (b) 1.89 T for (c)and 2.2T for (d), It is 1.68 T for(e) and 1.8 T for (f). They are all of the permitted values.



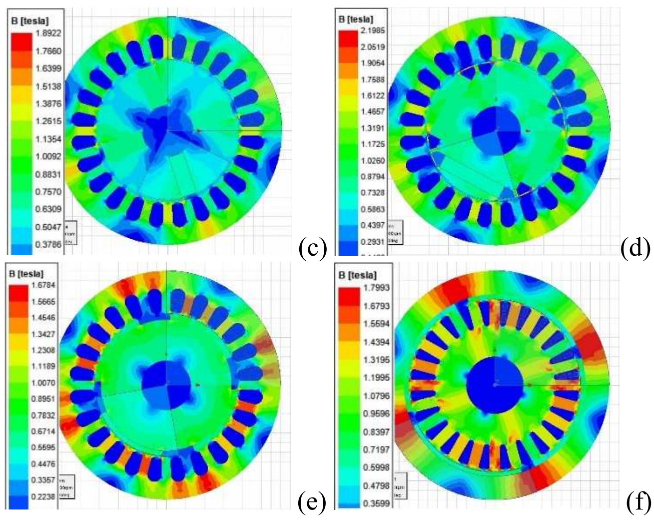


Fig. 6. SPMSM inner rotor surface magnet flux density (a). IPMSM inner rotor V-shape embedded magnet flux density (b). BLDCM inner rotor embedded channel mount magnet flux density (c). BLDCM inner rotor embedded magnet flux density (d). BLDCM inner rotor surface magnet flux density (e). BLDCM outer rotor flux density (f).

Figure 7 shown the B-H curve of the steel (M19_24G) we use at rotor and stator. The curve from the data point is shown red.

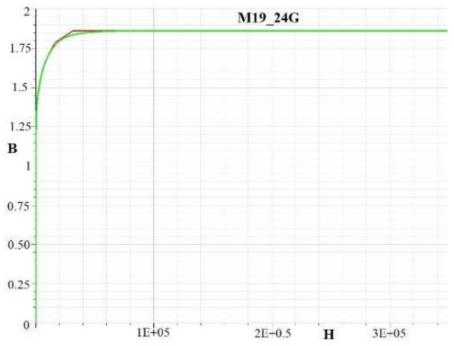


Fig. 7. B-H curve of the steel (M19_24G).

From Fig. 8. to Fig. 13. the motor torque curves are shown.

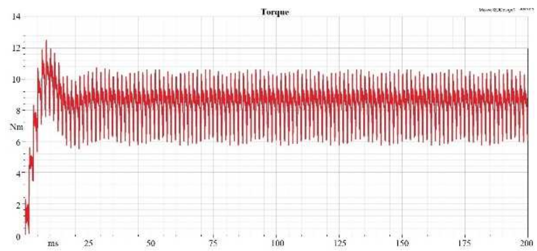


Fig. 8. SPMSM inner rotor surface magnet torque curve.

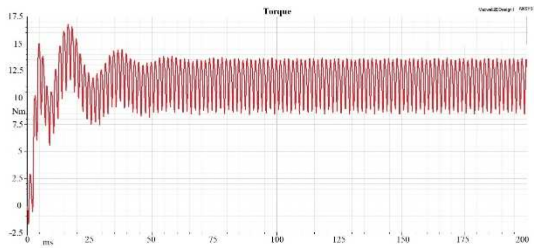


Fig. 9. IPMSM inner rotor V-shape embedded magnet torque curve.

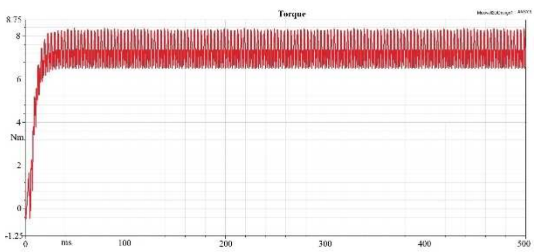


Fig. 10. BLDCM inner rotor channel mount magnet torque curve.

