A quantitative and qualitative comparison of all commercially motor technologies by means of e-mobility

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***Abstract*—In this study we compare different technologies of electrical motors. All motors are classified in two groups based on the winding configuration. If the coils are wounded around one tooth winding is called concentrated otherwise called distributed which coils are spanned several teeth. All electrical motors are belong whether concentrated or distributed winding. Electrical motors may have one of BLDC, Stepping motor (SM), Switched reluctance motor (SLM), Brushed DC motor, Permanent magnet synchronous machine (PMSM), Axial-flux,Synchronous reluctance motor (SynRM) and Induction motor (IM) for both round rotor and squirrel cage technologies. There are numerous suppliers that manufacture electric motors for different applications, but choosing a typical motor for a certain application is not so easy, especially when customers are dealing with a pile of aforementioned motor technologies. By a quantitative comparison between different motor technologies, one can easily find which motor can fulfill the requirements subjected to constraints and objectives. These characteristics include volume [mm^3], nominal power [W], nominal torque[$N.m$], rotor inertia [$g.cm^2$], price and complexity of the motor. Thus the main objective of this paper is to give crystal clear information to customers for having the optimal choice. More than 250 motors are chosen for this study.**

***Index Terms*—Electrical motor, BLDC, PMSM, concentrated winding, distributed winding, Induction motor, IM squirrel cage.**

I. Introduction

If we classify Electric motors, all of them will belong to whether concentrated or distributed winding. Concentrated windings are split up in four categories which are brushless direct current motor (BLDCM), stepping motor(SM), Switched reluctance motor(SRM) and DC motor. Further BLDCM and SM belong to permanent magnet category, while brushed DC can also have permanent magnets. On the other hand distributed winding motors cover permanent magnet synchronous machine(PMSM), Induction motor(IM) squirrel cage and IM with wound rotor. In this study we focus within a range up to 3000 [W] for aforementioned technologies, manufactured by different suppliers. The name and number of suppliers are provided in the table I. In section II and III principles of the machines for concentrated and distributed winding are provided. In section IV a quantitative comparison in terms of speed, torque, power, volume, price and rotor inertia are given and finally in section V, we conclude and propose the future work on different motor technologies by means of e-mobility.

TABLE I
Machines, topology and associated suppliers

Motor technology	Number of machines	Name/Number of suppliers
BLDC	46	GEMS, Dunkermotoren/ 2
Stepping motor	24	Nanotec, FESTO/ 2
SLM	12	Rocky mountain, Found motor / 2
Brushed DC	69	Dunkermotoren-Sunrise motor/ 2
PMSM	39	Beckhoff, ABB/ 2
Induction machine	46	GAMAK-MT motori electrici/ 2
SynRM	17	Siemens, SICEMOT0RI/ 2

II. Concentrated winding electric motors

Electric motors with concentrated windings have smaller and more compact structure, thus they are more lightweight, while distributed winding are cheaper and spanning the windings are easier and consequently cheaper. Figure 1 shows the diagram chart of all electric motors.

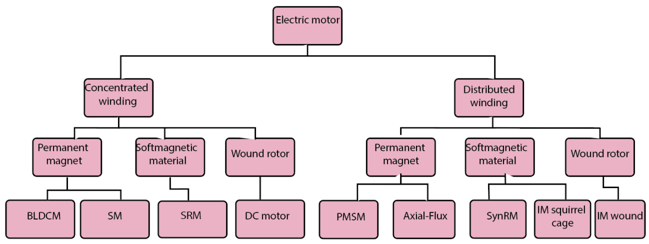

Fig. 1. Classification of electrical motor concentrated and distributed winding including brushless DC (BLDC),Stepping motor(SM), Switched reluctance motor (SLM),Brushed DC motor, Permanent magnet synchronous motor (PMSM), Induction motor (IM), Synchronous reluctance motor (SynRM), Axial- and Radial-flux motor.

A. Brushless DC motor (BLDC)

Brushless permanent magnet direct current motor provides higher efficiency in compare with its brushed counterpart. The control of BLDC needs a change of phase between its coil to communicate with the phases of permanent magnet. Rotor becomes permanent magnet and Stator stands for coil winding which is called commutation. Based on magnet arrangement Rotor and Stator can have different pole pairs and different number of winding respectively. Unlike it's name, BLDC motor is an AC motor. With more pole-pairs, commutation occurs more frequently. There is a trade-off between the gap of rotor and stator and eddy current. Smaller the gap will lead to smaller eddy current, but it should be taken in to account that any contact between stator and rotor can cause to significant damage to the motor. Figure 2 illustrates a 2D surface of a BLDC motor.

