Landscaping and Review of Traction Motors for Electric Vehicle Applications

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***Abstract*- With increasing penetration of electric vehicles, electric motor technologies have also seen rapid evolution. This paper reviews and provides a landscape of several topologies of traction motors employed in electrical vehicle traction applications. An emphasis has been made to showcase trends in volumetric power density and gravimetric power density of traction motors since they directly affect end product weight, packaging, and efficiency. A study and classification of motor topologies based on permanent magnet use, the location of the permanent magnets inside the motor, magnetic and reluctance components of torque, and design trends in rotor and stator have been discussed. Several key Original Equipment Manufacturers (OEM) products have been used in this analysis and thus, the paper provides a useful reference for understanding the product evolution and forecasting future trends.**

I. Introduction

The current state of the art of traction motors has been reviewed in this section. A handout [1] from the U.S. Department of Energy (DoE) has listed key targets for traction motor and Power Electronics Inverter Module (PIM) of the electric drive system for the years 2020 and 2025 have been shown in TABLE 1.

TABLE 1: DoE targets for Traction Motor and PIM

DoE Targets	Cost ($/kW)		Power Density (kW/L)	
	2020	2025	2020	2025
Traction Motor	4.7	3.3	5.7	50
PIM	3.3	2.70	13.4	100

Design matrices of traction motors employed in electric vehicles have been reviewed in several papers. Comparison of technical characteristics of traction motors employed in several types of electric vehicles has been discussed in previous literature [2]. The differences between AC motors, DC motors and their suitability towards electric vehicle traction applications and their adoption in battery-operated electric vehicles and hybrid electric vehicles have been evaluated in the existing literature. A comprehensive data of drive cycle

TABLE 2: Specifications of Commercially Available Traction Motors

	EV Type	Motor Type	Power (kW)	Torque (N.m)	Speed (peak RPM)	VPD (kW/L)	GPD (kW/kg)
Jaguar I-Pace 2019 [6]	BEV	PMSynRM	294	696	13000	6.37	7.73
Nissan Leaf 2019 [6][17]	BEV	PMSynRM	110	320	10400	2.619	-
Tesla M3 2018 [6]	BEV	PMSynRM IM	Rear:285 Front: 145	750 (total)	18100	Rear: 10.27 Front: 8.977	Rear:9.21 Front:6.22
Chevy Bolt 2017 [7]	BEV	PMSynRM	150	360	8810	3.49	4.44
Toyota Prius 2017 [8]	PHEV	PMSynRM	53	-	17000	5.7	5.69*
Audi e-Tron SUV 2016 [8]	PHEV	IM, IM	Front: 135 Rear: 165	Front: 309 Rear: 355	6000	-	-
BMW i3 2016 [8]	BEV	PMSynRM	125	250	11400	9.1	3.58
Chevy Volt 2016 [8]	PHEV	PMSynRM	112	400	-	-	3.07
Cadillac CT6 2016 [9]	PHEV	IPMSM	2x75	-	-	-	-
Honda Accord 2014 [4]	HEV	IPMSM	125	110	8000	8.5	2.9
Chevy Spark 2014 [7]	BEV	PMSynRM	-	540 (peak)	4500	-	-
Nissan Leaf 2012 [9]	BEV	PMSynRM	80	280	10390	-	1.42
Sonata HSG 2012 [8]	HEV	IPMSM	30	45	15000	7.42	1.9
Toyota Prius 2010 [8]	HEV	IPMSM	60 (peak)	207 (peak)	13500	4.8	1.6
Lexus 2008 [8]	HEV	IPMSM	110 (peak)	300 (peak)	10230	6.6	2.5
Toyota Camry 2007 [8]	HEV	IPMSM	70 (peak)	270 (peak)	14000	5.9	1.7
Honda Accord 2006 [8]	HEV	IPMSM	12.4	136	6000	--	-
Toyota Prius 2004 [8]	HEV	IPMSM	50	400	6000	3.3	1.11
Nissan Hypermini 2003 [8]	FCEV	IPMSM	24	130	6700	-	0.4
GM EV1 1999 [22]	BEV	IM	102	149	7000	-	-