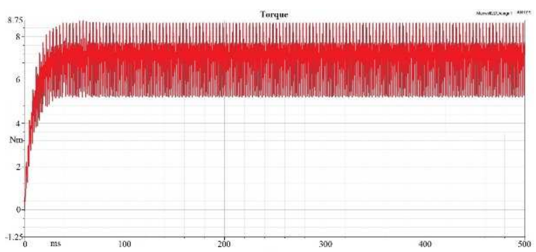


Fig. 11. BLDCM inner rotor embedded magnet torque curve.

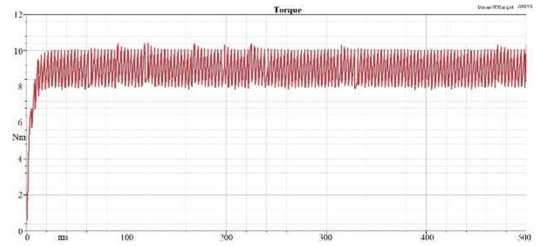


Fig. 12. BLDCM inner rotor surface magnet torque curve.

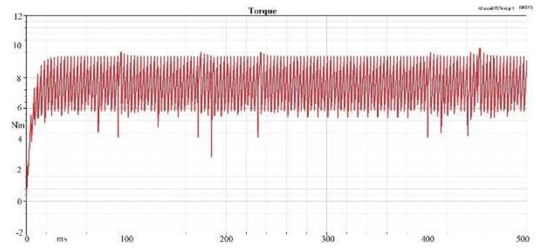


Fig. 13. BLDCM outer rotor torque curve.

The motor with the least torque ripple is surface magnet BLDCM with 12.56%. Fig. 14 summarizes the torque ripple.

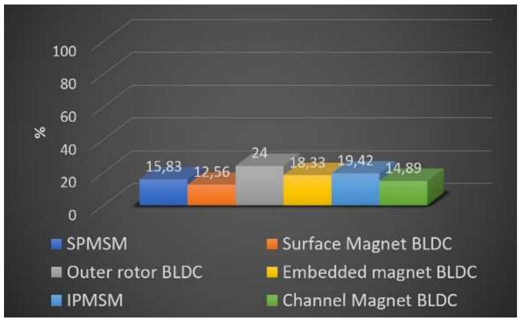


Fig. 14. Torque ripple comprasion.

A comparison of the air gap flux density (B) is shown in Fig. 15. since surface magnet rotors are closer to the stator winding, the air gap flux density is higher (0.68 T and 0.66 T), and it is less in embedded magnet motors.

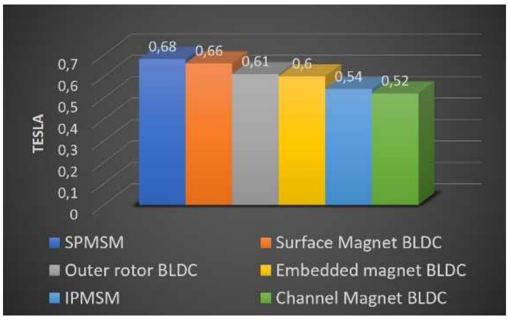


Fig. 15. Air gap flux density comprasion.

In Fig. 16. armature thermal loads at full load are compared and shown. The motor with the least thermal load was the outer rotor BLDCM with a value of 34.19 A^2/mm^3. This motor was followed by SPMSM, IPMSM, surface mount BLDCM, channel mount BLDCM and embedded magnet BLDCM.

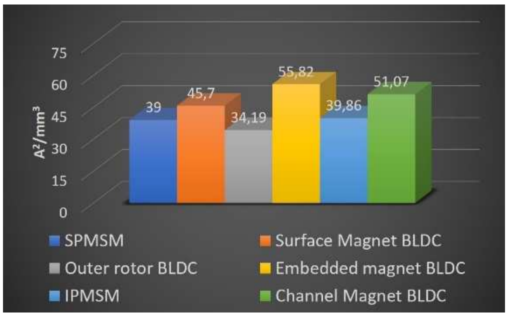


Fig. 16. Armature thermal load comprasion.

