Comparative Study of Electric Drives for EV/HEV propulsion system

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Abstract: **large scale electrification of transportation industry can be viewed as a paradigm shift in the way sources of energy are accessed, dispatched and consumed. Undoubtedly higher levels of fuel economy, reduced emission of greenhouse gases and other pollutants, and a lesser dependence on petroleum are among major incentives for many industrial and developing countries. The ultimate success of this transformation, in large part, depends on development of low cost, compact, efficient, fault tolerant, and quiet adjustable speed motor drives. The present article provides a comparison among major adjustable speed drives which are currently considered for electric propulsion. In addition, Double Stator Switched Reluctance Machine (DSSRM) as an alternative candidate will be introduced.**

I. INTRODUCTION

Transportation industry has witnessed an unprecedented demand over the past few years. With new strong economies emerging from China and India, the quest for means of personal transportation will further increase. Given the concentration of population in major cities, occurrence of a health crisis is inevitable. Furthermore, dependence of the conventional transportation industry to petroleum is destined to cause economic, political, and social turmoils around the world. While some may argue that there is no short term shortage of fossil fuels and the climate change is not life threatening, the fundamental fact remains as it is only a matter of time when lack of sustainability in transportation industry will cause irreparable harm to our planet and the humankind. Electrification of the transportation industry, by no means, represents a new idea. To the contrary, transportation industry started based on a battery operated electric propulsion unit. However, given the ease of refueling using liquid fuels internal combustion engines gradually dominated the field. Interestingly about a century later, and given the substantial progress in control of adjustable speed drives, battery technology and charging infrastructure continue to be the single impeding factor in mass production of electric vehicles. In spite of significant progress in development of Li-ion batteries and fast charging equipment over the past two decades, development of high efficiency, low cost, and reliable electric propulsion units plays a very important role in overall success of an electrified transportation industry. The metrics which are typically used for testing the adequacy of adjustable speed drives include:

- Torque Density
- Efficiency
- Fault tolerance
- Speed range
- Cost
- Acoustic noise and vibration

In this article three major candidates for development of electric propulsion units will be discussed. This includes permanent magnet synchronous machine, induction machine and switched reluctance machine. As an alternative, a Double Stator Switched Reluctance Machine (DSSRM) will be included in the mix. This comparative study will provide a reasonable framework for selection of electric propulsion units.

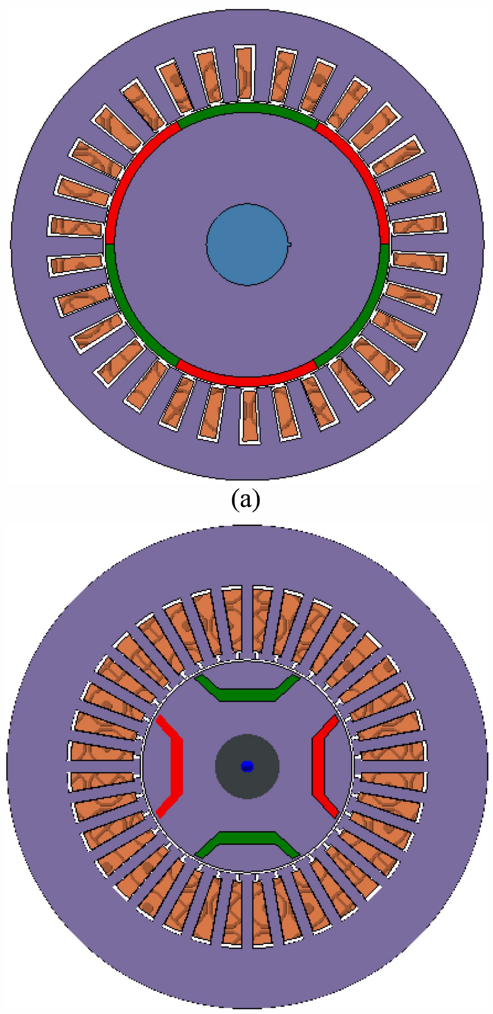
II. PERMANENT MAGNET SYNCHRONOUS MACHINES

Electromagnetic torque generated in Permanent Magnet Synchronous Machine (PMSM) is due to the reaction between stator magnetic field and the rotor magnetic field which is originated from Permanent Magnet (PM) material. The stator core is made out of stacked steel laminations with a number of slots for placing windings. The windings are usually distributed with short or full pitch. The permanent magnet in the rotor can be mounted differently. Depending on the location of the PM, the machine can be a Surface Mount Permanent Magnet Synchronous Machine (SMPMSM) or Interior Permanent Magnet machine (IPM) in which magnet buried in the rotor iron core.