*hybrid system net power density, IM: Induction Motor

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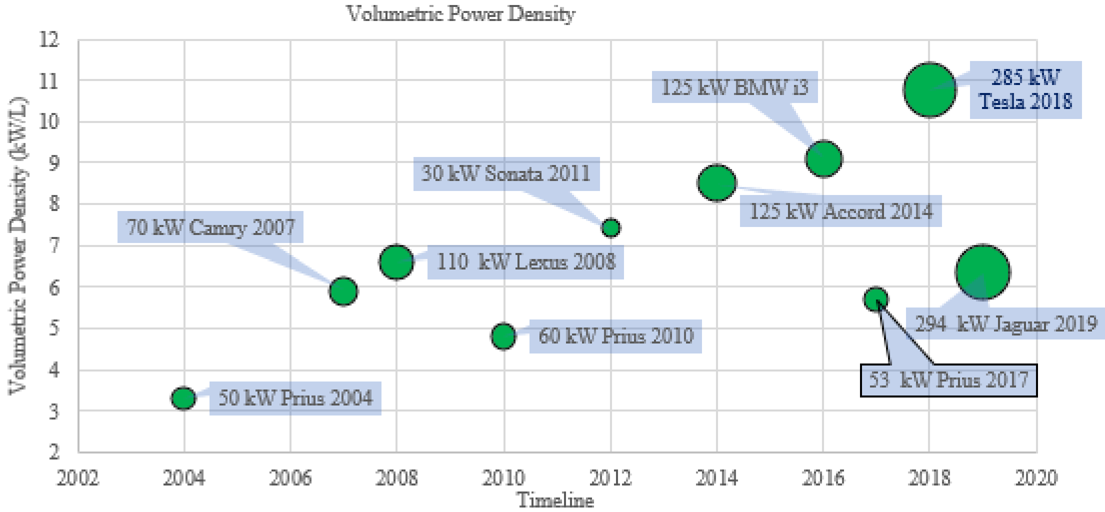


Figure.1. Trend in volumetric power density of commercially available traction motors from the year 2004 to 2020.

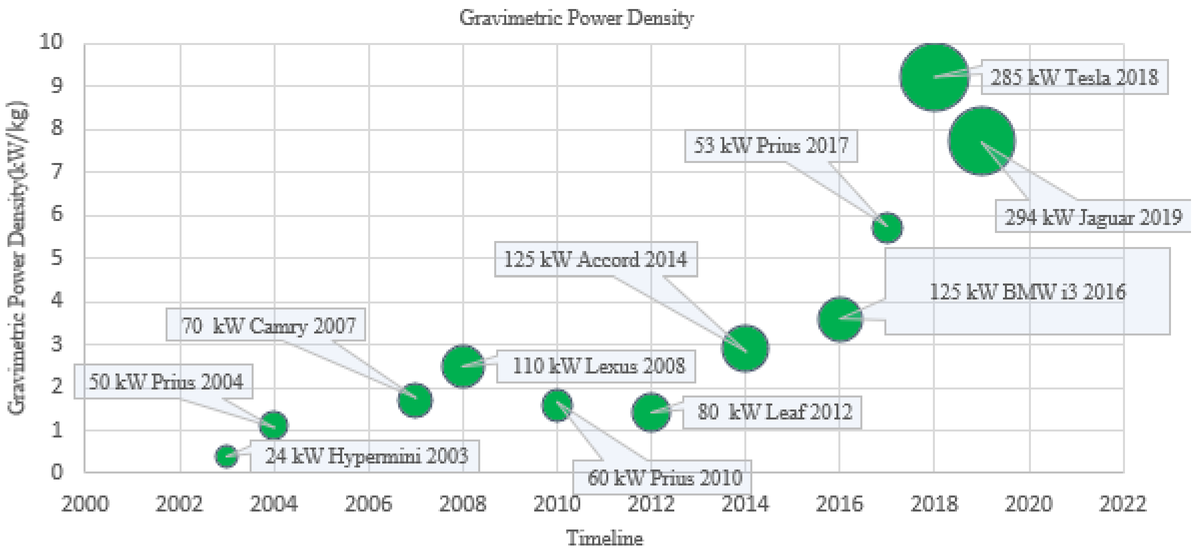


Figure.2. Trend in gravimetric power density of commercially available traction motors from the year 2003 to 2020.