Fig. 17. compares the cost of PM motors. Since PMs are the most important factor affecting the cost of PM motors, the total amount of magnets used in the motor has been evaluated [13].

The minimum magnet is 0.5 kg. with SPMSM and surface magnet BLDCM. These two motors are followed by outer rotor BLDCM, channel mount embedded magnet BLDCM, V-shape embedded magnet IPMSM, and embedded magnet BLDCM. According to these data, it is possible to use less magnets in motors with surface mount magnets. Since the embedded magnets are far from the stator, it is necessary to use more magnets, but there are two important advantages to embedded magnet motors.

- At high rotor speeds, the back emf generated in the stator windings is less due to the embedded magnets, so embedded magnets may be preferred more in high-speed motors. As the rotor speed increases, the back emf increases [14].
- Demagnetization strength of embedded magnets is higher than surface mount magnets [14].

In addition, since the magnets in these motors are embedded in the rotor, they are more protected against swinging and breaking compared to surface mount magnets.

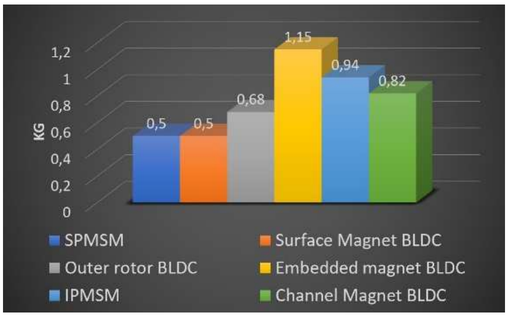


Fig. 17. PM weight comprasion.

Fig. 18. compares electrical loading of PM motors. The minimum electrical loading was 8.31 A/mm with outer rotor BLDCM. This is followed by SPMSM, IPMSM, surface magnet BLDCM, embedded magnet BLDCM and channel mount embedded magnet BLDCM. High electric loading indicates more current flow, which will cause more heat generation inside the motor. The most advantageous motor type in this regard is the outer rotor BLDCM.

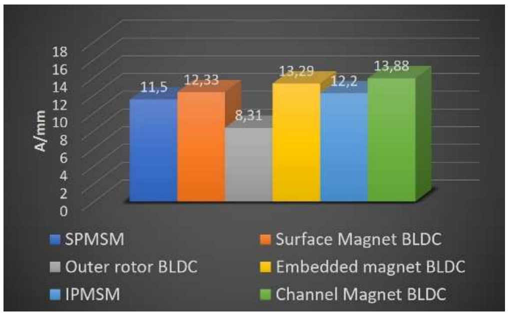


Fig. 18. Specific electric loading.

In terms of efficiency, when the motors with the same volume, same torque/volume, and other same parameters indicated in Table I are compared, the most efficient motor is IPMSM with V-shape magnets with 93.21%. One of the most important reasons for this result is that the stator-rotor flux bond of IPMSM with V-shape magnets is realized with a much more efficient structure and shape compared to other motors. That's why; V-shape IPMSM has higher reluctance torque than other motor types. Efficiency is also higher than 90% for other motors. This is followed by outer rotor BLDCM, SPMSM, surface mount magnet BLDCM, channel mount embedded magnet BLDCM and embedded magnet BLDCM, respectively [14],[15]. This situation is shown in Fig. 19. The V-shaped embedded magnet IPMSM creates an effect similar in shape to the contribution of the barriers (cavities) to the flux distribution in synchronous reluctance motors. Because the most ideal linkage is achieved by placing the magnets at approximately these angles. The idea of filling the barriers in synchronous reluctance motors with permanent magnets is based on this fact. It is possible to design more efficient and higher torque motors by combining the advantage of the rotor made of iron material in the synchronous reluctance motor with the advantage of permanent magnets.