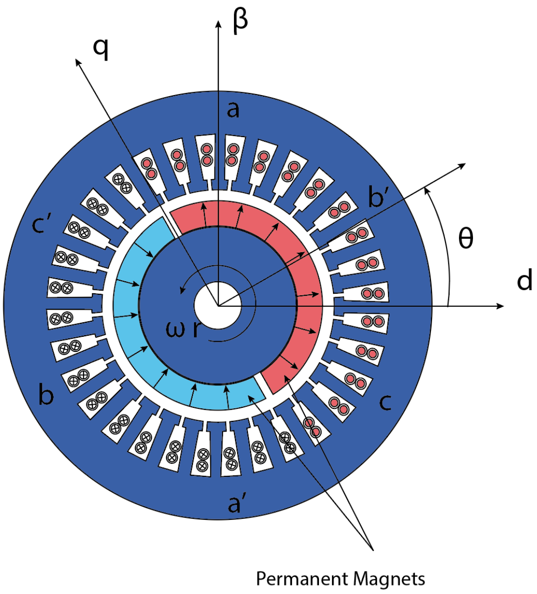

Fig. 2. A cross section of a BLDC motor

B. Stepping motor(SM)

Stepping motors are not a good choice for high speed applications, but in terms of nominal torque $[N.m]$ and power density they are good options. They are packed and provide maximum torque based on their volume [1]. Figure 3 illustrates a cross section of a stepping motor.

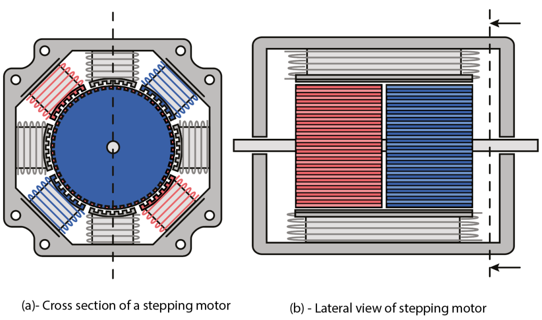

Fig. 3. (a)- Cross section and (b)- Lateral view of a stepping Stepping motor [1]

C. Switched reluctance motor(SLM)

Switched reluctance motors (SRM) seems to be interesting for several applications thanks to its simple structure, cost and reliability. SLMs have not any winding and magnet in their rotors [2]. SRMs are suited for applications with high speed and torque with high efficiency [3]. Figure 4. shows two different designs for a three and four phase SLM.

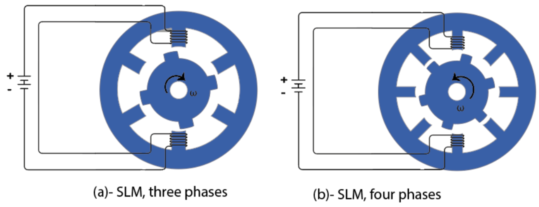

Fig. 4. SLM with (a) three and (b) four phases

SLMs have been used vastly in hybrid electric vehicles (HEVs)[4]. They can provide high torque and power density, high reliability, wide-speed operating range. beside, maintenance of SLMs is cheaper than the other motor topology. Among all advantages of SRMs, high torque ripple and noise are the major drawbacks of this technology [5].

D. Brushed DC motor

Brushed DC motors are used in many applications thanks to their high speed and lower price in compare with their Brushless counterparts. Figure 5 shows a three phase brushed dc motor.

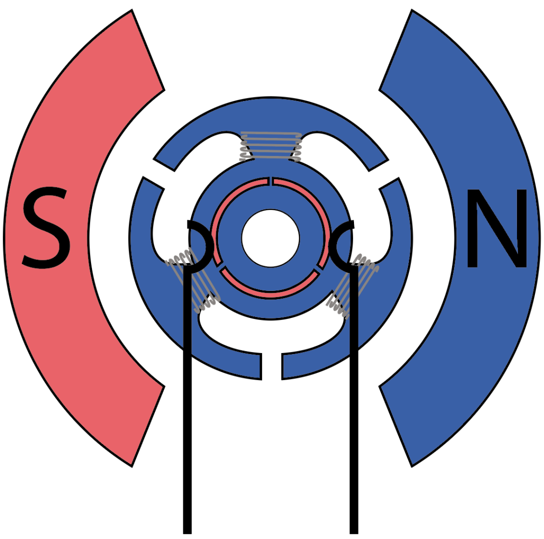

Fig. 5. Operating principle of a three- phase Brushed DC motor

III. Distributed winding electric motor

A. Permanent magnet synchronous machine(PMSM)

In permanent magnet synchronous motors, magnets can be located inside or outside of the rotors. Figure 6 illustrates different topology for PMSM motors.