capabilities of different traction motors have been reviewed in several papers [4] [23] consists of the comparison of synchronous motors, internal permanent magnet synchronous motors, and induction motors. The efficiency and cost factors of DC motors, induction motors, switched reluctance motors, permanent magnet-based motors, and flux switching motors for traction applications have been reviewed in another paper [5]. However, the existing literature review of different topologies of traction motors is not extensive and design matrices have not been profiled. A study of torque capabilities of several types of permanent magnet synchronous motors employed in traction applications has been reviewed in this paper. Volumetric power density and gravimetric power density of traction motors have been profiled. An extensive list of specifications of traction motors used in Battery Operated Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), Plugin Hybrid Electric Vehicles (PHEV), and Fuel Cell Electric Vehicles (FCEV) have been listed in TABLE 2. Permanent Magnet Assisted Synchronous Reluctance Motor (PMSynRM), Induction Motor (IM), and Internal Permanent Magnet Synchronous Motor (IPMSM) are popular among electric vehicle traction applications.

Wound field induction motors are known for poor power factor and low power density because of the presence of copper winding on the rotor in addition to the stator of the motor. Classical wound field machines have been designed to operate from pure AC may often need power electronic converters to control speed and torque. The field winding is eliminated by inclusion of permanent magnets in the electric motors come with the advantages of high volumetric power density (VPD) and gravimetric power density (GPD). Improvement in power factor, high torque per Ampere capability and extended constant speed region operation of permanent magnet motors fit them well for electric vehicle traction applications.

Permanent magnet motors cannot be operated from direct AC and the presence of power electronic converters is unavoidable to initiate the operation of the motor. However, speed and torque control of induction motor is much simpler compared to permanent magnet-based motors may still find it as one of the suitable candidates for electric vehicle traction applications. A trend in VPD in kW/L and GPD in kW/kg of the traction motors to timeline has been shown in figure.1 and figure.2. The area of the bubble in the graphs is proportional to the power rating of the traction motor. High VPD and GPD have been observed in battery-operated electric vehicles (BEV). A trend in the adoption of PMSynRM over IPMSM has been observed among BEV and PHEV automakers in recent years. Various topologies of traction motor have been detailed in further sections that will declassify the advantages of PMSynRM.

II. TRACTION MOTOR

Classic topologies of induction and synchronous motor have been replaced by permanent magnet (PM) based motors except in Audi E-Tron SUV 2016 and Tesla Model 3. Various topologies and equations of the torque relevant to PM-based traction motors have been discussed in this section.

A. Topologies

Classic topology of synchronous motor and induction motor has armature winding on stator and field winding on the rotor, operates on the principle of rotating magnetic field. Rotating magnetic field set up by alternating current in stator locks the poles set up by field winding on the rotor at synchronous speed in case of synchronous motor. Poles set up by the field winding on the rotor of the induction motor always try to align with rotating magnetic poles set up by stator and rotates at a speed less than synchronous speed. There isn't a significant change in the winding topology of induction motors over the years. The operating principle of PMSynRM and IPMSM is same as

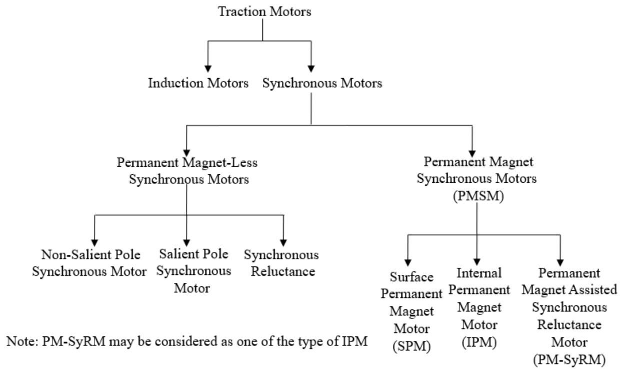


Figure.3. Classification of different topologies of traction motors.