Due to the usage of high energy permanent magnet material, the PMSM can save space and reduce losses in the rotor windings. It also saves the energy which is typically used for magnetizing the machine. These attributes turns PMSM a high torque and high power density machine with relative high efficiency, especially at low speeds. Currently, IPM is used in a majority of Electric and Hybrid Electric Vehicles (EVs and HEVs) in US markets including *Nissan Leaf* [2], *Chevy Volt* [3], *Toyota Prius* and *Honda Insight* [1].

As the magnetic field caused by PM is not adjustable, the induced back-EMF increases proportionally with the rise of rotor speed. This brings about the challenge for operating PMSM at high speeds. Demagnetizing current has to be injected into the stator windings to lower the induced back-EMF in order to obtain necessary torque for operation at high speed.

978-1-4673-1372-8/12/$31.00



(a)

(b)

Figure 1. Cross section of a surface mount PMSM (a) and an interior permanent magnet synchronous machine (b)

As a result, the efficiency at high speed is degraded and the machine has a limited speed ratio in constant power region (especially in SMPMSM drives). A larger speed ratio in the constant power region is desirable in the design of electric propulsion units.

In addition, permanent magnet material is prone to high temperature. The high operating temperature reduces the remnant flux density and thus reduces the torque capacity of the machine. Under the conventional distributed winding configuration, there are electrical, physical, thermal, and magnetic couplings between different phases. The mutual coupling among phases would encourage a sustained current under single phase short circuit condition and reduces the reliability of the machine.

Additionally, the risk of discontinuity and the monopoly in supply chain of high energy rare earth metals have stimulated rapid fluctuations in the price of rare earth metals over the past couple of years. This trend and high demand leads to the high cost of permanent magnet materials. With the growing markets for PM wind generator and EV/HEV, the price will likely continue to increase in the long run. Usage of rare earth PM leads to the high cost of the machine which is not favorable for the development of EV/HEV. Table I illustrates key information about commercially available PMSM drives used by the automotive industry. Table II illustrates the dependency of the power density in a commercially available PMSM drive which is used for electric propulsion of a HEV.

TABLE I
TORQUE DENSITY OF PM MACHINES [4]-[9]

	Air Cool	liquid Cool	
Parameters	IPMSM[4]	IPM[Toyota 2rd] [5]-[9]	IPM [Toyota 3rd][5]
OD	146mm	269mm	264mm
Stack length	224mm	84mm	50mm
Active Volume	3.75L	4.774L	2.737 L
Winding type	Distributed	Distributed	Distributed
Slot fill factor	0.6	0.84	0.84
Airgap (mm)	0.7 mm	0.73mm	
Speed range (rpm)	5000 – 12000	1200-6000	2790-13900
Power	35kW	50kW	50kW
Torque (NM)	70 NM	400 NM	207NM
Current Density (A/mm2)	6A/mm^2	18A/mm^2	19A/mm^2
Torque density per active volume	18.66NM/L	83.78NM/L	75.6 NM/L
Knee point Efficiency	90%	85%	88%

TABLE II
CONTINUOUS POWER OF PRIUS MOTOR AS A FUNCTION OF TEMPERATURE,[8]-[9]

Coolant Temperature	Torque	Torque density	Power
35(°C)	167.3	35NM/L	21kW
50(°C)	159.6	33.43NM/L	20kW
74(°C)	145.7	30.52NM/L	18kW
103(°C)	117.8	24.675 NM/L	15kW

III. CAGE INDUCTION MACHINES

The electromagnetic force in cage Induction Machine (IM) is generated by the virtue of the reaction of stator field and rotor field. However, the rotor field in IM is due to the induced currents in the rotor bars. The stator structure and winding configuration of IM is similar to that of the stator in PMSM. The rotor is made of iron core and short circuited copper or aluminum bars. The overall structure is more rugged than PMSM with considerably lower cost. IM is the most mature electric machine used by the industry. The development of power electronics and control theory has made the IM a good option for adjustable speed drive application. An IM drive has been used in the Tesla roadster.