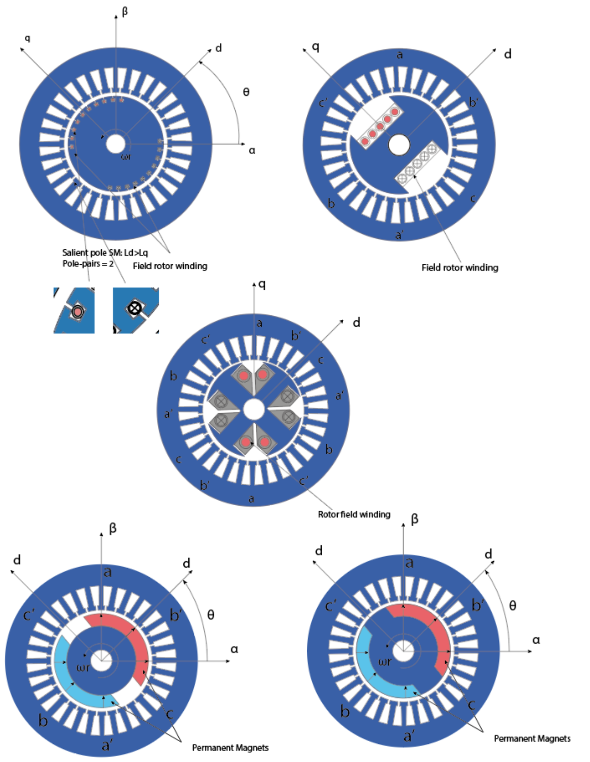

Fig. 6. Different designs for PMSM technology

B. Induction motor (IM)

In an electric motor there are two magnetic field which generated by rotor and stator. While stator magnetic field is rotating, the idea is that rotor align its magnetic field with the stator magnetic field. The three phase set of currents in the stator have equal amplitude with a phase difference of 120°. These currents flow in the stator winding and generate the magnetic field. Among proposed configuration for rotor winding, four rotor winding is the most complete which are denoted by f, d_1, q_1 and q_2, where f stands for field winding, q_2 stands for eddy currents in rotor and d_1 and q_1 represent dampers. Figure 7 illustrates two different designs for IM with and without permanent magnets.

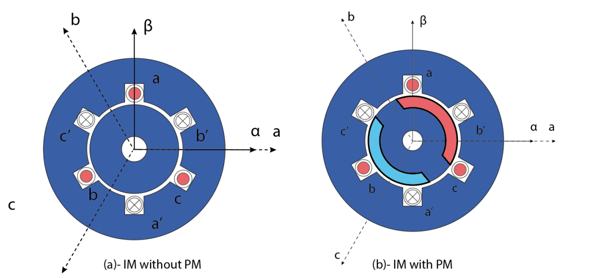

Fig. 7. Induction motor (a) with and without (b) permanent magnet

Among the differences between induction motor and synchronous machine, the basic one is that the IM unlike the synchronous machine is an asynchronous machine. There are two types of rotor construction in Induction machines. In continue both of them are investigated.

1) IM wound rotor: In Wound rotor induction motor, rotor has three winding likewise stator winding; the windings which are located in slots are connected to slip rings and by rotating the rotor they rotate accordingly, while brushes stay stationary

2) IM squirrel cage rotor: Induction motor squirrel cage is used to convert electrical energy to mechanical motion. It is low cost and due to not having brushes the maintenance is cheap in compare with BLDC motors.

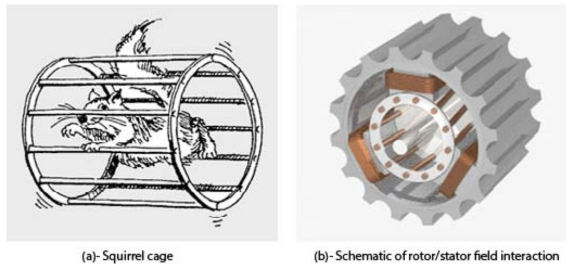

Fig. 8. (a)- Squirrel cage and (b)- Stator/Rotor magnetic field interaction [6]

C. Synchronous reluctance motor (SynRM)

Suppliers try to cut the electricity bill and increase efficiency by changing the design of the motor. Some of these designs contains the curvature flux barrier versus the conventional flux barrier that decrease the cogging torque. High quality magnets are installed in the curvature flux designs. Figure 9 illustrates different designs of SynRM technology.

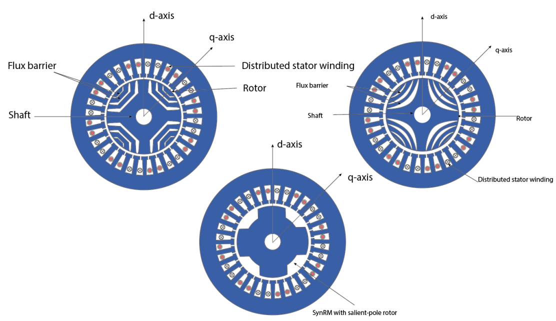

Fig. 9. Three different designs for SynRM motor technology

D. Axial-flux motor

In Axial-flux motor technology two rotor are used to balance the force due to rotor placement in front of the stator. According to Magnax Belgium Co. Axial-flux technology, lowers core losses up to 85%. Further a 22.5$[kg]$ motor provides 300$[kW]$ which is a significant improvement in EVs [7].