classic synchronous motor except filed winding is replaced by permanent magnets. Permanent magnet-based motors which operate on the principle of operation same as of synchronous motor are often called as Permanent Magnet Synchronous Motors (PMSM). PMSM is available in different topologies may be classified under synchronous motors. The steady-state torque equation of PMSynRM and IPMSM can be well understood by going through the geometry of different topologies of synchronous motors as shown in figure. 4. Surface Permanent Magnet Motor (SPM), IPM, and PMSynRM may be sub-classified as PMSMs. Non-salient pole synchronous motor, salient pole synchronous motor, and

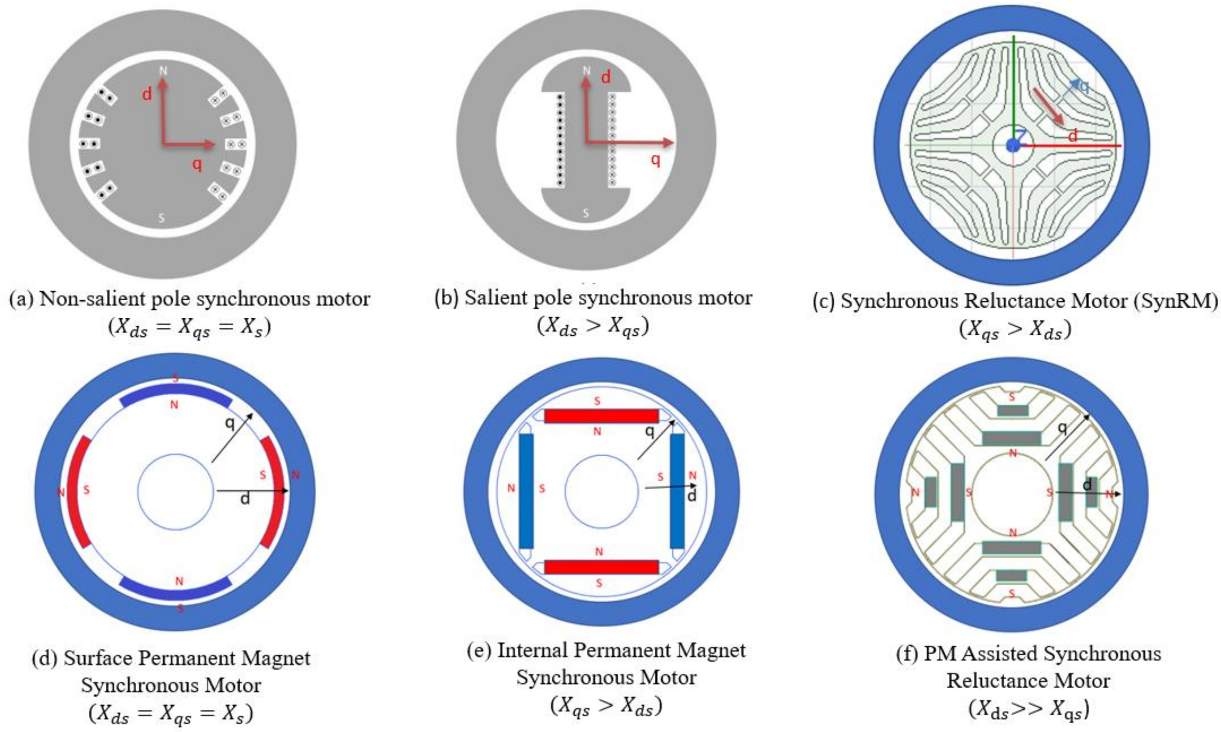


Figure. 4. Schematic of geometry of different topologies of synchronous motors.

synchronous motor are classic topologies of synchronous motor.

Classic topologies of synchronous motor have distributed winding on the stator and concentrated winding on the rotor except for synchronous reluctance motor. The stator winding of SPM and IPM may be sinusoidally distributed or concentrated winding based on the application. PMSynRM has sinusoidally distributed winding on the stator [11]. The field winding is replaced by permanent magnets in the case of SPM, IPM, and PMSynRM. The nomenclature used in this paper has been listed in table 3.