The existence of the rotor winding introduces copper losses in the rotor and causes difficulty in cooling the rotor. The requirement of magnetizing current reduces the efficiency and the torque density of the machine when compared to PMSM. Nevertheless, the controllable magnetizing current enables the machine operating over a wide speed range and improves the machine efficiency at high speeds. Moreover, IM does not use high cost PM material. This is a significant merit in terms of raw material cost.

IM also has electrical, thermal, physical, and magnetic coupling between different phases. This endangers its ability to continuously operate under fault. Table III summarizes the performance characteristics of three commercially available IM which are used for electric propulsion of EV/HEV.

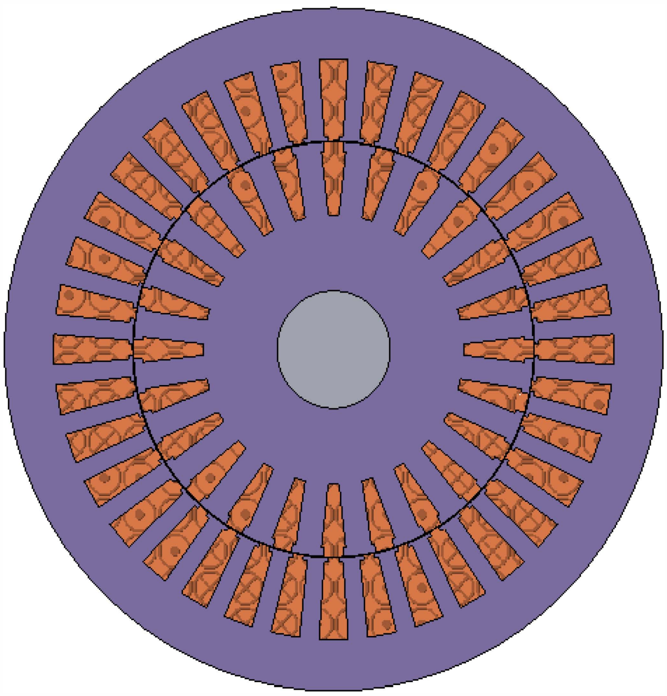


Figure 2: Cross section view of an induction machine

TABLE III
PERFORMANCE CHARACTERISTICS OF INDUCTION MACHINES FOR ELECTRIC PROPULSION

	Liquid cool		Air cool
Parameters	IM[10][9], 8 pole	IM [11], 4 pole	IM[12], 4pole
OD	269mm	240mm	200mm
Stack length	84mm	190mm	300mm
Active Volume	4.774L	8.595L	9.424 L
Winding type	Distributed	Distributed	Distributed
Speed range	1500 – 6000rpm	1750-6000rpm	2200rpm-
Power	47kW	40kW	15kW
Torque	297NM	250NM	65NM
Air gap	0.7 mm	0.7 mm	0.5mm
Current Density	15.7A/mm^2		
Torque density per active volume	62NM/L	29NM/L	6.9 NM/L
Efficiency	83.1%	91% *	89.2%

*estimated

IV. Switched Reluctance Machines

Torque generation in Switched Reluctance Machine is due to the tendency of rotor and stator salient poles to reach alignment hence minimizing the reluctance. Compared to the other AC machines, Switched Reluctance Machine (SRM) has a very simple structure. Its stator has concentrated windings. Its rotor is made of laminated steels which are punched together to form a solid piece. There is no permanent magnet or coil on the rotor. This structure makes switched reluctance machine a rugged machine with relatively low manufacturing and maintenance cost while providing a very large speed ratio in the constant power region [13].