IV. Quantitative comparison including torque, speed and power

A. Speed compared to power

By comparing nominal speed (rpm) to rated power (W), figure 10 is obtained. This comparison covers all technologies investigated in this study.

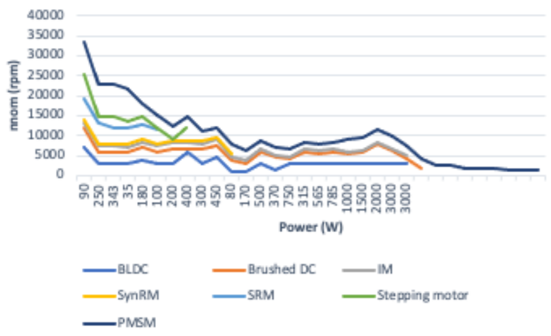

Fig. 10. Nominal speed compared to power

B. Torque compared to volume

By comparing nominal torque (N.m) to motor volume $(mm^3$, figure 11 is obtained. This comparison covers all technologies investigated in this study.

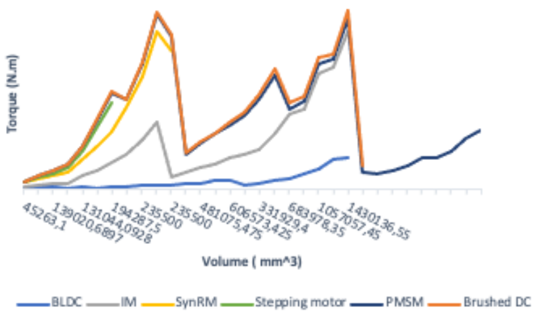

Fig. 11. Motor torque compared to motor volume

C. Power Density

Figure 12 shows the motor power compared to motor volume for all technologies.

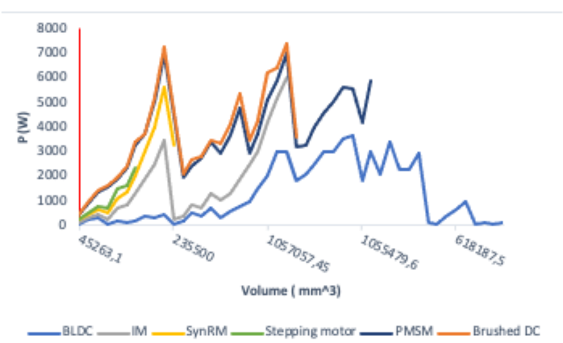

Fig. 12. Motor power compared to motor volume

D. Acceleration and overload capacity

Maximum acceleration is an important factor in dynamic applications. Therefore by dividing maximum torque by rotor inertia, and plotting it over motor power Figure 13 is obtained.

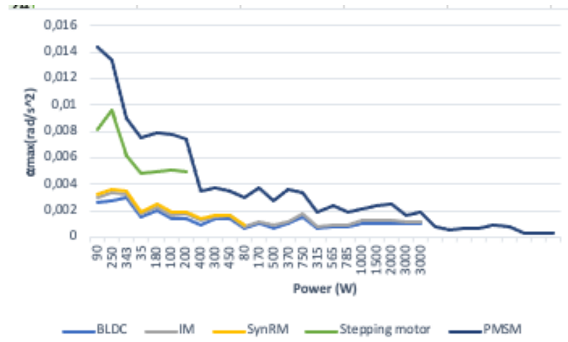

Fig. 13. Maximum acceleration compared to motor power

E. Concluding comparison

Table II summarizes the quantitative comparison for all motor technologies. It shows how each technology suits different applications in terms of speed, torque, power density, acceleration and price.[1].

TABLE II
Performance of different motor technologies on different criteria (1: the best, 7: the worst)

Motor tec.	Speed	Torque	Power density	Acceleration	Price
BLDC	7	6	6	5	-
Stepping motor	2	2	2	2	-
SRM	3	-	-	-	-
Brushed DC	6	1	1	-	-
PMSM	1	3-4	3-4	1	-
SynRM	4	3-4	3	3	-
Induction machine	5	5	5	4	-

V. Conclusion

This study showed the importance of classifying and comparing of different types of commercialized motor technologies. One can simply find which motor can fulfill the requirements based on objectives and constraints. Further, merits and demerits of different type of motor technologies were discussed. Two supplier were chosen for each technology and based on each motor characteristics, different plot were illustrated to show which technology better suits different applications. This comparison gives crystal clear vision to customers by considering 250 electric motors from all existing motor technologies.

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