TABLE 3: NOMENCLATURE

Parameter	Explanation
T	*Output torque in N.m*
P	*Number of poles*
V_s	*Source Voltage to the motor*
E	*Induced EMF in Volts*
X_{ds}	*Reactance along direct axis in ohms*
X_{qs}	*Reactance along quadrature axis in ohms*
ω	*Mechanical speed in rad per sec*
δ	*Rotor angle or torque angle*

SPM is analogous to a non-salient pole synchronous motor since the cylindrical providing a uniform air gap. Permanent magnets are placed on the surface of the cylindrical rotor for SPM. It must be noted that width of the permanent magnet is considered an air gap. The direct axis is defined along the north pole and the quadrature axis is defined along with the south pole setup by field on the rotor. Reluctance is proportional to the width of airgap, inductance and inductive reactances are inversely proportional to the width of airgap and hence reactances along direct and quadrature axis is equal in the case of non-salient pole synchronous motor and SPM i.e. $X_{ds} = X_{qs}$.

IPM is analogous to a salient pole synchronous motor. Flux set up by the field winding along direct axis has minimum reluctance path since the air gap is minimum and flux along quadrature axis has maximum reluctance path since the air gap is maximum in case of salient pole synchronous motor. Thus, inductance and inductive reactance along the direct axis is more than the quadrature axis i.e. $X_{ds} > X_{qs}$. Similarly, the flux path along the direct axis of IPM experiences more reluctance since the width of the permanent magnet and length of airgap offer higher reluctance. Flux path along quadrature axis of IPM experiences low reluctance since it has cross only the length of the air gap. Thus, $X_{qs} > X_{ds}$ in the case of IPM.

PMSynRM is analogous to synchronous reluctance motor with multiple air barriers offering a high reluctance path [28] [29] [30]. The synchronous reluctance motor has no back EMF due to the absence of the field winding of the rotor. Flux path along the direct axis of synchronous reluctance motor experiences low reluctance path compared to flux along quadrature axis i.e. $X_{qs} > X_{ds}$. Similarly, flux along the direct axis has multiple permanent magnets embedded in air barriers in addition to the length of airgap experiences high reluctance path compared to flux along quadrature axis. Thus, $X_{ds} >> X_{qs}$ since the width of multiple permanent magnets offers more reluctance compared to IPM or classic synchronous reluctance motor [36]. The difference between reactances along the direct and quadrature axis has a greater influence on the torque produced by PMSM.

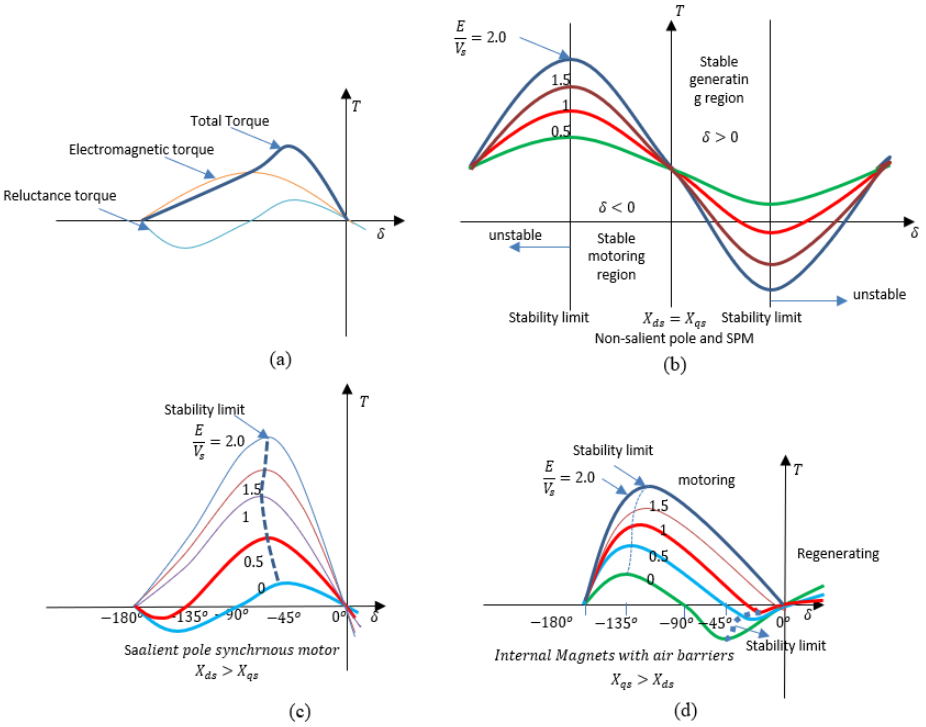


Figure.5. (a). Generic characteristic curve of torque versus rotor angle (b). Torque capability curve of non-salient pole synchronous motor or SPM with similar reactances $X_{ds} = X_{qs}$ (c) Torque capability curve of salient pole synchronous motor (d) Torque capability curve of synchronous motor with internal permanent magnets and airbarriers.