SRM offers a torque density which is comparable to induction machine. A 50kW air cooled SRM [14]-[15] was designed for an electric bus application. This machine has a torque density of 13.33NM/L and the 15kW air cooled SRM [17] used in a small electric vehicle has a torque density of 11.9NM/L. The liquid cooled machine with more than 20A/mm^2 current density in the winding and a relatively small air gap has torque densities ranging from 45NM/L to 61NM/L [6], [16]. Considering the concentrated winding of the machine (i.e. a smaller end coil), the overall torque density would be more competitive.

Switched reluctance machine has negligible coupling between different phases. The torque production of one phase is independent of the other phases. This modular torque generation feature makes SRM a good option for applications which require high reliability.

SRM has several advantages for applications in automotive industry [13]. High torque/power density, extended constant

TABLE IV
PERFORMANCE CHARACTERISTICS OF SRM DRIVES FOR ELECTRIC PROPULSION

	Liquid Cooled		Air Cooled	
	SRM1	SRM2	SRM	SRM
OD	269mm	269mm	280mm	250mm
Stack length	135mm	84mm	290mm	190mm
volume	7.672L	4.774L	17.85L	1.33 L
Winding type	Conc.	Conc.	Conc.	Conc.
Airgap	0.5 mm	0.3mm	0.65 mm	0.5mm
Rated speed	1200rpm	1500rpm	2000rpm	1500 rpm
Power	50kW	50kW	50kW	17kW
Maximum torque	340Nm	294 NM/L	340Nm	111NM
Current Density	24A/mm^2	20A/mm^2		
Torque density	45NM/L	61NM/L	13.33N.M/L	11.9NM/L
Knee point Efficiency	90%	88.2%	88%	88%

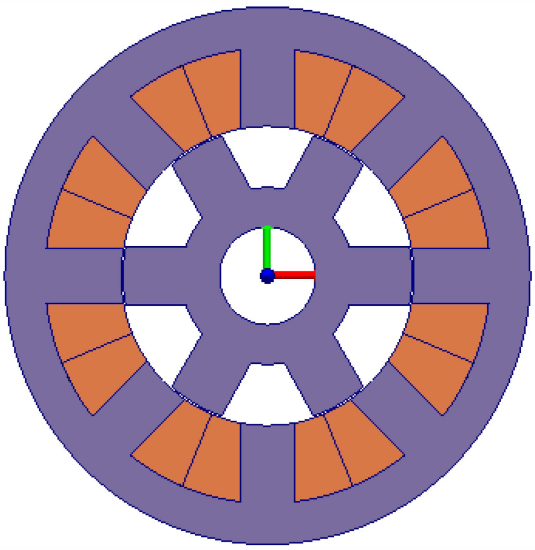


Figure 4: Cross section view of a switched reluctance machine

power region speed range, high reliability and fault tolerant capability and low cost are among them. Noise and torque ripple has been the major drawback of the SRM. Table IV illustrates performance characteristics for three SRM drives which are used in electric propulsion of EV cars.

V. Double Stator Switched Reluctance Machines

Double Stator Switched Reluctance Machine (DSSRM) is a novel switched reluctance machine which is recently conceptualized and developed in the Renewable Energy and Vehicular Technology lab, at the University of Texas at Dallas. It has two stators and one rotor. The outer stator is made out of stacked steel laminations with selected number of poles. The inner stator has similar configuration with outer stator. Full pitch windings are placed in the stator slots as showed in Fig.5. The inner stator and outer stator phases can also be controlled separately for the sake of flexibility and reliability under faulty conditions. By default, the inner and outer stator phases are connected in series for the simplicity of analysis and control. The rotor is made out of six uniform segment poles mounted on a round metal cage.

Similar to conventional SRM, DSSRM has modular torque production features and an extended speed range. Nevertheless, it greatly improves the torque density, torque ripple and acoustic noise.