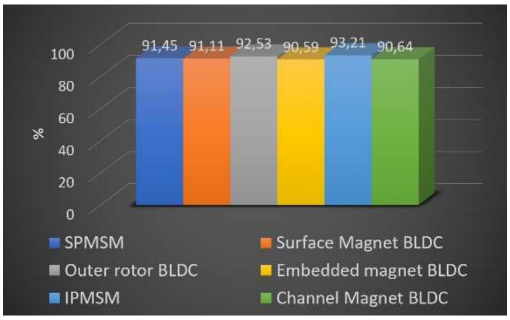


Fig. 19. Efficiency of motor comprasion.

The motor with the highest average torque was IPMSM with 11.49 Nm. Fig. 20 summarizes the average torque.

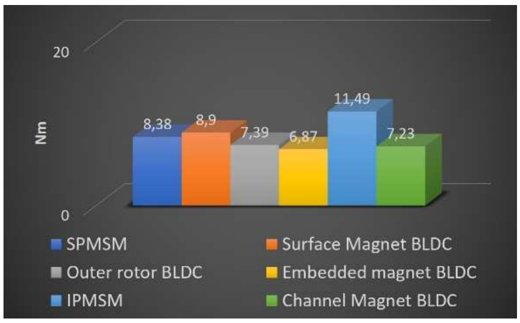


Fig. 20. Average torque of motor comprasion.

In general, the output data at full load is given in Table II.

TABLE II. OUTPUT PARAMETERS

OUTPUT FULL LOAD DATA	SPMSM	IPMSM	BLDCM	BLDCM	BLDCM	BLDCM	Unit
Rotor Position	Inner Rotor	Inner Rotor	Inner Rotor	Inner Rotor	Inner Rotor	Outer Rotor	
Magnet Position	Surface	Interior	Channel	Embedded	Surface	Surface	
Iron-Core power Loss	17.92	21.84	38.99	38.76	41.38	31.21	Watt
Copper power Loss	44.24	53.55	57.92	63.32	51.84	43.18	Watt
Transistor Loss	30.52	0	14.48	10.29	11.36	10.03	Watt
Diode Loss	7.56	0	0.54	0.46	0.55	0.47	Watt
Total Loss	112.23	87.39	123.97	124.87	117.14	96.94	Watt
Armature Thermal Load	39	39.86	51.07	55.82	45.7	34.19	A^2/mm^3
Specific Electric Loading	11.5	12.2	13.88	13.29	12.33	8.31	A/mm
Output Power	1200.32	1200	1200	1202.19	1200.15	1200.25	Watt
Input Power	1312.55	1287.36	1323.88	1327.05	1317.3	1297.2	Watt
Efficiency (%)	91.45	93.21	90.64	90.59	91.11	92.53	
Rated Speed	1500	1500	1504	1503	1501	1505	rpm

V. CONCLUSION

In this study, the following results have been obtained at 1.2 kW and 1500 reference rpm for PM motors, considering efficiency by using ANSYS/RMxprt software.

- The most efficient motor is IPMSM with V-shape embedded magnets with 93.21%.
- In DC control motors, the most efficient motor is the outer rotor BLDCM with an efficiency of 92.53%.
- SPMSM had the least iron loss with 17.92 W.
- The least copper loss was 43.18 W with outer rotor BLDCM.
- The least transistor and diode loss is “0” watt and IPMSM with V-shaped embedded magnets. Because the stator windings are fed with a 3~AC with phase difference without using a controller in this motor.
- Minimum electrical loading is 8.31 A/mm. It is realized with outer rotor BLDCM.
- When the designed motors were transferred from the ANSYS/RMxprt software to the ANSYS/Maxwell software, the highest torque is obtained from the V-shape embedded magnet IPMSM with 11.49 Nm and the minimum torque is obtained by the embedded magnet BLDCM with 6.87 Nm.
- highest torque is obtained from the V-shape embedded magnet IPMSM with 11.49 Nm and the minimum torque was obtained by the embedded magnet BLDCM with 6.87 Nm.
- The motor with the least torque ripple is surface magnet BLDCM with 12.56%.
- As PMs influence the cost, the embedded magnet BLDCM with the heaviest PM is the most expensive motor. This study will help the motor designers and researchers to compare the PM motors selection for electric vehicles initially.

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