B. *Torque Equation*

The generic equation of torque (1) produced by the synchronous motor has magnetic and reluctance components that may apply to different topologies of the synchronous motor. The difference in magnetic and reluctance components of the torque is based on the shape of the rotor, place of permanent magnets, and air barriers [12] [13].

$$T \cong -\left(\frac{3P}{2\omega}\right)\left[\left(\frac{V_s E}{X_d}\right) sin\delta + \left(\frac{1}{2}\right)\frac{V_s^2(X_d - X_q)}{X_d X_q} sin2\delta\right] \quad (1)$$

First-term of generic torque equation (1) is called magnetic torque and the second term is called as reluctance torque. Thus, reluctance torque is negligible in the case of non-salient pole synchronous motor and SPM. Salient pole synchronous motor, IPMSM, and PMSynRM have both magnetic and reluctance torque due to the difference between reactances along the d-axis and q-axis. Synchronous reluctance motor has no magnetic torque since no back EMF is induced due to the absence of field winding.

TABLE 4: COMPARISON OF DIFFERENT VARIANTS OF MOTORS

Motor Type	X_{ds} vs X_{qs}	T_{em}	T_{re}	Winding Type
No-salient pole	$X_{ds} = X_{qs}$	High	0	Distributed
Salient pole	$X_{ds} > X_{qs}$	High	Low	Distributed
SPM [31]	$X_{ds} = X_{qs}$	High	Low	Distributed/ Concentrated
IPM	$X_{qs} > X_{ds}$	High	Moderately High	Distributed/ Concentrated
PM-SyRM	$X_{qs} >> X_{ds}$	High	Very High	Distributed
BLDC	$x_d = x_q$	High	Zero	Concentrated

$T_{em} = electromagnetic\ torque, T_{re} = reluctance\ torque$

Thus, the torque produced by PMSynRM outperforms other topologies of PMSM [10]. Torque capability curves of different topologies of synchronous motors have been shown in figure.5. The synchronous motor with internal permanent magnets and air barriers i.e PMSynRM is capable of delivering more torque by harnessing the reluctance component of the torque with an increase in saliency.

III. DESIGN TREND

Design trend in stator and rotor of traction motors has been discussed in this section.

A. *Design Trend in Rotor*

The size and number of permanent magnets embedded inside the rotor of PMSM have a significant influence on torque and the overall cost of the motor [10]. To deliver the same torque, the size and number of permanent magnets used in IPMSM are more compared to the PMSynRM. An alternative method to decrease the cost of the motor while increasing the torque is by providing air barriers on the rotor. Thus, air barriers on the rotor of PMSynRM [26] [27] increase the reluctance torque which helps in achieving the cost targets [15]. Teardown reports [16], [17] of Toyota Prius by ORNL have been shown in figure.6 , and table 5 as an example to show a trend in adapting air barrier design of the rotor to improve the volumetric power density and gravimetric power density while cutting the costs per kilowatt.

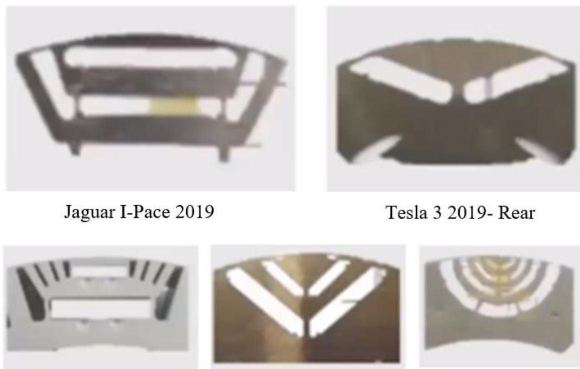
Further, a reduction in the size and number of PMs on the rotor increased the speed specification of the motor. A similar