The DSSRM has much higher torque density than conventional switched reluctance machine [18]-[20]. Table V shows two designs of DSSRM, one air cooled design with the current density limitation of 6A/mm^2 and one liquid cooled machine with 10A/mm^2 current density. The DSSRM has similar torque density to that of a PM machine as shown in the table. However, the material cost is much less than PM machines due to absence of rare earth material. According to [19] the machine material cost is only half of PM machine. The DSSRM owes its high torque density merit to three advantages brought by its superior structure. First, the DSSRM ensures higher force produced in motional direction. Second, within the limited space, the total winding slots area are more than twice of PMSM which allows for more current being injected into the machine. Third, the rotor radius is larger. For the sake of properly distributing the stator excitation and balancing the radial force generated by inner and outer stator, the rotor radius needs to be enlarged as compared to with PMSM.

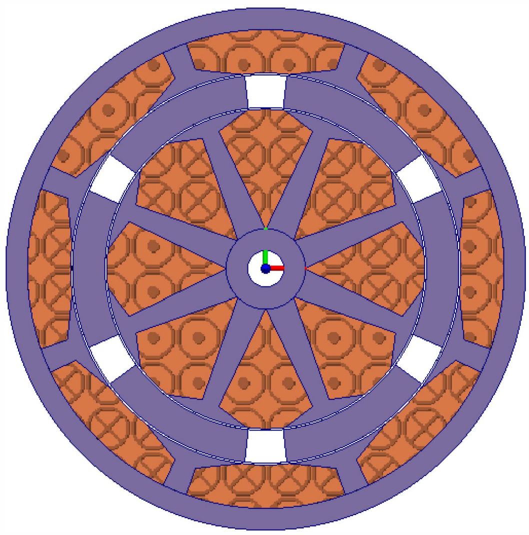


Fig.5 cross section of double stator switched reluctance machine

TABLE V
PERFORMANCE CHARACTERISTICS OF DOUBLE STATOR SRM DRIVES

	DSSRM1 Air cooled	DSSRM2- liquid cooled
Pole number	8/6	12/8
OD	228.6mm	210mm
Stack length	152.4mm	75mm
Volume	6.255L	2.6L
Winding type	Distributed	Distributed
Slot fill	0.5	0.6
Speed range	2000rpm-6000rpm	4000-10000rpm
Power	29kW	50kW
Torque	137N.M	113 N.M
Airgap	0.5 mm each, 1mm total	0.4mm each
Current Density	6A/mm^2	10A/mm2
Torque density	21.9 NM/L	43.46NM/L
Efficiency at Knee	88%	93%

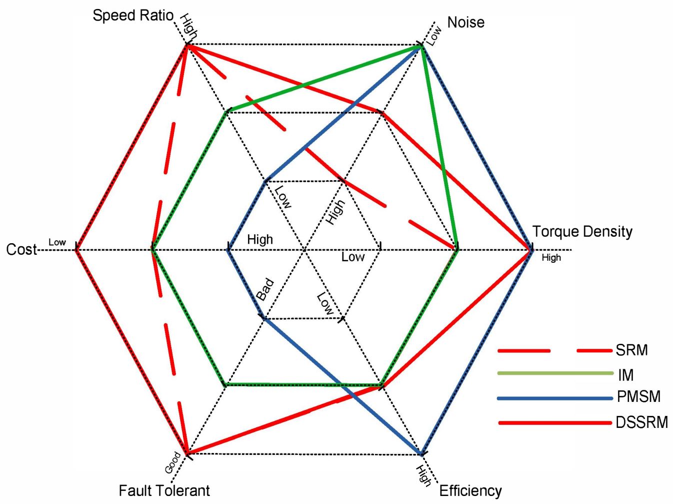


Figure 6: Comparison among various contenders for electric propulsion of cars

VI. CONCLUSIONS

Development of an electric propulsion unit is a multi-folded task which needs to satisfy several boundary conditions including but not limited to efficiency, power density, speed ratio, acoustic noise and vibration, and certainly cost. The following chart summarizes our findings based on existing commercial and research prototypes. It appears that there is more room in conceptualization, design and development of electric machines which can improve many of the performance criterions listed here.

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