TABLE 5: DESIGN SPECIFICATIONS OF ROTOR OF TOYOTA PRIUS

	Stack Length (Inches)	Power (kW)	Speed (RPM)
Toyota Prius 2002	3.5	33	6000
Toyota Prius 2004	3.3	50	6000
Toyota Prius 2010 [13]	2	60	13000
Toyota Prius [4] 2017	2.4	53	17000

type of design has been adopted by other manufacturers was reported by Munro Associates [10] has been shown in the figure. 7. Chevy Volt has adapted semi-circular type of barriers [25], slots are filled with ferrite magnets while the remaining have V or U-type air barriers, and slots are partially filled with high flux dense Neodymium (NdFeB) magnets.

Figure. 6. Design trend in rotor of Toyota Prius over the years from 2002 to 2017.



Jaguar I-Pace 2019 Tesla 3 2019- Rear

BMW i3-2014 Chevy Bolt 2017 Chevy Volt 2017

Figure. 7. Design trend in air barrier type rotors of PM-SyRM by different manufacturers.

B. *Design Trend in Stator*

No significant change in the winding topology on the stator side of the motor over the years except for the adaption of advanced technology to wound the stator to increase the slot fill factor [37-39]. Distribution winding is more popular among traction motors but the power density has to be compromised when compared to concentrated winding. Concentrated winding results in non-sinusoidal induced voltage would limit the application of SPM motors. However, fractional slot type of concentrated windings would introduce a non-linearity by increasing inductance along direct axis would result in induced

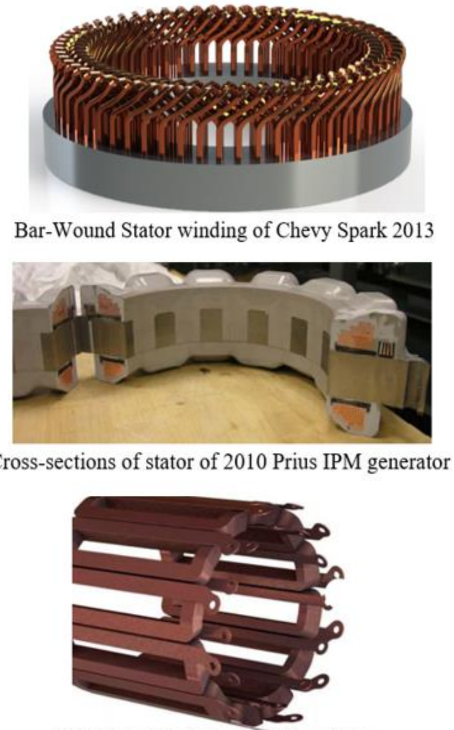


Figure. 8. Design trend in stator windings of PMSMs for electric vehicle traction applications.

voltages near to sinusoidal [18]. Some of the examples of a design trend in stator windings have been shown in figure. 8.

Design of concentrated winding by modular approach [17], distributed winding of Bar-Wound type [18][24], and 3D printed coils [19][20] have been reported as the proven methods to increase the power density, and mass production of the stators can be expedited as well. An efficient cooling methodology that aids the current density and electric loading of the motor [32-35] [40] would further improve the power

TABLE 6: CURRENT DENSITIES OF PMSM UNDER CONTINUOUS OPERATION [11]

Condition	Current Density (A/mm^2)
Totally Enclosed	1.5-5.5
Air-over, fan cooled	5-10
Liquid cooled	10-30
Liquid cooling in ducts	23-31

density of the motor. Typical values of current densities of PMSM under continuous operation have been shown in table 6.

IV. CONCLUSION

State of the art and trend in design matrices of traction motors employed in commercially available electric vehicles have been reviewed. The volumetric power density in kW/L and gravimetric power density in kW/kg of the traction motors have been profiled. The torque capability of several topologies of permanent magnet synchronous motors has been evaluated. Design trends in the rotor and stator of the traction motors to improve the volumetric power density and gravimetric power density profile of the traction motors have been discussed. It can be concluded that Permanent Magnet Assisted Synchronous Reluctance Motor (PMSynRM) outperforms other variants of traction motors in delivering higher torque with an increase in the saliency due to air barriers and enhanced speed capability could be achieved since the volume and weight of permanent magnets embedded in the rotor is low.

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